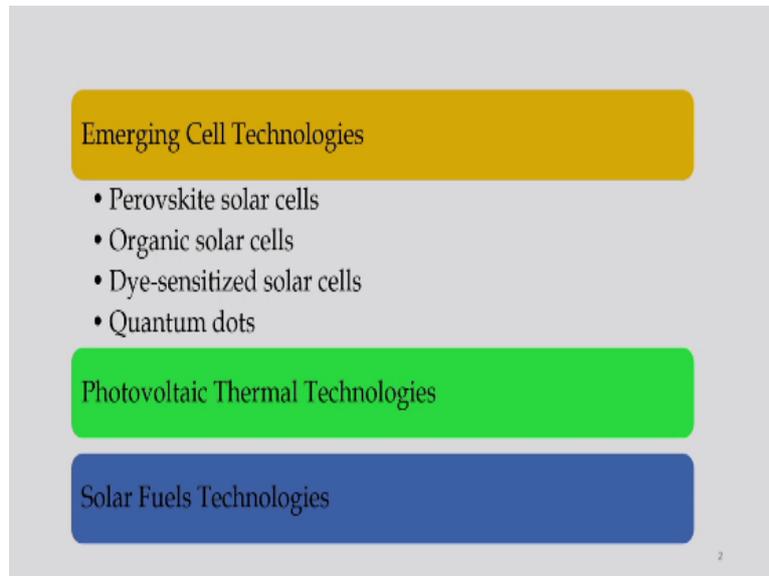


Solar Energy Engineering and Technology
Dr. Pankaj Kalita
Center for Energy
Indian Institute of Technology, Guwahati
Lecture 32
Emerging Solar Energy Technologies

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Dear students, today we will be discussing about emerging solar energy technologies which includes emerging cell technologies, photovoltaic thermal technologies, solar fuel technologies. Under emerging cell technologies, we will have perovskite solar cells, organic solar cells, dye-sensitized solar cells and quantum dot solar cells. So, attempt of the researcher is to increase the conversion efficiency at lower cost for these solar technologies.

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Perovskite Solar Cell

- Perovskite is calcium titanium oxide (CaTiO_3) mineral.
- Discovered in 1839 in the Ural Mountains of Russia and named after the Russian mineralogist L. A. Perovski.
- The ability of halide perovskite to convert electricity to light was initially discovered in 1990 in the LED configuration while light to electricity conversion was reported almost two decades later.



So, we will move on. So, first come to the perovskite solar cells. So, this perovskite is calcium titanium oxide, CaTiO_3 mineral and it was discovered in 1839 in the Ural Mountains of Russia and named after the Russian mineralogist, L. A. Perovski, so he is here. He is the guy who has first invented. The ability of halide perovskite to convert electricity to light was initially discovered in 1990s in the LED configuration; while light to electricity conversion was reported almost two decades later.

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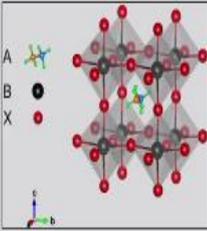
Perovskite Solar Cell (contd.)

➤ A perovskite solar cell use organic-inorganic metal halide perovskite as photon absorber layer. The term "perovskites" is used to describe a group of compounds characterized by the general formula ABX_3 .

➤ $\text{CH}_3\text{NH}_3\text{PbI}_3$ perovskite is a semiconducting compound with a direct bandgap of 1.55 eV.

Properties of $\text{CH}_3\text{NH}_3\text{PbX}_3$

- Strong absorption across the visible region of solar spectrum.
- Long carrier diffusion length of $1\mu\text{m}$.
- Weak exciton binding energy of 45 meV.
- A low charge recombination rate.



A is an organic cation (CH_3NH_3^+)
B is a metal cation (Sn^{2+} ; Pb^{2+})
X is a halide anion (Cl^- ; Br^- ; I^-)

A perovskite solar cell use organic-inorganic metal halide perovskite as photon absorber layer. The term perovskite is used to describe a group of compounds characterized by the

general formula ABX_3 . So, if you see this figure, from that it can be concluded that what is A? A is an organic cation; its chemical formula is something like $CH_3NH_3^+$ and B is a metal cation or inorganic cation.

So, it's may be Sn^{2+} or may be Pb^{2+} and X is a halide anion; may be Cl^- or Br^- or maybe I^- . So, if we see, its chemical formula will be something like this. It is a perovskite is a semiconducting compound with a direct bandgap of 1.55 eV. So, why it is so important? We must know the properties of $CH_3NH_3PbX_3$. So, let us see the properties. So, this perovskite is a strong absorption across the visible range of solar spectrum.

It is a long carrier diffusion length of 1 μm . It has weak excitation binding energy of 45 meV. A low charge recombination rate.

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Perovskite Solar Cell (contd.)

- The device structure of PSC is derived from that of dye-sensitized solar cell (DSSC), where the dye material is replaced with perovskite material.
- In 2009 PSC started with efficiency of just 3.8 %.
- PSC has recorded an efficiency of 22.1 % in 2017.
- The fastest advancing solar technology.

Fabrication techniques of PSCs

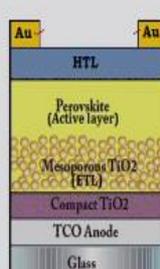
- Spin coating
- Spray coating
- Dip coating
- Vapor deposition

Advantages of PSCs

- ✓ Method of preparation is easy
- ✓ Having high $V_{oc} = 1.1 V$

Problems need to be addressed

- Instability in atmosphere/humidity
- Larger in size ($\eta=22.1\%$ for 0.095 cm^2)
- Pb is toxic.



Structure of Perovskite solar cell

ETL: electron transporting layer

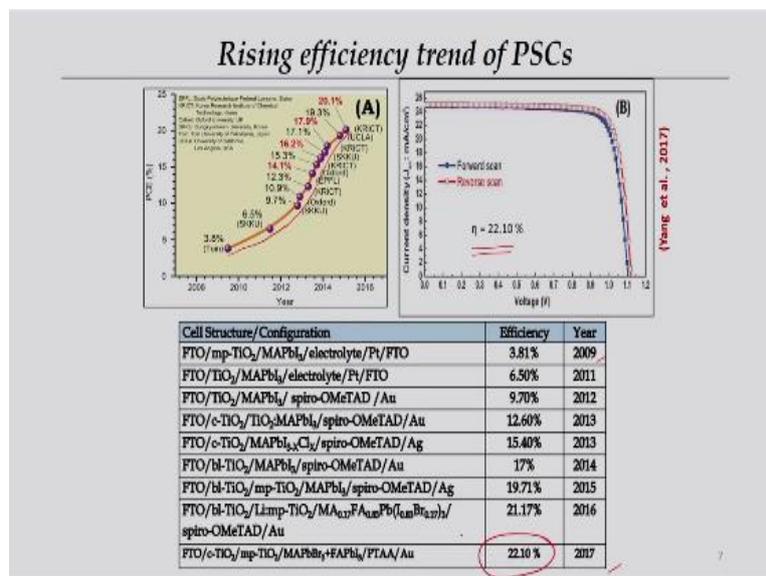
The device structure of PSC, that is perovskite solar cell is derived from the dye sensitized solar cell which is abbreviated as DSSC; where the dye material is replaced with perovskite material. In 2009, PSC started with an efficiency of just 3.8 %. So, this PSC has recorded an efficiency of 22.1 % in 2017. You see, how fast it attains a very high conversion efficiency. So, that is why this PSC is one of the fastest advancing solar technology.

