Physics of Renewable Energy Systems
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Lecture 37
Introduction to Fuel Cells

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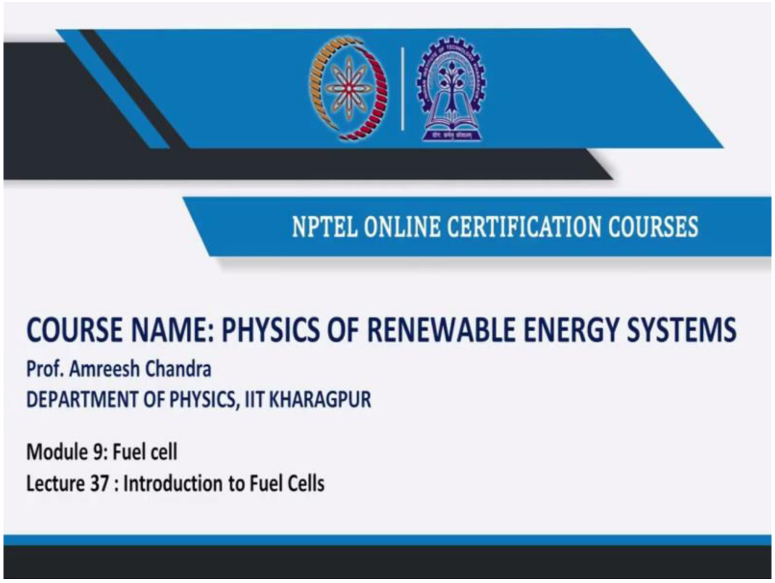

Hello, so, let us start the first lecture of the next module. Today, I will be giving you an introduction to the field of fuel cells. Why do we need them? What are the advantages and disadvantages associated with fuel cells?

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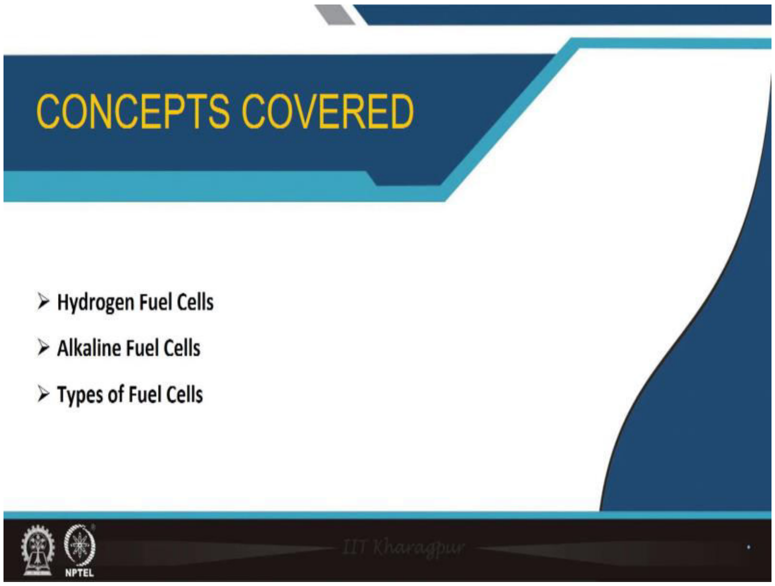

We will be focusing mostly on hydrogen fuel cells, alkaline fuel cells. And based on the discussion on these two types of fuel cells, we will also then go on to describe the other types of fuel cells which are there and are being investigated.

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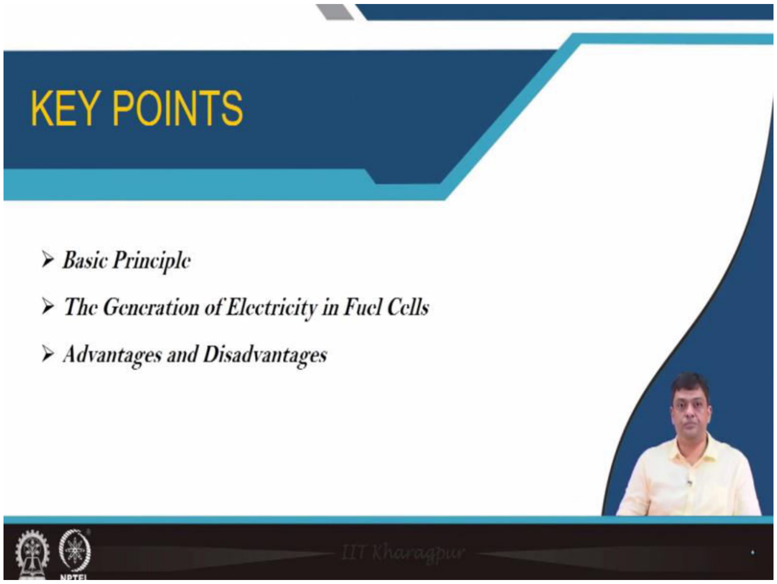

You will understand the basic principle which is used to fabricate or the principle which drives the fuel cell. Why this technology is once again coming back and generating interest as a source for electricity generation. Till now, there are been a lot of disadvantages associated with fuel cell technology that has led to reduced number of focused research going on in India for the last two decades or so.

But now, with the advent of nanotechnology and nanomaterials and our understanding about these two concepts, that is nanotechnology and nanomaterials, we are once again reviving interest in the field of fuel cells. And you will understand why that is happening.

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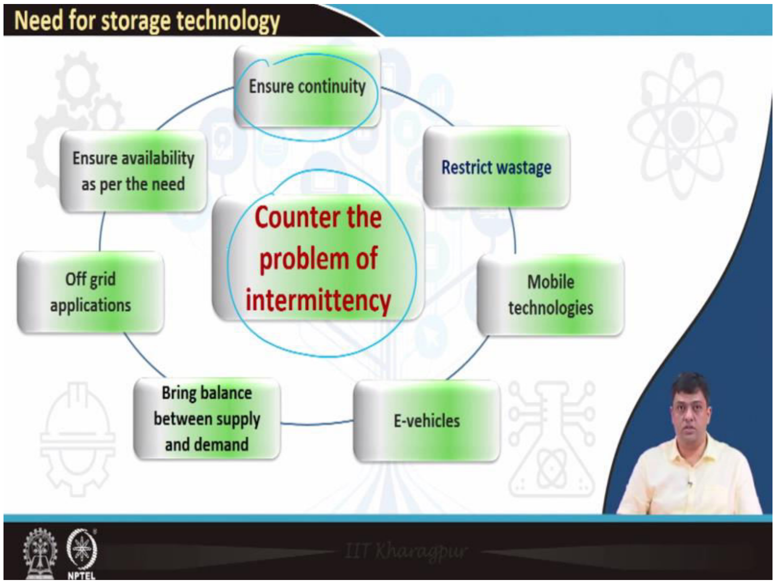

We started the discussion over the last three weeks or so, with the need for energy storage technology We had mostly talked about three concepts that you need storage technologies to ensure continuity, to ensure sustainability and mostly to ensure that you are having the capability to counter the problem of intermittent nature of a renewable based source. And that was the reason why you had energy storage technologies.

