Physics of Renewable Energy Systems
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Lecture 22
Basics of Mechanical Energy Storage

Hello. Let us continue with our discussion on energy storage technologies. In the previous lecture, you have seen the use of solar based energy storage technologies and how those can be useful for India.

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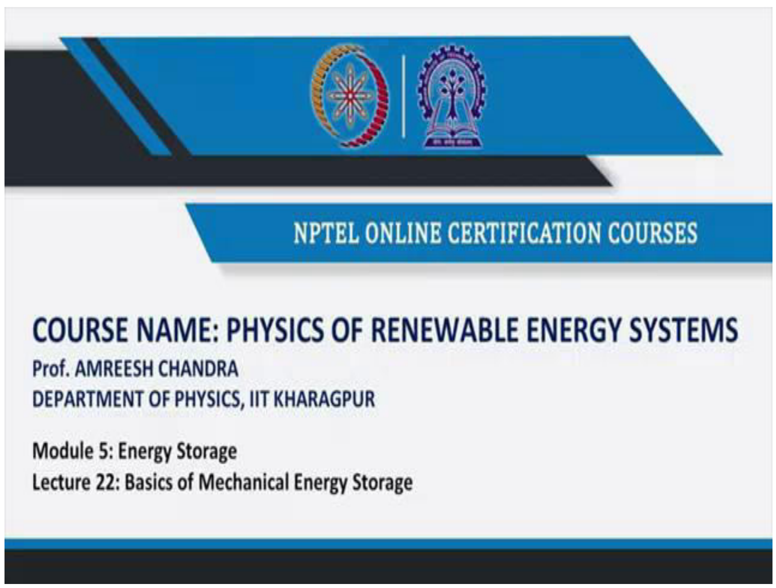

We will talk about the next classification of the storage technologies, the classification which we had mentioned as mechanical energy storage technologies. In today's lecture, I will talk to you about the basics of mechanical energy storage technologies and also give you an example on one of the mechanical based energy storage system that is used.

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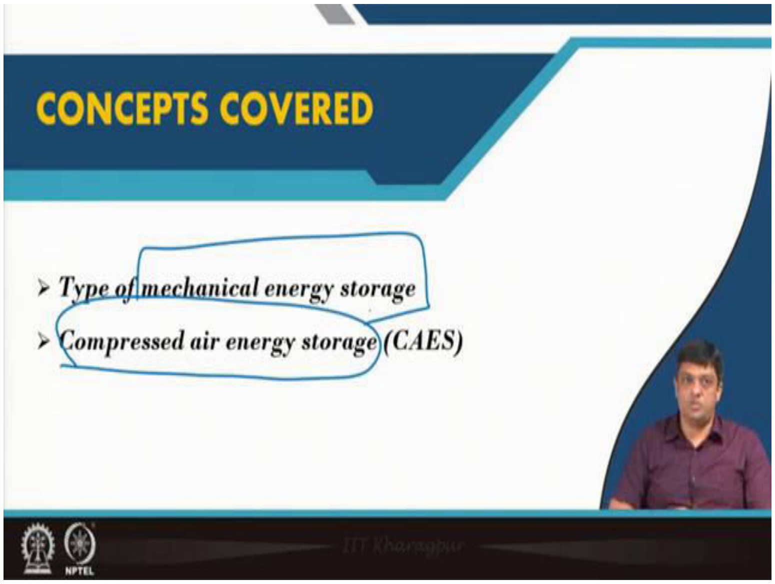

We will give you the example which is based on compressed air energy storage technology and this comes under the heading of mechanical energy storage systems. So, these are the two main topics which would be covered in today's lecture.

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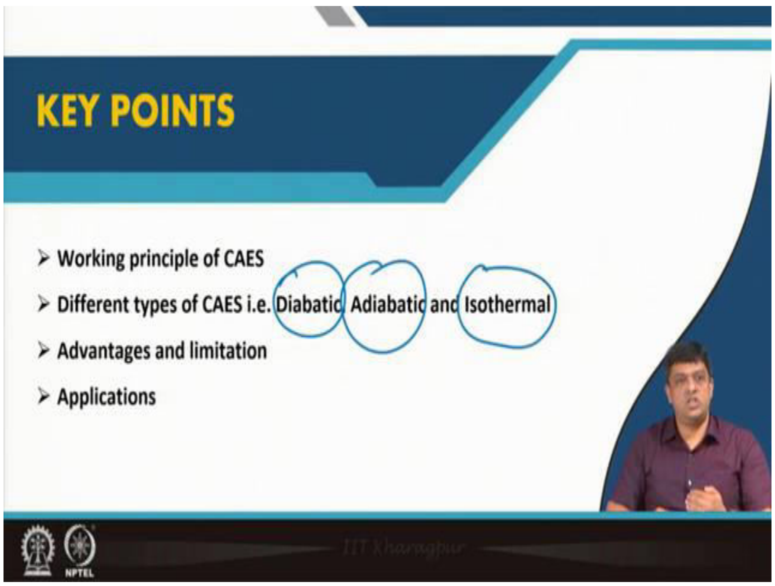

You will be able to understand the working principle of the compressed air energy storage system. You will see that there are different types of the storage technology that is the compressed air energy storage technology, they are diabetic, adiabatic or isothermal type. How they differ from each other that will also be explained. Each of them have certain advantages and limitation which restricts their use.

I have not said limitations, because I will be talking to you about one of the major limitations and then we can go to the minor associated limitations which are there with each of these technologies. And finally, you will also be able to explain the areas where such kind of systems can be easily used.

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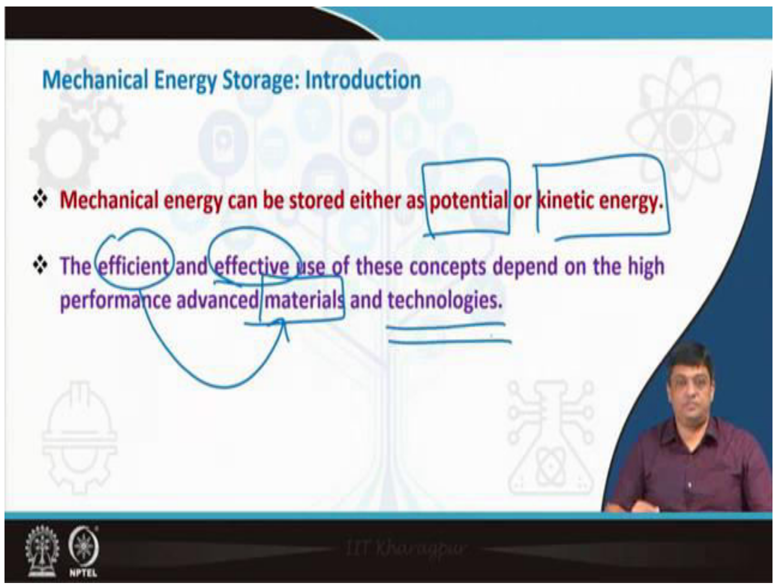

The mechanical energy storage technologies are the ones which are storing energy either in the form of potential energy or kinetic energy. The efficient and the effective use of these concepts depend on the high-performance advanced materials and technologies. This is a sentence written on this slide. What does it mean?