So, what are different techniques used for making these perovskite solar cells? May be spin coating, may be spray coating, may be dip coating or may be vapor deposition technique.

What are the advantages of the solar cell? So, this method of preparation is easy and it has high V_{oc} , so it is about 1.1 volt. What are the problems to be addressed in order to utilize this perovskite for large scale application?

Instability in atmosphere or humidity is a primary concern and cell area requirement would be large compared to other solar cells and this lead, Pb is toxic. So, this figure shows the structure of perovskite solar cell. As you can see, we will have this electrode, gold, then HTL is hole transport layer and then we will have electron transport layer and then we will have compact TiO_2 then TCO anode and then glass. So, this kind of configurations is present in case of perovskite solar cells.

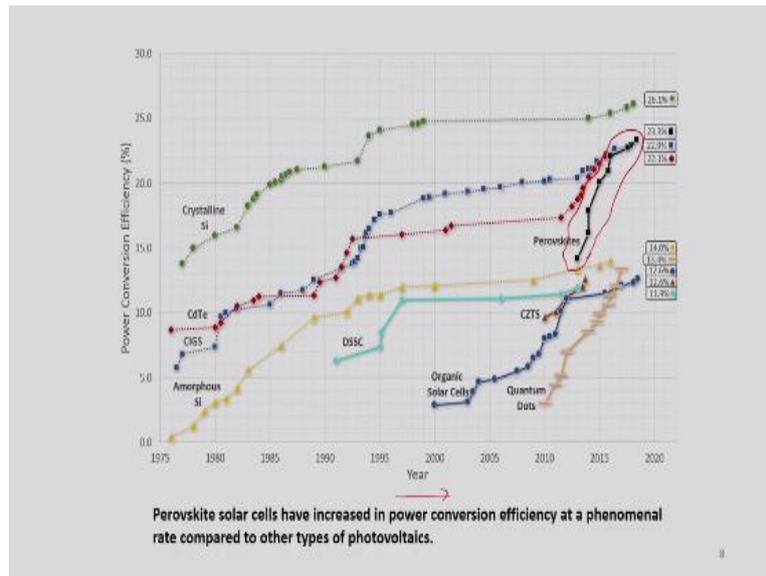
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So, if we see the rising efficiency trend, what we can see, it has got quick momentum to achieve a very high conversion efficiency. So, it was started in 2009 and see how fast it attains more than 20 % power conversion efficiency. And also we can see, current density versus voltage, so this blue color line is for forward scan and red color line is for reverse scan. So, what we can see here, it's conversion efficiency is about 22.1 %.

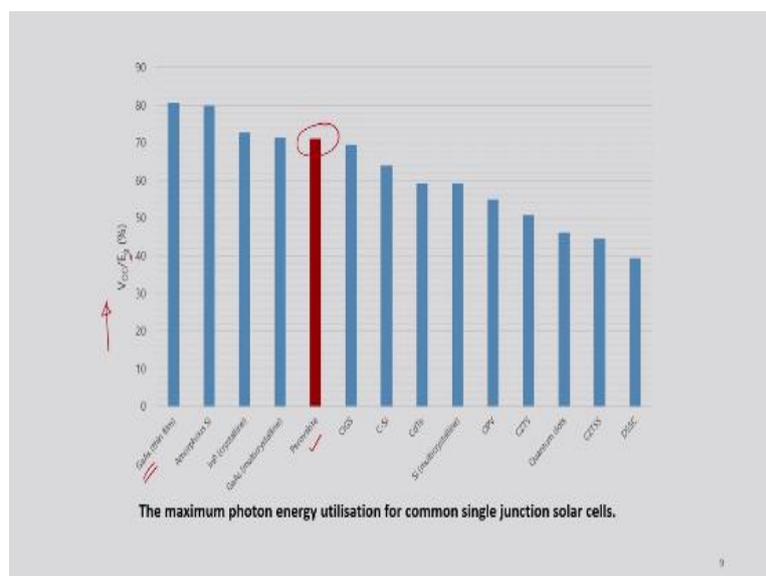
So, there are many configurations what we can see and also we can see the conversion efficiency starting from 2009. So, in 2017, it attains an efficiency of 22.1 %.

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And this figure shows the comparison of the perovskite solar cells with other solar cell technologies. So, vertical axis shows power conversion efficiency and horizontal axis shows years. As you can see, the development of all those solar cells, they are very steadily increasing; but if we look into the perovskite solar cells, you see, the rate of increase of power conversion efficiency with time is very very high.

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And this slide shows the maximum photon energy utilization for common single junction solar cells. If we compare this perovskite solar cells and if we have $\frac{V_{oc}}{E_g}$, that is bandgap in

percentage and with respect to perovskite, what we can see, this perovskite is having very good photon energy utilization compared to other solar cell material, except gallium arsenide as we understand, it is having very high conversion efficiency, but cost is very, very high.

So, what we are looking for, we need high conversion efficiency at lower cost as far as third generation solar cells are concerned.

