Indian Institute of Science

Design of Photovoltaic Systems

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NPTEL Online Certification Course

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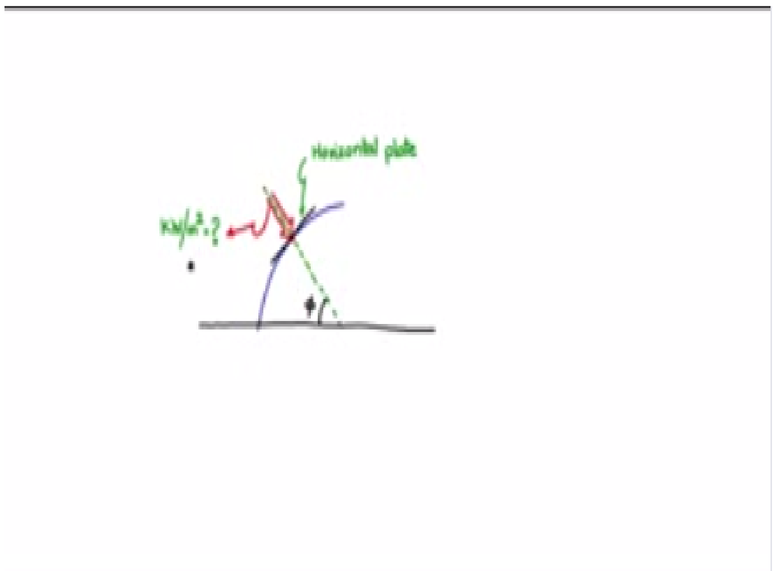

Consider the profile of the earth surface are shown and on the surface of the earth let us consider a locality at as specific latitude. Now from the center of the earth draw a line passing through the chosen locality like this, this black line now here is the equatorial plane and this angle here is the latitude angle. Let us place a horizontal flat plate at the chosen latitude like this, so this horizontal flat plate is the focus of interest and we need to find out how much insulation falls on this plate.

This is kept tangentially to the locality point here and we need to find what is the normal incidence of solar insulation that is falling on it so this is the estimate that we need to find out from the solar geometry. Remember that the horizontal plane that we have indicated here does not appear horizontal to us but to a person standing at the locality this plane will be horizontal and which and it will also lie on the horizon plane. So this is said or this is considered as horizontal with respect to a person standing at the locality keep that in mind and then we will look at the corresponding solar geometry and try to estimate this.

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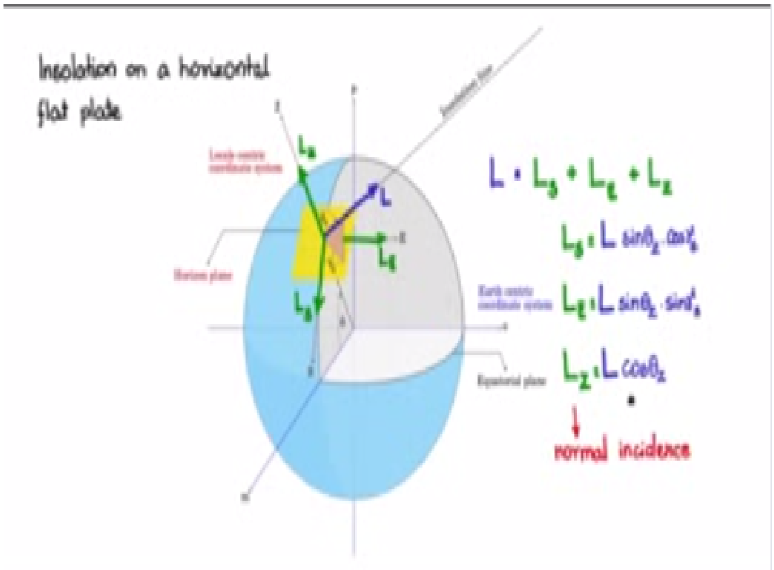

This coordinate acts a system you are now familiar with this is a familiar figure this is the locality of interest and this is the local centric coordinate system this is the horizon plane this yellow plane, this horizon plane can be considered as the horizontal flat plate on which we want to now estimate the amount of insulation falling on it normally. This is the latitude angle ϕ, this is the azimuth angle and this is the zenith angle and this line joining the locality to the center of the sun is the insulation line.

