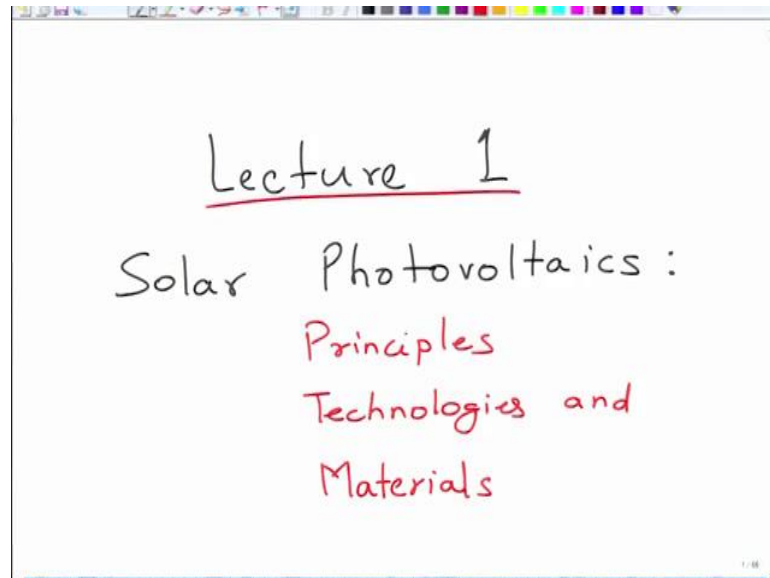


**Solar Photovoltaics: Principles, Technologies and Materials**  
**Prof. Ashish Garg**  
**Department of Material Science & Engineering**  
**Indian Institute of Technology, Kanpur**

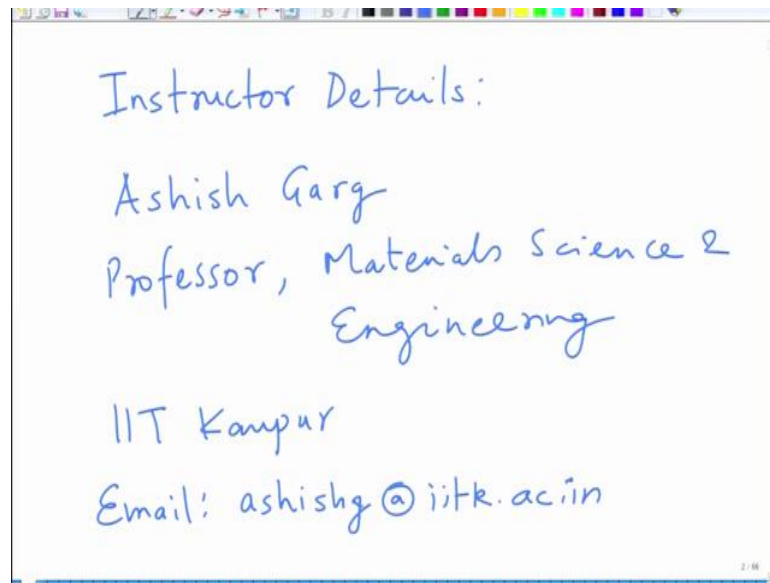
**Lecture – 01**  
**Introduction to Solar Energy**

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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.

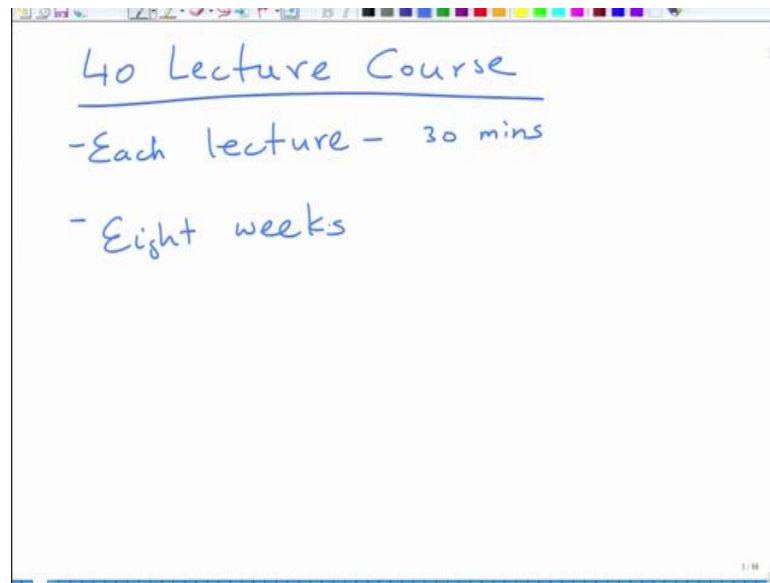
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So, this is the first lecture in which we are going to start talking about this course. So, for this course let me just provide you my details. So, my name is Ashish Garg. I am a professor at Material Science and Engineering Department, at IIT Kanpur.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

