


**Physics of Renewable Energy Systems**  
**Professor Amreesh Chandra**  
**Department of Physics**  
**Indian Institute of Technology Kharagpur**  
**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.

(Refer Slide Time: 00:56)



The slide features a blue header with two circular logos: the Indian Institute of Technology Kharagpur logo on the left and the NPTEL logo on the right. Below the header, a blue banner contains the text "NPTEL ONLINE CERTIFICATION COURSES". The main content area is white and contains the following text: "COURSE NAME: PHYSICS OF RENEWABLE ENERGY SYSTEMS", "Prof. AMREESH CHANDRA", "DEPARTMENT OF PHYSICS, IIT KHARAGPUR", "Module 5: Energy Storage", and "Lecture 22: Basics of Mechanical Energy Storage".

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.

(Refer Slide Time: 01:20)

**CONCEPTS COVERED**

- *Type of mechanical energy storage*
- *Compressed air energy storage (CAES)*

IIT Kharagpur  
NPTEL

The slide features a blue header with the title 'CONCEPTS COVERED' in yellow. Below the title, two bullet points are listed: '➤ Type of mechanical energy storage' and '➤ Compressed air energy storage (CAES)'. The text 'Type of mechanical energy storage' is circled in blue. In the bottom right corner, there is a small video feed of a man in a purple shirt. The footer contains the IIT Kharagpur and NPTEL logos.

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.

(Refer Slide Time: 01:44)

**KEY POINTS**

- Working principle of CAES
- Different types of CAES i.e. Diabatic, Adiabatic and Isothermal
- Advantages and limitation
- Applications

IIT Kharagpur  
NPTEL

The slide features a blue header with the title 'KEY POINTS' in yellow. Below the title, four bullet points are listed: '➤ Working principle of CAES', '➤ Different types of CAES i.e. Diabatic, Adiabatic and Isothermal', '➤ Advantages and limitation', and '➤ Applications'. The words 'Diabatic', 'Adiabatic', and 'Isothermal' are circled in blue. In the bottom right corner, there is a small video feed of a man in a purple shirt. The footer contains the IIT Kharagpur and NPTEL logos.

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 diabatic, 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.

(Refer Slide Time: 02:52)

The slide is titled "Mechanical Energy Storage: Introduction". It features two bullet points: "❖ Mechanical energy can be stored either as potential or kinetic energy." and "❖ The efficient and effective use of these concepts depend on the high performance advanced materials and technologies." The second bullet point has "efficient and effective use" circled in blue, with arrows pointing to "high performance advanced materials and technologies". There are also blue boxes around "potential or kinetic energy" and "high performance advanced materials and technologies". The slide includes a presenter in the bottom right corner and logos for IIT Bombay and NPTEL at the bottom.

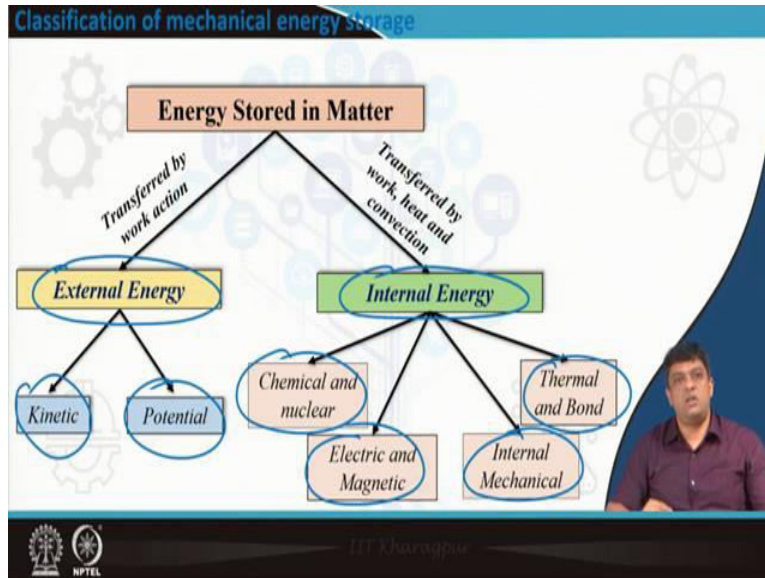
The mechanical energy storage technologies are the ones which are storing energy either in the form of potential energy or kinetic energy. The efficient and the effective use of these concepts depend on the high-performance advanced materials and technologies. This is a sentence written on this slide.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

(Refer Slide Time: 05:31)



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.