Efficient use, we will come to effective bit later. Efficient, that means, you must have materials which are able to give you high efficiencies, you must have technologies which are able to synergistically contribute in improving the efficiencies and they do not lead to in the loss of the performance or the efficiency.

Effectively, you are talking about systems or technologies those are based on materials which can be used in various applications, while they maintain high levels of efficiency. So, this is what this sentence means. And the moment we talk about materials, you will see that you can make such systems using various kinds of materials.

They can be heat insulators, they can be heat exchangers or they can be any other kind of materials that are used to fabricate the various components, because these technologies involve many components and each of these components are made using different types of materials, so the performance of the materials which are used in different components have to be of high order then only this technology will become effective.

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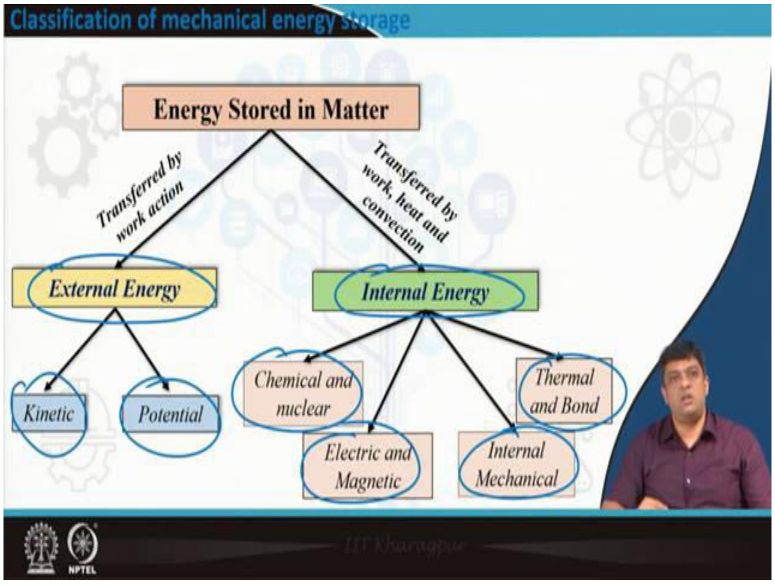

The mechanical energy storage technology is mostly classified under two types of heading. The one which is storing the energy which is in the form of let us say external energy that is transferred by the work action or the ones where you are talking about internal energy or the change in the internal energy which is transferred by work, heat and convection. So, if you are talking about the energy stored in matter due to external energy then you are talking about the kinetic energy or change in the potential energy.

When you are talking about energy stored in matter because of changing heat, convection or work, then, and you are talking about the internal energy of the matter or the material, then you are talking about the change in chemical and nuclear energy, electric or magnetic energy, the internal mechanical or the thermal or the energy associated with the bond structure of the material. So, these are the typical ways in which you talk about the energy stored in matter and if you can use these then can you make systems which can be useful for energy storage.

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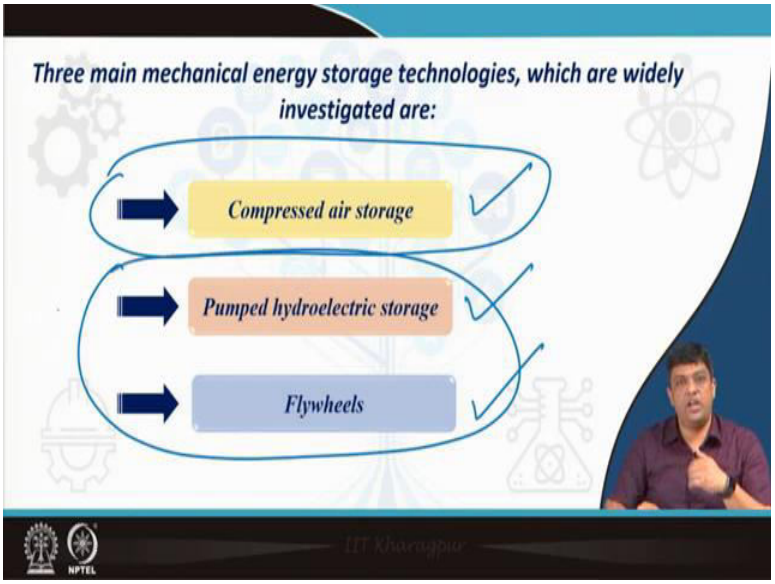

There are three main mechanical energy storage technologies which are being investigated and to an extent also being proposed for use in India, the first one is the compressed air storage technologies, the pumped hydroelectric storage technologies, and the third, the flywheels. I hope to cover the first topic in today's lecture and the other two, I will be covering in the next lecture.

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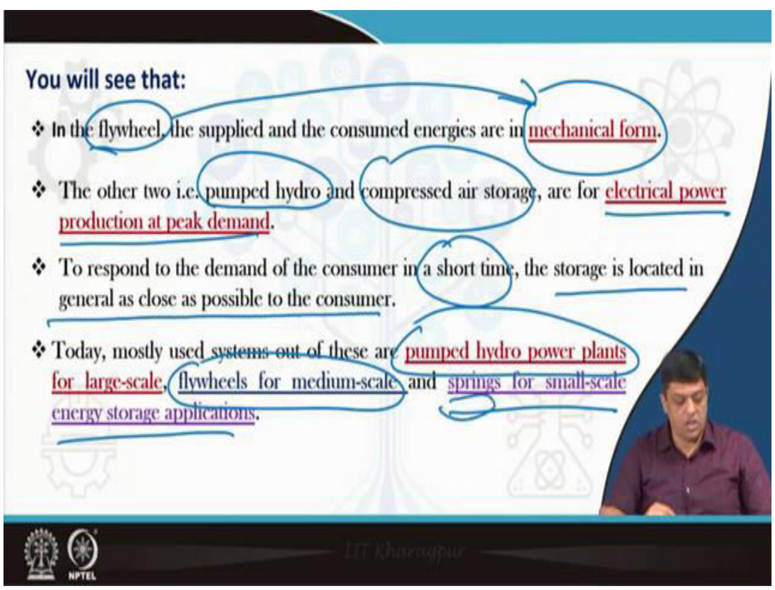

You will see that in the flywheel, the supplied and the consumed energy are both in the mechanical form. So, this is important. In flywheel, the supplied and consumed energy. So, the energy you store and the energy you extract are both in the form of mechanical energy. In the other two examples, that is pumped hydro or compressed air storage you have the condition where you are talking about the electrical power production at peak demand. So, you are having electrical power.

