# Introduction

In 2015 statistics released by the Department of Energy and Climate Change in the United Kingdom tell us that 29.5 per cent the countries energy was generated using gas and 22.6 per cent was generated using coal. 24.7 per cent was generated through renewable sources the most notable being wind and solar energy. (1). Overall this means 52.1 per cent of the energy produced came from non-renewable sources; sources that will eventually no longer exists. Sources that also release carbon dioxide when combusted that will contribute to the greenhouse effect and global warming. Coal and gas together are responsible for more than 90 per cent of the planets carbon dioxide emissions (2). Carbon dioxide being the one of the main contributor to global warming. Therefore it is important to develop the renewable energy field and too look into alternatives in order to preserve the remaining resources and to reduce the potentially devastating effects global warming will have on our planet. It has already been established through the works of Mehleri et al (3), Li et al (4), Kacira et al (5) and many others that tracked solar panels perform better than their fixed counterparts. The key problem I have identified with most tracked solar panel solution though is that they very expensive, in the region of several thousand pounds. I believe that more interest can be generated in solar energy and solar power if tracked solutions are more accessible to your average person and to develop a comprehensive logging and measurement system to showcase the benefits of such a system.

# Aims and Objective

The aim of this project is to develop a logging system to record the total energy produce by a tracked solar panel on any given day and to develop a cost effective, efficient tracking system using readily available 2016 technology.

The logging system will need to do the following:-

* Record the physical parameters of the panel this includes.
  + The maximum power output.
  + The size of the panel, eg the surface area.
  + The angle of the panel.
  + The orientation of the panel; which direction is the panel facing.
* Record certain environmental parameters
  + The current time, day, month, year etc
  + The location of the panel, the latitude and longitude
  + The current weather
* Most importantly the current energy being produced
  + The total power(W)
  + The potential difference(V)
  + The current(A).
* Display logged data in an easy to understand and user friendly way.

The Tracking system will need to do the following:-

* Accurately determine the suns current position in the sky
  + Through the use of equations
  + Using sensors and a feedback system to find the optimal position.
* Angle the panel correctly given the suns position.
  + Though if directly at the sun isn’t optimal then it could find a better of the sky.
* Feed the current status of the system into the logging system.
  + Properties such as the current angle of the panel

# Tasks

## The Tracking System

* Design the Raspberry Pi, servo circuit using a CAD tool to aid in the development later on
* Construct the Raspberry Pi, servo circuit to allow the Raspberry Pi to control the servo motors.
* Implement calculating the suns position using the solar altitude equation.
* Implement servo control to angle and orient the photovoltaic panel.
  + Construct the circuit to allow a Raspberry Pi to control the servo motors.
* Investigate the effectiveness of a closed loop system for angling a photovoltaic panel
  + If proven to be effective and time allows implement this functionality into the tracking system.
* Test Tracking System on a variety of days, and weather condition to ensure stable operation.

## The Logging and Measurement System

* Implement recording the properties related to the current performance of the photovoltaic panel. Such as the potential difference and current being produced.
  + This may require constructing a simple digital multimeter.
* Organize and display data in an informative and easy to read manner through the use of graphs and tables.
  + Design and implement an intuitive, easy to use graphical user interface front end for the logged data.
* Implement gathering environmental data at the current time such as weather through the use of third party API’s.
* Implement a wide of range of error handling techniques to ensure the system is stable when operating.
  + Ensure that error messages are useful and understandable.
* Thoroughly Test logging and measurement system to ensure that there are no unforeseen crashes or bugs.

# Sources of Information and Resources Required.

## Physical Resources

## Raspberry Pi

The raspberry pi will be the centre of the project, it will control the tracking system and do all the logging. The current version of the Raspberry Pi, the Raspberry Pi 3 Model B would be optimal as it features a stronger quad core processor than its predecessor the Raspberry Pi 2. (6) Older models however should be sufficient as they all feature GPIO pins to control the hardware components and a strong processor. The raspberry pi 3 can be purchased for around £31.65 including VAT from various online retailers including element 14 (7), Allied Electronics (8) and Amazon (9).

