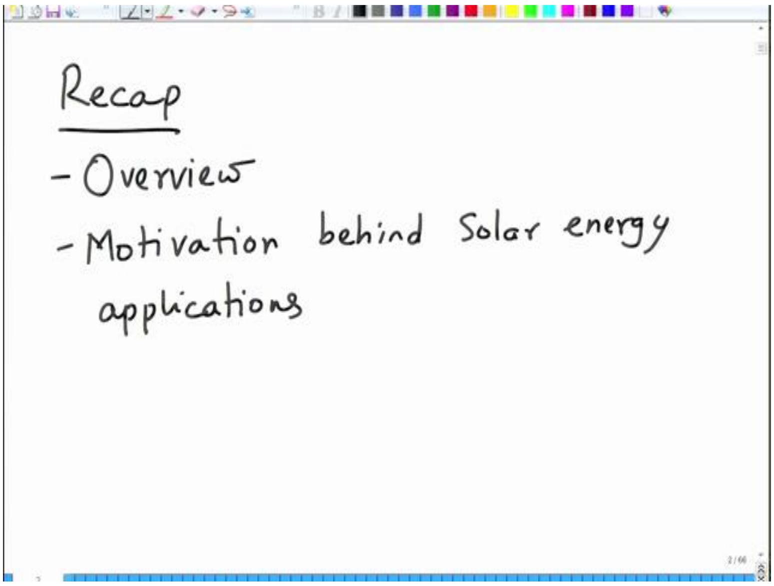
Solar Photovoltaics: Principles, Technologies and Materials

Prof. Ashish Garg
Department of Material Science & Engineering
Indian Institute of Technology, Kanpur

Lecture – 02
Solar Radiation

So, welcome again to the second lecture of the course Solar Photovoltaics – Principles, Technologies and Materials.

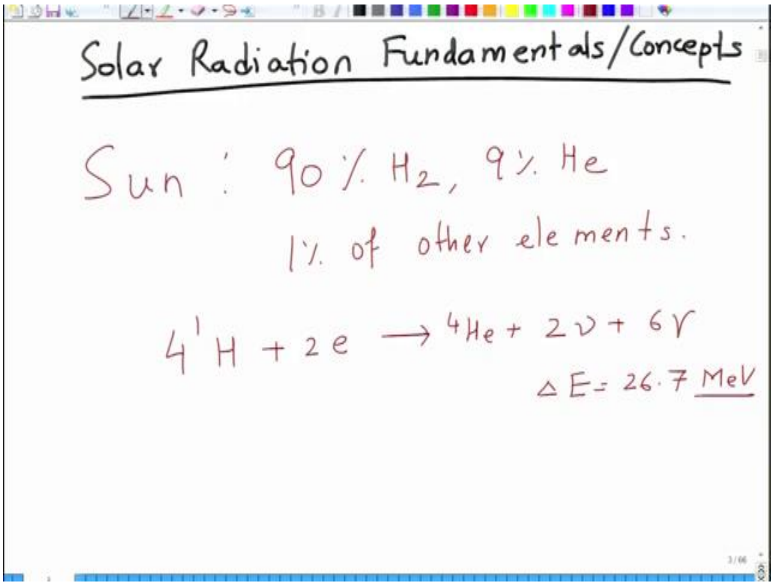
(Refer Slide Time: 00:28)



So, just recapping in the last lecture we did not do anything significant in last lecture, but nevertheless. So, we just had a overview of the course that what we will do over the course of next 40 lectures and we also had a look at motivation for solar energy applications.

And, this is mainly because since we are all running out of fossil fuels in relatively shorter course of time and given that we have a lot of pollution problems because of fossil fuel related energy, there is a strong need to develop nonpolluting solutions and from sources which are sort of in some sense permanent just like solar energy. So, there are many sources of energy, but solar energy out of all the sources is one of the most attractive ones because of near permanent nature and very high amount of energy that is available to the mankind especially in countries like India, which are hot and warm countries where sunlight is abundant throughout the year.