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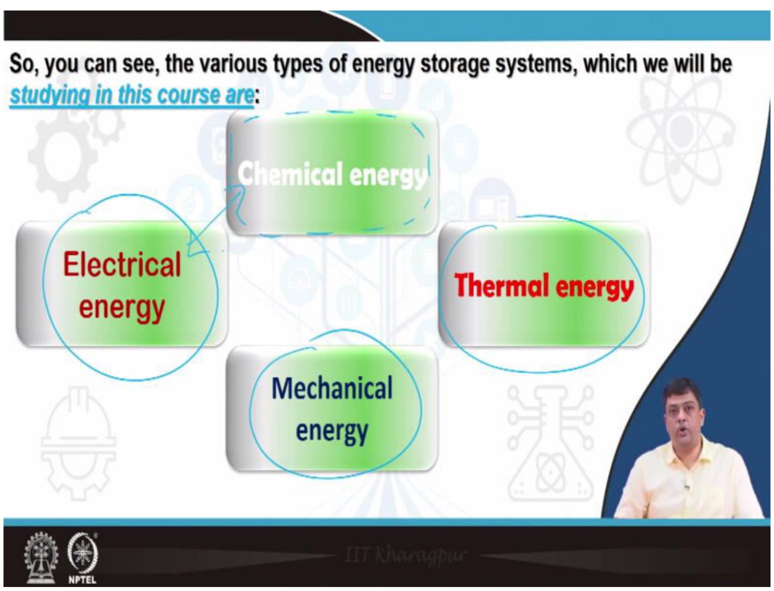

We have talked to you till now about thermal energy storage devices, we have talked to you about mechanical energy storage technologies, we have talked about electrical or electrochemical energy storage technologies. And today, we will start with the final topic which is to be covered in this course, related to energy storage section, where we will talk about the fuel cell technology which is at the interface of electrical and chemical based energy storage technologies.

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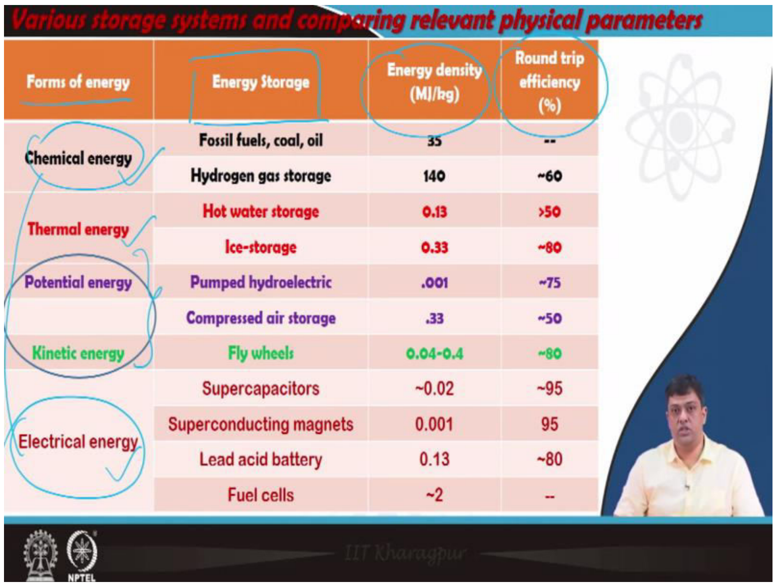

We had seen that depending upon the form of the energy that is either chemical, thermal, mechanical or electrical based, you can have very different energy densities or round tip efficiencies that are associated with the different kinds of energy storage devices that are put under a certain subheading. With this table, you see, we had mostly kept fuel cells under electrical energy. But there are people who also keep fuel cells at the interface of chemical and electrical energy.

So, this is a very good example, where we will use concepts like double layer formation at the electrode electrolyte interface that was leading to the storage capacity in capacitors or batteries. And then also, we will also talk about the use of catalysts in the systems which will lead to the change in the activation energy and the activation barriers, which are mostly used to explain various kinds of chemical reactions. So, therefore, the use of fuel cell can either be kept under chemical energy or electrical energy.

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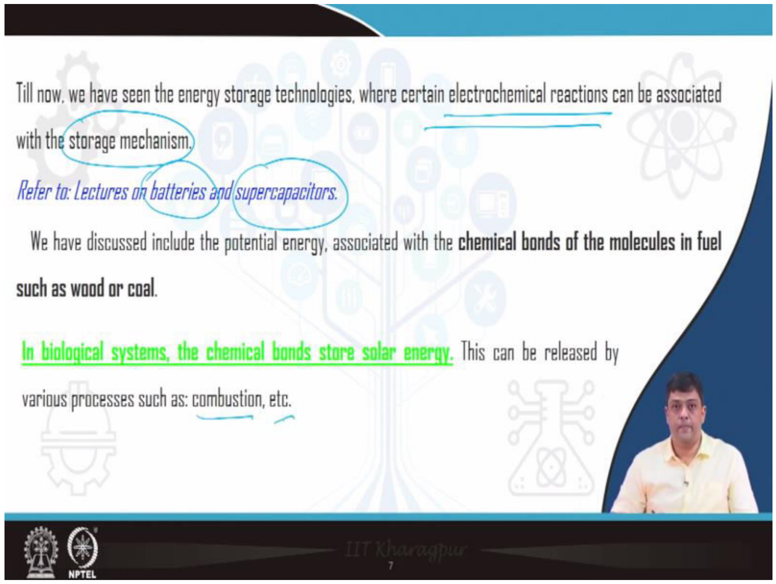

Till now, we have seen a few energy storage technologies, predominantly the ones where we were using the electrochemical reactions and those were driving the storage mechanism. So, you can once again read and refer to the lectures or the notes on lithium-ion batteries and supercapacitors.

We have also discussed the use of potential energy associated with the chemical bonds of the molecules in fuels such as wood or coal that can lead to energy. We have also discussed biological systems where the chemical bonds store solar energy and then you can use these kind of systems to extract energy or drive processes such as combustion or other.

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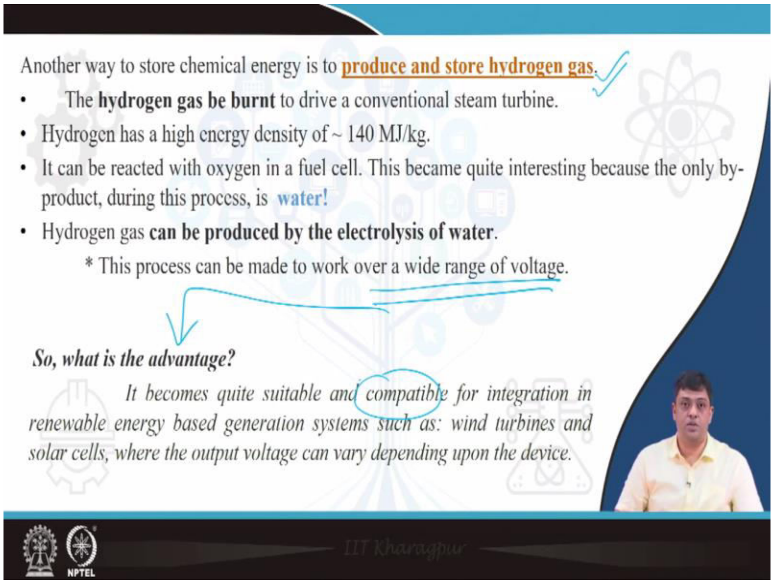

Over the last few decades, we have now clearly realized that there is another way to store chemical energy and that is to produce and store hydrogen gas. If this hydrogen gas is burned, then it can be used to drive conventional steam turbine. So, you use hydrogen gas as the fuel and then the steam which is generated that can drive the turbines which we had discussed earlier. The advantage is that hydrogen has a very high energy density that is of the order of 140 mega joules per kg.

So, it is a huge energy density associated with the fuel and is much, much higher than your petroleum products. So, this can act as a fantastic source to drive steam turbines. In addition, if you play with the chemistry, then hydrogen can react with oxygen in a fuel cell or if you just consider reaction of hydrogen with oxygen, then it gives you a very interesting byproduct because the only by product which you get here is water.

So, you can actually combine hydrogen and oxygen get water and during this reaction, if you can extract the heat, then you can also get heat energy or if you can get electrons then you can use it to drive an electrical circuit. Hydrogen gas can be easily produced by the electrolysis of water and this process can actually be made to work over a wide range of voltage.

