Solar Photovoltaics: Principles, Technologies and Materials
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Lecture – 01
Introduction to Solar Energy

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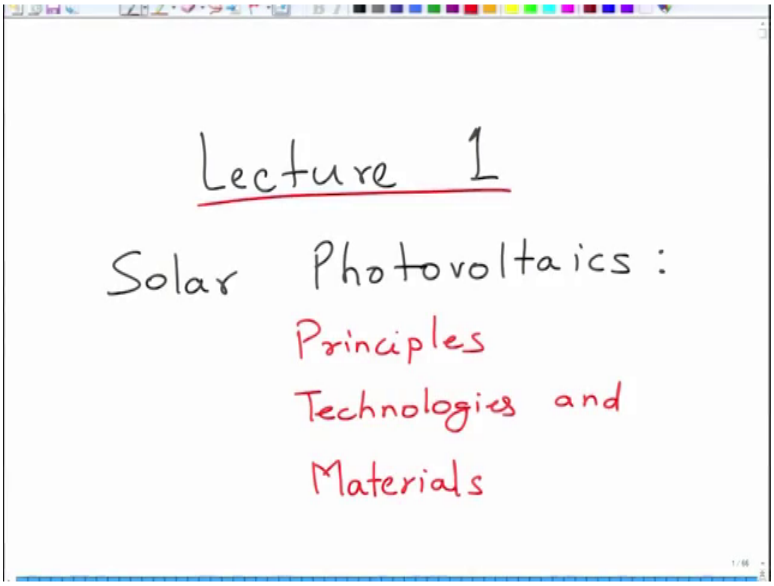

Ok, so welcome to you all in this new course on Solar Photovoltaics in which we will be talking about principles of solar photovoltaics, technologies that are currently in use as well as those which have been researched over past few decades, and the materials which are used in these technologies. In terms of type of materials, the issues, and various other material aspects.

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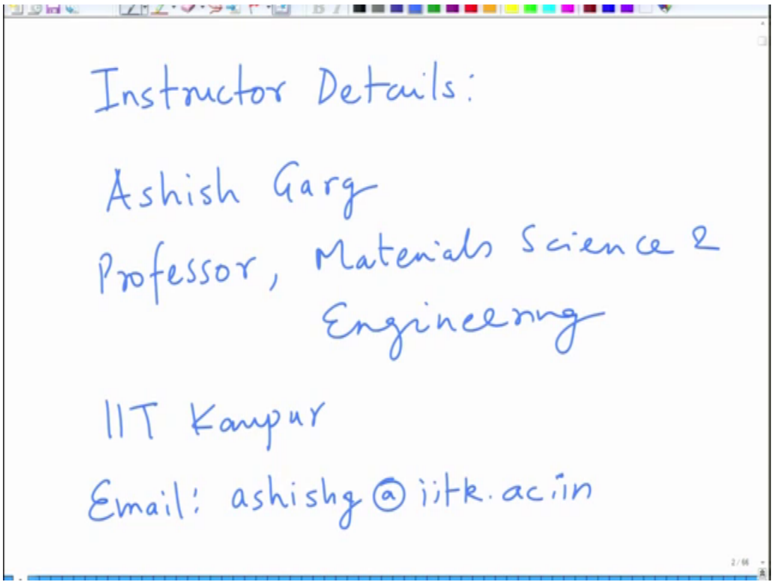

So, this is the first lecture in which we are going to start talking about this course. So, this course; so my name is let me just provide you my details. So, my name is Ashish Garg. I am a professor at Material Science and Engineering Department, and at IIT Kanpur ok. My email id is iitk dot ac dot in.

You will be able to access the course details online as well. There will be two (Refer Time: 01:45) of mine Mr. Sudhir (Refer Time: 01:47) and mister Ajay Singh, who will help you with the questions that you may have. And if you have any if they cannot solve your problems, and I will try and solve your problems. And you will have weekly assignments on various topics, after which you will have exams.

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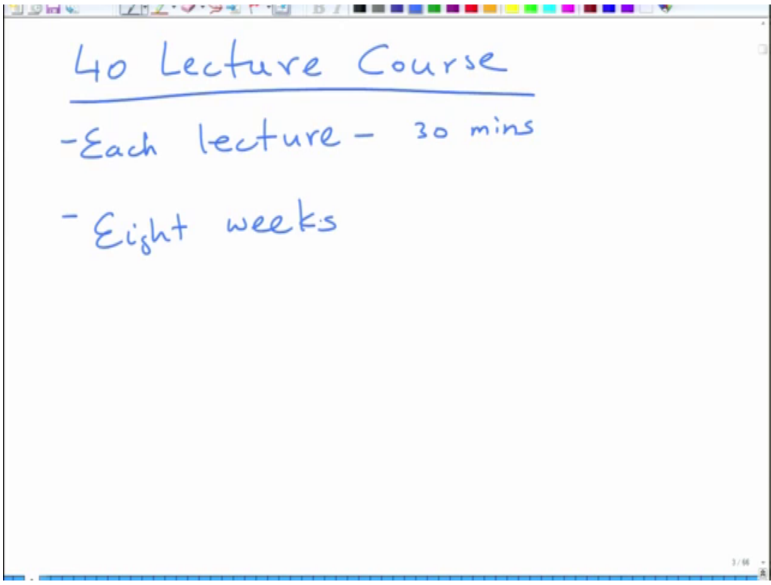

So, this course is basically it is divided in, it is a 40-lecture course. So, each lecture is a 30-minute lecture, approximately 30 minutes lecture. And so basically you will have 8-weeks. And over these 8-weeks, we will cover various aspects of solar photovoltaics.

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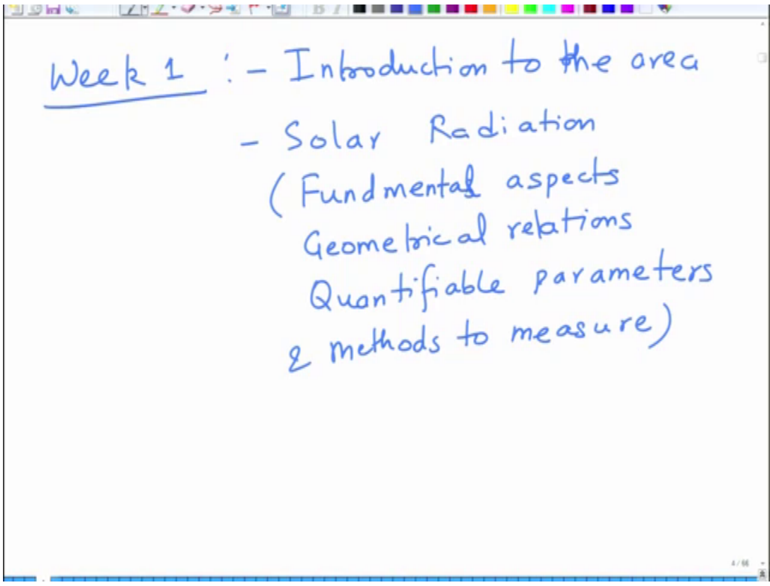

We will discuss about basically introduction to solar cells, introduction to the area. And then we will talk about solar radiation, you see the moment we talk of solar technologies. We first need to learn about what are solar radiation, what does it consists of how do you define various matrices to quantify solar radiation, and then how do you measure it. So, we will look at basically fundamental aspects of solar radiation. Then we will look at geometrical relationships with the earth, and then quantifiable parameters, and methods to measure. So, this we will cover in the first week hopefully.