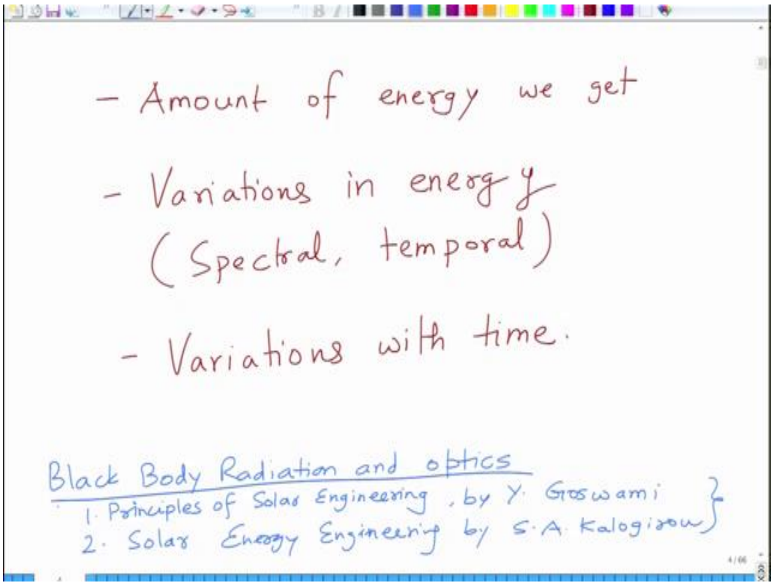
(Refer Slide Time: 01:48)



So, now we will move forward with our discussion. To begin with we will start with solar radiation fundamentals or you can say concepts. So, this will be done primarily in the first week. So, if you look at the sun, it is about 90 percent of hydrogen and 9 percent of helium and about 1 percent of other elements. So, the energy which is produced at Sun is through this reaction 4 $_1$ H plus 2 e giving rise to $_4$helium plus 2 nu plus 6 gamma and this reaction has energy of 26.7 MeV.

We can easily convert this into temperature and this is a huge amount of energy. There is no reactor that has been made in the world which can generate this much amount of energy which is the order of 25 or 26 MeV. However, not all of this energy is available to us.

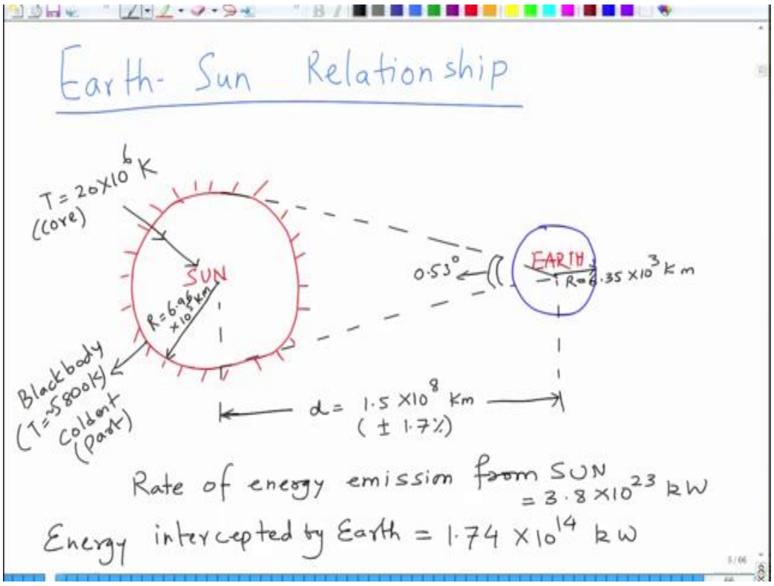
(Refer Slide Time: 03:21)



So, what we are interested in is working out what is the amount of energy we get from available wavelength. This energy is not available all the time. For example, at night even during the day the intensity changes. So, what are the variations and these variations could be spectral as well as temporal. So, they could be time dependent, wavelength dependent. and season dependent as well

So, there are lot of works which have been done. We will not be able to cover all of them, but we will we will try to concise this information in such a manner, so that you get a gist of what are the variation, what are the losses that happened to the solar energy when it reaches the earth and how do the variation take place over the period of time.

