Energy Conservation and Waste Heat Recovery

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Lecture - 53
Energy Storage Systems - III

Good morning. Welcome back to the next lecture of Energy Conservation and Waste Heat Recovery. So, in the last lecture we were discussing about energy storage systems, where we left off at that point we were talking about compressed air energy storage. So, it is a type of mechanical energy storage where the energy stored is energy stored in the form of compressed air.

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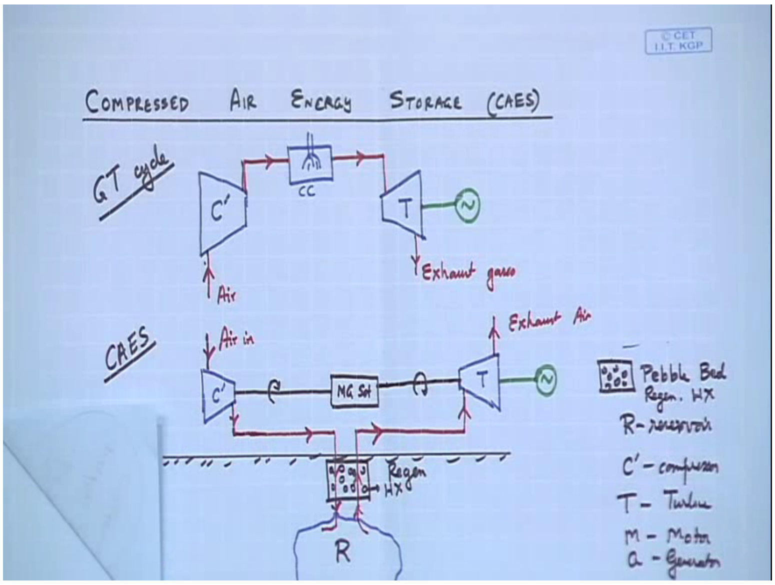

So, this is what we were discussing last time. These are the schematics that we had drawn and if you see what it essentially follows over here is we have a compressor where air comes in and the air is at probably at atmospheric pressure and at normal temperature and then, it is compressed.

Now, as the air is compressed, what happens is its pressure rises, its volume shrinks definitely and as and its temperature also rises, then that pressurized air what is done is, it is stored in a reservoir and we are going to talk about what these reservoirs are. So, it is stored in a reservoir, but before storing what we want to do is, we want to cool it down because on compression, its temperature rises. So, we would like to cool it down to a lower temperature because in that case what happens is the volume that it will occupy will be even lesser.

So, the volume of reservoir that is required to store this compressed air is going to be lower. This is during off peak hours when we have excess energy. So, we use that extra energy to run the compressor during peak hours when we need that energy back. The compressed air is fed to a turbine to a gas turbine. In this case, air turbine and in the turbine, it is expanded. So, that if pressure comes down and the exhaust air comes out of the turbine and then, this turbine gives us is a peaking turbine that gives us the additional electricity.

Now, we know that as it enters the turbine, it should have high temperature. If the turbine inlet temperature is high, we get more work out of it, right. Therefore, we need to heat it up. So, the way it is done is we use a regenerative heat exchanger. Pebble bed is one example through which the compressed air is passed before storage and the heat is transferred to the pebble bed which absorbs the heat and retains that. And when the compressed air is fed to the turbine, it is first made to pass through this regenerative heat exchanger, so that it heats up and then, it goes to the turbine. So, this is where we stopped.

