TALLINNA TEHNIKAÜLIKOOL
TALLINN UNIVERSITY OF TECHNOLOGY

Department of Materials and Environmental Technology

# ANALYSIS OF SOLAR PHOTOVOLTAIC PRODUCTION BASED ON CHIHUAHUA'S WEATHER CONDITIONS

# FOTOGALVAANILISE PÄIKESEELEKTRI TOOTMISE ANALÜÜS CHIHUAHUA ILMASTIKU TINGIMUSTE NÄITEL

**MASTER THESIS**

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Tallinn, 2018

**AUTHOR'S DECLARATION**

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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**THESIS TASK**

**Student:** Felix Efren Gonzalez Reyes, 165546KAYM

**Study programme**: KAYM, Materials and Process of Sustainable energetics

**Main speciality**: Process of Sustainable Energetics

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**Thesis topic**:

(In English) ANALYSIS OF SOLAR PHOTOVOLTAIC PRODUCTION BASED ON CHIHUAHUA'S WEATHER CONDITIONS

(In Estonian) FOTOGALVAANILISE PÄIKESEELEKTRI TOOTMISE ANALÜÜS CHIHUAHUA ILMASTIKU TINGIMUSTE NÄITEL

**Thesis main objectives**:

1.To evaluate and calculate the how the weather conditions affect the production of PV energy

2. To propose an optimal orientation for solar PV panels for the city of Chihuahua

3.To improve already installed PV systems by facing them to a new angle

**Thesis tasks and time schedule:**

| No | Task description | Deadline |
|---|---|---|
| 1. | Analysis of the weather data for the years 2010-2016 for the city of Chihuahua | |
| 2. | Manage founding for the project | |
| 3. | Installation of two PV systems facing to different locations | |
| 4. | Analysed the data generated | |

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# 1. PREFACE

This work was inspired by a simple thought, “why to face the solar panels to the South if I see that the mornings are sunnier than the afternoons”. To answer this question I went to the internet, and I found that the same questions have already been answered, there are models and internet pages that calculate the optimum point for a PV solar system, but the more I looked the more I found that most of the models are based on just one year data. After living in Chihuahua, México and in Tallinn, Estonia I know how the weather can change year to year between a “good” year and a “bad” year, so it got me thinking, why not to analysed some years in order to predict where to face the solar panels.

This project started getting shape after professor Eduard Latõšov agreed to be my thesis supervisor and after that I decided to focus my thesis work, first I was thinking about making my analysis here in Estonia, but several factors limited my research, I didn't a have place to install two solar panels, I didn't have the contacts to get better deals on the price of the parts and more important I didn't have the required money. So at the end of 2017 I went to México in order to start analysing the data, trying to secure some founding for the project and make the installation

Eduardo Rodriguez was the sales person that helped me secure government funding in order to install the project; his company were the ones in charge of installing the two PV modules.

More than anything I hope this works help to change the common idea to face the PV panels to the magnetic south, if with the data and with the data I will get in the upcoming months I hope to persuade the companies that are installing PV modules to use the angle proposed on this work in order to generate more energy with the same resources and besides the economic impact this can have, to help to mitigate the climate change

Special thanks to my thesis supervisor, Eduard Latõšov, to Eduardo Rodriguez for all his support while installing the PV panels, to my work and my bosses at Taxify but specially, to my wife, for always supporting me with any idea that gets into my head.

# 2. LIST OF ABBREVIATIONS

| | |
|---|---|
| BRICS | Brazil, Russia, India, China, South Africa |
| DARS | Delta Average Radiation of the Sun |
| GHI | Global Horizontal Irradiance |
| NREL | National Renewable Energy Laboratory |
| PV | Photovoltaic |
| W | Watt |

# 3. INTRODUCTION

This work will focus on the optimization for solar production based on the unique weather condition for each city, with this new method of calculating an optimal angle of where to face the PV panel is intending to create conscience of facing the PV modules to a more optimal angle based on weather data. In order to measure the different energy produced; this work considers the power output for two similar fixed PV modules, each having a different position on the plane of azimuth. Both of them on the same site, just three meters apart from each other and the aim of the study is to calculate the difference of the total energy produced of each system. The installations are placed in Chihuahua, México. Since the installation is on the northern Hemisphere, one of the installation will be facing the solar South (called true south), and the other installation will be facing a suggested point calculated. The two main sources for inspiration of this work are.

One is Rhodes and his research "A multi-objective assessment of the effect of solar PV array orientation and tilt on energy production and system"[34]This study was the main source of inspiration for going ahead with this work, this studies made on the USA show how important is the unique weather condition for each city and area and how it affected the production of solar energy, and the work even suggested an orientation depending on the location.

The other great source of material for this research is Mertens and his book "Photovoltaics"[23]. If Rhodes talks about the importance of the weather condition, Mertens talks about the relationship between the weather and the radiation, and how a "cloudy" day can affect the direct radiation and the diffused radiation (see figure 12).

This optimum point will be focusing on the effect that the local weather has in the city of Chihuahua and the developed of the analysis will be around the nominal Global Horizontal Irradiance (GHI) and the real GHI that the city of Chihuahua received between the years 2010 and 2016, during the hourly analysis of the weather conditions of those years, was determined that a more optimum angle in the plane of azimuth was 9° degrees East of South (171° in the azimuth plane), this is based on the unique weather behaviour of the city of Chihuahua were overhaul the afternoons tend to be more cloudy than the mornings, therefore an installation facing South but slightly east will be optimized the energy production from a photovoltaic solar system.

In order to better analyse the weather data for this work a new concept is introduced called DARS (Delta Average Radiation of the Sun) that is the difference of the real irradiation versus the theoretical radiation, this data is listened in this work as an average in order to better understand the weather behaviour during a specific parameters, and being able to answer questions like “how the weather at 8am in Chihuahua?” The value of the DARS for this questions is 0.125, meaning that on average, counting all the meteorological data from 2010 to 2016 for the city of Chihuahua, there is a 12.5% change to have a meteorological conditions that will reduce the solar radiation (for this work are consider clouds). A complementary data is that there is an 87.5% change to have a sunny weather at 8am in Chihuahua. All the DARS are arranged in several forms in order to calculate the needed data.

The results of this experiment will greatly challenge the common idea of installing a PV solar system with the south marked by a compass. The main goal of this work will be to assure that a PV system can be significantly improved with a minimum monetary capital required just by adjusting the angle over the azimuth on which the PV system is installed, also the results will show how much economic impact will have to hypothetically change the Solar PV installations in the city of Chihuahua to this suggested angle on the plane of azimuth. It is important to mention that due to the time limit of this work, this study will just show the results of the months of March and April, meaning that there will not be enough statistical data to assure that this method is 100% trustworthy. But I hope in the near future to have more data about this methodology and be able to publish the results of this work in order for the work here been written to be replicated.

# 4. IMPORTANCE OF RENEWABLE ENERGIES

The renewable energies or green energies are inexhaustible and clean sources of energy. Some of the differences from fossil fuels are mainly the diversity of the energies. Also the green energies help to mitigate the climate change by reducing the carbon dioxide on the atmosphere. Moreover the cost and the efficiency of the technology required to harvest the renewable sources into energy have improved over the last two decades.

The investment on renewable energy has overpassed the investment on fossil fuels, meaning that the private sector and the governments have trusted more the sustainable energy than the fossil source of energy such as gas and oil. That is one of the reasons that the source of sustainable energy has grown more over the last decade. Some governments, local and national, have pushed the idea of a 100% commitment to support renewable energy in various sectors. [1]

Some factors were essential for the rapid growth of sustainable energetics over the last 40 years, and according to the Renewable Energy Policy Network for the 21st Century (REN21), these factors were mostly economical. Several energy crises forced some governments to invest in a more secure source of energy, in order to stop depending of the volatility of the fossil fuels and the countries that control the market. Such countries that were pioneers into the monetary investment in the green energies were USA, Denmark, Germany and Spain. [1]

Around the world many treaties have been signed between different countries in order to mitigate the climate change and to promote the use of sustainable energies, among those treaties, one of the most important is the Kyoto Protocol. It was signed in 1997 and its main objective was to reduce the emissions that are cause of the greenhouse effect. A more recent treaty in order to mitigate the climate change was Paris Agreement, which calls for 100% sustainable power source or 80% diminishments in ozone depleting substance outflows by 2050, almost 1,000 city chairmen from five main countries marked the Paris Agreement. [2]

The definition of sustainable development is such development that satisfies the present needs without compromising the resources for future generations. In order to be truly sustainable, the resources cannot be consumed faster than they can be renovated, also the residuals of such process cannot be generated faster than they can be absorbed by the environment. [3]

The main technologies to harvest the renewable sources of energy are Biopower (biomass), Geothermal, Hydropower, Ocean Power, Solar and Wind energy.

The development in renewables has been driven by a few elements. As a matter of first importance, we see a worldwide trust that sustainable power assumes a key part in relieving the harmful gases in atmosphere and subsequently reducing global warming. [2]

And because governments have more trust on renewable energies, with incentives they are trying to get the population more involved in the developing of sustainable energies, such incentives are often tax reduction or a monetary help in order to promote renewable energy. This promotion of renewable energy can be applied to a wide aspect of economic and social development, such promotions can be:

- Lowering the taxes of goods related to green energies.
- Making tax free revenue or reducing the tax revenue for companies that are manufacturing or installing renewable energy products.
- Incentives to schools to promote more studies related to sustainable energetics.
- Monetary compensations or discount in the price for companies and private owners that install green energy equipment in order to have less electrical dependency on the grid.
- Scholarships in order to promote sustainable energies among students.
- Higher taxes on fossil fuels.

In the year 2004, just 46 countries had implemented a renewable energy policy that will push their governments to achieve a higher involvement in sustainable energy, less dependency on the fossil fuels and a higher efficiency on the use on energetics. A decade later, 164 countries had implemented a policy with a target on their use of energetics. [4]

It was mentioned that the governments trust more renewable energies, but trust cannot be measured, investment can. The total investment in renewable energy in the 2005 was 72.8 billion of USD, and just ten years later, the investment almost quadruples (see Table 4.1). The technologies that manage a bigger investment of capital were the solar power and the wind power. [2]

In the year 2015 the global capacity from sustainable technologies was 1,849 GW, with more than 1,000GW coming just from the hydropower. China is the country that is leading the total capacity worldwide, just China alone has around 500 GW of capacity of sustainable energy, more than USA, Germany, Italy and Spain all combined. [2] Table 4.1 shows the investment in different renewable energy technologies from the year 2005 to the year 2015.

| NEW INVESTMENT BY TECHNOLOGY | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Billion USD | | | | | | | | | | |
| Solar power | 16.1 | 22.2 | 38.9 | 61.6 | 64.4 | 103.7 | 154.8 | 146.2 | 119.1 | 143.8 | 161.0 |
| Wind power | 29.0 | 39.8 | 61.2 | 75.4 | 79.8 | 98.7 | 84.2 | 81.9 | 90.6 | 105.7 | 109.6 |
| Biomass and waste-to-energy | 9.7 | 11.9 | 16.2 | 17.1 | 14.7 | 15.7 | 18.0 | 13.5 | 10.5 | 10.4 | 6.0 |
| Biofuels | 7.3 | 7.6 | 6.7 | 7.6 | 6.2 | 7.9 | 7.2 | 6.4 | 5.5 | 5.5 | 3.9 |
| Hydropower <50 MW | 9.6 | 28.2 | 28.3 | 18.5 | 10.4 | 10.1 | 10.3 | 7.2 | 5.7 | 4.7 | 3.1 |
| Geothermal power | 1.0 | 1.5 | 1.9 | 1.7 | 2.9 | 2.8 | 3.7 | 1.8 | 2.4 | 2.6 | 2.0 |
| Ocean energy | 0.1 | 0.9 | 0.8 | 0.2 | 0.3 | 0.3 | 0.3 | 0.3 | 0.2 | 0.4 | 0.2 |
| **Total New Investment** | **72.8** | **112.0** | **154.0** | **182.2** | **178.7** | **239.2** | **278.5** | **257.3** | **234.0** | **273.0** | **285.9** |

Table 4.1. Investment in renewable technology. [2]

Spain leads the investment and the installation of Solar Thermal Power with 2.3GW out of a global total of 4.8 GW, almost half of the global capacity. Europe is the region that has more capacity of sustainable energies per capita in the world. [2]

| TECHNOLOGY | Global | EU-28 | BRICS' | China | United States | Germany | Japan | India | Italy | Spain |
|---|---|---|---|---|---|---|---|---|---|---|
| | GW | | | GW | | | | | | |
| Bio-power | 106 | 36 | 31 | 10.3 | 16.7 | 7.1 | 4.8 | 5.6 | 4.1 | 1 |
| Geothermal power | 13.2 | 1 | 0.1 | ~0 | 3.6 | ~0 | 0.5 | 0 | 0.9 | 0 |
| Hydropower | 1,064 | 126 | 484 | 296 | 80 | 5.6 | 22 | 47 | 18 | 17 |
| Ocean power | 0.5 | 0.3 | ~0 | ~0 | 0 | 0 | 0 | 0 | 0 | ~0 |
| Solar PV | 227 | 95 | 50 | 44 | 26 | 40 | 34 | 5.2 | 18.9 | 5.4 |
| Concentrating solar thermal power (CSP) | 4.8 | 2.3 | 0.4 | ~0 | 1.7 | ~0 | 0 | 0.2 | ~0 | 2.3 |
| Wind power | 433 | 142 | 180 | 145 | 74 | 45 | 3 | 25 | 9 | 23 |
| **Total renewable power capacity** including hydropower | **1,849** | **402** | **746** | **496** | **202** | **97** | **65** | **83** | **51** | **49** |
| **Total renewable power capacity** (not including hydropower) | **785** | **276** | **262** | **199** | **122** | **92** | **43** | **36** | **33** | **32** |
| **Per capita capacity** (kilowatts per inhabitant, not including hydropower) | 0.1 | 0.5 | 0.1 | 0.1 | 0.4 | 1.1 | 0.3 | 0.03 | 0.5 | 0.7 |

Table 4.2. Global installation of renewable energies in the year 2015. [2]

# 5. SOLAR GEOMETRY

The earth has roughly 12,700 kilometres of diameter and has a movement around the Sun in a relatively circular trajectory; it is well-known that our planet has two kinds of movements, one around the Sun and one around Earth's own axis. The distance between the Sun and our planet is roughly 150 million kilometres. The time that Earth makes one trip around the Sun is commonly known as one calendar year, when in truth is 365.242189 days (365 days, 5 hours, 48 minutes and 45 seconds)[5]. Those 5 hours, 48 minutes and 45 seconds are the reason why every 4 years it is added an extra day in February, such year is called the "leap year". [5]
For the translation movement around the Sun is following an ellipse of low eccentricity in which the Sun occupies the spotlight. [6]

In the spinning motion, the Earth rotates on itself around its polar axis, perpendicular to the terrestrial equatorial plane. Between the polar axis and the plane of the ecliptic there is an angle of 23.45° this angle between the equatorial plane and the line between Earth and Sun is variable throughout the year. Just at the spring and fall equinoxes is the declination angle is equivalent to 0°. This variable angle is the cause of the seasons (summer, winter, autumn, spring), of which the Sun appears higher in the summer and the winter; the days are shorter than those of summer. This angle is called solar declination. [7]

## 5.1 Solar declination

The solar declination (Figure 5.1) reaches its minimum at the equinoxes (September 21st and March 21st). The solar declination reaches its maximum of 23.45° two times a year on the summer solstice and the winter solstice. For the northern hemisphere the summer solstice is on June 21st and the winter solstice is on December 21st. [8]

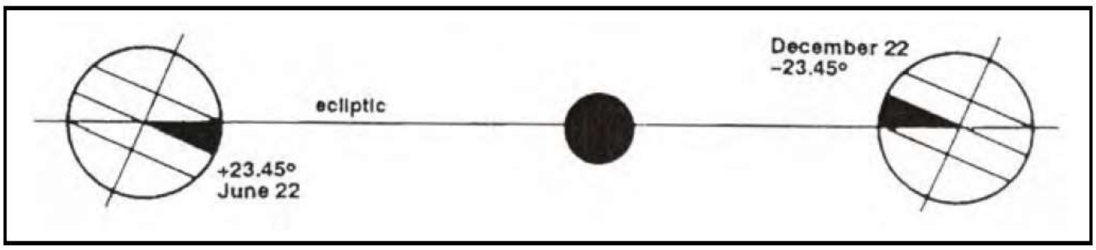


Figure 5.1. Solar Declination. This image graphically shows the changes between the two biggest solar declinations, the winter solstice and the summer solstice.[5]

The estimation of the solar declination takes certain values that define the seasons and their dates of transition. In the equinoxes the solar declination is zero, so the sunrise and sunset are considered to be by the East and West, making this an equal length of day and night. Figure 5.2 shows the values of the Solar declination angle in a year.