So, you can electrolysis the water and what will happen you will get hydrogen. What is the immediate advantage you get? The immediate advantage becomes that this strategy becomes suitable and also compatible, it is important to understand suitability is there, but whether it is compatible with the kind of energy generation units which we are learning, yes, it is also compatible, so that it can work together with the generation systems which we have discussed.

Generation systems like turbines, wind turbines, solar cells and because this process can work over a wide range of voltage, this gives an additional advantage that if you combine with wind turbines or solar cells, where the output can actually vary, then also the process will continue because it can work over a range of voltage. So, it becomes suitable and compatible for integration with the renewable based energy generation systems.

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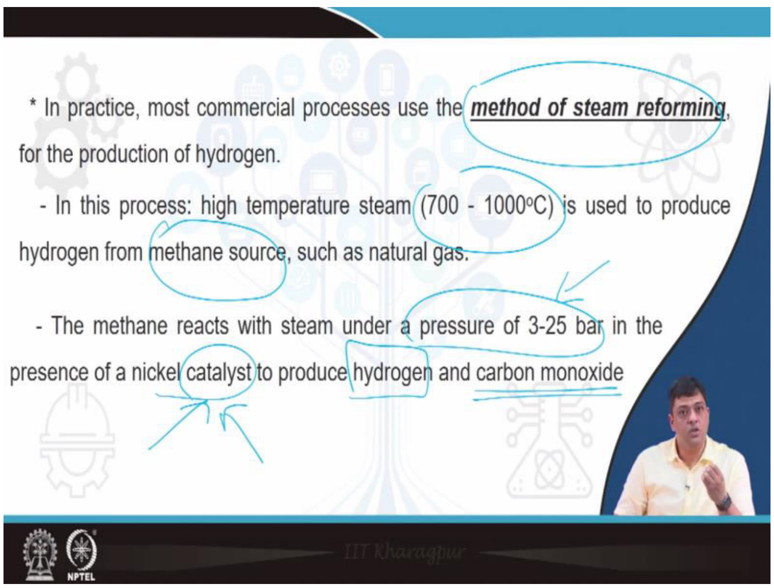

In practice, the most commercial process used to produce hydrogen is the method of steam reforming. This is the most common process where you have high temperature process and is in this the high temperature steam is used to produce hydrogen from methane as the source and this can come from any natural gas also. What happens? Methane reacts with steam at slightly higher pressures in presence of a catalysts and this produces hydrogen and carbon monoxide.

You should understand that this reaction is actually taking place at high temperature as well as high pressure and it is using a catalyst. How do you actually perform this experiment? Increasing the temperature is understood, but at the same time you are talking about conditions where you should also ensure that the pressure is high.

You will see in the next module that there are various processes where you can initiate such kind of reactions, where pressure can also be increased and temperature can also be increased simultaneously and then the reaction can be induced. If some of you already know or have an idea about the protocols, then we are indicating towards the hydrothermal processes.

You have already seen that I have marked a point which is catalysts. Now, catalyst what is the role of catalyst in these kinds of reactions? We have not used catalyst till now in any other discussions earlier then why do we need catalyst? So, these concepts will also become clear as we go along.

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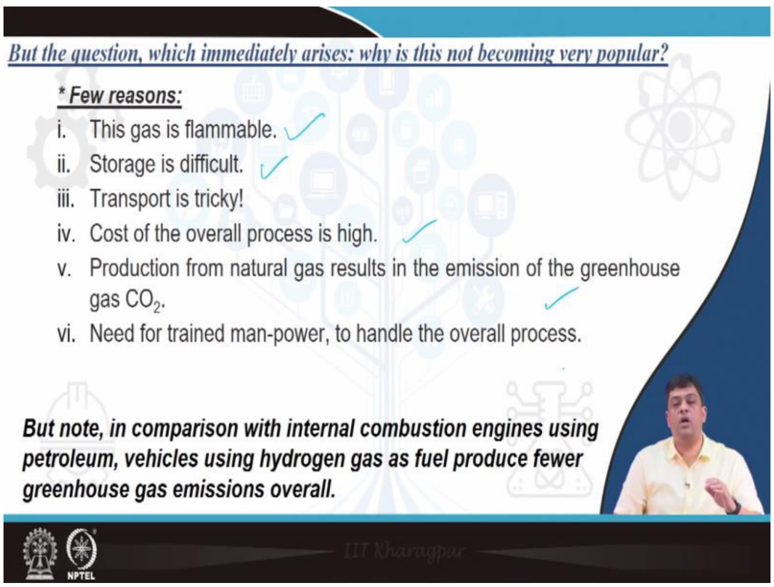

So, it looks to be very advantageous, it looks to be simple, then why is it not becoming very popular or visible around us? There are reasons which are still to be addressed before this technology becomes readily available to common use. The reasoning which can be listed are the gas is flammable. So, that is known to us. Now, how do you actually store hydrogen you just cannot store in, in a vessel. So, how do you store hydrogen gas?

There are various strategies now being proposed and you will see that one of the most common strategy which is coming out is the use of hydrogen storage materials. Again, you will see that materials will play a very important role in storage of the gas itself. And there are various types of materials being proposed. Till now, transport is bit tricky, how do you transport this gas and because of these processes the cost increases.

But you see that you are actually, during the reaction you can lead to emission of greenhouse gases. And all the processes which we have discussed can only be tackled by trained manpower. And therefore, you need to have highly skilled and trained manpower which is not easy or is not cheap you if you have skills, if you are trained manpower, then the cost also goes up of the overall process because you are associating salary of these trained manpower's.

But the advantage remains that in comparison to the internal combustion engines which are using petroleum products, the vehicles or the engines or the processes using hydrogen gas as the fuel produce fewer greenhouse gases overall. So, the number of gases which are going to impact the environment comes down and therefore, the use of hydrogen as the fuel gives you an added advantage that you can actually reduce the overall carbon footprint.

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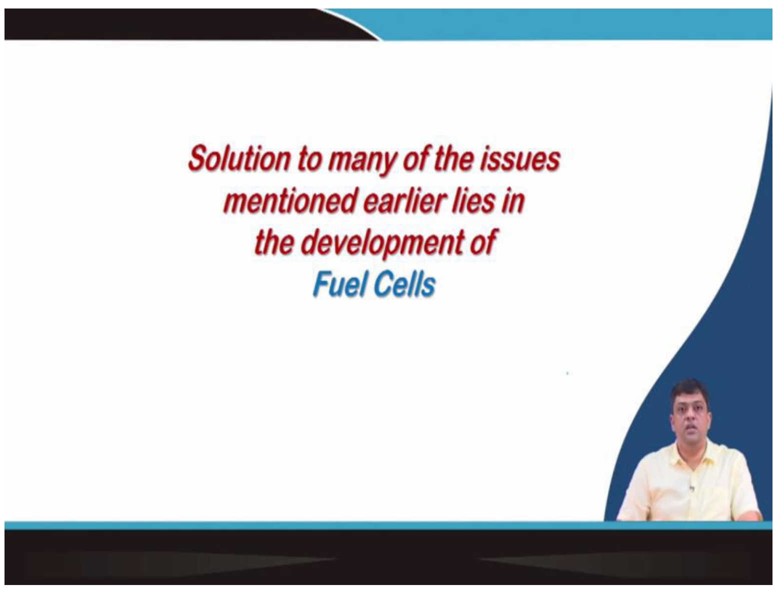

