Operating correction factor of PV system

Effects of temperature, angle of incidence and inverter in PV system performance

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Abstract

In this project, the correction factor of different solar panels of the laboratory of the University of Gävle, located in Sweden, is going to evaluated. The solar modules’ working conditions are different from the ones used to test them in the laboratory. In the laboratory, the output energy of the modules is less than in working conditions, and therefore a correction factor is going to be calculated from the data collected, in order to describe the factors that affect the performance of the solar modules.

Also, the obtained correction factor validity for different PV systems it is going to be examined, determining which system has a better correction factor and the energy losses due to temperature, angle of incidence and micro invertor.

Key words: photovoltaic, correction factor, temperature, angle of incidence, irradiation, micro invertor.
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Nomenclature

A  Area of the modules [m²]
b₀  Angle of incidence correction factor
CIGS  Copper indium gallium selenide
d  Day of the year in Julian calendar
d+t+m  Silicon diode +Silicon Tigo+ Silicon module inverter
E  Correction for the solar time [°]
e⁻  Electrons
E_{out}  Output energy [kWh]
G  Solar irradiance [W/m²]
H  Heat transfer coefficient [W/m²·K]
h  Irradiance [kWh/m²]
hh  Solar hours [h]
l  Current [A]
K₀(θ)  Angle of incidence correction coefficient
Kₜ  Temperature coefficient correction
Lᵢ  Local meridian [°]
L_{st}  Standard meridian [°]
mm  Solar minutes [min]
n  Negative layer
p  Positive layer
P  Power [W]
P_{in}  Input power of the micro inverter [W]
P_{module}  Power given by the module [W]
P_N  Nominal power of the solar panel [W]
P_{out}  Output power [W]
P_{peak}  Peak power of the solar module [kw]
P_{theoretical}  Theoretical power given by the module
PV  Photovoltaic
T_{ambient}  Ambient temperature [°C]
T_{module}  Temperature of the solar module [°C]
U  Voltage [V]
V_{oc}  Open circuit voltage [V]
αₛ  Solar altitude [°]
β  Tilt angle of the modules [°]
γ  Azimuth angle of the panels [°]
δ  Declination [°]
η  Efficiency [%]
η_{inverter}  Micro inverter efficiency
θ  Angle of incidence [°]
θ_Z  Zenith angle [°]
λ  Latitude [°]
φ  Correction factor [%]
φ_{theoretical}  Theoretical correction factor [%]
ω  Hour angle [°]
1. Introduction

Due to the nuclear fusion reactions that occur inside the sun, it emits energy as solar radiation and part of it reaches the earth, which represents the planet’s main energy resource. The net solar power arriving to the earth is 8000 times the current rate used by humans in nuclear and fossil fuels. Also, it is renewable, non-polluting and inexhaustible as well as being the driving force for other renewable energies as wind, hydropower or biomass. (Godfrey, B. 2012; Vanex, F. et al. 2016)

A photovoltaic system is one that generate electricity from light. In this way, energy arriving from the sun can be collected and converted into electrical energy so that can be used in household or industrial applications.

In this document the main parameters that affect how energy is collected by the solar modules of the laboratory of the University of Gävle (Sweden) are going to be examined. The system is formed by different solar modules, as can be appreciated in Fig. 1, and micro invertors.

![Fig. 1 Installation of the solar modules in the laboratory of the University of Gävle.](image)

As the route of the sun varies during the year, the energy collected in the panels differ during the day. Also, taking into account that the solar modules are shadowed early in the mourning and in the afternoon, by the architecture of the building, Fig. 2, only the data between 9 a.m. and 14 p.m. has been taken into account.

The solar cell is formed by a p-n diode, an electrical semiconductor usually made of silicon, and doped normally with phosphorous and boron in the n and p layer respectively. The photons irradiated by the sun penetrate in the PV cell and transfer their energy to electrons of the panel producing an electrical field, moving electrons to the n side and holes (or positively charged particles), to the p side (Wenham, S.R. et al. 2007). The photovoltaic, PV, cells are tested under standard test conditions which are different form their performance conditions. In this document, the effect of temperature, angle of incidence and the micro invertor in the performance of solar cells is going to be analysed.
There solar modules that are going to be considered are Silicon diode, Silicon Tigo, Silicon module inverter and thin film, Fig 3. The characteristics of the used modules are summarized in Table I.

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<th>Peak power $P_{peak}$ [kW]</th>
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<td>6</td>
<td>0.195</td>
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<td>6</td>
<td>0.195</td>
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<tr>
<td>Silicon Module inverted</td>
<td>6</td>
<td>0.195</td>
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<tr>
<td>Thin film</td>
<td>9</td>
<td>0.85</td>
</tr>
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The panes are located in the laboratory of the University of Gävle (60°4’N and 17°06’E). There are installed with a tilt of 40°, as it can be appreciated in Fig.4 and they are orientated 12° towards the east.
Fig. 4 Tilt of the solar modules

The system installation parameters are summarized in Table II:

Table II Parameters of the solar modules installation.

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<tr>
<td>Azimuth</td>
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<td>Latitude of the panels</td>
<td>λ</td>
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</tr>
<tr>
<td>Altitude of the panels</td>
<td>Λ</td>
<td>-17°06’</td>
</tr>
<tr>
<td>Standard meridian</td>
<td>Lst</td>
<td>-15°</td>
</tr>
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</table>
Operating correction factor of PV system

2. Method and objectives

To perform this project 10 minutes datasets have been recollected from the installation of different solar panels of the laboratory of the University of Gävle on the months of August and September of the year 2016, between 9:00 am and 2:00 pm.

Starting with the data of obtained energy from the solar panels for each ten minutes the aim of this project is to determine the correction factor of the performance of the solar cells due to the temperature, angle of incidence and efficiency of the invertor.

To carry out this project four different solar modules have been considered:

- Silicon diode: 6 series connected silicon modules with bypass diodes.
- Silicon Tigo: 6 series connected silicon modules with bypass diodes and TIGO-optimizer.
- Silicon module inverter: 6 series connected silicon modules with bypass diodes and module inverter.
- Thin film: 9 series connected thin film CIGS modules with bypass diodes and module inverter.

Correction factors have been calculated for the output energy of the silicon diode modules, silicon Tigo modules, silicon module inverter modules, thin film modules and silicon diode, siliconTigo and silicon module inverter the three together (d+t+m).

To take the measurements the following equipment has been used:

- To measure the ambient temperature, a thermometer has been used, which measures the temperature in Celsius degrees each 10 minutes, and with a precision of three decimals.
- The solar irradiance has been measured with a tilted pyranometer in the same plane as the module and a horizontal pyranometer has been used to measure the diffuse irradiation (W/m²). The data have been collected every 10 minutes with four decimal precision.
- The output energy, measured in alternating current, of each of the examined PV system every 10 minutes with eight decimals precision in kWh.

Then, using the measured data, the effect of the angle of incidence, temperature and micro inverter factors in the final energy production has been calculated, as well as, the correction factor of the module. Next, there correction factor has been further adjusted with the heat transfer coefficient and micro inverter efficiency.

Finally, a comparison between the measured output energy from the panels and the output energy calculated with the correction factor has been carried out in order to assess the proposed model’s validity.
3. Theoretical background

3.2 Solar cell performance

Henri Becquere described in 1839 the photovoltaic effect, where electrical voltage is created from solar beam when strike a surface made of a specific material. In 1954 the scientist managed to supply energy to a load using the photovoltaic effect.

