ARC 7302: Thesis (Research)
or
Final Project (Design)

(Draft Report)

Optimization of PV systems; IRR as objective

Submitted by

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Contents

Vision

To make sustainability free for all, ensuring that every child has access to education on sustainability and providing all students with the tools and knowledge to become leaders in building a sustainable future.

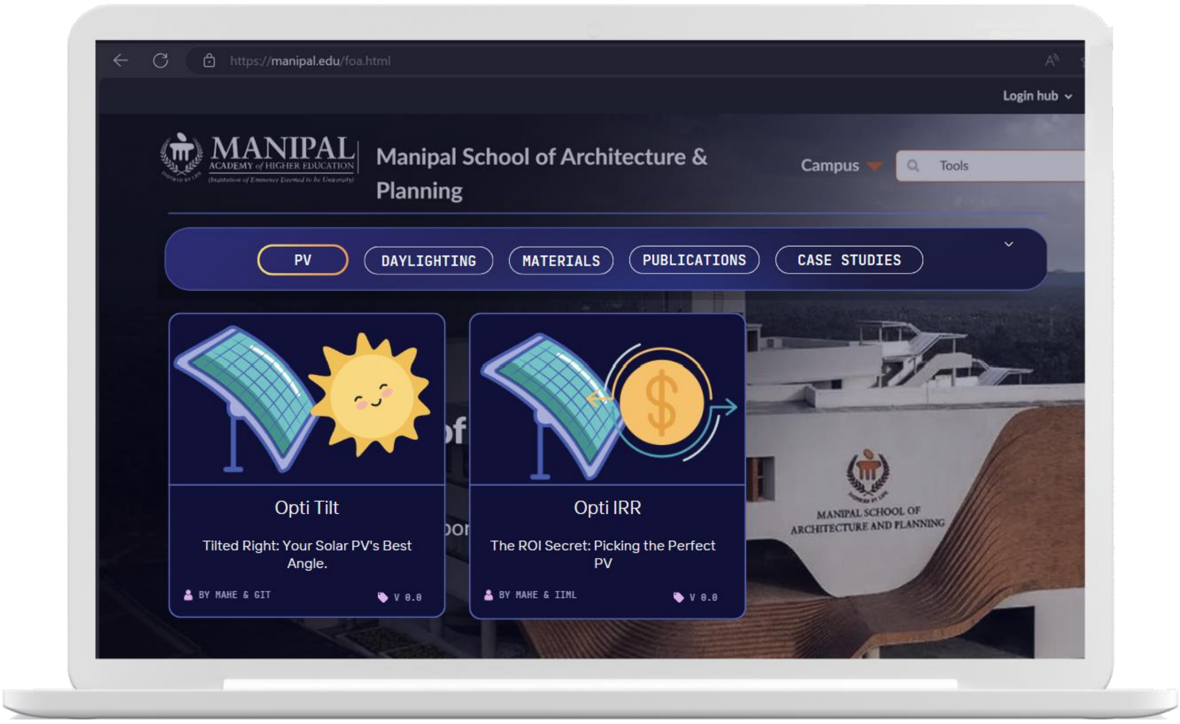
Mission

To create and provide free innovative tools and resources.

Objective

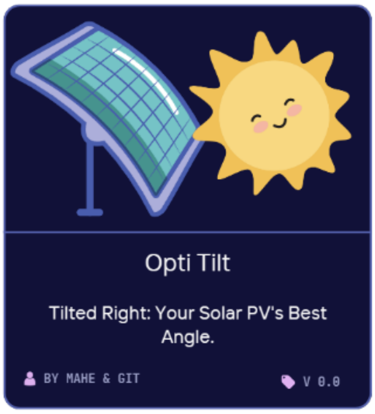
To design and develop a simple tool that optimizes photovoltaic (PV) systems with the primary objective of maximizing the Internal Rate of Return (IRR)

Interface

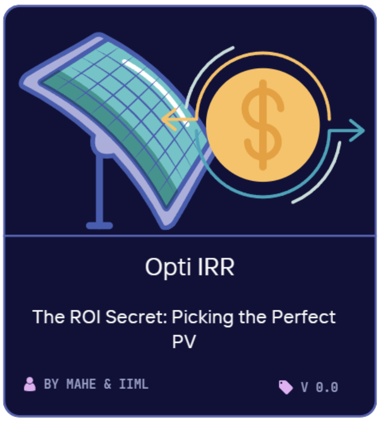


Tilted Right: Your Solar PV's Best Angle.

The ROI Secret: Picking the Perfect PV



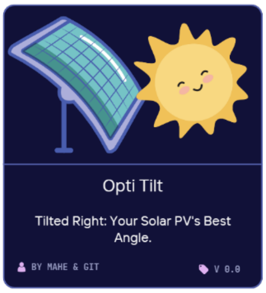
Tilted Right: Your Solar PV's Best Angle.



The ROI Secret: Picking the Perfect PV

ECBC Daylight Compliance Simplified

PV Tools



"Opti Tilt" is the next evolution in solar panel optimization. In contrast to PV Watts, which relies on default angle settings, "Opti Tilt" empowers users to automatically determine the ideal tilt angle for their solar panels keeping EPI as objective. This innovative tool provides precise monthly and annual angle recommendations, ensuring maximum energy production. Unleash the full potential of your solar system with precision and efficiency—because every degree counts when it comes to harnessing the power of the sun.

“Opti IRR" transforms PV system selection, prioritizing the highest Internal Rate of Return (IRR). It's more than just choosing a system—it offers guidance on maintenance, from cleaning schedules to tilt adjustments for peak energy production. Powered by advanced regression analysis, "Opti IRR" considers energy rates and regional development, providing a customized, efficient, and economically sound solution for your solar investment. Get ready to unlock the full potential of your PV system's financial returns.