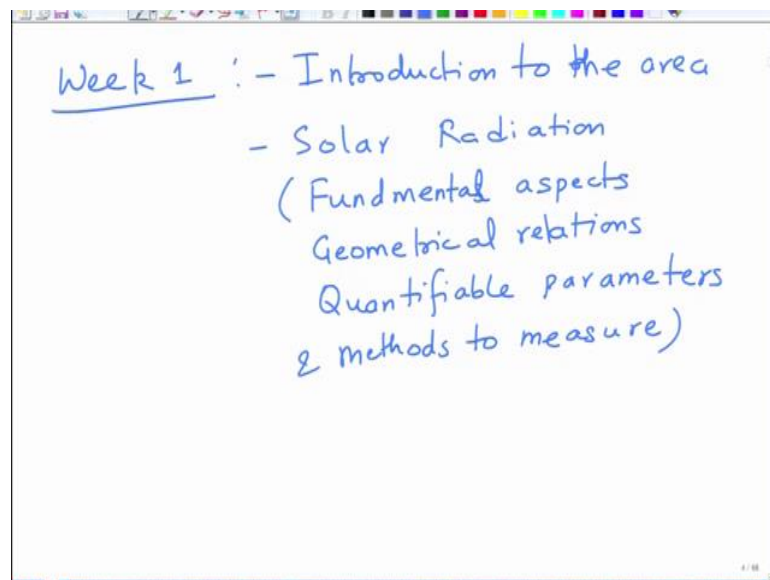
You will be able to access the course details online as well. There will be two TAs of mine Mr. Sudhir Ranjan and Mr. Ajay Singh, who will help you with the questions that you may have. And if they cannot solve your problems, then I will try to solve your problems. And you will have weekly assignments on various topics, after which you will have exams.

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

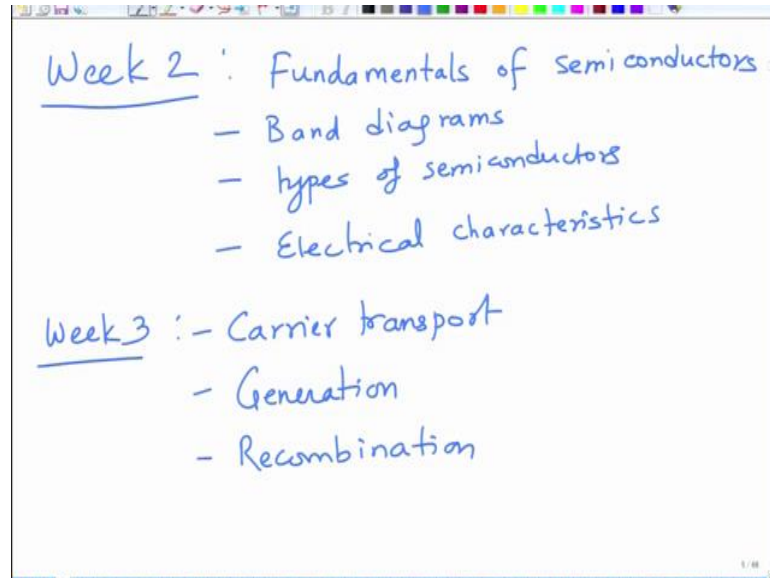
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We will discuss basically about introduction to solar cells, introduction to the area. And then we will talk about solar radiation, you see the moment we talk of solar technologies. We first need to learn about what are solar radiation, what does it 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, we will cover this in the first week hopefully.

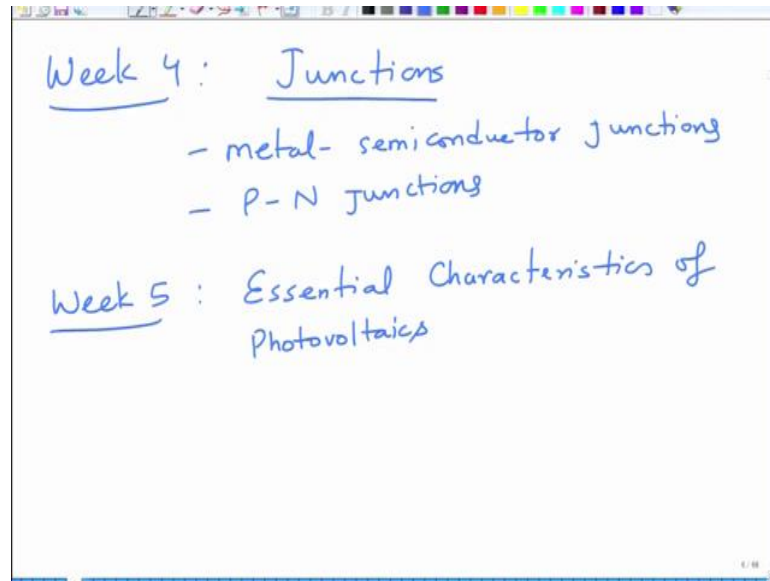
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And then in the week-2, we plan to undertake essentially basics of semiconductors. Most of the solar cell technology especially solar photovoltaics, are built around semiconductors. So, essentially, we will look at semiconductor band diagram, types 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, 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 them to recombine. So, these three aspects are crucial to understand, various physical processes in semi controlled in solar cell devices.