(Refer Slide Time: 04:38)



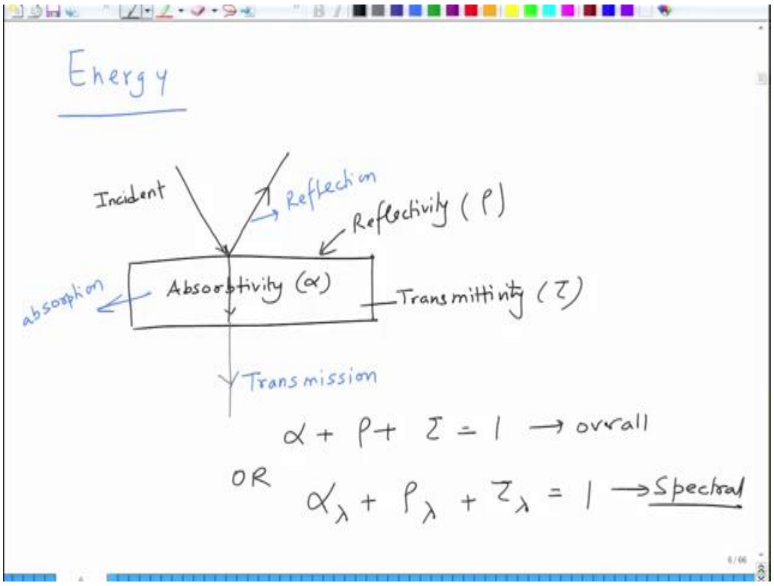
So, if you look at the Sun-Earth relationship or Earth-Sun relation. So, this is somewhere here our Sun is if we see the Sun red, and let us say if we draw the earth in blue. So, this is Sun and this is Earth. So, sun would be something like a bright shining and this would be Earth full of we know water and mountains and earth and land or whatever. And, the Sun temperature is of the order of 20x10$_{6}$ 6 Kelvin and this temperature is at the core we can say and the outer surface is like a black body which is the coldest and the temperature here is about 5800 Kelvin, it is approximately 5800 Kelvin.

The radius of Sun is approximately about 6.96x10$_{5}$ 5 kilometers. On the other hand, Earth has a radius of about 6.35x10$_{3}$ kilometers. So, we can see that there is a difference of nearly two orders of magnitude in the radius of Sun and Earth. So, Earth is a lot smaller than Sun. So, the angle which is subtended by Sun at the center of earth is about nearly half a degree. So, to be precise it is about 0.53 degrees and the center to center distance taken as d is about 1.5x10$_{8}$ 8 kilometer and there is a variation of about 1.7 percent.

So, of course, this figure is not drawn up to that scale. So, it is just a schematic diagram. So, the rate of energy emission from Sun is about 3.8x10$_{23}$ 23 kilowatts, and, due to large size of sun it emits a large amount of energy, but Earth being small and at a large distance from the sun subtends a smaller angle, the energy which is intercepted by Earth is about 1.74x10$_{14}$ kilowatts. This is what we saw last time i.e. 174 peta watts. So, this is the energy which is intercepted by Earth that comes from the Sun.

Now, not only we received the radiation from the Sun, the amount of energy which reaches particular surface depends upon the time during light is available outside and so on and so forth.

(Refer Slide Time: 09:14)



$$\alpha + \tau + \rho = 1$$
$$or\ \alpha_\lambda + \tau_\lambda + \rho_\lambda = 1$$