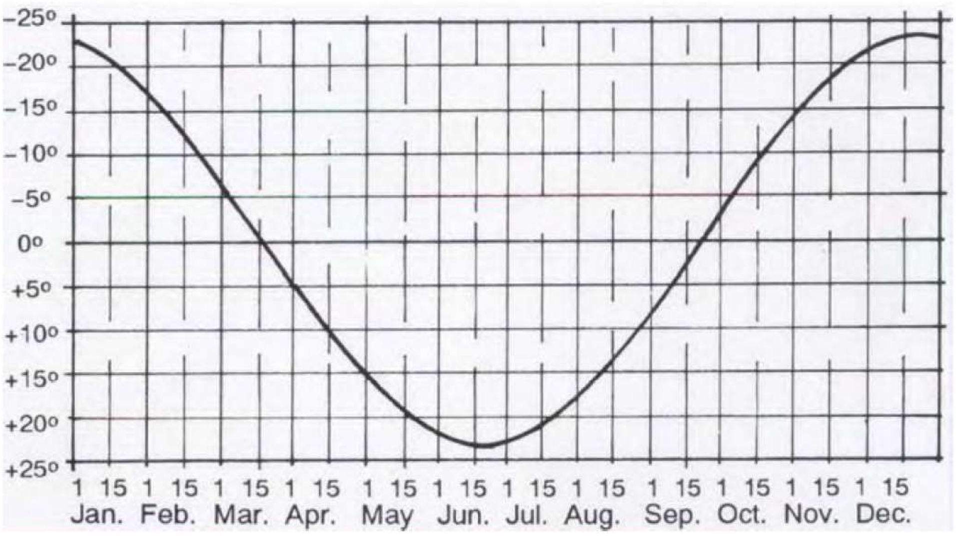


Figure 5.2. Yearly solar declination for the southern hemisphere. [5]

In the June solstice the solar declination takes the value of d = +23.45°. This mean that in the Northern Hemisphere it is called summer, creating the longest day of the year, with the Sun rising in the upper east and setting in the northwest. In the December solstice the solar declination takes the value of d = -23.45° (Negative). In the Northern Hemisphere this solstice is called winter, and it makes the shortest day of the year, with the Sun rising in the southeast and setting in the southwest. [5]

## 5.2 Earth's imaginary lines

The meridian is the non-existent circular segment that crosses the Earth's surface from the North Pole towards the South Pole (or vice versa). All the meridians have the same length. The solar noon point occurs when all points belonging to the same meridian observe the Sun in an intermediate place between sunrise and sunset, reaching the maximum height in the sky, such point is just an instant.[5]

The equatorial line is an imaginary line that divides the earth into two hemispheres; such divisions are called Northern Hemisphere and Southern Hemisphere. The equatorial line is perpendicular to the Earth's rotation axis, also during the spring and autumn equinoxes the Sun is perpendicular to the Equator line. The Ecuadorian line is considered as the base parallel with a value of zero. There are other imaginary lines that are parallel to the Equator line, it is defined that lines in the northern Hemisphere have a positive value and those on the southern hemisphere have a negative value. The latitude for the equatorial line is 0°, also the maximum latitude (the one at both poles) is 90° that are considered to be the Earth's poles, since it is adopted that the northern latitudes take positive values, the North Pole is +90° and the South Pole takes the value of -90°. [5] Figure 5.3 illustrates the Earth's imaginary lines for the summer solstice for the northern hemisphere and their altitude angles.

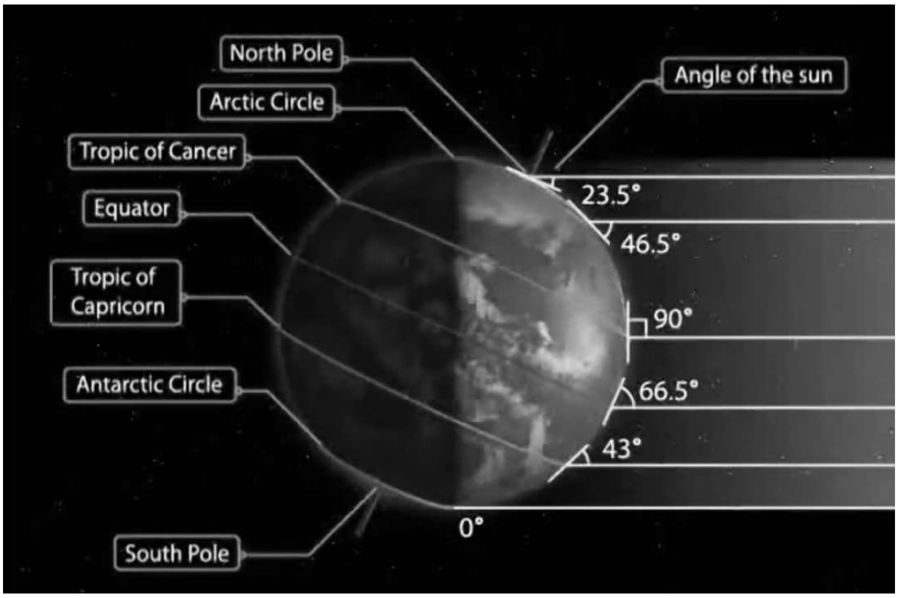


Figure 5.3 Sun's radiation during summer solstice.[40]

There are 5 major latitude lines on Earth (all of them imaginary), one of them is mention to be the Equator, and the other 4 are: the Tropics (Capricorn and Cancer), the Arctic Circle on the northern hemisphere and its counterpart the Antarctic Circle on the southern hemisphere.

The tropic line is an imaginary circle that is located in the latitude with a value of 23.45°. This is the same value that the solar declination takes at its highest. This means that the rays of the Sun arrive to the tropic perpendicular with an angle of 23.45° having as a reference the equatorial line. Also on the tropics once a year such angles become zero and the Sun is perfectly perpendicular to the tropic line, such dates are the solstices. In the southern Hemisphere the tropic is called Capricorn with a value of -23.45°. [8]

In the northern hemisphere the tropic is called Cancer, with a value of +23.45°. Throughout the year the sun rays are perfectly perpendicular between the tropic of Cancer and the tropic of Capricorn.

The other two major latitude lines are the Arctic Circle and the Antarctic Circle. This two imaginary circles are located in the latitude with a value of 66.5°. During the solstice of winter one of those points experience the polar night, an event when the Sun does not rise over the horizontal. The other point will experience their counterpart, the Midnight Sun, an event when the Sun does not set over the horizontal. [9]

## 5.3 Solar time and solar Angle

The official time is a point on the planet that its main purpose is to measure the time connected to a meridian, called time zone, which fills in as a kind of reference for a particular region. At present there are 39 zones around the planet. All the time zones are referenced from the Greenwich Mean Time or GMT considering negative the time zones found west of Greenwich and positive those found east of this time zone. It is possible to confirm that the real sunlight based day, characterized as the time passed between two successive strides of the Sun by the local meridian, changes consistently throughout the year. [10]
The yearly change of this variation is zero, and consequently the normalized Sun based day is used, called mean solar day.[10]
There are 4 important angles when referring to the solar position on the Sun [11]. (See figure 5.4)

- **Azimuth (AZI).** This angle measures the Sun over the horizontal plane. Normally it is considered north as 0° or 360° and from base on that considers the other cardinal points in a clockwise direction. (90° for East, 180° for South and 270° for West)
- **Altitude (ALT).** This angle measures the Sun based in the horizontal plane, meaning the angle that is formed between the horizontal and the Sun.
- **Zenith (ZEN).** Can be considered the complementary angle of the Altitude because this angle measures the vertical plane and the Sun's position.
- **Hour angle (HRA).** This angle measures the solar noon respect to the time of the day. Each solar hour is represented with 15° (360° of the full rotation of the Earth divided between the 24 hours that a day has). (See figure 5.5)

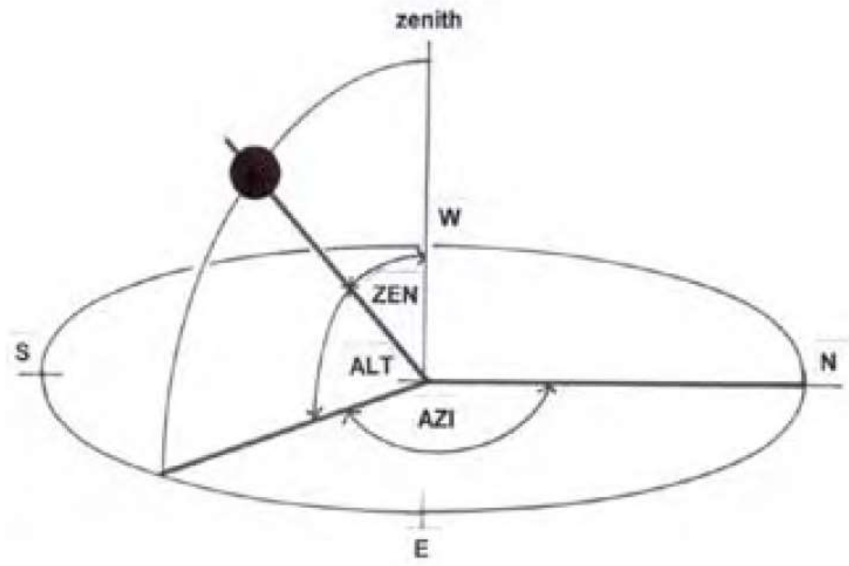


Figure 5.4. Angles for solar position. This graphic represents the different angles in order to relation the position of the Sun on Earth.[5]

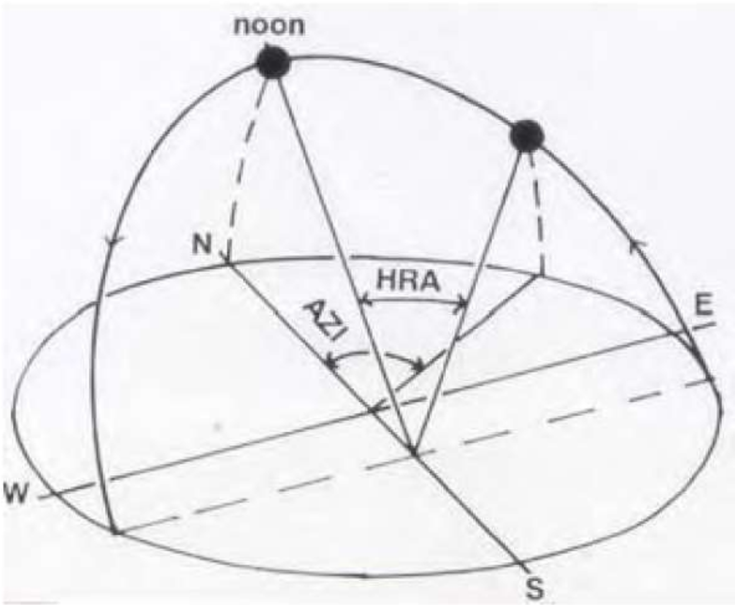


Figure 5.5. Hour angle at noon. This graphic represents the hour angle at noon.[5]

On the two equinoxes it is considered that the sunrise would appear exactly in the east, and the sunset would be exactly in the west. As well the value of the Altitude (ALT) will be 90° minus the latitude (value without consider on which hemisphere). On this day it is considered that the Zenith is the same as the latitude (absolute value of the LAT). [11] Figure 5.6 shows a graphic 3D description of the change of the Sun's path for the Northern Hemisphere

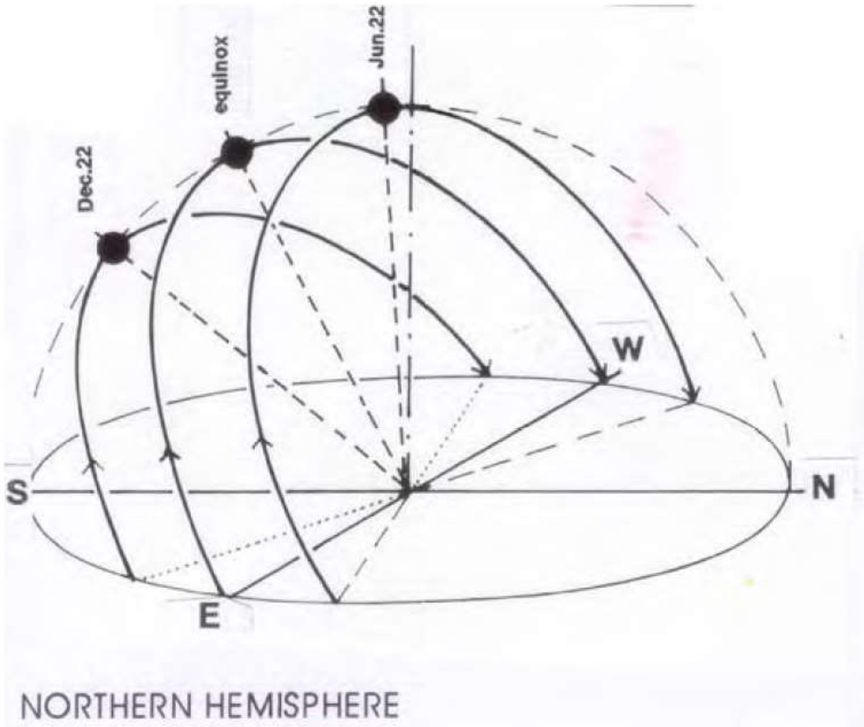


Figure 5.6 Sun's path for the Northern Hemisphere. [5]

Because of the change of the Earth's tilt, also the length of the day's changes during the year, during the equinoxes, the Sun's rays will hit the surface on the Equator on exactly 90°. Meaning a solar declination of 0° , on these days (21st September and 21st of March) the length of the day on every point on the Earth will be 12 hours, it doesn't matter on which hemisphere, the length of the day and the night will be the same on the Equator, North Pole and South pole.[12] But this equality between day and night is technically just two times a day, after this day the Earth continues its moving circle and eventually reaches the solstices, when the solar declination reaches its maximum, meaning that the Sun's rays are perfectly perpendicular on one of the tropics, for the Northern Hemisphere will be the tropic of Capricorn on June 21st. On this specifically day, the length of the day on the tropic of Capricorn is 13 hours and 27 minutes, meaning the longest day (polar days) for the Northern Hemisphere and the shortest for the Southern Hemisphere (polar nights).[12] Figure 5.7 illustrates the Earth's imaginary lines for both of the equinoxes and their altitude angles and figure 5.8 illustrates the Earth's imaginary lines for the winter solstice for the northern hemisphere and their altitude angles.

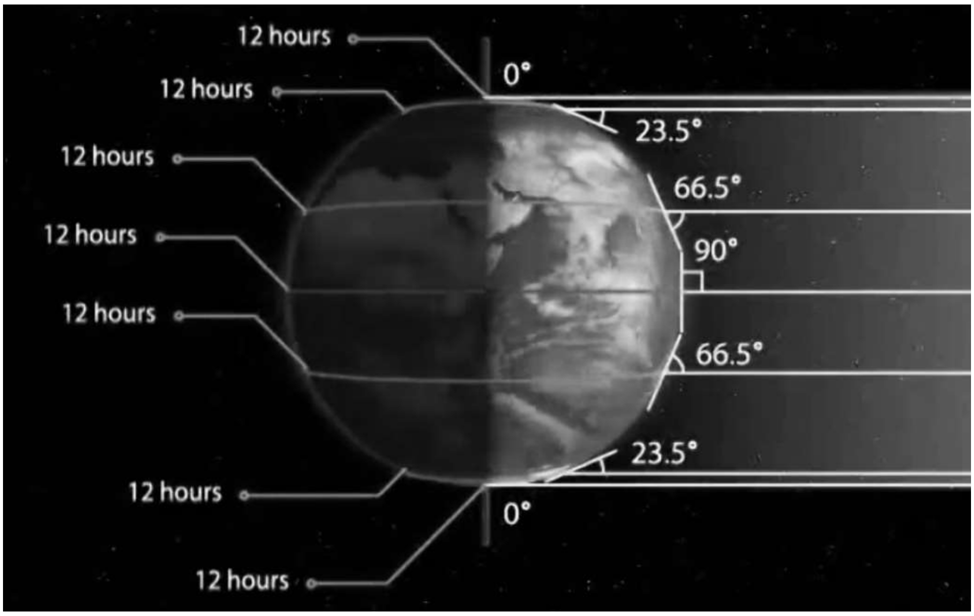


Figure 5.7. Sun's radiation during the equinoxes.[40]

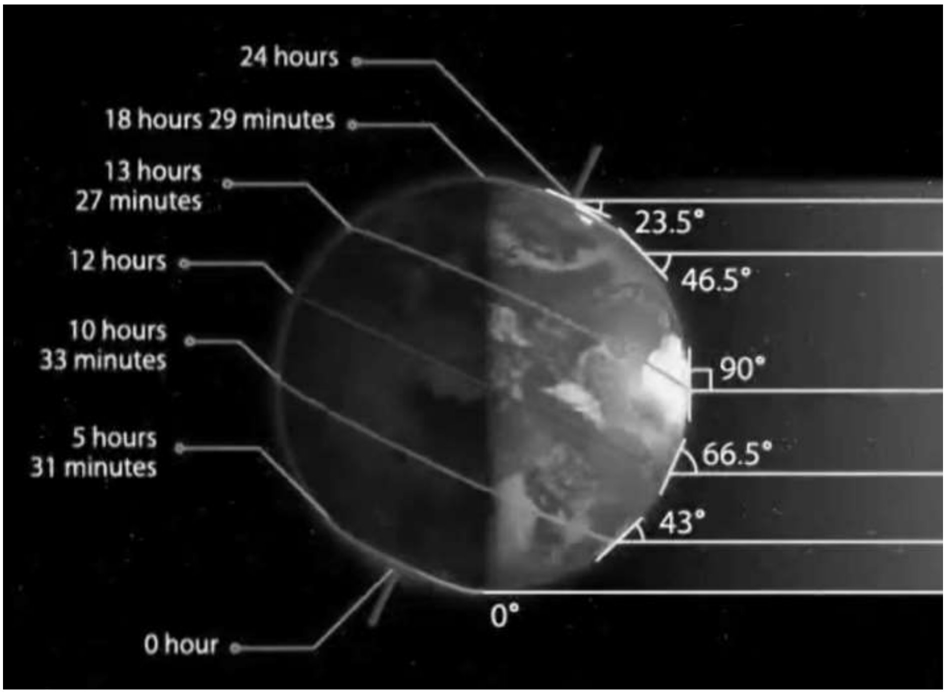


Figure 5.8-. Sun's radiation during winter solstice. [40]

# 6. ONE EARTH, TWO NORTHS

Earth has two norths, one was mentioned earlier and is called the real north or solar north. Real north (or true north) is where all the meridians converge. Its counterpart is the real south. Real south and real north are where the axis of the Earth is located.[13]

Earth generates a magnetic field, and of course like all magnetic fields Earth as well has two magnetic fields, called Magnetic North and Magnetic South, this point is where the lines of the magnetic field are directed. The Magnetic north is where the compass points north and its counterpart is the Magnetic South. Unlike the real poles (north and south) that they are opposite to each other, the Magnetic North pole and Magnetic South pole geographically are not exactly opposite. This is because the magnetic poles are constantly moving. And because the magnetic north is not a fixed point like the true north, these days is located around 1,600 km away from the true north and located in northern Canada and moving, but not significantly enough to be noticeable in a period of a year.[13]

The angle formed in the plane of Azimuth between the true north and the magnetic north is called magnetic declination. As well as the magnetic north, the magnetic declination changes in time, but also the magnetic declination changes from place to place. In some places for a period of time, the normal compass can point true north while pointing the magnetic north.[13]

# 7. IMPORTANCE OF SOLAR PV

The basic source of energy is without any doubt the solar energy. Solar energy is fundamental for the evaporation of the water that eventually creates clouds that then produce rain. Solar energy helps in warming up the soil, the photosynthesis of the plants and even the creation of some winds. The solar energy, not just a source of energy, is a source of life.