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Dye-sensitized solar cells

The DSSC device consists of 4 components:

- **Semiconducting electrode**
 - n-type TiO_2 and p-type NiO
- **Dye-sensitizer**
 - Light harvesting and electronic transition
- **Redox mediator**
 - $\text{I}^- / \text{I}_3^-$ or $\text{Co}^{\text{II}} / \text{Co}^{\text{III}}$ complexes
- **Counter electrode**
 - Carbon or Pt

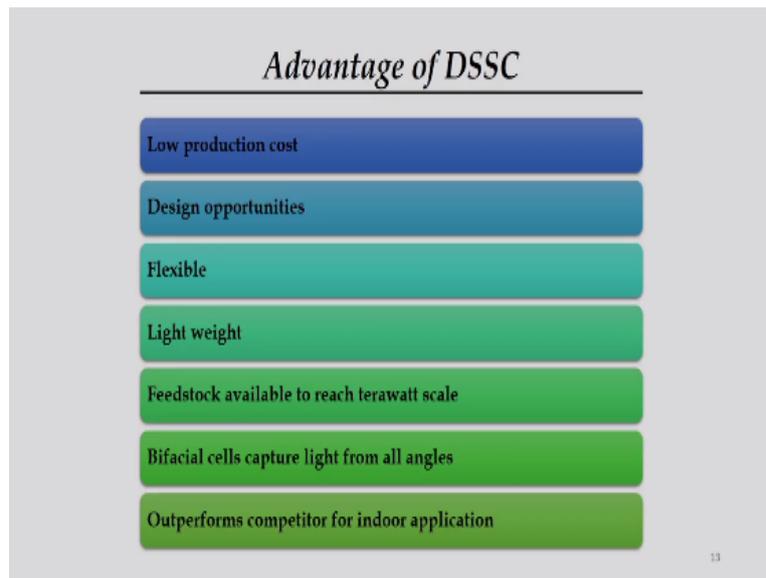
A dye-sensitized solar cell is a low-cost solar cell belongs to the group of thin film solar cells. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte, a photoelectrochemical system.

11

So, we will see now what happens in case of dye sensitized solar cells. So, in case of dye sensitized solar cells, it consists of four components. First component is semiconducting electrode, second component is dye sensitizer then third component is redox mediator and fourth component is counter electrode. These are the four components we require for dye sensitized solar cells.

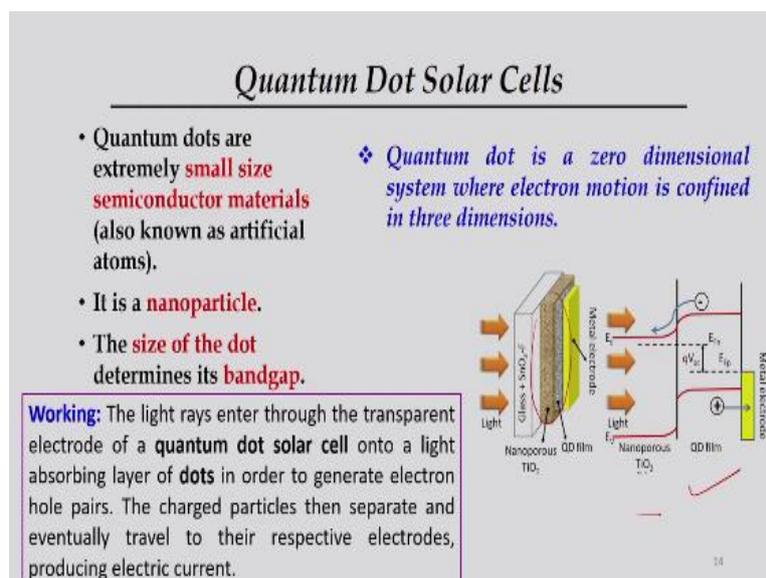
So, if we need to know how it works. A dye sensitized solar cell is a low cost solar cell belongs to the group of thin film solar cells. It is based on a semiconductor formed between a photo sensitized anode and an electrolyte, a photo-electrochemical system.

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So, what are the advantage of this dye sensitized solar cells? It is having lower production cost, it has got design opportunities, it is flexible, it's a light weight and feedstock available to reach terawatt scale, lot of raw materials are available for this kind of cells and bi-facial cells capture light from all angles. So, that is very good advantage of this kind of solar cells and it outperforms competitor for indoor application.

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Now, let us learn quickly what is quantum dot solar cells? So, quantum dots are extremely small size semi conductor material. It is also known as artificial atoms; it is a nanoparticle. The size of the dot determines the bandgap. The quantum dot is a zero dimensional system,

where electron motion is confined in three dimensions. How it works? The light rays enter through the transparent electrode of a quantum dot solar cell on to a light absorbing layer of dots in order to generate electron-hole pair.

The charged particles then separate and eventually travel to their respective electrodes producing electric current, so which is shown in this figure. The transparent cover and then solar radiation has to be observed and then electron has to be separated. So, we can learn this figure as well. So, since we have learned many things about, how this semiconductor works, so there is no point of discussing the things here again.

So, this is a transparent glass cover, it travels and it absorbs, because that has to be absorbed, then hole and electron pair will be generated and then if electric field is generated by providing external voltage, then we can generate electricity.

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Quantum Dot Solar Cells-Advantages

- Due to their tuneable property, quantum dots are integrated in various types of solar cells to increase the power efficiency.
- They are used as alternative to molecular dyes in DSSC.
- Cost of fabrication is significantly lower.

❖ *These nanoparticle based cells prove to be promising candidate for scalable high efficiency and low cost solar cells.*

15

Now, what are the advantages of this quantum dot solar cells? Due to their tuneable property, quantum dots are integrated in various types of solar cells to increase the power efficiency. They are used as alternative to molecular dyes in dye sensitized solar cells and cost of fabrication is significantly lower in this case of solar cell. And these nanoparticles which is used here in quantum dot solar cells, proved to be promising candidate for scalable high efficiency and low cost solar cells.

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PV/T collector

- Solar energy is the most prominent renewable energy source due to its availability around the globe.
- The annual energy potential from solar energy is 23,000 TWy [<http://www.abb-conversations.com>].
- Solar photovoltaic technology is widely accepted.

PV uses light in the range 300-1150 nm

16

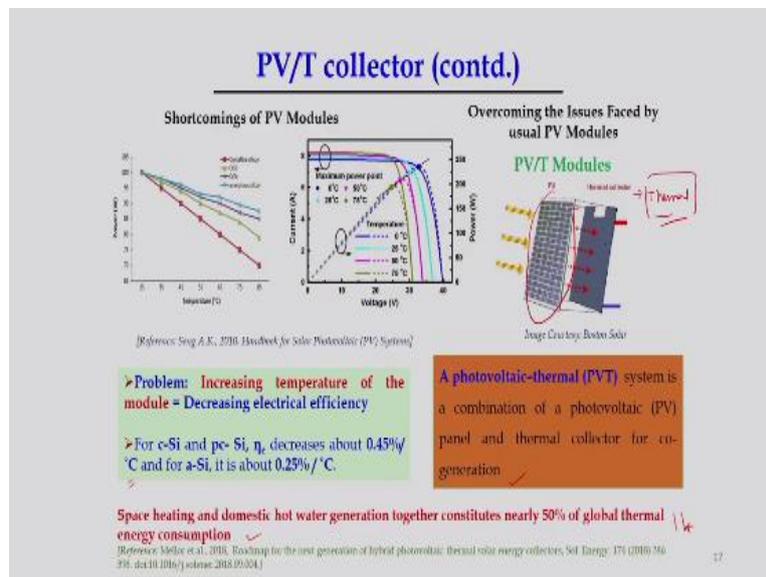
Now, come to the PVT collectors, what is the need of this PVT collectors and what are the difficulties associated with PV collector? So, before we start with the difficulties and then probable solutions, let us have a look about the importance of this part of the system. That solar energy is the most prominent renewable energy sources due to its availability around the globe which is clearly understood by now.