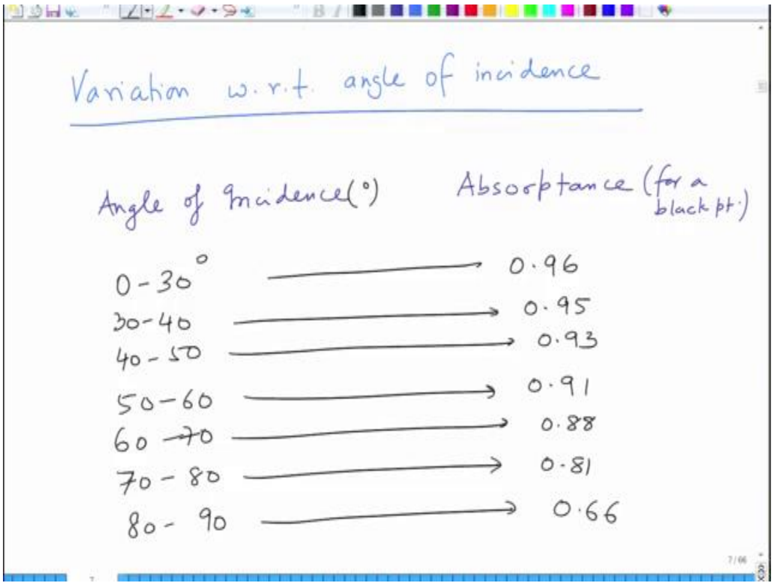
So, if you want to make precise calculations of energy that is passing through a surface. So, let us say we have this surface and this body has absorptivity of alpha. So, we have some incident radiation. This surface will have some absorptivity, reflectivity and certain transmittivity, represented by alpha, rho and tau. So, depending upon all these coefficients some incident radiation may get reflected some may get absorbed inside and the remaining may go out, ok.

So, all of these three components have to conserve, because the energy is conserved, as a result we can say that for a given material alpha plus rho plus tau is equal to 1 or we can also say that for a given wavelength alpha lambda plus rho lambda plus tau lambda is equal to 1; this is spectral and this is what we can say as overall.

So, depending upon the type of material on which the solar radiation is incident some of it is going to be reflected, some of it is going to be absorbed and some of it is going to be transmitted. So, if you have a solar panel, it will have various layers. So, depending upon what kind of surfaces is on top, some may get reflected, some will get absorbed and if it is opaque material it is very likely that none of it is going to be transmitted, most of it is going to be absorbed.

So, the idea behind making a solar cell is to minimize the reflection losses and minimize transmission losses. We would like to make a device in such a manner so that maximum amount of light is absorbed and this is where material design comes into picture. And, so the amount of energy which is optically transmitted is also dependent upon the angle of incidence.

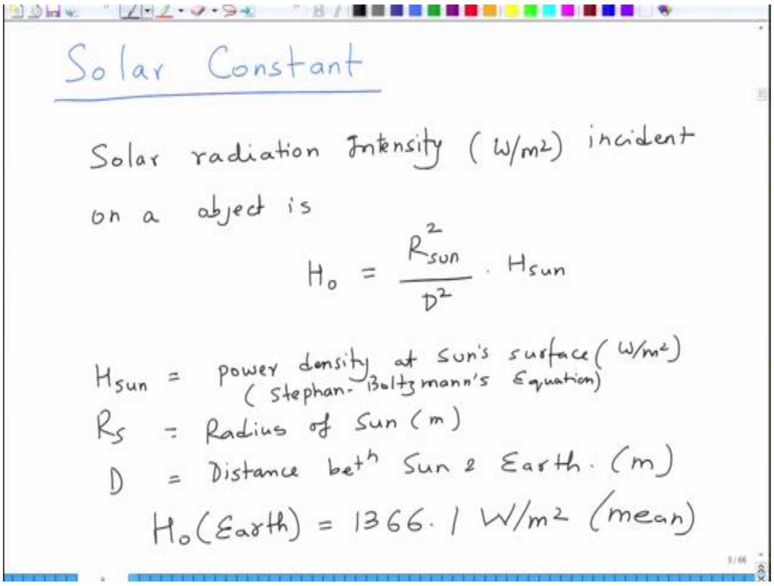
(Refer Slide Time: 12:12)



So, if we look at the variation, for instance angle of incidence and absorptance, let us say for a black point. So, if we write various angles, let us say 0 to 30 degree, 30 to 40 degree, 40 to 50 degree. So, this is in degrees, 50 to 60, 60 to 70, 70 to 80 and 80 to 90. So, if we write the values here this would be about 0.96, this would be approximately 0.95 this would be approximately 0.93, this would be 0.91, this would be 0.88, this would be 0.81 and if we go to normal angle this value falls off about 0.66.