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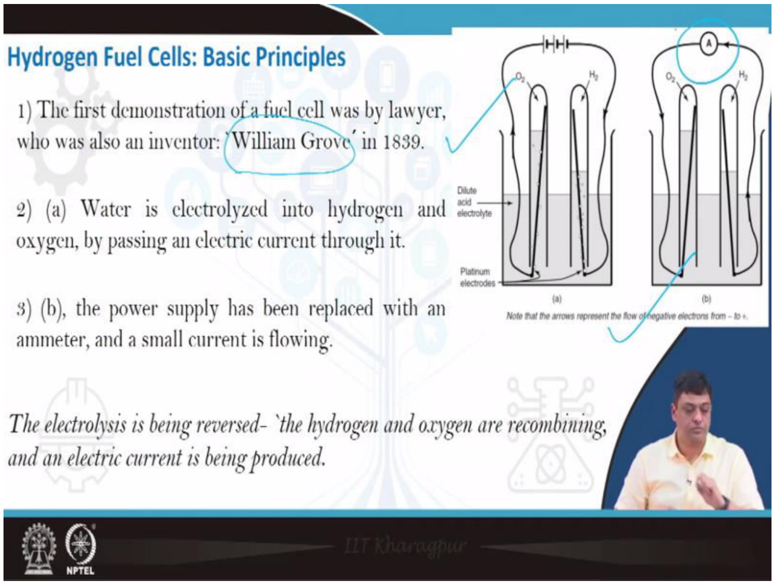

So, let us see how these solutions have come up in fuel cell. In fact, as we have been discussing and moving in most of the modules so let us again proceed in the same manner in this module also. Let us see the development of fuel cell. The concept of fuel cell actually was proposed way back in 1839 by a lawyer, William Grove. And he was a lawyer by profession by but an inventor. So, he was inventing high end scientific or technological devices or scientific concepts were being proposed by William Grove.

And the first example of a fuel cell is actually attributed to William Grove which he had proposed in 1839. So, what you see in the figure a, is that water is, is electrolyzed into hydrogen and oxygen by passing an electrical current through it. And if you reverse the process, then you see in figure b, what is happening, you are having the power supply which is replaced by an ammeter and a small current is flowing through it, because you have reversed the process where hydrogen and oxygen are now recombining and a small electric current is being produced.

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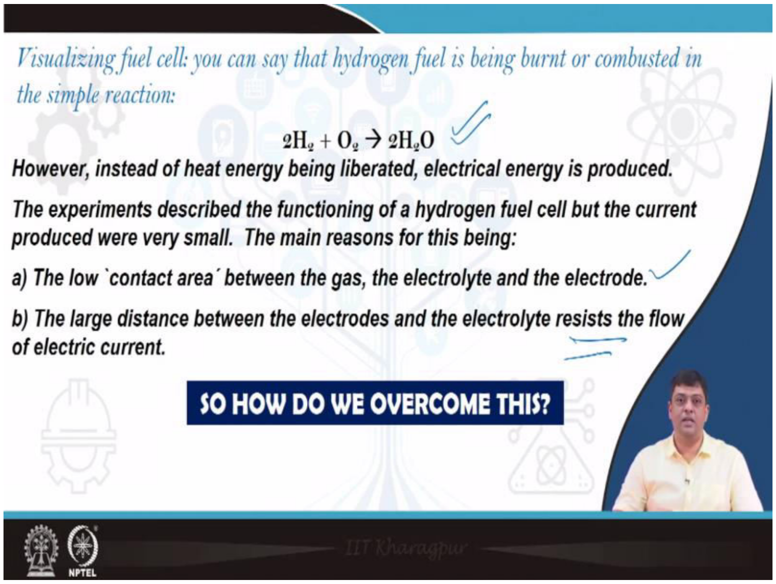

So, if you visualize a fuel cell in a very simple manner, what are you having? You can say that you are using hydrogen fuel which is being burned in a simple reaction to get water. So, you have the reaction. But instead of the heat energy being liberated, you are getting the electrical energy. The experiments describe the functioning of the hydrogen fuel cell, but the currents which were obtained were very small.

And hence, the whole idea was accepted but it did not kick off rapidly. The limited current which you were observing at that time, if you see the literature, then the main reasons which now can be attributed to the observation of low current are that the low contact area between the gas, the electrolyte and the electrode. So, effectively the reaction was happening at a very small area. And therefore, the currents which you are obtaining were quite low.

In addition, there was a large distance between the electrodes. So, the electrodes were far apart and the electrolyte had the resistive effects and the electrolyte itself resisted the flow of electric current. So, if I tell you that these are the two limitations of the first fuel cell which was supposedly proposed, what will you say? Why do not you use an electrode which has large area?

In addition, you ensure that the contact between the electrolyte the gas and the electrode actually occurs over a large area, it is not just that you increase the area of the electrode, but do not ensure that the design is such that the, the interaction between the three is again in a limited area. So, you must ensure that the interaction between the gas, the electrolyte in the electrode is also over a large surface area. So, what will you do?

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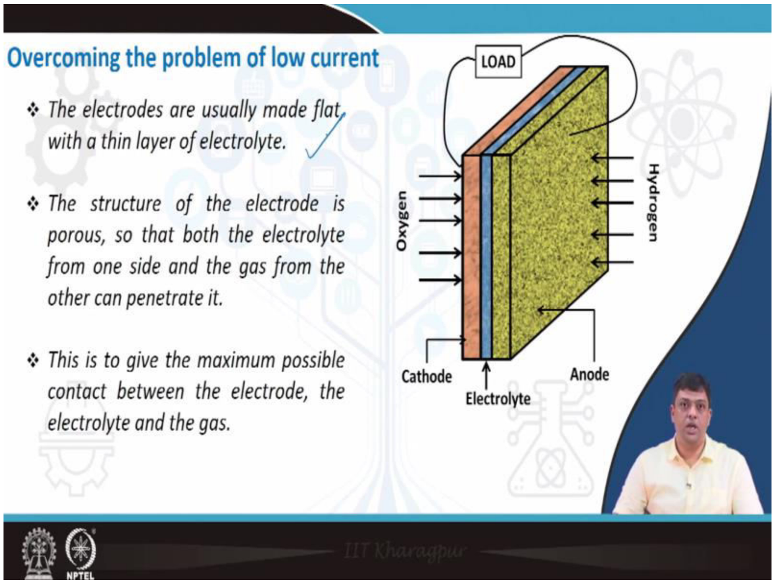

And that was actually addressed in a very simple manner. So, what was done? The electrodes were then made flat with a thin layer of electrolyte. So, you had larger size electrodes, but they were flat. So, electrolyte were interacting throughout the surface of the electron. In addition, you also have to introduce the gas. Gas if it is coming from the ambient surrounding. Then what you need to do? Then, you need to allow the gas to go in. Going from where? From the electrode.

Now, if the gas has to move in, then the idea was that the structure of the electrodes were so, that it was porous in nature. So, it was allowing the gas to penetrate and then you had the interaction of the electrolyte, the gas and you had the electrode which was facilitating the interaction. This way you had higher contact between the electrode, the electrolyte and the gas and the currents which you obtain could be enhanced.