(Refer Slide Time: 07:17)

Three main mechanical energy storage technologies, which are widely investigated are:

- Compressed air storage
- Pumped hydroelectric storage
- Flywheels

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.

(Refer Slide Time: 08:01)

You will see that:

- ❖ In the flywheel, the supplied and the consumed energies are in mechanical form.
- ❖ The other two i.e. pumped hydro and compressed air storage, are for electrical power production at peak demand.
- ❖ To respond to the demand of the consumer in a short time, the storage is located in general as close as possible to the consumer.
- ❖ Today, mostly used systems out of these are pumped hydro power plants for large-scale, flywheels for medium-scale, and springs for small-scale energy storage applications.

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.

(Refer Slide Time: 10:27)

Advantages and limitation of these storage systems:

- ❖ *Storage efficiency is higher than that of thermal and also higher than some electrical and chemical storage systems.*
- ❖ **There are losses during transfer of energy in and out of storage and to consumer.**

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.

(Refer Slide Time: 11:52)

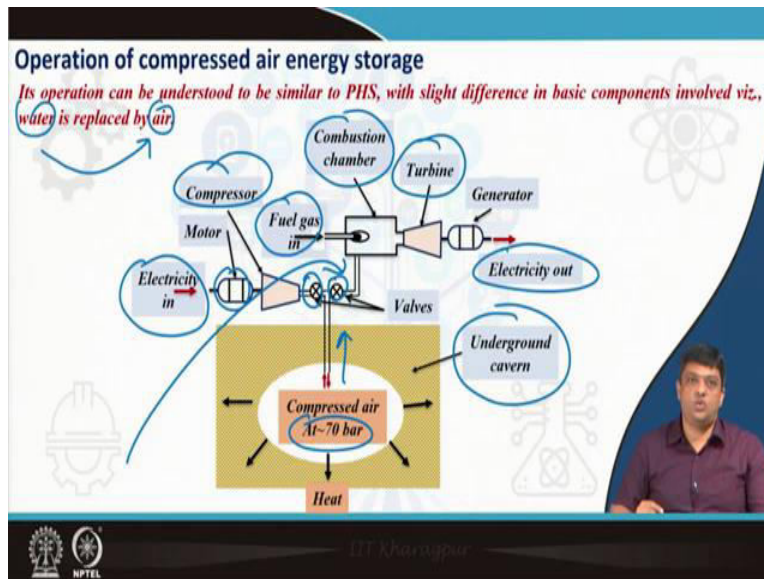
**Compressed air energy storage (CAES)**

- 1) Compressed air energy storage (CAES) is a way to store energy generated during low demand periods for use during the peak load periods.
- 2) Concept used since 1870's
- 3) The basic idea is quite simple.

The slide features a blue and white background with technical icons like a hard hat, a gear, and a circuit board. A presenter is visible in the bottom right corner. Logos for IIT Kharagpur and NPTEL are at the bottom.

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.

(Refer Slide Time: 12:53)



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.

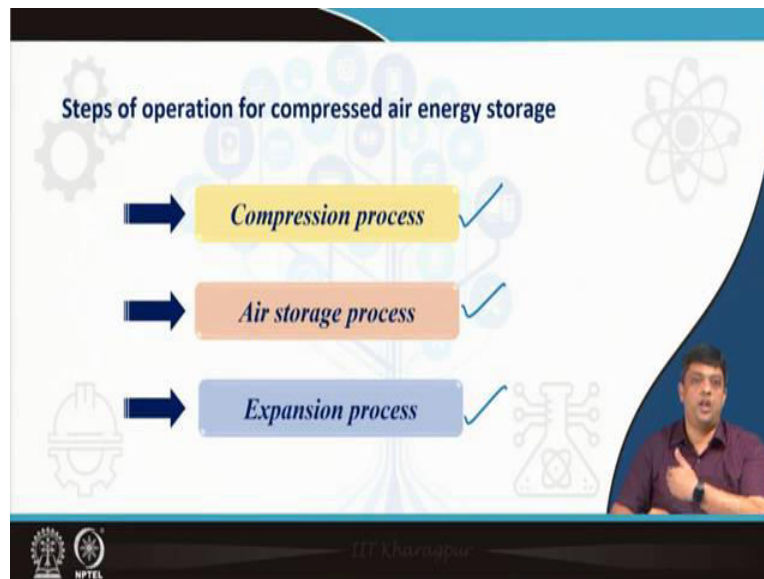
The air is stored at high pressures around 70 bars. Then you have two valves. When you want to have the generation of electricity, you allow the compressed air to come out by opening this valve. This valve allows the compressed air to move towards the combustion chamber where you can again heat this 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.