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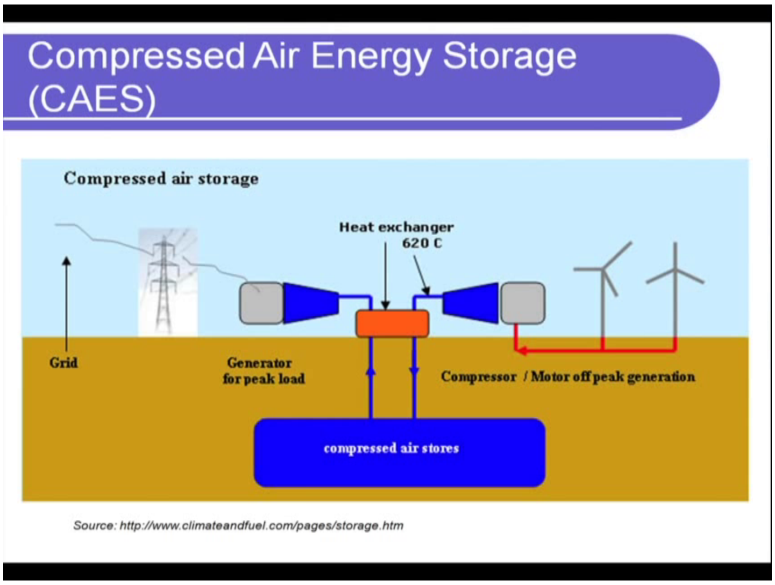

Compressed Air Energy Storage (CAES)

Source: http://www.climateandfuel.com/pages/storage.htm

So, what we would like to do is in this slide, this is pretty much essentially what is shown here that we have during the off peak hours, we have additional generations. So, the compressor compresses the air and is stored in compressed air storage. And then, during peak hours the compressed air is fed into a turbine which generates electricity, right and we are showing the heat exchanger which we talked about should be a regenerative heat exchanger, because this flow from the compressor and the flow through the turbine. So, this flow and this flow is not happening simultaneously. So, that is why the heat has to be given up by the compressed air and stored somewhere and then, passed on to the compressed air before it goes to the turbine you are in the peak hours, right.

Now, let us talk about what these compressed air storage reservoirs are. So, typically the reservoirs are we going to create these reservoirs underground. Now, that is going to be a humongous task, but the good thing is typically these reservoirs can be the abundant mines, the mines from which you have already excavated and now they are abundant. So, they are already underground, under the ground. So, we can use that large reservoir and pump in the compressed air.

Now, typically what is used are the mines, the salt mines. See in a salt mine what happens is compared to let us say coal mine sub where actually workers go underground and dig, hammer the walls and dig the material out. In case of salt mines, what happens is the salt is, we typically pass water through this. We pump water in, it dissolves the salt and then, it is pumped out. Therefore, what happens is number one the walls of these salt mines underground. Salt mines are very smooth and it does not have cracks because we have not really hammered it to extract the salt out. So, this underground salt mines, these caverns, the abundant salt mines are very good candidates for compressed air energy storage, ok.

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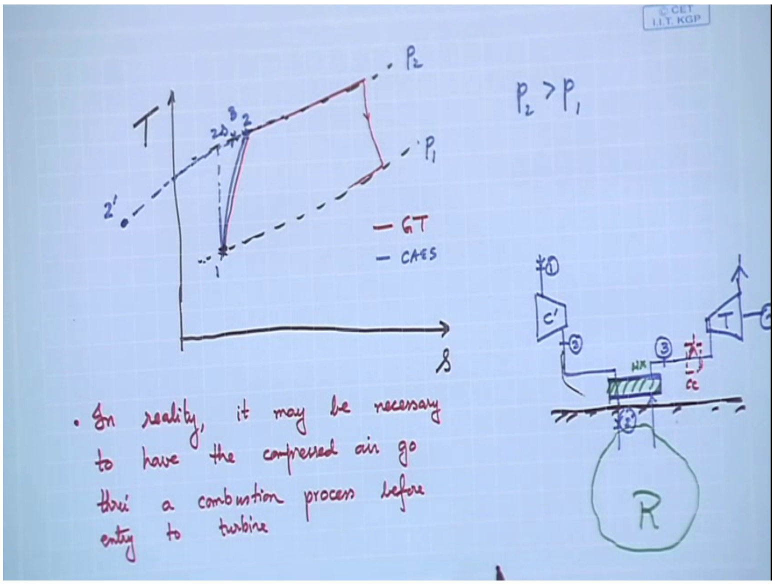

- In reality, it may be necessary to have the compressed air go thru a combustion process before entry to turbine

So, let us talk about from our experience of thermodynamics. Let us do a little bit of a thermodynamic analysis as to what is happening. So, let us say, let us talk about our regular TS diagram, right. So, what happens in a regular Brayton cycle or in a gas turbine cycle this is; where is my starting point and let us say this is one isobar and this is another isobar. So, in a Brayton cycle what happens is the gas is isentropically compressed from a pressure P1 to pressure P2 and P2 is greater than P1.