Future Projects

1. Daylighting:

"Opti Daylight ECBC" meticulously evaluates architectural designs, offering a detailed analysis of your building's compliance with ECBC daylighting standards. Furthermore, it employs a unique reverse engineering approach to optimize the Window-to-Wall Ratio (WWR) within your design. This comprehensive tool goes beyond mere assessment, providing practical guidelines on how to achieve and elevate ECBC compliance, ensuring that your project aligns with the highest standards of energy efficiency and sustainability.

2. Materials: Selecting the right materials. IRR as objective and environmental constraints.
3. Shading device: Best shading device IRR and Thermal comfort as objective.

Abstract

PV system efficiency peaks when solar panels are aligned perpendicularly to incident radiation. Therefore, while solar trackers are the most efficient, their economic feasibility is questionable due to higher upfront and operational costs. Solar panels require maintenance due to dust/soiling impacting efficiency, and adjusting tilt angles six times annually captures 99.5 percent of solar radiation. Hence, this study aims to identify optimal monthly and seasonal angles for further economic evaluation. Addressing the need for a computationally efficient tool, this research develops a mathematical model that utilizes the Energy Performance Calculator (EPC). It determines the optimal tilt angle for solar panels using data extracted from the EnergyPlus Weather (EPW) data file to find the optimal placement of solar panels, allowing for further modifications, but not limited to, shading, albedo, BIPV, environment, and architectural variables. The analysis contrasts the EPC model with other solar geometry models, presenting a 3rd-order polynomial fit that correlates the ideal tilt to latitude for Rooftop PV and BIPV. The study underscores the importance of calculating precise tilt angles for accurate results in their respective locations.

Significance / Rational of the Study

(below texts are not linked to reference)

Studies indicate that there is a 0.08% efficiency loss with a 1° deviation from the south, particularly in the direction of azimuth. (Adnan Aslam).

(Addressing the Review 1 questions)

If solar panels are set to a fixed tilt angle, it is recommended that the annual optimum tilt angle aligns with the latitude of the installation location. However, the tilt angle deviates about +15° and -15° from the latitude in winter and summer, respectively. (JanneViitanen)

Adjusting the tilt angles of solar panels becomes more impactful in regions further from the equator, especially in locations with latitudes lower than 30°S or higher than 30°N. In several regions globally, tilt angles contradict the rule of thumb, deviating significantly due to distinct cloud patterns (Ch. Breyer). The PV panels' tilt angle varies with location, emphasizing its dependence on specific site conditions. (Adnan Aslam)(Ch. Breyer)(add others).

As bifacial PV systems become more prevalent, replacing monofacial modules, Recent efforts in academia and commercial software development focus on creating accurate models, with increased complexity due to the need to quantify rear irradiance. (Radovan Kopecek)

The development of the mathematical model holds significant worth as it can be transformed into an open-source tool, facilitating consultants in providing site-specific recommendations. The determination of optimal tilt angles on a monthly and seasonal basis becomes instrumental in assessing the Levelized Cost of Electricity (LCOE) and Internal Rate of Return (IRR) for diverse PV systems in various regions. For example, comparing a dual-axis manual tilt solar panel with fixed and active solar trackers. This valuable information equips consultants and consumers with the necessary insights to make informed decisions, ensuring the selection of the most suitable solar system for specific locations.

Objectives of the Study

- Develop a computationally accessible, user-friendly mathematical model integrated into buildings for further analysis of various designs.

- To determine and analyze monthly and seasonal optimal tilt angles as crucial parameters for advancing research in the economic evaluation of diverse solar panel systems.

Research questions:

1. What is the difference between the annual optimal tilt angle and latitude for various locations?
2. What is the percentage increase in efficiency achieved when solar panels are adjusted to their optimal tilt angle on a monthly and seasonal basis?

Hypothesis for Research Question 1: (it has been proven that there is a difference in various region so idk if this is valid)

Null Hypothesis (H0): There is no significant difference between the optimal tilt angle and latitude for various locations.

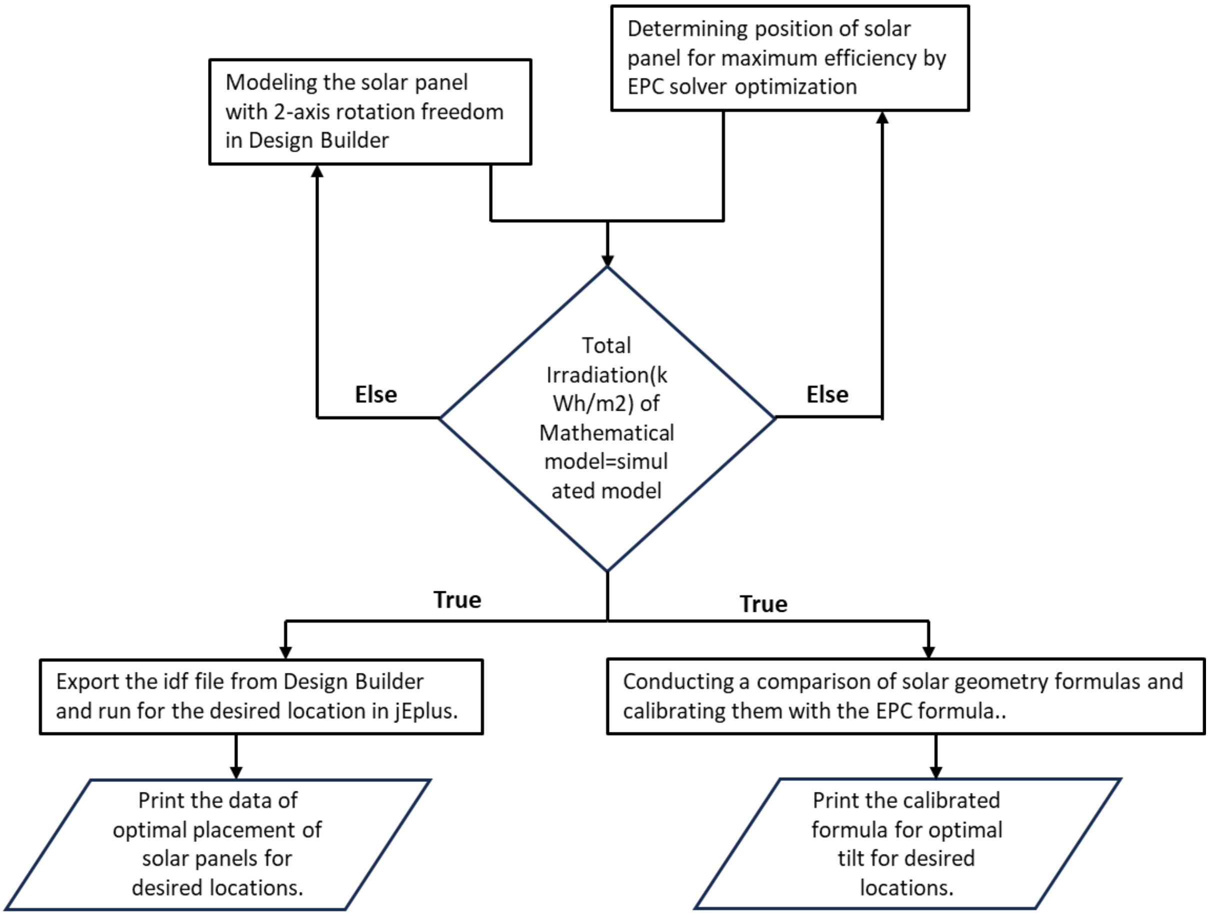
Alternative Hypothesis (H1): The optimal tilt angle significantly differs from latitude for various locations.