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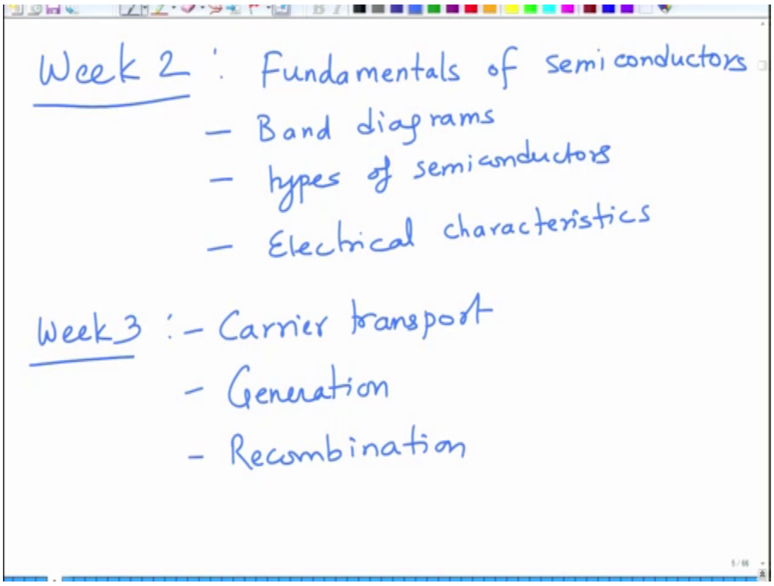

And then in the week-2, we plan to undertake essentially, see most of the solar cell technology especially solar photovoltaics, they are built around semiconductors. So, it is essential to know the basics of semiconductors, so we will learn about fundamentals of semiconductors. So, essentially we will look at semiconductor band diagram, types of semiconductors, electrical characteristics of semiconductor materials and so on and so forth.

And then once we have an understanding of semiconductors, then we will talk about basically three aspects. Since, you have semiconductors with carriers in electrons and holes, we will talk about carrier transport, we will talk about generation. Generation means, what happens when you shine light on a semiconductor, what how do charge carriers get generated. And then we will talk about recombination, because the moment you generate charge carriers there is also a tendency for of them to recombine. So, these three aspects are crucial to understand, various physical processes in semi controlled in solar cell devices.

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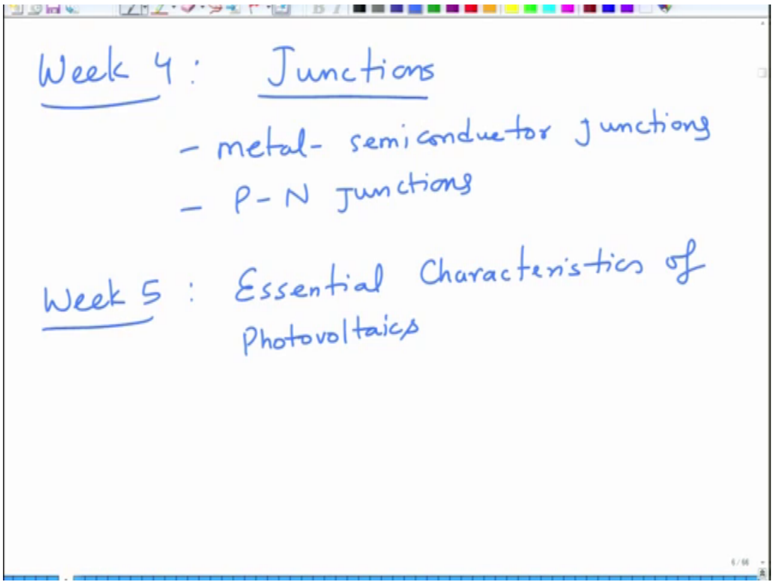

And then in week-4, we will undertake various junctions, because a typical semiconductor solar cell device is a P-N junction. I will and these semiconductors are also attached to metals on both sides to make electrical contacts. So, as a result we will talk about metal-semiconductor junction, and then P-N junction.

And then in week-4, week-5 sorry we will do we will understand the essential characteristics of photovoltaic devices. Essential characteristics was photovoltaics in terms of electrical parameters, what kind of circuits can be depict solar cell in the form of what kind of resistances are there, what kind of quantifiable parameters are there to define the solar photovoltaics ok.

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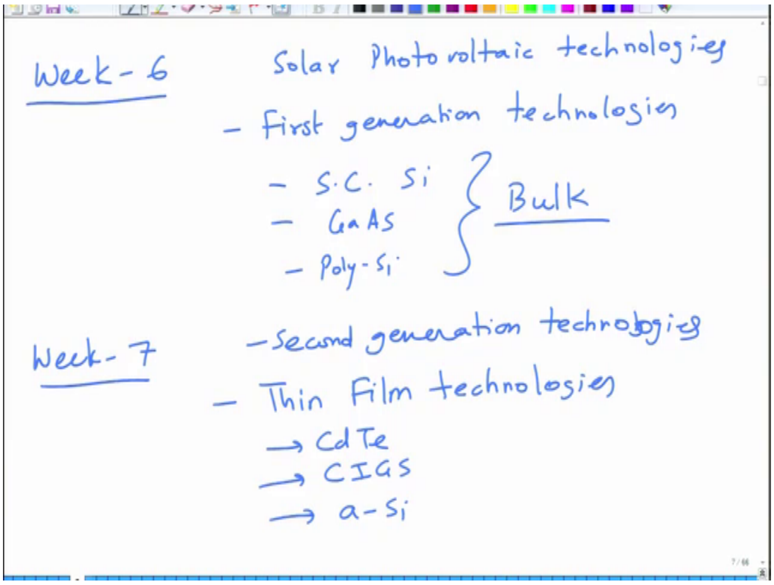

And then week-7, we will week 6 sorry week-6, we will define with we will start with the solar photovoltaic technologies. And in this the first week we will discuss first generation solar technologies. The solar cell technology solar photovoltaic technologies, these are divided in three categories broadly. First one is solar first generation technology, which is primarily based on single crystal silicon, poly-silicon as well as gallium arsenide. So, first generation technologies.

So, basically single crystal silicon, gallium arsenide poly-silicon ok. And we will talk about technologies in general, we will talk about what the current numbers are what current issues are what kind of materials are used, how materials are fabricated, those issues we will talk about in this week.

Then similar issues we will talk about in the week-7 about second generation technologies. And in second generation technologies are basically around thin film technologies. So, these are essentially bulk technologies ok. Bulk means were a thick wafer is used to make a silicon a solar cell.