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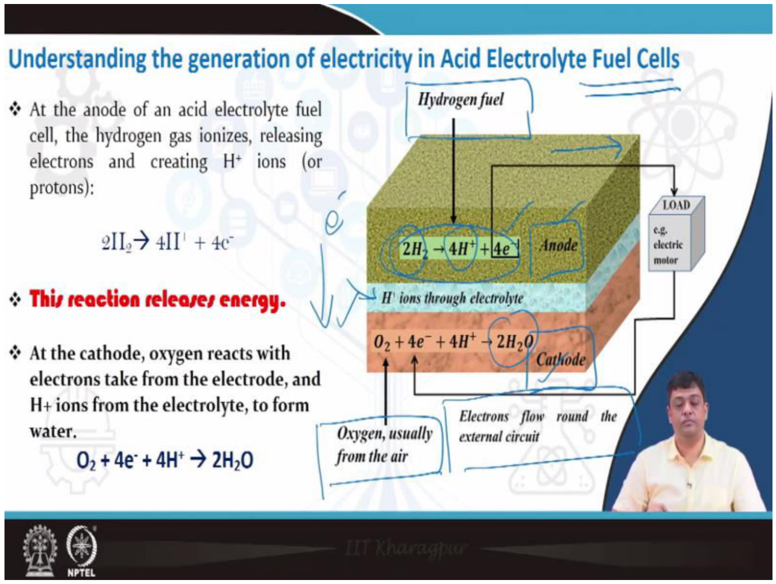

So, if you want to see the reactions, what was basically happening? So, you had the anode, the cathode. Electrons flow around the external circuit, oxygen is usually from the air and you were using hydrogen as the fuel. So, you had hydrogen breaking into 4H plus and giving 4 electrons. Now, H plus half ions have to go through. But do you actually want that the electrons should also go through? If you allow the electrons to go through, what will happen?

You will have short circuit. So, do you want that obviously not, but you want you want H plus to go through so, that the electrons can go through the external circuit and then recombine in the cathode side and you have the charge neutrality condition and what you get is water. So, what should be the nature of the electrolyte? It should be proton conducting. So, it should be proton conducting, but not electron conducting.

Again, just like the concept we are, we had discussed in batteries and capacitor you should have ion conducting membrane, but not the ion conducting membrane which was being used as the separator in those two technologies, which we discussed in the previous three weeks. So, you now, you have the anode, the cathode and the electrolyte. I have repeated these three things anode, cathode and electrolyte.

You have already seen in the previous modules that you can have different types of anodes; you can have different types of cathodes and you can also have different kinds of proton conducting electrolytes or membranes. And hence, you can now easily make different kinds of fuel cells, because you can synthesize different kinds of cathodic material or anodic materials and also you can have different kinds of electrolytes or membranes. Hence, the fuel cell technology is coming back and attaining prominence.

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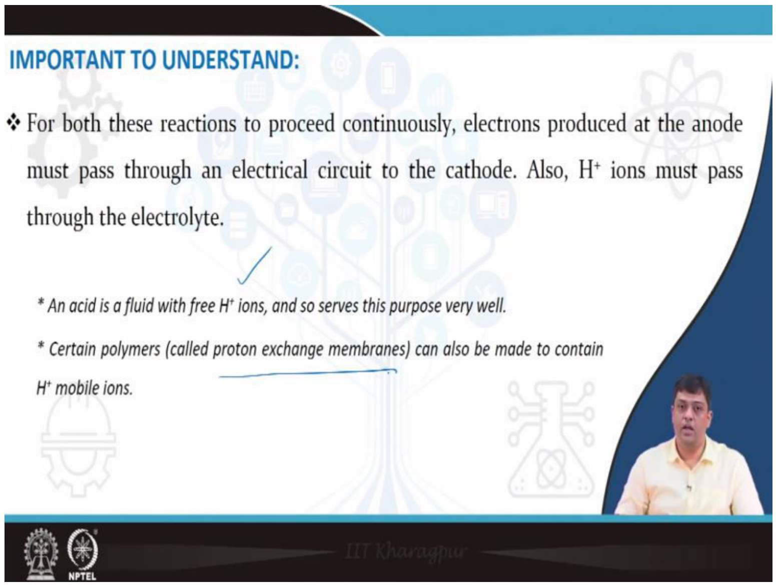

At this point, please remember I have mentioned two things that electrons produced at the anode must pass through the electrical circuit so as to reach the cathode and the protons must pass through the electrolyte. And I hope you remember what is an acid? Acid is something which has free H plus ions and hence, this can work as a very good electrolyte in acid fuel cell and you can also otherwise replace this with proton action membranes, which actually does the same purpose that they allow the protons to go through whereas, they prevent the flow of electrons.

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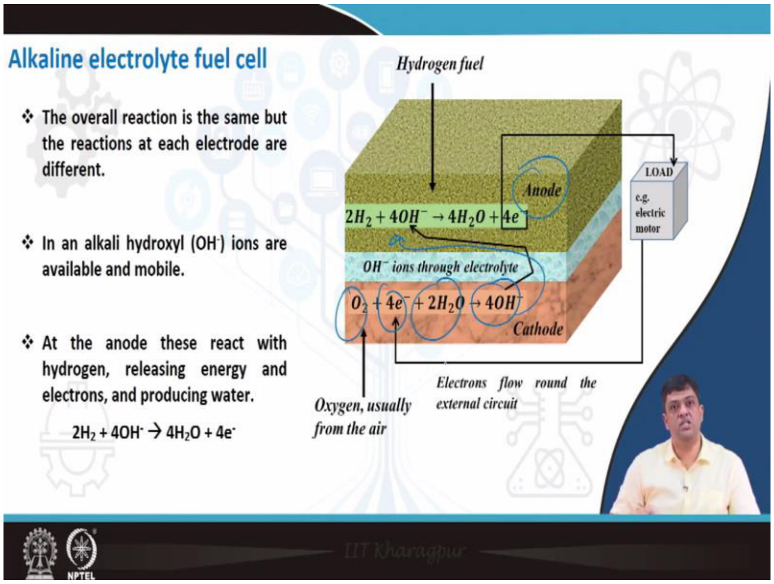

The next one came was that you replaced your acidic electrolytes and then you started using alkaline electrolytes and you had the advent of alkaline electrolyte fuel cells or AFC's, Alkaline Fuel Cells. The overall reaction is the same, but the reactions at each electrodes are slightly different. So, the overall functioning is the same, but what you get is slightly different. So, now, you are getting 4OH minus radicals.

So, you are getting alkaline hydroxyl ions and these are mobiles and at the anodes these react with hydrogen releasing energy and electrons and producing water. So, the concept was similar, but now, the flow of the mobile ion which you are considering is slightly different. So, there you are considering the flow of H plus and now you are considering the flow of OH minus. And then therefore, the reactions which are taking place occur at the different electrodes and the byproduct which you see is now at the anode.

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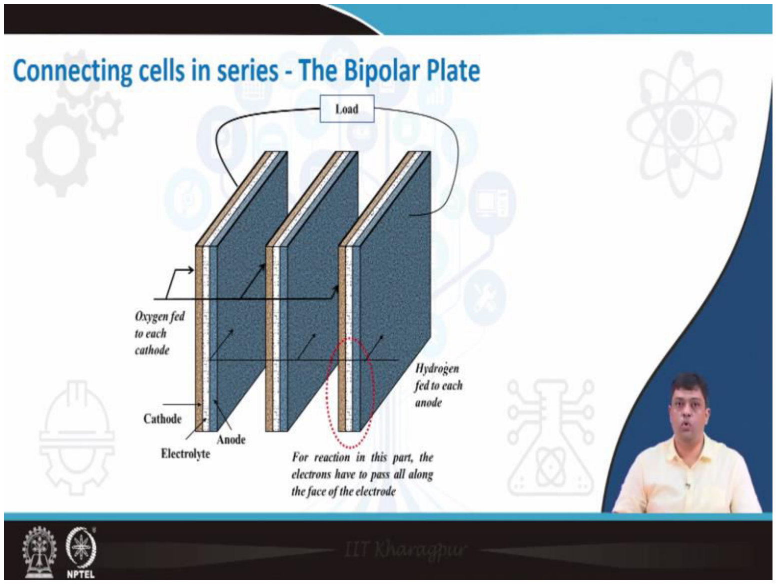