So, here also that is what happens. So, here also if I quickly draw a compressed air energy storage, let us say this is 1 and this is 2 and then, it goes underground of course. So, this is my ground level and my compressed air actually grows underground into the reservoir. So, this is 0.2 and then here it is, but typically as we know that in a compressor you know in a real case you never get isentropic compression. So, this is 2 as this is absolutely isentropic compression, but actually what will happen is, we will have a slight deviation and there will be a rise in entropy and 0.2 will be somewhere there, ok.

Thereafter, what happens is these two is actually cooled down a little bit at that high pressure. So, probably we will end up, I am sorry to come to this side we will end up somewhere let us say to prime. So, we have a heat exchanger here. Let me use a different color, the green color, sorry. So, this is my heat exchanger. So, what happens is this is two and then, this is two prime, ok.

Thereafter what happens is again this 2 prime goes back to not to maybe somewhere here and let us call that 3. So, this is 0.3 and then, it is fed to the turbine right, sorry, clear. Now, the point is that we really do not see that combustion phenomenon that we actually see in a gas turbine cycle, right. If you recall a gas turbine would have looked something like this, right. So, this would have been a gas turbine cycle and this is my compressed air energy storage.

Now, ideally the problem is here. This is a very ideal case where whatever we have put in, we do not add any other energy to the compressed air. Just we essentially pass it through a regenerative heat exchanger and we get turbine work out, but in reality you may need to add some in reality. We may need to add some combustion over here to increase its temperature further. So, I would write it here. In reality, it may be necessary to have the compressed air go through a combustion process before entry to turbine, ok which means it may be necessary to have a combustion chamber here or before here, clear.

So, this is reality. Ideally if it is perfectly adiabatic, then it is not a problem and that is what we will see later.

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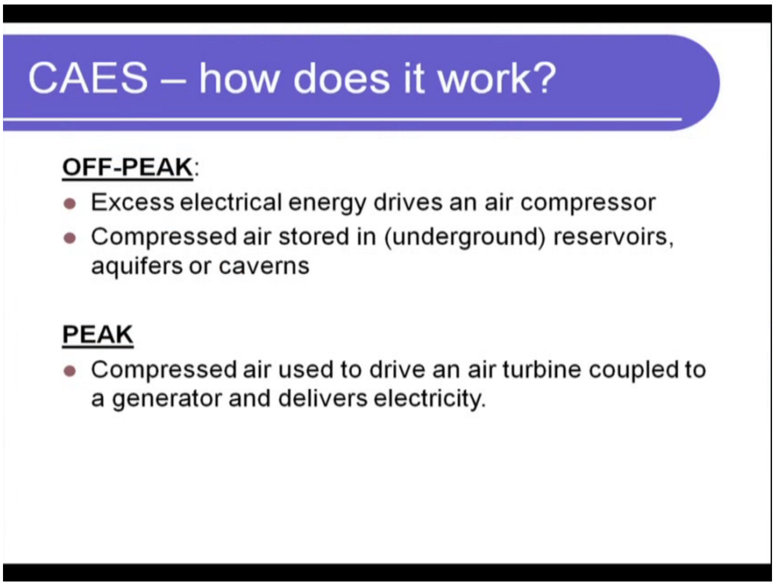

CAES – how does it work?

OFF-PEAK:

- Excess electrical energy drives an air compressor
- Compressed air stored in (underground) reservoirs, aquifers or caverns

PEAK

- Compressed air used to drive an air turbine coupled to a generator and delivers electricity.

So, let us just summarize what we discussed over here how it works. Excess electrical energy during off peak hours rise an air compressor and the compressed air is stored in underground reservoirs. Typically, we said the abundant salt mines are very good candidates and the compressed air during peak hours drives an air turbine coupled to a generator and generates additional electricity, clear. So, this is how it works and this is what we discussed to all these diagrams etcetera.

