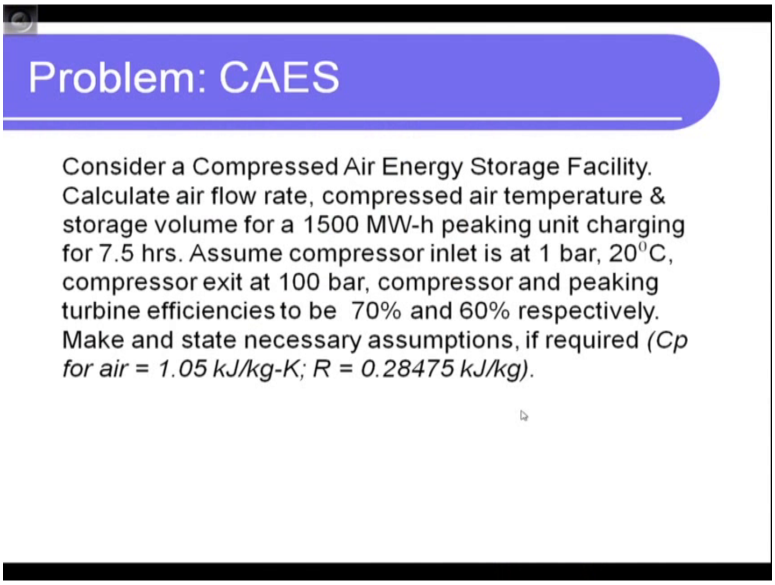
Energy Conservation and Waste Heat Recovery
Prof. Anandaroop Bhattacharya
Department of Mechanical Engineering
Indian Institute of Technology, Kharagpur

Lecture – 59
Energy Storage Systems – IX

Hello and welcome, we will continue with our course on energy conservation and waste heat recovery. So, in the last lecture what we did was we kind of wrapped up our discussion on energy storage systems; during the course of that series of lectures, we learnt about several energy; energy storage technologies somewhat them mechanical storage we talked about superconducting magnetic energy storage and then we talked about electro chemical storage chemical storage thermo chemical storage and so on and thermal energy storage of course.

So, today what I will do is in this lecture; we will just spend some time to solve a few problems based on what we have learnt and in the process what we are going to do is we are going to put into use our learnings to see that in practical situations if we have an energy storage system how do we calculate lets say the power that we can get out of it the efficiency of that energy storage system and so on.

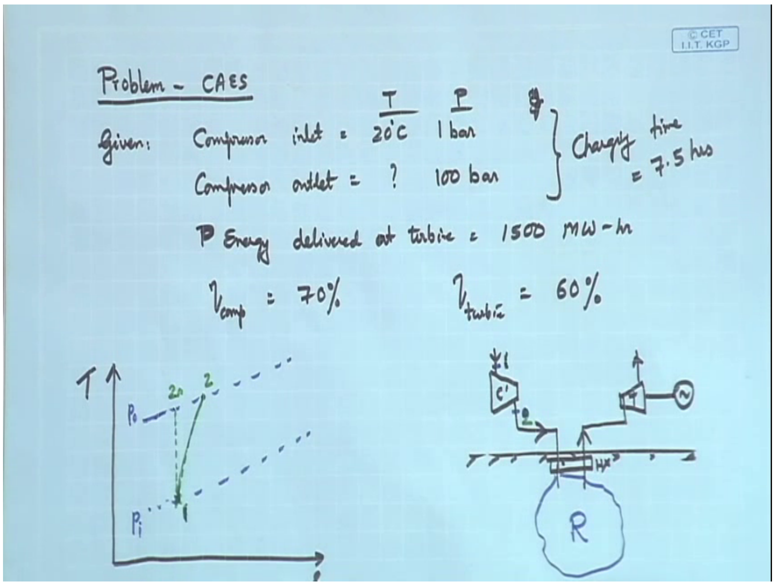
(Refer Slide Time: 01:28)



So, the first problem that I have is from compressed air energy storage. So, what it says is consider a compressed air energy storage facility and what we have to do is we have to calculate air flow rate, we have to calculate compressed air temperature and storage volume and several things are given. For example, what is given is the peaking unit is 1500 megawatt hour, all right and it is charging for 7.5 hours and then the compressor inlet conditions are given pressure and temperature and compressor exit pressure is also given the peaking turbine efficiencies and the compressor efficiency both are given and they are not very high as we can see and then a few properties are given.