So, we can see that absorptance for a black point changes from nearly 96 percent at angles from 0 to 30 degree to about 0.66 at normal nearly normal radiation. So, we can see that it is not beneficial to have sunlight coming directly into the solar cell. It is a good idea to have solar radiation coming at certain angle perhaps up to about 60 degrees where absorptance is maximum. So, again these are all optical design factors which one has to keep in mind when the radiation is coming.

(Refer Slide Time: 14:15)



Solar Constant, $H_o = R_{sun}^2 . H_{sun} / D^2$

So, the amount of energy which is reaching us is defined by a quantity called as solar constant. So, we are not going to physics of solar radiation like Planck's Law and black body radiation. If we really want to know about black body radiation, we would suggest you to read Solar Thermal Engineering book by Y. Goswami and another book you can consider is by yeah so, you can consider this another book solar Solar Energy Engineering by S. A. Kalogirou.

So, these two books give you good idea about. So, for this book is the first ones name is different, first ones name is Principles of Solar Engineering by Yogi Goswami he is an expert on solar thermal devices and then Solar Energy Engineering by solar test Soteris A. Kalogirou and that is again a good book. These two books give you fair details about blackbody radiation, the optical principles and the knowledge about the relation of transmission with respect to index of refraction and reflection and so on and so forth.

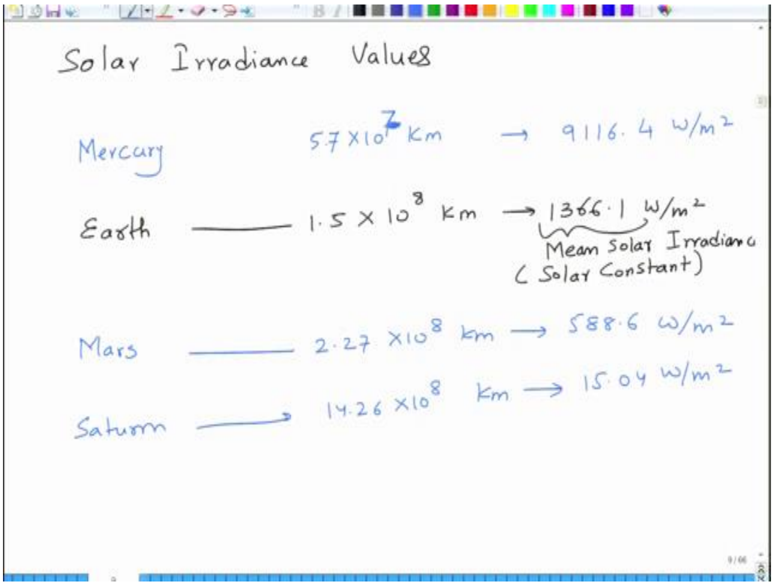
So, these two books would be able to give you a brief account of those things. So, unfortunately, we do not have sufficient time to get into those details, but what we wanted to point out was if we have certain amount of radiation coming on the surface the amount of radiation that is going will have some reflection losses, some absorptance and some transmission. From the perspective of a solar cell it is important to maximize the absorption and minimize the reflection and transmission and this is where material design and solar cell design comes into picture and not only that the angle of incidence also plays a important role in how much energy are going to receive inside the how much energy to absorb within the solar cell.

So, for instance you can see here, that if your angle of incidence is near normal you have nearly 65 percent of absorption for a blackbody considering it is a black body whereas, most of the surfaces of grey in nature as a result this figure is going to be even lower and for a incidence angle of less than let us say 60 degrees you have more than 90 percent absorption, and these figures will change when you change the type of surface that is to convert from black to grey.

So, let us now look at solar constant. Solar radiation intensity in watt /m^2 that is incident on object is given as $H_o = (R^2_{sun} / D) \times H_{sun}$. H_{sun} is power density at Sun's surface in watt/m^2 and this is basically from Stephen Boltzmann equation. Stephen Boltzmann equation for a black body can give power density and this R_{sun}, so, let us just right here from Stephen equation.