The solar energy is a source of energy that has many advantages comparing with other sources of energy, but as well presents some difficulties in trying to harvest such renewable energy. Some of the advantages are that the solar energy is 100% renewable, is inexhaustible, it can be predicted with a small error and after installation the production of energy is pollution free and it is easy to maintain. On the other side the solar energy is relatively expensive to harvest, its production is intermittent between the day and night and some of the variations on the production are far away from human control (weather changes). These challenges make the solar energy production to required optimal engineering changes in order to be more efficiently produced, cheaper and simpler to be storage. [14]

Over the last decades the world has developed a higher need for energetics, and the solar rays, with the right equipment can be transformed into electrical energy and thermal energy. The electrical energy produced directly from the Sun is called photovoltaic (PV) energy.

A brief introduction of what is a solar photovoltaic system. A PV system is the equipment that is used to produce electrical energy from the solar radiation. The principal component is the PV module that is formed of cells that are capable of transforming the solar radiation into electrical energy. [15]

Solar silicon photovoltaic cells were discovered in 1918, by Jan Czochralski, a Polish engineer. Early solar photovoltaic cells were not very efficient and also they were expensive to maintain. While time passed, the technology improved and became cheaper to manufacture and more efficient. In the 21st century, the efficiency continues to rise and the future forecast shows that there are no signs that the efficiency would stop increasing.[16]
The price of the PV solar cells has decreased more than 700% since 1995; it is noticeable that the cost for solar models fell drastically between 1998 and 2011. The average cost for a multi crystalline silicon solar module was reducing on an average of 8% yearly. [16] (See figure 7.1).

Around the year 2011 the price of the PV stopped decreasing rapidly and ever since we have seen a trend of stability with a small yearly reduction on the price.[16]

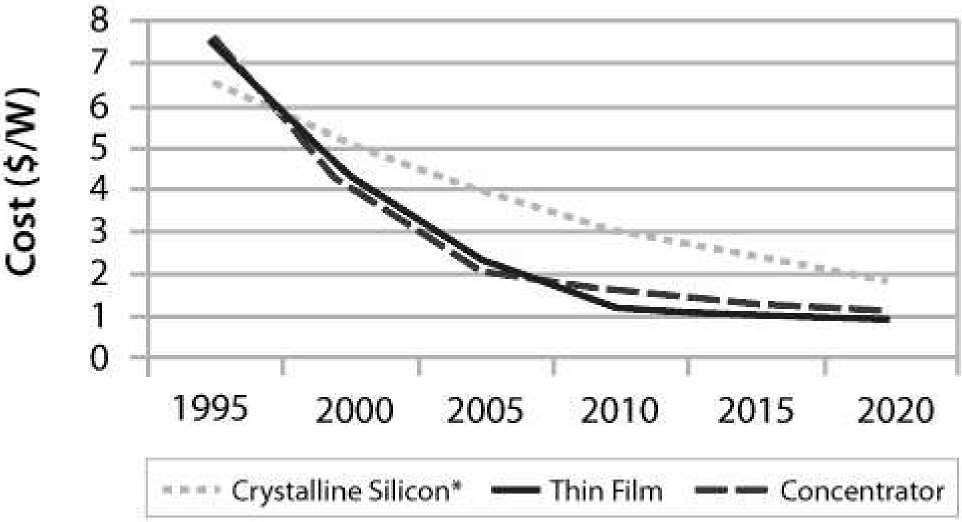


Figure 7.1. Price of solar PV modules. Graphical description of the prices through the years 1995-200 of different minds of solar PV modules [16]

Installation of solar PV had also got cheaper, not just the basic components like the inverter and the solar module and the payback time of the installation is today more attractive to the private sector to invest in this technology. A study in the USA shows that the total price of a PV installation for a residential use has dropped from $7.2 USD per Watt in 2010 to $2.8USD per Watt in 2017. [17] Table 7.1 shows the breakdown of the cost for domestic PV installations connected to the grid. Other costs are referred to land acquisitions, different taxes and other costs that are not directly connected to an installation of a Solar PV system.

| USD per Watt | **2010** | **2017** | **% decreased** |
|---|---|---|---|
| **Other Cost** | 2.2 | 1.2 | 45 |
| **Install Labour** | 1.2 | 0.7 | 41 |
| **Structural and Electronic components** | 0.4 | 0.3 | 25 |
| **Inverter** | 0.7 | 0.2 | 71 |
| **Module** | 2.7 | 0.4 | 85 |
| **Total** | **7.2** | **2.8** | **61** |

Table 7.1. Cost of solar Installation in 2010 and 2017.[17]

As seen as in the table 7.1, the total cost of implementing a solar PV System got 61% cheaper over 7 years. This means that besides the technology getting cheaper also the "know how" played a great role in securing more affordable PV installations in the USA. 41% price reduction of the direct labour cost was obtained mainly because the experience that the industry obtained over the years in installing solar PV equipment. The smallest of the price reductions is from the structural and electronic components, and it is because of that the price of the materials for electric wiring needed for the installation of the PV system has experience an increase on the global market. But the most important reduction on the price was on the technology itself, 85% reduction on the solar Module and 71% on the Solar Inverter, meaning this technology definitely is getting more accessible and the payback times are getting more attractive to house owners to invest on PV technology.[17] The industrial silicon PV cells produced in 2017 usually offer efficiency between the 13% and the 17% (figure 7.2). [17]

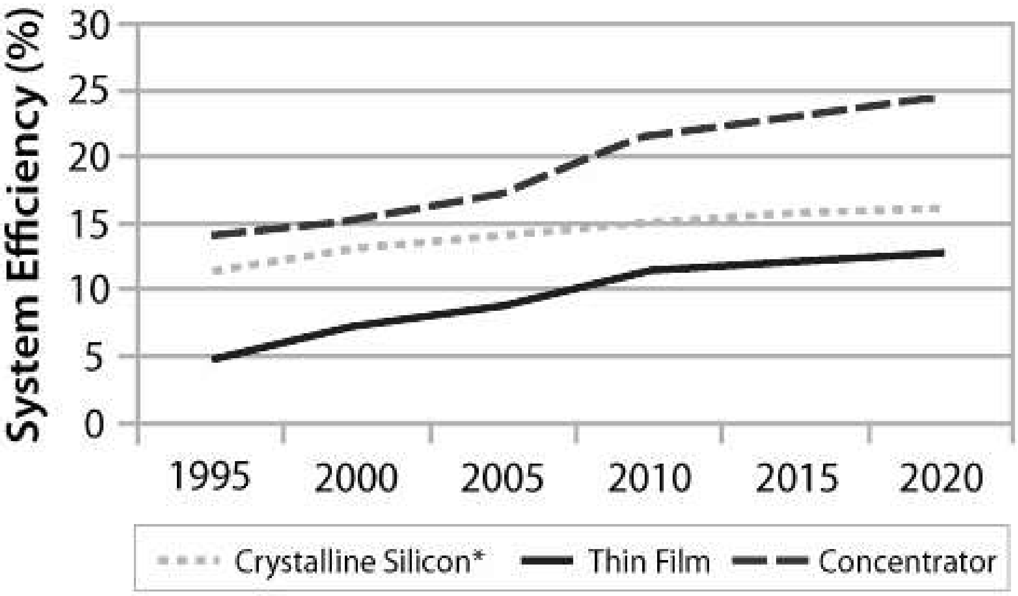


Figure 7.2. The evolution of the efficiency of the solar cell technologies of the year 1995 and the predictions for 2020[16]

Just in the year of 2010 more solar PV systems were installed than the past 20 years combined but even though there is a big growth, there is huge potential for generating energy from the Sun. In places like Middle East, Africa, Latin America and south Asia the possibilities are enormous. Some governments are willing to invest in Solar PV in order to secure their electrical needs, and stop depending on the fluctuations of the energy market. Because of the easy installation method, cheap to maintain, and as was mentioned before, the prices are getting more affordable.[18]

For example in 2004 the total installations around the globe of renewable energy were 800GW, by the end of 2013, the total worldwide installations were 1,560GW, an increase of 95%. But during the same period of time, the global solar photovoltaic energy increased a total of 5,246% from 2.5GW in 2004 to 18GW by the end of 2013. An increase so big that no other source of energy even comes close to this exponential growth of Solar PV, not even other renewable solar energy capacities, such like concentrating solar thermal and solar hot water, with a growth of 750% and 562% respectively.[1]

The power generated by solar PV at the end of 2015 representing a 1.8% of the total world's energy needed that year. Solar PV panels help to generate electricity from small towns outside energy grip in developed countries, to summer houses, also to factories that seek to reduce their electrical bills.[1]But this growth is not just about more installations, yes more money is invested in Solar PV and more solar farms are installed every year more than any other form of sustainable energy, actually even more than any other kind of source of energy, including non-renewables sources.[19] Part of the success of the Solar PV is the incentives some governments are giving in order to produce energy from the Sun. These incentives could be from tax exemptions, incentives, financial aid or credit and marketing about new technologies.[4]

The top five countries that are investing into Solar PV Energy are, in order of investment, China, Japan, the USA, the UK and India.  And the top five countries with an installed capacity of solar photovoltaic sources of energy by the year 2015 are, in order, China, Germany, Japan, the USA and Italy. Another metric very important to mention is the top 5 countries with an installed PV capacity per capita, again in order, Germany, Italy, Belgium, Japan and Greece.[2]

The Installations in 2015 went for a record 40 GW, lifting the worldwide aggregate to 267 GW. China, Japan and the United States again represented the larger part of the market share worldwide, however developing markets on all continents contributed essentially to worldwide development, driven to a great extent by the reduction in the cost of the PV panels. By the end of 2015, 22 nations had enough capacity to meet over 1% of their power requirements.

Just China itself added more PV capacity than the USA, the UK, India, Germany, Korea, Australia, France and Canada all combined. 2015 also was the year when Germany lost its first place as the country with the most solar PV capacity, since 2015 China has more solar capacity than any other country in the world.[2]

It used to be that just the developed nations were the ones investing into solar PV technology. Germany, Japan, the UK, the USA were the pioneers of the developing of solar photovoltaic technology, but now the technology reached a higher efficiency and the prices are not as expensive as 10 years ago. With more accessible prices, better efficiency and the need to meet the energy demand, many countries are investing into solar PV equipment in order to secure their energy needs and trying to mitigate the dependence on fossil fuels. New emerging markets around the globe are expecting to expand aggressively in PV solar energy. In addition to new government programs, more taxes incentives, the rising of interests in society and a much more friendly economical payment of the investment.

These are some the causes why many governments in countries are investing in solar energy and why it is not just the developed countries that are interested in farming solar energy. Regions like Latin America, Africa, South Asia, Eastern Europe and Oceania will experience an increase on the total of solar PV panels in order to meet their energy demands. Just in the year 2016 around 50 solar PV plants bigger than 50 MW were installed in 23 nations. Countries like Guatemala, México, Kazakhstan, Brazil, Pakistan, Philippines, Australia and Uruguay were among those nations that installed PV systems in order to meet their energy needs better.[19]

| | TOTAL END-2014 | ADDED 2015 | TOTAL END-2015 |
|---|---|---|---|
| | | GW | |
| **TOP COUNTRIES BY ADDITIONS** | | | |
| China | 28.3 | 15.2 | 43.5 |
| Japan | 23.4 | 11 | 34.4 |
| United States | 18.3 | 7.3 | 25.6 |
| United Kingdom | 5.4 | 3.7 | 9.1 |
| India | 3.2 | 2 | 5.2 |
| Germany | 38.2 | 1.5 | 39.7 |
| Republic of Korea | 2.4 | 1.0 | 3.4 |
| Australia | 4.1 | 0.9 | 5.1 |
| France | 5.6 | 0.9 | 6.6 |
| Canada | 1.9 | 0.6 | 2.5 |
| **TOP COUNTRIES BY TOTAL CAPACITY** | | | |
| China | 28.3 | 15.2 | 43.5 |
| Germany | 38.2 | 1.5 | 39.7 |
| Japan | 23.4 | 11 | 34.4 |
| United States | 18.3 | 7.3 | 25.6 |
| Italy | 18.6 | 0.3 | 18.9 |
| United Kingdom | 5.4 | 3.7 | 9.1 |
| France | 5.6 | 0.9 | 6.6 |
| Spain | 5.4 | 0.1 | 5.4 |
| India | 3.2 | 2 | 5.2 |
| Australia | 4.1 | 0.9 | 5.1 |
| **World Total** | **177** | **50** | **227** |

Table 7.2 Solar PV installation by 2015. [2]

As seen in table 7.2, the worldwide PV capacity installed by the end of 2014 and all the added capacity of each of the top ten countries with PV capacity in the world. Also on the same table it is notable how China is aggressively adding PV capacity.

Another important issue to be considered for the Solar Green Energy is that it has a high social value, from all the sources of renewable energy the solar energy (both Photovoltaic and Thermal) is the one that is more socially accepted by the European society [20]. Meaning that the solar energy is likely to be more socially accepted in Europe, (Perez, 2010 talks about his studies in Europe).

# 8. SOLAR RADIATION ON PV SYSTEMS

Most of the energy that our planet received comes from the Sun, when the solar race pass through our atmosphere, the solar radiation experiment a process of reflection, attenuation, and diffusion but alter the radiation characteristics. The energy that our planet receives from the Sun perpendicular to a surface is called solar constant, and according to the NASA, this value is 1,353 W/m². The reflection in the clouds reduces the radiation on the surface of the Earth. This energy is a combination of infrared and ultraviolet radiations, as well as visible light.[15]

The total radiation from the Sun can be calculated considering three different sources of irradiation, such sources are: direct radiation, diffuse irradiation and reflected radiation.[15]

**Direct Radiation** can be considered the total radiation coming straight from the Sun in a straight line. The direct radiation basically depends of the solar geometry, the azimuth and the angle over the horizon, also for the direct radiation is important to consider the attenuation of the solar rays produced in the sky (ashes, smog, smoke but mainly clouds).

**Diffuse Radiation** is the total relation from all the sky but the Sun, this includes the Rays of the Sun that are dispersed in the atmosphere. This irradiation has to consider that the properties of the atmosphere changes in a random form.

**Reflected Radiation** is a kind of radiation that is reflected from the ground. Normally this radiation tends to be very small and in most cases it tends not to be accounted for.[21]

## 8.1 Atmosphere and solar irradiation

Solar irradiance is measured by a pyrometer, an electrical device that estimates the solar irradiance on the horizontal surface. The units for the solar irradiance are the Watt/square meter. The engineer Konrad Mertens on his book “Photovoltaics: Fundamentals, Technology and Practice“ assures that the direct radiation is bigger than the diffuse radiation, his studies in Braunschweig, Germany about cloudy days in comparison with sunny days and how it affects both the direct and the diffuse radiation (See Figure 8.1). [23].

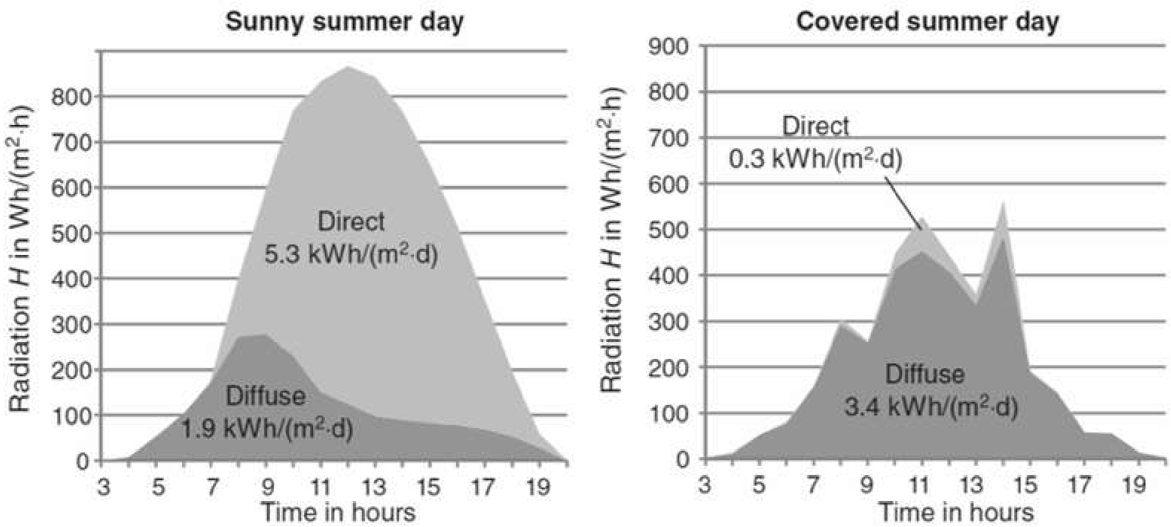


Figure 8.1 Irradiation of a sunny day vs. a covered day. Studies results of measuring the Direct and diffuse radiation made by Mertens comparing a sunny day and a covered day (cloudy day).

## 8.2 Solar alignment

The power made by photovoltaic generator is bigger when the radiation is directly into the PV system. The total of the effective radiation includes losses because of the reflexion, effect that is caused because of the angle between the direct Sun rays and the perpendicular of the face of the module. The bigger the angle, the bigger the reflected radiation. Also it is important to mention that there are two kinds of reflected radiations, one from the ground to the PV system that in most cases can be considered zero.

Solar trackers or solar optimal positions are required in order to make the solar PV system more efficient. Considering that the direct radiation is bigger than the diffuse radiation and that the losses for reflection are lower if the PV system is facing the Sun, the principal objective of solar trackers is to reduce the angle formed between the Sun's rays and the surface of the PV modules during the daily movement of the Sun in the sky.[22]

There are two main types of installations for solar PV Panels, tracking devices and static installations.

## 8.3 Static Systems

The static or fixed system is the most common type of solar PV installation, normally they face the Equator (facing North on the southern Hemisphere and South on the northern Hemisphere) with an inclination or tilt angle (β angle) depending mostly on the latitude where the PV is installed. [23] The figure 8.3 shows the tilt angle and the interaction of the three different radiations over a fixed solar PV module.