The PV cell, converts the sunlight energy into electricity using an adapted electrical semiconductor, or diode, usually, it is made of silicon, the second more abundant element in the earth (Vanex, F. et al. 2016). Silicon is the most usual element of solar cells, although, other materials can be used to build a PV cell, like thin film modules. Since the silicon is the more extended building material in PV cells, the collar cell performance is going to be explained for those cells.

A PV cell has two crystalline silicon doped layers which are modified to produce more energy, that is, to facilitate the loose or attraction of electrons. The n type, or negative layer, is doped with phosphorus, which has one more valence electron than silicon, therefore it has overabundant of free electrons, e\(^-\). Whereas the p type is doped with boron, which have one less valence electron than silicon p type layer, has a lack of free electrons. Since the absence of a negative charge can be considered a positive charge or hole, it is called p type or positive layer. (Godfrey, B. 2012; Vanex, F. et al. 2016)

Joining a p and a n type layer a p-n junction is obtained. This junction sets an electric field, where the n type layer has an excess of electrons that move to the p type layer where there is a lack of electrons or extra holes where the electrons can be ubicated, creating an electrical current, I. (Godfrey, B. 2012; Vanex, F. et al. 2016)

![Fig. 5 p-n junction in a solar cell performance.](image-url)
The light arriving from the sun is form of energy particles called photons. When a photon with a specific energy or wavelength, the same as the bandgap energy, reaches the p-n junction it transfers its energy to an electron, releasing it from the atom. The “free” electron moves leaving holes behind that attract the electrons leaving another hole. In this way, a current of electrons, or electric current is created, going from the p side to n side and another of holes going from n to the p side, going in opposite directions (Godfrey, B. 2012). In the surface of the cell there are placed two metal collectors to feed the load with the energy generated by the cell, Fig. 5. The PV cell are series or parallel connected forming a PV panel in order to be able to produce more energy and reach the amount required by the load. That provides electrical energy to the electric circuit or load that they are connected to. (Vanex, F. et al. 2016)

3.2 PV module efficiency

The performance of a solar cell must be tested under standard test conditions. The measures are taken at a temperature of the module

\[ T_{\text{module}}=25^\circ \text{C} \]

and the solar irradiation, incident from the sun in the module should be

\[ G=1000\text{W/m}^2 \]

when the sun is at zenith, that means, the angle of incidence is \[ \theta=0^\circ \]

When the sun is at its zenith, the distance that the sun beam travels through the space to the solar module is the minimum. (Godfrey, B. 2012)

In this way, the peak power of a solar cell, \( P_{\text{peak}} \) measured in kW, is calculated under standard. It is determined by the following equation:

\[ P_{\text{peak}} = \eta \cdot A \quad (1) \]

Where:
- \( P_{\text{peak}} \): peak power [kW]
- \( \eta \): efficiency [%]
- \( A \): area of the modules [m\(^2\)]

3.2 PV modules output power

The output power, \( E_{\text{out}} \), and hence the energy, given by a solar cell will be different than the peak power since the irradiance is going to have another value, being the theoretical power given by a solar cell directly proportional to the received irradiance:

\[ P_{\text{theoretical}} = P_{\text{peak}} \cdot \frac{G}{1000} \quad (2) \]
Where:
- $P_{\text{theoretical}}$: theoretical power given by the module [W]
- $P_{\text{peak}}$: peak power of the solar modules [W]
- $G$: solar irradiance [W/m$^2$]

In the case of the solar modules of the laboratory of the University of Gävle, there are tilted

$$\beta = 40^\circ$$

do, the irradiance has been measured in the tilted pyranometer, as it has the same inclination as the modules.

To calculate the peak power of the used solar modules, the nominal output power of one solar panel has been multiplied by the installed quantity of solar panel in each module:

$$P_{\text{peak}} = a \cdot P_N \quad (3)$$

Where:
- $P_{\text{peak}}$: Peak power of the solar modules [W]
- $a$: Number of solar panels
- $P_N$: Nominal power of the solar panel [W]

Even thought, measured output power and the theoretical output power does not concur. This difference occurs because the data of the panels have been measured at different conditions than the specific ones for the performance of a solar cell mentioned in the previous section, 3.2. Solar cell performance.

In the used data set the temperature, solar irradiance and angle of incidence of the panels are different from the solar cell performance conditions. Therefore, in the following sections, the effect of each one of them is going to be calculated, in order to obtain the correction factor.

### 3.3 Used PV systems

To carry out this project there four different solar modules have been considered:

- Silicon diode
- Silicon Tigo
- Silicon module invertor
- Thin film

The silicon modules are crystalline silicon modules with bypass diodes in order to minimize the influence of shadows in the solar module. The silicon Tigo, also contains a power optimizer, which reduce the effect of shadows. Finally, the module invertor converts the direct current into alternating current.

The thin film or CIGS, instead of being made of silicon, is a copper indium gallium selenide solar cell. The examined system, also contains bypass diodes and a module inverter.
3.4 Effect of temperature

The solar cell operates at a higher temperature than the 25°C of the standard test conditions, when the temperature increases, the solar cell open circuit voltage, $V_{oc}$, decreases, so, the output voltage, $U$, also is reduced.

The operating temperature of the solar cell is given by the temperature of the ambient and the solar irradiance or the intensity of the sunlight in the module. (Wenham, S.R. et al. 2007)

To understand the effect of temperature the power, $P$, produced by an electric source when it is connected to a load, such as the solar panels, must be explained. It is the product of the current $I$, measured in Ampere, that is, flow of electric charge, and voltage, measured in Volt, meaning, the difference of potential.

$$P = I \cdot U$$  \hspace{1cm} (4)

Where:
- $P$: power produced [W]
- $I$: current [A]
- $U$: voltage [V]

As it has been mentioned before, the solar cell is a diode, and the increase of temperature affects the electrical efficiency, and therefore, the performance of photovoltaic cells. The energy emitted by the sun arrives to the earth as photons or light and heat. As there has been explained in the section 3.2 Solar cell performance the energy carried by the photons is used to generate electric power, whereas the remainder energy, is heat that contributes to increasing the temperature of the solar cell. (Dubey, S. et al. 2013)

On one hand, when the temperature of a semiconductor increases, the electrons receive more energy, so, they become free electrons. The same effect that occurs in a solar cell with the photons. In this way, the increase of temperature produce a decrease in the resistance, and the current of the cell increases. (Electrotechnik, 2016)

On the other hand, the increase of temperature causes a decrease in the bandgap energy, that is, the energy required to free an electron decreases. Since the bandgap energy has decreased, the potential difference between the electrons and the excited or free electrons decreases, causing a reduction of voltage. (Crossley, R. 2015)

As a result of high temperatures in the solar cell performance, the current given by the panel increases, but, the voltage is reduced. Since the decrease of the voltage is bigger than the increase of the current the power of the panel is reduced.

To evaluate this, the temperature coefficient is used, which express as a negative percentage the effect of temperature in the panel. It describes the effect that module’s temperature has when it works at a higher temperature than 25°C. (The green age, 2016)
3.4.1 Temperature correction

The temperatures of the modules have been estimated from the ambient temperatures and the irradiance measured with the pyranometer, according with the formula 5:

\[ T_{\text{module}} = T_{\text{ambient}} + \frac{G}{h} \]  

In which:
- \( T_{\text{ambient}} \): Ambient temperature [°C]
- \( G \): Irradiance [W/m²]
- \( h \): Heat transfer coefficient [W/m²·K]

To carry out these calculations, the following heat transfer value will be used:

\( h = 20 \text{ W/m}^2\cdot\text{K} \)

As the ambient temperature and the irradiance are the same for different modules, as well as the heat transfer coefficient, the modules have been operating at the same temperature.