Hypothesis for Research Question 2: (It obviously gives more efficiency maybe I can say not more than 15% or 10%)

Null Hypothesis (H0): There is no significant increase in efficiency when solar panels are adjusted to their optimal tilt angle on a monthly and seasonal basis.

Alternative Hypothesis (H1): Adjusting solar panels to their optimal tilt angle on a monthly and seasonal basis significantly increases efficiency.

Methodology



Research Gap

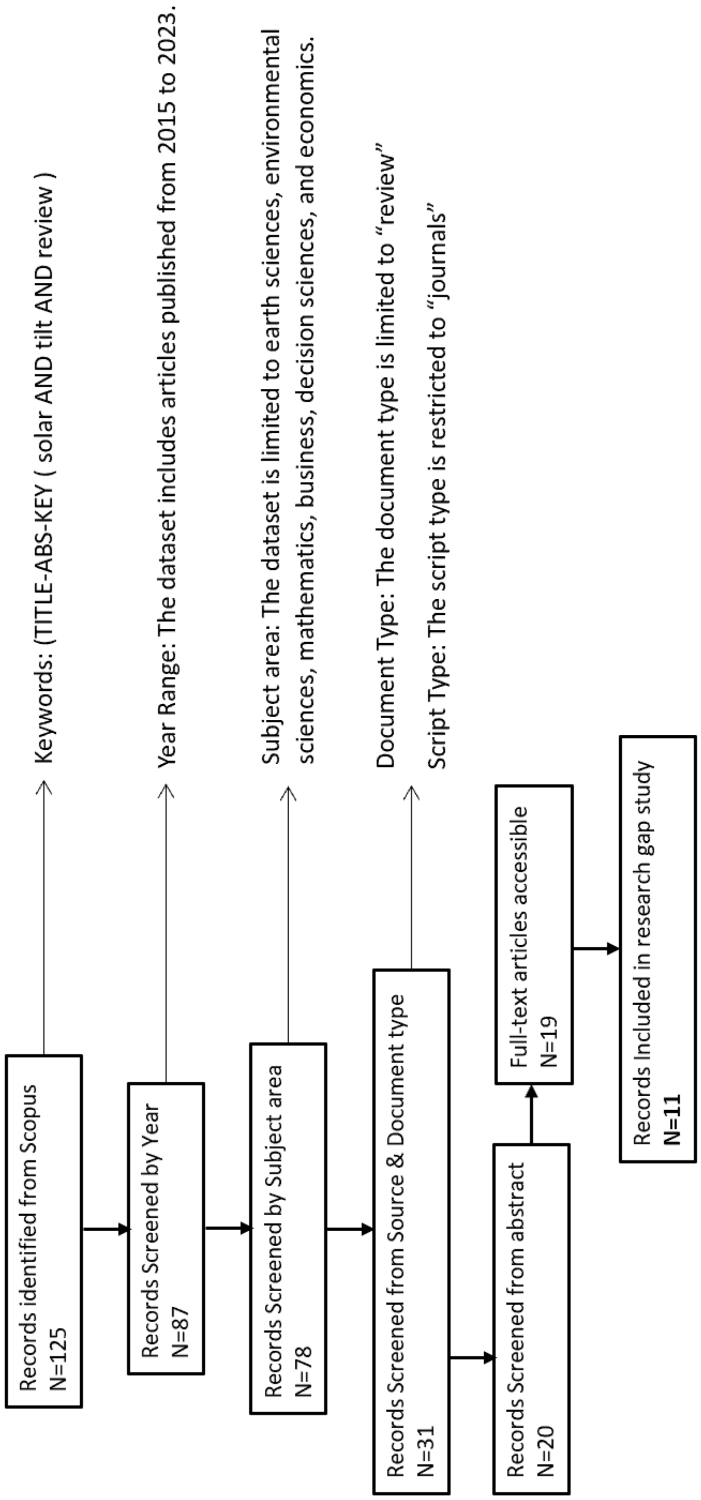


Fig 1: The process of acquiring literature for the study of the research gap

Previous Research Question: Prior to addressing the research gap, I formulated the following research question to guide my investigation

1. What is the percentage increase in solar panel efficiency when they are fixed at the optimal tilt angle?
2. Which PV module exhibits the lowest Energy Performance Index (EPI) among commercially available options?
3. Which PV module exhibits the lowest internal rate of return (IRR) among commercially available options?