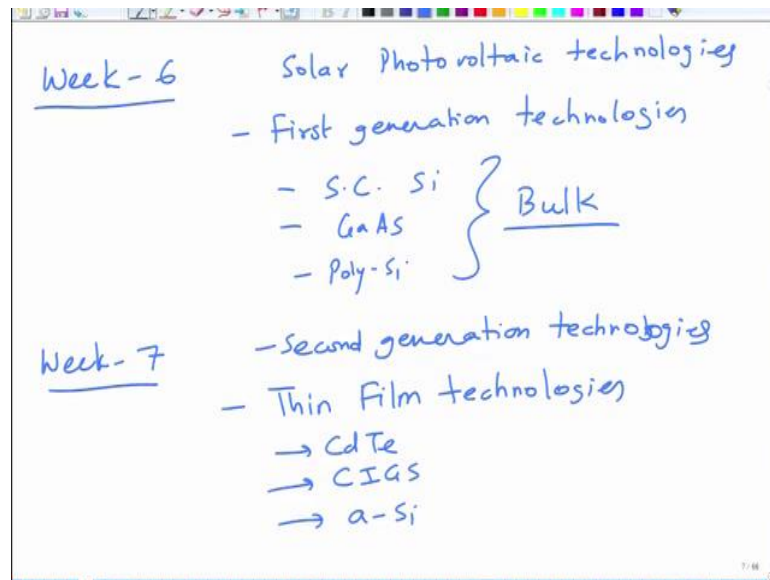
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And then in week-4, we will undertake various junctions, because a typical semiconductor solar cell device is a P-N junction. These semiconductors are also attached to metals on both sides to make electrical contacts. So, as a result we will talk about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

And then in, week-5 we will understand the essential characteristics of photovoltaic devices. Essential characteristics, photovoltaics in terms of electrical parameters, what kind of circuits can 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.

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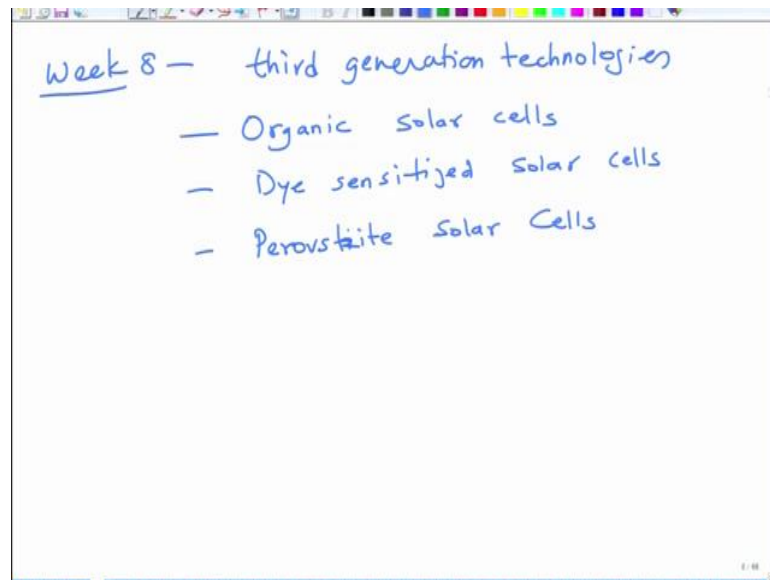
And then in week-6, we will start with the solar photovoltaic technologies. And in this, in the first week we will discuss about first generation solar technologies. Solar photovoltaic technologies, are divided in three categories broadly. So, the first one is first generation technology, which is primarily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

And then we will talk about various technologies in general, we will talk about what the current numbers are, what current issues are and 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. Second generation technologies are basically around thin film technologies. So, these are essentially bulk technologies. Bulk means where 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, CIGS 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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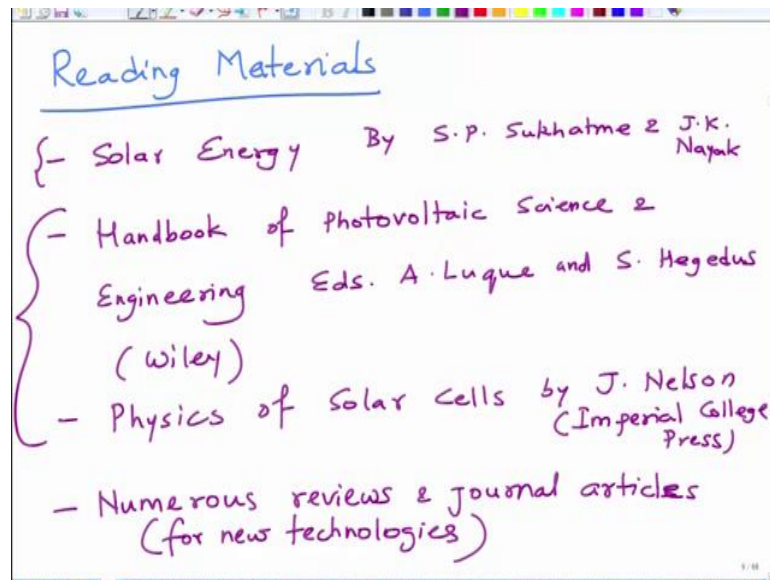


And then in week-8. In the final leg of the course, we will talk about third generation technologies, where we will mainly talk about organic solar cells, which are flexible lightweight based on polymers. Then we will talk about dye sensitized solar cells, these are also thin film technologies. But they are solution-based technologies, can be made printable 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 sensitized 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 the work on these started somewhere around late 90's, perovskite work started around 2000 well we 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 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.