In the second generation technologies the amount of material was reduced by depositing material in a thin film form. So, essentially these are thin film technologies as we call them. And these are primarily based on cadmium telluride, CI GS or Copper Indium Gallium Selenide, and amorphous-silicon. So, these were the three major technologies, which evolved as second generation solar cell technologies.

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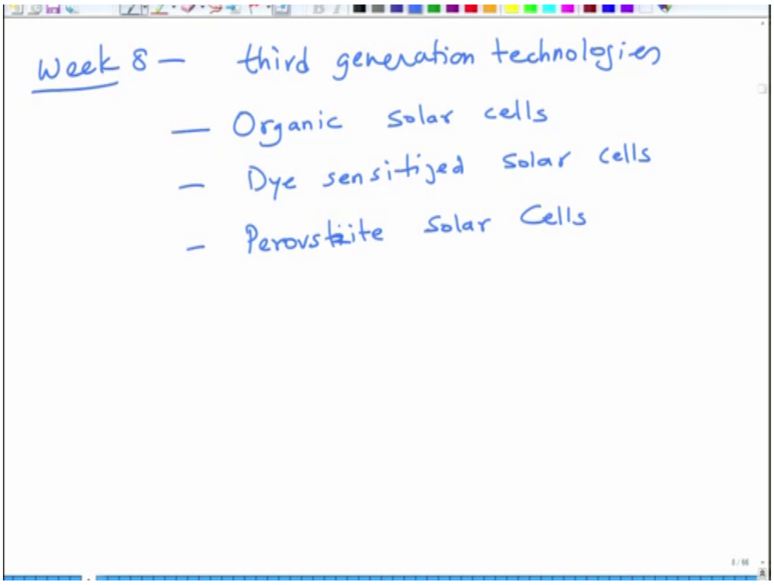

And then in week-8. In the final leg of the course, we will talk about third generation technologies, where we will mainly talk about organic, solar cells, which are flexible lightweight based on polymers. Then we will talk about dye sensitized solar cells, these are also thin film technologies. But, they are solution based technologies printable can be made using mass production techniques using liquid-materials, liquid-precursors, and so on and so forth.

So, they have lot of advantages in terms of perovskite solar cells. So, these organic dye sensitize and perovskite solar cells are the ones, which are basically primarily solution based technologies. And they hold promise for future solar cells, which can be made cheaply using techniques such as printing or solution processing.

Now, so these the work on these started somewhere around late 90's, perovskite work started around 2000 well I would say about 2010 or so. And these are right now technologies of tremendous interest, because they hold a lot of promise for future low cost solar cell technologies. And then so in week 6, 7, 8, we will primarily discuss about the technologies, the materials which are used, the material issues that we have, and outlook where are these technologies going forward to. So, this will be the focus for last 3 weeks, where we will mainly talk about the technologies. So, this is essentially the outline of the course.

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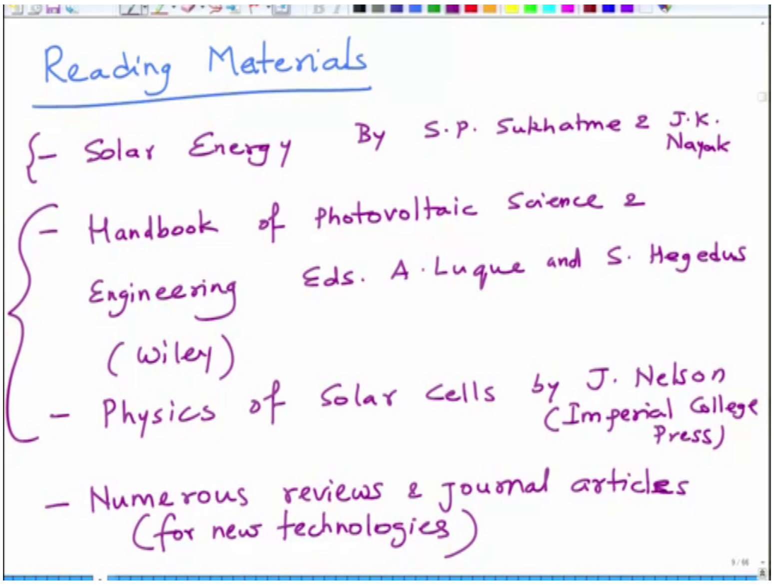

Let me now tell you about certain reading material, in reading material your first book that you would like to be reading about solar fundamentals as Solar Energy by S P Sukhatme, and JK Nayak. This is the book which is which is although its own solar thermal primarily, it has first couple of chapters dedicated to fundamentals of solar radiation. So, if you want to learn about solar radiation, go to this book.

Then second book is about the solar photovoltaics and semiconductors. So, I would say you can go through Handbook of Photovoltaic Science and Engineering, which is a very good book edited by A Luque and S Hegedus, and this is a book of Wiley publishers. This is a fantastic book to learn about fundamentals of photovoltaic science and technologies, and also on basics related to semiconductors and in general photovoltaics.

And another book that I will recommend is Physics of Solar Cells by Jenny Nelson, this is basically Imperial College Press. Again a very good book from the perspective of fundamentals as well as technology. So, these two books are primarily course based, these are the primary these are two books, which you have to consider towards this course. And this first book is for the week-1 part of the course.

In addition to these three books, you can read numerous there are a lot of reviews, and journal articles which can be referred to especially for new technologies. You see these two books cover technologies, which are first generation and second generation. Third generation technologies, however are not covered very well in the text books.

So, as a result to know about the third generation technologies you have to go to resources such as these review papers and general articles. Especially, for perovskite solar cells there are a lot of good reviews nowadays for organic solar cells, and for dye sensitized solar cells. So, this is basically for primarily for new technologies ok. And these two will cover aspects fundamental aspects of solar cells, semiconductors as well as first two generation technologies.

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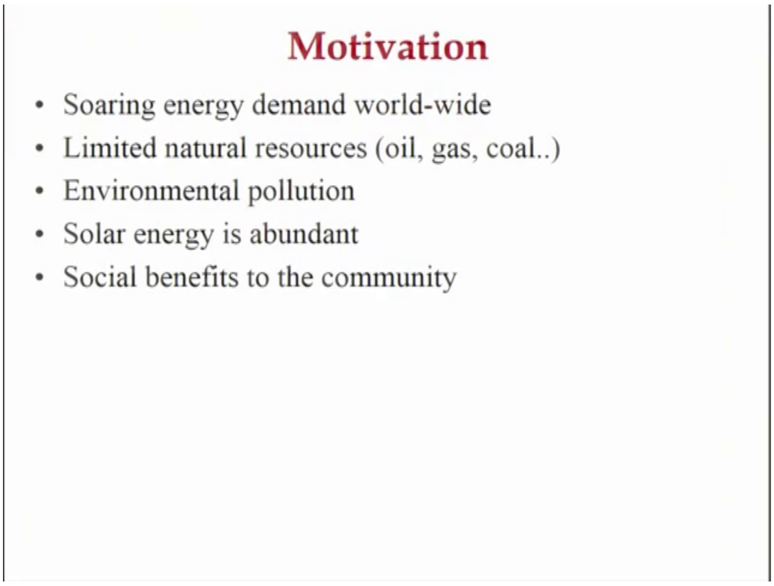

So, what is the so let me first begin with what is the motivation for this course. So, if I go back to if I go to the slides for this course, so the motivation for solar energy or solar photovoltaics is its from various factors. First factor is that energy demand world-wide is very rapidly increasing with the increase in population, with the increase in change in the lifestyle. For example, lifestyle of people in India has changed dramatically over past 20 30 years. And then with the advent of lot of gadgets with the advent of life around electricity, we require and for the work for the progress of country in terms of science and technologies one requires to produce electricity non-stop.