Let us now find the insulation on a horizontal flat plate located at the chosen locality here. Now consider a vector like this which represents the insulation from the sun at that locality, now that vector is at an angle θ_z zenith angle from the zenith axis. Now this insulation vector can be resolved into components orthogonal components along all these axis and these resolve components or something like this so let us say that I name this as L_S component along the south axis or the local coordinate system component along the east axis or the local coordinate system I will call it as L_E.

And the component along the zenith axis vertically up I will call it as L_Z, observe that L_Z is vertically up normal to the horizon plane and therefore you varies a horizontal plane placed at the locality L_Z alone is normal to the horizontal flat plate, so it is very important for us to find what is this value of L_Z and that will give us the effective insulation at a place on a horizontal fate plate collector.

Now we know that L is the vectorial sum of L_S+L_E and L_Z so their vectorially add a, to give you the insulation coming from the sun. Now what are each of these quantities in terms of the parameters of the coordinate system, so L_S which is along these south axis is L and this being θ_z this will be 90-θ_z therefore this would be projection would be sinθ_z and this projection is cosγ_s, so this would be the value of the insulation vector along this south axis.

Likewise the value of the insulation vector along the east axis will be L sinθ_z and sinγ_s, and the component of the insulation along this z axis or the zenith axis is nothing but L cosθ_z and this Lcosθ_z is the important insulation vector as that is normal to the horizon plane or normal to a horizontal flat plate placed at the locality. So L_z alone is the insulation which is at normal incidence to the horizontal flat plate, L_S and L_E are along the horizontal flat plate so they do not contribute to any effective insulation on the horizontal flat plate.

Now how do we estimate Lcosθ_z, θ_z is the zenith angle and we do not know directly so we should try to estimate θ_z from known parameters like latitude angle is known we know the place location of the place, time of the day ω hour angle and these are the parameters which are known to us and which we know which can measure and in terms of those we should express this, so that we get this L_Z with measurable parameters using measurable parameters.

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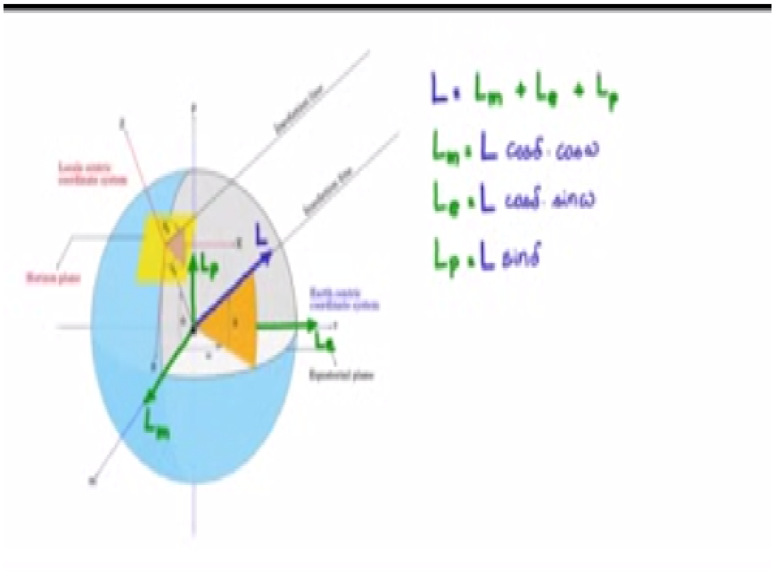

Let me shift the coordinate system to the left I am also including the earth centric coordinate system also in this figure so you see the meridional axis m, the east of the meridian and the polar axis p, and I have included the insulation line also joining the center of the earth to the distant sub, as the sun is very far from the earth we can consider the insulation line is parallel in either of the coordinate system.

And in this earth centric coordinate system let us see how the insulation L gets resolved into. Consider an insulation vector L like this and this insulation vector can get resolved into three orthogonal components along a meridional axis or on the east of the meridian and the polar axis like this, so let us say we have along the meridional axis it gets resolved as L_m and along the east of the meridian axis as another insulation vector and we will call it as L_e and one along the polar axis we shall call it as L_p.

And L the insulation vector is the vectorial sum of L_m along the meridional axis, L_e along the east of the meridian axis plus L_p along the polar axis. Now from this coordinate system we can easily reduce that L_m=Lcos of this angle δ and cosω would be along L_m, so clearly you can write it as L cosδ and to cosω and along the east of the meridian L_e we can write it as Lcosδ sinω so you will get it as cosδ sinω and L_p along the polar axis would be Lcos of this angle this angle is nothing but 90-δ so you will have L_p along the polar axis has Lsinδ.