The annual energy potential from solar energy is about 23,000 TW yearly and this solar photovoltaic technology is widely accepted everywhere. And this figure, what we can see with time, the rise in solar photovoltaic energy generation, we can see here. It is huge in 2008, it is about 177 GW of energy which is already produced by solar energy. Now, this spectrum is also familiar to you, it shows the radiation intensity versus wavelength.

So, this wavelength, visible range is used for PV conversion and this is the structure of the PV if we cut the PV module and we will have this kind of things; like we will have first glass then we have transparent conductive oxides, TCO metal grids and then we will have solar cells and then we will have back metal contact then tedler. And then solar radiation is received here in this absorber or in the solar cell where the solar cell is located.

And some part of radiation is reflected back and there are some losses like convective losses and radiative losses, and from the bottom also heat losses will be taking place; so the amount of heat goes off is significant.

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So, what are the shortcomings of PV modules? So, this figure shows the power versus temperature. As you can see here, with increase in temperature this power decreases, that is power means this power delivered by the PV modules or PV cells. And this figure shows the effect of temperature on this open circuit voltage and short circuit current. At the same time, we can see the variation of power with respect to the voltage.

So, if you follow this blue line which is at 0 °C, so V_{oc} is maximum. When temperature increases from 0 to 25 then 25 to 50 then 50 to 75, we can see the change of V_{oc} . Since we know that this power developed by the PV cell or module is a function of open circuit voltage. So, if this decreases, then power delivered by the PV cell or module decreases, so it is a concern.

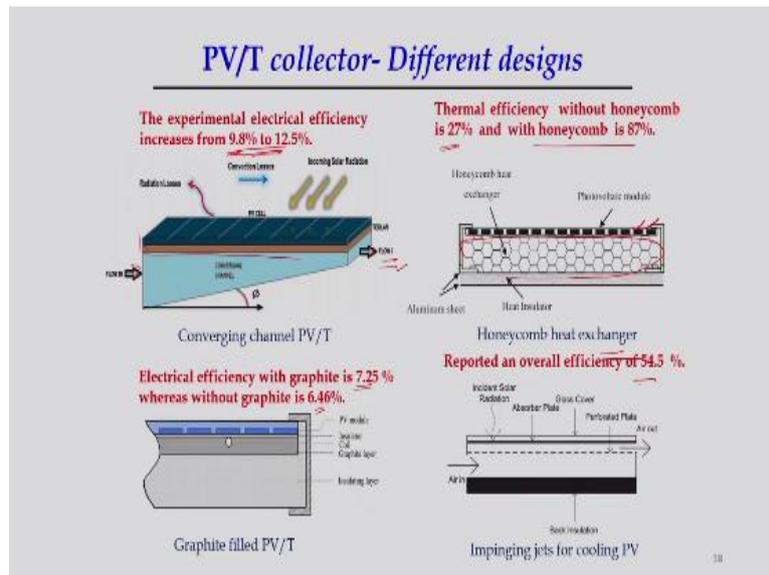
So, how to reduce this effect? If we can do something by providing cooling effect to maintain the temperature, at say 25 °C, then what we are expected; we are expected higher conversion efficiency. So, problem is increasing temperature of the module means decreasing electrical efficiency. For single crystalline silicon cell and polycrystalline silicon cells, this efficiency decreases about 0.45 % per degree increase in temperature.

And for amorphous silicon, it is about 0.25 % per degree increase in temperature. So, how to overcome the issues faced by usual PV modules? So, one option is by providing cooling effect, by using some arrangement at the beneath of the PV module. So, this is a PV module. At the back side, if we make some kind of arrangement which provides some kind of cooling effect, that actually increases the utility of thermal energy as well as increases the electrical conversion efficiency.

So, this photovoltaic thermal system is a combination of photovoltaic panel and thermal collector for cogeneration. So, by doing this what we can get, we can get improved electrical efficiency as well as we will get some kind of useful heat gain, which can be applied for different applications. So, for example, the space heating and domestic hot water generation together constitute nearly 50 % of global thermal energy consumption.

So, if we can make this kind of management, so we can of course, contribute here for providing hot water by using the same PV technology, if we insert one channel just beneath to the PV module.

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So, the experimental electrical efficiency increases from 9.8 % to 12.5 % by providing cooling effect in the PV module. So, if we consider this is a PV module, so some fluid is injected just beneath of the PV module and hot fluid can be taken out from the other end and that can be used for different thermal applications and by doing so, what we can get, we can increase the electrical conversion efficiency.

This is another structure, that is called Honeycomb heat exchanger. So, this structure what happens, thermal efficiency without Honeycomb is about 27 % and with Honeycomb, it is reported to be 87 %. So, this is the PV module and this just beneath of the PV module. Another configuration is graphite filled PV/T. So, here electrical efficiency with graphite is found to be about 7.25 % whereas without graphite, it was about 6.46 %.

Also impinging jets for cooling PV has been reported in many of the literature; it is found that air is introduced in one end of the PV and collect from the other end and this provides a cooling effect to the PV and as reported, an overall efficiency of 54.5 has been achieved by doing this configuration.

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PV/T collector-Experimental setup

Name of the instrument	Parameter measured
Pyranometer	Solar radiation
Thermocouple and data acquisition system	Fluid inlet temperature
	Fluid outlet temperature
	PV/T surface temperature
	Absorber temperature
	Ambient temperature
PV Analyzer	Maximum voltage ✓
I-V curve tracer	Maximum current ✓
Temperature gun	Cell temperature ✓