So, as a result the energy requirement of this country, and not only our country, but also world-wide has increased tremendously. And this has put lot of pressure on the resources that are available to us as humankind. So, the traditional source resources for making electricity is in the form of oil, gas, or coal. However, we all know that the resources of oil, gas, and coal are limited. They are not abundant, they are not everlasting, and we need to develop technologies which can create electricity for us without changing the ecology without deteriorating the environment.

Moreover, the as when I talk about the environment oil, gas, coal or any other source which is based on fossil fuels is essentially a conversion of raw material, which is present in the atmosphere in the earth to electricity, and this process is quite energy intensive. And this also leads to creation of pollutants. Pollutants like carbon monoxide, carbon dioxide, sulfur oxide, methane, nitrous, nitrogen based gases and so on and so forth, and lot of dust. So, pm 2.5, pm 110 kind of particulate matter is generated.

All these byproducts of an energy generation using fossil fuels are heavily polluting. And this can be seen nowadays especially in our country, we are in winter in Northern India you have substantial amount of haze in the atmosphere which is not good for us. As a result we need to consider technologies which can tackle this problem of looming problem of environmental pollution. And this is in fact, one of the main drivers behind development of new technologies which are environment friendly.

And this is where solar energy is very important because solar energy as we all know is abundant you know of course everything has a life even sun has a life, but that lifetime is far beyond our expectations or our imagination. So, in a practical way the solar energy which comes from sun is abundant. So, and this is where scientists have been working for the past few decades could develop technologies which can harness this solar energy to convert into useful energy even in the form of heat or in the form of electricity to fulfill our energy requirements.

And of course, if you are able to do that it also brings a lot of social benefits to the community because you know solar technologies can not only be grid connected they can also be standalone. So, somebody who is living on a mountain somewhere does not need to connect his house his or her house to grid, he or she can directly produce electricity from the sun by installing a little solar panel on top of his house. So, there are a lot of immense social benefits too especially to communities which are not in mainstream which are sort of disconnected, but in general the overall community also there is lot of social benefit in terms of energy availability.

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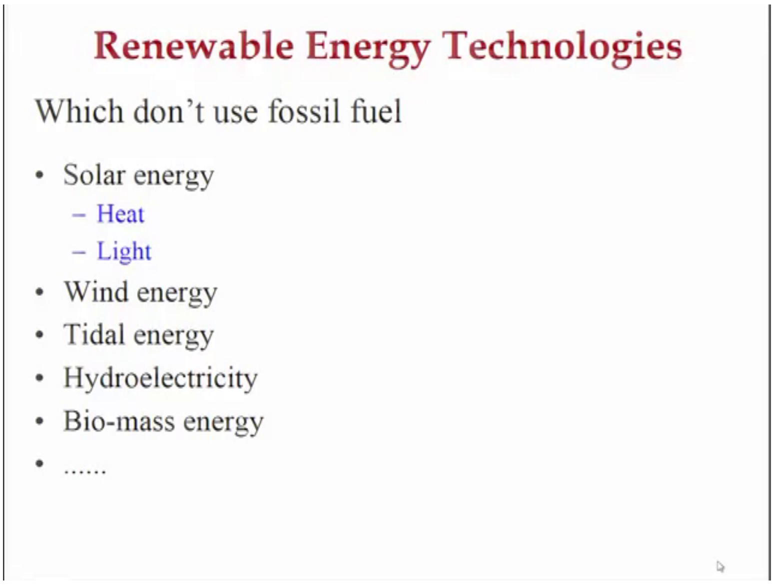

So, what are the renewable energy technologies in this case, which basically do not use. So, the idea is that we need to develop technologies which are not fossil fuel based, so that the pollution or the environmental problem during the energy generation stage can be minimized. But also we minimize the use of fossil fuel itself because generate because you know mining of coal and exploitation of natural gas itself has many ramifications in that in the form of environmental damage.

So, whatever technologies that we rely upon that these technologies are called in renewable energy technologies, which means the source of them is renewable it just keeps renewing name itself. So, first is the solar energy. Solar energy has two major components, solar energy can be converted into heat and light. So, the solar energy has heat and it has light. The heat part of solar energy could be useful for generating heat in the form of hot water in the form of water filtration and so on and so forth. And the other part of solar energy is light which can be used to basically generate electricity. So, these two components of solar energy heat and light can together be used to generate electricity as we will see in this course.

And then the other forms as well wind energy, tidal energy. Wind energy is wherever you have a decent wind velocity, especially around the coastal area of the country or various other countries in Europe which have high wind velocity. They can generate they can convert this wind energy into useful electrical energy using wind turbines. One can, one can also think of converting tidal energy or offshore shore energy into the energy which is available into tides of the sea to convert it into electricity. Then there is hydroelectricity, there is biomass energy, and there are a lot of other methods of energy conversion which people are thinking. Along all of these solar energy stands out because simply because sun is a you know abundant source and it is available everywhere, especially for a country like India which has very high solar irradiance, it is really wonderful.

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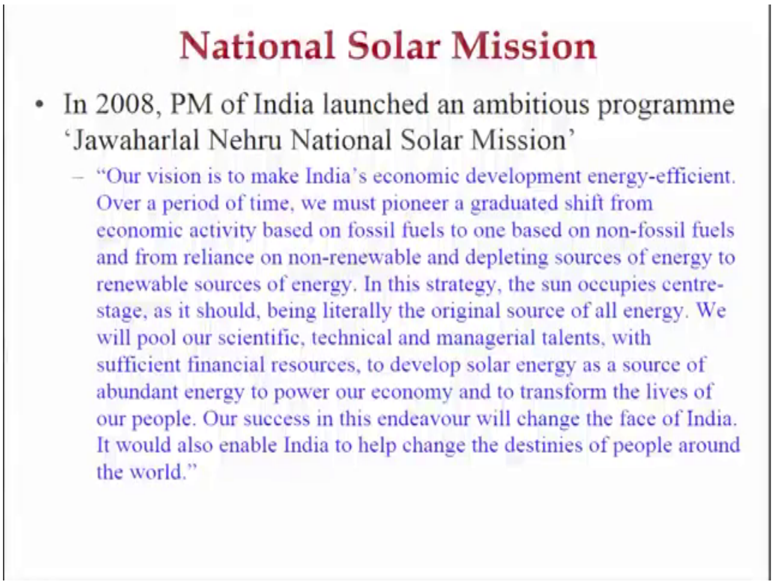

And in the light of this in 2008 Prime Minister of India launched a very ambitious program called as Jawaharlal Nehru Solar National Solar Mission. And in that, so I will not read the whole paragraph, but the idea was to generate enough solar power for the country, so that people of this country benefit. And we have we have energy availability in comparison to a lot of other developed countries, and also to steer various technology development and industrial development in the country.