Here the resolved components are in terms of δ and ω, δ is the declination ω is the hour angle both δ and ω hour angle or reducible can be determined knowing the time of the day and time of the year we can calculate that and we know how to calculate that, then for L_m, L_e, L_p can be easily determined. We had also resolved this insulation vector along the local coordinate system and we are interested in a normal incidence to the horizontal plane placed at the locality. How do we make use of these resolved components along with the resolved component the insulation at the local centric coordinate system?

Because local centric coordinate system is hand there earth centric coordinate system have a different origins, so one assumption that we can make here is that the radius of the earth is very small compared to the distance from the sun. so in addition to the insulation lines being parallel they can be merged so which means we push the horizon plane straight down to this center of the earth and merge the origins of the local centric coordinate system and the earth centric coordinate system then we will able to relate these resolved components obtain from the earth centric coordinate system with the resolved components of the local centric coordinate system and make the relationship.

This assumption is valid in the sense that r, the radius of the earth is very small compared to the distance from the sun and without loss of generality we can push this coordinate system and make it merge to the center of the earth.

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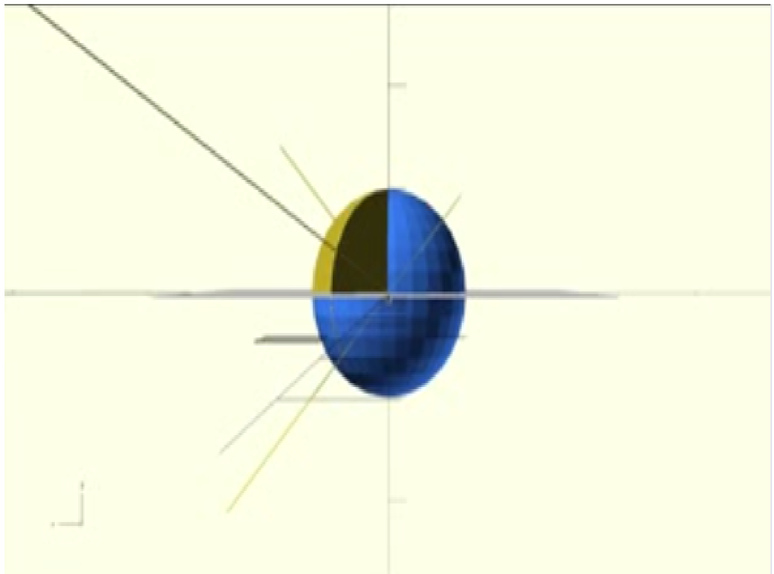

Let me give you a 3D visualization of merging the two coordinates systems such that they both have the same origins. So what I am going to do is take this local centric coordinate system and try to push it down to the center of the earth such that this origin and this origin are the same. First what I will do is I will make the horizon plane a bit bigger such that when I push it down it will stick out of the globe so that you will able to recognize where the horizon plane is and how it is oriented and also I will make the coordinate axis of the local centric system little longer so that when we push it down to the center of the earth this will still project out.

Obverse now that I have made the horizon plane bigger much bigger I have increased the lens of the south axis or the horizon plane and the east axis on the horizon plane. Now we will push this whole system down to the center of the earth when you push the horizon plane down such that the horizon origins met and merge at the center of the earth.

You see that the insulation line also merged together the east on the horizon plane is same as the east, east of the meridian so both the axes east merged together this is the south axis on the horizon plane so if you rotate you will see that the horizon plane cuts through the center and you will be able to realize it much better in this angle see that the south axis the east axis is coming in like this they have the horizon at this point at the center of the earth both are centric and local centric horizons are same and you see this was the zenith axis continues to be the zenith axis normal to the horizon plane.

So if one positions on the east axis and looks in this direction so it will appear as though like this and we are positing standing on the east axis so it looks like a line, here and you see the horizon plane in this fashion here and this is the insulation line you have the zenith axis the polar axis is right up the meridian meridional axis is along this line, the east of the horizon and the east of the meridional axis will appear like a point here it is in that turning out of the screen.