Answers:

1. Within ±30◦ latitudes, for fixed tilt bifacial vs. monofacial we predict a 20-30% gain, and an additional 20-40% gain for single axis bifacial tracking [1]. With the combination of bifacial modules in simple single axis tracking systems, energy yield increases of more than 40% can be expected compared to fixed tilt monofacial installations. [2]. Solar trackers are designed to follow the location of the sun which results in the 10–25% more output efficiency of the PV panels. revealed that the two axis trackers are more efficient than single axis trackers. The efficiency of the two axis sun tracker is even more than 98.5%. [3].
2. The study reveals that double axis ST in form of polar-axis and azimuth/elevation featuring the solar movement models and the dynamic closed loop feedback control are the most effective and generally give more than a 40% improvement in energy return compared to fixed PV panels. [4].
3. The cost of energy generated from a PV tracking system is higher than the energy produced from a fixed system because of the running cost and the initial cost of the tracking system, which makes their economic advantages questionable. [4].

Need for Research:

1. **Development of Mathematical Formula:** The development of a mathematical formula that incorporates environmental conditions will provide a more accurate and reliable method for determining the optimal tilt angle for solar PV systems in any location. This formula will enhance the precision of system design and improve energy generation efficiency.
2. **Economic Analysis and IRR Calculation:** Conducting an in-depth economic analysis, specifically focusing on the calculation of the Internal Rate of Return (IRR), is essential to assess the financial performance and economic viability of different tracking systems, including fixed-tilt, 2-axis tracking, and 3-axis tracking systems. This analysis will enable informed decision-making by considering the long-term economic benefits and costs associated with each system. Develop a formula or methodology that can determine the most economically favourable system for any location based on the IRR analysis.
3. **Systematic Review of Optimum Tilt Angle:** A systematic review of the literature on the topic of optimum tilt angle for solar PV systems is necessary. This review will consolidate existing knowledge, identify research gaps, and provide insights into the technical and economic aspects of determining the optimal tilt angle.

Table 1: Summary of Research Gap findings

SL no	Title	Year	Authors	Research Gap	Need for Research
1	The recent advancements in the building integrated photovoltaic/thermal (BIPV/T) systems: An updated review	2022	Abdelrazik A.S.; Shboul B.; Elwardany M.; Zohny R.N.; Osama A.	Despite the existing literature on building integrated photovoltaic/thermal (BIPV/T) systems, there is a research gap regarding the optimization of tilt angles for achieving optimal performance.	Further research is needed to investigate and optimize the tilt angles of BIPV/T systems in order to maximize their energy generation potential and overall efficiency. This research is essential to address the challenges associated with BIPV/T systems, such as the need to provide optimal tilt angles for optimal performance.
2	Advances in Solar PV Systems; A Comprehensive Review of PV Performance, Influencing Factors, and Mitigation Techniques	2022	Aslam A.; Ahmed N.; Qureshi S.A.; Assadi M.; Ahmed N.	Despite the growing trend of utilizing solar PV systems for large-scale electricity generation, there is a research gap in accurately predicting the electricity output of PV power plants.	•Further research is needed to develop techniques and models that can accurately estimate the electricity generation of PV power plants. •Since the angle of inclination of PV panels varies depending on the location, site-specific studies are necessary to maximize solar radiation absorption and energy yield. Investigating and addressing these research gaps will contribute to improving the reliability and predictability of PV performance, enabling better planning and implementation of solar PV systems on a larger scale.
3	A review of next generation bifacial solar farms: Predictive modeling of energy yield, economics, and reliability	2021	Khan M.R.; Patel M.T.; Asadpour R.; Imran H.; Butt N.Z.; Alam M.A.	Despite the advancements in bifacial solar farms, there is a research gap in terms of long-term degradation studies and accurate predictions of energy yield. While the review paper addresses the combination of economics and reliability in the context of bifacial solar farms, there is still a research gap in terms of developing comprehensive and accurate predictive models that integrate these factors.	•Conduct long-term degradation studies for accurate predictions in bifacial solar farms. •Optimize the design of bifacial farms to achieve the most cost-effective operation (LCOE optimization). •Develop simplified modeling tools that are accessible and computationally efficient. •Explore machine learning-based approaches for accurate predictions and design of next-generation compound PV systems
4	Bifacial photovoltaics 2021: Status, opportunities and challenges	2021	Kopecek R.; Libal J.	Despite the increasing use and potential benefits of bifacial photovoltaic (PV) systems, there is a research gap in accurately modeling and quantifying the energy yield of these systems due to the increased complexity in capturing rear irradiance.	•Predict and analyze the cost-effectiveness of monofacial and bifacial PV modules, considering regression analysis for future cost projections. •Evaluate the efficiency of monofacial modules at different tilt angles and compare them with bifacial modules, considering optimal angles for maximum energy generation. •Investigate the impact of monofacial and bifacial PV systems on small-scale installations, focusing on surface effects and structural considerations.
5	Performance improvement for building integrated photovoltaics in practice: A review	2021	Dai Y.; Bai Y.	Despite the existing literature on (BIPV), there is a research gap in evaluating the actual energy-harvesting performance and cost-effectiveness of BIPV systems considering both electricity generation and heat utilization. Additionally, a limited number of literature reviews focus on this aspect.	•Evaluate the energy-harvesting performance and cost-effectiveness of BIPV systems considering both electricity generation and heat utilization. •Conduct systematic reviews to understand the strain effects on PV cells and applicable mechanical scenarios for different types of PV cells in BIPV systems. •Investigate the thermal and mechanical performance of BIPV prototypes in real outdoor environments, particularly in load-carrying scenarios.