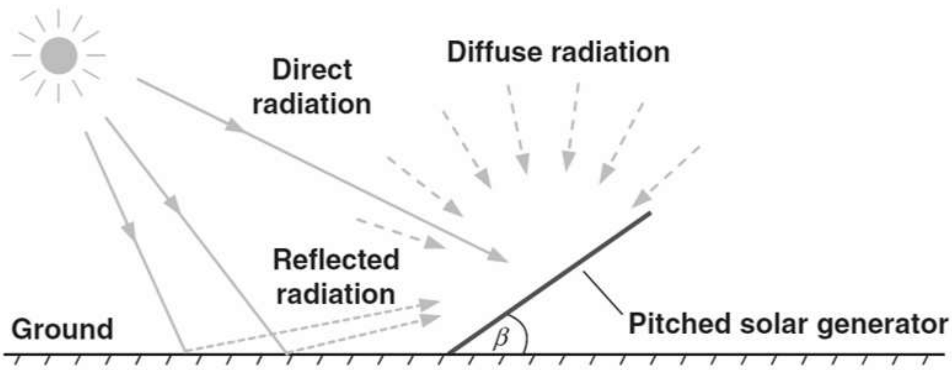


Figure 8.3. Graphical representation of the radiations over a PV module.[23]

The tilt angle of solar PV above the horizontal lane differs from place to place, meaning that the same installation but his can be easily calculated as a rule of thumb, meaning that for example in the northern hemisphere has been proposed to use 0.9 times the latitude of the location facing to the equator [24] .But locations over the Antarctic and the arctic circle don't follow such rue. [24]

Considering that the solar PV panels are oriented to the Equator and with an angle of inclination considering the horizontal plane. It can be calculated the angle between the PV surface and the Sun's rays.[25] Such angle can be calculated with the formula 1.

$$\mathrm{Cos}\theta = \cos(\Phi-\beta).\cos\varsigma.\cos\omega + \mathrm{sen}(\Phi-\beta).\sin\varsigma$$

Formula 1 Calculations for the tilt angle of a PV module.[26]
θ = Angle between the sun's rays and the surface of the solar PV module.
Φ = Latitude
β = Angle of inclination or tilt angle
**ς** = Solar declination
ω = Solar Angle
n = Day of the year

## 8.4 Tracking devices for PV panels

Solar trackers are devices that help to truly maximize the energy production of the solar PV panel. The function of these devices is to “follow” the Sun. There are many kinds of solar trackers but the double axis is the best method to follow the solar radiation effectively. This method allows the PV module to point directly to the Sun and subsequently, optimize the production of electrical energy. These double axis systems are called solar trackers, and they are devices that help to truly maximize the energy production of the solar PV panel. These solar trackers tend to be expensive, but its function is to directly face the PV Modules to the Sun’s rays and obtaining a better efficiency of the system. Not just throughout a day, but in the different seasons. It is important to mention that the inclination of the sun is not the same in a day of January than in a day of July, which is why these solar trackers have to be programmed to follow the Sun on its path on over the horizon.

The second best method to harvest the solar energy is the system with an azimuthal following. These trackers are single axis and are cheaper than the double axis. This meaning that the system tracks the solar movement on a daily basis, facing east during the sunrise, and west on the sunset.[21]. In the figure 14 it is appreciated the difference between a solar tracker of 2 axis and a fixed installation. Most companies assure a minimum of a 35% increase on performance with a 2 axis tracker compared to a fixed installation. Figure 8.4 shows the comparison between the 2 installations on a day in August in the USA.

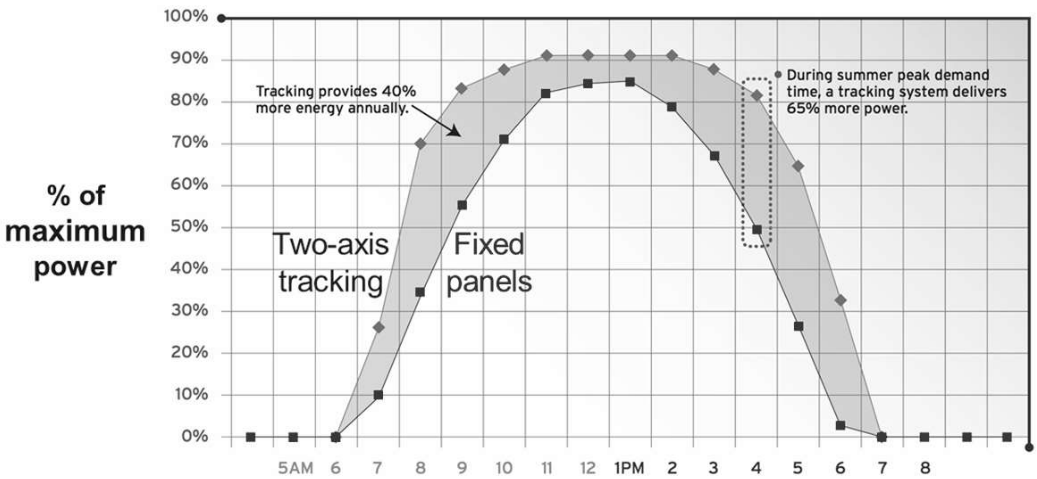


Figure 8.4. Two axis vs. fixed panels. [27]

The cheaper option of solar trackers is the horizontal axis trackers. These trackers can be easily manual and just be adjusted monthly or seasonally. Morse affirms that in order to have a better yearly efficiency on a semi fixed PV installation, can be improved by considering the result as the optimum point on the equinox. To make the system more efficient he suggests adding 29° 45 days before the summer solstice and subtracting 29° 45 days before the winter solstice. The yearly change for a seasonally installation can be dictated on the table 8.4.[24] Table 8.4 shows the suggestion for a tilt angle adjusted by seasons.

| **Season** | **Formula in degrees** | **Date of angle adjustment** |
|---|---|---|
| **Spring** | latitude (.9) | 45 days before the Spring Equinox |
| **Summer** | latitude (.9) +29 | 45 days before the Summer Solstice |
| **Autumn** | latitude (.9) | 45 days before the Autumn Equinox |
| **Winter** | latitude (.9) -29 | 45 days before the Winter Solstice |

Table 8.4. Seasonally adjustment of β.

# 9. CHIHUAHUA MÉXICO

The city of Chihuahua is located in the northern state with the same name, in México. The city is located between the Samalayuca desert, Tarahumara Mountains and the plains of Delicias. The city has a total population of 878, 000. The PIB per capita is the third highest in México with 10,386 USD. The city has a strong manufacturing industry especially in the aerospace field as well as big agriculture, with mention with the walnuts production; currently Chihuahua City has the spot number 1 globally in walnuts production. [28]

The city has a strategic location, the Pan-American highway passes through the city and the American border is just 320 kilometres away. Chihuahua city it is located on the Latitude: 28°38'07" N, 106°05'20" W and an altitude of 1,437 meters above the sea level.

## 9.1 Weather

The hot season lasts around 3 months, from late May to early August, with an average daily high temperature above 31°C. The cold season lasts almost 3 months, from late November to early February, with an average daily high temperature below 20°C. The driest months are February, March and April.[29] Figure 9.1 demonstrates the relationship between the daily temperature throughout the whole year. The horizontal axis represents the day of the year and the vertical axis is the hour of the day

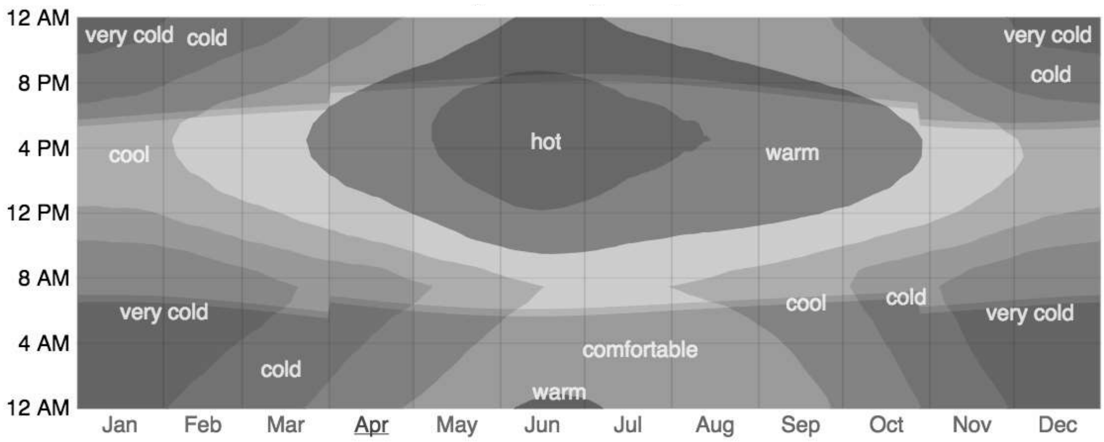


Figure 9.1. Average hourly temperature.[29]

In the city of Chihuahua, the cloudy season experiences significant variation over the course of the year. The clear skies' season starts in the beginning of March and lasts until early June.[29] Figure 9.2 illustrates the percentage of the cloudy cover of the sky in Chihuahua, the horizontal axis represents the day of the year.

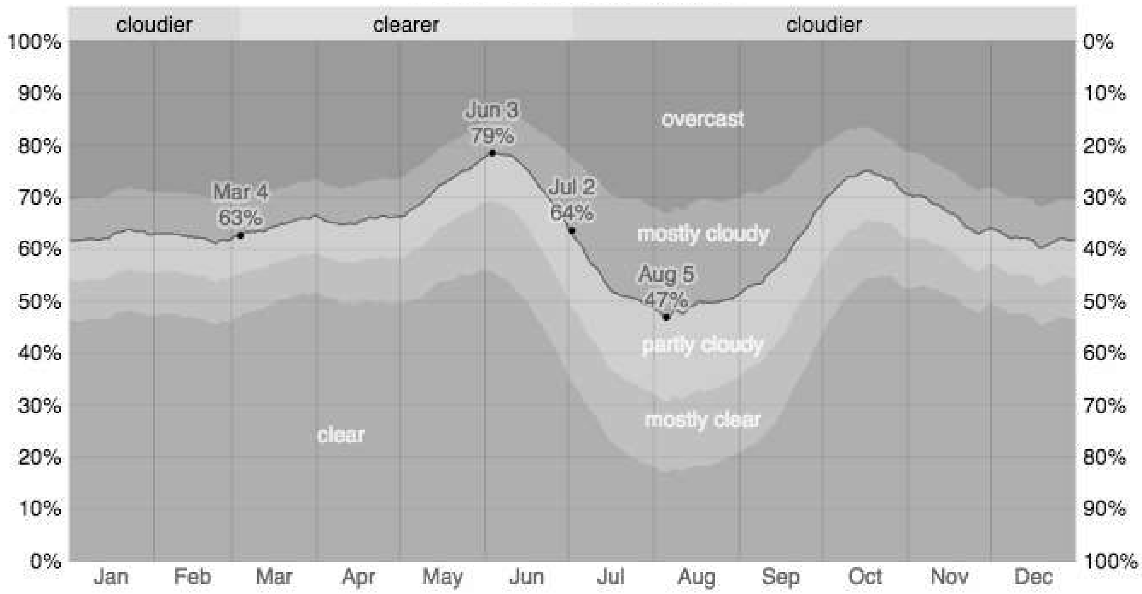


Figure 9.2. Cloud Cover categories. [29]

In Chihuahua City the cloudy season is directly related to the rainy season that as well has duration of approximately 5 months from early June to the end of October. [29] Figure 9.3 shows the average monthly rainfall of Chihuahua City.

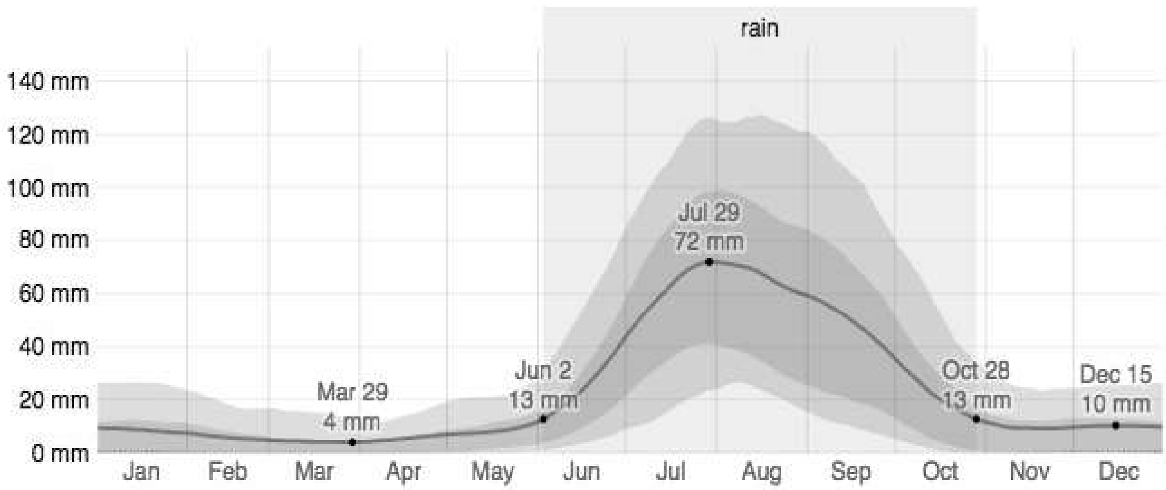


Figure 9.3. Average monthly rainfall. [29]

## 9.2 Solar Irradiation in Chihuahua

Chihuahua City is located above the tropic of Capricorn, meaning that the solar declination has a big impact on the sunshine hours throughout the year. The shortest day in Chihuahua is December 21 (Winter solstice) with 10 hours and 19 minutes of sunshine and the longest day is June 21 (Summer solstice) with 13 hours and 58 minutes of sunshine. .[29] Figure 9.4 illustrates the yearly hours of Sunshine.

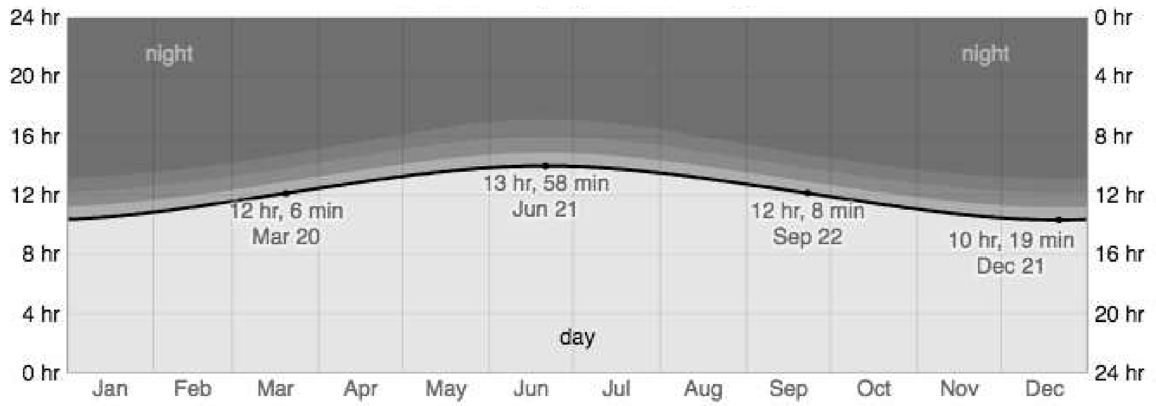


Figure 9.4. Hours of daylight and twilight. [29]

The city of Chihuahua has a high period of solar energy input from early April to early July, with a daily average of global irradiation energy of 7.3 kWh/m². The lower period of solar energy is from early November to early February, with a daily average of global irradiation energy of 4.7 kWh/m². [29] Figure 9.5 illustrates the yearly average of solar energy of Chihuahua.

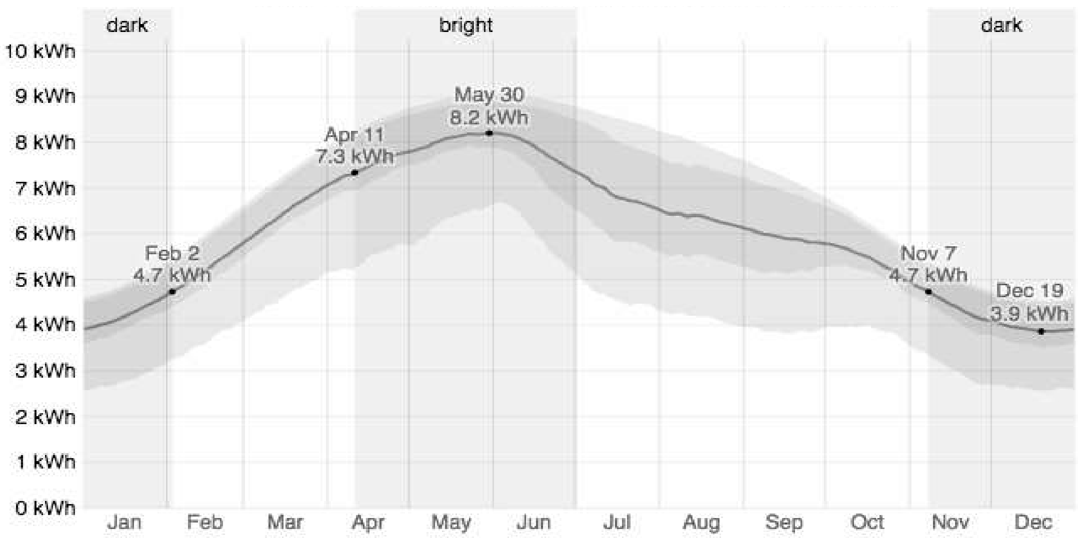


Figure 9.5. Irradiation in Chihuahua [29]

The solar irradiation for the city of Chihuahua can be graphically described on the figure 9.6 where it shows the solar altitude (ALT) over the plane of azimuth (AZI). The line in the middle shows the Sun's path in the equinoxes, the lower line is the Sun's path in the winter solstice and the upper line is the Path on the summer solstice.