Considering the temperature corrections, the used temperature coefficient is different for the used solar modules as there are made of different materials. So, the temperature coefficient for the silicon modules is

\( \gamma_{\text{Si}} = 0.44\%/\text{°C} \)

and for the Thin film modules it is

\( \gamma_{\text{TF}} = 0.38\%/\text{°C} \)

To calculate the temperature correction equation 6 has been used.

\[ K_T = 1 - \frac{(T_{\text{module}} - T_{\text{ambient}}) \cdot \gamma_T}{100} \]  

In which:
- \( K_T \): temperature coefficient correction
- \( T_{\text{module}} \): temperature of the solar module [°C]
- \( T_{\text{ambient}} \): ambient temperature [°C]
- \( \gamma_T \): temperature coefficient [%/°C]

3.5 Effect of the angle of incidence

The intensity of energy that arrives outside the Earth atmosphere from the sun is called the solar constant and has a value of 1368 W/m², even though, it is inconstant due to solar flares and sun spots, the distance between the earth and the sun, the effect of the atmosphere like absorption and diffraction of solar beam, weather, geographic location or latitude, season, hour of the day, etc. (Vanex, F. et al. 2016)

The route of the sun varies during the year, so the distance between the earth and the sun depend of the day of the year. In this section the effect of the position of the sun in the sky in the performance of solar panels, is going to be analysed, as, the energy available depend on the position of the sun in the sky at each moment.
The angle between the sun beam and the direction of the surface is called angle of incidence, Fig. 6. This angle gives the available sun energy that the panel can use to convert into electric power (Vanex, F. et al. 2016). As it can be appreciated in the Fig. 7, the value of the angle of incidence varies during the day.

Fig. 6 Angle of incidence

Fig. 7 Angle of incidence during the 3rd of April in Gävle
3.5.1 Angle of incidence correction

To calculate the angle of incidence, the following equation can be used:

$$cos(\theta) = \cos(\delta)\sin(\omega)\sin(\beta)\sin(\gamma) + \cos(\delta)\cos(\omega)\sin(\lambda)\sin(\beta)\cos(\gamma)$$
$$\quad - \sin(\delta)\cos(\lambda)\sin(\beta)\cos(\gamma) + \cos(\delta)\cos(\omega)\cos(\lambda)\cos(\beta)$$
$$\quad + \sin(\delta)\sin(\lambda)\cos(\beta)$$ \hspace{1cm} (7)

Where:
- $\theta$: angle of incidence [°]
- $\delta$: declination [°]
- $\lambda$: latitude [°]
- $\gamma$: azimuth [°]
- $\omega$: hour angle [°]
- $\beta$: tilt [°]

The route of the sun varies during the year, so the distance between the earth and the sun depend on the day of the year. The equation to calculate the position of the sun in each moment uses the variables of equation 7, called solar angles and there are used to describe the solar geometry.

The solar angle is calculated from solar time, which it is determined by the solar noon, referring to when the sun is facing the south of a location. The solar time and local time are coincident but ca be mismatched due to two factors:

- The difference between the standard longitude, which determines the local time zone, and the local longitude, which is the longitude of a specific position. 0° longitude goes thought Greenwich in England and starting from there in 15° steps are defined t the standard time zones, those values are positive to the east of Greenwich and negative in the west, Fig 8. Each degree of difference it is equal to 4 min of solar time difference.

Fig. 8 Latitude and longitude
The elliptical rotation of the earth around the sun is determined by the correction of time, $E$.

$$\text{solar time} = \text{local time} + 4 \cdot (L_{st} - L_i) + E$$  \hspace{1cm} (8)

Where:
- $E$: correction of solar time [min]
- $L_{st}$: standard meridian [°]
- $L_i$: local meridian of the location [°]

To obtain the value of correction of solar time the following equations can be used

$$E = 229.2 \cdot (0.000075 + 0.001868 \cdot \cos(B) - 0.032077 \cdot \sin(B) - 0.014615 \cdot \cos(2B) - 0.04089 \cdot \sin(2B))$$  \hspace{1cm} (9)

Where $B$ is defined by the equation 10, and $d$ is the day of the year of the Julian calendar.

$$B = \frac{360 \cdot (d - 1)}{365}$$  \hspace{1cm} (10)

Hour angle, is expressed in degrees of earth rotation before or after solar noon at a given longitude with respect to the solar time:

$$\omega = 15^\circ \cdot \left( hh - 12 + \frac{mm}{60} \right)$$  \hspace{1cm} (11)

In which:
- $\omega$: hour angle [°]
- $hh$: solar hour [h]
- $mm$: solar minutes [min]

As the hour angle is calculated in relation to the solar time solar time has to be calculated in hour and minutes, $hh:mm$, solving equation 8:

$$hh:mm = \text{solar time} - \text{normal time} = 4 \cdot (L_{st} - L_i) + E$$  \hspace{1cm} (12)
Solar altitude, $\alpha_s$, is the angle defined by the line of the sun and the line to the horizon, Fig. 9. The complementary angle is called zenith angle, $\theta_Z$, and is the angle between the line of the sun and the line to a point above the horizon, both angles have a maximum value of 90°, Fig. 10.

The surface azimuth angle, Fig. 11, is defined with respect to the surface, in this case, the azimuth of the solar panels. It is the orientation between the surface and the south, following the agreement, this angle is positive towards west and negative towards east. If the solar panel is installed toward the sun, then $\gamma=0$. 

---

**Fig. 9 Solar altitude during the 3\textsuperscript{rd} of April in Gävle**

**Fig. 10 Zenith and azimuth angles, $\theta_Z$ and $\alpha_s$**

**Fig. 11 Azimuth angle, $\gamma$**
The angle which the surface is tilted from the horizontal is called tilt angle or elevation, Fig. 13.

\[ \beta \]

*Fig. 12 Tilt angle, \( \beta \)*

The angle measured in degrees between the sun and the line of the equator is defined as declination and it has a value of

\[ \delta_{\text{summer solstice}} = 23.45^\circ \]

in summer solstice and

\[ \delta_{\text{winter solstice}} = -23.45^\circ \]

in winter solstice, that is, positive values for the north of the celestial equator and negative values for the south of the celestial equator. The declination is the reason for the different seasons during the year. In winter and summer equinoxes the declination has a value of

\[ \delta_{\text{equinoxes}} = 0 \]

*Fig. 13 Declination, \( \delta \)*
The declination depends on the day of the year and it determines the seasons, as it is shown in Fig.14, and is calculated as a function of the day of the year:

$$
\delta = 23.45 \cdot \sin \left( \frac{360 \cdot (284 + d)}{365} \right) 
$$

(13)

Where:
- $\delta$: declination [°]
- $d$: day of the year in the Julian calendar

Finally, the correction of the angle of incidence is described by the 14 equation:

$$
K_b(\theta) = 1 - b_0 \left( \frac{1}{\cos \theta} - 1 \right) 
$$

(14)

In which:
- $K_b(\theta)$: correction factor for angle of incidence [%]
- $b_0$: angle of incidence correction factor
- $\theta$: angle of incidence [°]

### 3.6 Micro inverter

Since the solar cell produce direct current, DC, it has to be converted to alternating current, AC, using a micro inverter. The aim of the micro inverter is to maintain constant the input and output energy whereas the wave shape is changed from a non polarized wave into an alternating wave with 230V and 50Hz. To do so, it uses semiconductors that have some operating losses, due to switching or resistance of the semiconductor, among others.