All these technologies are so designed that they can respond to the demand or varying demand at the consumer end at a very fast rate. So, they have a fast response time. The consequence is that they have to be so designed that the storage is located at a place which is near to the consumer or the end user. Today, mostly we are using systems which are based on pumped hydro power plants for large scale use, flywheels are used for medium scale, and springs for small scale energy storage applications.

So, you can then talk about, if somebody says, I need a mechanical based energy storage technology for large scale use, what are we indicating, we are indicating towards the use of pumped hydro, for medium scale flywheels and springs for the small scale.

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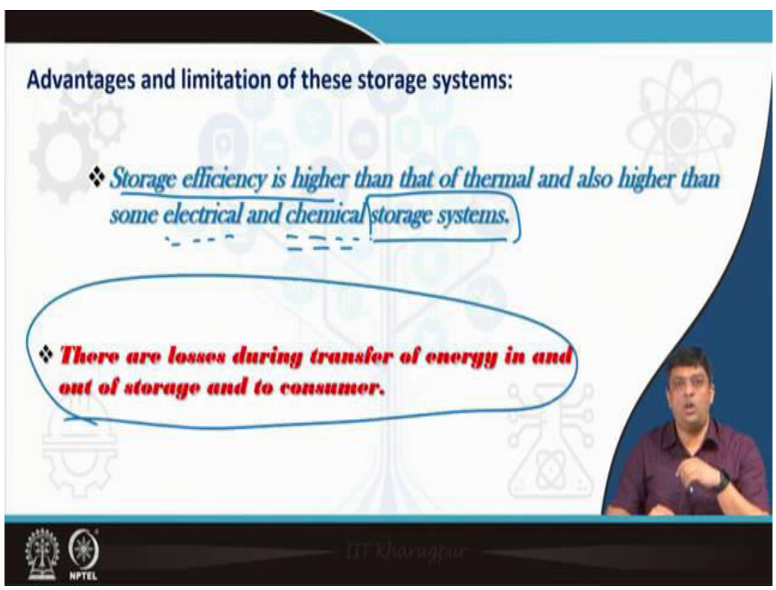

The advantage which is associated with this technology is that the storage efficiency is higher than the thermal based energy storage systems which we discussed in the previous lecture. And mostly the storage efficiency is also higher than the electrical or chemical based energy storage systems. So, we had talked about four classifications, energy storage systems based on mechanical energy storage, thermal energy storage, electrical energy storage and chemical energy storage. Which technology is supposedly having the highest efficiency? It is the mechanical based energy storage technologies.

The problem is that there are a lot of losses which can occur during the transfer of energy in and out of the storage facility and while it is being transferred to the end user. So, this is the major limitation of the whole process.

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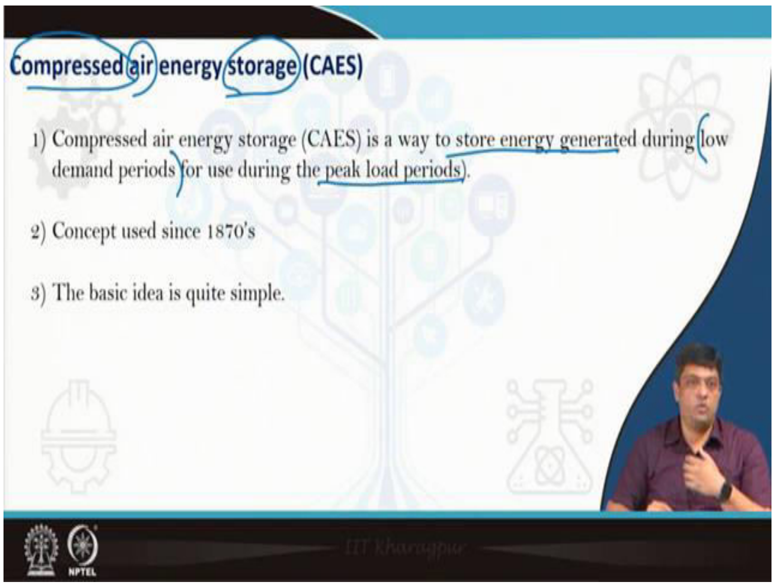

Let us talk about the first example that is the compressed air. Immediately you should be able to understand, what are we going to do, we are going to compress the air and that is going to act as the storage. So, compressed air energy storage process is the way to store energy generated when the demands are low. But they can be used at a later stage when the peak load condition is obtained. This concept has been used for a long period now and the idea is also quite simple.

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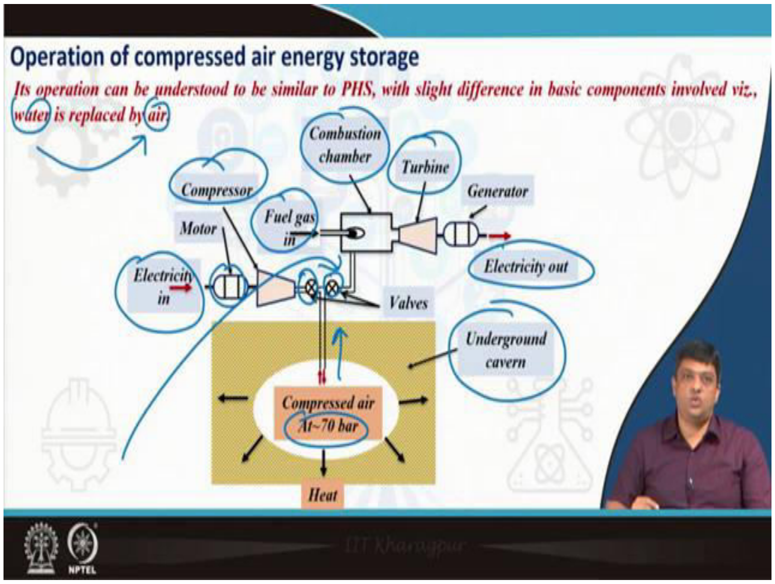

This is a typical compressed air-based energy storage system. You can understand this whole concept similar to pumped hydro system, but with a slightly different concept or the component which is used to store energy. Here you have replaced water by air. So, you replace water by air.