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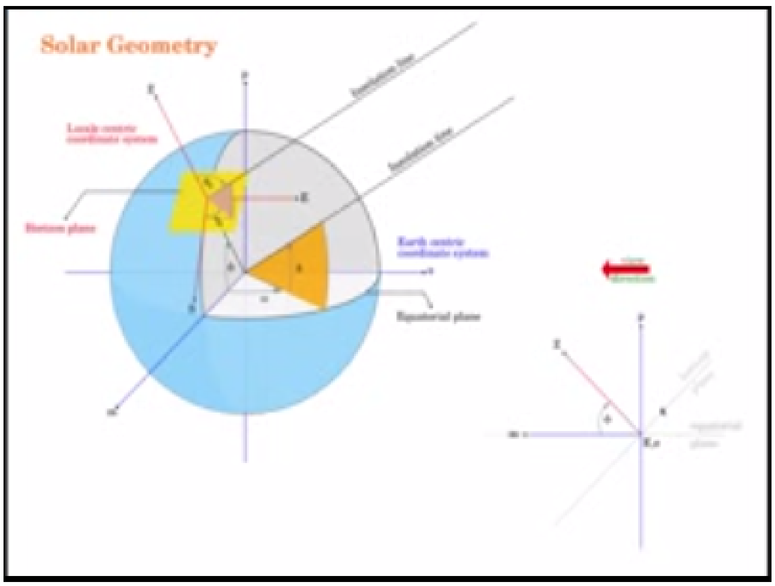

Coming back to the 2D graphics, let us view standing here, let us view in this direction so when you view in this direction we saw the visualization in 3D and let us try to capture it in 2D. You will see of course this vertical axis t the polar axis like this and then viewing from this direction the equatorial plane will cut across as the equatorial plane and the horizon plane cuts across and we saw that cuts across through the origin because we have made the origins of the two coordinate system the same and the horizon plane cutting through the horizon will look like this from this view direction.

And from this view direction we will see this line the meridional axis it will appear here this point would be the two east, the east of the meridian and the east on the horizon plane the meridional axis this is the azimuth axis, this is zenith axis right from the origin it continues up normal to the horizon plane and that is z this angle would be ϕ the latitude and this is what you would see if you are standing on this side that is if you are standing on the side and facing towards the center of the earth you would see this kind of a profile of the coordinate axis.

In this way if the horizon plane and equatorial plane are merged like this with the two coordinate systems local and equatorial coordinate systems merged together we have this two merged coordinate systems in this fashion and the variables like the insulations in the earth centric coordinate system and the local centric coordinate systems can be related by this angle ϕ and that is what we now proposed to do so that we bring in a relationship of the insulation such that it is along the zenith axis in terms of the latitude the hour angle and the declination.

We have seen that the insulation vector L resolved into the three orthogonal coordinates of the local centric coordinate system, we have seen L resolved into L_S along the south axis, L_E along the east axis and L_Z along the zenith axis and it is of interest for us to find out this insulation vector along the zenith axis which is $L\cos\theta_z$ the zenith angle. We have also seen the insulation vector being resolved along three orthogonal axis of the earth centric coordinate system and then we have the L_m along the meridional axis, L_e along the east of the meridian axis and L_p along the polar axis given in this fashion has a function of δ declination and ω.

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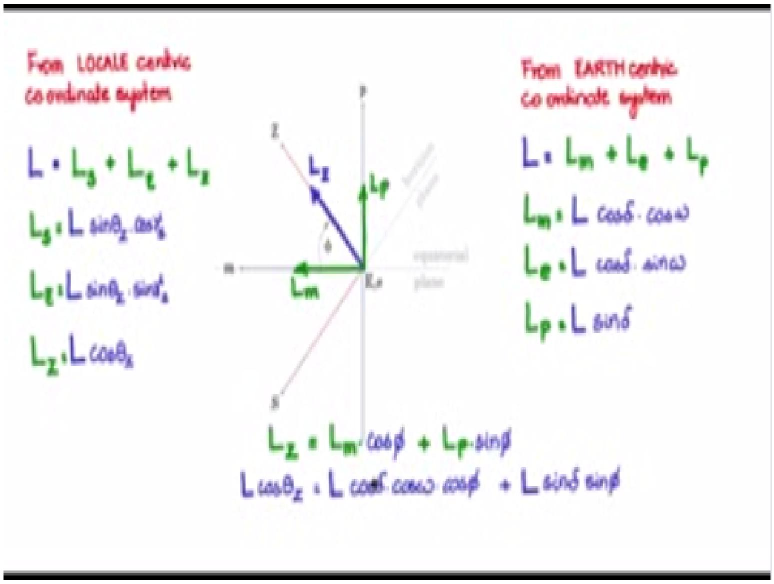

Now let me put down the two sets of equation, so from the local centric coordinate system we have the insulation L which is a vectorial sum of L_S, L_E and L_Z and from the earth centric coordinate system we have L has a vectorial sum of L_m, L_e and L_p L polar. I have also seen that if we stand on the east axis the both east from both the coordinate system east of the meridian and also east on the horizon plane.