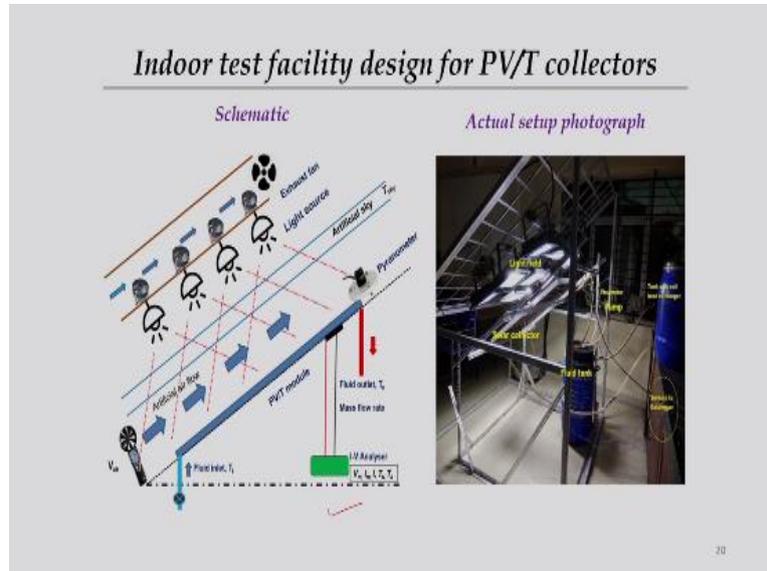
19

So, what we have done here at IIT Guwahati? So, we have purchased one PV module and then we have done something just beneath to the PV module and we tried to see how this can be used as a PV/T module. So, for this arrangement, for calculation or to investigate the performance of this module, what we have done, we have made some kind of arrangement like we have a pump attached with a flow meter, so that regulated amount of fluid can be injected through the tubes which is placed beneath of the PV module.

And then we will have IV tracer, then temperature gun, then pyranometer, and then data acquisition system to monitor the temperature at different locations. So, this is the photograph of the experimental facility what we have developed at IIT Guwahati and the kind of instruments used and then their measuring parameters are shown in this table, like pyranometer is used for global radiation.

And thermocouples and data acquisition systems are used for fluid inlet and outlet temperature, PV surface temperature, absorber temperature, ambient temperature and PV analyzer is used for maximum voltage measurement and IV curve tracer is used for maximum current measurement and temperature gun is used for cell temperature.

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Also we have developed one indoor facility because every time we will not get the amount of solar insolation required for testing. So, we have developed a setup so that we can perform the experiments in the lab itself. So, these lights are installed at a particular light, that was optimized and then PV module to be tested is installed here and then other measurement techniques are installed.

And then we will have data acquisition system to measure all those parameters. And of course, we have IV analyzer from where we can get V_m , I_m , I and these two, T_s and T_a as well. So, once we know these parameters, then we can calculate the performance of the PV/T collector at different irradiance. And this is the actual setup photograph what we have developed for the performance investigation of PV/T module.

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Formulation

Electrical efficiency: $\eta_e = \frac{P_n}{A \cdot G} = \frac{V_m \times I_m}{A \cdot G}$

Thermal efficiency: $\eta_{th} = \frac{\dot{m} c_p (T_n - T_p)}{A \cdot G}$

Energy efficiency: $\eta_{en} = \eta_e + \eta_{th}$

Exergy efficiency of a PV/T: $\eta_{ex} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}}$

$\dot{E}x_{in} = A \cdot G \left[1 - \frac{4}{3} \left(\frac{T_a}{T_{in}} \right) + \frac{1}{3} \left(\frac{T_a}{T_{in}} \right)^4 \right]$
 $\dot{E}x_{out} = \dot{E}x_n + \dot{E}x_t$
 $\dot{E}x_n = V_m \times I_m$
 $\dot{E}x_t = \dot{Q} \left[1 - \frac{T_a + 273}{T_p + 273} \right]$

Also we have to know how to calculate electrical efficiency? So, once we know this V_m and I_m and then amount of solar radiation which is falling on the collector and then area of the collector, so this is the area of the collector and this G is nothing but W/m^2 and this is in volt, in ampere and this is in m^2 . So, $W/m^2 \times m^2$ is W and at that top also, it is W .

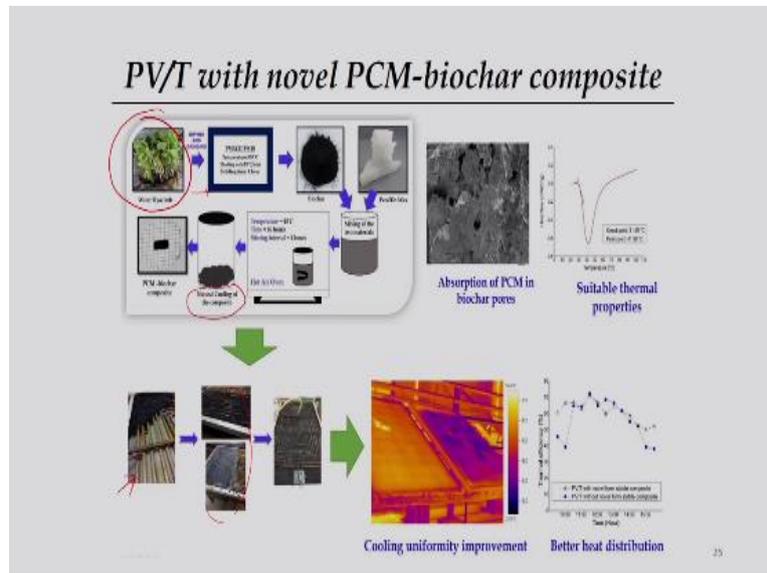
So, both numerator and denominator will be W , so finally it is a dimensionless. So, by using this equation, we can calculate what will be the electrical efficiency of the PV module. And then we can calculate thermal efficiency, once we know this inlet and outlet temperature of the fluid and specific heat of the fluid and then mass of the fluid which is circulated through the tubes, then we know what is q_u and this part is always known to us, because we have pyranometer and area is fixed.

So, from that we can calculate what is thermal efficiency and if we have to say about overall efficiency or energy efficiency, it is a combination of both electrical efficiency as well as thermal efficiency. So, if we add it, it will be something like this. And next may be, we are interested about exergy efficiency of a PV/T. So, how we can calculate it? So, Ex_{out} and Ex_{in} , so what is Ex_{in} ?

So, Ex_{in} can be calculated by using this expression and Ex_{out} compose of two things, electrical and thermal. And again, electrical part, we can use this expression and for thermal

part, we can use this expression. So, once we know this temperature values and then q_u , from there we can calculate what is exergy for thermal part and if we know V_m and I_m , we can calculate what is exergy in the electrical part. So, by doing this calculation, we can calculate what is the exergy efficiency of a PV/T module.

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Also there is emerging technology if we develop some kind of substance which can provide uniform temperature and that too stable. So, that is a very good idea. So, already we have initiated this kind of work. So, work is something like we have collected some kind of biomass. So, for our case it was water hyacinth and then we have pyrolyze it at certain conditions, temperature, heating rate and then holding time.