How does it work? You have electricity, you have the motor and then the compressor. This compressor compresses the air which is stored in at underground cavern. During the compression you can have the generation of heat. This heat can either be allowed to dissipate out of the cavern or you can maintain the heat if you want to have a condition where the air has to be maintained at such temperatures. So, you can have heat losses or you can also design to minimize heat losses depending upon what factors you are considering.

The air is stored at high pressures around 70 bars. Then you have two valves. When you want to have the generation of electricity, you allow the compressed air to come out by opening this valve. This valve allows the compressed air to move towards the combustion chamber where you can again heat this compressed air to a higher temperature, which can then react with the fuel gas resulting in generation of heat and then this is fed into the turbine. This turbine leads to the generation of electricity which can be collected.

So, what are you going to do? During the times when the load is much lower you will, but the source is available, if it is a renewable based source or even if you are talking about the existing grid, the load has gone down, but you have electricity, then you use that electricity to compress air and store that compressed air. When that demand goes up, then you open the valve and allow the air to flow into the combustion chamber and the whole process can be near instantaneous. This is the way the whole process actually works.

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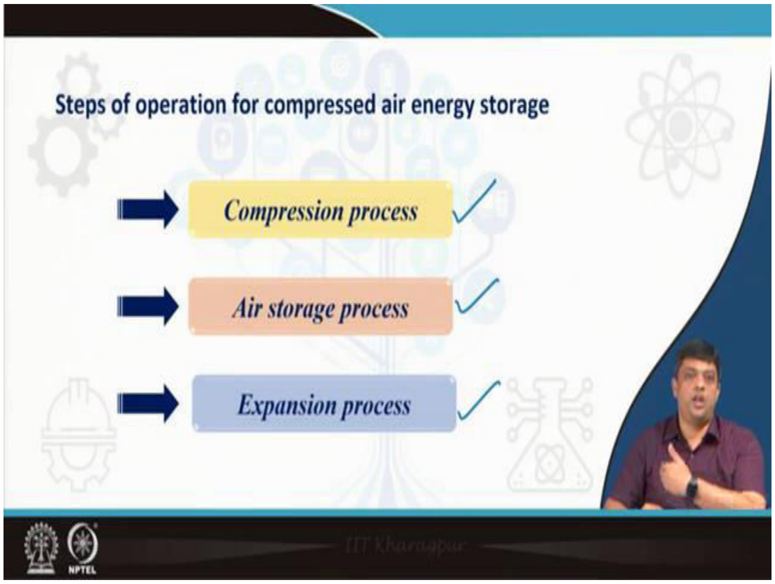

So, the process involves the step of compression, the storage and then the expansion of this compressed air when the valve two is opened and the compressed air is allowed to flow into the combustion chamber.

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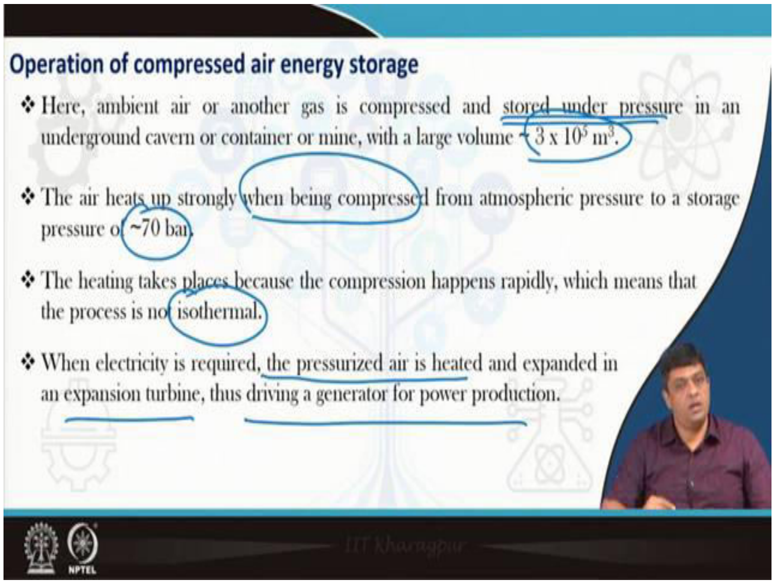

What will happen? The ambient air or another gas is compressed and stored under high pressure or it can be stored under high pressure in a container or even in a mine, but you have to store large amount of compressed air. And therefore, the size of the cavern or mine or the container we are talking about is quite large. The air heats up strongly when being compressed from atmospheric pressures to storage pressure of approximately 70 bar.

If you have this heated air being sent into the storage tanks, what will happen? The heating takes place and the process is no more isothermal. So, you move to a condition when the process is not isothermal and if there are losses because of this non-isothermal conversion then you are losing on the efficiency while you are converting the air at atmospheric pressure to a condition where it is compressed at high pressure.

You now have the compressed air which is stored and whenever the electricity is required this pressurized air is heated because you lost some of the heat out of the storage facility and when this pressurized air is heated and it expands then it is fed into the combustion chamber and there it reacts with the fuel then moves to the expansion turbine and thus drives the generator for power production. So, you also have to choose the fuel gas quite carefully so that the expansion turbine can be operated.

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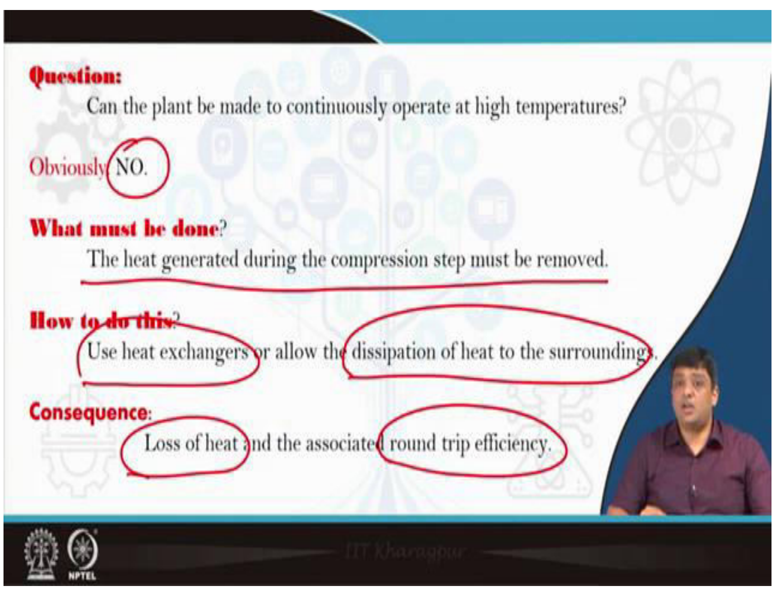

The moment I talk about the condition where you are having a state where high temperatures are observed continuously. Can you operate the plant continuously when the temperatures are extremely high? Obviously not, because that will lead to serious consequences. So, what must be done? So, you cannot operate the plant continuously at high temperatures. What needs to be done? This means that the heat generated during compression step must be removed or minimized.