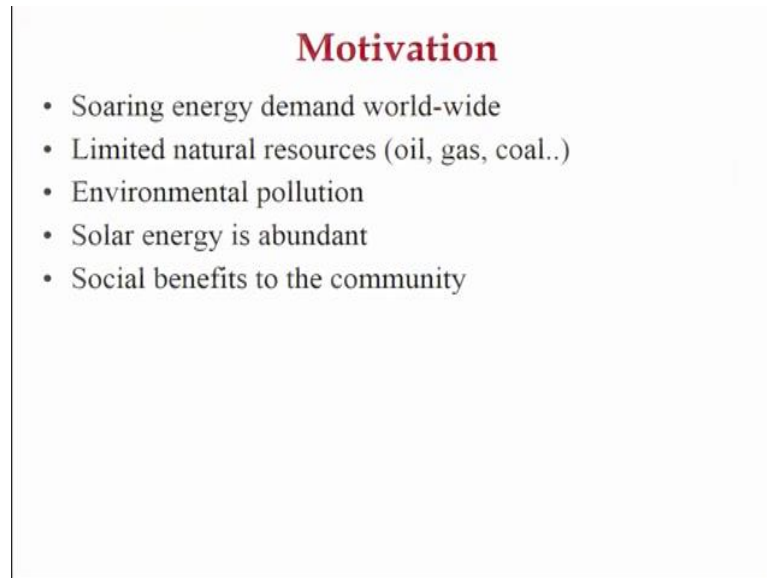
And another book that I will recommend is Physics of Solar Cells by Jenny Nelson, this is basically Imperial College Press. Again, a very good book from the perspective of fundamentals as well as technology. So, these two books are primarily course based, which we have to consider towards this course.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

In addition to these three books, you can read 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 primarily for new technologies. And these two will cover fundamental aspects of solar cells, semiconductors as well as first two generation technologies.

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**Motivation**

- Soaring energy demand world-wide
- Limited natural resources (oil, gas, coal..)
- Environmental pollution
- Solar energy is abundant
- Social benefits to the community

So, let us first begin with what is the motivation for this course. So, if we go back to slides for this course, so the motivation for solar energy or solar photovoltaics is 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 to produce electricity non-stop to work for the progress of country in terms of science and technologies.

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 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.

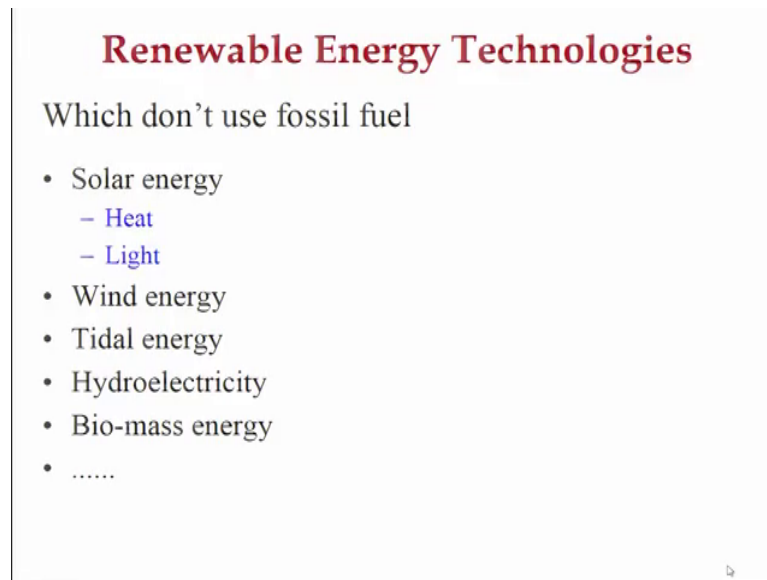
Moreover, when we talk about the environment oil, gas, coal or any other source which is based on fossil fuels is essentially a conversion of raw material, which is used to produce electricity, and this process is quite energy intensive. And this also leads to creation of pollutants in the atmosphere. 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 we 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, we 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, this is where scientists have been working for the past few decades which 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 we know that 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 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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**Renewable Energy Technologies**

Which don't use fossil fuel

- Solar energy
  - Heat
  - Light
- Wind energy
- Tidal energy
- Hydroelectricity
- Bio-mass energy
- .....