And we have generated biochar and we have added this biochar with paraffin wax and we have maintained some kind of proportions and finally we have done some kind of analysis and what we got, is a very good composite material for energy storage. So, this material was applied in the PV/T collector. So, we can see here, how we applied this and finally we get this kind of configurations.

And we have tested in both indoor and outdoor experiments. And it is found that, this is giving a very good result as far as stability and control of temperature is concerned. So, this two figures shows some kind of properties which is investigated for this analysis.

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Solar fuels technology

Solar fuels technologies use sunlight, water, carbon dioxide, and nitrogen from the air to produce fuels.

Solar fuels technologies are analogous to natural photosynthesis - plants make fuels (biomass) from sunlight.

Solar energy can be captured and stored directly in the chemical bonds of a material, or 'fuel', and then used when needed. These chemical fuels, in which energy from the sun has been stored, are called solar fuels. What is new here is not the fuels themselves, but the way that we can use energy from the sun to produce them.

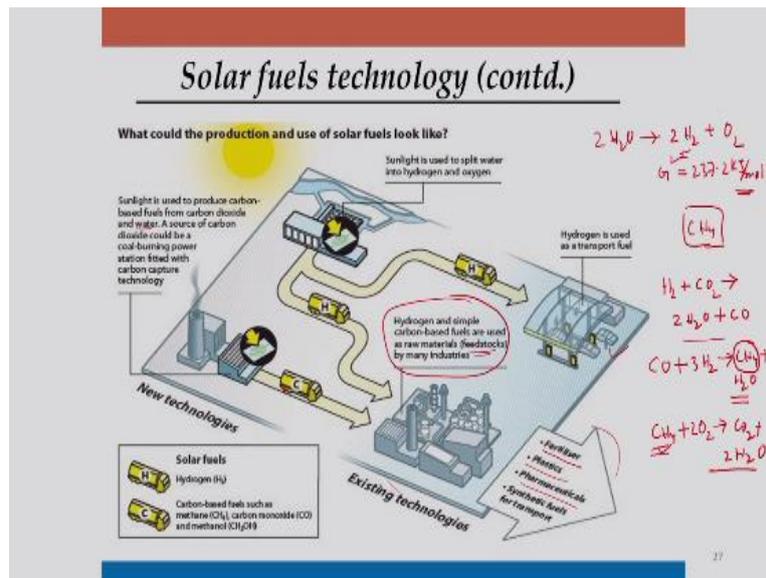
The word 'fuel' is used in a broad sense: it refers not only to fuel for transport and electricity generation, but also feedstocks used in industry.

26

Now come to the solar fuel technology. So, this solar fuel technologies use sunlight, water, carbon dioxide and nitrogen from the air to produce fuels. Solar fuels technologies are analogous to natural photosynthesis, where plants make fuels from sunlight. The solar energy can be captured and stored directly in the chemical bonds of a material or fuel and then used when needed.

These chemical fuels in which energy from the sun has been stored are called solar fuels. What is new here is not the fuel themselves, but the way that we can see energy from the sun to produce them. The word fuel is used in a broad sense, it refers not only to fuel for transport and electricity generation, but also feedstock used in industries.

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Now, have a look into this figure, so which represent solar fuel technology. So, what we can see here is, sunlight is used to split water into H₂ and O₂. So, if we consider H₂O which splits and convert H₂ and O₂. So, energy required for this reaction is given by Gibbs free energy and it has a value of G = 237.2 kJ/mol. So, this hydrogen can be used as a transportation fuel.

Also another way of storage of solar fuel is something like if we can store methane, which is easier than hydrogen. So, already we know the water shift reaction or water gas shift reaction something like, H₂ + CO₂ → H₂O + CO. So, this gas mixture is known as synthesis gas and that can be refined to finally obtain methane. So, finally what it will have, CO react with H₂, it will form CH₄ + H₂O.

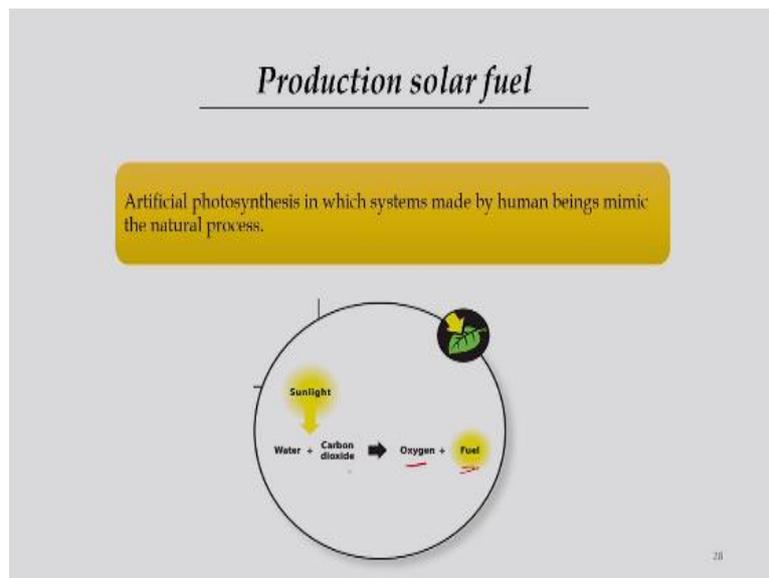
So, this CH₄ can be stored. So, whenever required so this methane will combust or we have to provide oxygen, sufficient oxygen for combustion, so it will generate CO₂ + H₂O. So, what happens now here, this sunlight is used to produce carbon based fuel from CO₂ and H₂O. So, here it is shown here, so once we have this carbon based fuel, that can be combusted and we can produce energy out of it; or maybe we can generate fertilizer, plastic, pharmaceuticals, synthetic fuel for transportation.

So, here in this case what happens, hydrogen and simple carbon based fuel are used as raw material or feedstock by many industries. So, what I mean to say here, so we can split

hydrogen and that can be used as transportation fuel, or we can generate methane and that can be combusted and again we can generate lot of product out of it. So, solar fuels if we talk about then hydrogen which can be stored.

And then second component is methane like carbon based fuel such as methane or may be carbon dioxide or may be methanol. So, these two can be stored and that can be applied wherever required for different applications.

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So, this artificial photosynthesis in which systems made by human beings mimic the natural process. So, already we know what happens when sunlight falls. In presence of sunlight, water and carbon dioxide converted to oxygen and fuel. This is something like glucose which is stored in the plant matter. So, reverse what we need to do for artificial photosynthesis.

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Advantages of solar fuels technology

Hydrogen or carbon-based feedstock such as carbon monoxide and methane could be produced from sunlight, water and carbon dioxide.

This would provide an alternative to natural gas, oil and coal as raw materials.

