Solar energy is the heat and light that we receive from the sun every day that is harnessed by plants for photosynthesis and by humans for heating water or generating electricity. The energy we receive is called solar irradiance or insolation; this is a measure of the power per unit of area generated by the sun. Outside of the Earth’s atmosphere the energy density is around 1353 W/m2, this is known as the solar constant (1), though not a true constant as the value varies depending on the time of the year. The actual solar insolation on the Earth’s surface is much lower due to energy being lost by being absorbed and reflected when traveling through the atmosphere. It is lowered even more so as the constant assumes 24 hours of direct light, which does not happen on the surface (1). The solar insolation can be used to calculate the electricity generated by an array of photovoltaic cells.

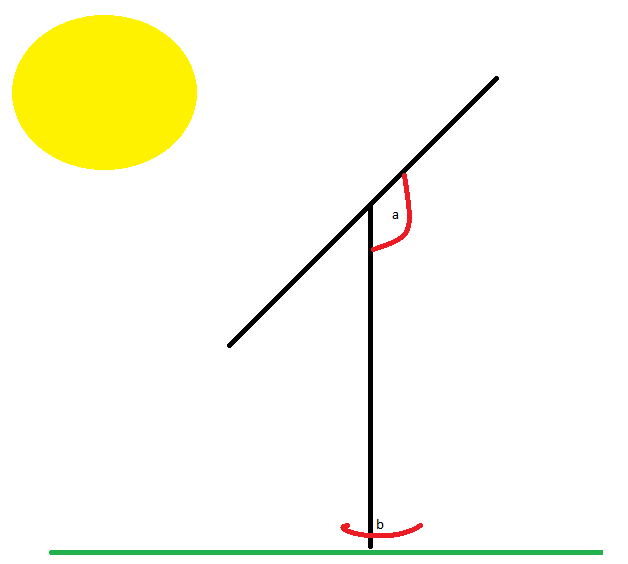
Photovoltaic cells work by being exposed to the thermal radiation emitted by the sun and converting the thermal energy into electricity. (2). It has many advantages, the key advantage being photovoltaic cells provide a clean, renewable source of energy that does not create any pollution whilst in operation. Though it is not without disadvantages as they are expensive to produce and the energy generated is dependent on external environmental factors such as the weather, in particular clouds that may obscure the sun. (2). The first practical photovoltaic cell (also known as a solar cell) was built in 1954 using crystalline silicon which is still to this day the most commonly produced solar cell due to its long life and the ease of mass production (3). There are then two types of crystalline silicon solar cell: monocrystalline and polycrystalline. Monocrystalline silicon solar cells are typically more expensive to purchase but are more efficient whereas polycrystalline silicon cells are cheaper but less efficient (3).

There are many factors that will affect the total energy a photovoltaic cell will generate. One such factor is the total solar insolence at any given time. As discussed earlier the solar insolence can vary depending on the weather conditions, time of year and the detector’s latitude/longitude. The energy generated also depends on the physical properties of the photovoltaic panel, for example its surface area, the direction that the panel is oriented, the tilt angle and the materials it is made of (polycrystalline versus monocrystalline).

In their article “The effect of weather conditions on the efficiency of PV panels in the southeast of UK” Ghazi and Ip look at how the weather affects the power generated by a photovoltaic panel array and in particular the build-up of dust on a panels glass cover. They carried out tests indoors “under controlled test conditions” with a temperature of 25oC and a solar irradiance of 1000W/m2 which they acknowledge will vary “depending on the locality”. They measured the weight of dust deposited and the transmittance(transmittance is the effectiveness of transferring radiant energy) and found the “maximum amount of transmittance reduction is about 5%” with their indoors tests. They also monitored the weathers effect on outdoor monocrystalline photovoltaic panels by selectively cleaning the panels. They found that rain and bird droppings contributed significantly to the dirt deposits on the panels and that weather such as high humidity, rain and wind led to poor efficiency with the panels (4). Their study doesn’t appear to make any reference to how the results were collected, whether they developed a computerised system to log the results at certain intervals or manually read readings. It is also does not mention what they used as a light source for their indoor tests.