Hence, you need to use heat exchangers to extract the heat or allow the heat to slowly dissipate out of this cavern or the container to the surroundings. The moment I allow the heat to dissipate what happens, I am talking about loss of heat. If I am talking about loss of heat, I am immediately integrating towards the reduced round trip efficiency with lower values. So, because of the limitation of maintaining low temperatures while you operate this plant that forces you to allow loss of heat and the moment I talk about the loss of heat I have forcefully reduced the round-trip efficiency.

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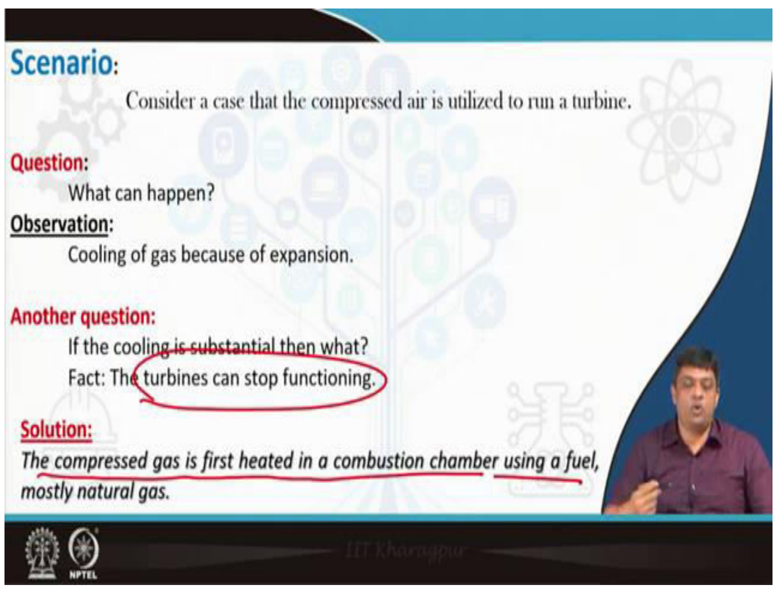

Let us try to understand the whole concept once again. Consider a case that the compressed air is utilized to run a turbine, what can happen? Cooling of gas because of expansion when you are taking the gas to the combustion chamber. If, now, the cooling is substantial that you have reduced the temperatures to room temperature or much lower than what will happen. You will not have the production of the steam or the gas which can run the turbines.

If you cannot run the turbines, then you will have the turbines which will stop. If the turbines will stop, your power output would be zero. Therefore, you need to have the condition where the compressed gas is first heated in the combustion chamber using a fuel which is mostly a natural gas and then this gas is fed into the gas turbines that is why you have the combustion chamber.

So, there are additional steps which come into picture that reduces the overall efficiency; first was forceful reduction in the heat which was associated with the air that was being compressed; and second, you have to have an additional step where you have to first heat the expanding gas using a fuel. So, you have actually added additional steps and then the moment you are adding more and more thermodynamically control steps then the efficiencies are coming down.

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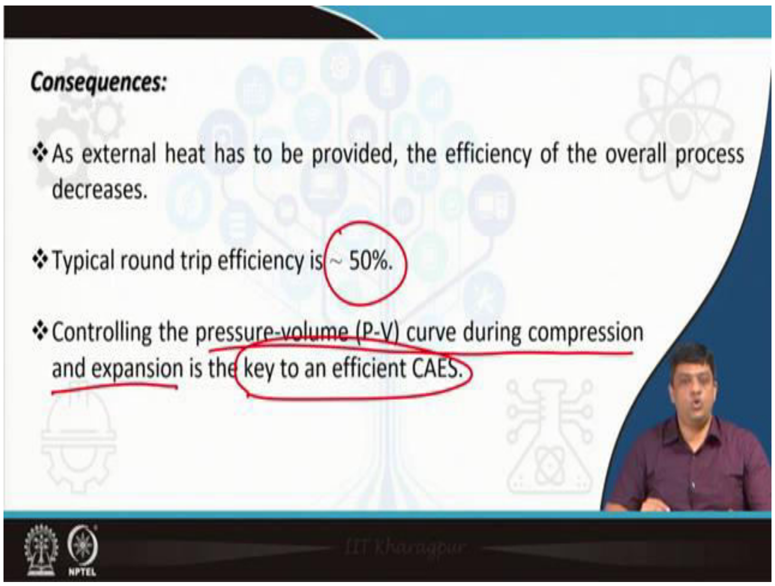

Because of the processes which are being added the round-trip efficiency that is obtained is approximately 50 percent. And if I have to control the whole process, then the pressure volume curve during the compression and expansion is the key for efficient compressed air-based energy storage technology. This should be clear to you by now.

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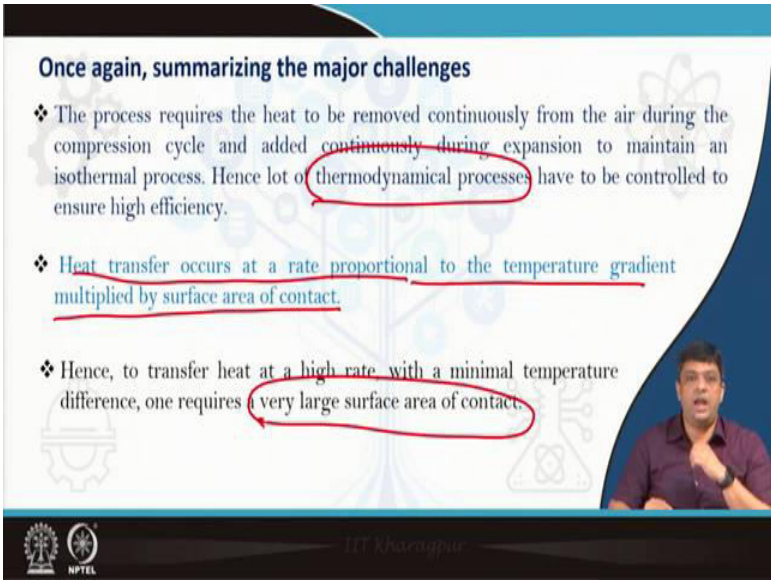

So, let us once again summarize the major challenges, you must have the condition that the process is such that does not lead to reduction in the efficiency. But what is happening, you must talk about a lot of thermodynamical process while describing the compressed air-based energy storage systems. Hence, you will have reduction in the efficiency. Because the heat transfer occurs at rate proportional to the temperature gradient multiplied by the surface area of contact, you must have very large surface area of contact so that you can maintain this high efficiency values.