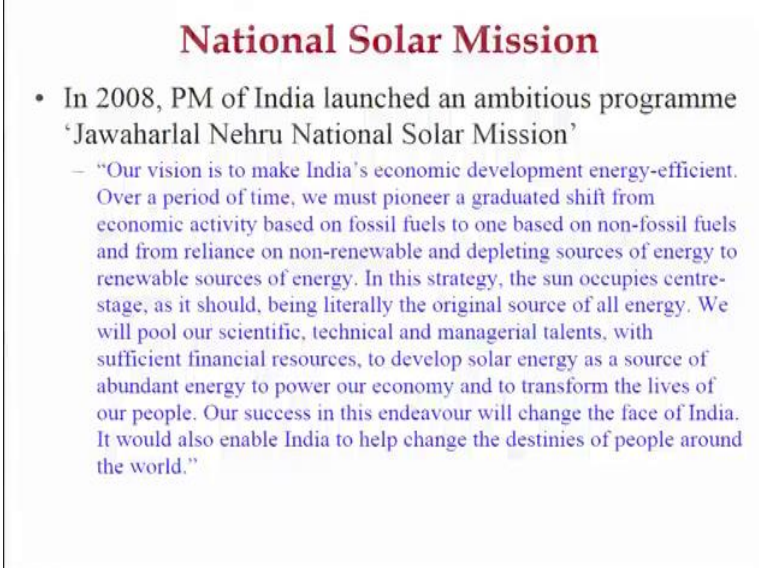
So, what are the renewable energy technologies in this case. So, the idea is that we need to develop technologies which are not fossil fuel based, so that the pollution or the environmental problem during the energy generation stage can be minimized. But also we minimize the use of fossil fuel itself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

So, whatever technologies that we rely upon are called as renewable energy technologies, which means the source of them is renewable and it just keeps renewing 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 there are other forms of energy as well such as wind energy and 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 convert this wind energy into useful electrical energy using wind turbines. One can, also think of converting tidal energy or offshore 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 we know that sun is abundant source and it is available everywhere, especially for a country like India which has very high solar irradiance, which is really wonderful.

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**National Solar Mission**

- In 2008, PM of India launched an ambitious programme ‘Jawaharlal Nehru National Solar Mission’
  - “Our vision is to make India’s economic development energy-efficient. Over a period of time, we must pioneer a graduated shift from economic activity based on fossil fuels to one based on non-fossil fuels and from reliance on non-renewable and depleting sources of energy to renewable sources of energy. In this strategy, the sun occupies centre-stage, as it should, being literally the original source of all energy. We will pool our scientific, technical and managerial talents, with sufficient financial resources, to develop solar energy as a source of abundant energy to power our economy and to transform the lives of our people. Our success in this endeavour will change the face of India. It would also enable India to help change the destinies of people around the world.”

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. So, in brief it pitches the idea of generating enough solar power for the country, so that people of our country can benefit. And we have considerable 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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## Targets of National Solar Mission

- To create an enabling policy framework for the deployment of 20,000 MW of solar power by 2022 (25 GW: 2018)
- To ramp up capacity of grid-connected solar power generation to
  - 1000 MW within three years – by 2013
  - an additional 3000 MW by 2017 through the mandatory use of the renewable purchase obligation by utilities backed with a preferential tariff.
  - 10,000MW installed power by 2017 or more, based on the enhanced and enabled international finance and technology transfer.
  - The ambitious target for 2022 of 20,000 MW or more, will be dependent on the 'learning' of the first two phases, which if successful, could lead to conditions of grid-competitive solar power. The transition could be appropriately up scaled, based on availability of international finance and technology.
- To promote programmes for off grid applications, reaching 1000 MW by 2017 and 2000 MW by 2022 .

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 are a lot of hefty targets that have been met, but since the pace of development is extremely fast, the targets are going to be steeper in future than now.

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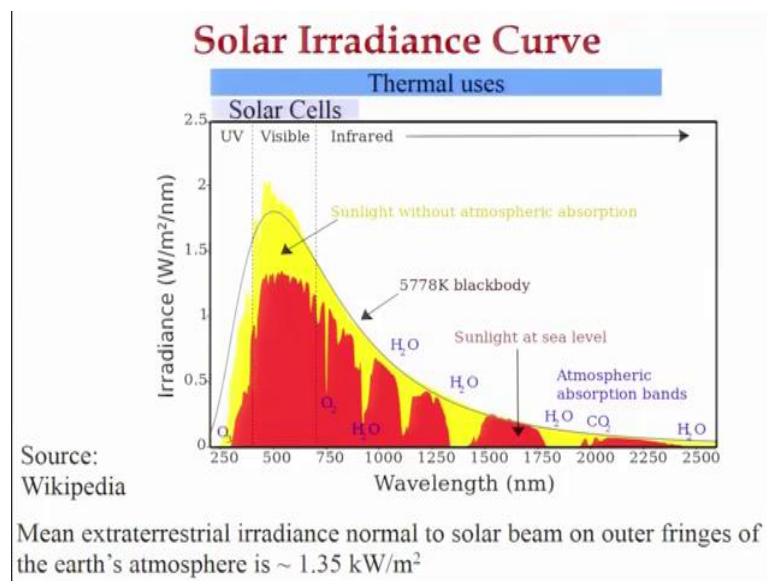
## Uses of Solar Energy