(Refer Slide Time: 16:29)



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.

(Refer Slide Time: 16:47)

**Operation of compressed air energy storage**

- ❖ Here, ambient air or another gas is compressed and stored under pressure in an underground cavern or container or mine, with a large volume  $\sim 3 \times 10^5 \text{ m}^3$ .
- ❖ The air heats up strongly when being compressed from atmospheric pressure to a storage pressure of  $\sim 70 \text{ bar}$ .
- ❖ The heating takes place because the compression happens rapidly, which means that the process is not isothermal.
- ❖ When electricity is required, the pressurized air is heated and expanded in an expansion turbine, thus driving a generator for power production.

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.

(Refer Slide Time: 19:20)

**Question:**  
Can the plant be made to continuously operate at high temperatures?

Obviously **NO**.

**What must be done?**  
The heat generated during the compression step must be removed.

**How to do this?**  
Use heat exchangers or allow the dissipation of heat to the surrounding.

**Consequence:**  
Loss of heat and the associated round trip efficiency.

NPTEL

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.

(Refer Slide Time: 21:17)

**Scenario:** Consider a case that the compressed air is utilized to run a turbine.

**Question:** What can happen?

**Observation:** Cooling of gas because of expansion.

**Another question:** If the cooling is substantial then what?  
Fact: The turbines can stop functioning.

**Solution:** The compressed gas is first heated in a combustion chamber using a fuel, mostly natural gas.

NPTEL

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.

(Refer Slide Time: 23:31)

**Consequences:**

- ❖ As external heat has to be provided, the efficiency of the overall process decreases.
- ❖ Typical round trip efficiency is ~ 50%.
- ❖ Controlling the pressure-volume (P-V) curve during compression and expansion is the key to an efficient CAES.

DT Khurshid

NPTEL

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.

(Refer Slide Time: 24:16)

**Once again, summarizing the major challenges**

- ❖ The process requires the heat to be removed continuously from the air during the compression cycle and added continuously during expansion to maintain an isothermal process. Hence lot of thermodynamical processes have to be controlled to ensure high efficiency.
- ❖ Heat transfer occurs at a rate proportional to the temperature gradient multiplied by surface area of contact.
- ❖ Hence, to transfer heat at a high rate with a minimal temperature difference, one requires a very large surface area of contact.

IT Khanna

NPTEL

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.

(Refer Slide Time: 25:28)

**Types of compressed air energy storage system**

- Diabatic System* ✓
- Adiabatic System* ✓
- Isothermal System* ✓

IT Khanna

NPTEL

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

(Refer Slide Time: 25:50)

**Diabatic CAES Method**

- ❖ Two existing commercial scale CAES plants in Huntorf, Germany, and in McIntosh, Alabama, USA, are based on the *diabatic method*.
- ❖ In principle, these plants are essentially like *conventional gas turbines*.
- ❖ Here the compression of the combustion air is separated from and independent to the actual gas turbine process.
- ❖ This gives rise to the *two main benefits* of this method.

The slide features a presenter in the bottom right corner and various technical icons in the background. Red circles and lines are drawn on the slide to highlight key terms and phrases.

There are systems which are already in place and are being used in countries like Germany and America, which are based on diabatic 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 difference 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.

(Refer Slide Time: 27:01)

**Diabatic CAES Method**

1) As the compression stage normally uses up about  $\frac{2}{3}$  of the turbine capacity, the CAES turbine can generate 3 times the output for the same natural gas input. As a result:

- ❖ The specific gas consumption and the associated carbon dioxide emissions is reduced by around 40 to 60%.
- ❖ The power-to-power efficiency is approx. 42% without and 55% with waste heat utilization.