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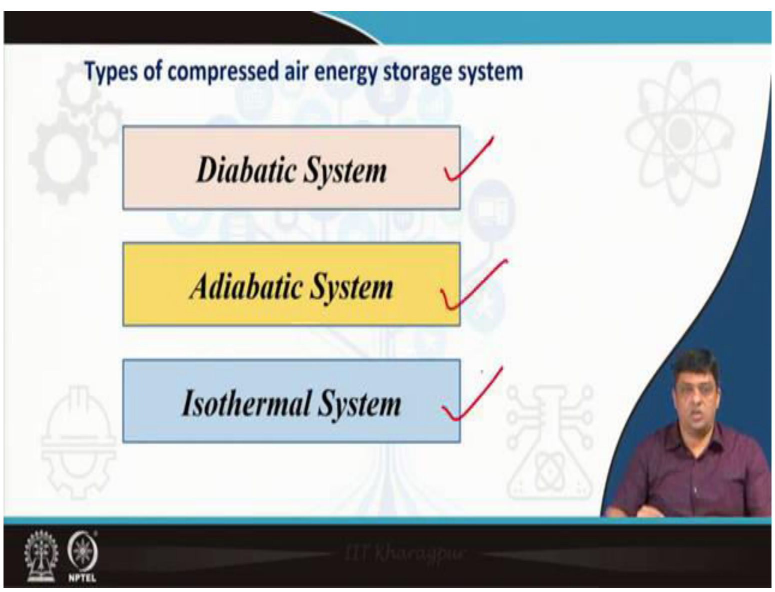

To look into these limiting factors, people have proposed different types of compressed air energy storage systems namely the diabetic type system, the adiabatic type system and the isothermal system.

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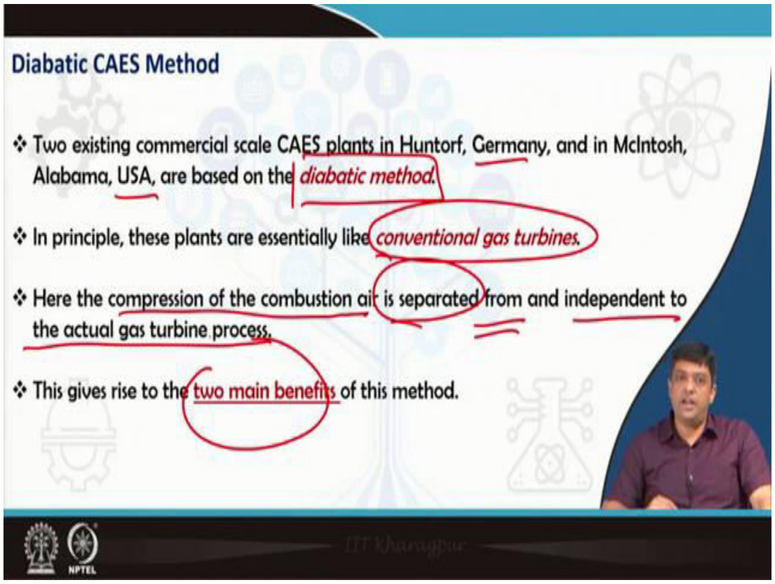

There are systems which are already in place and are being used in countries like Germany and America, which are based on diabetic method. These plants are essentially like the conventional gas turbines. So, they are conventional gas turbine type, but using the process of compressed air energy storage system which we discussed. But only different comes in is that the compression of the combustion air is separated from and is independent to the actual gas turbine process. So, you are able to separate the two processes. This gives rise to two more benefits.

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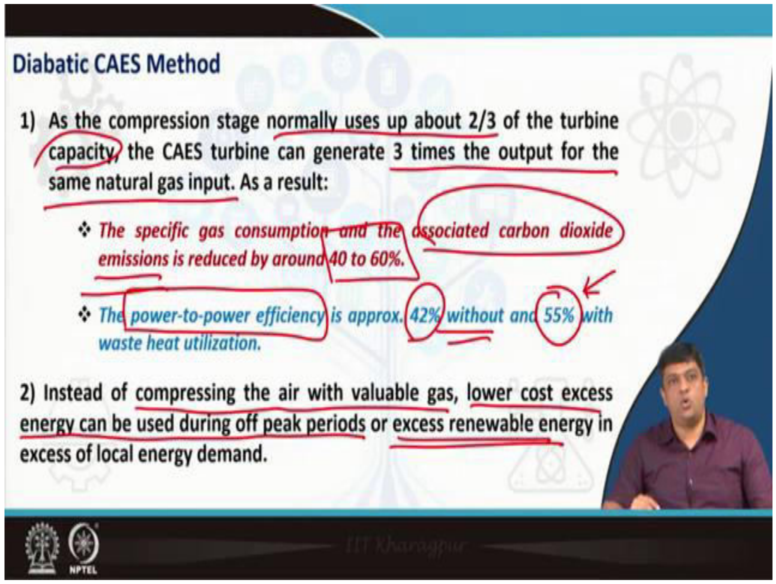

And these two more benefits are the ones where you can have the compression stage such that it normally uses up to about two-third of the turbine capacity. And it can generate three times the output for the same natural gas input. The result is the specific gas consumption and the associated carbon dioxide emission is reduced by 40 to 60 percent. So, you can reduce the carbon footprint of the whole technology significantly.

And power to power efficiency is nearly 42 percent without waste heat utilization, if you are allowing the heat to just dissipate and you are not worried about it, but if you are able to somehow take into consideration the waste heat utilization, then the power to power efficiencies can be further enhanced values as high as 55 percent.

And the second advantage which comes in diabetic compressed air-based energy storage is instead of compressing the air with valuable gas, lower cost excess energy can be used during off peak periods or even if you have this electricity being generated from renewable and they are being generated when the load is much lower, then those can also be used for the whole process.