- Solar energy powered electricity generation
  - Heat engines
  - Photovoltaics
- Space heating/cooling through solar architecture
- Potable water via distillation and disinfection
- Day-lighting
- Solar hot water
- Solar cooking

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 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, we do not need to use these kinds of lights to light the houses if we 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 we look at the solar irradiance curve, this plot 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. When it is plotted as a function of wavelength, we can see that it shows a maximum at somewhere around 500 nanometer which is in the visible range. So, this particular spectrum 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 falls somewhere in the visible region which is good, which is the useful part. So, we 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, we can see that if we have the black line which depicts the radiation emitted by a black body at about 6000 Kelvin, to be precise it is about 5778 Kelvin.

This black curve has the energy under this black curve and 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 primarily is energy of the sunlight that is available to us at the sea level. So, we can see that there is some deterioration from yellow to red, but it is still the energy available. If we look at the irradiance, it is about 1.3 watt per meter square per nanometer about 500 nanometers wavelengths.

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

But nevertheless, this is what is the solar irradiance curve that is available; so, it's basically simulated plot for a blackbody at 5778 Kelvin. And this shows that, most of the energy is centered in the visible and IR region, and this 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 earth's atmosphere is about 1.35 kilo watt per meter square. So, on every meter square area on the outer fringes of earth's atmosphere, we get energy of about 1.35 kilowatt which is significant amount of energy.

So, in this whole plot, if we now look at these segments, the first segment from UV to is at about 900 nanometer, 800 nanometer is useful for conversion through solar cells or solar photovoltaic. Whereas, thermal uses of solar energy range is directly somewhere around 300 nanometer to 250 nanometers to right up to IR region. 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 photovoltaics.

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Yearly Solar fluxes & Human Energy Consumption*	
Solar Flux	3,850,000 EJ
Wind	2,250 EJ
Biomass	3,000 EJ
Primary energy use (2005)	487 EJ
Electricity (2005)	56.7 EJ

\*EJ: Exajoules or  $10^{18}$  J

- The amount of solar energy reaching the surface of the planet is massive ( $1.7 \times 10^{17}$  W)
  - In one year, it is about twice as much as will ever be obtained from all of the Earth's non-renewable resources of coal, oil, natural gas, and mined uranium combined. (Hermann, Energy, 31 (12) 1685-1702 (2006))

So, let us look at some more numbers. So, these are the yearly solar fluxes and human energy consumption. So, essentially if we look at it, solar flux that is available to us is about 3,850,000 exajoules. And one exajoules is about  $10^{18}$  joules. So, we can see the amount of solar flux that is available to us is huge when we compare with the other energy. So, wind energy is 2,250 exajoules and 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. We 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. The amount of energy that reaches the planet is about  $1.7 \times 10^{17}$  watts in terms of watts. So, somebody make this calculation and 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.

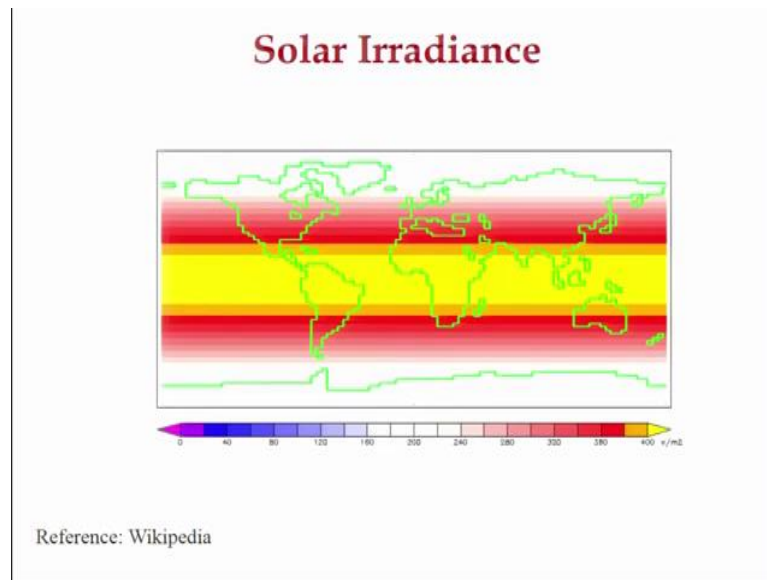
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So, we can see that here we have 174 petawatts of energy that is coming to the surface out of 174 petawatts, 10 is reflected by the atmosphere, 35 petawatts is reflected by the clouds, and then earth's surface reflects about 7 petawatts. And the remaining is absorbed by land and oceans and of course 33 is absorbed with atmosphere. And out of this 89 is absorbed in atmosphere, we have 12 that goes away via conduction as well as by rising that that 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 we 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 us energy that is incident on the whole globe. And we can see that this is where India is located. So, the most intense band is the yellow band which is about 400 watts per meter square. And if we go to orange red and so on and so forth energy reduces. We can see that the yellow band and the orange band passes through a large part of Africa, Mediterranean and India. So, on the solar irradiance part, 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.

