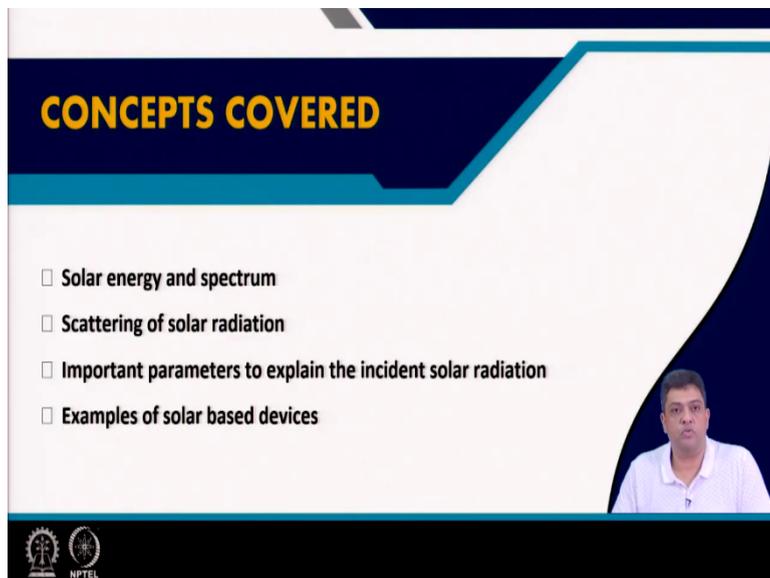


Physics of Renewable Energy Systems
Professor. Amreesh Chandra
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Indian Institute of Technology, Kharagpur
Lecture 3
Solar Radiation

Hello, welcome back to the course on Physics of Renewable Energy Systems. Till now we have seen that what are the various energy sources which are available to us and you have also got an idea about the importance of few of those sources for our country and how do we want to exploit those sources, so that the energy needs of the fast developing country like ours can be catered to.

And now, let us start going into details of each of them and we will follow the protocol that we will pick up one of the topic, then we will try to complete that and then only we will shift to the next topic or the next energy source which can be exploited for our use. So, let us start looking at solar radiation which is basically used for the exploits in solar devices. And then in subsequent lectures we will start focusing more and more on solar based devices.

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CONCEPTS COVERED

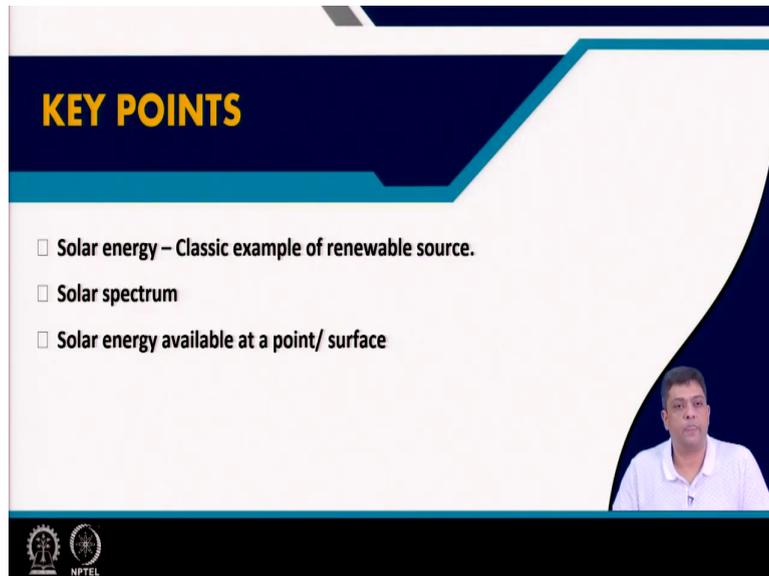
- Solar energy and spectrum
- Scattering of solar radiation
- Important parameters to explain the incident solar radiation
- Examples of solar based devices

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And the topics which I plan to cover in today's lecture are the solar energy, where do we get solar energy from, what is solar spectrum. If there is a radiation which is travelling through, then do we get the complete spectrum, which is hitting a surface is it available to us for exploits or there are other phenomena which restricts the use, the use of the complete spectrum that, so that means, what happens when there is scattering of solar radiation.