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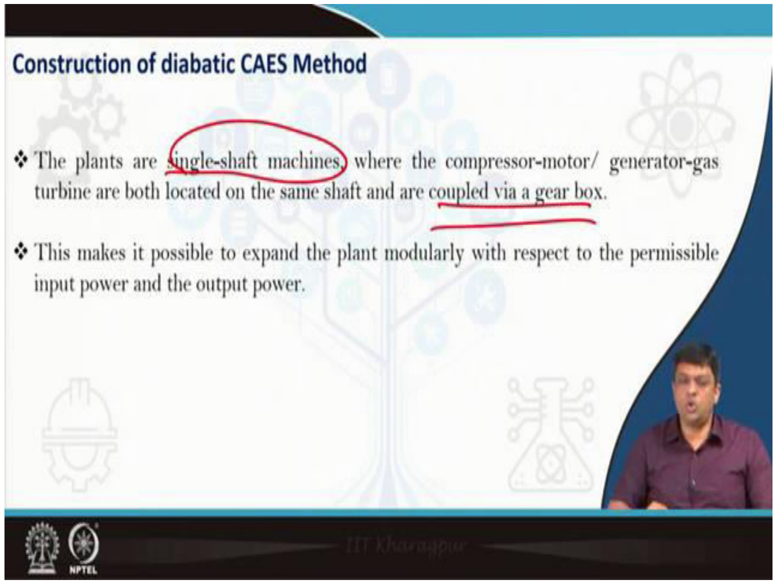

The construction of the diabetic type compressed air energy storage system is driven by the fact that it uses single-shaft machines where the compressor motor, the generator gas turbine are both located on the same shaft and are coupled via a gear box. What happens? This makes it possible to expand the plant module wise. So, you can add one module, the second module, the third module, because the whole plant is made on single shaft. So, if I can make one module, it is ready. I can install it. I do not have to install decoupled systems to make it operational. So, it becomes useful.

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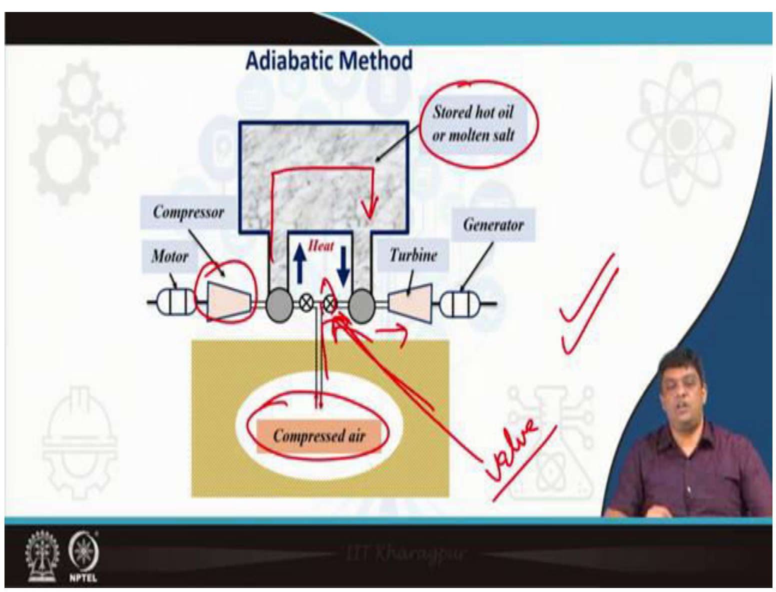

This is a typical process of an adiabatic process which we had proposed while we are giving the classification of the compressed air type energy storage system. So, we had talked about the diabetic and now let us see about the adiabatic. Here, you have a slightly different process. You can have the compressor which can actually be used to also heat the oil or molten salt and it can then also be used to generate the compressed air. So, you are, while you are compressing you are generating heat. That heat is extracted by the oil while the compressed air is stored in the cavern or the container.

What will you do? In the previous case when the simple compressed air energy storage system was being taught you had an initial component that was the combustion chamber where this gas which was expanding needed to be heated again using a fuel which was mostly natural gas and that increase the temperature and then that gas was fed into the gas turbine which was connected to the generator unit. So, you had an additional step where the gas or the chamber where the fuel gas was being added.

So, in this case, do you see the combustion chamber? No, you do not see the combustion chamber. Why, because the stored heat is actually extracted when you need to run the turbine. This heat will combine with the compressed air which is flowing out once the second valve is opened and that will be able to heat the air and this air will then move to the gas turbines and that will lead to the generation of electricity. So, I have reduced the step.

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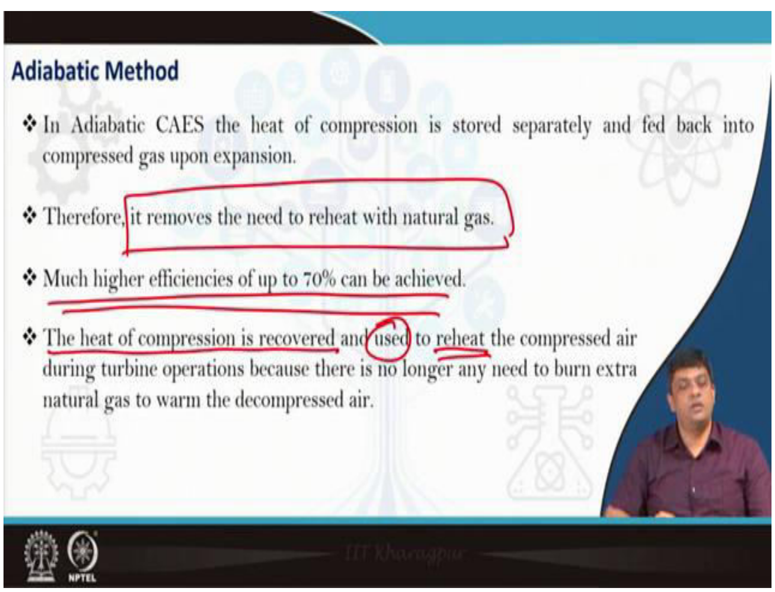

The major advantage becomes, as I just discussed, it removes the need to re-heat with natural gas. And as I have reduced the steps which were there and you were talking about the thermodynamical limits coming in because of those steps, the efficiencies of the adiabatic method can be enhanced immediately and nearly 70 percent efficient systems have been achieved. In this whole process, the heat of compression is recovered. It is used. It is used for what? It is used to reheat the compressed air. So, you also reduce the carbon footprint, because you are not using any natural gas to reheat the compressed air.