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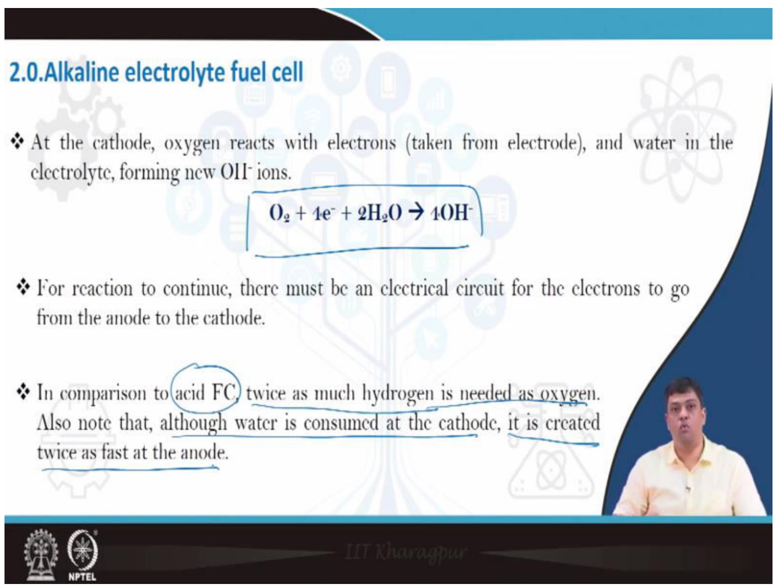

You can combine these cells together and you can again get the stack of fuel cells and then you can increase the overall current which can flow through the external point. So, at this point, we have already seen the reactions which take place in the alkaline electrolyte fuel cell and in comparison, to the acidic fuel cell twice as much hydrogen is needed as oxygen but, water is consumed in cathode it is created twice as fast as the anode. So, you do consume water, but you also produce water at a much faster rate.

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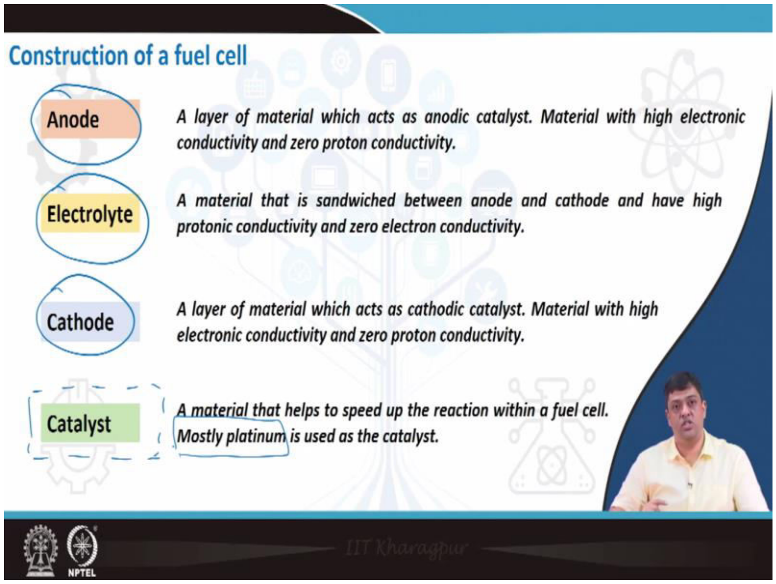

Now, one thing must be clear to you, the functioning of fuel cell will depend on what it will depend on the kind of anode material you use, the electrolyte you use, the cathode material which you use and in addition, a new concept comes into picture that is catalyst. Because, if you can increase the rate of reaction, then the overall process will become even more efficient.

And catalysts are therefore, used in fuel cells so, as to speed up the reactions within the fuel cells. And mostly till date, platinum is used but with the advent of nanotechnology and nanomaterials, there are much cheaper, readily available and useful catalysts which can be produced in bulk are being utilized to develop the next generation fuel cells.

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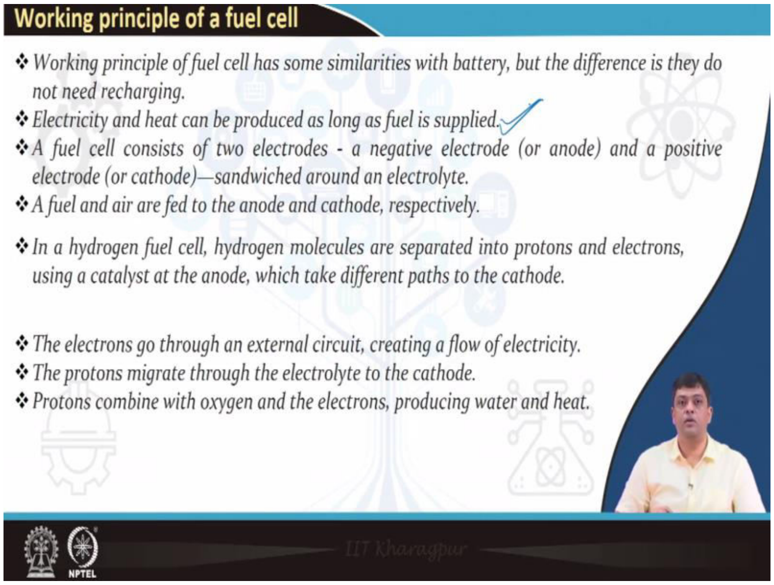

So, I hope the working of the fuel cell is clear by now and this is just the revision of the same, if you want to understand everything I have said till now. There is a slight difference between the working principle of a fuel cell from the battery. What is that? That fuel cells do not need recharging.

And you have already seen that during the working of a fuel cell electricity and heat can be produced as long as the fuel is supplied. So, you keep on supplying hydrogen and the process will continue. The main components are the anode, the cathode material, the electrolyte and in addition the catalysts.

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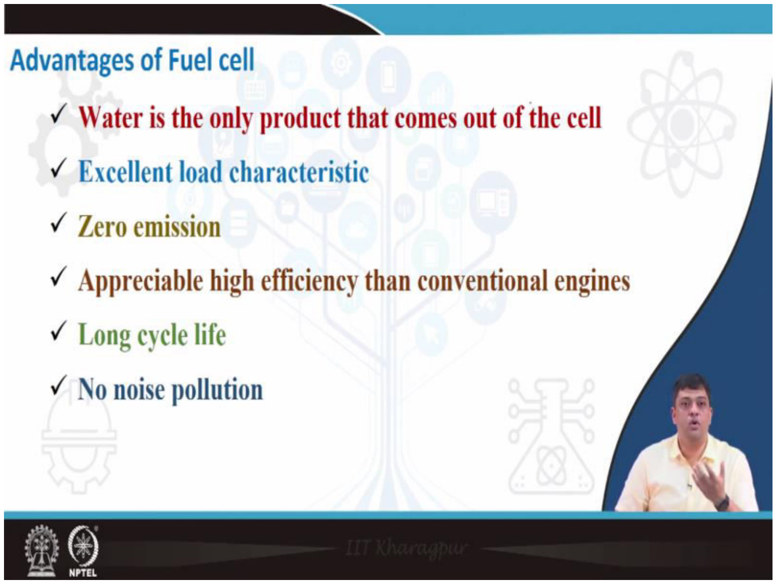

So, the immediate advantages which you can see that water is the byproduct which you are obtaining. It can have excellent load characteristics. If you have water as the byproduct then the overall emission which you are talking is practically zero which is emission in terms the ones which are going to affect the environment. So, you do not have toxic emissions.

The process can be quite efficient if you use efficient materials. As you have seen, that the process can continue as long as the fuel is being supplied. So, you have long cycle life of these fuel cells and the operation is quite silent. And so, the overall functioning of the fuel cell does not lead to noise pollution.