## Photovoltaic Panels

The solar panels are one of the most important items as without them the tracking and logging system cannot be tested appropriately. A Perlight 250W monocrystalline photovoltaic panel can be purchased in the United Kingdom from the online retailer BuyPVDirect.co.uk for the low price of £117.50 (10). Even better is a Panasonic HIT N Series 330W hybrid photovoltaic panel for £381.85 including VAT from online retailer navitron.org.uk (11). Unfortunately those aren’t really necessary for the project and neither me or the university can afford them so a simple PK Green 10W monocrystalline panel for £22.99 from Amazon (12) should be sufficient.

## Servomechanisms(Servo).

In order to move the panel I will use servos connected to the Raspberry Pi. The PK Green Solar panel I found on Amazon is listed as weighing 1.3kg (12). This means that the servo needs to be able to move 1.3 kilograms worth of solar panel. Servo are rated based on their speed to cover 60o and their torque. Speed isn’t that important as the sun doesn’t move particularly quickly and quick movements could damage the panel however the torque is important. Servo torque is measured in kg/cm, this means a servo rated at 5kg/cm can move 5kg at 1cm away from the pivot, or 2.5kg at 2cm. I think if the photovoltaic panel is mounted at around 5cm away from the servo, this means a servo rated for 10kg/cm should be sufficient as it will provide 2kg of torque at 5cm. The Alturn ADS-966HTG Digital Servo purchasable for £36.99 from servoshop.co.uk would be a suitable option, it is rated for 16.6kg/cm of torque at 4.8V which is more than enough (13).

## Various Electrical Components

Building of the tracking system and monitoring system will require construction of an electrical circuit. This will mostly take place on breadboard connected to the Raspberry Pi. As with all circuit board work resistors of various ratings will be needed, a breadboard and various male/female jumper cables.

## Software Resources

The Raspberry Pi will be running Raspbian, a variant of the Debian Linux distribution designed to run on the Raspberry Pi. Raspbian is free and open source, an image for the operating system can be downloaded at no cost from raspbian.org (14). Development will take place on both the Raspberry Pi in Raspbian and on my home computer that will runs both Windows 10 and Debian. Windows 10 was free through the university and Debian is free and open source so can be downloaded and installed at no cost.

Development will be done using the Python programming language, specifically python3. Python3 is the newest version of Python, replacing the python 2.x series in 2008. Python is also free and open source so it can be used without the need to purchase a license (15). I have opted to use Python as it is a very versatile language capable of doing the calculations needed and interacting the GPIO pins on the Raspberry Pi without the need for complicated external libraries. It also runs natively on the Raspberry Pi, this is important because the Raspberry Pi uses an ARM processor, with a different instruction set to my desktop computer if using a compiled language then code compiled on my desktop machine would not work on the Raspberry Pi.

Most importantly for software related problems I will need Google. When problems arrive that I cannot fix. I will look to Google for help. This will most likely lead to websites such as StackOverflow, the Python documentation or Wikipedia

# Project Risks

## Data Loss

Hard disk drives occasionally fail and as such any data of them is for the most part lost. This can happen any time to anyone. In order to minimise loss in such an event I will ensure that I make back-ups of all my work. All my work is committed to a repository on an external server and this repository is then backed up to a NAS I keep in my home. Therefore I have a copy of my work on the server and on my NAS at any given time.

Scope Creep

As I develop the project I will think of more and more features than I can implement, this may mean that I spend too much time developing extra features rather than core features and the project will become unfocused and unsuccessful. To make sure this does not happen I will keep a list of core features that have to implemented before anything else can be added. If I think of a cool feature to add then will add it to a second list of extra features. As I will work iteratively, once I have implemented the core features in the next iteration of the system I can begin to add extra features. It may be possible that the scope has already increased passed what I will reasonably be able to implement, however I am confident in my abilities so I do not think this is the case.