So, if we are given this problem how do we solve. So, let us remember what did we do let us write down what all is given to us; what is given to us.

(Refer Slide Time: 02:25)

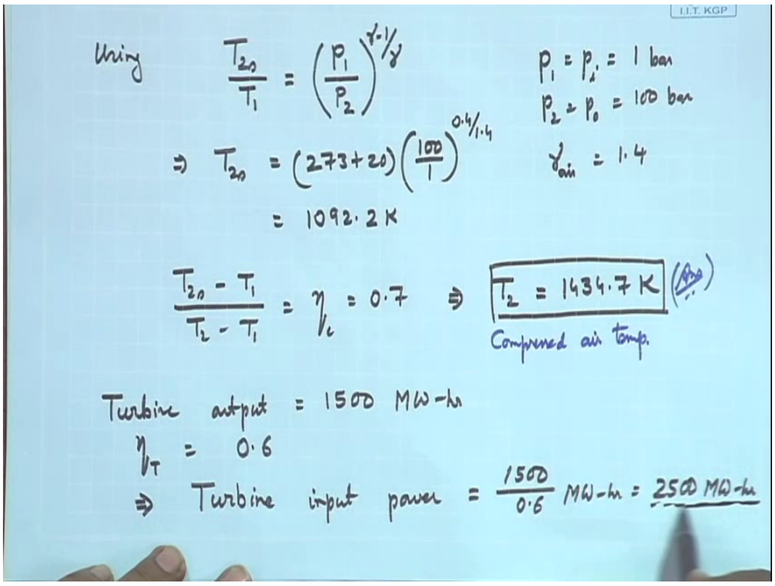


So, the problem is on compressed air energy storage given is compressor inlet what is that is 20 degree centigrade and it is 1 bar. So, for one atmosphere compressor outlet, the temperature is not known what is known is it is at 100 bar. So, this is temperature this is pressure, all right, what else is given it is given that the storage or whatever the energy storage or energy delivered should be equal to at turbine should be equal to 1500 megawatt hour clear and then there are few other things that are given like the compressor. So, the compressor efficiency is 70 percent and the turbine efficiency the peaking turbine that is 60 percent and a few other properties are given or it is also given that the charging time. So, which is the time when the storage happens is 7.5 hours. So, these conditions what do we have to do? What we have to do is we have to solve this problem.

So, let us what will do is instead of going into the details of calculations etcetera we are going to focus more on the steps how do we systematically solve a problem like this. So, this is compressed air energy storage and the first thing that is given is a compressor what is happening in the compressor now recall what happens in the compressor the; let us say this is my th diagram and it is more of the compressor stage in a bray ton cycle or it is e; similar to the compression stage in the bray ton cycle where this is my P 1 or P inlet this is my P outlet, again recall if I just simply draw a compressed air energy storage, this is my compressor this is my ground level and this is my storage reservoir and then again this is my peak in turbine and from here I get electricity and I get this exhaust and there is probably a heat exchanger over here clear.

So, what I have is; I have 2 point here compressor inlet and compressor outlet. So, this is pi and P naught what happens over here is if I look at the cycle then this is my point I all let us call it one and let us call this 2. So, this is my 1 to 2 and if it is isentropic, then I would have landed up a 2 s, but since the compressor is not isentropic I will end up somewhere in 2, this pressure is what this pressure is one bar and this pressure is 100 bar, all right.

(Refer Slide Time: 07:01)



So, my first step is let me try to put it half and half here and keep solving. So, my first thing is I am going to use the relation using if it is isentropic compression, I can write T 2 s by T 1 is going to be P 1 over P 2 to the power gamma minus 1 by gamma P 1 equals to pi is equal to 1 bar P 2 is equal to P outlet is equal to 100 bar.

So, therefore, this gives quickly just go to through 273 plus 20 remember these are absolute temperatures times hundred over one and for air gamma for air we know is 1.4 otherwise from the given data we can also calculate we have the value of r and the value of Cp for air given. So, we can also calculate gamma, but we know that gamma for air will come to the point 1.4. So, let us right at 1.4; 1.4. So, this gives me T 2 s is 1092.2 Kelvin.