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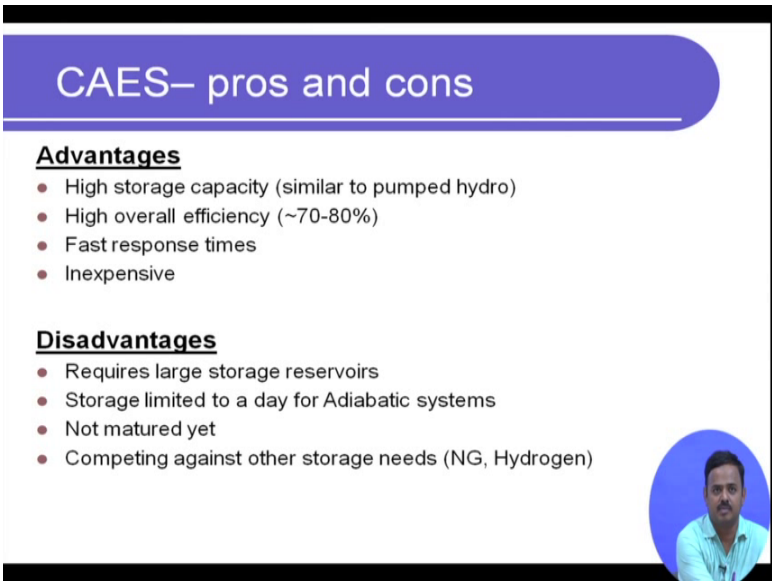

CAES– pros and cons

Advantages

- High storage capacity (similar to pumped hydro)
- High overall efficiency (~70-80%)
- Fast response times
- Inexpensive

Disadvantages

- Requires large storage reservoirs
- Storage limited to a day for Adiabatic systems
- Not matured yet
- Competing against other storage needs (NG, Hydrogen)

So, what are the advantages? Again what is the kind of energy that we can store? It is a large amount, huge if it is possible. So, high storage capacity is similar to pumped hydro whatever we saw overall efficiency can be quite high, 70 to 80 percent response times are relatively fast, I mean reasonably fast. It is inexpensive as long as you have the salt mine and that is the first disadvantage. We do not have these large storage reservoirs abundantly available across the world.

Secondly, for adiabatic systems, the storage is limited because what is an adiabatic system which is where we do not need that additional energy supply through combustion. Adiabatic system is where there is no heat loss. So, the compressed air hardly loses any heat and comes out at the same temperature, but that is not possible because first of all in the reservoir itself. There will be some heat loss to the ground and also, the regenerative heat exchanger that we use cannot hold that thermal energy for too long. It will also by law of nature is going to dissipate that heat over some time, ok.

So, that is the problem and especially now when you have other, we talk about natural gas, we talk about hydrogen natural gas which can be liquefied. Hydrogen can be liquefied. So, these are the competition of compressed air energy storage. Therefore, it is competing against some very impressive or attractive alternatives.

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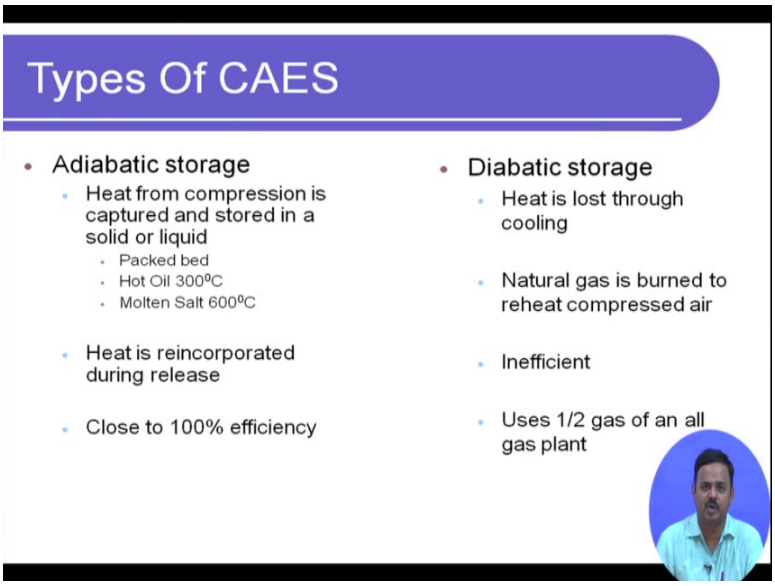