Personal Problems

Any problems that arise relating to myself will probably take precedence over working on this project. If such problems arise then I will ensure I adjust my time plan to ensure I make up for lost time. If severe problems arise that drastically affect my ability to complete the on schedule then I have may have the option of filling out the university Notification of Exceptional Circumstances form, that will give me extra time to complete the project. I however do not foresee any serious problems arising in the next couple of months.

# Professional Issues

I do not believe there are any ethical issues surrounding this project.

## Data Protection

In this project I will not be storing or asking users at all to enter in any personal information. Therefore I cannot breach the Data Protection Act as I will not store any data that in need of protection.

## Licensing

I may use external API’s and will need to ensure that I do not breach their terms and conditions. I will also use open source software that is mostly licensed under GNU General Public License therefore I will need to follow any conditions set by that. Python which I will be making heavy use of in particular is licensed under the Python Software Foundation License.

Computer Misuse

I cannot think of any ways in which this project can be used maliciously that would result in any sort of criminal prosecution. The project most likely will not require an internet connection at all, this will remove a very large portion of possible malicious attack vectors.

# Time Plan

## Gantt Chart

# Literature Survey

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 (16), 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 (16). 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. (17). 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. (17). 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 (18). 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 (18).

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 (19). 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 (3). 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 (3). 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 (3). 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” (3).

The alternate to a fixed solar panel as discussed by Mehleri et al is a tracked panel. The first tracked system was developed in 1962 by Finster (20) and was of a purely mechanical design. 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 (5). 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. (5)

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. (5)

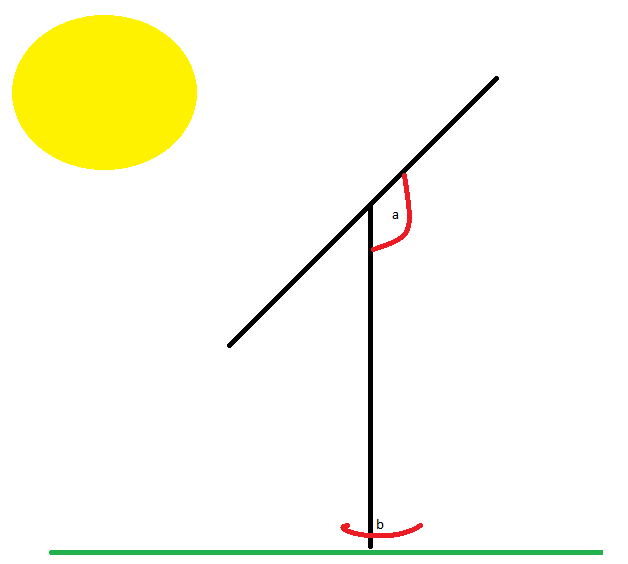
 As Kacria et al found a tracked photovoltaic panel has the potential to produce more power than its fixed alternative. However there are two types of tracked panel. Kacria et al used a two axis panel, these tracking systems can change both the orientation and tilt angle of the panel. Figure 1 demonstrate 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” (4).

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 (4).