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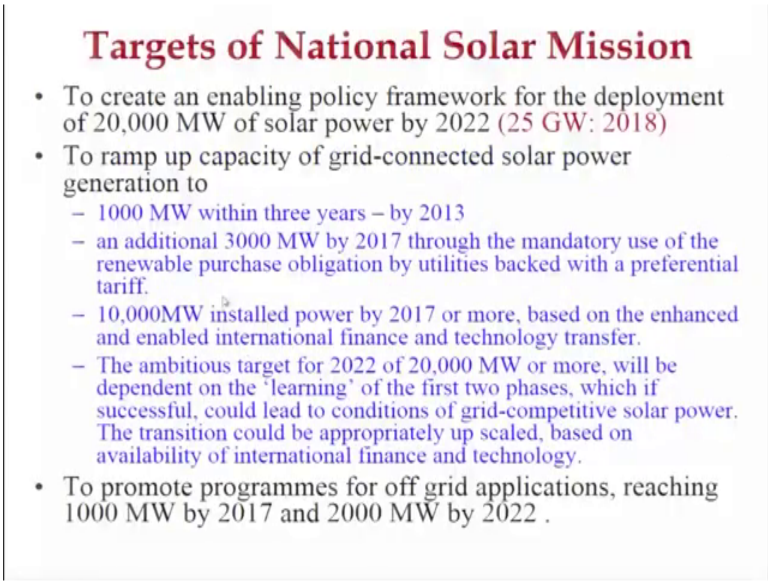

So, the targets of this mission were to create a policy framework, so that we are able to deploy 20,000 megawatt, 20 giga watt of power by 2022. We are in 2018. And right now approximate deployed capacity in this country is 25 giga watts. So, we have already exceeded that target which is very good. And so there were a lot of hefty targets lot of them have been met, but since the phase of development is extremely fast, the targets are going to be steeper in future than now.

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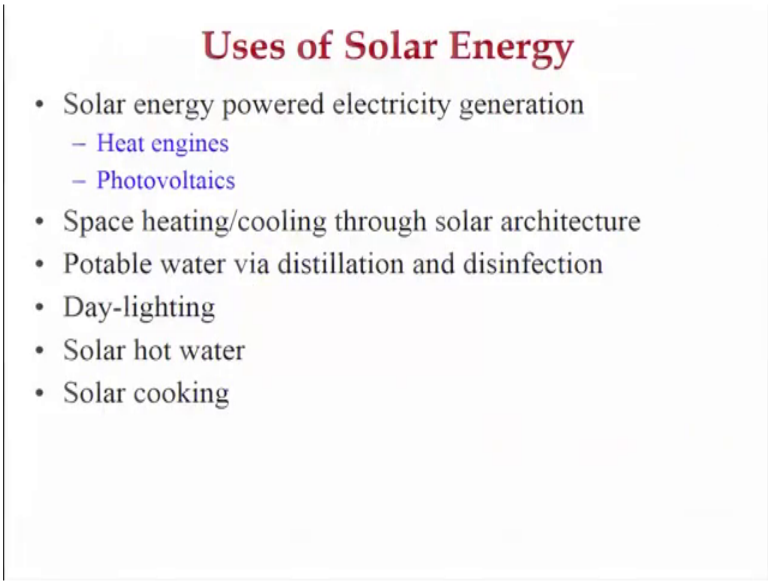

So, what are the uses of solar energy? Well, solar energy can lead to generation of electricity through two means first is the use of heat engines which is basically by running the turbines, conversion of heat into electricity, and then use of photovoltaics which can be done by converting light into electricity. And solar energy can also be used to conduct is space heating or cooling through solar architecture. It can also be used for disinfection of water via distillation or disinfection processes using UV.

And then one can also use solar light for day lighting, you do not need to use these kind of lights to light the houses if you intelligently design the windows. Solar can also be used for using hot water such as for example, in IIT Kanpur we have solar thermal flat panels everywhere in every hostel which provide enough hot water for various purposes, and it is also used for cooking. So, there are multiple uses of solar energy which can be useful to us.

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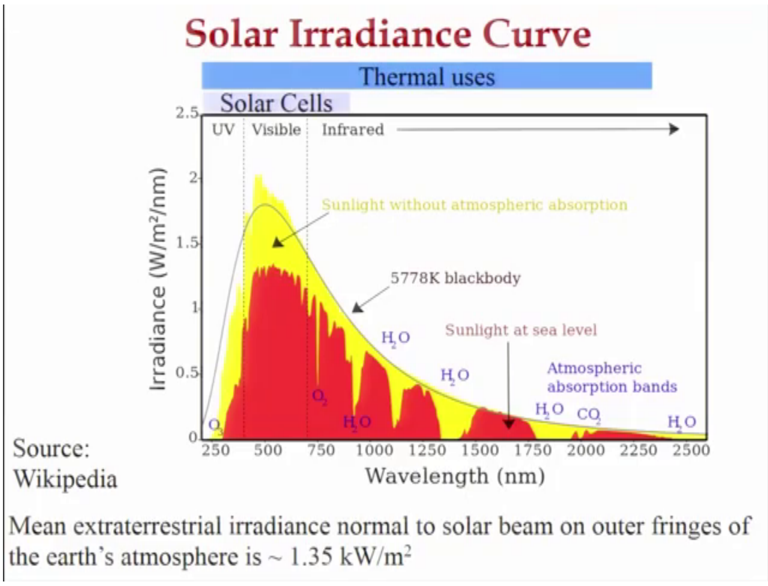

So, if you look at the solar irradiance curve, so this is a plot which plots a radiance in watt per meter square per nanometer. So, essentially energy per unit area for that particular wavelength per nano meter. So, it is a spectral irradiance you can say. When it is plotted as a function of wavelength, you can see that it shows a maxima at somewhere around 500 nanometer which is in the visible range. So, this particular spectra has three major reasons, first is the UV which is on the left, for wavelengths smaller than about 400 nanometer, 350-400 nanometer. Then somewhere in the middle up to about 700 nanometer we have visible range which is what we see. And then at much longer wavelengths or lower energy we have infrared region.

And it turns out that the peak of solar irradiance is it falls somewhere in the visible region which is good, which is the useful part. So, you can see that all the solar irradiance curve is very broad. Now, most of the energy is centered around the visible region and this is what we have to harness. So, it has various components. You can see that you have the black line depicts the radiation which is emitted by a black body at about 6000 Kelvin, to be precise it is about 5778 Kelvin.

This black curve has so the energy under this black curve has various contributions. The yellow part is the one which is the sunlight which is without any atmospheric absorber absorption, the energy which is not absorbed by the atmosphere. And then we have these red bands which are the energy in the red is the one which is sunlight that is available to us at the sea level. So, you can see that there is some deterioration from yellow to red, but it is still the energy available. If you look at the irradiance, it is about 1.3 watt per meter square per nanometer about 500 nanometer wavelength.