To maximise the total solar radiation a photovoltaic panel receive its needs to be angled such that the rays of light arrive perpendicular to the panel. This means that more rays of light are absorbed by the panel rather than reflected. For panels located in the northern hemisphere it is advised that the panels face south and at an angle approximate to their latitude (5). In their article “Determination of the optimal tilt angle and orientation for solar photovoltaic arrays” Mehleri et al suggests that there is an optimal tilt angle and orientation for photovoltaic arrays; where tilt angle is the angle of the panel and the orientation is the direction the panel is facing. The article intends to look at static panels rather than tracked panels as the author deems tracking systems as “expensive and are not always applicable”. Ultimately the paper is looking at how the tilt angle of a photovoltaic panel and its orientation can be modified to maximised the solar irradiance on the panel and the further goes on to look at how the variance the power produced can be minimized across a given time period (5). To do this the authors generated several computerised models using techniques such as neural networks and fuzzy logic to predict the solar irradiance on a tilted surface (5). They found that if they tilt angle was changed twice a year for a winter and summer then photovoltaic power generation increased by 3.5% and not only improves the performance but the “uniformity of the power output” (5).

The alternate to a fixed solar panel as discussed by Mehleri et al is a tracked panel. There panels follow the movement of the sun in the sky so that the they’re always pointing towards it. In their article “Determining optimum tilt angles and orientations of photovoltaic panels in Sanliurfa, Turkey” Kacira et al look at the power generated between two 120W single crystalline photovoltaic panels, one of which is at a fixed tilt angle of 14o, facing south and the second is a two axis tracked panel that will follow the sun throughout the day (6). They measure the current, and voltage readings of the panels along with environmental factors such as the air temperature, wind speed, temperature of the panels and the angle of the tracked and fixed panel. The measurements were carried out every hour between 6am and 6pm; the article does not mention whether they did this manually or through a computerised system. The authors found that a two axis tracked photovoltaic panel generated 34.6% more power than its fixed counterpart, though it is noted that this is just the result of one days measurement and the total benefit will vary depending on the time of the year. (6)

In a separate experiment the Kacira et al also changed the tilt angle of a fixed panel from 0o to 60o at solar noon (the point at which the sun is at its highest point in the sky). Like Mehleri et al they found that lower tilt angles produced better results in summer and higher angles produced more electricity in winter. Kacira et al also noted that it is a better to alter the tilt angle of the panel per season and that doing it every day or every month is not an optimal option. (6)

As Kacria et al found a tracked photovoltaic panel has the potential to produce more power than its fixed alternative. However there are two types of tracked panel. Kacria et al used a two axis panel, these tracking systems can change both the orientation and tilt angle of the panel. Figure 1 demonstrate a dual axis tracker whereby angle a is modifiable along with angle b. The alternative is a single axis system that just changes the tilt angle, this would mean with regards to figure 1 only angle a can be modified. Li et al in their article “Optical Performance of Vertical Single-axis Tracked Solar Panels” note that dual axis tracked panels perform better though the complicated tracking mechanism means that a single axis system is often “technically and economically more attractive” (7).

Figure 1: Dual Axis Solar Tracker

In their article Li et al looked at comparing the annual collected solar radiation between single axis tracked photovoltaic panels, full two axis tracked panels and fixed panels. Using some complicated mathematical equations to estimate the solar gain of the single axis tracked panels the authors found that single axis tracked panels performed much better than fixed panels, but performed 5-6% worse than dual axis tracked panels (7).

One manufacturer of single axis tracked photovoltaic systems is a German company called LORENTZ. They were founded in 1993 and produce a wide range of products including solar pumps and solar tracking systems (8). One of their offered solar tracking systems is the “ETATRACK active 2000” a “Single-axis tracking system for PV Modules”. The system supports panels with a surface area of up 20.5m2 and boasts low energy usage and suitability of high wind speeds. LORENTZ also claim that their tracked system offers “up to 40%” more energy than a fixed installation, which given the works of Kacira et al and Li et al seems to be appropriate (9). LORENTZ do not sell their trackers directly but do so through partners. One such partner is an English company called “Wind and Sun”. Excluding VAT the “ETA-2000”; the LORENTZ panel discussed earlier costs £3,214.51 with VAT(20%) this brings the cost to £3857.41 (10). It should be noted that this is the cost for the tracking system and does not include installation for which no quote is given.