The losses produced in the micro inverter are expressed as the operating efficiency $\eta_{\text{inverter}}$, which is a relation between the output and input power. An ideal micro inverter is one with no losses, that is, the input and output power is the same, $\eta_{\text{inverter}}=100\%$.

$$
\eta_{\text{inverter}} = \frac{P_{\text{out}}}{P_{\text{in}}} 
$$

(15)

In which:
- $\eta_{\text{inverter}}$: efficiency of the micro inverter [%]
- $P_{\text{out}}$: output power of the micro inverter [W]
- $P_{\text{in}}$: input power of the micro inverter [W]

The micro inverter does not affect the performance of the PV system, like the temperature and the angle of incidence. However, the calculated output energy, considering the effects of temperature and angle of incidence, is in direct current and to compare with the measured output energy, the losses caused by the inverter must be added.
### 3.7 Operating correction factor correction factor

The correction factor, $\varphi$, expresses the relation between the output energy of a solar cell when it works at different conditions than the standard test conditions, and it can be calculated with the following equation:

$$ E_{out} = \varphi \cdot P_{peak} \cdot H $$

Where:
- $E_{out}$: output energy [kWh]
- $\varphi$: operating correction factor [%]
- $P_{peak}$: peak power [kW]
- $H$: irradiance [kWh/m²]

The correction factor considers the effect of performance temperature of the modules, $K_T$, angle of solar beam incidence correction, $K_b(\theta)$, and the efficiency of the inverter, $\eta_{inverter}$. Consequently, the operating factor can be calculated based on these corrections:

$$ \varphi = K_T \cdot K_b(\theta) \cdot \eta_{inverter} $$

As the aim of a PV systems is to generate energy, the best correction factor has a value of

$$ \varphi = 1 $$
4. Measurements

The amount of irradiance that has been received through the months of August and September between the 9 a.m. and 2 p.m. has a value of

\[ H = 125 \text{ kWh/m}^2 \]

The amount of energy produced by the solar panels in the months of August and September between 09:00 and 14:00 for the used PV systems Silicon diode, Silicon Tigo, Silicon module inverter, Silicon diode + Silicon Tigo + Silicon module inverter \((d+t+m)\) and Thin film are summarized on Table III.

<table>
<thead>
<tr>
<th>Energy (kWh)</th>
<th>Silicon</th>
<th>Thin film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode</td>
<td>TIGO</td>
<td>Module inverter</td>
</tr>
<tr>
<td>115.180</td>
<td>118.440</td>
<td>122.170</td>
</tr>
</tbody>
</table>
5. Results

5.1 Peak power

To calculate the peak power of Silicon diode, Silicon Tigo, Thin film and d+t+m equation 3 has been used. In Table IV the peak power of the used module systems is summarized:

<table>
<thead>
<tr>
<th></th>
<th>$P_{\text{peak}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode</td>
<td>6·0.195=1.17kW</td>
</tr>
<tr>
<td>Tigo</td>
<td>6·0.195=1.17kW</td>
</tr>
<tr>
<td>Module inverter</td>
<td>6·0.195=1.17kW</td>
</tr>
<tr>
<td>Thin film</td>
<td>9·0.085=0.765kW</td>
</tr>
<tr>
<td>d+t+m</td>
<td>18·0.195=3.51kW</td>
</tr>
</tbody>
</table>

5.2 Used factors

Table V summarises the chosen factors used in equations 5, 6, 14 and 15 to calculate the correction factors due to temperature, angle of incidence and module invertor.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of incidence correction factor</td>
<td>$b_0$</td>
<td>0.1</td>
</tr>
<tr>
<td>Heat transfer value</td>
<td>$h$</td>
<td>20 W/m²·K</td>
</tr>
<tr>
<td>Invertor efficiency d+t+m</td>
<td>$\eta_{\text{inverter}}$</td>
<td>0.9%</td>
</tr>
<tr>
<td>Invertor efficiency diode</td>
<td>$\eta_{\text{inverter}}$</td>
<td>0.9%</td>
</tr>
<tr>
<td>Invertor efficiency module inverter</td>
<td>$\eta_{\text{inverter}}$</td>
<td>0.9%</td>
</tr>
<tr>
<td>Invertor efficiency Thin film</td>
<td>$\eta_{\text{inverter}}$</td>
<td>0.9%</td>
</tr>
<tr>
<td>Invertor efficiency Tigo</td>
<td>$\eta_{\text{inverter}}$</td>
<td>0.9%</td>
</tr>
<tr>
<td>Temperature coefficient for silicon modules</td>
<td>$\gamma_{\text{Si}}$</td>
<td>0.44%</td>
</tr>
<tr>
<td>Temperature coefficient for thin film modules</td>
<td>$\gamma_{\text{TF}}$</td>
<td>0.38%</td>
</tr>
</tbody>
</table>
5.3 Theoretical correction factor

Equation 16 defines the output energy of a solar panel. Solving the equation, the theoretical correction factor of the solar module performance can be calculated:

$$\varphi_{\text{theoretical}} = \frac{E_{\text{out}}}{P_{\text{peak}} \cdot H}$$

(18)

Table VI summarises the value that the correction factors should have.

**Table VI Theoretical correction factor**

<table>
<thead>
<tr>
<th></th>
<th>Diode</th>
<th>Tigo</th>
<th>Module inverter</th>
<th>d+t+m</th>
<th>Thin film</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{out}}$ (kWh)</td>
<td>115.18</td>
<td>118.44</td>
<td>122.17</td>
<td>355.79</td>
<td>82.35</td>
</tr>
<tr>
<td>$P_{\text{peak}}$ (kW)</td>
<td>1.17</td>
<td>1.17</td>
<td>1.17</td>
<td>3.51</td>
<td>0.765</td>
</tr>
<tr>
<td>$H$ (kWh/m$^2$)</td>
<td>124956.56</td>
<td>124956.56</td>
<td>124956.56</td>
<td>124956.56</td>
<td>124956.56</td>
</tr>
<tr>
<td>$\varphi_{\text{theoretical}}$ (%)</td>
<td>0.79</td>
<td>0.81</td>
<td>0.84</td>
<td>0.81</td>
<td>0.86</td>
</tr>
</tbody>
</table>

5.4 Calculated correction factor

The correction factor of temperature, angle of incidence and invertor has been calculated. To do so, the theoretical model power has been calculated, that means the output that the panel generate if it works at standard test conditions. Then the amount of energy that has been lost for each factor has been calculated, as can be seen in Table VII.

**Table VII Losses of energy due to temperature, angle of incidence and invertor**

<table>
<thead>
<tr>
<th></th>
<th>Diode</th>
<th>Tigo</th>
<th>Module inverter</th>
<th>d+t+m</th>
<th>Thin film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical model power (kWh)</td>
<td>146.19</td>
<td>146.19</td>
<td>146.19</td>
<td>438.59</td>
<td>95.59</td>
</tr>
<tr>
<td>Temperature losses (kWh)</td>
<td>9.85</td>
<td>9.85</td>
<td>9.85</td>
<td>29.55</td>
<td>5.56</td>
</tr>
<tr>
<td>Angle of incidence losses (kWh)</td>
<td>1.67</td>
<td>1.67</td>
<td>1.67</td>
<td>5.01</td>
<td>1.09</td>
</tr>
<tr>
<td>Invertor losses (kWh)</td>
<td>14.62</td>
<td>14.62</td>
<td>14.62</td>
<td>43.86</td>
<td>9.56</td>
</tr>
<tr>
<td>Temperature &amp; angle of incidence losses (kWh)</td>
<td>24.47</td>
<td>24.47</td>
<td>24.47</td>
<td>73.41</td>
<td>15.12</td>
</tr>
<tr>
<td>Temperature &amp; angle of incidence &amp; invertor losses (kWh)</td>
<td>26.14</td>
<td>26.14</td>
<td>26.14</td>
<td>78.42</td>
<td>16.21</td>
</tr>
</tbody>
</table>
Operating correction factor of PV system