Types Of CAES

- Adiabatic storage
  - Heat from compression is captured and stored in a solid or liquid
    - Packed bed
    - Hot Oil 300⁰C
    - Molten Salt 600⁰C
  - Heat is reincorporated during release
  - Close to 100% efficiency
- Diabatic storage
  - Heat is lost through cooling
  - Natural gas is burned to reheat compressed air
  - Inefficient
  - Uses 1/2 gas of an all gas plant

So, what we will look at right now is; what are the different types of CAES. Adiabatic storage we already talked about. So, heat comes through the compression is captured and stored in this solid or liquid which is what we saw in that regenerative heat exchanger.

Packed bed is one, hot oil, molten salt, these are all different types and the heat is reincorporated to the compressed air during release and it is close to 100 percent efficiency. As I said if the off peak storage and peak release happens within a day, because otherwise what happens is the regenerative heat exchanger itself will lose the captured heat and also, in the reservoir itself the compressed air will also lose some amount of heat clear compared to that diabetic storage heat is lost through cooling.

So, that combustion chamber that I saw where we typically use natural gas that is burnt to reheat the compressed air. So, it is inefficient. However the amount of gas that it will use is definitely much lower. It is half or even lower. Then, what you would need if you say that I just want to operate a gas turbine plant and use natural gas as the combusting fuel. So, that way of course compared to operating a gas turbine plant with natural gas as the fuel, this is much better in terms of energy consumption from fossil fuel. However it has got its own other disadvantages, clear.

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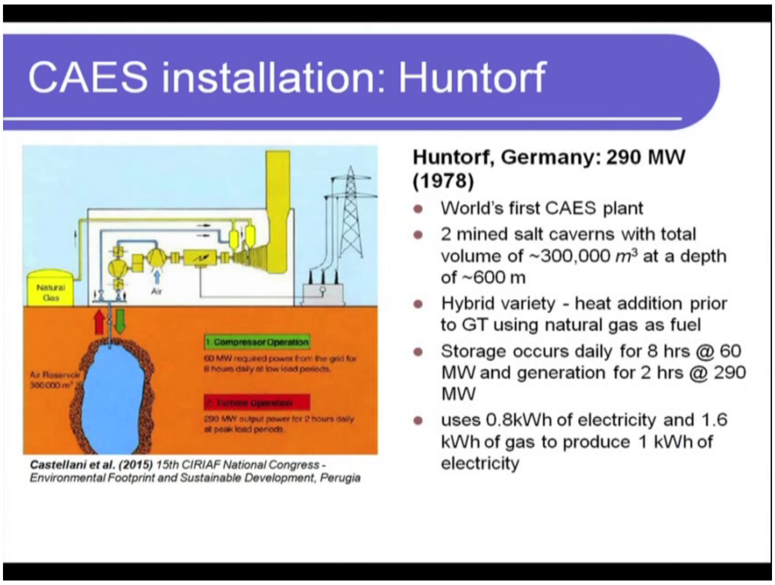

CAES installation: Huntorf

Huntorf, Germany: 290 MW (1978)

- World's first CAES plant
- 2 mined salt caverns with total volume of ~300,000 m^3 at a depth of ~600 m
- Hybrid variety - heat addition prior to GT using natural gas as fuel
- Storage occurs daily for 8 hrs @ 60 MW and generation for 2 hrs @ 290 MW
- uses 0.8kWh of electricity and 1.6 kWh of gas to produce 1 kWh of electricity

Castellani et al. (2015) *15th CIRIAF National Congress - Environmental Footprint and Sustainable Development, Perugia*

So, next what we are going to do is, we are going to talk about a couple of installations, the number of installations across the world, however it is not as you know as widely implemented as pumped hydro, but still there are some. So, the first one that was installed was in Germany. It is called the Huntorf installation in 1978. So, you can see it is almost running for now about 40 years is the world's first compressed air energy storage plant. So, what happened, there were two mined salt caverns and the overall volume was around 300,000 meter cubed. Imagine 300,000 meter cubed.