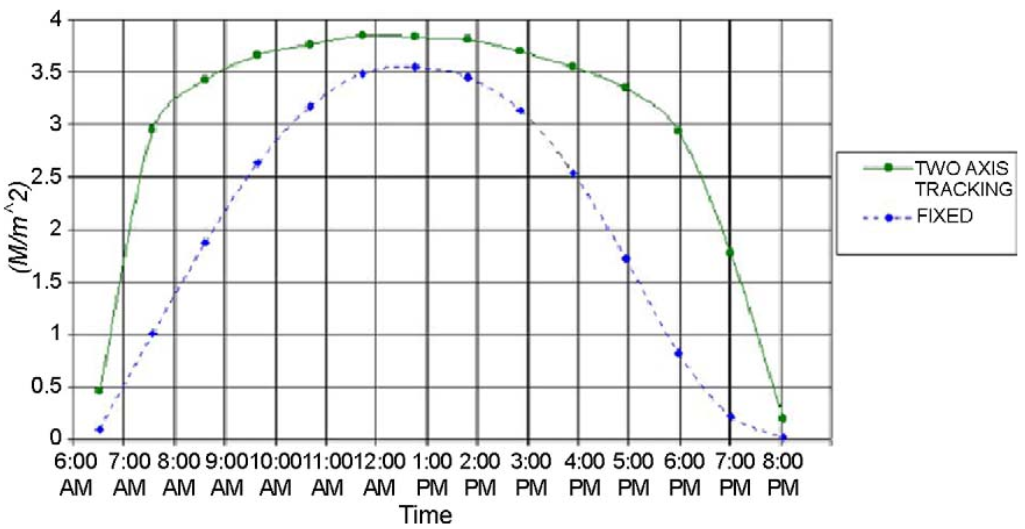
Mamlook et al in their article “A Programmable Logic Controller (PLC) to Control Two Axis Sun Tracking System” looked at designing and created a dual axis open tracked system using programmable logic circuit (21). They used the PLC to periodically to rotate the panel at set intervals in correlation to where the sun would be that was determined using mathematical formulae. This was done as they estimated the motors and control system would use less than 2% of the total collected energy (21). Ultimately they found that their two axis tracking system resulted in a 41.34% increase in daily solar collection compared to a fixed one (21) and they organised the hourly recording into the graph (Figure 2). 

Figure 2: Mamlook et al, Comparison between fixed and tracked solar system (21)

Al-Mohammad et al developed a similar system to Mamlook et al, as they used a single axis tracking system that was control by programmable logic circuit(PLC) (22). However it differed in that instead of using mathematics to determine the suns position, Al-Mohammed et al used two photo-resistive sensors and shadows to determine the level of light (22). They found that power generated was greatly increased during the mornings and evenings, with 40 per cent increase in the hours between 0600 and 1000 and between two and four per cent during the day (22).

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 (23). 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 (24). 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 (25). 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 (26).

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 (26).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 (26). 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 (26). 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 (26). 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 (26).

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 (26) 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 (26).

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 (26).

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 (26).

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 (27). 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 (27). 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 (27). 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.

Rubio et al formulate a similar solution in which they take a two stepped approach. In their system they have two defined modes, a normal tracking mode and a search mode (28). In normal mode the system would simply follow solar models in order to predict where the sun would be. However when a set error boundary was met (defined by Rubio et al) in their algorithm the Search mode would begin. In search mode Rubio et al had the system begin a spiral movement until the system could detect the sun (28). Like Roth et al, Rubio et al used a pyrherliometer to detect the solar irradiance. In their results they found that the power generated was 55% than that of a standard open loop system.

The benefits of a closed loop solution are clear and a hybrid solution similar to Rubio et al seems to be optimum however when considering the costs of such a system specifically the reliance on pyrheliometer is problematic as it is specialised and expensive piece of equipment. Another option to detect the light to use another type of electro-optical device and enhance the accuracy through the use of photodiodes mounted on the photovoltaic panel like Heredia et al (29). However Mousazadeh et al characterise these as being complex which makes them expensive and unreliable (30).

To conclude I believe that a single axis tracked system using the solar altitude to predict the suns location would provide the most cost efficient solution for maximising the solar energy produced however I would like to personally experiment with a closed loop solution. The biggest challenge with a closed loop system being how to detect where the brightest area of sky would be. I think this could be done more simply than measuring the solar irradiance. I think it would be possible to simply sample areas of the sky with the panel and record the power output, where the power output is highest will most likely be the clearest area of sky. A dual axis system may provide more energy as Li et al found I agree with their conclusion that the more complicated mechanical aspects of dual axis system would mean constructing and maintaining such a system would offset the slight increase in energy production.

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