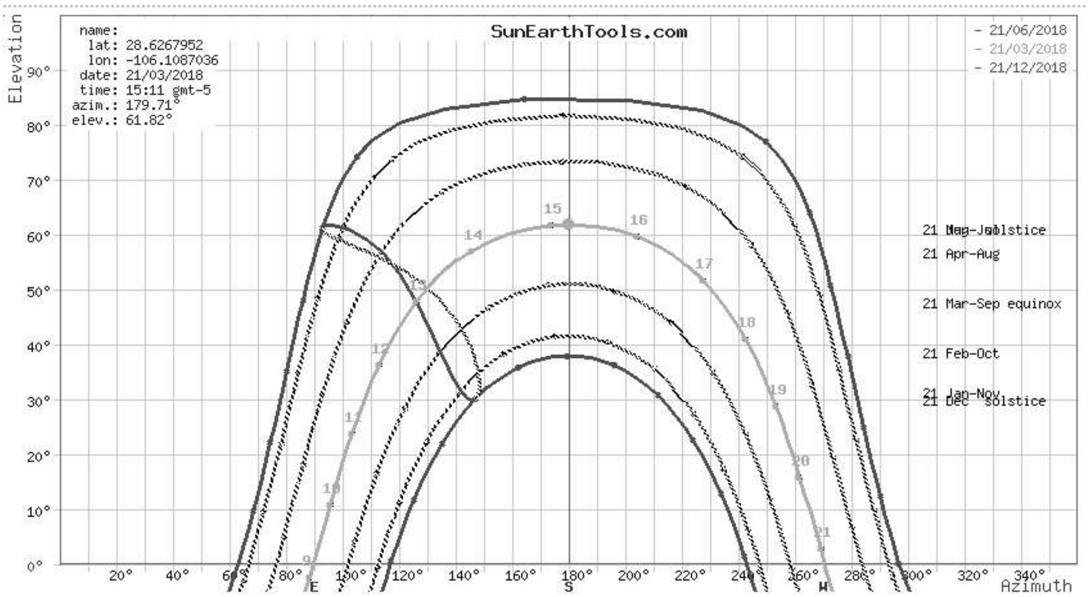


Figure 9.6. Sun's path for Chihuahua through the year for the city of Chihuahua Mexico.[30]

## 9.3 Magnetic Declination for Chihuahua

According to the National Oceanic and Atmospheric Administration (NOAA) the magnetic declination for the city of Chihuahua by the end of the year 2017 was 7° 42' East with a yearly change of 0° 6' West (Figure 9.7).[31] This information matches the magnetic declination angle calculated by the Natural Resources of Canada (NRCAN).[32]If the magnetic declination is to 7° 42' to the east, this means that the magnetic south, the point where the compass points to the south is actually 7° 42' west of south.


Figure 9.7. Magnetic Declination for Chihuahua. This figure illustrates the magnetic declination for Chihuahua at the end of 2017 on a map.[33]

# 10. IMPACT OF THE LOCAL WEATHER ON SOLAR PV PRODUCTION

The technical optimum for a solar PV system in the northern Hemisphere would be to face to the real south, meaning 180° on the Azimuth field.[13] But it is important to consider that every city has a different climate that is why every city should be treated as unique for a solar installation. Meteorological factors as smog, fog, clouds and temperature can affect the production of energy obtained by the Sun, as well as other factors such as the terrain of the city, it is important to consider if there are mountains nearby that could produce some shading to the PV System. It is important to consider a shading evaluation before installing a PV system in order to know if the solar equipment would reduce its productivity by shadings generated by trees, buildings, mountains, events and other PV systems. Apart from the shading evaluation a weather evaluation as well is needed.

A weather evaluation is needed because different weather conditions can block or reduce the solar radiation into the PV system and therefore reduce solar PV panel efficiency at different times of the day, changing the optimal orientation of the panels. This work's main objective will be to determinate and analyse a new orientation angle in the azimuth for the city of Chihuahua.[34]

## 10.1 Weather data

In order to analyse the weather behaviour of Chihuahua city, this work is inspired on the works of Rhodes [34] and Mertens [23], both of them worked with analysis of solar PV related the weather conditions. Rhodes and his team were analysing better orientations on the plane of

Azimuth for solar modules across the USA. Mertens evaluate the difference of the received energy between a cover day (cloudy) and a sunny day.

This work analyses the irradiation that the city of Chihuahua has received from the 1st of January of 2010 to the 31st of December 2016. This work has used the weather data collected by the National Renewable Energy Laboratory (NREL) from the year 2010 to 2016.
The global horizontal irradiance (GHI) was the main source of yearly data used for this work. The units used by the NRL for the GHI are $W/m^2$.
The NREL has two different data for GHI, total nominal or theoretical energy that a square meter is supposed to receive during an interval of an hour, and the actual irradiance during the same hour. In the nominal measurement they call it cleansky GHI. [35]

Factors like smog, dust, fog but especially clouds are making the real irradiance lower than the nominal irradiance [23]. This work considers differences between the irradiations to be the main source of data for determining the weather behaviour. These differences are calculated hourly and its value represents the proportionality between the cleansky GHI and the real GHI. This proportion for this work is considered in function of the formula 2.

$$\Delta = (\text{cleansky GHI - real GHI})/\text{cleansky GHI}$$

Formula 2. Delta of radiations.
$\Delta$ = Solar Radiation delta
Cleansky GHI = Nominal radiation
Real GHI= Real Radiation

For example on the 9th of April of 2010, at 2pm the city of Chihuahua supposed to have a global irradiance of 958 $w/m^2$ but due weather conditions (clouds) the real global irradiance was just 83$w/m^2$. Using the formula 2 will mean $\Delta = (958\ w/m^2 - 83\ w/m^2)/958\ w/m^2 = 0.913$, meaning that due weather conditions the city of Chihuahua didn't receive 91.3% of the irradiance it supposed to receive. In order to corra evaluate the data from the NREL. A double check was made in another database. For the same day the weather database, the "WEATHER UNDERGROUND" website provides a very similar data for that day, pointing out that, around 2pm on the 9th of April of 2010 the city of Chihuahua had a cloudy weather.[36]

There is a strong relation between a higher $\Delta$ and a more cloudy weather. [23] There are 52,560 data inputs for each year from the NREL database, and a total of seven years were analysed. In order to better manage such quantity of data and to have a better overview of the weather conditions for each parameter, this work suggests the use of a new parameter called Delta Average of Radiation of the Sun (DARS). DARS value will be directly related with clouds in the sky, the higher the DARS, the more cloudy the weather. The DARS will help this work to better present the average weather conditions for the city of Chihuahua during a determinate parameter. The average yearly values can be found on the appendices section (Appendices 1-7 for the yearly data and appendice 8 for the average). It is essential to consider that these values are adjusted to the time zone and to the time change of Chihuahua. The Total average of the DARS can be seen in figure 10.1.

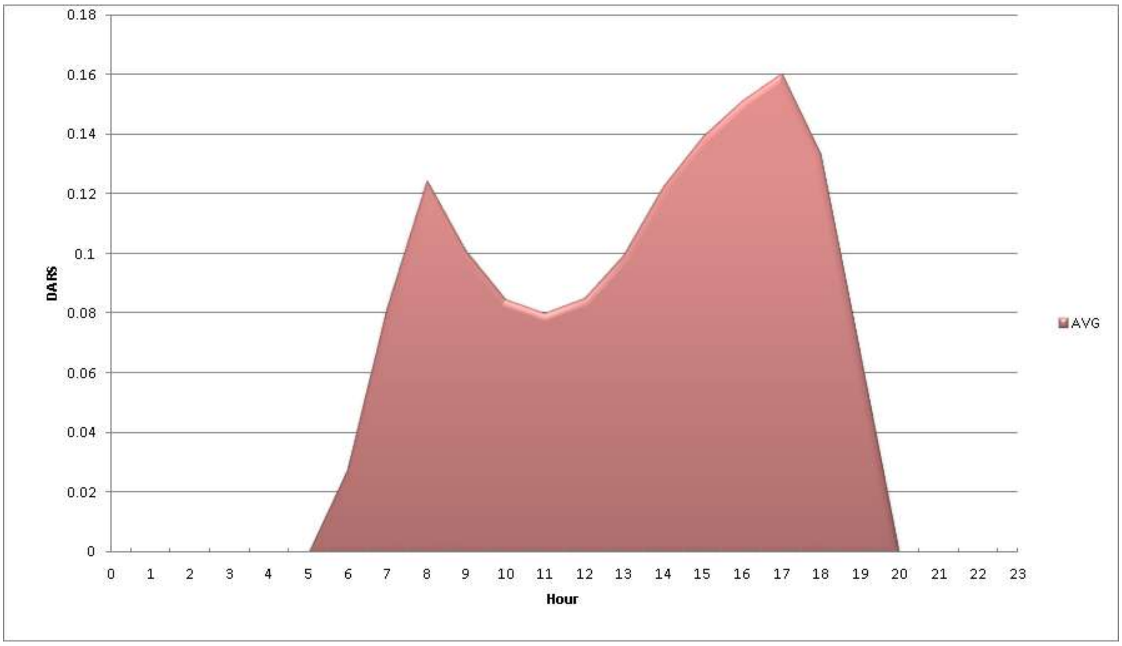


Figure 10.1. Average hourly DARS of the seven years analysed can be seen in this figure

With the DARS calculated, it is possible to determinate the weather behaviour based on seven years of weather data (see appendice 12). In the figure 10.2 it can be seen how 2011 presents the lowest DARS of the seven years analysed, Chihuahua suffered the worst drought over the last 150 years. [37]

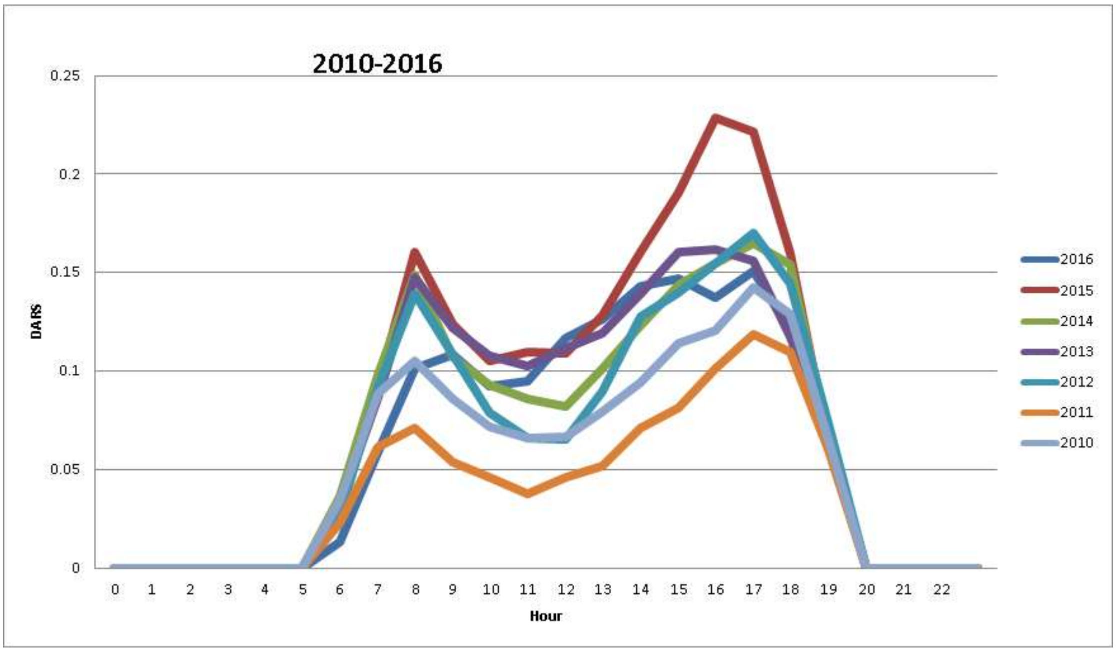


Figure 10.2. Hourly DARS by year. This figure shows the average hourly DARS for each year

The monthly DARS average of the seven years analysed can be seen in the figure 25. Note that on figure 10.3 it can be seen a great difference between difference years on the same month. Reason why is important to consider several years in order to base the study and not only one year that could be an atypical weather behaviour year.

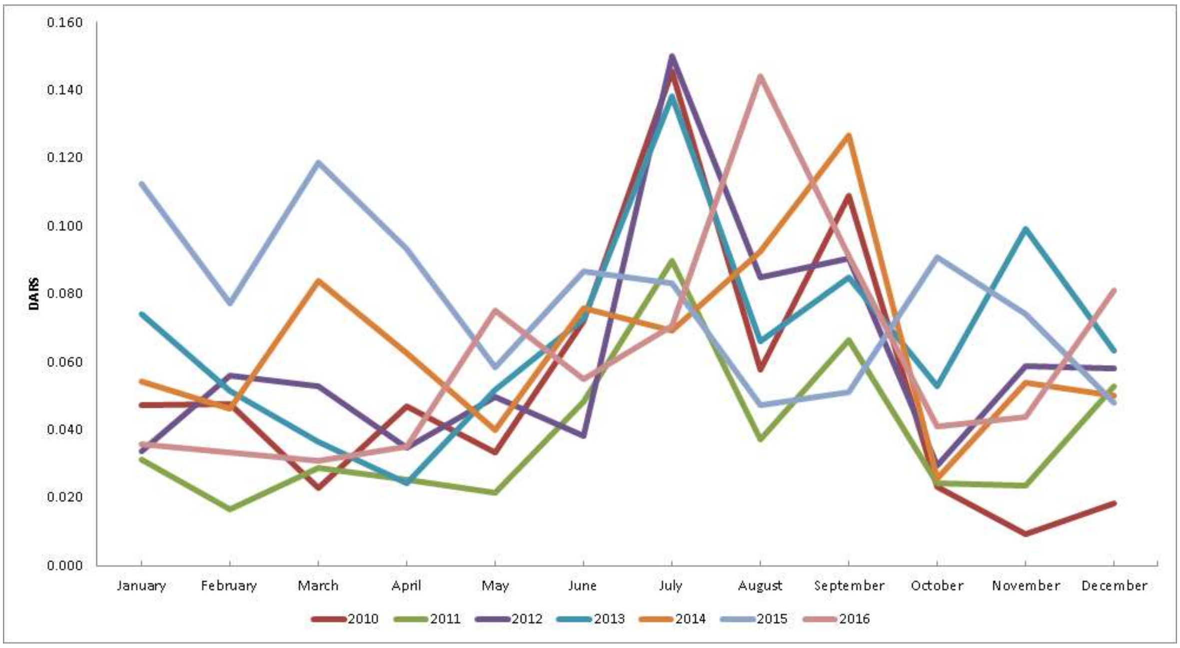


Figure 10.3. Monthly DARS average of 2010-2016. Still can be seen that the year 2011 shows the lowest DARS during rainy season (from early June to the end of October) which could be deduced that there were few clouds on the sky.

With the DARS calculated and as it can be seen in the figures and with the data from the appendices, two main statements can assume.

1. During the afternoons the weather in Chihuahua tends to be cloudier than in the mornings.
2. July and August represent the months with the cloudiest weather in Chihuahua.

## 10.2 Suggested solar orientation for Chihuahua

The PV solar panels generate the most energy when receiving direct irradiation and in order to get the most irradiation PV panels should face to the Equatorial line. But, for Chihuahua city, where is clearly that the afternoons tend to be cloudier than the mornings, a East of South orientation is suggested by this work. Figure 10.4 shows the proportion of the cloudy and the sunny hours.

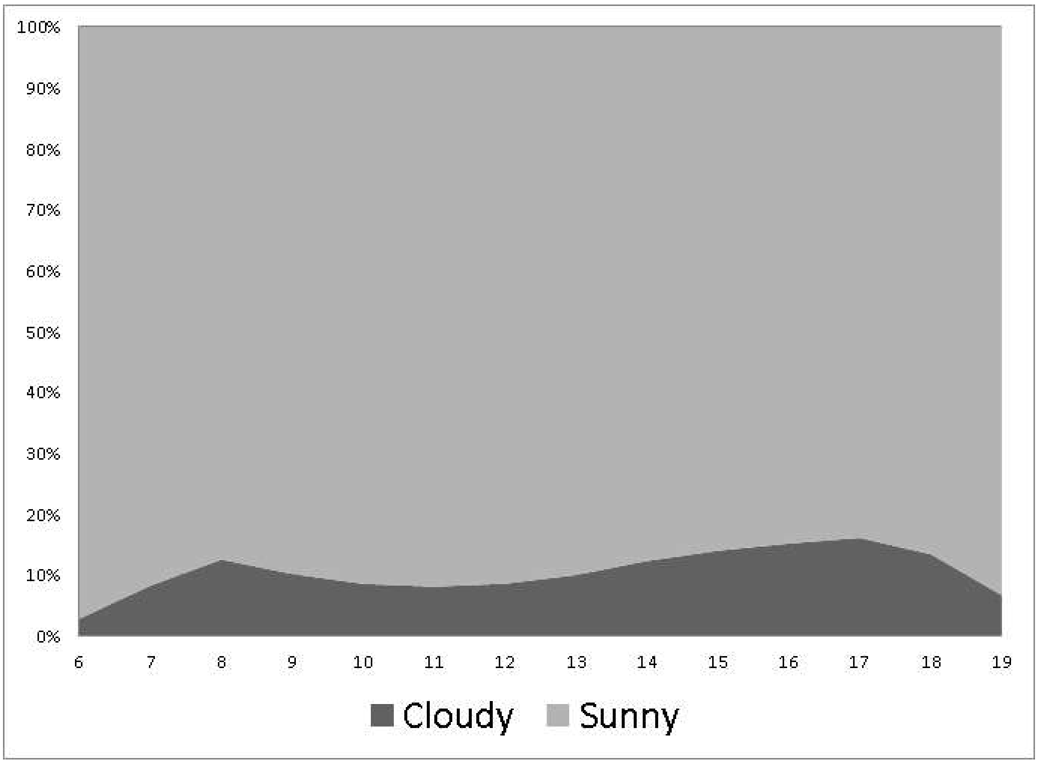


Figure 10.4. Hourly DARS is used as a cloudy factor. This image shows that even that comparing with the image 10.2, Chihuahua is still a very sunny city. Data can be found on appendice 12.