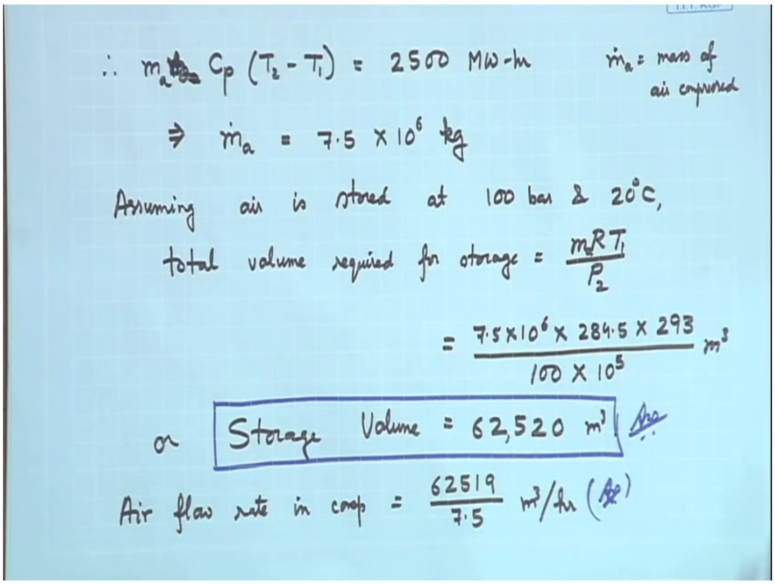
Next what we will do is, but this is this temperature I need the outlet temperature the compressor. So, use the definition of efficiency. So, I can write T 2 s minus T 1 divided by T 2 minus T 1 is equal to the compressor efficiency which is given as point seven. So, from here using everything I will get T 2 is going to be 1434.7 Kelvin. So, this is one data point I have, all right.

So, if you look at the question once again what I have got is the second answer compressed air temperature and this is my compressed air temperature, right. So, let us write that down this is my compressed air temperature. So, this is one answer.

Now, I have to calculate 2 more things and those are what is the flow rate and what is the storage volume that would be required. So, how do I calculate that I have the temperature value right now? So, what we will do is next is for a turbine input for sorry for a turbine output what is it given it is given that the turbine output in this case and when turbine it is a peaking turbine is 1500 megawatt hour, right, I also know that the turbine efficiency is given to be 0.6. So, therefore, turbine input power is going to be 1500 divided by 0.6 megawatt hour or 2500 megawatt hour, right this is an important piece of data.

Now, what is this 2500 megawatt hour? So, therefore, if I look at it this is the energy that is being delivered from here. So, that must be equal assuming there is no loss that must be equal to the energy that they pumped in right assuming no loss in the heat exchanger no loss to the reservoir since it is not given those are assumptions, we are going to make clear.

(Refer Slide Time: 11:30)



So, therefore, I can write from here then therefore, the compressor that is by compressing the air there is the energy I has stored. So, therefore, I can write m dot air which is a mass flow rate of air times Cp right times T 2 minus T one. So, this is a mass of air not mass flow rate I am sorry ma will be equal to 2500 megawatt hour where m dot a is mass of air compressed clear.

So, that is the case I will get megawatt hour you have to change. So, 2500 times 10 to the power 6 and hours you have to put it as 3600 Cp is given to us; Cp is 1.05 kilo joules per kg Kelvin that value is given in the I am sorry; that value is given over here in the problem . So, therefore, and T 2 and T 1 we already know we have calculated T 2 and T 1 was given to be 20 degree. So, 293 Kelvin therefore, this will give me m dot air is equal to 7.5 times 10 to the power 6 kg.

So, next what will do is assuming air is stored at 100 bar and 20 degrees centigrade recall here after this I will its said 100 bar and it is cooled down by this heat exchanger and we are assuming that it will cool down to the original temperature 20 degree centigrade it may not be what that is assumption we are making because the problem statement says make an state necessary assumptions, all right make an state necessary assumptions, all right. So, therefore, 100 degrees and 20; sorry, 100 bar and 20 degree centigrade I can write the total volume required for storage. So, therefore, storage volume whatever you going to use you are going to use pv equals to m a R T clear.