<table>
<thead>
<tr>
<th></th>
<th>Diode</th>
<th>Tigo</th>
<th>Module inverter</th>
<th>d+t+m</th>
<th>Thin film</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AUGUST</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical model power (kWh)</td>
<td>79.77</td>
<td>79.77</td>
<td>79.77</td>
<td>239.31</td>
<td>52.16</td>
</tr>
<tr>
<td>Temperature losses (kWh)</td>
<td>7.27</td>
<td>7.27</td>
<td>7.27</td>
<td>21.81</td>
<td>4.11</td>
</tr>
<tr>
<td>Angle of incidence losses (kWh)</td>
<td>0.69</td>
<td>0.69</td>
<td>0.69</td>
<td>2.07</td>
<td>0.45</td>
</tr>
<tr>
<td>Invertor losses (kWh)</td>
<td>7.98</td>
<td>7.98</td>
<td>7.98</td>
<td>23.95</td>
<td>5.22</td>
</tr>
<tr>
<td>Temperature &amp; angle of incidence losses (kWh)</td>
<td>15.26</td>
<td>15.26</td>
<td>15.26</td>
<td>45.77</td>
<td>9.33</td>
</tr>
<tr>
<td>Temperature &amp; angle of incidence &amp; invertor losses (kWh)</td>
<td>15.95</td>
<td>15.95</td>
<td>15.95</td>
<td>47.84</td>
<td>9.78</td>
</tr>
<tr>
<td><strong>SEPTEMBER</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theoretical model power (kWh)</td>
<td>66.29</td>
<td>66.29</td>
<td>66.29</td>
<td>198.86</td>
<td>43.34</td>
</tr>
<tr>
<td>Temperature losses (kWh)</td>
<td>2.54</td>
<td>2.54</td>
<td>2.54</td>
<td>7.61</td>
<td>1.43</td>
</tr>
<tr>
<td>Angle of incidence losses (kWh)</td>
<td>0.89</td>
<td>0.89</td>
<td>0.89</td>
<td>2.68</td>
<td>0.58</td>
</tr>
<tr>
<td>Invertor losses (kWh)</td>
<td>6.21</td>
<td>6.21</td>
<td>6.21</td>
<td>18.63</td>
<td>4.06</td>
</tr>
<tr>
<td>Temperature &amp; angle of incidence losses (kWh)</td>
<td>8.75</td>
<td>8.75</td>
<td>8.75</td>
<td>26.25</td>
<td>5.49</td>
</tr>
<tr>
<td>Temperature &amp; angle of incidence &amp; invertor losses (kWh)</td>
<td>9.64</td>
<td>9.64</td>
<td>9.64</td>
<td>28.93</td>
<td>6.08</td>
</tr>
</tbody>
</table>

To calculate the correction factor caused by a specific parameter equation 18 has been used, but instead of the output energy the energy loss caused by the temperature, angle of incidence or invertor found on the Table VII has been used.

Table VIII, Table IX, Table X, Table XI and Table XII, show the calculated correction factors for temperature, angle of incidence and invertor, for the examined PV systems.
<table>
<thead>
<tr>
<th>DIODE</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No correction</td>
<td>1</td>
</tr>
<tr>
<td>Power correction temperature</td>
<td>0.93</td>
</tr>
<tr>
<td>Power correction angle of incidence</td>
<td>0.99</td>
</tr>
<tr>
<td>Power correction inverter</td>
<td>0.90</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence</td>
<td>0.92</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence &amp; inverter</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TIGO</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No correction</td>
<td>1</td>
</tr>
<tr>
<td>Power correction temperature</td>
<td>0.93</td>
</tr>
<tr>
<td>Power correction angle of incidence</td>
<td>0.99</td>
</tr>
<tr>
<td>Power correction inverter</td>
<td>0.90</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence</td>
<td>0.92</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence &amp; inverter</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MODULE INVERTER</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No correction</td>
<td>1</td>
</tr>
<tr>
<td>Power correction temperature</td>
<td>0.93</td>
</tr>
<tr>
<td>Power correction angle of incidence</td>
<td>0.99</td>
</tr>
<tr>
<td>Power correction inverter</td>
<td>0.90</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence</td>
<td>0.92</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence &amp; inverter</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>D+T+M</th>
<th>$\phi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>No correction</td>
<td>1</td>
</tr>
<tr>
<td>Power correction temperature</td>
<td>0.93</td>
</tr>
<tr>
<td>Power correction angle of incidence</td>
<td>0.99</td>
</tr>
<tr>
<td>Power correction inverter</td>
<td>0.90</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence</td>
<td>0.92</td>
</tr>
<tr>
<td>Power correction temperature &amp; angle of incidence &amp; inverter</td>
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<td>Power correction inverter</td>
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<tr>
<td>Power correction temperature &amp; angle of incidence</td>
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<td>Power correction temperature &amp; angle of incidence &amp; inverter</td>
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5.5 Measured power and model power

The images, in Fig. 14, Fig. 15, Fig. 16, Fig. 17 and Fig. 18 show the relationship between the measured output energy from the modules, Y axis, and the calculated output power with the correction factor of the modules, X axis, for the examined solar modules, Diode, Tigo, Module inverter, D+T+M and Thin film.

![Fig. 14 Relationship between measured power and model power of silicon diode modules for the months of August and September of 2016](image)

The equation of the trend line in Fig. 14 is:

\[ y = 0.881x + 0.0629 \]

![Fig. 15 Relationship between measured power and model power of silicon Tigo modules for the months of August and September of 2016](image)

The equation of the trend line in Fig. 15 is defined as:

\[ y = 0.9211x + 0.0387 \]
The trend line in Fig. 16 is described by the following equation:

\[ y = 0.892x + 0.039 \]

The trend line in Fig. 17 is:

\[ y = 0.9023x + 0.136 \]
Operating correction factor of PV system

The equation of the trend line in Fig. 18 is:

\[ y = 0.8097x + 0.0425 \]

Table XIII summarised the gain and offset values of the linear equations of the Fig. 14, Fig. 15, Fig. 16, Fig. 17 and Fig. 18.

<table>
<thead>
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<th>Gain</th>
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<td>Tigo</td>
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<td>Module inverter</td>
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<td>d+t+m</td>
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<td>0.136</td>
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<tr>
<td>Thin film</td>
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<td>0.0425</td>
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6. Discussion

The concussions can be summarized as the PV module with the best correction factor, the best calculated correction factor and the amount of lost energy due to the parameters of temperature, angle of incidence and invertor.

The PV system with best correction factor is the one that has the higher correction factor, and therefore, the one with better efficiency, or less losses. Based on the calculated theoretical correction factor and calculated correction factor, the PV system with the better correction factor is the Thin film.

Besides, according to the figures of the Appendix I and Appendix II, because the curves of the model power and measured power are the more resembling, the best calculation of the correction factor has been made for Tigo modules. This conclusion concurs with the one taken based on the gain and offset errors. Also, based on the offset and gain errors and the graphics of Appendix I and Appendix II, the correction factor is valid for intermediate power values.

According to the energy losses, the major energy loss is caused by the invertor and are proportional to the output energy, as can be seen in Appendix III and Apppendix IV. On the other side, the losses due to angle of incidence are the smaller energy losses, but unlike the invertor loses, they increase during the day hours and seasons. Finally, the energy losses caused by the temperature, are not proportional to the ambient temperature, because of the effect of the diffuse radiation.