2) Instead of compressing the air with valuable gas, lower cost excess energy can be used during off peak periods or excess renewable energy in excess of local energy demand.

Dr. Manoj Kumar

NPTEL

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 diabatic 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.

(Refer Slide Time: 28:57)

### Construction of diabatic CAES Method

- ❖ The plants are single-shaft machines where the compressor-motor/ generator-gas turbine are both located on the same shaft and are coupled via a gear box.
- ❖ This makes it possible to expand the plant modularly with respect to the permissible input power and the output power.

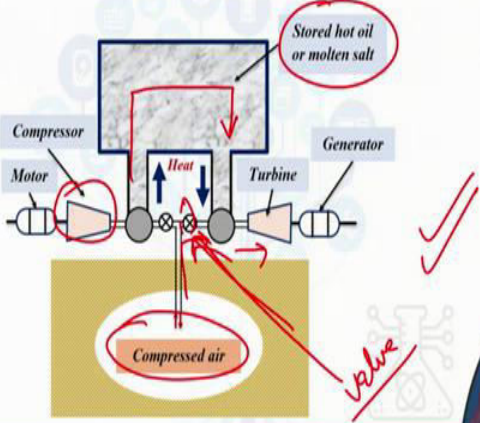


NPTEL


The construction of the diabatic 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.

(Refer Slide Time: 29:56)

### Adiabatic Method



Compressor  
Motor  
Generator  
Turbine  
Stored hot oil or molten salt  
Heat  
Compressed air  
valve



NPTEL



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 diabatic 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.

(Refer Slide Time: 32:20)

**Adiabatic Method**

- ❖ In Adiabatic CAES the heat of compression is stored separately and fed back into compressed gas upon expansion.
- ❖ Therefore, it removes the need to reheat with natural gas.
- ❖ Much higher efficiencies of up to 70% can be achieved.
- ❖ The heat of compression is recovered and used to reheat the compressed air during turbine operations because there is no longer any need to burn extra natural gas to warm the decompressed air.

NPTEL

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.

(Refer Slide Time: 33:26)

**Isothermal system**

- ❖ This type of CAES system eliminates the need for fuel.
- ❖ No need for high temperature thermal energy storage.
- ❖ Can minimize the compression work.
- ❖ Ensures maximum expansion work done through isothermal compression/expansion.

The slide features a blue header and footer. The footer contains the logos of IIT Kharagpur and NPTEL, along with the name 'Dr. Kharagpur'. A small video inset in the bottom right corner shows a man in a purple shirt speaking.

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.

(Refer Slide Time: 34:06)

**Advantages and limitations of compressed air energy storage system**

**Advantages**

- ❖ Increased energy saving ✓
- ❖ Enhanced air quality ✓
- ❖ Reduce CO<sub>2</sub> emission ✓
- ❖ No fuel requirement (Adiabatic method) ✓
- ❖ Low maintenance cost ✓
- ❖ Improved system stability ✓

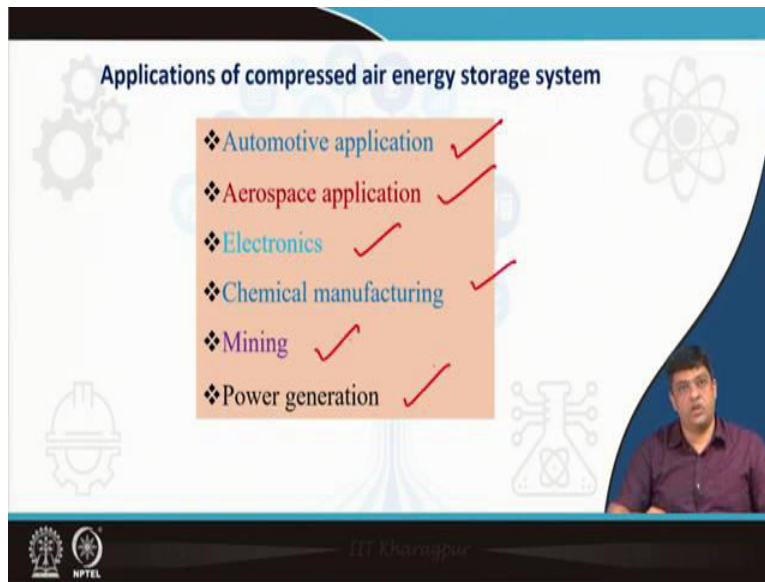
**Limitations**

- ❖ Spontaneous combustion of coal may results in uncontrollable fire
- ❖ Contamination of water
- ❖ Salt waste

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.