There is an 8.3% possibility to have a cloudy morning (6AM to 12PM), 9.2% to have a cloudy midday (12PM to 2PM) and a 12.4% possibility to have a cloudy afternoon (2PM to 8PM). 4.1% chances to have cloudier afternoons than mornings. Moreover direct solar irradiation is better for PV energy production than diffused irradiation. [23] Based on this data and the one on the appendice 12, this work assumes that there is a chance that a slightly East of South orientation for a PV Panel will be more efficient than an installation facing sought.

But in order to calculate a better orientation over the plane of Azimuth a number of series were introduced by this work.
We have to consider few factors:

- That the mornings can or not are sunnier than the afternoons.
- An orientation to the real south is 180°.
- When the sun is at the highest is at midday.
- At midday, the sun will face straight (over the plane of Azimuth) to a PV module that is facing to 180°.
- A PV system facing south but slightly to the east will produce more energy on the mornings.
- A PV system facing south but slightly to the west will produce more energy on the afternoon.
- Would be logical to face a PV system to an angle lower than 180° if on average, there is sunnier weather in the mornings than in the afternoons.
- Would be logical to face a PV system to an angle higher than 180° if on average, there is less sunny weather in the mornings than in the afternoons.

We start by giving a measurement of the sun irradiation using the hourly DARS previously calculated. The next three formulas represent the morning, afternoon and midday sunnier ratio.

$$\sigma 1= \sum_{n=0}^{12}(1-DARS)$$

Formula 3 is representing the morning sunnier factor.
**σ** 1=morning sunnier factor
n= hour of the day

$$\sigma 2= \sum_{n=12}^{13}(1-DARS)$$

Formula 4 is representing the midday sunnier factor.
**σ** 2= midday sunnier factor
n= hour of the day

$$\sigma 3 = \sum_{n=13}^{23} (1 - DARS)$$

Formula 5 is representing the morning sunnier factor.
**σ** 3= afternoon sunnier factor
n= hour of the day

With the sunnier factor calculated, it is important to have a reference between the sunnier factor from the morning related to the midday, such factor (ω) can be calculated for both the morning and the afternoon.

$$\omega_{morning} = \frac{\sigma 1}{\sigma 2}$$

Formula 6 Relationship between morning and midday

$$\omega_{afternoon} = \frac{\sigma 3}{\sigma 2}$$

Formula 7 Relationship between morning and midday

Also it is necessary to calculate the average of the both factors.

$$\omega_{AVG} = \frac{\omega_{morning} + \omega_{afternoon}}{2}$$

Formula 8 Average of the morning and afternoon factor.

For the optimum angle over the plane of Azimuth use formula 9. This is consider that if the result is smaller than 180° is meaning that overhaul an East of South orientation for a PV system is better than facing it to the real south, as well as the result is higher than 180° means that an orientation west of south is recommended.

$$\alpha = 180 \left[ 1 - \left( \frac{\omega_{morning} - \omega_{afternoon}}{\omega_{AVG}} \right) \right]$$

Formula 9. Optimum angle.

Using the formulas 3-9 for the city of Chihuahua the appendice 17 was created and it was divided by months for better understanding. The result is that for an optimum angle, based on the weather conditions of Chihuahua between the years 2010-2016 this work suggests a 9° East of South orientation. (171° in the azimuth plane)

## 10.3 Experiment

In order to test out that the suggested orientation for a PV panel was better than the real south an experiment was made to verify this theory. A total of two PV modules were installed, one facing the real south (180°) and the other one facing the previously suggested orientation (171°). The experiment is taking place in Chihuahua with a total of 8 solar panels with a capacity of 260W each. Two solar inverters were needed with the capacity to be able to monitor the energy produced online. The installation was made on the 18th of January 2018 but the online monitoring was started on the 26th of February 2018.

The tilt angle was calculated based on the rule proposed by Morse of using 0.9 times the latitude, the city of Chihuahua is located in the latitude 28.639578 and using the proposed rule by Morse, the solar installation was fixed with a tilt of 26° with the horizontal. Due to the lack of resources the optimum tilt angle will not be calculated in this work. The installation facing the real South (180°) will be referred to as SF1 and the one facing to the suggested orientation (171°) will be referred to as SF2. In the graphical material section there are some pictures of the installations.

Total cost of the installation was $112,521 pesos (£4,847 euros at time of writing) from which $50,000 pesos were subsidized by the Mexican Government and $50,000 pesos were given as a credit by the national Electric company of México (CFE).

## 10.4 Results

For the analysis of this work, just the months of March and April are considered. The analysis for the rest of the year will continue being tested but due time limitations, will not be considered for this paper. The results show that there is a significant improvement on the energy produced. Again we have to consider that March is technically the sunniest month, and by not facing the PV system to real South there were some losses, but those losses were minimum and were immediately compensated by the production in April. See Appendice 14 for the daily solar PV production collected by the SF1 and SF2.

Also figure 10.5 and figure 10.6 represent the production of the installations of March and April respectively.

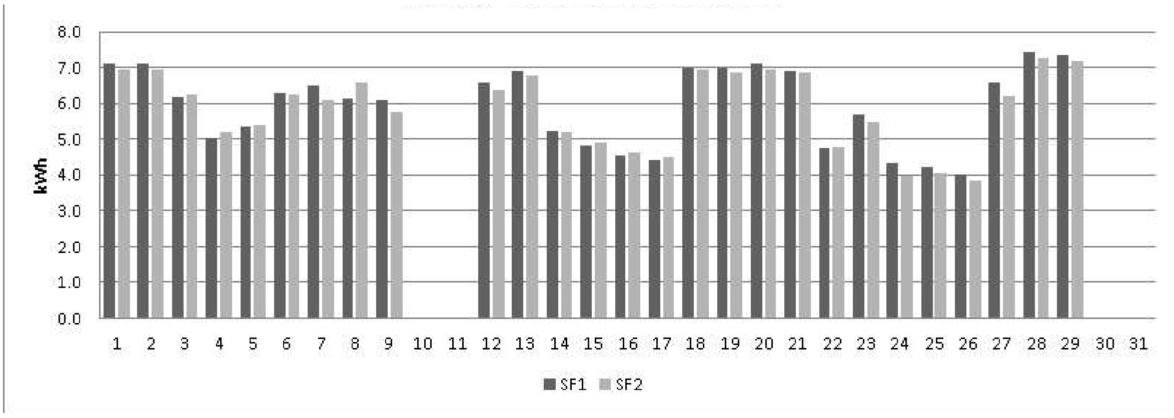


Figure 10.5. Energy Produced in March. For more information about the production for the days 10, 11, 30 and 31 see appendice 14.

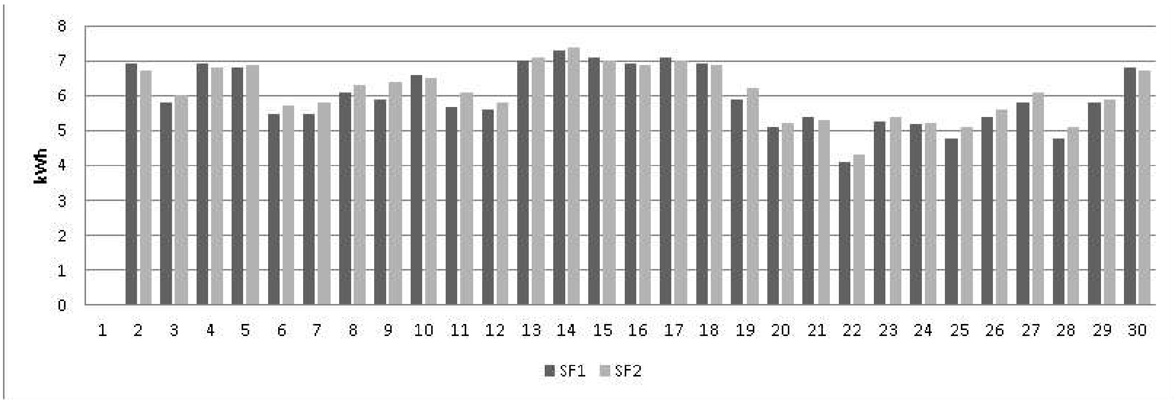


Figure 10.6. Energy Produced in April. For more information about the production for the first day of April see appendice 14.

The next table 10.1 summarises the results of the experiment. Meaning that actually there is an improvement on the energy produced with the proposed angle, and to double check this results and taking a look on the appendice 17, it can be seen that April has a slightly better performance than March. 1% improvement on average between March and April gives credibility to the this work, and this is based on the some of the driest months, a higher percentage of improvement are expected over the months of June, August and September, but specially for the month of July.

| | March | | April | |
|---|---|---|---|---|
| | SF1 | SF2 | SF1 | SF2 |
| Total of Energy Generated in kWh | 160 | 158.3 | 173.8 | 177.4 |
| Avereage daily Energy Generated in kWh | 6 | 5.9 | 6 | 6.1 |
| Number of days analized | 27 | | 29 | |
| Different between installations in kWh | -1.7 | | 3.6 | |
| % of change | -1% | | 2% | |

Table 10.1. Energy produced and % of change

Also we have to consider the magnetic declination of the city of Chihuahua that is about 7° to the East, meaning that a PV installation facing to the south will be actually facing to the West of South. This work cannot analyse the changes between the real South and the magnetic South.

## 10.5 Discussion and suggestions for further work

The main goal for this work is to generate an optimal angle for better solar energy produced in the city of Chihuahua, analysed the energy produced by a solar PV system pointing to the suggested point calculated (171° in the azimuth plane) and its twin satellite installation point to the real South. Now it is important to mention that this work was based on two of the driest/sunniest months of Chihuahua, in order to properly determinate a result with a confident it will be necessary to have at least one year of solar data in order to make a decision. Nevertheless it is important to mention that the optimum point is not where the magnetic south is located and this work can supposed that even the real south is more efficient than the magnetic south for a PV installation in the city of Chihuahua. During the month of March the equipment facing to the real South (SF1) produced 1% more energy than the one to facing to the recommended point (SF2). And in April (a less sunny month) the SF1 produced 2% less energy than the SF2.

This work will continue gathering data and by the first quarter of 2019 the results will be published in a local newspaper of the city of Chihuahua. Since the cloudiest months are yet to be analysed it is expected that the yearly PV production from the SF2 installation will be 3% to 4% higher than from the SF1.

Producing more energy doesn't mean that it is the best economical approach. Most of the decisions at the very end will be evaluated in the economic impact. Many countries around the globe have different energy prices during the day and night, some of them even hourly differences depending on the demand of electricity. [38] But México has one standard tariff of electricity, so in this case for Chihuahua, producing more electricity no matter the hour is the best economical approach.

In order to have an idea of how much energy is installed in Chihuahua, a small survey was made among 14 of the biggest companies related to solar energy in Chihuahua. Such answers can be found on appendice 16. Since the magnetic south is slightly facing West, and the optimum angle for Chihuahua is facing East of South, it can be presume that there is a double potential cost of for facing a solar PV module to the Magnetic South instead of the optimum angle.

Considering the average answer for the total of PV energy as the total amount installed, the total of solar energy installed would be 19MW. Considering that this very small survey represents the total of the energy installed and how is installed it can be assumed the following for the city of Chihuahua:

1. 50% of the solar PV installations are faced to the magnetic South. About 9.97MW are facing to the magnetic South in Chihuahua City.
2. 43% of the solar PV installations are faced to the real South. Meaning that about 8.41MW are facing to the real south.
3. Just 7% of the solar PV installations are faced to an optimal orientation. About 1.33MW have an optimal or calculated angle.

Considering the appendice 17, this works calculates that an improvement of about 3.79% can be made in Chihuahua city if the installations faced to both the Magnetic and the real South are changed towards the 171° in the azimuth plane. Of course this is just theoretical and not taking into consideration many external factors like shading and terrain were the PV modules are installed.

# 11. SUMMARY

This analysis consider the effects of two identical PV installations, one facing 9° East of south and the other facing to the real south (171° and 180° on the azimuth plane respectively) during a period of 2 months' time in the city of Chihuahua México. The results are very consistent with other previous studies regarding solar optimization for maximizing the total yearly energy produced. However this analysis and the intermediate results considering the local weather have the potential to increase the energy produced in Chihuahua, México without any mayor additional capital investment, just by changing the current installations to a more efficient angle.

Due to the fact that the PV data comes from just two months (March and April) there won't be enough data to accurate determinate if this suggested angle is better than the magnetic south to face a PV system, but, with the weather data this work have on the previous years, around 3% increase yearly could be archive by facing the installation some degrees East of South instead of the magnetic South that for the city of Chihuahua will be facing West of South. It is important to mention that this suggested angle is not the optimal angle and also not the most convenient to everyone, there are cases that this adjustment is not ideal or monetary profitable:

- For installations with tilted roofs.
- When shading is involved a new analysis has to be conducted.
- When the energy prices fluctuate during the day or season.
- When the lifespan of the PV system is about to expire.

Based on the results of the orientations we are hoping to have relative higher energy production from the SP2 during the months of May, August and September but especially during the months of June and July. On the other hand we are considering a higher production of energy on the SP1 during the months of November, December and January. But overall the optimum production for solar PV energy is facing the system to 171° over the plane of Azimuth.

The results from this work also show that they are different optimal orientations based on the month, as seen in appendice 17 the optimum orientation for a solar system in the summer months like June and July is 158° in the plane of Azimuth, meaning that during those months, statistically speaking the mornings are sunnier but in the winter time (November, December

and January) the recommended orientation is 181°in the plane of Azimuth. Meaning that there is a potential gain of energy production with installation of a seasonally orientation.
Maybe this information is not as relevant for the solar PV production but I find this information relevant for the solar thermal power, especially for the solar water heating systems because in the winter times is when the warm water is needed the most.

This research experienced some limitations, nevertheless the project is still running and more data is generated on a daily basis that one day could truly help the community in Northern México to produce more efficient renewable energy.

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# 13. APPENDICES

**Appendice 1. Hourly average data for the year 2010**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 11.4 | 0.000 |
| 1 | 0.0 | 0.0 | 149.8 | 10.8 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 10.2 | 0.000 |
| 3 | 0.0 | 0.0 | 133.2 | 9.8 | 0.000 |
| 4 | 0.0 | 0.0 | 121.9 | 9.5 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 9.3 | 0.000 |
| 6 | 5.1 | 6.1 | 97.1 | 9.7 | 0.030 |
| 7 | 78.3 | 91.3 | 84.4 | 11.6 | 0.090 |
| 8 | 253.3 | 282.4 | 71.7 | 14.6 | 0.110 |
| 9 | 459.4 | 502.7 | 59.4 | 17.8 | 0.090 |
| 10 | 642.8 | 692.9 | 47.8 | 20.3 | 0.070 |
| 11 | 777.1 | 831.7 | 37.6 | 22.1 | 0.070 |
| 12 | 846.2 | 906.8 | 30.0 | 23.3 | 0.070 |
| 13 | 837.7 | 911.3 | 29.2 | 24.2 | 0.080 |
| 14 | 763.5 | 845.0 | 36.2 | 24.6 | 0.090 |
| 15 | 629.3 | 713.9 | 46.2 | 24.3 | 0.110 |
| 16 | 462.8 | 529.9 | 57.7 | 23.2 | 0.120 |
| 17 | 264.8 | 312.8 | 69.9 | 21.1 | 0.140 |
| 18 | 94.0 | 115.1 | 82.5 | 18.5 | 0.130 |
| 19 | 10.4 | 13.7 | 95.3 | 16.3 | 0.070 |
| 20 | 0.0 | 0.0 | 107.9 | 15.0 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 14.0 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 13.0 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 12.2 | 0.000 |

GHI and Clearsky GHI units in $w/m^2$
Temperature units are in Celsius
DARS is the delta of the two GHI (see formula 2)

**Appendice 2. Hourly average data for the year 2011**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 12.7 | 0.000 |
| 1 | 0.0 | 0.0 | 149.8 | 12.0 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 11.4 | 0.000 |
| 3 | 0.0 | 0.0 | 133.2 | 10.9 | 0.000 |
| 4 | 0.0 | 0.0 | 121.8 | 10.4 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 10.2 | 0.000 |
| 6 | 5.4 | 5.8 | 97.1 | 10.6 | 0.023 |
| 7 | 82.9 | 91.1 | 84.3 | 12.6 | 0.061 |
| 8 | 268.6 | 282.6 | 71.7 | 15.9 | 0.071 |
| 9 | 480.8 | 503.8 | 59.4 | 19.2 | 0.054 |
| 10 | 666.1 | 694.9 | 47.8 | 21.8 | 0.046 |
| 11 | 805.6 | 834.5 | 37.6 | 23.8 | 0.038 |
| 12 | 870.2 | 910.9 | 30.0 | 25.2 | 0.046 |
| 13 | 870.4 | 915.8 | 29.2 | 26.1 | 0.052 |
| 14 | 789.3 | 849.4 | 36.2 | 26.7 | 0.071 |
| 15 | 660.1 | 718.4 | 46.2 | 26.4 | 0.081 |
| 16 | 479.9 | 533.3 | 57.7 | 25.4 | 0.101 |
| 17 | 277.9 | 314.7 | 69.9 | 23.3 | 0.119 |
| 18 | 97.3 | 115.1 | 82.5 | 20.4 | 0.110 |
| 19 | 10.6 | 13.1 | 95.3 | 18.1 | 0.060 |
| 20 | 0.0 | 0.0 | 107.9 | 16.6 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 15.5 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 14.4 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 13.5 | 0.000 |

GHI and Clearsky GHI units in $w/m^2$
Temperature units are in Celsius
DARS is the delta of the two GHI (see formula 2)