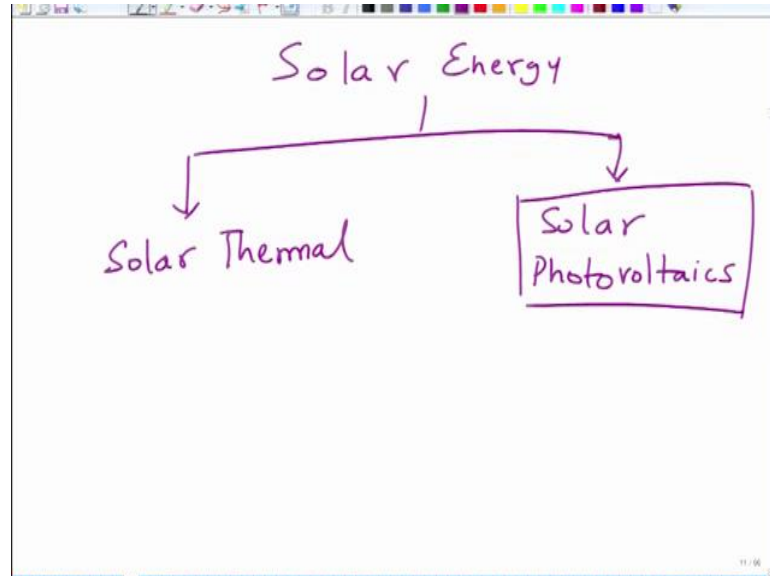
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- Large solar energy incident on India

- Especially western part

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 we solar thermal, and the second is solar photovoltaics. And it is this solar photovoltaics that we will study in this course. So, let us have a look at some pictures of these technologies.

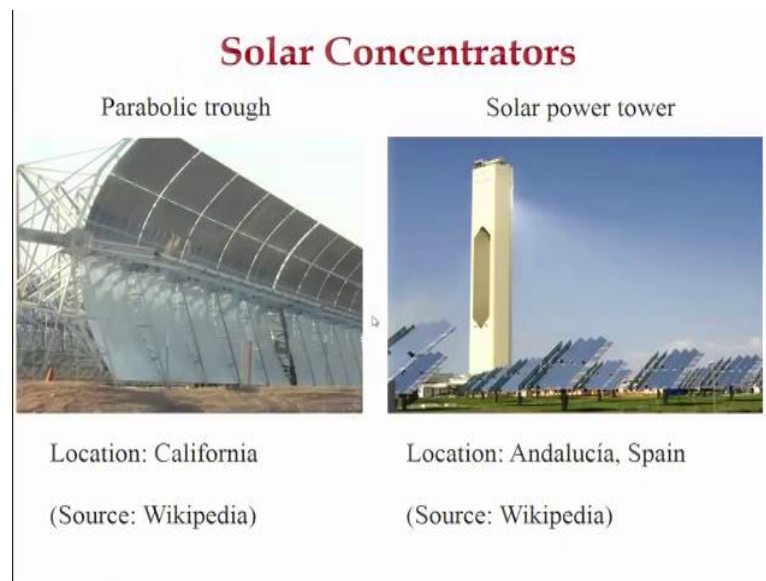
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So, this is for instance a picture of open rooftop thermal collector, where we have these thermal collectors which are connected to these storage tanks, these panels are inclined to

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 working fluid which is typically water in these flat panel collectors. And there are tubes underneath somewhere in this panel in which there is hot cold water inlet and hot water outlet. The hot water is stored in these tanks which is taken away for the use. So, this is the design of a typical open rooftop thermal collector.

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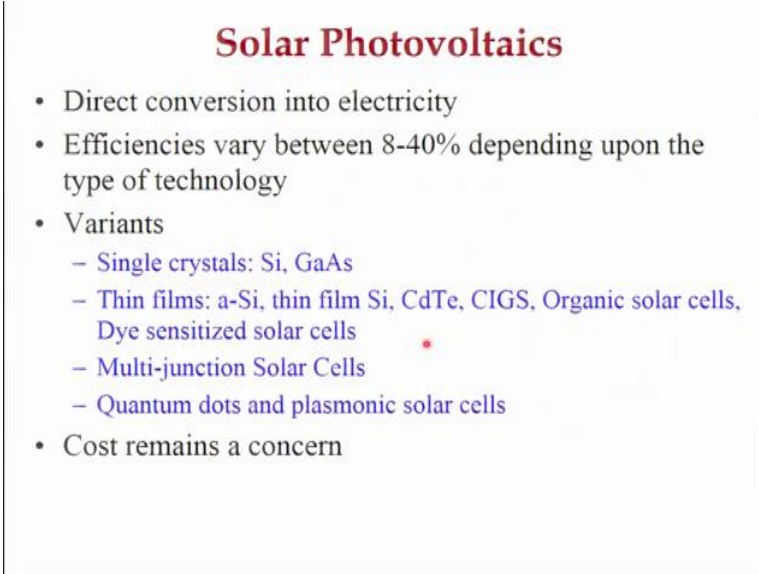
And solar energy can also be used in the form of solar concentrators. So, in the previous case, the energy of the area of the collector is equal to area of the receiver, because it is a flat panel. What happens in concentrator is we use a curved surface which is a reflecting surface. So, area of receiver is far higher as compared area of he reflecting surface, but area of the surface which receives the sunlight 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, we can see here, the central tube along which we have a working fluid as water or some sort of oil or something else. And this gets heated through the reflection of sunlight from a large surface area. So, essentially this surface is the concentrating surface which concentrates energy which is incident onto a smaller area, 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, 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, we have a smaller area surface which is collecting power from these reflecting surfaces. So, this is basically again solar concentration kind of technology. So, this is solar thermal typically.