We will also cover the important parameters which are used to explain the incident solar radiation. And finally, I will give you the examples of solar based devices, some of which will be covered during this course and which are extremely useful for our country. So, these are the concepts which we will cover in today's lecture.

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KEY POINTS

- Solar energy – Classic example of renewable source.
- Solar spectrum
- Solar energy available at a point/ surface

And hopefully, by the time we finish this lecture, you will be able to defend this claim that solar energy is a classic example of a renewable source. What is a solar spectrum, you will be able to explain to others if somebody asks you. And if solar energy is available on a particular surface, then what percentage of that total energy is actually available to us to for conversion, let us say from solar to mechanical or solar to electrical. So, that are the, those are the key points which you will be able to explain by the time we finish this lecture.

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Our main source of energy - The Sun

- ❖ Classic example of renewable and sustainable source.
- ❖ Formation of oil and coal – RESULT of the photosynthesis in trees and vegetation.
- ❖ Solar energy penetrating into the ground lead to shallow geothermal energy.

The solar energy can be harvested using photo-chemical or photo-physical processes.

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We all know that Sun has always been considered as the main source of energy, it has always been explained to us that Sun is the main source of energy for Earth. And for this course, we will take this as a classic example of renewable and sustainable source.

Renewable, why, it is naturally occurring, and it does not leave its own carbon footprint, and it is a sustainable source. It was available before us, it is available to us and it will remain available for few billions of years to come. So, this is a classic example of a renewable and a sustainable source.

Why is it called the main source of energy, even if you look into other forms, which we have sub classified into the energy sources, like fossil fuels or others, you will find that the origin of theirs or there is at least some contribution from solar energy during the formation of those energy sources.

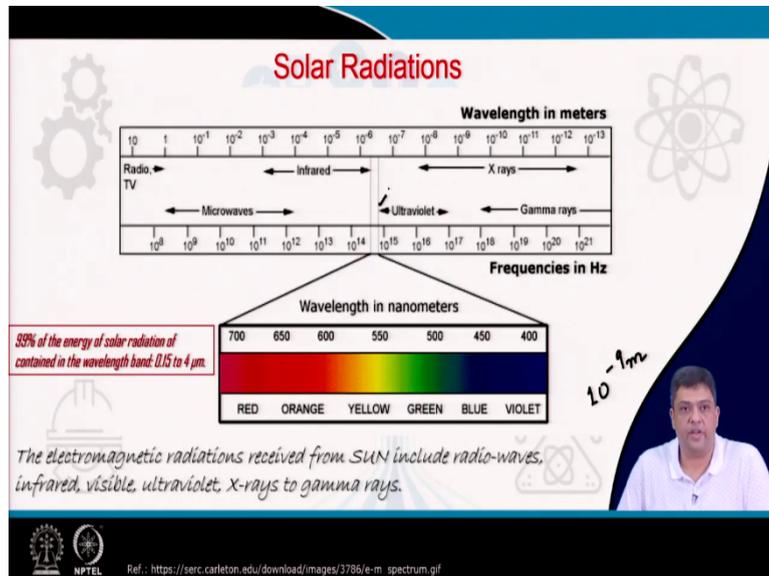
For example, if you take formation of fossil fuel or coal, these are actually a result of photosynthesis in trees and vegetations which lead to the growth of trees becoming bigger, and then they have their own life, and then they die and then they are actually compressed in earth over millions of years and then they get converted into fossil fuels.

Second, if you take solar light falling on Earth, it actually also penetrates the surface of the earth and just below the Earth's surface they heat the earth surface and these, and if you can explore those kinds of heat, which is getting deposited on the, just below the Earth's surface,

then that kind of energy is the formation of shallow geothermal energy. So, Sun and solar energy are at the core of most of the other energy sources.

And therefore, you can always find that the solar energy can be harvested using photo chemical processes or photo physical processes. And that is the main reason we are starting the details of this course, by understanding solar based energy systems.