So, if I look at this room for example, the floor to ceiling is about I say nominally 10 feet. Probably the length and width are about 20 feet each, maybe even a little less. So, 20 into 20 that is 400 times 10, that is 20 feet. 20 feet is around how many meters? 6 meters. So, let us say 6 meters and 3 meters, so18 times 3 that is 54. So, 54 meter cubed is the volume of this reasonably large room which you cannot see, but I can tell you this is a classroom that can accommodate I would say around 50 people. So, that is 54 cube meter cubed and we are talking about 3000 meter cubed. So, you can imagine the size of the reservoirs we are talking about here, ok.

Now, let us see how this works. This is not an adiabatic plant; this is a diabetic plant that is more real. So, what you see here is natura. This is during compression, this is air coming in. It has a two stage compression. As you can see compressor 1, compressor 2 and then, it comes down clear two stage compression during release. This is how it comes up and then, it goes through one combustion chamber where natural gas is supplieda and then, the expansion is two stages. So, you have first one turbine, then again another combustion and again a second turbine from where we generate the electricity. So, what do we have compared to the simple diagram that we drew over here or even here? For example, what we have actually is a two stage compression and a two stage expansion, clear and between the two stages expansion there is another combustion chamber.

So, if I have to again draw it schematically, let me keep it here and let me quickly draw. What is happening, it would look something like this.

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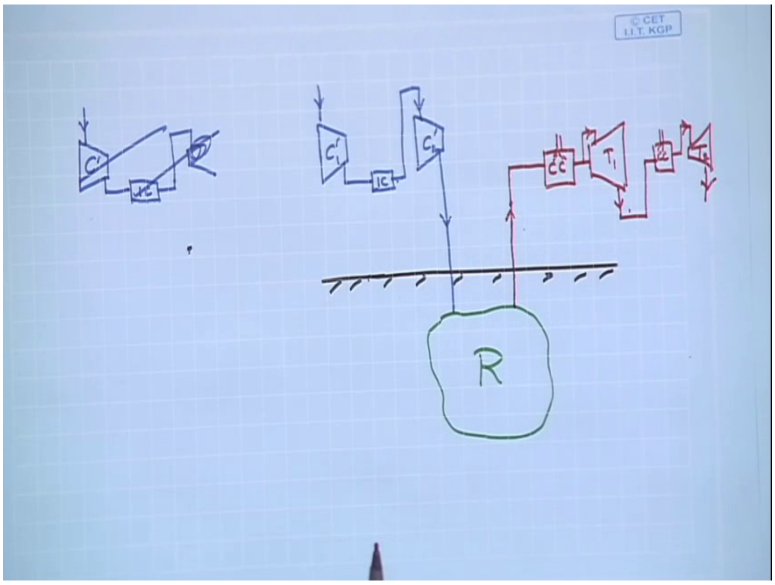

Compressor 1, there will be an intercooler. We all know what an intercooler is by now. Oh sorry I m sorry. We have two compressors; compressor 1 and compressor 2. So, we have an intercooler and then, this compressed here is sent to the storage is a wire clear. Then, during expansion what happens is again very schematically this comes up and first you have a combustion chamber, then turbine one comes out again. There is a combustion process and then, it goes to turbine 2. So, turbine 1 turbine 2 and then, it comes out.

So, two stage compression, two stage turbine, there is no heat exchanger here and then, what happens is then you have two turbines, clear. So, this is how it works what are some of the other whatever numbers for this. So, heat addition as we saw storage offers daily for 8 hours at 60 megawatts and generation is for 2 hours at 290 megawatts. So, that is the rating. So, it is only for 2 hours because the amount of storage actually this 300,000 meter cubed is actually not very high.

So, that is why the storage is not very high. So, you can see 8 hours at 60 megawatts, 6 is of 48. So, it is like 480 megawatts of storage and the generation is for 290 watts megawatts at for 2 hours. So, you may now ask me that we are storing for 80 megawatts and we are generating what 580 megawatts. How is that possible? The amount of electricity that we are generating is more than what we had stored and then, there will be some losses at compressor turbine etcetera. So, where is it going?