Table 1: Summary of Research Gap findings

6	An overview on performance of PV plants commissioned at different places in the world	2020	Srivastava R.; Tiwari A.N.; Giri V.K.	-	•Improve the prediction of actual electricity output from PV plants under real outdoor conditions. •Evaluate the impact of PV module material on PV plant performance. •Determine the optimal tilt angle and positioning of PV panels for optimal results in energy generation.
7	Non-cumulative only solar photovoltaics for electricity load-matching	2019	Freitas S.; Brito M.C.	While there is existing knowledge on the impact of orientation and tilt angles on the electricity production of PV arrays, there is a research gap in understanding how production profiles can be effectively matched with electricity demand. Optimizing the orientation and tilt of PV systems based on factors such as wholesale prices, generator dispatch, peak demand timing, and pricing structures can enhance the value of PV systems.	•Explore strategies to optimize the orientation and tilt of PV systems based on criteria such as wholesale prices, generator dispatch, and peak demand timing. •Assess the wholesale market value of PV-generated electricity at different tilt and azimuth angles in various regions. •Investigate the integration of electricity storage as a complementary measure for load-matching in non-cumulative solar photovoltaics.
8	Solar irradiance estimation models and optimum tilt angle approaches: A comparative study	2018	Danandeh M.A.; Mousavi G. S.M.	-	•Develop accurate solar irradiance estimation models for various geographical locations. •Conduct comparative analysis of tilted irradiance models for different countries. •Determine the optimum tilt angle values for PV systems in different cities and countries.
9	Analysis of the impact of dust, tilt angle and orientation on performance of PV Plants	2018	Babatunde A.A.; Abbasoglu S.; Senol M.	Limited research exists on the specific yield of PV systems and the impact of dust, tilt angle, and orientation on system performance, with a focus on technical factors rather than economic analysis and storage integration.	•Economic analysis: Incorporate cost analysis, payback period, and energy cost evaluation to assess the economic viability of PV systems. •Further research is needed to explore the integration of storage facilities and their impact on optimizing PV system orientation and tilt. •Cleaning strategies: Conduct system-specific cleaning studies and explore the impact of progressive dust accumulation on a daily, weekly, and monthly basis. •Long-term monitoring: Perform annual monitoring of dust effects on PV plants, considering the influence of tilt angle on soiling. •Significant variables: Determine the key parameters influencing PV system performance and their predictive value for specific yield.
10	An imperative role of sun trackers in photovoltaic technology: A review	2018	Singh R.; Kumar S.; Gehlot A.; Pachauri R.	There is a research gap in the literature regarding a comparative economic assessment of sun trackers in photovoltaic technology.	-
11	Recent advancements and challenges in Solar Tracking Systems (STS): A review	2018	Nsengiyumva W.; Chen S.G.; Hu L.; Chen X.	There is a need for further research to determine the specific factors contributing to the cost reduction in solar tracking systems (STS), such as whether it is primarily attributed to the use of tracking systems or concentrators.	•Investigating the impact of double-axis solar tracking systems (STS) with closed-loop tracking control units on the electrical performance of large-scale solar energy harvesting devices. •Developing improved and more flexible solar tracking systems (STS) that are cost-effective and enhance overall system performance.

EPC solar radiation calculation

Data from EPW:

1. Egh = Global Horizontal Radiation {Wh/m2},
2. Eb = Direct Normal Radiation {Wh/m2}
3. Ed = Diffuse Horizontal Radiation {Wh/m2}

Direct Radiatiion:

Ydy= Year Day number

τ(Tau)= in minutes(how is this in min?) recheck this since it is dimensionless

- $\tau = (2*\pi*(Ydy-1))/365$

Subtracting 1 from Ydy is a normalization step, bringing the counting to start from 0 instead of 1.

In other equations it is denoted as B.

ET= equation of time

- $ET=2.2918*((0.0075+0.1868*COS(\tau)-3.2077*SIN(\tau)-1.4615*COS(2*\tau)-4.089*SIN(2*\tau))$

The equation of time represents the difference between mean solar time (a uniform time scale based on the mean position of the sun) and apparent solar time (the actual time based on the sun's position in the sky). This difference arises because of the elliptical shape of the Earth's orbit and its axial tilt.

The equation of time is influenced by various factors, including the Earth's orbit eccentricity and axial tilt. The constants and trigonometric functions in the formula are used to model these effects. The specific coefficients like 2.2918, 0.0075, 0.1868, 3.2077, 1.4615, 4.089, etc., are determined based on astronomical observations and calculations.

Clock time= LST (local solar time) [0-24]

TS/AST = Apparent solar time

TZ= Weather data time zone

LSM= Local Standard Meridian" or "Longitude of the Standard Meridian.

- $LSM=15*TZ$

The standard meridian for a time zone is typically a multiple of 15 degrees. The Earth's rotation takes approximately 24 hours to complete a full rotation, covering 360 degrees of longitude. Therefore, the Earth rotates at a rate of 360/24=15 degrees per hour. Each hour corresponds to 15 degrees of longitude.

- $AST= =LST+ET/60+(Lon-LSM)/15$

δ = Solar declination, deg

- $\delta = 23.45*SIN((Ydy +284)/365*2*\pi)$

Solar declination refers to the angle between the Earth's equatorial plane and the line connecting the center of the Earth to the Sun. It represents the latitude at which the Sun is directly overhead at noon on a particular day. The solar declination angle changes throughout the year due to the tilt of the Earth's axis and the elliptical shape of the Earth's orbit around the Sun.