**Appendice 3. Hourly average data for the year 2012**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 13.0 | 0.000 |
| 1 | 0.0 | 0.0 | 149.9 | 12.3 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 11.7 | 0.000 |
| 3 | 0.0 | 0.0 | 133.3 | 11.3 | 0.000 |
| 4 | 0.0 | 0.0 | 121.9 | 10.9 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 10.7 | 0.000 |
| 6 | 5.1 | 5.6 | 97.1 | 11.1 | 0.027 |
| 7 | 78.3 | 89.7 | 84.4 | 13.0 | 0.092 |
| 8 | 244.6 | 278.5 | 71.7 | 16.1 | 0.139 |
| 9 | 449.4 | 497.8 | 59.4 | 19.3 | 0.108 |
| 10 | 636.6 | 687.6 | 47.8 | 21.8 | 0.079 |
| 11 | 775.1 | 826.4 | 37.6 | 23.6 | 0.066 |
| 12 | 844.8 | 901.4 | 30.1 | 24.9 | 0.065 |
| 13 | 826.0 | 906.1 | 29.3 | 25.7 | 0.090 |
| 14 | 732.3 | 840.1 | 36.2 | 26.1 | 0.128 |
| 15 | 610.9 | 710.6 | 46.2 | 25.7 | 0.140 |
| 16 | 444.7 | 527.1 | 57.7 | 24.6 | 0.155 |
| 17 | 256.5 | 310.6 | 69.9 | 22.6 | 0.170 |
| 18 | 87.1 | 113.6 | 82.6 | 19.9 | 0.144 |
| 19 | 10.0 | 13.1 | 95.3 | 17.8 | 0.073 |
| 20 | 0.0 | 0.0 | 107.9 | 16.4 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 15.5 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 14.6 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 13.7 | 0.000 |

GHI and Clearsky GHI units in $w/m^2$
Temperature units are in Celcius
DARS is the delta of the two GHI (see formula 2)

**Appendice 4. Hourly average data for the year 2013**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 12.0 | 0.000 |
| 1 | 0.0 | 0.0 | 149.8 | 11.3 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 10.8 | 0.000 |
| 3 | 0.0 | 0.0 | 133.2 | 10.4 | 0.000 |
| 4 | 0.0 | 0.0 | 121.8 | 10.0 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 9.8 | 0.000 |
| 6 | 5.0 | 5.7 | 97.1 | 10.2 | 0.032 |
| 7 | 79.7 | 90.6 | 84.3 | 12.0 | 0.087 |
| 8 | 245.5 | 280.6 | 71.7 | 14.9 | 0.148 |
| 9 | 447.0 | 500.2 | 59.4 | 17.8 | 0.122 |
| 10 | 621.6 | 689.9 | 47.8 | 20.2 | 0.108 |
| 11 | 748.7 | 828.4 | 37.6 | 21.9 | 0.103 |
| 12 | 809.1 | 903.7 | 30.0 | 23.1 | 0.111 |
| 13 | 805.1 | 908.2 | 29.2 | 23.9 | 0.119 |
| 14 | 730.5 | 842.1 | 36.2 | 24.3 | 0.139 |
| 15 | 603.2 | 712.0 | 46.2 | 24.0 | 0.160 |
| 16 | 444.5 | 528.4 | 57.7 | 23.0 | 0.161 |
| 17 | 263.7 | 312.0 | 69.9 | 21.0 | 0.156 |
| 18 | 93.4 | 114.3 | 82.5 | 18.5 | 0.117 |
| 19 | 9.9 | 13.0 | 95.3 | 16.4 | 0.067 |
| 20 | 0.0 | 0.0 | 107.9 | 15.2 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 14.3 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 13.4 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 12.6 | 0.000 |

GHI and Clearsky GHI units in w/m²
Temperature units are in Celcius
DARS is the delta of the two GHI (see formula 2)

**Appendice 5. Hourly average data for the year 2014**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 12.8 | 0.000 |
| 1 | 0.0 | 0.0 | 149.8 | 12.2 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 11.7 | 0.000 |
| 3 | 0.0 | 0.0 | 133.2 | 11.3 | 0.000 |
| 4 | 0.0 | 0.0 | 121.8 | 10.9 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 10.7 | 0.000 |
| 6 | 5.0 | 6.0 | 97.1 | 11.1 | 0.037 |
| 7 | 79.6 | 91.2 | 84.3 | 13.0 | 0.098 |
| 8 | 245.0 | 280.6 | 71.7 | 15.9 | 0.149 |
| 9 | 449.6 | 499.5 | 59.4 | 18.9 | 0.107 |
| 10 | 627.1 | 688.7 | 47.8 | 21.3 | 0.093 |
| 11 | 759.0 | 826.8 | 37.6 | 23.0 | 0.086 |
| 12 | 828.9 | 901.6 | 30.0 | 24.2 | 0.082 |
| 13 | 814.5 | 905.9 | 29.2 | 25.0 | 0.101 |
| 14 | 735.4 | 839.9 | 36.2 | 25.4 | 0.123 |
| 15 | 606.2 | 709.7 | 46.2 | 25.0 | 0.144 |
| 16 | 443.6 | 526.9 | 57.7 | 24.0 | 0.155 |
| 17 | 256.9 | 311.3 | 69.9 | 22.0 | 0.165 |
| 18 | 89.2 | 114.8 | 82.5 | 19.5 | 0.154 |
| 19 | 10.5 | 13.5 | 95.3 | 17.5 | 0.066 |
| 20 | 0.0 | 0.0 | 107.9 | 16.1 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 15.2 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 14.3 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 13.5 | 0.000 |

GHI and Clearsky GHI units in $w/m^2$
Temperature units are in Celcius
DARS is the delta of the two GHI (see formula 2)

**Appendice 6. Hourly average data for the year 2015**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperatur e | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 12.8 | 0.000 |
| 1 | 0.0 | 0.0 | 149.8 | 12.2 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 11.8 | 0.000 |
| 3 | 0.0 | 0.0 | 133.2 | 11.3 | 0.000 |
| 4 | 0.0 | 0.0 | 121.8 | 11.0 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 10.7 | 0.000 |
| 6 | 5.2 | 5.9 | 97.1 | 11.1 | 0.029 |
| 7 | 78.8 | 90.0 | 84.3 | 12.9 | 0.092 |
| 8 | 243.6 | 277.8 | 71.7 | 15.8 | 0.161 |
| 9 | 443.9 | 495.5 | 59.4 | 18.6 | 0.124 |
| 10 | 620.4 | 683.9 | 47.8 | 20.9 | 0.105 |
| 11 | 737.2 | 821.6 | 37.6 | 22.6 | 0.110 |
| 12 | 803.0 | 896.3 | 30.0 | 23.7 | 0.109 |
| 13 | 790.3 | 900.5 | 29.2 | 24.6 | 0.128 |
| 14 | 705.7 | 834.7 | 36.2 | 24.9 | 0.160 |
| 15 | 575.1 | 704.7 | 46.2 | 24.4 | 0.190 |
| 16 | 406.2 | 522.3 | 57.7 | 23.4 | 0.229 |
| 17 | 241.0 | 307.6 | 69.9 | 21.5 | 0.221 |
| 18 | 86.8 | 112.8 | 82.5 | 19.2 | 0.160 |
| 19 | 10.5 | 13.3 | 95.3 | 17.2 | 0.064 |
| 20 | 0.0 | 0.0 | 107.9 | 16.0 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 15.1 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 14.2 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 13.5 | 0.000 |

GHI and Clearsky GHI units in $w/m^2$
Temperature units are in Celcius
DARS is the delta of the two GHI (see formula 2)

**Appendice 7. Hourly average data for the year 2016**

| Hour | AVG | | | | |
|---|---|---|---|---|---|
| | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 12.9 | 0.000 |
| 1 | 0.0 | 0.0 | 149.9 | 12.3 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 11.8 | 0.000 |
| 3 | 0.0 | 0.0 | 133.3 | 11.4 | 0.000 |
| 4 | 0.0 | 0.0 | 121.9 | 11.0 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 10.8 | 0.000 |
| 6 | 5.7 | 6.0 | 97.1 | 11.1 | 0.013 |
| 7 | 83.5 | 91.2 | 84.4 | 13.0 | 0.059 |
| 8 | 252.4 | 280.4 | 71.7 | 15.9 | 0.102 |
| 9 | 449.2 | 499.2 | 59.4 | 18.8 | 0.108 |
| 10 | 630.3 | 688.3 | 47.8 | 21.2 | 0.092 |
| 11 | 751.5 | 826.3 | 37.6 | 23.0 | 0.095 |
| 12 | 799.6 | 901.2 | 30.1 | 24.1 | 0.117 |
| 13 | 791.9 | 905.3 | 29.3 | 24.9 | 0.127 |
| 14 | 719.8 | 839.2 | 36.2 | 25.2 | 0.143 |
| 15 | 605.2 | 709.6 | 46.2 | 24.9 | 0.147 |
| 16 | 453.3 | 526.8 | 57.7 | 23.8 | 0.137 |
| 17 | 258.7 | 311.3 | 69.9 | 21.9 | 0.151 |
| 18 | 93.2 | 115.0 | 82.6 | 19.4 | 0.121 |
| 19 | 10.8 | 13.6 | 95.3 | 17.3 | 0.068 |
| 20 | 0.0 | 0.0 | 107.9 | 16.0 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 15.1 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 14.3 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 13.6 | 0.000 |

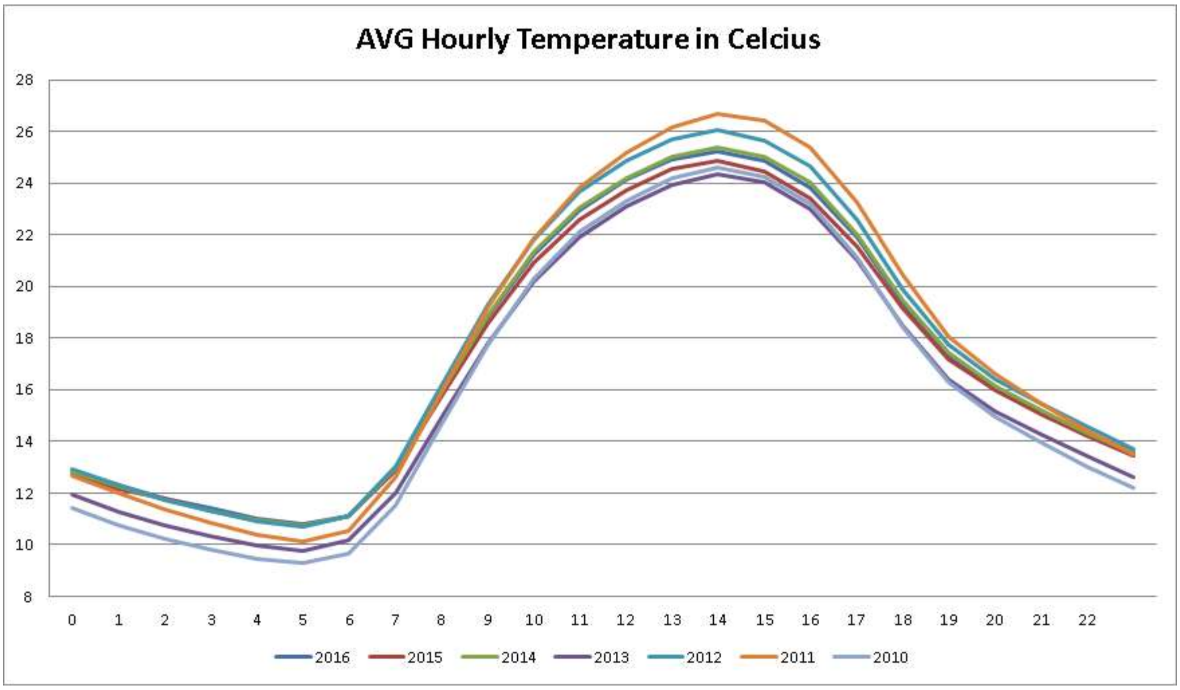
GHI and Clearsky GHI units in $w/m^2$
Temperature units are in Celcius
DARS is the delta of the two GHI (see formula 2)

**Appendice 8. Hourly average data for the years 2010-2016**

| AVG | | | | | |
|---|---|---|---|---|---|
| Hour | GHI | Clearsky GHI | Solar Zenith Angle | Temperature | DARS |
| 0 | 0.0 | 0.0 | 149.3 | 12.5 | 0.000 |
| 1 | 0.0 | 0.0 | 149.9 | 11.9 | 0.000 |
| 2 | 0.0 | 0.0 | 143.1 | 11.3 | 0.000 |
| 3 | 0.0 | 0.0 | 133.2 | 10.9 | 0.000 |
| 4 | 0.0 | 0.0 | 121.8 | 10.5 | 0.000 |
| 5 | 0.0 | 0.0 | 109.7 | 10.3 | 0.000 |
| 6 | 5.2 | 5.9 | 97.1 | 10.7 | 0.028 |
| 7 | 80.2 | 90.7 | 84.4 | 12.6 | 0.082 |
| 8 | 250.4 | 280.4 | 71.7 | 15.6 | 0.125 |
| 9 | 454.2 | 499.8 | 59.4 | 18.6 | 0.101 |
| 10 | 635.0 | 689.5 | 47.8 | 21.1 | 0.085 |
| 11 | 764.9 | 828.0 | 37.6 | 22.9 | 0.081 |
| 12 | 828.8 | 903.1 | 30.0 | 24.1 | 0.085 |
| 13 | 819.4 | 907.6 | 29.3 | 24.9 | 0.100 |
| 14 | 739.5 | 841.5 | 36.2 | 25.3 | 0.123 |
| 15 | 612.9 | 711.3 | 46.2 | 25.0 | 0.140 |
| 16 | 447.9 | 527.8 | 57.7 | 23.9 | 0.151 |
| 17 | 259.9 | 311.5 | 69.9 | 21.9 | 0.161 |
| 18 | 91.6 | 114.4 | 82.5 | 19.3 | 0.134 |
| 19 | 10.4 | 13.3 | 95.3 | 17.2 | 0.066 |
| 20 | 0.0 | 0.0 | 107.9 | 15.9 | 0.000 |
| 21 | 0.0 | 0.0 | 120.2 | 14.9 | 0.000 |
| 22 | 0.0 | 0.0 | 131.8 | 14.1 | 0.000 |
| 23 | 0.0 | 0.0 | 142.0 | 13.2 | 0.000 |

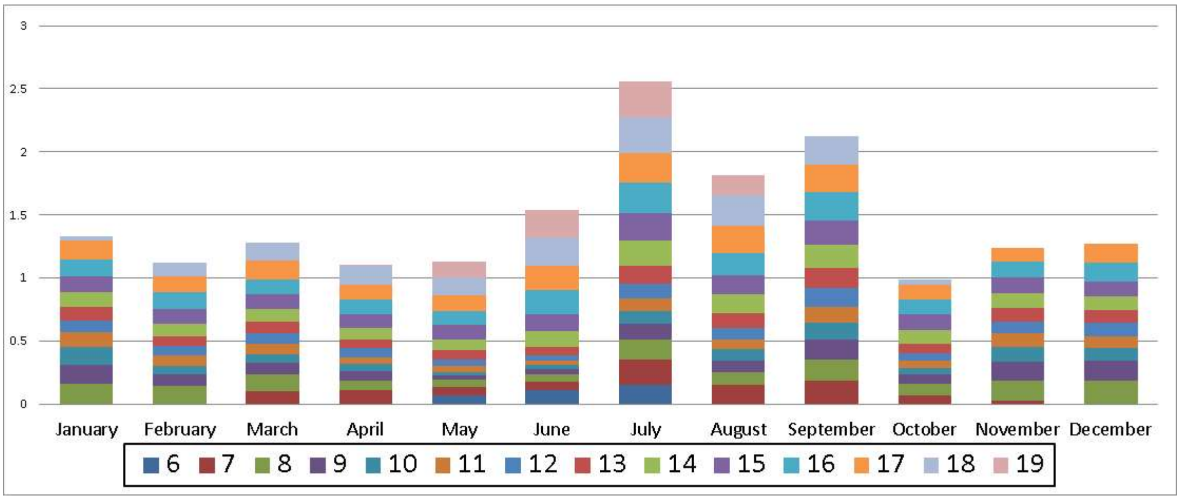
GHI and Clearsky GHI units in w/m²
Temperature units are in Celsius
DARS is the delta of the two GHI (see formula 2)
Morning hours are highlighted in colour yellow
Midday hours are highlighted in colour red
Afternoon hours are highlighted in colour orange

**Appendice 9. Hourly average temperature for the years 2010-2016**



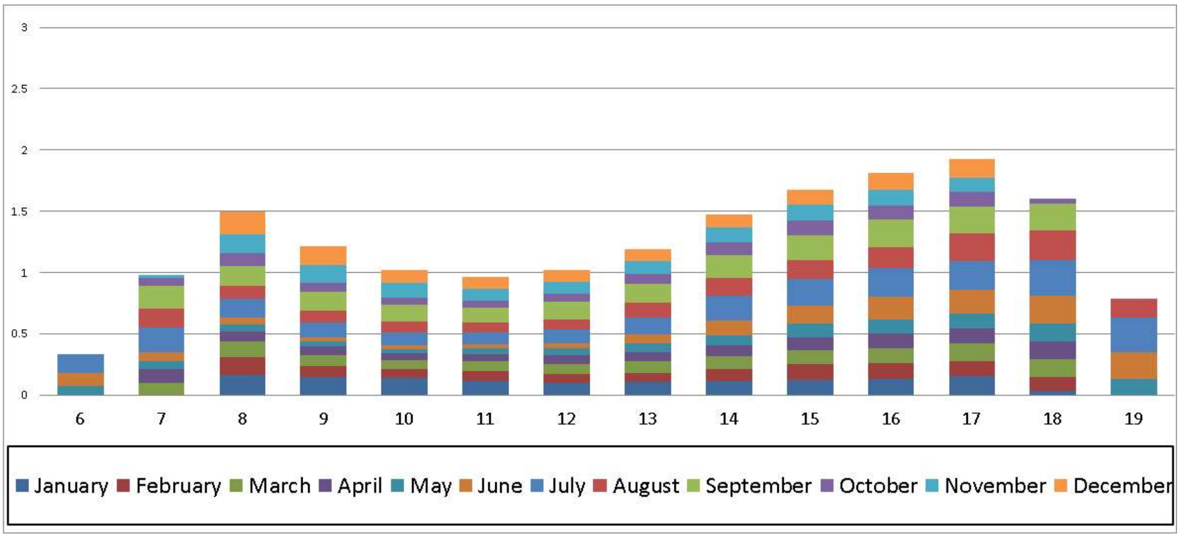

It can be seen that 2011 represents the warmest average temperature of the six years analysed.