And somewhere at higher wavelength in these bands we have absorption bands. So, I have depicted some of them for example, you have oxygen absorption, you have a water absorption H 2 all the H 2 Os depict absorption by the moisture. And then somewhere at very high wavelength, you have absorption by the CO 2. So, you can see here that if you have CO 2 present in that atmosphere, you are going to trap this part of radiation this is what is basically related to global warming. So that is why we say that you have if you have large amount of CO 2 and methane in the atmosphere, they trap the heat and this is what happens. So, these are the CO 2 sort of absorption bands at about 2000 nanometer or so.

But nevertheless this is what is the solar irradiance curve that is available that is; so, its basically simulated plot at for a blackbody at 5778 Kelvin. And this shows that the energy most of the energy is centered in the visible and IR region, and this is what is available for us to be harnessed. So, as per the calculations, the mean extraterrestrial irradiance which is normal to solar beam available on the outer fringes of earth at earths' atmosphere is about 1.35 kilo watt per meter square. So, on every meter square area on the outer fringes of earth's atmosphere, you get energy of about 1.35 kilowatt which is significant amount of energy.

So, in this whole plot, if you now look at these segments, the first segment from UV to you can say about 900 nanometer, 800 nanometer is useful for conversion through solar cells or solar photovoltaic. Whereas, thermal uses of solar energy range directly somewhere around 300 nanometer 250 nanometers right up to IR region. So, IR region is far more broad thermal uses, so IR region is far more broad and this is what is very useful for thermal uses. Whereas, the part which is high energy part centered around the visible region is what is useful for the solar photovoltaic's.

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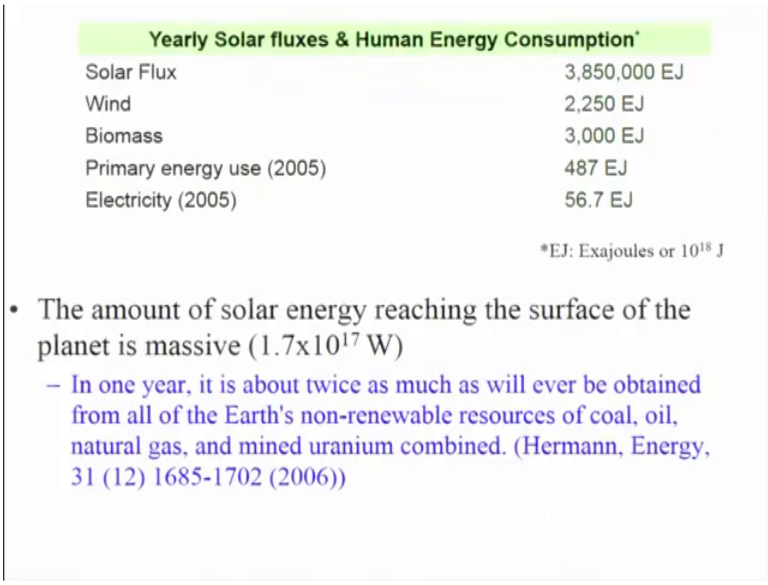

So, let me give you some more numbers. So, these are the yearly solar fluxes and human energy consumption. So, essentially if you look at it solar flux that is available to us is about if you look at the figures, it is here 3,850,000 exajoules. And one exajoules is about 10 to the power, it is equal to 10 power 18 joules. So, you can see the amount of solar flux that is available to us is huge when you compare with the other energy. So, wind energy is for example, 2,250 exajoules. Biomass has 3,000 exajoules.

The primary energy use as per the data available of 2005 is about 500 or maybe right now it is about 1000 exajoules or so. Whereas, out of this electricity is about 60 exajoules. You can see that there is a huge potential in the form of solar energy that is available to us. The amount of energy that is available is about 3.8 million exajoules, whereas what we consume is about 100, maybe the figure right now is about 100 exajoules.

So, essentially the amount of solar energy that reaches the surface of planet is huge. It is about, if you look at, so this is the solar flux, but the amount of energy that reaches the planet is about 1.7 into 10 to power 17 watts in terms of watts. So, somebody make this calculation and he turned he said that, so this is a paper in energy in 2006, it was speculated that in 1 year, the energy that falls on the surface of planet is about twice as much as we will ever obtain from other non-renewable sources of energy such as coal, oil, natural gas as well as nuclear energy. So, this speaks a lot about solar energy, the amount of solar energy that is available to us is simply huge.

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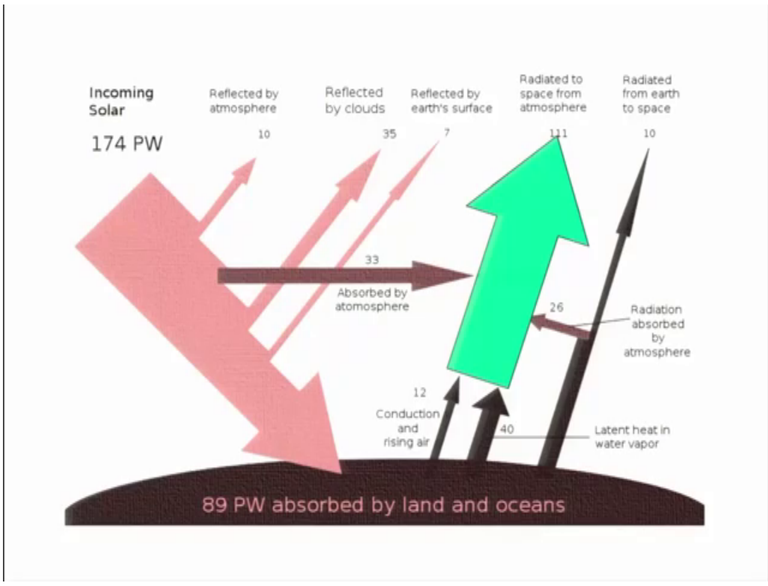

So, you can see that here you have 174 petawatts of energy that is coming to the surface out of 174 peta watts, 10 is reflected by the atmosphere, 35 peta watts is reflected by the clouds, and then earth's surface reflects about 7 peta watts. And the remaining is absorbed by land and oceans and of course 33 is absorbed with atmosphere. And out of this 89 which is absorbed in atmosphere, you have 12 that goes away via conduction as well as by rising that that a the air that rises.

And then 40 goes as latent heat in water vapor. And then out of this then we have the third portion which is about 36. Out of 36, 26 goes as radiation which is absorbed by atmosphere, and 10 goes as radiation from the earth to space. So, if you count these 33, 12, 40 and 26 this is basically 111 petawatt which is a radiation radiated to the space from the atmosphere. So, basically this is the mathematics of the whole energy that comes in and goes out.