Solar energy would also replace fossil fuel-derived energy in the production process.

29

So, what are the advantages of solar fuel technology? Hydrogen or carbon based feedstock such as carbon monoxide and methane could be produced from sunlight, water and carbon dioxide. So, this would provide an alternative to natural gas, oil and coal as raw material. Solar energy would also replace fossil fuel derived energy in the production process, what we can understand now.

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Artificial photosynthesis

➤ This process mimic nature with inorganic semiconductor materials that are able to split a water molecule into oxygen and hydrogen using the energy of sunlight.

Pathway of artificial photosynthesis from sunlight to fuel

Challenges in Artificial photosynthesis

- Integrating the different processes and materials involved, from capturing and channeling sunlight for producing chemical fuels.
- Identifying inexpensive catalysts to drive different aspects of the process.
- Developing ways to avoid the system degradation.

30

So, if we pay attention about artificial photosynthesis, what happens, so this process mimics nature with inorganic semiconductor materials that are able to split a water molecule into oxygen and hydrogen using the energy of sunlight. So, input is sunlight and then we have

artificial photosynthesis then product is solar fuel like hydrogen or may be carbon based fuel and finally we have transportation fuel or raw material for industry or may be electricity generation.

What we have already understood and this is the pathway of artificial photosynthesis from sunlight to fuel. So, what are challenges in artificial photosynthesis? So, first challenge is integrating the different processes and materials involved, from capturing and channeling sunlight for producing chemical fuels. And then second challenge is identifying inexpensive catalyst to drive different aspect of the process. And third challenge is developing ways to avoid the system degradation.

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Water splitting

For storing solar energy as chemical energy in the form of hydrogen, **water splitting** can be used,

$$2H_2O \rightarrow 2H_2 + O_2$$

The energy required for this reaction is given by the Gibbs free energy and it has a value of $G = 237.2 \text{ kJ/mol}$. In solar water splitting this energy is provided by the sun.

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graph TD; A[Water Splitting methods] --> B[Electrolysis Of Water]; A --> C[Photo Electrochemical Water Splitting (PEC)];
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31

So, now let us discuss about water splitting. So, what happens for storing solar energy as chemical energy in the form of hydrogen, water splitting can be used. So where, $H_2O \rightarrow H_2 + O_2$. So, already we have discussed, the energy required for this reaction is given by Gibbs free energy and it has a value of about 237.2 kJ/mol. This solar water splitting, the energy required for water splitting is come from sun.

So, there are different methods of water splitting. So, one is electrolysis of water and other one is photo electrochemical water splitting.

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Electrolysis of water

Hofman- Voltmeter lab scale method

At anode,

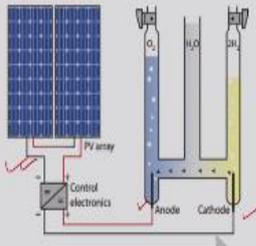
$$H_2O \rightarrow \frac{1}{2} O_2 + 2H^+ + 2e^-$$

At cathode,

$$2H^+ + 2e^- \rightarrow H_2$$

Overall reaction is,

$$H_2O \rightarrow \frac{1}{2} O_2 + H_2$$



Cathode	Platinized (Black) Platinum	An Over Potential Of -0.07 V
Anode	Nickel	Over Potential Of +0.56 V

Combining these two voltages and the over potentials we can understand that the typical over potential is usually around 0.8V. For an over potential is of 0.8V ,

32

PV system with an overall efficiency of around 60%.

solar-to-hydrogen efficiency of $\eta_{SH} = \eta_{PV} \eta_{WES} = 10.9\%$.

So, now let us learn about electrolysis of water. So, this method is known as Hofman Voltmeter lab scale method. What happens, there are three tubes. First tube is cathode and then this tube is anode and in between we will have water reservoir. So, this has to be filled with time and initial energy required will be supplied from this solar array. So, at the anode reaction will be, $H_2O \rightarrow \frac{1}{2} O_2 + 2H^+ + 2e^-$ and this will be in the electrolyte.

And this will retained in the anode and at the cathode, $2H^+ + 2e^- \rightarrow H_2$. And overall reaction will be something like, $H_2O \rightarrow \frac{1}{2} O_2 + H_2$. So, here cathode material is Pt and has an overall potential of about 0.07 V and anode material is Ni and overall potential of about +0.56 V and here is the cathode is -0.07 V.

So, if we combine these two voltages here and here; the over potentials, we can understand that the typical over potential is usually around 0.8 V. For an over potential is of 0.08, then an efficiency of around 60 % will be there in that conversion system. And if we consider the PV conversion efficiency is 18 %, then solar to hydrogen efficiency will be multiplication of 0.18 and 0.6; what we will get is about 10.9 %.

So, if we have over potential of 8 V and under that condition, we will get an efficiency of 60 % for the internal process. And then if we consider PV efficiency of 18 %, then overall efficiency will be 10.9 %.

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Photo electrochemical (PEC) water splitting

The diagram illustrates the components and energy levels of a PEC device. On the left, a cross-sectional view shows a layered structure: Electrolyte, Pt-coated glass, a BVO4 photo anode, a gradient-layer, a TiO2 layer, a glass substrate, a p-Si layer, and an n-Si layer. A voltage source is connected across the photo anode and the n-Si layer. On the right, an energy band diagram shows the conduction and valence bands for the photo anode, the gradient layer, the TiO2 layer, the p-Si layer, and the n-Si layer. The band gap of the PEC device is indicated by a red arrow.

(PEC) device consisting of a BVO4 photo anode and a tandem a-Si:H/n-Si:H solar cell.

Band gap of PEC

The photons reach the surface of the **photo electrode**, which is made of a **photoactive semiconductor**. It creates **electron-hole pair**. The **electrons and holes will be separated** by an electric field, and both will be used in the **two half reactions** involved in the **overall water splitting process**.

To generate the required electrical field, a **voltage source is required**, (for example a solar cell). The photo electrode can be either an **anode or a cathode**.

And quickly let us learn what is photo electrochemical water splitting. So, the photons reach the surface of the photo electrode, this is a photo electrode which is made of a photoactive semiconductor. It creates electron hole pair. The electrons and holes will be separated by an electric field and both will be used in the two half reactions involved in the overall water splitting process. To generate the required electrical field, a voltage source is required.

And this voltage source is nothing, but solar PV energy. The photo electrode can be either an anode or a cathode which is shown here. So, this is about bandgap of this photo electrochemical water splitting process. So, you can see the bandgap of different level.