By adding 284 to Ydy, we shift the starting point from January 1st to the winter solstice (around December 21st), 2 * π converts it into radians, The sine function returns a value between -1 and 1, representing the vertical component of the solar declination. The value 23.45 represents the axial tilt of the Earth, which causes the variation in solar declination throughout the year. The adjustment of starting the calculation from 284 (around the winter solstice) is made to align with the time when the solar declination angle reaches its maximum negative value.

H or (θ_h) = Hour angle: angular displacement of the sun east or west of the local meridian due to the rotation of the earth, in degree.

- $H = 15*(AST - 12)$

The Hour Angle is an angular measurement of the Sun's position in the sky relative to the observer's local meridian. AST-12 calculates the difference between the apparent solar time AST and 12, which represents solar noon. The difference between the current time and solar noon gives us the hour angle. 15 is to convert time to degree.(1hr=15degree lat). By measuring the hour angle of the Sun, we can determine how many hours it has moved since local solar noon.

β = solar altitude in radians

The solar altitude angle is the apparent angle of the sun above the horizontal plane, observed from a specific location on Earth's surface. It indicates how high or low the sun appears in the sky at a particular moment and location.

- $Sin\_\beta=COS(Lat*\pi/180)*COS(\delta*\pi/180)*COS(\theta_h*\pi/180)+SIN(Lat*\pi/180)*SIN(\delta*\pi/180)$
- $\beta = Sin^{-1}(Sin\_\beta)$

why was equation divided in excel?

- $\beta=Sin^{-1}(COS(Lat*\pi/180)*COS(\delta*\pi/180)*COS(\theta_h*\pi/180)+SIN(Lat*\pi/180)*SIN(\delta*\pi/180))$

This could be one equation. Since there are dependence for Sin_β.

Solar altitude in degrees

- $\beta = 180/\pi$

α or φ = Solar azimuth

- $Sin\_\alpha = SIN(\theta_h*\pi/180)*COS(\delta*\pi/180)/COS(\beta)$
- $Cos\_\alpha=(COS(\theta_h*\pi/180)*COS(\delta*\pi/180)*SIN(Lat*\pi/180)-SIN(\delta*\pi/180)$
- $*COS(Lat*\pi/180))/COS(\beta)$
- α_1 option1 $=ASIN(Sin\_\alpha)*180/\pi$
- α_2 option2= $=ACOS(Cos\_\alpha)*180/\pi$

Solar azimuth in degree

- $\alpha =IF(Sin\_\alpha > 0, \alpha_2, IF(Cos\_\alpha>0, \alpha_1, -180- \alpha_1))$

Sin_α = It provides information about the component of solar azimuth in the north-south direction.

Cos_α= It provides information about the component of solar azimuth in the east-west direction.

“IF logic” determines the correct quadrant for the solar azimuth.

Gamma: Surface-solar azimuth, >90: in shade

For surface azimuth 0, -45, -90, -135, 180, 135, 90, 45 i.e. S, SE, E, NE, N, NW, W, SW respectively.

- γ= Absolute value of (α - surface azimuth)

If is γ greater than 90 degrees, it suggests that the surface is not directly facing the sun and is likely in shade.

Cosθ= angle of incidence, angle between the incident beam and the surface's normal vector

Cosθ for 0 =

- Cosθ=Cos((β)*COS(γ * π /180)*SIN(sigma*π/180)+SIN(β)*COS(sigma*π/180)

γ is for 0 i.e South

- θ= ACOS(Cosθ)*180/π

By calculating the angle of incidence (θ), you can determine the amount of solar radiation that directly strikes a surface.

Et,b=Beam component, Wh/m2

For 0 i.e South

- Et,b= IF(AND(γ>90,γ<270),0,IF(Cosθ<0,0,$Eb*Cosθ))

Check if the surface azimuth (γ) is between 90 and 270 degrees:

- If true (surface is facing away from the sun), set Et to 0.
- If false, proceed to the next step.

Check if the cosine of the angle of incidence (Cosθ) is less than 0:

- If true (angle of incidence is greater than 90 degrees), set Et to 0.
- If false, proceed to the next step.

Calculate Et:

- Multiply the direct normal radiation (Eb) by the cosine of the angle of incidence (Cosθ).
- Set the result as the value of Et.

Why 270 and not 360?

The cosine of the angle of incidence (Cosθ) can be negative when the angle of incidence is greater than 90 degrees, indicating the absence of direct solar radiation, and sets the beam component (Et) to 0 accordingly.

Diffuse component

For 0 i.e south

- Y= MAX(0.45,0.55+0.437*Cosθ+0.313*(Cosθ^2))

The equation is a quadratic function that models the relationship between the angle of incidence and the diffuse radiation. The coefficients 0.55, 0.437, and 0.313 determine the shape and characteristics of the quadratic curve.

The "MAX" function is used to ensure that the calculated diffuse component is not lower than a minimum value of 0.45. This prevents negative or excessively low values, ensuring a minimum level of diffuse radiation is maintained.

Different models or empirical relationships may exist for estimating the diffuse component based on various factors such as location, time of year, and atmospheric conditions.

Ground reflected component

ET,r= ground reflected total radiation incident on the nonvertical inclination

- Et,r= (Eb*SIN(β)+Ed)*rou_g*(1-COS(sigma*π/180))/2

r_g= 0.14= ground reflectivity - assign the overcast sky

- Hourly Global Solar Radiation (W/m2) = Et,b+Et,d+Et,r

Monthly Averaged Data

For Jan and 0 i.e. South:

=AVERAGEIF(Output_H!$B$25:$B$8784,Output_M!$C25,Output_H!G$25:G$8784)

$B$25:$B$8784=Month example Jan

G$25:G$8784= South

The formula calculates the average solar radiation for a specific month.