A m R T by P and in this case what is it P is P 2 in ma RT. So, what did we have 7.5 n 10 to the power 6 times R, it is given already 0.284; 75 kilo joules per kg clear. So, what we will do is will convert it joules therefore, 284.5 times the temperature is again back to T 1 which is 293 divided by the pressure is hundred bar hundred one bar is 10 to the power 5 or 100 kilo Pascals or 10 to the power 5 Pascals. So, this will be in meter cubed turns out to be 62520; these calculations you may get a different values that is; so, therefore, I would write storage volume is this and this is also an answer the last part is easy because they ask what is the last part was calculate air flow rate.

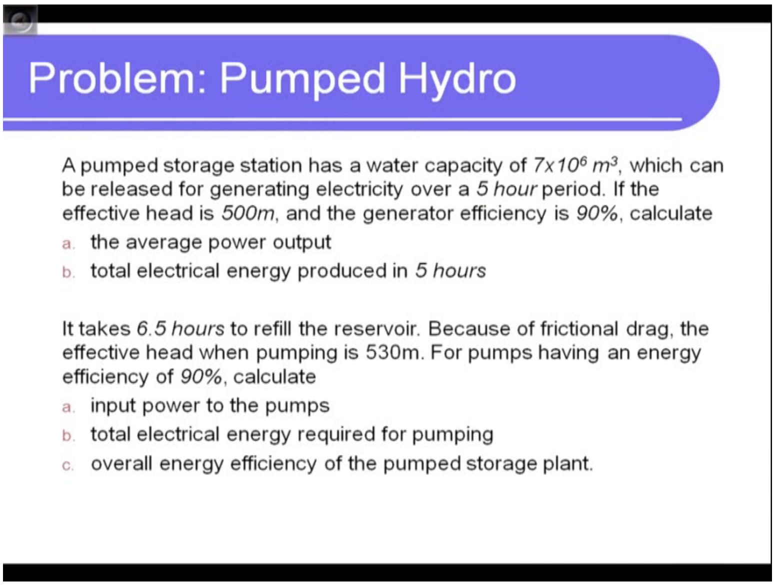
So, air flow rate in compressor is going to be what the volume divided by 7.5 hours is that the given that is given the charging time is 7.5 hours here. So, therefore, I will write it as 62519 that is the volume divided by 7.5. So, that is going to be the meter cube per hour whatever it comes out be all right.

So, this is how we solve these problems. So, first thing that we did was we found out the temperature at 0.2 because there is a compressed air temperature next we had to find out what is the volume that is required. So, for that we were given what is output power. So, using the turbine efficiency we got the input power to the turbine which must be equal to the energy input and our input energy to the turbine and that must be equal to the input energy that was stored in the reservoir assuming no losses again. So, therefore, if we know the input energy what we could find was that is equal to m C P delta T. So, m dot times CP times T 2 minus T 1. So, from there we found out; what is the mass flow or the what is the mass of air that was stored.

So, mass of air was known and then knowing the assuming that off with the pressure will be at hundred bar and assuming that the temperate it was cool down why this regenerative heat exchanger back to 20 degrees which is an assumption which we clearly stated we could find out using the ideal gas law we could find out what is the volume of the storage and then once we know the volume this is what was stored it took a 7.5 hours to fill up this by the compressor. So, divided by 7.5 will be the value in flow rate of air into the reservoir, all right. So, I hope this problem give you a feel of how to solve these problems, right. So, this was a compressed air energy storage type of a facility energy storage facility and we even some input conditions and some assumptions and making some assumptions we are able to get some values.