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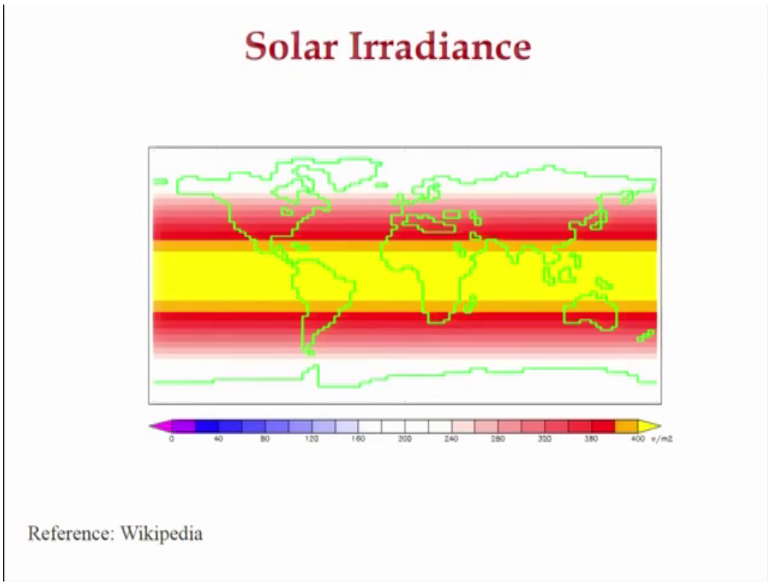

So, this is the solar irradiance plot. And this solar irradiance plot tells you for the whole globe the energy that is incident. And you can see that this is where we are this is India somewhere here and this. So, the most intense band is the yellow band which is about 400 watts per meter square. And if you go to orange red and so on and so forth energy reduces. You can see that the yellow band and the orange band passes through a large part of Africa, Mediterranean and India. So, solar irradiance, so India is very lucky to be on the part of the planet where solar irradiance is extremely high. And this is what India makes an exciting destination for the deployment of solar technologies. So, there are technologies.

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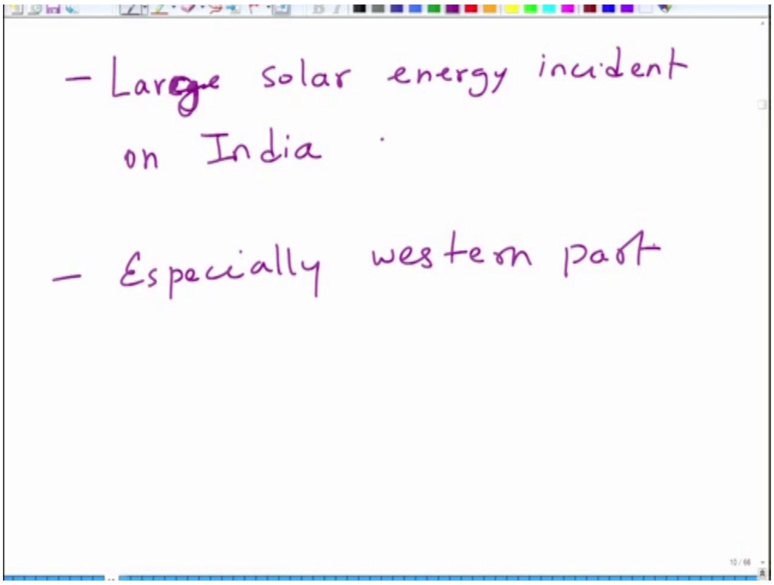

So, basically we can say that large solar energy incident on India especially western part of the country and this is where solar energy can be useful.

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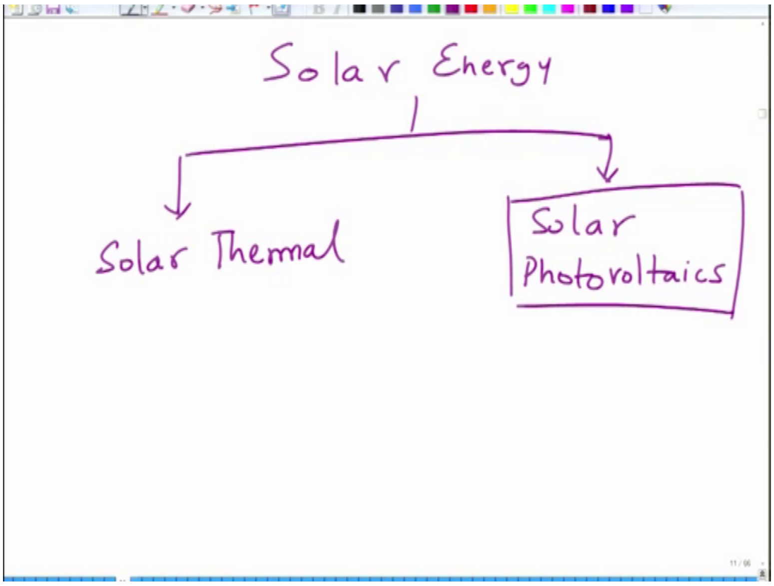

So, solar energy is essentially useful in two contexts. The first context is you can say the solar thermal, and the second is solar photovoltaics. And it is this solar photovoltaics that we will study in this course. So, let me show you some pictures of these technologies.

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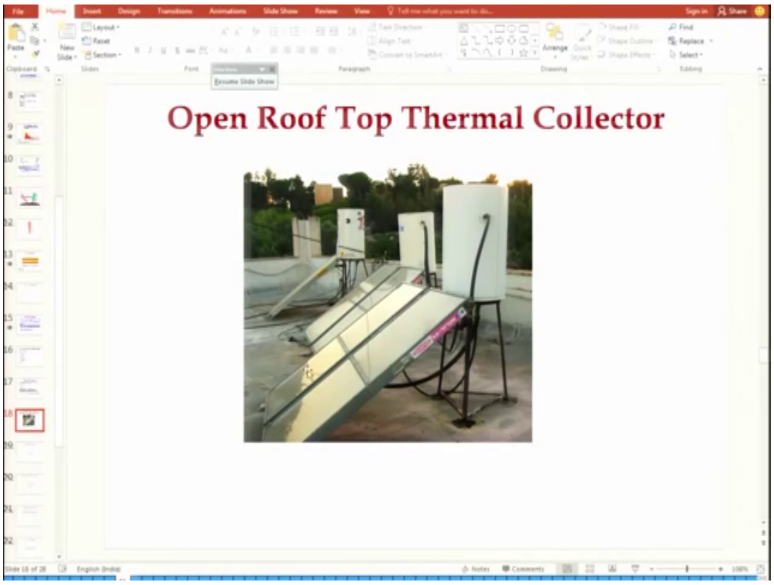

So, this is for instance a picture of this is a picture of open rooftop thermal collector, where you have these thermal collectors which are connected to these storage tanks, these that the panels are inclined to at certain angle so as to maximize the collection of energy. And they have some black body, some black material which absorbs energy, and this energy is converted to heat which is taken away by the fluid working fluid which is typically water in these flat panel collectors. And there are tubes underneath somewhere in this panel and which and the hot water so that you have a cold water inlet and then you have a hot water outlet. The hot water is stored in these tanks which is taken away for the use. So, this is what is the design of a typical open rooftop thermal collector.