In order for a tracked system to be able to point the photovoltaic panel towards the sun, it needs to know where the sun is in the sky. This obviously varies depending on the time of the day, the current season and latitude and longitude of the panel. It also depends on more scientific matters such as the solar declination and the solar hour angle (11).

The current solar declination is a measure of the Earths current tilt. We observe the Earths tilt through seasons but in actuality its measureable and reaches a maximum of 23.45o (11).We know this as the summer solstice, the longest day of the year, alternatively -23.45o is the winter solstice and the shortest day of the year. Thankfully there is already an equation to calculate solar declination as detailed below.

The solar hour angle represent the number of degrees the sun has moved in the sky. The sun moves approximately 15o every hour and a value of 0 indicates the sun is directly above, this is known as solar noon (11). The current solar hour angle can be calculated using the equation below and will be needed later when calculating the solar angle.

This equation then further introduces a new unknown. The solar time, this is usually different from the time we would see on a watch or clock (standard time) but can be calculated with another equation (11). Solar time is different than the time we are familiar with because a day is not actually 24 hours long, it takes the earth 23 hours 56 minutes and 4.1 seconds to complete a rotation on its axis. This is known as a sidereal day (11). In order to convert standard time (clock time) into solar time we use the equation below.

We first need to calculate the longitude time correction though. We need to this because our time is based off of the prime meridian. The prime meridian is the hypothetical line drawn through Greenwich, England and is the basis of Greenwich Mean Time(GMT) though now more formally referred to as Coordinated Universal Time (UTC). Each time zone is then defined every 15o and labelled UTC+1 for one hour ahead or UTC -5 for five hours behind UTC, these are known as standard meridians (11).

The second value we need is the analemma time correction. This takes into account the fact that the Earth doesn’t rotate perfectly on its axis (11) and we can’t guarantee that the sun will be in the same place year after year. The equation to account for this is known as the equation of time(Et). However we first need to calculate a coefficient B that is based on the current day (11).

B is then used in the equation below to give us the analemma time correction.

This finally gives us everything needed to calculate the solar time (11).

We now have everything we need to calculate the solar altitude. This is the angle that the photovoltaic panel will need to be if it is going to be pointing directly at the sun. All that’s left is to enter the results from equations previously discussed into the equation below (11).

If looking to construct a solar tracking system for photovoltaic panels knowing this equation is very important. Although there are websites such as suncalc.net or SunEarthTools.com that will take the various attributes and perform the calculation for you, none of them provide this data in the form of an API so that it is easy to consume from an external source. Doing the calculation ourselves also allows the tracker to operate without the need for an internet connection and removes the reliance on an external source. It will help to keep the costs of such a system low as if an API is found it will most likely require a paid license, and keeping costs low is very important considering the extremely high cost of existing systems.

Using the solar altitude equation to calculate the suns position is not the only way we can determine the suns position, and it may not always be the best. Using a closed loop system in which a series of sensors detect light levels in certain circumstances could be a more favourable solution, in particular in the United Kingdom where we tend to have very cloudy days. A closed loop system may be able to detect where there are and are not clouds and point the panel at an area of clear sky rather than a cloudy bit. Roth et al in their article “Design and construction of a system for sun-tracking” looked at exactly this. They constructed a tracking system using closed loop servos that took input from a pyrheliometer, a device that measures solar irradiance (12). They used a computerised system that would detect when the sensor was covered by cloud and could not detect the sun, the system would reposition itself until it could detect the sun again (12). They concluded that after constructing and testing their “low cost sun tracker” that the system worked stably and that the system could be adapted for using with larger photovoltaic panels (12). They performed their study in 2004 which by today’s standards is quite old and though they don’t state the technology they used to build they do describe it as cheap. This should mean that constructing a similar system today using 2016 technologies should be even cheaper.

The cost of such a system is important to consider, as mentioned before existing systems such as the LORENTZ trackers are very expensive and not very accessible to your average person. Using low cost electronics such as Raspberry Pi’s or Arduinos that have sufficient computing power to perform the calculations needed and the modularity to allow for the additions of high torque servos that can support the weight of a photovoltaic panel a simpler cheaper system could be built to allow for more every day access to tracked photovoltaic systems.