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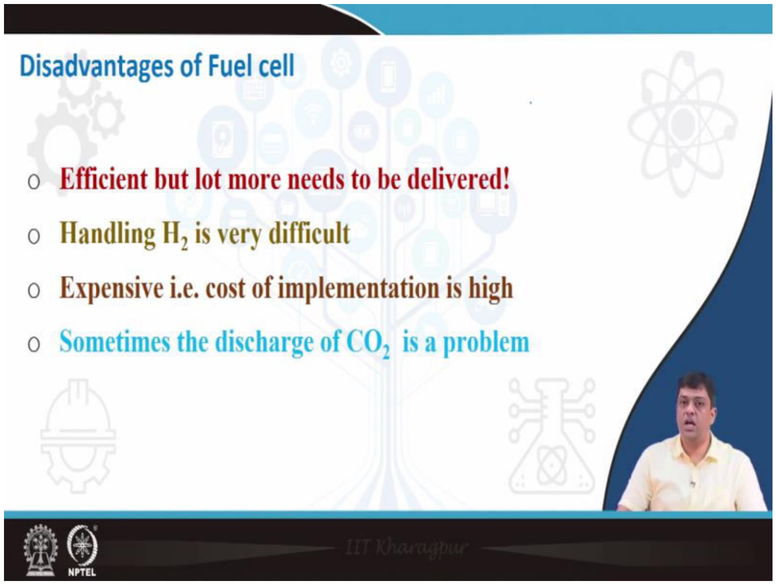

But there are still disadvantages which are associated with the operation or the construction of the fuel cells. And once you can overcome this, the disadvantages mentioned here, fuel cells will become quite important to us. They are efficient, but lot more needs to be delivered in terms of energy densities coming out of these fuel cells.

Till you have even more efficient materials to store hydrogen and then deliver it for ensuring the working of the fuel cells, handling of hydrogen continues to be a limiting factor. Overall construction is still on the expensive side because you use expensive catalysts the, the fabrication of the membranes and the, the whole system involves many steps. And therefore, the product, the product becomes quite expensive. And sometimes the discharge of CO_2 is a big problem.

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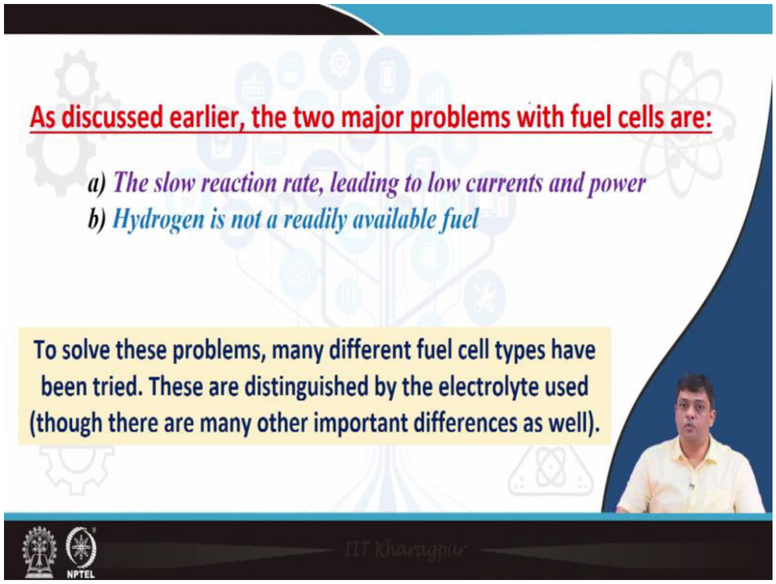

So, just a revision. What are the two major problems? Slow reaction rate, leading to low currents and powers. And hydrogen is still not readily available fuel and there are problems associated with the transport of hydrogen itself. So, if you can counter these problems, you will get the advantages which are quite a few and then fuel cells will become very useful to us.

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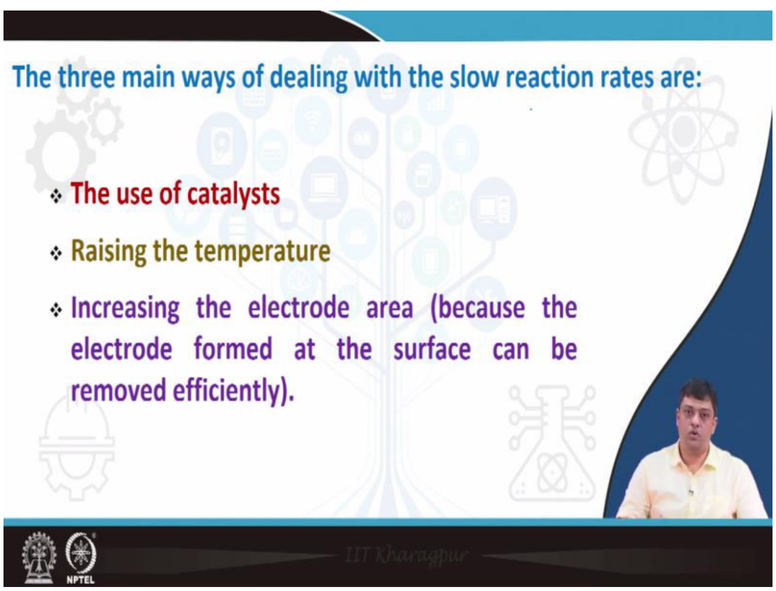

So, what are the ways people are working and you can see that these are the factors which can be used to counter these low reaction rates. If you want to increase the reaction rate, what should be the way? Obviously, people will say yes use a catalyst or you raise the temperature so that the activation barrier height lowers down and then the transfer can take place and you have the reactions moving much faster.

And in addition, increase the electrode area so that the contact between the gas, the electrolyte and the electrode, where you have deposited the catalysts also that can increase and then you have a higher reaction rates. So how do you want to increase the electrode area? Maybe from previous modules also you have seen that probably we are indicating towards the use of nanomaterials where you will have very high specific surface areas and that can lead to enhanced contact areas between the gas, the electrolyte and the electrodes area.

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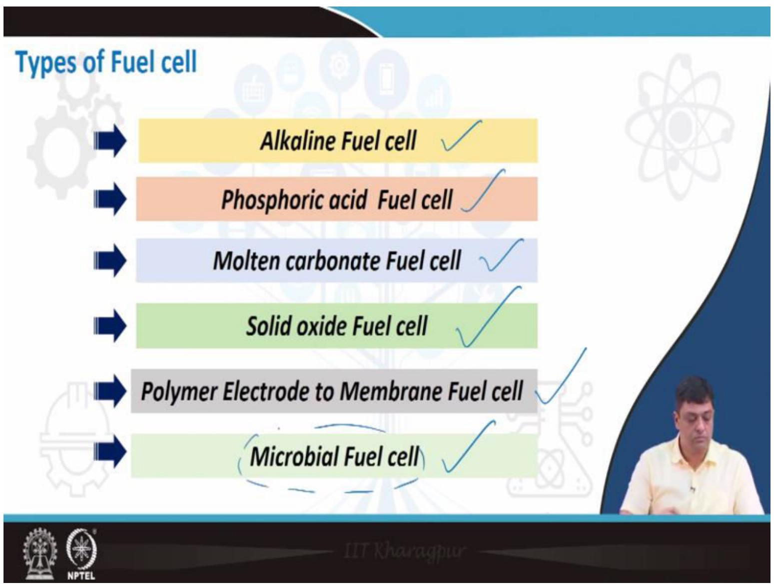

So, based on the operation, based on the kind of membranes or the temperature range or the source of fuel which you are using there are various types of fuel cells, you have alkaline fuel cells, you have phosphoric acid fuel cells, you have molten carbonate fuel cells, you have solid oxide fuel cells, then you have polymer electrode to membrane fuel cell and a technology which is very interesting, where you use the bio wastes as the source for extracting electrons is the microbial fuel cells and a lot of work is actually being done in India in this field.