This we can find in the books which we mentioned earlier and R_{sun} is basically the radius of Sun in meters and D is the distance between Sun and Earth again in meters. This is what is the solar radiation density that is incident upon a object.

(Refer Slide Time: 19:16)



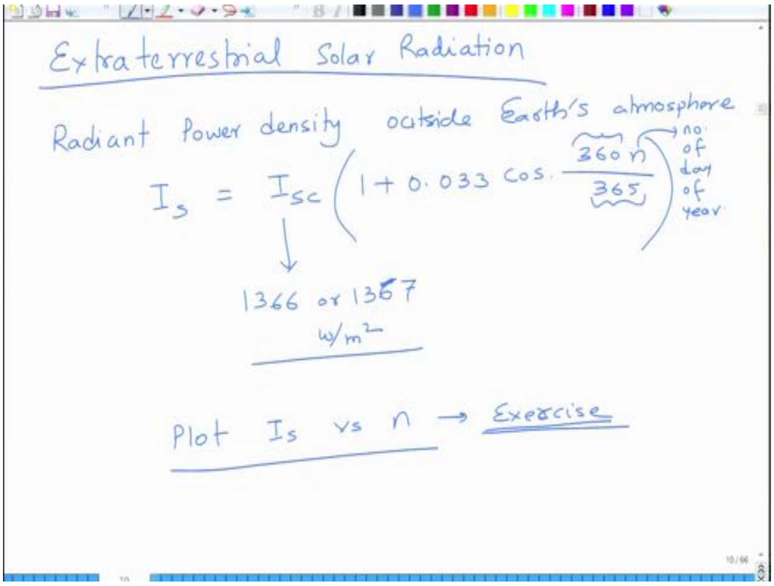
So, if we now look at the values of solar irradiance. So, depending on the distance of earth it is about 1.5×10^8 kilometers and let me see if this was the right figure. So, yeah, it is about 1.5 or 8 kilometers and this gives a value of about 1366.1 watt/m^2. So, this what is the mean solar irradiance and this is also called as solar constant.

So, if we go to previous slide value of H_o on earth is 1366.1 watt/m^2, which is the mean value. There will be some fluctuation in this value if there is some fluctuation in the distance. So, distance have error of about 1.5 percent which means this value will also have that much error, but we take it as about 1366.

Comparing with other planets, for example, if you look at Mercury ok; Mercury is at a distance of 57×10^6 kilometer or 5.7×10^7 kilometer. This has a solar constant of about 9116.4 watt/ m^2. So, nearly 6-7 times increase in the value whereas, if we look for something like Mars; Mars has a distance of about 2.27×10^8 kilometer and this corresponds to value of about 588.6 watt/m^2. And, if we look at something like we do not know Saturn which is very far, Saturn has a distance of 14.26×10^8 kilometer so this has a value of about 15.04 watt/m^2.

So, Mercury being closer to Sun has much higher value of solar irradiance somewhere in between a value of about 1366 watt/m^2 whereas, the values for Mars and as you go farther and farther, they drop significantly in fact, at Pluto it would be even smaller, it is less than a watt/m^2. So, it is not a good idea to have a solar cell on Pluto.

(Refer Slide Time: 22:29)