VBA

```
'Solar Radiation
    Windows(WeatherFile).Activate
    Range("N9:P8768").Copy
    Windows(FileName).Activate
    Sheets("EPW_Data").Range("H10").PasteSpecial Paste:=xlPasteValues, Operation:=xlNone,
SkipBlanks _
        :=False, Transpose:=False
```

```
Function SolarRadForTiltAngle()
    'Find the EPW file in a given directory
    str_EPWFileName = Dir(WeatherDirectory & WeatherFile)
    If str_EPWFileName = False Then
        'Do nothing
    Else

        Sheets("EPW_Data").Range("sigma").Copy
```

```
    Sheets("EPW_Data").Range("a8800").PasteSpecial Paste:=xlPasteValues, Operation:=xlNone,
SkipBlanks _
        :=False, Transpose:=False

  '01----------------
  Sheets("EPW_Data").Select
  Range("sigma").Select
  ActiveCell.FormulaR1C1 = "01"
  Sheets("Output_M").Range("_MonthlySolarRad").Copy
  Sheets("Output_M").Range("_01").PasteSpecial Paste:=xlPasteValues, Operation:=xlNone,
SkipBlanks _
    :=False, Transpose:=False

  Sheets("Output_H").Range("_HourlySolarRad").Copy
  Sheets("Esol").Range("_Hourly01").PasteSpecial Paste:=xlPasteValues, Operation:=xlNone,
SkipBlanks _
    :=False, Transpose:=False
```

Sheets("Output_M").Range("_MonthlySolarRad").Copy: This line copies the range named "_MonthlySolarRad" from the worksheet named "Output_M".

Sheets("Output_H").Range("_HourlySolarRad").Copy: This line copies the range named "_HourlySolarRad" from the worksheet named "Output_H

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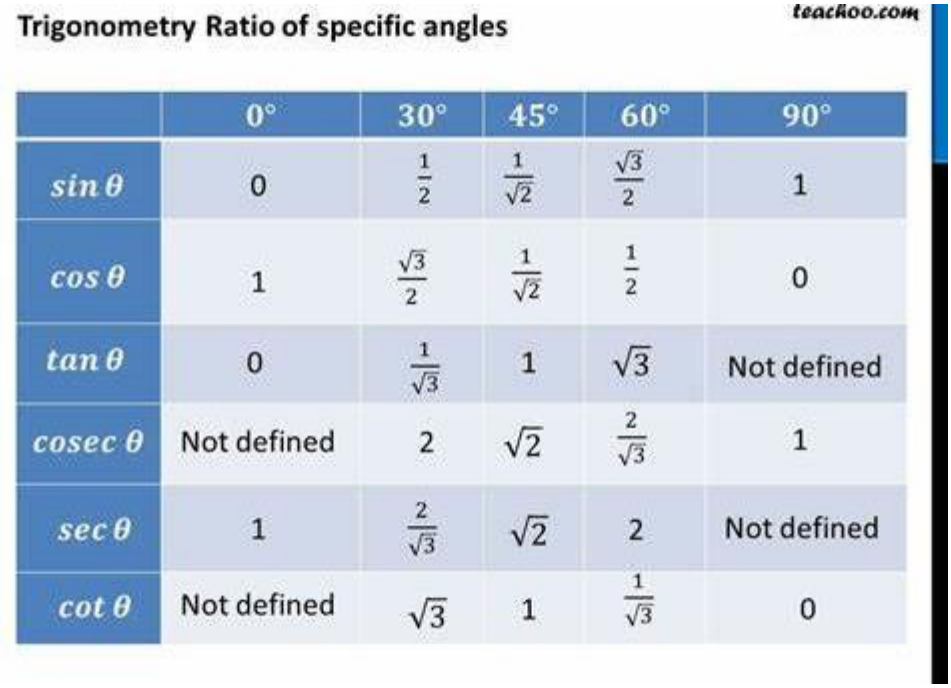
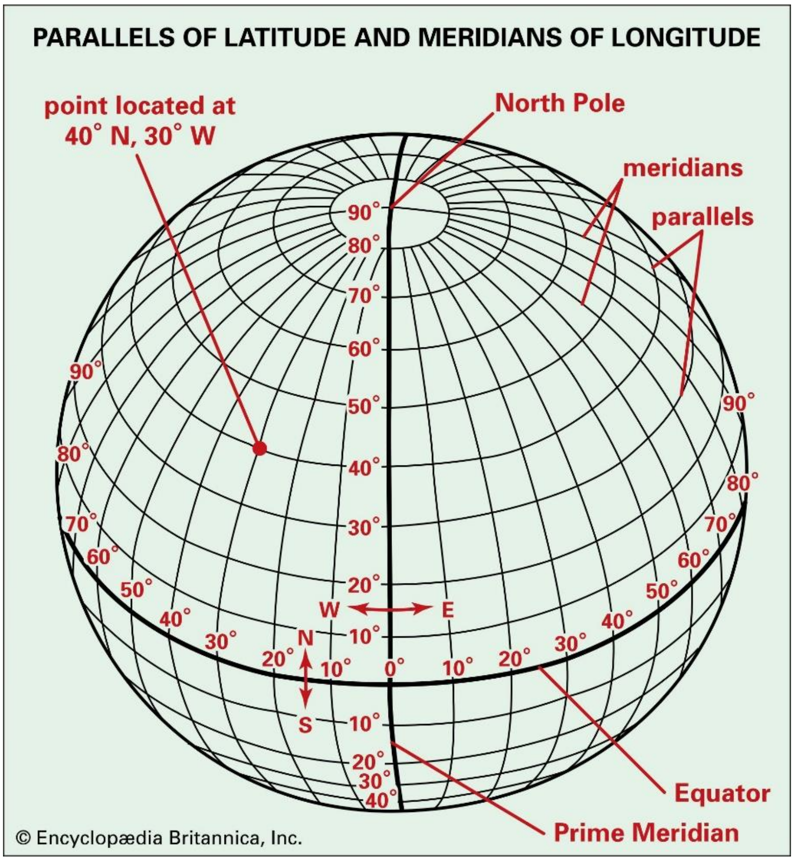
https://www.youtube.com/watch?v=Mx9AJJSKIL4