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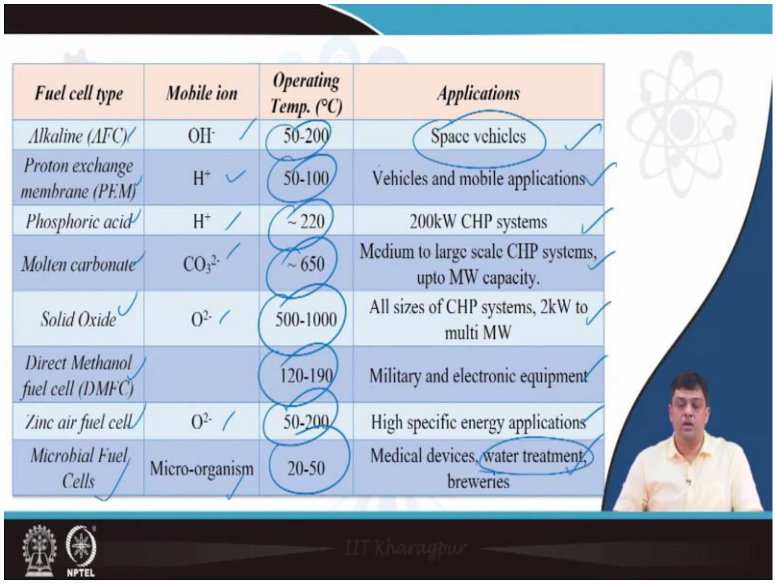

Fuel cell type	Mobile ion	Operating Temp. (°C)	Applications
Alkaline (AFC)	OH^-	50-200	Space vehicles
Proton exchange membrane (PEM)	H^+	50-100	Vehicles and mobile applications
Phosphoric acid	H^+	~ 220	200kW CHP systems
Molten carbonate	CO_3^{2-}	~ 650	Medium to large scale CHP systems, upto MW capacity.
Solid Oxide	O^{2-}	500-1000	All sizes of CHP systems, 2kW to multi MW
Direct Methanol fuel cell (DMFC)		120-190	Military and electronic equipment
Zinc air fuel cell	O^{2-}	50-200	High specific energy applications
Microbial Fuel Cells	Micro-organism	20-50	Medical devices, water treatment, breweries

In terms of their operating temperatures, you can clearly see that it can vary. So, you can use different kinds of fuel cells, they will be operated in different temperature range, you will have different kind of mobile ions in these fuel cells and they will be using different kind of catalysts and based on the energy densities which you can get out of these fuel cells, the range of applications can be quite varied. So, you can go from water treatment to space vehicles and they are all dependent on the parameter that is energy densities delivered by the fuel cells.

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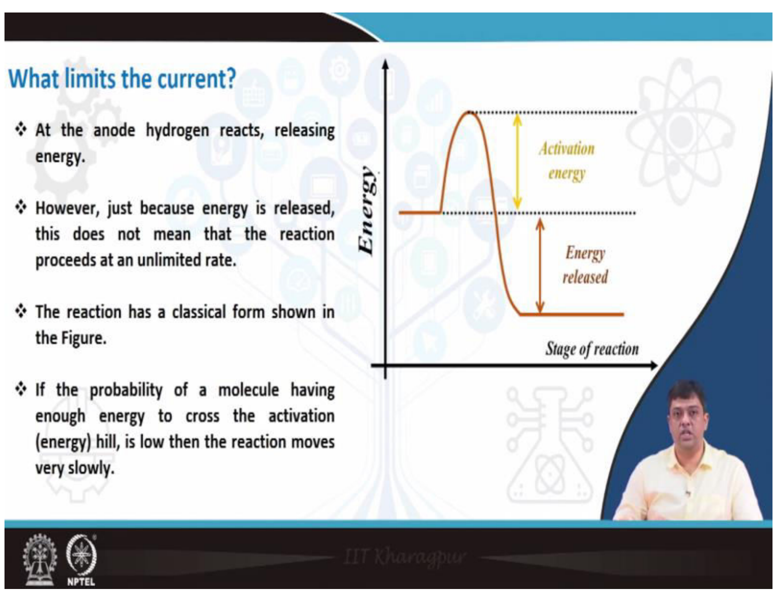

In the next lecture onwards, you will see that the limiting factors again come from the activation barrier. And how do we counter this limitation will become clear in the next two lectures. I have just given you this slide so, that you have an idea as to what is the problem which is there and how are we countering this problem in the fuel cell technology.

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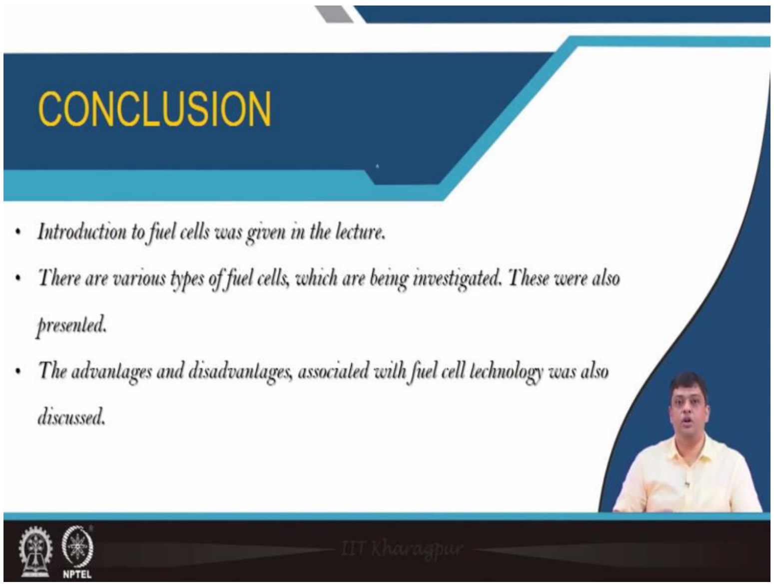

So, I hope today you have understood the basics of fuel cell. What are the various types of fuel cells? Why do we classify the fuel cell based on the materials that are used to fabricate the fuel cells? What are the reactions taking place in fuel cells, the advantage that you have zero emission of toxic waste and mostly you have water as the byproduct which is a big advantage in the fuel cell technology?

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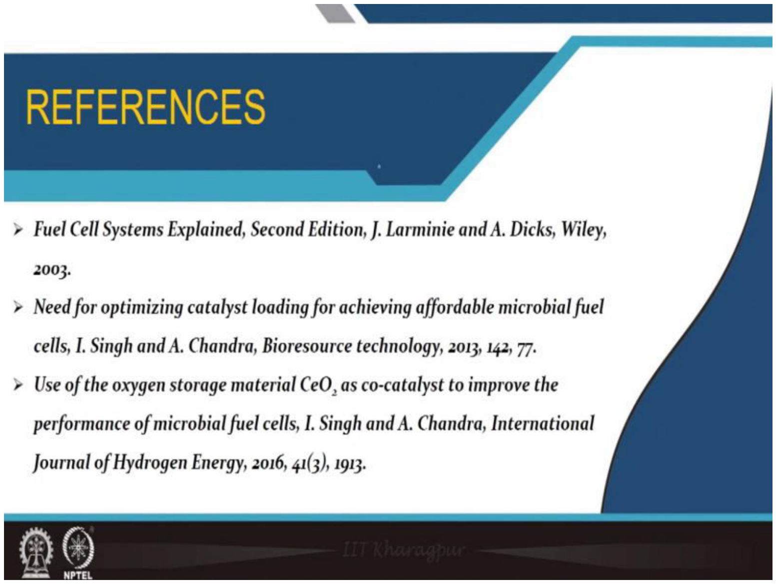

But there are also disadvantages associated with this technology that needs to be addressed before fuel cells become very important to us. These are the major references which were used to prepare the lecture notes today, and you can refer to them for further knowledge and I thank you for attending today's lecture.