(Refer Slide Time: 35:39)



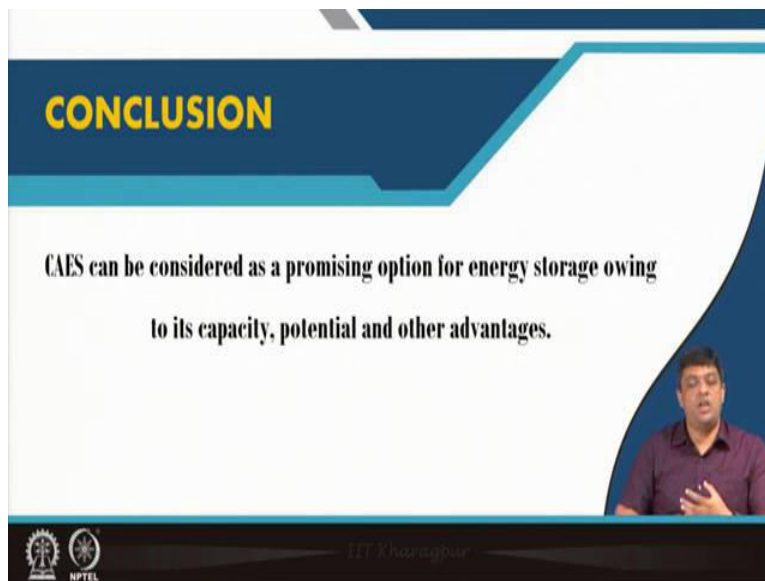
**Applications of compressed air energy storage system**

- ❖ Automotive application ✓
- ❖ Aerospace application ✓
- ❖ Electronics ✓
- ❖ Chemical manufacturing ✓
- ❖ Mining ✓
- ❖ Power generation ✓

The slide features a list of six applications, each preceded by a blue diamond icon and followed by a red checkmark. The background includes faint icons of gears, a hard hat, and a molecular structure. A small inset video of a man in a purple shirt is visible in the bottom right corner. The NPTEL logo and 'IIT Kharagpur' are at the bottom.

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.

(Refer Slide Time: 36:01)



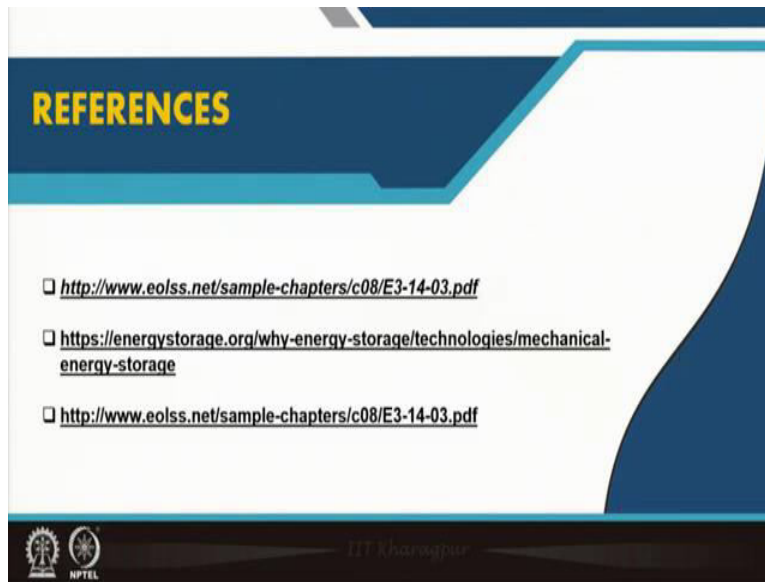
**CONCLUSION**

CAES can be considered as a promising option for energy storage owing to its capacity, potential and other advantages.

The slide has a blue and white background with a diagonal design element. A small inset video of the same man in a purple shirt is in the bottom right corner. The NPTEL logo and 'IIT Kharagpur' are at the bottom.

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.

(Refer Slide Time: 36:37)



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.