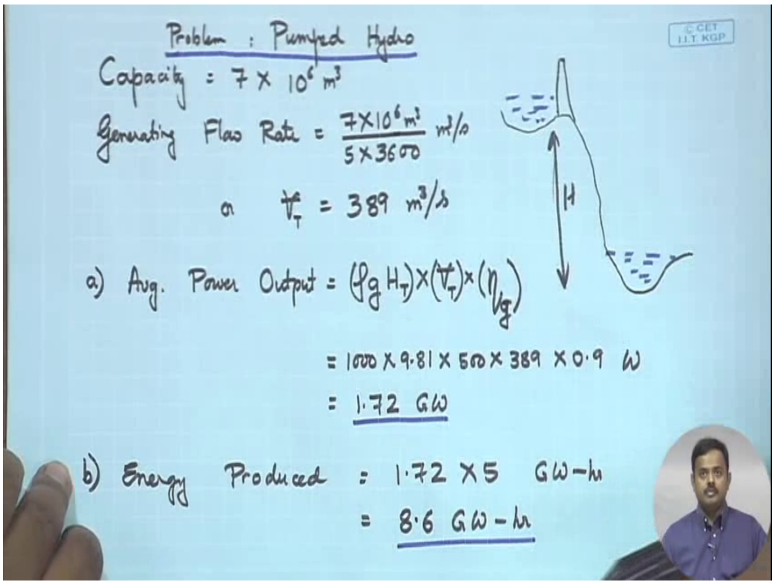
Now you may get a problem we have to solve a problem where some of the things that we solve for are given and some of the things that was given in the problem is unknown.

(Refer Slide Time: 18:30)



So, it is more the method that we used which is important ok let us move on to the next problem and this problem is on pumped hydro. So, the pump hydro case what is given is there is a pump hydro storage system the water capacity or the volume of water that is pumped up from the base reservoir work to the top reservoir is given.

(Refer Slide Time: 18:48)



So, remember you have base reservoir here and then at the top of the cliff you have another reservoir. So, this is my base reservoir and this is my top reservoir.

So, this is my prompt hydro problem and you say that there can be released for generating electricity over a 5 hour period. So, when we actually extract the energy out of when we use the store energy we can use it for 5 hours, if the effective head is 500 meters. So, effective head is may or may not be equal to total head this is my head the effective head may be less than this because there will be some losses effective at 500 meters and the generative efficiency is 90 percent calculate the average power output and the total electrical energy produced in 5 hours . So, this is what is shown here in this here again.

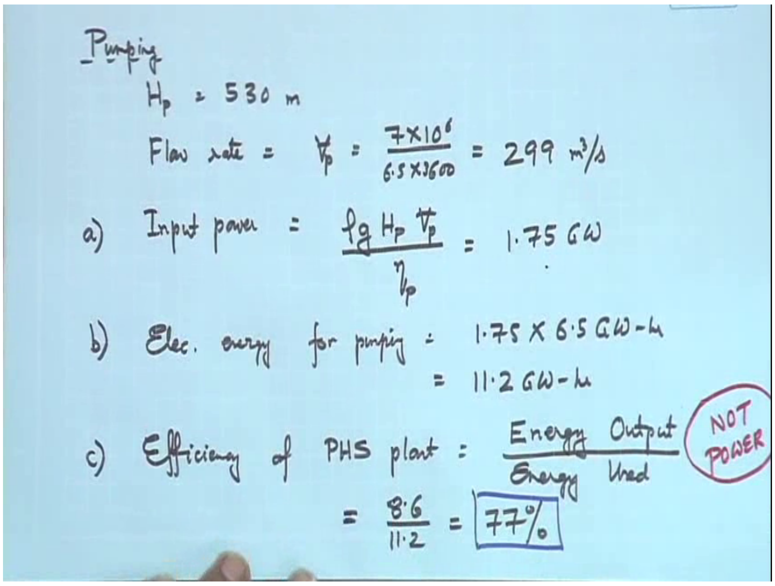
So, the effective head is 500 meters generated efficiency is given calculate the average power output and the total electrical energy produced in 5 hours, all right. So, let us first do this and then will compare the second part. So, first will see the capacity this is pumped hydro problem what is given you know the capacity is 7 times 10 to the power 6 meter cubed, this is a volume of water that is pumped up clear. So, therefore, generating flow rate this is when the power is generated; what is the flow rate into the turbine right; what is the flow rate into the turbine during power generation.

So, I can write it as 7 into 10 to the power 6 divided by. So, this is the amount the volume which is fed to the turbine over a period of 5 hours. So, I would write it as 5 into 3600 there is a number of seconds in 5 hours, we take cube per second and it comes out to be 389 meter cubed per second. So, what are what are will ask for we are ask what is the average power output. So, average power output; what is it going to be. So, power is we know volume flow rate times pressure drop right. So, we can write it as rho g ht which is the what is it this is the effective head in the turbine times flow rate or let me write down here flow rate normally we denote by V. So, we will also write it as v T v turbine and then what this is one this is the flow rate times the output is this is the input to the turbine output would be we have to multiply that by the turbine efficiency which is given sorry generator efficiency; sorry, I will write it has eta g generator efficiency is given as 90 percent clear.