6.2 Correction factor efficiency

On one hand, according to the calculated theoretical correction factors, shown in Table VI, the thin film modules have the better correction factor with a value of

\[ \Phi_{\text{Thin film}} = 0.86 \]

as it is the one with higher values, and therefore, the one that produces the least power losses. The next with higher correction factor is the module invertor module

\[ \Phi_{\text{module invertor}} = 0.84 \]

followed by the Tigo modules

\[ \Phi_{\text{Tigo}} = 0.81 \]

and finally, the diode modules

\[ \Phi_{\text{diode}} = 0.79 \]

On the other hand, regarding to the calculated correction factor shown in Table VIII, Table IX, Table X, Table XI and Table XII for diode, Tigo, module inverter, d+t+m and Thin film, respectively, the Thin film has the higher correction factor

\[ \Phi = 0.84 \]

and the rest have the same correction factor

\[ \Phi = 0.83 \]
In all the modules, the higher power loss is produced by the inverter\[\eta_{\text{inverter}}=0.9\]
whereas the angle of incidence caused the smallest loss of power\[K_\theta(\theta)=0.99\]
and the temperature causes a loss of\[K_{\text{T-silicon}}=0.93\]
for diode, Tigo, module inverter and d+t+m modules, and\[K_{\text{T-CIGS}}=0.94\]
for Thin film modules. The amount of power loss by each of the factors for all the modules is shown in Table VII.

6.3 Correction factor validity
In the images, Fig. 14, Fig. 15, Fig. 16, Fig. 17 and Fig. 18 there is a linear relationship between the measured power and model power. The trend line of the relationship between both measurements must be linear with a value of slope, or gain, of 1 and offset of 0, having the trend line the equation\[y=x\]
which means that the correction factor calculated for the output energy is correct. According with the values of gain and offset shown in the Table XIII, the lower gain error is for Tigo modules and the lower offset error, also, is for Tigo modules, those values indicate that the best relationship between measured power and model power, and hence, calculated correction factor, are for Tigo modules.

To compare the model power and the measured power, the figures of the Appendix II, show 10 min data sets of measured power and model power for each 10 min. Besides, in Appendix I, a more detailed comparison is shown between the model power and measured power of the used PV models during 9 a.m. and 2 p.m. four randomly chosen days.

In Fig. 39, Fig. 40, Fig. 41 and Fig. 42, of Appendix II, comparison is shown between the model power and measured power for the diode modules. Analysing those figures, can be seen how the model power for low power values, 0-0.1 kW, has lower values than those of measured power, whereas, for high powers, 1kW, the model power has higher values compared with the measured power. But the used correction factor is suitable to describe the performance of diode module with no extreme power generation, low or high. That, can be observed in the graphics of Appendix I, Fig. 19, Fig. 20, Fig. 21 and Fig. 22.
Paying attention to Appendix II in the images Fig. 43, Fig. 44, Fig. 45 and Fig. 46, the
difference between the model power and measured power is smaller than for diode
PV models. Although, like with the diode modules, the Tigo modules correction factor
is appropriate for intermediate values. As can be observed with major detail in Fig. 25,
Fig. 26, Fig. 27 and Fig. 28 of Appendix I, the model power curve follows the curve
described by the measured power. Among the examined PV systems, Tigo is the one
that has the most similar measured power and model power.

Comparing the model power with the measured power of the module inverter PV
system, Appendix I Fig. 27, Fig. 28, Fig. 29 and Fig. 30 and in Appendix II Fig. 47, Fig. 48,
Fig. 49 and Fig. 50, the model power calculated with the correction factor has a similar
value with the measured for intermediate values of power, as for low values the model
power is lower than the measured power and for power high values the model power
has a higher value than the measurements.

Regarding to the graphics Fig. 31, Fig. 32, Fig. 33 and Fig 34 of the Appendix I, as there
are drawn together the model power and measured power of diode, Tigo and module
inverter PV systems, the model power curve has less sharp points. Even so, paying
attention to the images Fig. 51, Fig. 52, Fig. 53 and Fig. 54 of the Appendix II, for high
power values the model power has higher values than measured power and for low
power values the measured power has higher values than the model power.

Finally, the images shown in the Appendix I, Fig. 35, Fig 36, Fig. 37 and Fig. 38 and in
the Appendix II, Fig. 55, Fig 56. Fig. 57 and Fig. 58, taking into account that the peak
power of the Thin film modules is lower than for the others, the difference for high
and low of model power and measured power is bigger than in diodes, Tigo and
module inverter PV systems. That indicates that the calculated correction factor is not
valid for high and low power values, as for high measured power values, 0.6 kW, the
model power is higher and for low measured power values, 0-0.1 kW, the model
power is lower than the measured power.

### 6.4 Energy losses

In Appendix II and Appendix IV the losses produced for each of the factors,
temperature, angle of incidence and micro inverter are presented. The graphics of
Appendix III show the energy losses for all the examined PV modules system during the
months of August and September of 2016 between 9:00 and 14:00, as well as the
temperature during both months. In the Appendix IV the same losses can be
appreciated more precisely, during four days of August and September between the
same period of time.

As it can be appreciated in some figures of the Appendix III, Fig. 59, Fig. 60, Fig. 61 and
Fig. 62, and figures of the Appendix IV, Fig. 79, Fig. 80, Fig. 81 and Fig. 82, the bigger
energy losses are produced due to the inverter. Those losses are proportional to the
produced energy by the diode PV modules. Comparing the effect of the temperature in
the graphics, Fig. 59, Fig. 60, Fig. 61 and Fig. 62, it can be appreciated how the effect of
temperature is not proportional to the energy decreases caused by temperature.
Looking at the graphics of Appendix III, it can be appreciated that for the month of August, images Fig. 63 and Fig. 64, the temperature causes a similar drop of energy, meanwhile, the month of September, figures 65 and Fig. 66, the loss of energy caused by the inverter is bigger than the one caused by the temperature. One reason for this phenomenon, can be the difference of the temperature during the examined month or the variations of the irradiance, as there can be seen in the equation 5. And the smallest energy loss area of the graphic is produced by the angle of incidence, Fig. 83 Fig. 84, Fig. 85 and Fig. 86, and it increases in the afternoon.

As well as in diode and Tigo PV systems, for module inverter PV systems, Appendix III graphics Fig. 67, Fig. 68, Fig. 69 and Fig.70 and Appendix IV images Fig. 87, Fig. 88, Fig. 79 and Fig. 90, the power decrease caused by temperature is not proportional to the ambient temperature. Even though, the inverter causes more energy loses than the temperature. As in the diode and Tigo, in module inverter PV system the effect of angle of incidence increases as the sun moves towards the west. This happens because the modules are orientated 12º to the east.

For the energy losses of the diode, Tigo and module inverter PV systems, the decrease caused by the angle of incidence are almost insignificant, Appendix III images Fig. 71, Fig. 72, Fig. 73 and Fig.74, but as it can be appreciated with more precision during one day period in the Appendix IV graphics Fig. 91, Fig. 92, Fig. 93 and Fig. 94, it increases during the day. As is it illustrated the output energy and energy losses of the three silicon modules, the output energy losses are bigger because they are proportional to the generated power. Also, in the month of August the decrease due to temperature is similar to the one caused by the inverter, whereas in the month of September it is smaller.

Finally, examining the Thin film PV system module losses, Appendix III and Appendix IV, in the month of August, Fig. 75, Fig. 76, Fig. 95 and Fig. 96 the decrease of energy cause by the angle of incidence is minimum, but, in for the month of September, Fig. 77, Fig.78, Fig. 97 and Fig. 98 they increase. On the contrary, the energy losses caused by the temperature decrease in the month of September although the temperature remains in similar values.