Trigonometry Ratio of specific angles

teachoo.com

	0°	30°	45°	60°	90°
$\sin\theta$	0	$\frac{1}{2}$	$\frac{1}{\sqrt{2}}$	$\frac{\sqrt{3}}{2}$	1
$\cos\theta$	1	$\frac{\sqrt{3}}{2}$	$\frac{1}{\sqrt{2}}$	$\frac{1}{2}$	0
$\tan\theta$	0	$\frac{1}{\sqrt{3}}$	1	$\sqrt{3}$	Not defined
$\text{cosec}\,\theta$	Not defined	2	$\sqrt{2}$	$\frac{2}{\sqrt{3}}$	1
$\sec\theta$	1	$\frac{2}{\sqrt{3}}$	$\sqrt{2}$	2	Not defined
$\cot\theta$	Not defined	$\sqrt{3}$	1	$\frac{1}{\sqrt{3}}$	0



PARALLELS OF LATITUDE AND MERIDIANS OF LONGITUDE

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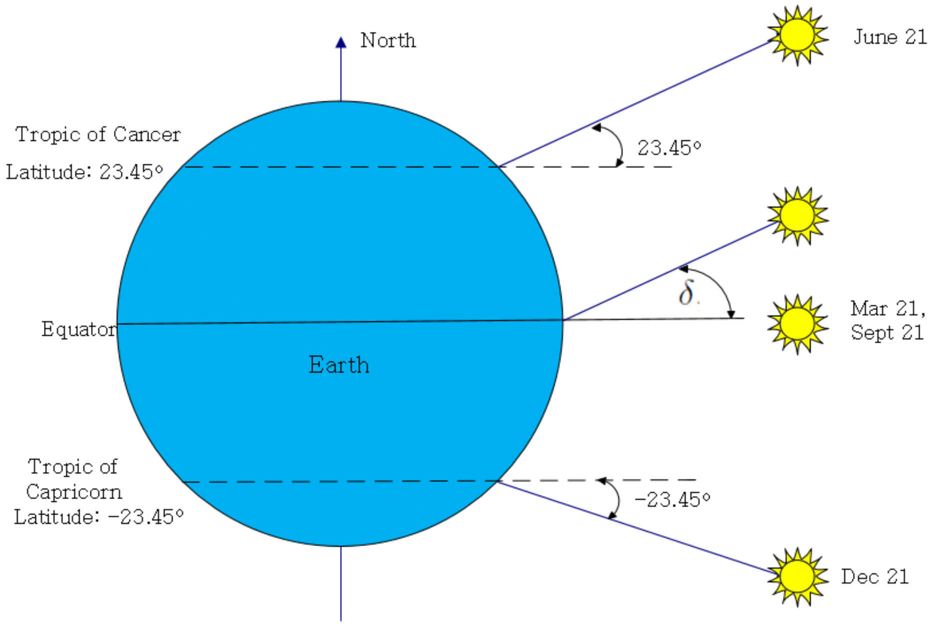
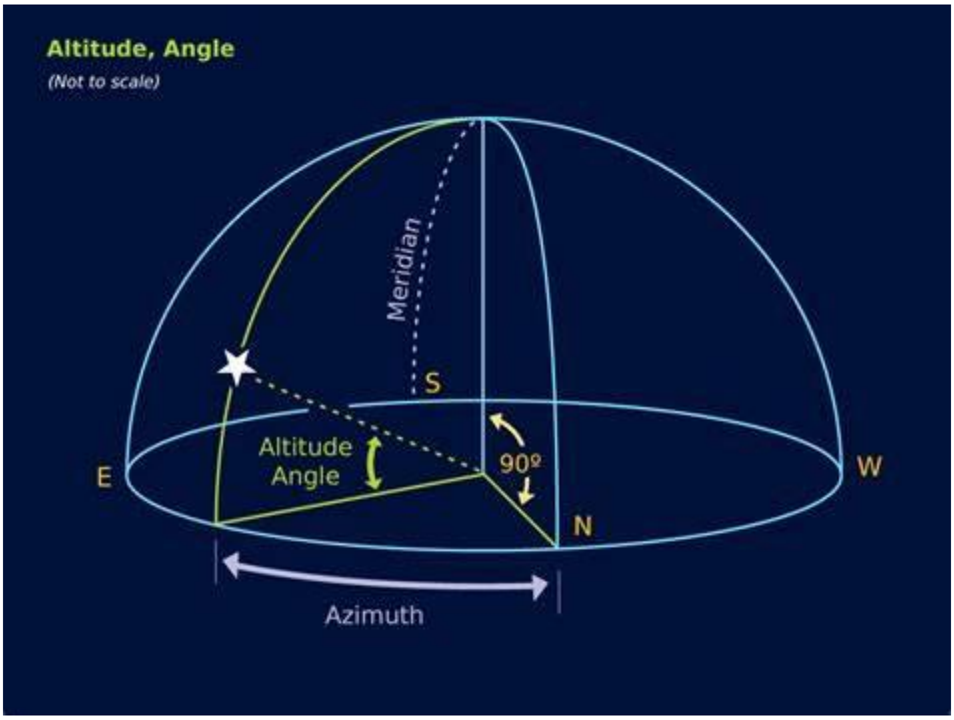

North
June 21
Tropic of Cancer
Latitude: 23.45°
23.45°
δ
Equator
Mar 21,
Sept 21
Earth
Tropic of
Capricorn
Latitude: −23.45°
−23.45°
Dec 21


Altitude, Angle
(Not to scale)
Meridian
S
E
W
Altitude
Angle
90º
N
Azimuth