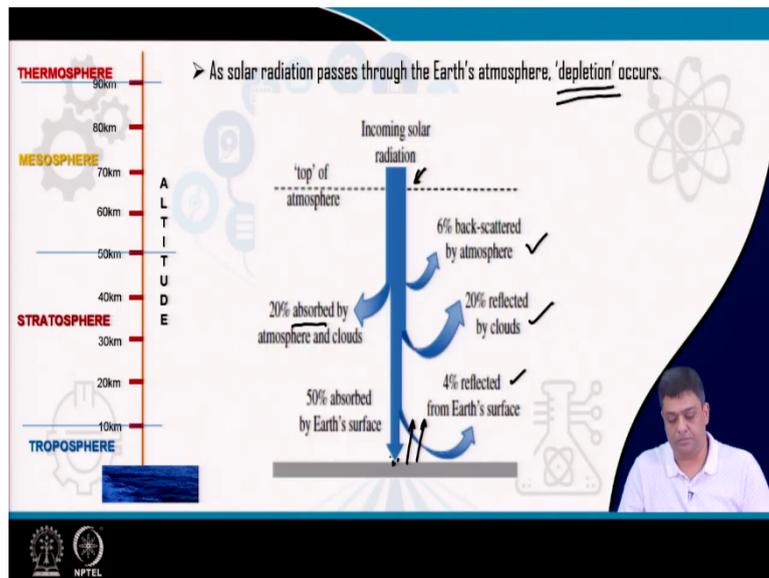
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So, the solar radiations can be explained in terms of wavelength or frequencies of the electromagnetic radiations. The electromagnetic radiations received from Sun include the radio waves, the microwaves, infrared, ultraviolet, X rays, and gamma rays and somewhere in the middle we have the visible spectra. And if you look into the visible spectra, if the wavelengths are written in terms of nanometres, that is 10 raised to the power of minus 9 metres, then you have the spectra somewhere around 700 to 400 nanometres.

So, if somebody asks you what would be the wavelength of ultraviolet, then you will find that the ultraviolet wavelengths are somewhere starting from this point. So, looking at this spectra you can talk in terms of the frequencies of the wave or the wavelength of the waves. And 99 percent of the energy of solar radiations are contained in the band of 0.15 to 4 micrometres. So, 99 percent of the energy which is available in the solar radiation is actually available in this band. And therefore, if you can exploit this band, you can make various devices.

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So, as the solar radiation passes through the Earth's atmosphere what happens. So, let us say there is an X amount of radiation which is falling on the point where it is entering the Earth's atmosphere, what happens in troposphere or at sea level? Do we get the complete radiation reaching the sea level, no there are various phenomena which actually take place and there is significant depletion in the solar radiation and the amount of radiation which reaches the surface is much reduced.

So typically, for an incoming solar radiation 6 percent are backscattered by the atmosphere. So, you have the radiation which is falling and then, they are just getting scattered back to the top of the atmosphere and they are becoming, they are dissipating as heat or they are not reaching the sea level. Now, you can have clouds, you have nano particles dispersed in air, you have gaseous then because of that nearly 20 percent of the radiations are actually absorbed by the atmosphere and clouds, and 20 percent are reflected by clouds.

Now, the amount of radiation which is now remaining is around 54 percent. So, out of this 54 percent the radiation which hits the surface is again reflected from the surface and that is estimated as approximately 4 percent. So, effectively 50 percent of the solar radiation which actually was entering the Earth's atmosphere is available to us at the sea level.

So, you can clearly see you have, let us say you have 100 percent, only 50 percent is available for use. And then you will see that there are other factors, which actually further reduce the amount of solar radiation which is available to you for any exploits.

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The slide contains the following text:

- Depletion in solar radiation occur due to the simultaneously occurring processes viz.,
 - (i) Selective absorption by molecular oxygen, ozone, CO_2 , water vapour.
 - (ii) Rayleigh scattering molecules of different gases.
 - (iii) Mie scattering
- Nearly half of the scattered radiation is lost to space; the remaining move towards the earth's surface from different directions as diffuse radiation.
- Considerable depletion can also occur in a cloudy atmosphere.

The diagram illustrates the sun's radiation reaching the Earth's surface. It shows three paths: (a) Direct radiation passing straight through the atmosphere to the ground. (b) Rayleigh scattering from atmospheric molecules, where shorter wavelength radiation is scattered more effectively. (c) Mie scattering from clouds, which scatters all wavelengths more equally. The diagram also shows some radiation being lost to space.