The amount of the energy lost by each one of the examined factors can be seen in the Table VII. It be seen that the total amount of energy has been lost in the inverter is the following

\[ \eta_{\text{inverter}} = 90\% \]

for all the PV system used as can be appreciated in the Table VIII for diode, Table IX for Tigo, Table X for module inverter, Table XI for d+t+m and Table XII for Thin film. The next parameter that has caused more energy losses is the effect of temperature, with an effect of

\[ K_{T-\text{silicon}} = 93\% \]

for silicon modules and

\[ K_{T-CIGS} = 94\% \]
for CIGS modules.

Finally, the angle of incidence causes the smallest energy losses, with

\[ K_b(\theta) = 99\% \]

of efficiency. But, regarding to the amount of energy lost in the months of August and September, the loses caused by the angle of incidence increase in September. Paying attention to the losses caused by the temperature and the inverter, in August both have similar values, unlike in September, as can been appreciated in the figures of the Appendix III and Appendix IV.

To analyse more carefully this phenomenon, and knowing that the losses of the inverter are constant and the ones caused by the effect of temperature varies according to the temperature of the module, which relies on the ambient temperature and on diffuse radiation, comparison has been carried out of the average ambient and module temperature and total diffuse radiation with the losses caused in the different PV systems during the period between 9 a.m. and 2 p.m. of four days in Table XIV. It, can be appreciated that for both days of August the module temperature is much higher than the ambient temperature, which produces big energy losses. But, in September, the module temperature is slightly higher than the ambient temperature. In addition, although, the ambient temperature of the 7th of September is higher than both days of August, the energy lost due to the temperature is lower. As it can be seen, this is because of the diffuse radiation.

Regarding the energy losses due to the angle of incidence, it can be seen in Table VII and Table XIV, that it increases when the days pass, as well as, later in the day, Fig. 79 to Fig. 98. This can be affirmed looking at the image in Fig 103 of Appendix VI. There, it can be seen how the angle of incidence decreases in midday and has its higher value during the afternoon. Also, as it is latter during the year, the value increases, causing more energy losses due to angle of incidence.

Figures of Appendix V show this. In the images, Fig. 99 and Fig. 100. It can be appreciated how in August there is a smaller difference between the diffuse irradiation and the irradiation measured at 40°, the same as the solar modules, whereas in September there is a significant difference.

Regarding the difference between the ambient and module temperature, it can be appreciated how when the diffuse irradiation increases the difference among both temperatures increases and when it decreases the opposite happens. To examine the effect on temperature losses, Fig. 101 and Fig. 102, the diffuse irradiation, irradiation in 40° and the decrease due to temperature for the examined PV systems are drawn in the graphic. As the diode, Tigo, and module inverter are silicon modules, the three have the same value. In the figures, it can be appreciated that the diffuse irradiation and the losses caused by the temperature are proportional, and that in August the diffuse radiation is bigger the energy losses caused by the temperature. Even though, the losses caused by the temperature and angle of incidence together are lower than the ones caused by the inverter.
7. Conclusion

The peak power calculated under standard test conditions decreases when the PV performs under different conditions. The increase of temperature and angle of incidence cause energy losses in the operation of the modules, as well as, the inverter.

The most suitable PV system for the location is the Thin film, because it has the largest correction factor, as they are made with other materials that have less temperature coefficient value than the ones made of silicon. The used micro invertors are the same for all the modules, so it has the same efficiency and as they are located in the same geographic location with the same tilt angle the angle of incidence, also, have the same value.

There are three options to reduce energy losses, as there are three parameters that affect the performance of PV systems:

- As the losses caused by the temperature, around 6%-7%, depend of the ambient temperature, solar irradiance, heat transfer coefficient and temperature coefficient, one or more of those parameters must be changed one or more of those parameters. The temperature coefficient is a physical property of the used material in the construction of the PV model. The ambient temperature and solar irradiance depends on the climate, and as the output power depends on the irradiance it must be as high as possible. So, to reduce the temperature of the modules the heat transfer coefficient should be increased, equation 5, as that is the easier parameter that can be changed. Among the parameters that affect the heat transfer coefficient are the convection type and the speed of the air. Therefore, to reduce the energy losses caused by the temperature a refrigeration system can be installed.

- The energy available depend on the position of the sun in the sky at each moment, among other factors, in relation with the orientation of the solar module. Solar tracker mechanism can be used to improve the efficiency lost by angle of incidence, about 1%, of the solar panel. The solar tracker moves following the position of the sun in the sky, facing the solar panel surface toward the sun beam constantly and being the angle of incidence 0. In this way, the energy losses caused by the angle of incidence can be eliminated.

- The energy loses caused by the inverter, approximately 10%, exceed the losses caused by the angle of incidence and temperature together, so, it is the most important to correct and also the easiest, as currently there are available power invertors with better efficiency in the market.

Another important point is the weather, since, it affects the solar irradiance, like a cloudy day, affecting the generated energy. The only climate parameter that has been considered is the ambient temperature, ignoring the wind speed. The gusts of wind cool the surface of the PV modules due to the convection effect, and hence, reduce the energy losses caused by the temperature. To calculate with more precision the effect of the temperature on the solar cell performances the convection effect of the wind must be taken into account.
8. References

References made using the ISO 690:2013 standard for bibliographic referencing.


9. Appendix

9.2 Appendix I

**Fig. 19** Comparison between the measured output energy and calculated output energy of diode the 12th of August 2016

**Fig. 20** Comparison between the measured output energy and calculated output energy of diode the 24th of August 2016
Fig. 21 Comparison between the measured output energy and calculated output energy of diode the 7th of September 2016

Fig. 22 Comparison between the measured output energy and calculated output energy of diode the 30th of September 2016
Fig. 23 Comparison between the measured output energy and calculated output energy of Tigo the 12th of August 2016

Fig. 24 Comparison between the measured output energy and calculated output energy of Tigo the 24th of August 2016
Fig. 25 Comparison between the measured output energy and calculated output energy of Tigo the 7th of September 2016

Fig. 26 Comparison between the measured output energy and calculated output energy of Tigo the 30th of September 2016
Fig. 27 Comparison between the measured output energy and calculated output energy of module inverter the 12th of August 2016

Fig. 28 Comparison between the measured output energy and calculated output energy of module inverter the 24th of August 2016
Fig. 29 Comparison between the measured output energy and calculated output energy of module inverter the 7th of September 2016

Fig. 30 Comparison between the measured output energy and calculated output energy of module inverter the 30th of September 2016
Fig. 31 Comparison between the measured output energy and calculated output energy of d+t+m the 12\textsuperscript{th} of August 2016

Fig. 32 Comparison between the measured output energy and calculated output energy of d+t+m the 24\textsuperscript{th} of August 2016
Fig. 33 Comparison between the measured output energy and calculated output energy of d+t+m the 7th of September 2016

Fig. 34 Comparison between the measured output energy and calculated output energy of d+t+m the 30th of September 2016
Fig. 35 Comparison between the measured output energy and calculated output energy of thin film the 12th of August 2016

Fig. 36 Comparison between the measured output energy and calculated output energy of thin film the 24th of August 2016
**Fig. 37** Comparison between the measured output energy and calculated output energy of thin film the 7th of September 2016