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Photo electrochemical (PEC) water splitting

Requirements for semiconductor material for PEC

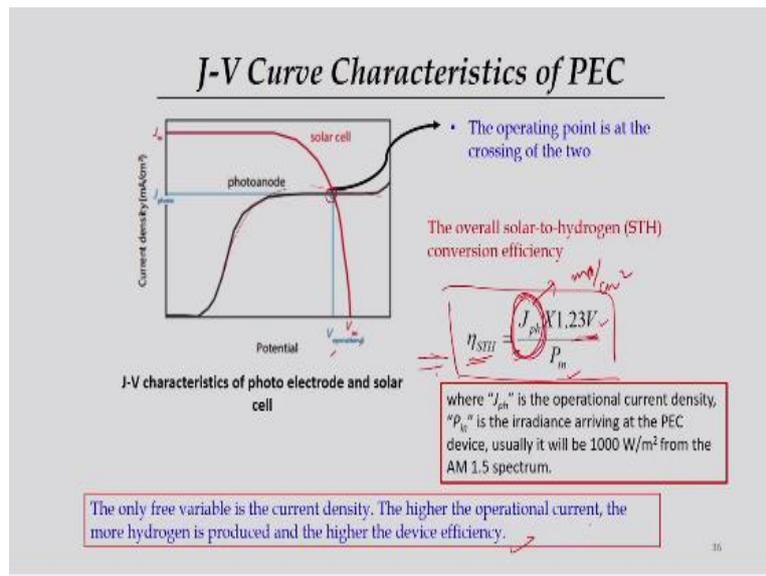
- It has to absorb the light that is incident on its surface.
- The charge carrier transport inside the material and separation into the two electrodes must be efficient.
- It has been estimated that materials with an energy band gap close to 2.1 eV have the potential to split water.
- The energy levels of the reactions have to be located somewhere in the energy band gap of the semiconductor.
- To further enhance the reaction, a catalyst may be added to the semiconductor surface.
- It is important to use materials that are photo chemically stable and relatively cheap.

30

So, requirements for semiconductor material for this photo electrochemical water splitting are, it has to absorb the light, that is incident on its surface. The charge carrier transport inside the material and the separation into the two electrodes must be efficient. It has been estimated that materials with an energy bandgap close to 2.1 eV have the potential to split water.

The energy level of the reactions have to be located somewhere in the energy bandgap of the semiconductor. To further enhance the reaction, a catalyst may be added to the semiconductor surface. It is important to use materials that are photo chemically stable and relatively cheap.

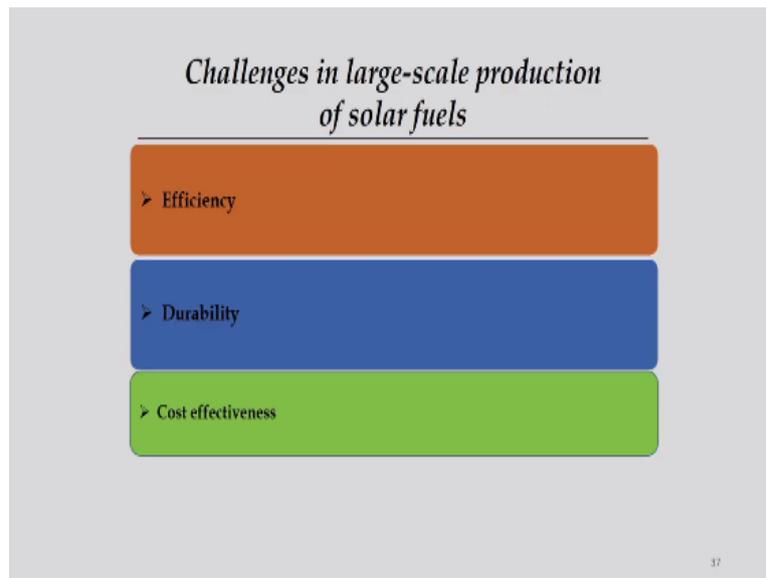
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And also have a look about the IV characteristics curve of this system. So, this is the current density and this is the open circuit voltage and if you see it goes something like this. So, this cross section point is considered and this is the current density and this is the potential. And this is the operating point of the system and the overall solar to hydrogen conversion efficiency can be expressed something like this, $\eta_{STH} = \frac{J_{ph} \times 1.23V}{P_m}$.

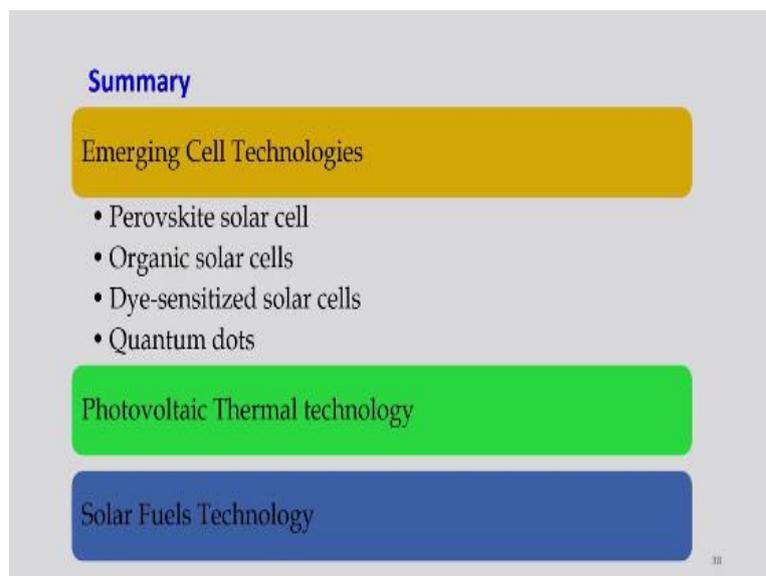
So, this is the current density which is mA/cm^2 and we will have this 1.23V and P is the irradiance arriving at the PEC. So here, this conversion efficiency is a function of current density. So, higher the operational current, that is current density, the more hydrogen is produced and the higher device efficiency. So, if we can increase this value, then it is expected to get higher overall solar to hydrogen conversion efficiency.

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So, there are some challenges in large scale production of solar fuels. What are the different challenges, is the efficiency. So, how to increase the efficiency of those systems; then durability, so lifetime has to be increased. And third point is cost effectiveness. So, how to reduce the cost of the system.

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So, let us summarize what we have discussed today. Primarily we have discussed emerging cell technologies which includes perovskite solar cell, organic solar cells, dye sensitize solar cells, quantum dot cells. And also we have discussed photovoltaic thermal technologies, what is the need, what is the importance of this kind of technologies for enhancing the electrical

efficiency. And also we can get thermal energy out of it. And also we have studied the different techniques for harvesting solar energy as a solar fuel. So, thank you very much for watching this video.