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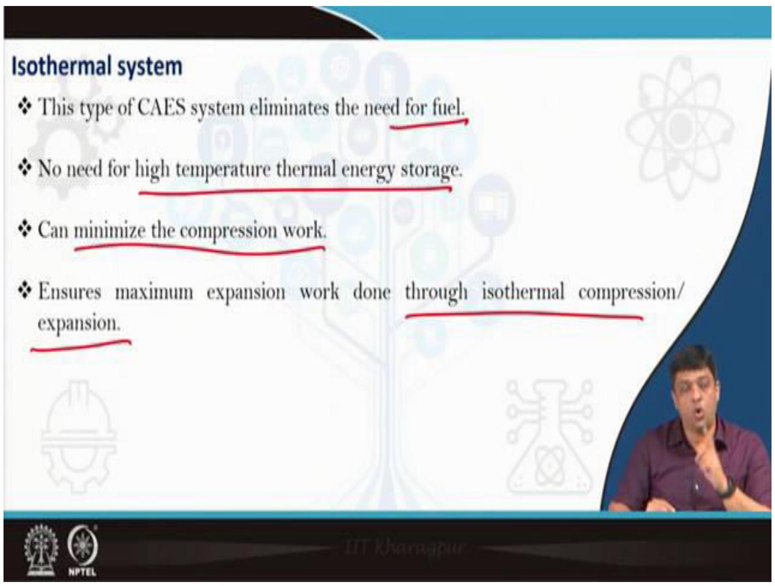

And finally, we have the isothermal systems where you can eliminate the use of fuel. You can also have a condition where it is there is no need for high temperature thermal energy storage systems. You can minimize the compression work. And ensure maximum expansion work is done through isothermal compression or isothermal expansion processes.

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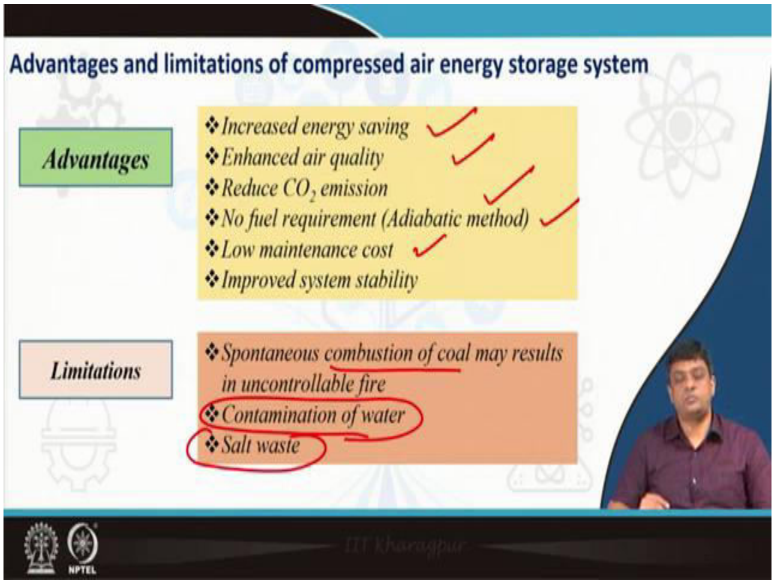

If I summarize, then the advantages and limitations of the compressed air-based energy storage technologies would be; you can increase the energy saving; you could also have enhanced air quality; reduce the carbon footprint. If you have any adiabatic processes, then you can also reduce the use of fuel such as natural gas. Once installed, the operation is much simpler, the process is stable and hence you have the low maintenance cost.

There are many systems which are still associated with certain limitations. Those are the combustion of coal may result in an uncontrollable fire. If your system is such that you are using water at places, then it can lead to contamination of water and you can also have salt waste if you are using salt at places to store heat, then you actually having, end up having salt waste.

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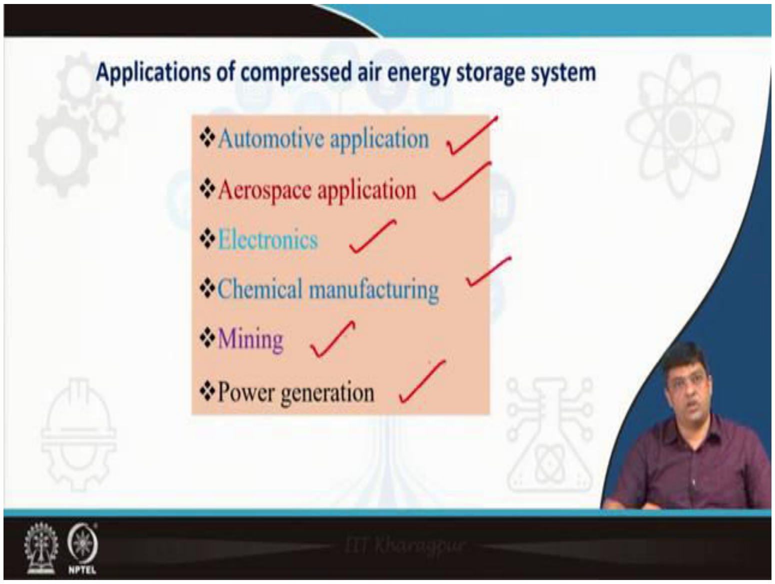

But the applications of compressed air energy storage systems are enormous. We have already been using it in automotive applications. We have talked about the use in aerospace applications, electronics, chemical manufacturing, mining and power generations.

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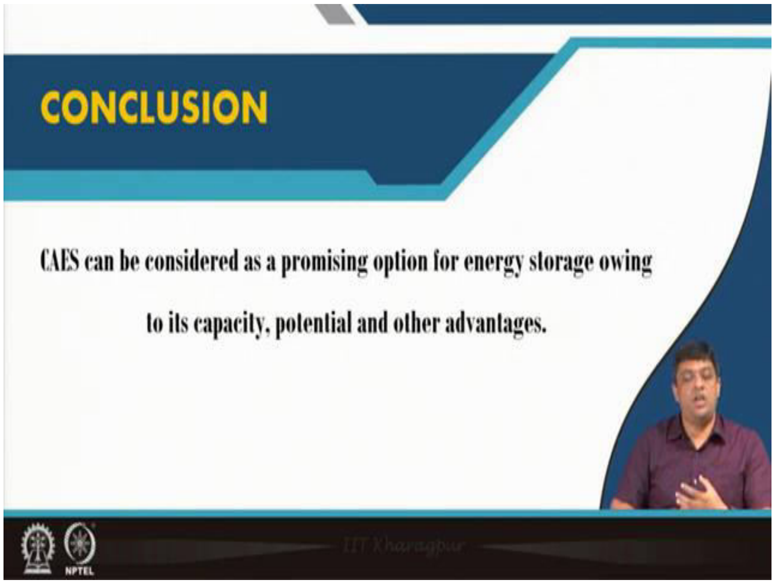

With the discussion we had today, I hope it is clear to you that the compressed air-based energy storage systems can be considered as a promising option for energy storage. Why they can be considered as a promising option, because they have the capacity to store large amount of energy and they have application in varied fields.

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These are the major references from which the data was obtained. And I thank you for attending today's lecture. And in the next lecture, we will talk about the flywheel and the pumped hydro. Thank you very much.