So you will see that the axis profiles are like this and then we have merged the horizon plan e0 horizon and the equatorial plane horizon this fashion, we can now represent or obtain the insulation along the zenith axis in terms of the equatorial plane or the earth centric coordinate system parameters. Now looking at the figure here L_z is along the zenith axis which is orthogonal to the horizon plane and L_z can be resolved into L_m on the earth centric coordinate system and also L_p on the earth centric coordinate system polar axis.

So L_m and L_p earth centric coordinate system vectors can form and give L_z the zenith axis vector which is what we want, so let us say L_z=L_m cosϕ, ϕ being the latitude angle here and also L_p sinϕ, so the vectorial sum or L_m cosϕ and L_p sinϕ will result in L_z. Now in each of their respective coordinate systems we have written down what is L_z and what is Lm and L_p, so substituting we find L cosθ_z this is the zenith angle equals L cosδ cosω is Lm which we are substituted here into cosϕ+ L_p which is L sinδ sinϕ. So this is the relationship that would come out so cosθ_z which is the cos of the zenith angle can be expressed whole in terms of declination hour angle ϕ the parameters related to the earth centric coordinate system.

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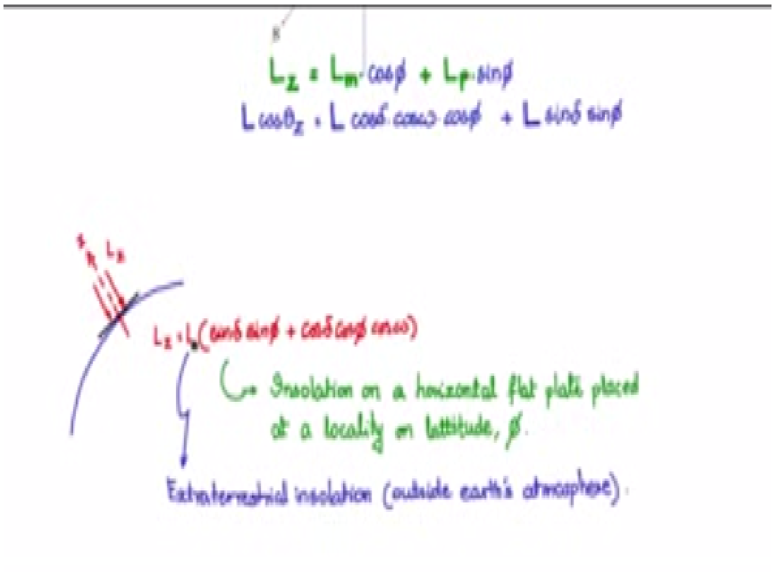

To summarize consider a portion of the earth surface and on the surface there is a locality point as shown here and at that locality point I am placing a horizontal flat plate collector and out interest is to say how much amount of insulation falls on it perpendicularly normal to that surface. So it is our interest to ask that along the z axis what is the amount of insulation L_z that is falling on this flat plate collector and that we saw from this equation L_z is nothing but L $\cos\theta_z$ where θ_z is the zenith angle.

But we do not know the zenith angle we know other parameters in the earth centric coordinates like the declination the hour angle latitude and such and therefore we know that now L_z can be written as L ($\sin\delta \sin\phi + \cos\delta \cos\phi \cos\omega$), so this would be the insulation that is falling on a horizontal flat plate placed at a locality located on the latitude ϕ. All these parameters are determinable knowing the time of the day, time of the year and the latitude.

Now this L is called the extra terrestrial insulation in kW/m^2 this is basically the insulation at the earth's outer most atmosphere that is outside the earth outer most atmosphere if you place a $1m/1m^2$ plate the amount of insulation falling on that is this L which is very close to the solar constant a $1.37kW/m^2$ however it will vary from the solar constant depending up on the time of the year we will discuss that shortly, but keep in mind that this is outside the earth's atmosphere.