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So, depletion in the solar radiation can occur due to simultaneously occurring processes. These processes are occurring simultaneously, you can have selective absorption by molecular oxygen, ozone, carbon dioxide, water vapour, these molecules are absorbing, their vibrational frequencies are changing and therefore, they have selective absorption and leading to reduction in the solar radiation which pass through the atmosphere.

You can have Rayleigh scattering, because of the various gaseous molecules which are available in that atmosphere, and you can also have the Mie scattering, which is due to the clouds. And as I explained in the previous slide, nearly half of the scattered radiation is lost to the space. So, I had explained that earlier the 50 percent and now the same thing is written here that nearly half of the scattered radiation is lost to the space. And the remaining move towards the earth surface from different directions as diffuse radiation.

So, you can have radiations which are coming down from after passing through clouds, you can have direct radiation which is coming through or you can have the diffuse radiations which are coming after and countering the Rayleigh scattering phenomenon. Therefore, considerable depletion can all occur in Earth's atmosphere. And if you have let us, say the whole area is full with clouds, then what do you expect?

Do you expect that no change will occur or do you expect that further depletion will take place, I guess the answer is clear that if it is extremely cloudy, then further depletion will take place and the radiation which is now reaching the Earth's surface would be further reduced.

So, it is clear to us that there are various phenomena because of which the radiation that is reaching the Earth's surface can undergo depletion.

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FEW RELATED BUT USEFUL INFORMATION

- 1) The fraction of the total solar radiant energy reflected back to space, due to the reasons discussed previously, is called albedo of the earth-atmosphere system and has a value of ~ 0.30 for the earth as a whole.
- 2) Depending upon latitude, altitude and season, the mean monthly value of direct solar radiation, normal to the solar beam, which is received in India at 12 noon varies from 0.51 to 1.05 kW/m^2 .
- 3) The solar radiation intensity falling on a surface is called irradiance or insolation and is measured in W/m^2 or kW/m^2 .
- 4) The total amount of solar radiation energy is called irradiation (J/m^2). It is denoted by H .
- 5) At the surface of the Sun, intensity of solar radiation is $\sim 6.33 \times 10^7 \text{ W/m}^2$.

Ref. Book - Adv. Ren. Ener. Sys. (Part I) by S C Bhatia, WPI Press (2014)

So, there are a few information which must be clear to you before we proceed further, these are certain terms those are used to explain the solar radiation which is reaching the earth. The first one is albedo, and this explains the total solar radiant energy which is reflected back to space. For example, if this value is 0.30, that means 30 percent of the radiation which was falling on Earth, let us say is actually being reflected back to space.

So, this the value of albedo gives us the magnitude of radiation which is reflected back to space. It is clear that depending upon the latitude, the altitude and the season the direct solar radiation that is the radiation normal to the solar beam, which will be received at a place will also change. And for India, let us say at 12 noon, it varies from 0.51 to 1.05 kilowatt per metre square.

The third term which is there to explain the solar radiation intensity is called irradiance or insolation, and it is measured in watt per metre square or kilo watt per metre square. So, irradiance is the total solar radiation intensity falling on a surface. Please do not get confused by the next term which I am going to explain that is irradiation, there is a difference between irradiation and irradiance.

Irradiance is actually explaining the power whereas, the total amount of solar radiation energy is called irradiation, and it is given in terms of joules per metre square. And the

symbol which is used to denote irradiation is H . And if you look in to the surface of the Sun, the intensity of solar radiation is approximately 6.33×10^7 watt per metre square. The value is so high because of the energy which is being generated during nuclear reactions.

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Let us consider an imaginary surface, which is perpendicular to the sun rays reaching the earth. The **solar constant (I_{sc})** defines the average radiation that falls on such a surface. The value is 1367 W/m^2 .

Normal from Sun's to earth's centre

Sun

Parallel sun's rays

Plane perpendicular to sun's rays

$I_0 (\text{W/m}^2)$

Question: Is the **solar constant (I_{sc})** really a constant?