**Appendice 10. Monthly DARS desglose by the hour.**

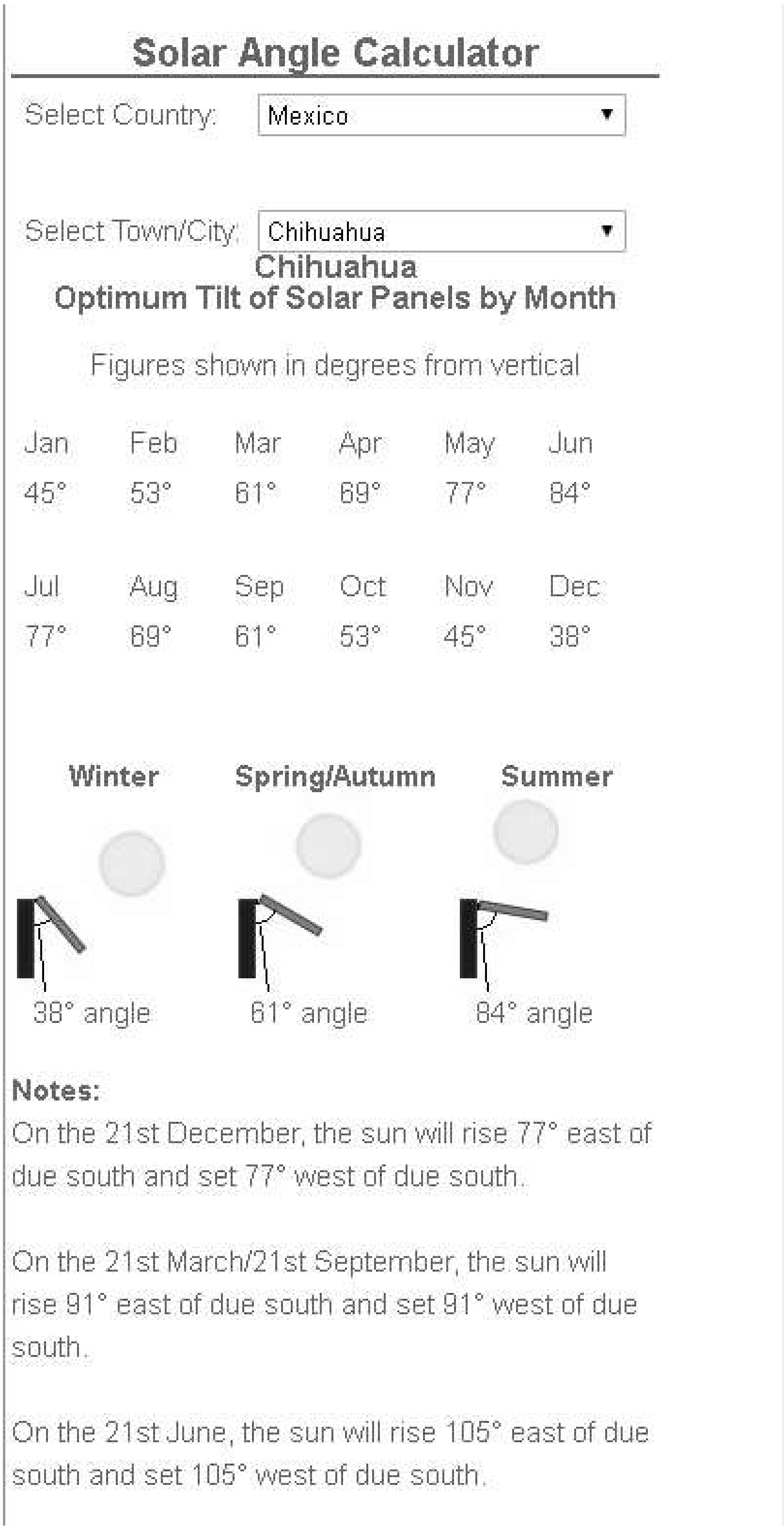



July is the month with more DARS, meaning that is the most cloudy, of the months

**Appendice 11. Hourly DARS desglose by each month.**



**Appendice 11. Optimum angle of inclination for a PV module**



## Solar Angle Calculator

Select Country: Mexico

Select Town/City: Chihuahua

**Chihuahua**
**Optimum Tilt of Solar Panels by Month**

Figures shown in degrees from vertical

| Jan | Feb | Mar | Apr | May | Jun |
|---|---|---|---|---|---|
| 45° | 53° | 61° | 69° | 77° | 84° |
| **Jul** | **Aug** | **Sep** | **Oct** | **Nov** | **Dec** |
| 77° | 69° | 61° | 53° | 45° | 38° |



**Notes:**
On the 21st December, the sun will rise 77° east of due south and set 77° west of due south.

On the 21st March/21st September, the sun will rise 91° east of due south and set 91° west of due south.

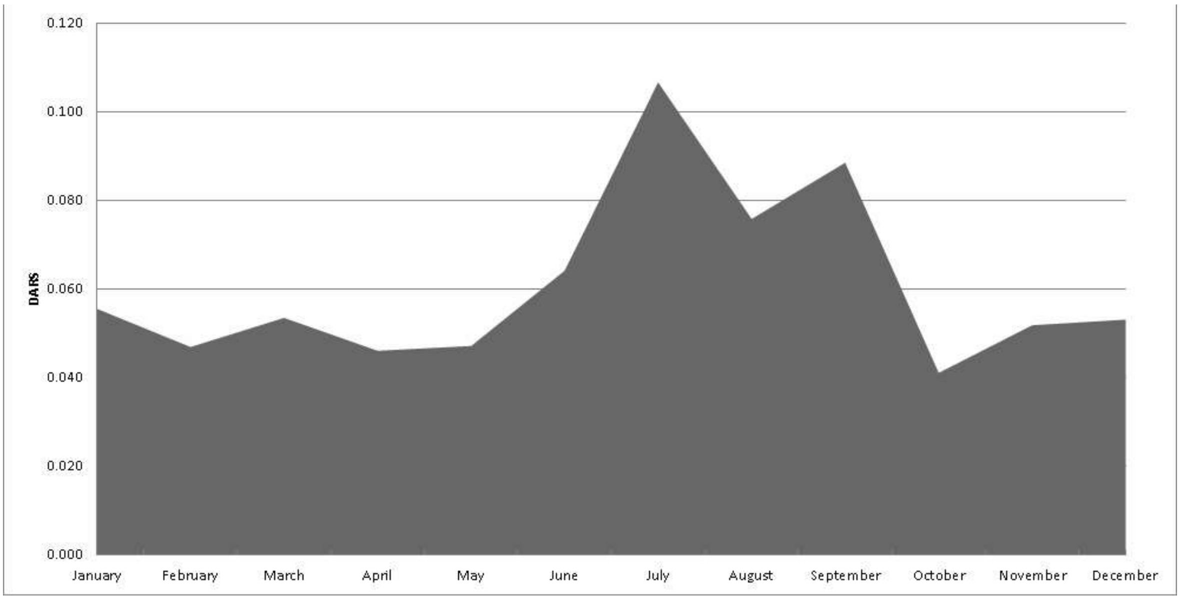
On the 21st June, the sun will rise 105° east of due south and set 105° west of due south.

Optimum vertical angle for each month and/or for the seasons suggested by the website www.solarelectricityhandbook.com for the city of Chihuahua. [39]

**Appendice 12. Hourly DARS divided by month**

| hour | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nor | Dec | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **5** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **6** | 0 | 0 | 0 | 0 | 0.07 | 0.11 | 0.15 | 0 | 0 | 0 | 0 | 0 | **0.03** |
| **7** | 0 | 0 | 0.10 | 0.11 | 0.07 | 0.07 | 0.20 | 0.15 | 0.19 | 0.07 | 0.03 | 0 | **0.08** |
| **8** | 0.16 | 0.14 | 0.13 | 0.08 | 0.05 | 0.06 | 0.16 | 0.10 | 0.17 | 0.10 | 0.16 | 0.19 | **0.13** |
| **9** | 0.14 | 0.09 | 0.09 | 0.07 | 0.03 | 0.04 | 0.12 | 0.09 | 0.15 | 0.07 | 0.15 | 0.15 | **0.10** |
| **10** | 0.14 | 0.07 | 0.07 | 0.06 | 0.03 | 0.04 | 0.10 | 0.09 | 0.14 | 0.06 | 0.12 | 0.10 | **0.09** |
| **11** | 0.12 | 0.08 | 0.08 | 0.06 | 0.04 | 0.03 | 0.10 | 0.08 | 0.13 | 0.05 | 0.10 | 0.10 | **0.08** |
| **12** | 0.10 | 0.07 | 0.08 | 0.07 | 0.06 | 0.04 | 0.11 | 0.08 | 0.15 | 0.06 | 0.10 | 0.10 | **0.09** |
| **13** | 0.11 | 0.08 | 0.09 | 0.07 | 0.07 | 0.07 | 0.14 | 0.12 | 0.16 | 0.08 | 0.11 | 0.10 | **0.10** |
| **14** | 0.12 | 0.10 | 0.10 | 0.09 | 0.09 | 0.12 | 0.20 | 0.15 | 0.18 | 0.11 | 0.12 | 0.11 | **0.12** |
| **15** | 0.13 | 0.12 | 0.11 | 0.11 | 0.11 | 0.14 | 0.22 | 0.15 | 0.20 | 0.12 | 0.13 | 0.12 | **0.14** |
| **16** | 0.13 | 0.13 | 0.12 | 0.12 | 0.11 | 0.19 | 0.24 | 0.17 | 0.22 | 0.12 | 0.12 | 0.14 | **0.15** |
| **17** | 0.15 | 0.12 | 0.15 | 0.12 | 0.12 | 0.19 | 0.24 | 0.22 | 0.22 | 0.12 | 0.11 | 0.15 | **0.16** |
| **18** | 0.03 | 0.11 | 0.14 | 0.15 | 0.14 | 0.23 | 0.29 | 0.24 | 0.22 | 0.04 | 0 | 0 | **0.13** |
| **19** | 0 | 0 | 0 | 0.00 | 0.13 | 0.22 | 0.28 | 0.16 | 0 | 0 | 0 | 0 | **0.07** |
| **20** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **21** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **22** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| **23** | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | **0.00** |
| | **0.06** | **0.05** | **0.05** | **0.05** | **0.05** | **0.06** | **0.11** | **0.08** | **0.09** | **0.04** | **0.05** | **0.05** | **0.06** |

**Appendice 13. Graphical representation of the monthly DARS average of the six years analyzed**



**Appendice 14. Energy generated by day in KWh**

| | MARCH | | | APRIL | |
|---|---|---|---|---|---|
| Day | SF1 | SF2 | Day | SF1 | SF2 |
| 1 | 7.1 | 7.0 | 1 | ** | ** |
| 2 | 7.1 | 7.0 | 2 | 6.9 | 6.7 |
| 3 | 6.2 | 6.3 | 3 | 5.8 | 6.0 |
| 4 | 5.0 | 5.2 | 4 | 6.9 | 6.8 |
| 5 | 5.4 | 5.4 | 5 | 6.8 | 6.9 |
| 6 | 6.3 | 6.3 | 6 | 5.5 | 5.7 |
| 7 | 6.5 | 6.1 | 7 | 5.5 | 5.8 |
| 8 | 6.2 | 6.6 | 8 | 6.1 | 6.3 |
| 9 | 6.1 | 5.8 | 9 | 5.9 | 6.4 |
| 10 | * | * | 10 | 6.6 | 6.5 |
| 11 | * | * | 11 | 5.7 | 6.1 |
| 12 | 6.6 | 6.4 | 12 | 5.6 | 5.8 |
| 13 | 6.9 | 6.8 | 13 | 7.0 | 7.1 |
| 14 | 5.3 | 5.2 | 14 | 7.3 | 7.4 |
| 15 | 4.8 | 4.9 | 15 | 7.1 | 7.0 |
| 16 | 4.5 | 4.6 | 16 | 6.9 | 6.9 |
| 17 | 4.4 | 4.5 | 17 | 7.1 | 7.0 |
| 18 | 7.0 | 7.0 | 18 | 6.9 | 6.9 |
| 19 | 7.0 | 6.9 | 19 | 5.9 | 6.2 |
| 20 | 7.1 | 7.0 | 20 | 5.1 | 5.2 |
| 21 | 6.9 | 6.9 | 21 | 5.4 | 5.3 |
| 22 | 4.7 | 4.8 | 22 | 4.1 | 4.3 |
| 23 | 5.7 | 5.5 | 23 | 5.3 | 5.4 |
| 24 | 4.3 | 4.0 | 24 | 5.2 | 5.2 |
| 25 | 4.2 | 4.1 | 25 | 4.8 | 5.1 |
| 26 | 4.0 | 3.9 | 26 | 5.4 | 5.6 |
| 27 | 6.6 | 6.2 | 27 | 5.8 | 6.1 |
| 28 | 7.4 | 7.3 | 28 | 4.8 | 5.1 |
| 29 | 7.4 | 7.2 | 29 | 5.8 | 5.9 |
| 30 | ** | ** | 30 | 6.8 | 6.7 |
| 31 | ** | ** | | | |

*During the weekend of the 10th of March, there were works going on in the roof and the system had to be shut down.
**At the end of March the system was out of internet credit and spent 3 days without collecting data.

**Appendice 15. The monthly DARS average for every of the six years analysed**

| Month | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | Total | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.047 | 0.031 | 0.034 | 0.074 | 0.054 | 0.112 | 0.036 | 0.055 | January |
| 2 | 0.048 | 0.017 | 0.056 | 0.051 | 0.046 | 0.077 | 0.033 | 0.047 | February |
| 3 | 0.023 | 0.029 | 0.053 | 0.036 | 0.084 | 0.119 | 0.031 | 0.053 | March |
| 4 | 0.047 | 0.025 | 0.035 | 0.024 | 0.062 | 0.093 | 0.035 | 0.046 | April |
| 5 | 0.033 | 0.021 | 0.050 | 0.052 | 0.040 | 0.059 | 0.075 | 0.047 | May |
| 6 | 0.072 | 0.048 | 0.038 | 0.073 | 0.076 | 0.087 | 0.055 | 0.064 | June |
| 7 | 0.146 | 0.090 | 0.150 | 0.138 | 0.069 | 0.083 | 0.071 | 0.107 | July |
| 8 | 0.058 | 0.037 | 0.085 | 0.066 | 0.093 | 0.047 | 0.144 | 0.076 | August |
| 9 | 0.109 | 0.066 | 0.090 | 0.085 | 0.127 | 0.051 | 0.091 | 0.088 | September |
| 10 | 0.023 | 0.024 | 0.030 | 0.053 | 0.026 | 0.091 | 0.041 | 0.041 | October |
| 11 | 0.009 | 0.024 | 0.059 | 0.099 | 0.054 | 0.074 | 0.044 | 0.052 | November |
| 12 | 0.018 | 0.053 | 0.058 | 0.063 | 0.050 | 0.048 | 0.081 | 0.053 | December |

**Appendice 16. Survey about solar energy in Chihuahua**

| Company | Telephone | Where do you face your solar PV panels? | What inclination angle do you use? | What do you think is the total capacity of solar PV energy installed in Chihuahua in MW | Additional comments |
|---|---|---|---|---|---|
| Ing.Eduardo Rodriguez | 6142901285 | Magnetic South | 27 | 20 | Company that installed this project |
| SIMOSOL | (614) 433-2186 | TRUE | 28 | 20 | |
| ISI SOLAR | (614) 423-1034 | Magnetic South | 28.6 | 20 | |
| SALARPLUS | (614) 185-1963 | Magnetic South | 26 | 15 | |
| ECOTEC | (614) 154-5338 | True | 22 | 10 | |
| Ing Julio Garcia. | 6141812548 | Magnetic | 31 | 20 | |
| Trinova | 614 172 2683 | True | 28 | 25 | |
| Solar smarth | 614 424 2405 | Magnetic South | 24 | 18 | |
| Jumo Energy | 614 297 4034 | True | 28.6 | 20 | |
| Santa Helena Solar | 6142166471 | Magnetic South | 30 | 102 | Maybe answered for the state of Chihuahua, including the city |
| Light Solar | 6141610152 | Magnetic South | 27 | 21 | |
| Chihuahua Solar | 6145404445 | Have their own | Have their own | 26 | Didn't want to share their orientation angle |
| Ecotec solar | (614) 259-4596 | True South | 22 | 10 | |
| Eco energia Global | 614 414 2488 | Magnetic South | 27 | 20 | |

**Appendice 17. Calculations for optimum angle for each month.**

| | $\sigma 1$ | $\sigma 2$ | $\sigma 3$ | $\omega\_morning$ | $\omega\_afternoon$ | $\omega\_AVG$ | $\alpha$ |
|---|---|---|---|---|---|---|---|
| **January** | 4.33 | 1.80 | 4.37 | 2.41 | 2.43 | 2.42 | 181 |
| **February** | 4.54 | 1.85 | 4.45 | 2.45 | 2.40 | 2.43 | 176 |
| **March** | 5.44 | 1.83 | 5.28 | 2.98 | 2.89 | 2.93 | 174 |
| **April** | 5.56 | 1.86 | 5.34 | 2.99 | 2.88 | 2.93 | 172 |
| **May** | 6.64 | 1.87 | 6.23 | 3.55 | 3.32 | 3.44 | 168 |
| **June** | 6.62 | 1.89 | 5.84 | 3.51 | 3.10 | 3.30 | 157 |
| **July** | 6.05 | 1.74 | 5.40 | 3.47 | 3.10 | 3.28 | 159 |
| **August** | 5.40 | 1.80 | 4.94 | 3.00 | 2.75 | 2.88 | 164 |
| **September** | 5.08 | 1.70 | 4.80 | 2.99 | 2.83 | 2.91 | 169 |
| **October** | 5.60 | 1.86 | 5.42 | 3.00 | 2.91 | 2.96 | 174 |
| **November** | 4.37 | 1.80 | 4.41 | 2.43 | 2.46 | 2.45 | 181 |
| **December** | 4.36 | 1.80 | 4.37 | 2.42 | 2.43 | 2.43 | 180 |
| **AVG** | 6.41 | 1.82 | 6.13 | 3.53 | 3.38 | 3.45 | **171** |

# 14. GRAPHICAL MATERIAL


Unpacking of the PV modules

Installation

Process with installation, note the compass used to calculate the magnetic south.


Installation SP1

PV module in the morning.


SF1 PV Module


SF2 PV module


Picture of the two solar inverters