Radiant Power Density, $I_s = \ I_{sc}(1 + 0.033 \ cos360n/365)$

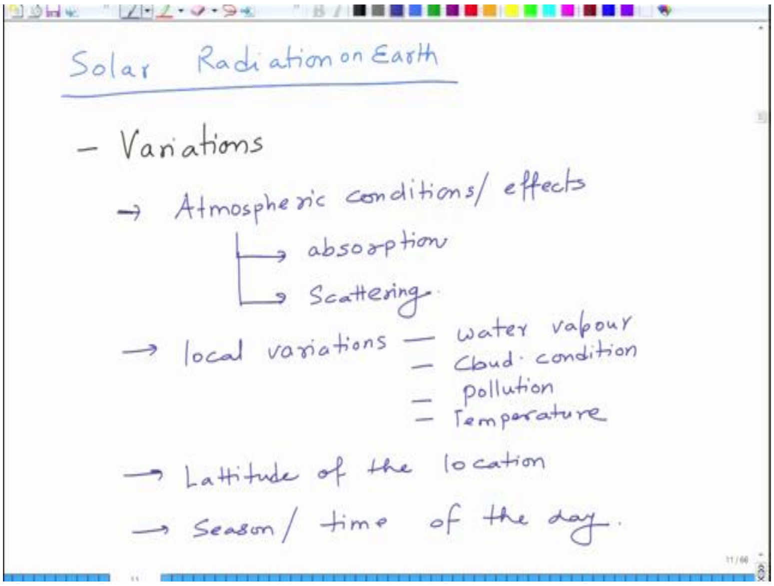
So, there is something now called as extraterrestrial solar radiation. So, we defined various things. So, the radiant so, the previous value was the solar constant which was a mean value of solar radiation that is incident on the Earth's surface.

Now, the radiant power density outside Earth's atmosphere is given as I_S, this is given through I_{sc} which is a solar constant. Now, this is dependent upon the number of the day of the year. So, this has given us 1 plus 0.033 into cos of 360 n divided by 365 year. So, this 365 is the number of days in the year, 360 degree is the angle around the circle and this n is the number of days of year. So, this I_{SC} has a value of 1366 or some people also say 1367 watt/m^2 and n is the day of the year. So, we can see that this value will change. So, this value of power density outside Earth's atmosphere will change depending upon the which day of the year we calculate.

So, this goes as solar constant multiplied by 1 plus 0.033 into cos of 360 into n divided by 365 and this n is the number of days of the year. So, you can see that if your n is equal to 365, so, this will be cos of 360 and cos of 360 is 1, right, cos of 2 pi is equal to 1. So, this will be approximately equal to the solar constant. So, you can calculate on which days it is going to be equal to the solar constant, on which days it is going to be minimum and so on and so forth.

There is going be some variation and it would be nice exercise to plot Is versus n. So, this is an exercise that you can carry out for a better understanding of results.

(Refer Slide Time: 25:24)



So, there are variations while you get a constant value on the outer atmosphere nearly constant value, there are variations with respect to the values which reach on the surface and these variations occur because of things such as atmospheric conditions and or conditions or effects and this is mainly due to the things like absorption and a scattering,

So, absorption could be because of more presence of a variety of molecules which can absorb the radiation and scattering could be because the presence of molecules as well as dust particles and so on and so forth. Then you have local variations which could be because of things like water vapor, how much moisture is present in that atmosphere, it depends upon the cloud condition and it also depends upon the pollution, how much pollution is there in atmosphere.

So, for example, if we look at the difference between clear day and the day when we have a smoke in the air. For example, even in winter suppose it rains today, tomorrow the sky may be very clear and as against to what it is today when it has not rained then a lot of moisture in the atmosphere, a lot of dust particles and lot of scattering of sunlight takes place which can the effect that sunlight from reaching us compared to the intensity that would reach on the clear day.

So, this is because of pollution, cloud condition, water vapor, temperature and so on and so forth and then it would also depend upon the latitude. Latitude of the location and then of course, it is going to be affected by season and time of the day. These things affect the amount of energy that reaches us. So, on one hand we are saying that we have a solar constant of 1366 or 67 watts/m^2 which is essentially the energy that is incident on the Earth, but Earth is not just a surface there is the atmosphere around it and this atmosphere around it affects the amount of energy that reaches us.

So, extraterrestrial radiation is basically solar constant multiplied by 1 point 1 plus 0.033 into cos of 360 n divided by 365. You can see that the value of this cos factor will vary between 0 and 1, right. The factor of 0.033 is not going to affect to large extent. So, value here is not going to change significantly, it is going to remain somewhere in the vicinity of 1366. It has some variation as a function of n, it is not going to hugely different.

However, what makes it really variable are these conditions. The atmospheric conditions such as the absorption, scattering, local variations because of water vapor, cloud condition, climate, pollution, temperature where you are whether you are in England or whether you are in India, whether you are in Sri Lanka or in Malaysia and the season and time of the year. So, we will further delve into these topics in the next lecture.