Ref. Book - Adv. Ren. Ener. Sys. (Part I) by S C Bhatia, WPI Press (2014)

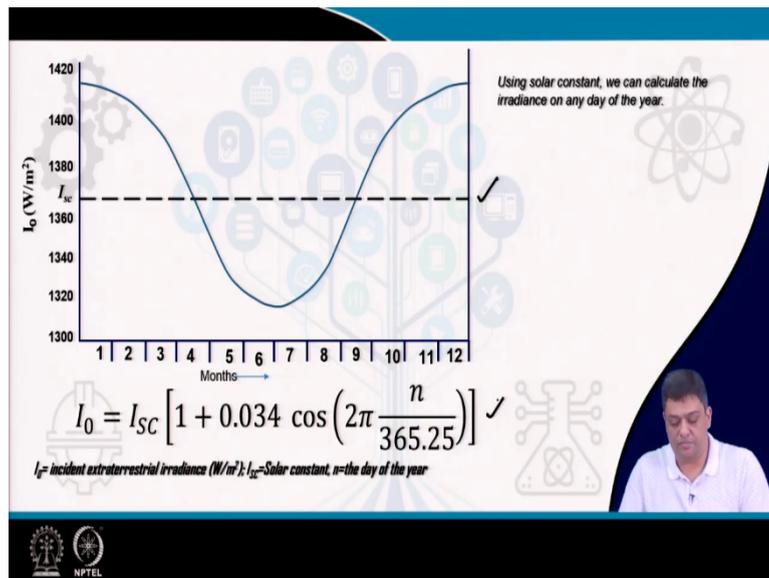
Let us try to understand the average radiation that falls on a particular surface that is perpendicular to the parallel rays reaching from Sun. So, from Sun, you have a surface which is drawn here and what is the value of average radiation that falls on such a surface, this value is called as solar constant and is denoted by I_{sc} . Why do we call this as an average radiation because there can be changes from one day to the other, one month to the other or 1 season to the other.

So, if you consider let us say from January to July, you will see that there is a variation of approximately 7 to 9 percent along with that, because of the Sunspots, thus there is also a variation in the source of approximately 0.25 percent and therefore, this value of solar constant can change and the value which is used is an average value and you will find that solar constant has a value of approximately 1367 watt per metre square.

So, let me ask you a very simple question. I am using this word solar constant. And if it is a constant, then why are we talking about the term average radiation? It should have one value. Actually, solar constant is not a constant, it is like a misnomer, but you take an average value and that value remains the same and, that is why it is termed as constant.

And I have just explained to you there are reasons because of which the value of the radiation which falls on a particular surface can change from one given day to the other or the other reasons which I give.

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So, let us plot the variation in the incident irradiance as a function of months. So, on the x axis, I have months on the y axis I have the incident extra-terrestrial irradiance. You can clearly see that it is not a constant. From one month to the other there is variation. And if you take an average of all the values throughout the month, you will find that, that value is approximately 1367 watt per metre square and that is the value which is given to a solar constant. And using this solar constant, we can calculate the irradiance on any day of the year.

And you can easily find out that the intensity I_0 will be equal to the solar constant into 1 plus 0.034 cosine of 2 pi n by 365.25, where n is the day of the year, I_{SC} is the solar constant and you can now using this formula find out the irradiance on any day of the year at a particular point.

Now, my question to you would be please have a thought, if the nature of this curve which is given to you remain same at each latitude, at each altitude. So, if you have a city, let us say very near to sea level or a city which is up in the hills, will the nature of this curve be exactly same or vary? And we will discuss this answer during our live discussion course, sessions.

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Can we make some estimate of the solar energy available at a surface?

What is the area of the disc? πR^2

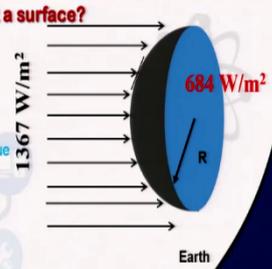
What is the average irradiance on unit area facing the Sun?
 $I_{SC} \times \pi R^2$

This value is then divided by half the surface area of the earth, which gives the value 684 W/m^2 .