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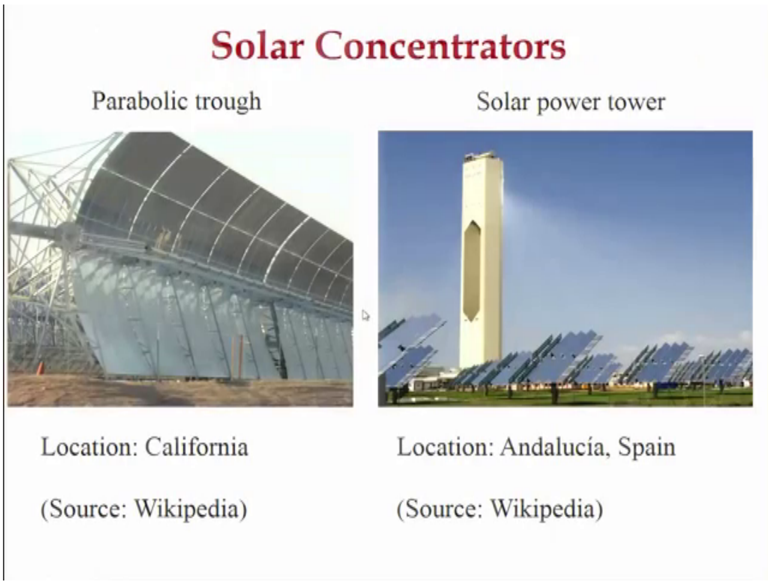

And solar energy can also be used in the form of solar concentrators. So, essentially what you do is that, so in the previous case, the energy of the area of the collector is equal to area of the receiver ok, because it is a flat panel. So, whatever the surface is available directly receiving the sunlight. What happens in concentrator is you use a curved surface which is a reflecting surface. So, area of receiver is far higher as compared to so area of you can say the reflecting surface you can say, do not worry about the receiver and collector terms as yet, but area of the surface which it receives the sunlight which is the curved surface is very large.

And all of this energy which falls on this curved surface is reflected back onto the central portion. So, you can see here, so this is the central tube. So, this is the central tube along which you have a working fluid let us say water or some sort of oil or something else. And this gets heated through the reflection of large surface through the reflection of sunlight from a large surface area. So, essentially so this surface is the concentrating surface which concentrates energy which is incident on it to a smaller area which carries which is basically a tube which carries the working fluid like water or oil.

So, this is a parabolic trough collector which is called a solar concentrator. Another design could be, you can have variety of these panels at various angles, and all of them are reflecting light to a particular point here. So, this is the solar power tower. So, you have a smaller area surface which is collecting power from these reflecting surfaces ok.

So, this is basically again solar concentration kind of technology. So, this is solar thermal typically.

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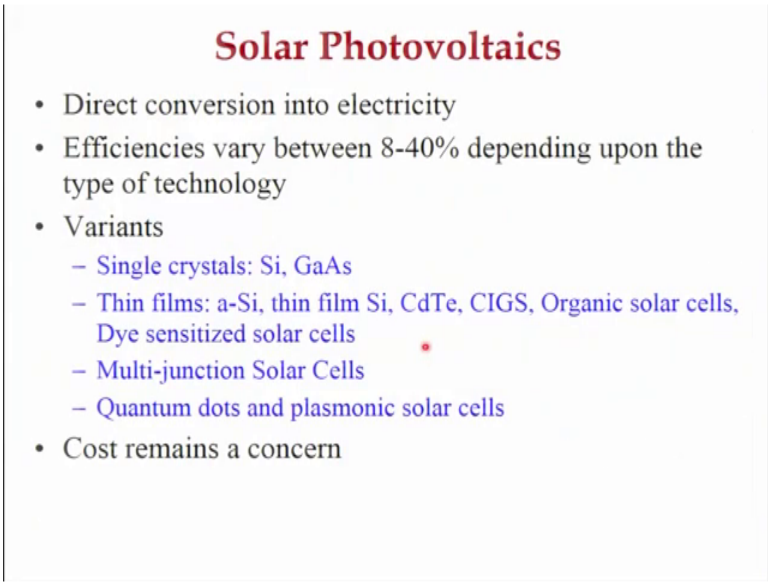

And then we can have solar photovoltaics which directly convert electricity cell solar energy into electricity. The efficiency is very and the cell level depending upon the type of technology between 8 and 40 percent, in fact, up to 40 percent that would be correct number. There are various variants single crystal technology such as silicon and gallium arsenide, thin films amorphous silicon, thin film silicon, cadmium telluride, CIGS, organic dye sensitized, then we have multi junction solar cells, quantum dots, plasmonic solar cells, a variety of technologies are there. These are all right now for many of these technology cost is a problem, but silicon is, but solar photovoltaics getting very cost competitive right now.

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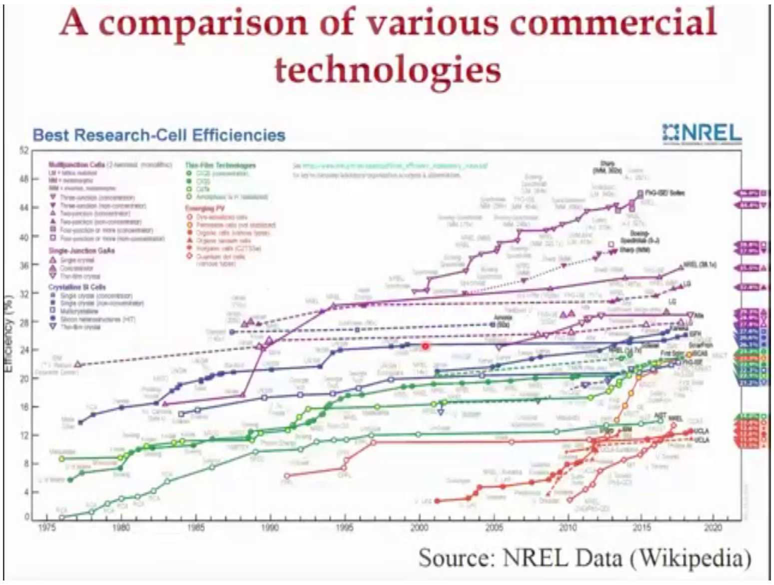

These are certain efficiencies which are on commercial scale. So, we can see that we have numbers as low as about 11.5, a 10 percent right up to about 46 percent. So, depending upon the type of technology you have variety of efficiencies available, not all of them are commercial though, many of them are right now under the lab scale.

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So, this is what a solar photovoltaic panel would look like. You have this desert sort of landscape in which you have this scores of solar panels which are all receiving energy on a barren land which was otherwise unuseful, and these are all converting direct light into electricity. So, this is what is the potential of sort of photovoltaics.

So, what we will do is that in the next class we will discuss about, so this is just introductory lecture. And the next class what we will talk about is solar radiation what is what do we mean by solar radiation, what is the spectrum like, what are the various mathematical terms that are used to define it. And then we will look at some of the geometrical relationship which sun makes with the earth, so that which are useful in estimating the amount of radiation that you get on a surface at a given location at a given time. And then we will look at what are the ways in which solar radiation is quantified and how do we measure it that we will do over pass over next three-four lectures ok.

So, thank you. So, with from the next class, we will be a little bit more focused in terms of content of this course. So, we will perhaps see each other in next class.

Thank you.