It is not an anomaly. You remember that we are adding energy over here through this combustion process like in a gas turbine. The work that we get out of turbine part of it is used to run the compressor, right. So, the work that we get out of the turbine is definitely much more than what the work that we put in for the compressor. Why? It is because we add additional energy to the system through the combustion process here. Also, we are doing the same. We are having combustion chamber. We are burning natural gas and adding energy to the compressed air. So, that is why we are getting 580 megawatts whereas, the stored energy over here before not considering any losses which is again not correct is only for 80 megawatts, ok.

So, here you see it uses 0.8 kilowatt hour. This is just an example. What is the normalized value if I have to produce 1 kilowatt hour of electricity? What the Huntorf uses is 0.8 kilowatt hour of electricity and 1.64 kilowatt hour of gas, clear. So, actually 0.8 kilowatt hour of electricity means that is the electricity which was used to run these compressors and then, we are adding actually 1.6 kilowatt hour of gas. So, that is what it is. So, this is the Huntorf installation and you can calculate the efficiency from here, from these numbers. I will leave it to you to calculate its 1 kilowatt hour and to produce that what we are using is 1.6 plus 0.8 is 2.4, right. So, we can calculate the efficiency, ok.

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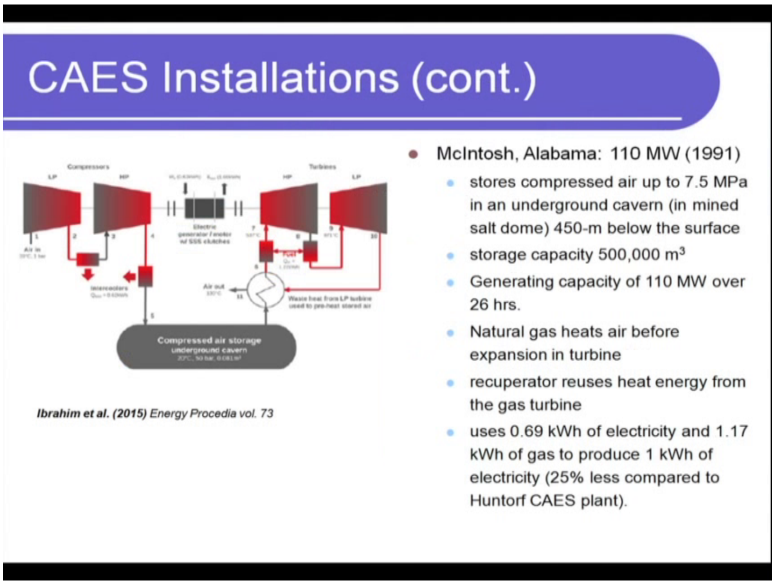

CAES Installations (cont.)

- McIntosh, Alabama: 110 MW (1991)
  - stores compressed air up to 7.5 MPa in an underground cavern (in mined salt dome) 450-m below the surface
  - storage capacity 500,000 m^3
  - Generating capacity of 110 MW over 26 hrs.
  - Natural gas heats air before expansion in turbine
  - recuperator reuses heat energy from the gas turbine
  - uses 0.69 kWh of electricity and 1.17 kWh of gas to produce 1 kWh of electricity (25% less compared to Huntorf CAES plant).

***Ibrahim et al.* (2015)** *Energy Procedia vol. 73*

So, that was Huntorf installation. The second one that was installed in 1991 was Mclntosh. It is a place in a Mclntosh plant in Alabama, USA and what it does is you can again read these numbers. It is underground at 450 mega. This is also an mined salt dome. The storage capacity here is 500,000 meter cubed compared that to 3000. So, definitely almost 67 percent larger than Huntorf generating capacity is 100 and 10 megawatts compared to 290 megawatts. So, this is lower power compared to Huntorf, but this can generate over 26 hours. So, 26 times 110, that is the megawatt hour of energy that can be generated.