What is the value of albedo, that we discussed earlier?
0.30

What would be the H i.e. irradiation/ unit area; lets say for a 12 h day?
 $H = 0.7 \times 684 \times 12 = 5.75 \text{ kWh/day}$

❖ Now, suppose the Sun has appreciable strength for 6 h, what will be the value of H?
✓ Can you now clearly understand why there is variations in the yearly profile of mean solar radiation at different locations?
✓ The solar cells are calibrated that there is 1000 W/m^2 available.



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So, by understanding the amount of solar radiation which falls on a chosen surface, can we actually now make an estimate of the solar energy that would be available on that surface, on that particular surface which we had chosen as an arbitrary surface which was perpendicular to the parallel rays coming in from Sun. Let us ask some questions. What is the area of the disk?

If the disk is very small and or if the disk is very large obviously, the radiation which will be falling on a smaller disk will be much less than a larger size disk, but what is the exact area of the disk we must calculate that. Now, what is the average irradiance on a unit area facing the Earth. Now, we know if you consider Earth, you have if half of Earth is facing Sun, then the other half is having night, that is it is away from the Sun.

So, what is the average irradiance on unit area that is facing Sun? what is the value of albedo that we discussed earlier? So, now we have radiation is available, but you also have back scattering because of which radiation is scattering back to space. So, what is that value, what would be the edge that is irradiation per unit area, let us say for a 12-hour day. We are considering that you have Sun rising at 6 o'clock in the morning and then setting at 6 o'clock in the evening and you have a 12 hour day.

So, we can consider that, what would be the total solar energy that would be available on this kind of a surface. And you will see the answers is, what is the area of this disk, πr^2 , r is the

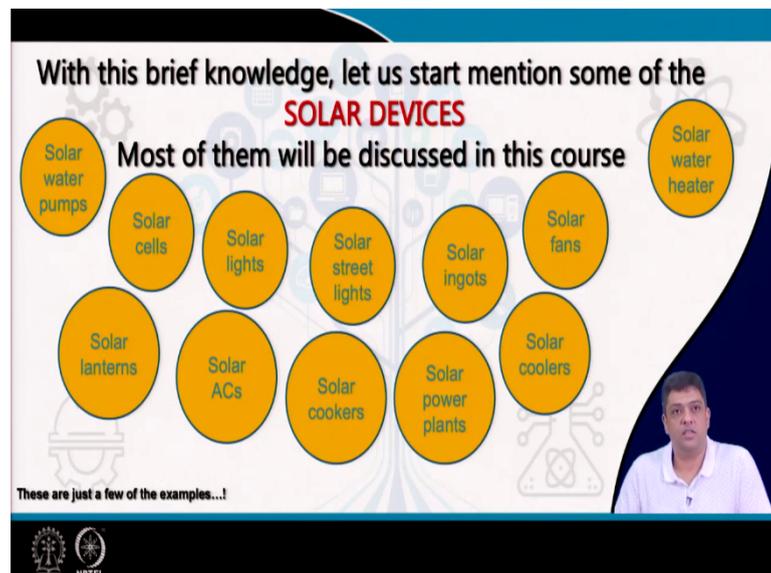
radius. What is the average irradiance on unit area facing the Sun, so that is the solar constant multiplied by πr^2 .

Now, this value is then divided by half the surface area of Earth. Why, $4 \pi r^2$ by 2? So, this value is $4 \pi r^2$ by 2 because you have radiation only available to one half. After this division, the value which you get is 684 watt per metre square. Now, we had explained earlier that, for Earth as a whole the value of albedo is 0.30. Therefore, what would be the irradiation per unit area, let us say for a 12 hour day, that would be approximately 5.75 kilo watt hour per day.

So, that is the amount of irradiation per unit area in a 12 hour day. So, let us consider a case when Sun has an appreciable strength for only 6 hours, then what will be the value of H, the value of H for that particular day will obviously be much smaller and you can calculate and check. This means that the yearly profile of mean solar radiation would be different even for a particular place.

And this will also change as we move from one location to the other an information which is useful to you at this point and will also be explained later, the solar cells that are available in the market are mostly calibrated by believing that the value of H, is 1 kilowatt per metre square that is the calibration value which is used for solar cells.