**Fig. 38** Comparison between the measured output energy and calculated output energy of thin film the 30th of September 2016
Fig. 39 Comparison between the measured output energy and calculated output energy of silicon diode modules from 1 to 15 of 2016 August
Fig. 40 Comparison between the measured output energy and calculated output energy of silicon diode modules from 16 to 31 of 2016 August
Fig. 41 Comparison between the measured output energy and calculated output energy of silicon diode modules from 1 to 15 of 2016 September
Fig. 42 Comparison between the measured output energy and calculated output energy of silicon diode modules from 16 to 30 of 2016 September
Fig. 43 Comparison between the measured output energy and calculated output energy of silicon Tigo modules from 1 to 15 of 2016 August
Fig. 44 Comparison between the measured output energy and calculated output energy of silicon Tigo modules from 16 to 31 of 2016 August
Fig. 45 Comparison between the measured output energy and calculated output energy of silicon Tigo modules from 1 to 15 of 2016 September
Fig. 46 Comparison between the measured output energy and calculated output energy of silicon Tigo modules from 16 to 30 of 2016 September
Fig. 47 Comparison between the measured output energy and calculated output energy of silicon module inverter modules from 1 to 15 of 2016 August
Fig. 48 Comparison between the measured output energy and calculated output energy of silicon module inverter modules from 16 to 31 of 2016 August
Operating correction factor of PV system

Fig. 49 Comparison between the measured output energy and calculated output energy of silicon module inverter modules from 1 to 15 of 2016 September
Fig. 50 Comparison between the measured output energy and calculated output energy of silicon module inverter modules from 16 to 30 of 2016 September
Fig. 51 Comparison between the measured output energy and calculated output energy of silicon diode, Tigo, module inverter modules from 1 to 15 of 2016 August.
Fig. 52 Comparison between the measured output energy and calculated output energy of silicon diode, Tigo, module inverter modules from 15 to 31 of 2016 August
Fig. 53 Comparison between the measured output energy and calculated output energy of silicon diode, Tigo, module inverter modules from 1 to 15 of 2016 September
Fig. 54 Comparison between the measured output energy and calculated output energy of silicon diode, Tigo, module inverter modules from 16 to 30 of 2016 September
Fig. 55 Comparison between the measured output energy and calculated output energy of thin film from 1 to 15 of 2016 August
Fig. 56 Comparison between the measured output energy and calculated output energy of thin film from 16 to 31 of 2016 August
Fig. 57 Comparison between the measured output energy and calculated output energy of thin film from 1 to 15 of 2016 September
Fig. 58 Comparison between the measured output energy and calculated output energy of thin film from 15 to 30 of 2016 September.
9.4 Appendix III

Fig. 59 Silicon diode modules energy losses from 1 to 15 of August 2016
Fig. 60 Silicon diode modules energy losses from 16 to 31 of August 2016
Operating correction factor of PV system

Fig. 61 Silicon diode modules energy losses from 1 to 15 of September 2016

*Fig. 61 Silicon diode modules energy losses from 1 to 15 of September 2016*
Fig. 62 Silicon diode modules energy losses from 16 to 30 of September 2016
Operating correction factor of PV system

Fig. 63 Silicon Tigo modules energy losses from 1 to 15 of August 2016

**Operating correction factor of PV system**

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**Power correction temperature & angle of incidence & inverter**

**Decrease due to temperature**

**Decreased u to angle of incidence**

**Decrease due to invertor**

**Ambient temperature**

---

*Fig. 63 Silicon Tigo modules energy losses from 1 to 15 of August 2016*
Fig. 64 Silicon Tigo modules energy losses from 16 to 31 of August 2016
Operating correction factor of PV system

Fig. 65 Silicon Tigo modules energy losses from 1 to 15 of September 2016
Fig. 66 Silicon Tigo modules energy losses from 16 to 30 of September 2016
Operating correction factor of PV system

Fig. 67 Silicon module inverter modules energy losses from 1 to 15 of August 2016
Fig. 68 Silicon module inverter modules energy losses from 16 to 31 of August 2016
Operating correction factor of PV system

Fig. 69  Silicon module inverter  modules energy losses from 1 to 15 of September 2016
Fig. 70 Silicon module inverter modules energy losses from 16 to 30 of September 2016
Operating correction factor of PV system

Fig. 71 Silicon diode, Tigo and module inverter modules energy losses from 1 to 15 of August 2016
Fig. 72 Silicon diode, Tigo and module inverter modules energy losses from 16 to 31 of August 2016
Operating correction factor of PV system

09/01-15 D+T+M

Power correction temperature & angle of incidence & inverter
Decrease due to temperature
Decrease due to angle of incidence
Decrease due to invertor
Ambient temperature

Fig. 73 Silicon diode, Tigo and module inverter modules energy losses from 1 to 15 of September 2016
Fig. 74 Silicon diode, Tigo and module inverter modules energy losses from 16 to 30 of September 2016
Operating correction factor of PV system

Fig. 75 Thin film modules energy losses from 1 to 15 of August 2016
Fig. 76 Thin film modules energy losses from 16 to 31 of August 2016
Operating correction factor of PV system

09/01-15 Thin film

Fig. 77 Thin film modules energy losses from 1 to 15 of September 2016
Fig. 78 Thin film modules energy losses from 16 to 30 of September 2016
9.5 Appendix IV

Fig. 79 diode modules energy losses in the 12th of August 2016

Fig. 80 diode modules energy losses in the 24th of August 2016
Fig. 81 diode modules energy losses in the 7th of September 2016

Fig. 82 diode modules energy losses in the 12th of September 2016
Operating correction factor of PV system

Fig. 83 Tigo modules energy losses in the 12th of August 2016

Fig. 84 Tigo modules energy losses in the 24th of August 2016
Fig. 85 Tigo modules energy losses in the 7th of September 2016

Fig. 86 Tigo modules energy losses in the 30th of September 2016
Operating correction factor of PV system

Fig. 87 module inverter modules energy losses in the 12th of August 2016

Fig. 88 module inverter modules energy losses in the 24th of August 2016
Fig. 89 module inverter modules energy losses in the 7th of September 2016

Fig. 90 module inverter modules energy losses in the 30th of September 2016
Operating correction factor of PV system

**Fig. 91 d+t+m modules energy losses in the 12th of August 2016**

**Fig. 92 d+t+m modules energy losses in the 24th of August 2016**
Fig. 93 d+t+m modules energy losses in the 7th of September 2016

Fig. 94 d+t+m modules energy losses in the 30th of September 2016
Operating correction factor of PV system

Fig. 95 Thin film modules energy losses in the 12th of August 2016

Fig. 96 Thin film modules energy losses in the 24th of August 2016
Fig. 97 Thin film modules energy losses in the 7th of September 2016

Fig. 98 Thin film modules energy losses in the 30th of September 2016
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<td></td>
<td>Angle of incidence losses (kWh)</td>
<td></td>
<td>0.52</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Inverter losses (kWh)</td>
<td></td>
<td>2.59</td>
<td>2.59</td>
</tr>
</tbody>
</table>
9.6 Appendix V

Fig. 99 Comparison between the irradiance and the temperature in August
Operating correction factor of PV system

**Fig. 100** Comparison between the irradiance and the temperature in September

**Irradiance & Temperature September**

- **Irradiance** (W/m²)
- **Temperature** (°C)
- **Irradiation 40°**
- **Diffuse Irradiation**
- **Ambient temperature**
- **Module temperature**

*Fig. 100 Comparison between the irradiance and the temperature in September*
Fig. 101 Comparison between the temperature and temperature losses in August
Fig. 102 Comparison between the temperature and temperature losses in August
9.7 Appendix VI

Fig. 103 Angle of incidence during different days for the location of the solar modules of the University of Gävle