So, this is also not an adiabatic plant. This also uses natural gas and we can see the schematic over here. This is also two stage compression with intercoolers and then, the compressed air as you can see look at this one here, the exhaust gas from the low pressure turbine which is still at a higher temperature is used to heat up the compressed air that is coming out of the storage reservoir before it enters the combustion chamber. So, the air is heated up using a recuperative heat exchanger because this is happening at the same time. This is during the release process during the peak hours. So, this exhaust gas that comes out of the turbine at a higher temperature is used to heat up the compressed air first. Then, it enters the combustion chamber where the fuel is natural gas goes to the high pressure turbine again undergoes a combustion process before it enters a low pressure turbine and comes out as exhaust gas, ok.

So, in many ways it is similar to Huntorf. The only thing is, it uses a recuperative heat exchanger to heat up the air before. So, as a result what happens is, the amount of gas that you need to burn to heat up the compressed air, that we get hydel turbine inlet temperature will be lower compared to Huntorf. So, that is what we see here. It is 0.69 kilowatt hour of electricity and 1.17 kilowatt hour of gas to produce 1 kilowatt hour of electricity. So, therefore, again here you can do the math. There we were using 2.4 here. What you are using is like 1.17 plus 0.69. So, 1.86 kilowatt hour of energy used to generate 1 kilowatt hour of electricity. So, this is almost 25 percent lesser compared to the Huntorf plant, clear.

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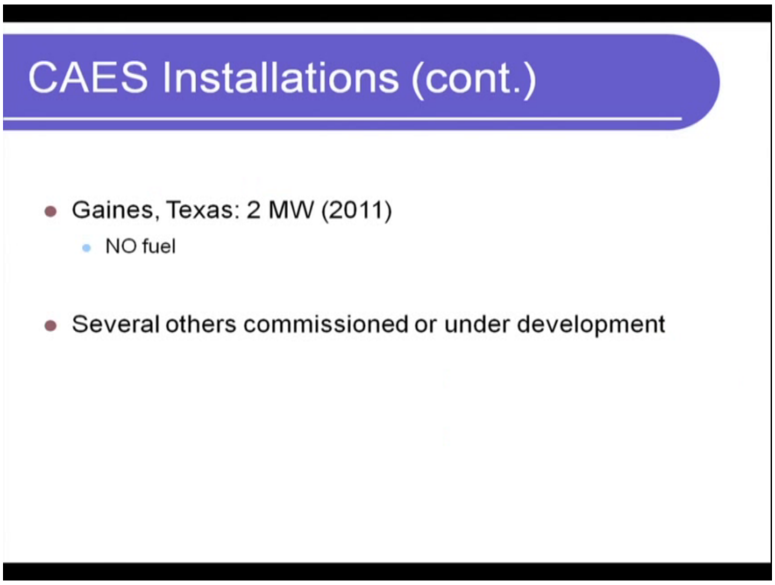

CAES Installations (cont.)

- Gaines, Texas: 2 MW (2011)
  - NO fuel
- Several others commissioned or under development

To continue Gaines, Texas in 2011, it is a small plant, 2 megawatt plant, but however there is no fuel. So, this is an adiabatic plant. The first adiabatic plant to the best of my knowledge under compressed air energy storage installations and then, there are several others that have been commissioned or under development. So, it is not really as I said it is not as widespread or as widely implemented as pumped hydro. The numbers of installations definitely are less or fewer, however this is still an attractive way. It is a very what should I say a very niche innovative way of storing energy in the form of compressed air.

So, that kind of brings us to an end to our discussion and compressed air energy storage and what we will do is, I will start with a new topic in the next class which is again going to be another method of mechanical energy storage which you are already familiar with. It is called Flywheel.

So far we will within this class what we did is, we wrapped up our discussion on compressed air energy storage. We looked at the two different types diabetic and adiabatic plants and adiabatic plants, there is no heat loss, but which is not very practical in diabetic plants. There is heat loss. Therefore, you need additional energy to heat up the compressed air before it enters the turbine. Then, we saw a couple of installations; the two most famous ones; Huntorf and Mckintosh. And we looked at how they work, looked at some of their numbers, their efficiency numbers and so on.

So, that kind of brings us to an end to the discussion on compressed air energy storage. And I will see you next time again with a new topic on Flywheel.

Thank you.