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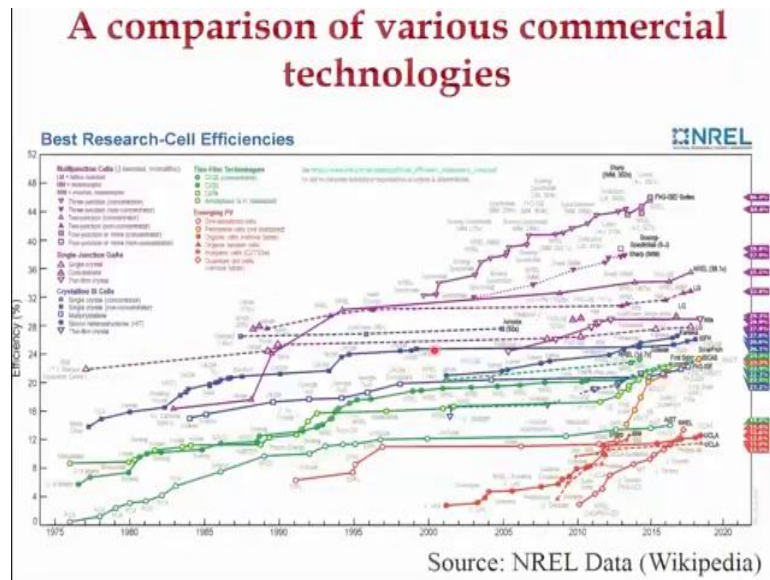


**Solar Photovoltaics**

- Direct conversion into electricity
- Efficiencies vary between 8-40% depending upon the type of technology
- Variants
  - Single crystals: Si, GaAs
  - Thin films: a-Si, thin film Si, CdTe, CIGS, Organic solar cells, Dye sensitized solar cells
  - Multi-junction Solar Cells
  - Quantum dots and plasmonic solar cells
- Cost remains a concern

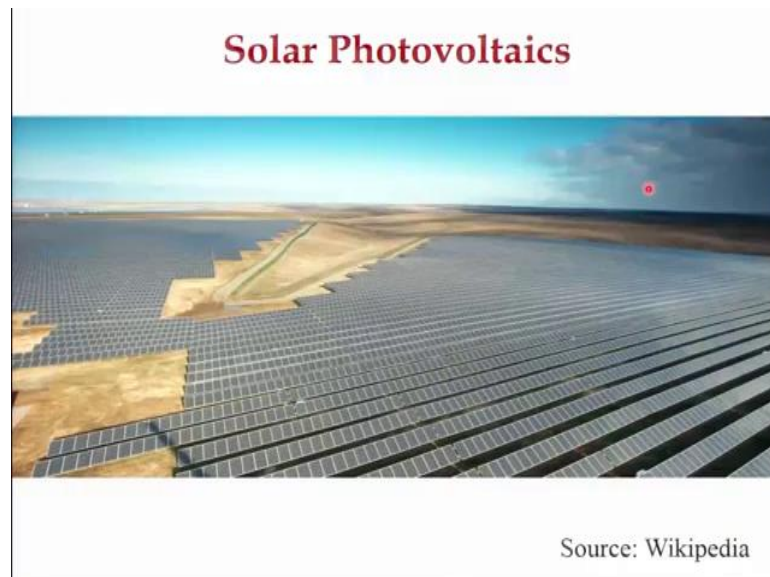
And then we can have solar photovoltaics which directly convert solar energy into electricity. The efficiency varies depending on the cell level and type of technology between 8 and 40 percent, in fact, up to 40 percent that would be correct number. There is various single crystal technology such as 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 many technologies available right now but technology cost is a problem, amongst which silicon solar photovoltaic devices are 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. We have this desert sort of landscape in which we have scores of solar panels which are all receiving energy on a

barren land which was otherwise un useful, and these are all converting direct light into electricity. So, this is what is the potential of sort of photovoltaics.

So, this is just an introductory lecture, what we will do is that in the next class discuss is that we will talk about what solar radiation 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, which are useful in estimating the amount of radiation that we 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?

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.