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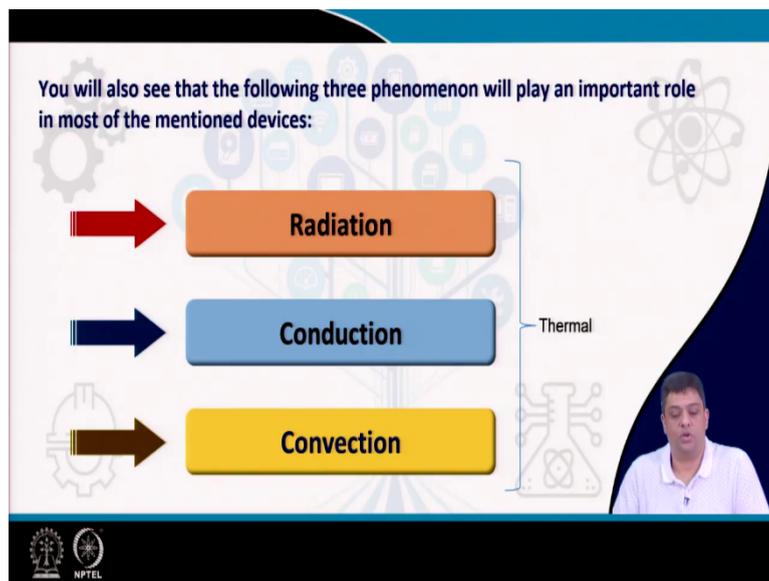


So, with this brief knowledge about the solar radiation, how it falls on a surface and the concept of irradiance and irradiation, you can understand that a lot of information is required before we start making solar devices. But there are n number of solar based devices which are

available in the market. Some of them are listed here. And these are just few of the examples and many more are being discovered or reported in literature at regular intervals.

These include solar based water pumps, solar cells, lights, solar street lights, solar ingots, solar fans, water heaters, coolers, power plants, air conditioners, cookers, lanterns and these are just few of them which I have listed, because they will be explained in the due course of discussion in this course. But the examples can be many more, these are just some of them.

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And throughout this discussion on solar based devices, you will find that there are concepts which have been taught to you in schools or in earlier classes, which will also play important role. And these are thermal radiation, thermal conduction and thermal convection. And I would suggest that you revise these 3 topics, because they will, the concepts would become very useful as we go along in this course.

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Summary of lecture

1. Introduction to solar radiation was given.
2. Few of the relevant parameters, associated with solar radiation were introduced.
3. It must be clear that the solar radiation falling on the surface is not constant and can vary owing to various factors, which were also introduced.
4. Some of the devices based on solar energy, that would be discussed in the course, were finally mentioned.

The slide features a background with a stylized tree of technology icons and a presenter's video feed in the bottom right corner. The NPTEL logo is visible in the bottom left corner.

So, let us summarise today's lecture. We have given you the introduction to solar radiation and the relevant parameters, those are associated with solar radiation. The concept must also be clear, where we have explained that solar radiation falling on a surface is not constant and it can vary owing to various factors. We have also given you some example, on solar based devices, some of which will be discussed in due course of time.

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In the next lecture, we will start our discussions on 'Solar Photovoltaic Systems'

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And in the next lecture, we will start our discussions on solar photovoltaic systems.

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The slide features a central graphic of a tree where the branches are composed of various icons representing technology and energy, such as a gear, a lightbulb, a Wi-Fi symbol, a smartphone, a document, a bar chart, a leaf, a battery, a plug, a magnifying glass, and a circuit board. The word "REFERENCES" is written in bold orange letters at the top left. Below it, two references are listed in a bulleted format. In the bottom right corner, there is a small video inset showing a man in a white shirt speaking. The slide also includes several faint icons: a hard hat and gear on the left, an atom symbol on the top right, and a circuit board on the bottom right. At the bottom left, there are logos for IIT Bombay and NPTEL.

REFERENCES

- "Physics of Energy Sources" by George C. King
- "Advance Renewable Energy Systems" by S. C. Bhatia.

And for today's lecture, these are the reference books which were us. With that, I thank you very much for attending this lecture.