So, therefore, this turns out to be everything is known rho is like thousand I will write it for the first time next time I will not 9.81 times pumping head was 500 times of volume flow rate is 389 times the generator efficiency is 0.9 and this will be what is this is going to be watts clear and this turns out to be 1.72 giga watts. So, this is my first answer and what is the energy produced that is easy because this is the energy that is produced times over a period of 5 hours. So, I would write it as 1.72 times 5 giga watt hour and this is 8.6 giga watt hour clear; all right. So, this is how we have solved it.

What is the next problem the next part says that he takes 6.5 hours to refill the reservoir which means during the pumping time. So, because of fictional drag the effective head when pumping is 530 meters and for pumps having an energy efficiency of 90 percent calculate input power to pumps total electrical energy the same thing like in turbine you want to do it for the pumps and overall energy efficiency of the pump storage plant; so, for pumping second part.

(Refer Slide Time: 24:44)



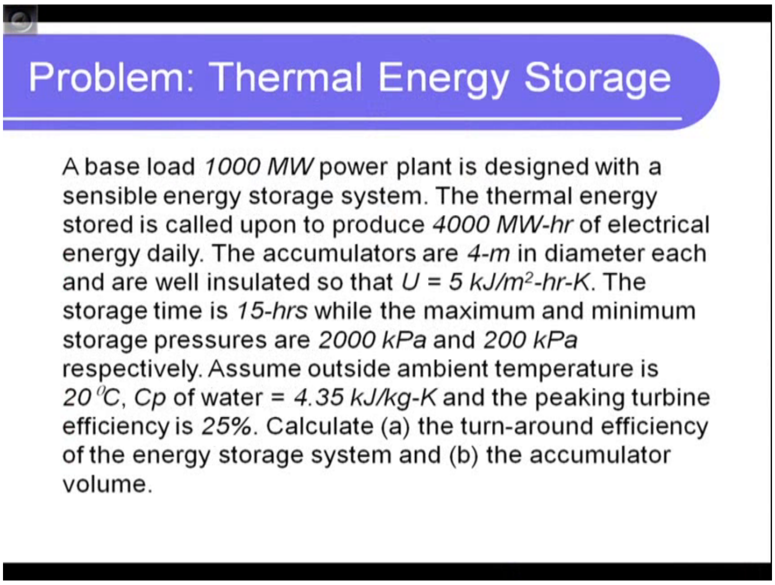
So, here I move a little fast; now that we know how to do things. So, effective head HP is 530 meters and what is the flow rate. So, this happens over 6.5 hours. So, what will do is we again see the same volume flow rate 7 into 10 to the power 6 divided by 6.5 into 3600 and that turns out to be 299 meter cube per second.

So, therefore, input power is going to be rho g pumping head times the flow rates to the pump this one this time is divided by the pumping power because the input power to the pump has to be more than the energy that is gained by the water that is pumped up. So, this we though all the values here. So, I am not writing everything and this turns out to be 1.75 giga watts. So, this is my a second one is electrical energy for pumping that is 1.75 times 6, sorry, 6.5 giga watt hour and that turns out to be 11.2 giga watt hour. See, last one was; what is the overall efficiency of the pumped hydro storage plant.

So, this one be very carefully this is going to be energy output divided by energy used I will write down again in capitals not power, normally in regularly when we solve for thermodynamic cycles etcetera; we use power input was power output verses power input. So, watts, but here we have to use energy why because the input and output do not happen simultaneously in a cycle it happens simultaneously. So, the time is the same, right. So, per unit times whatever is coming in per unit time that is going out? So, we do not care about the; so, the ratio of the power gives the efficiency, but in this case, it is an issue of energies, right. So, therefore, we are not going to use the power values power values if you recall what did we get we got 1.75 is the input power and 1.72 is output power.

So, efficiency is almost close to 100 percent, but that is not the case, right. So, therefore, here; what we will do is here we are going to use this one we are going to use a power which is 8.6 over 11.2 and that turns out to be around 77 percent, all right. So, I think these 2 problems sort of give us a feel of how to solve these problems come pertaining to energy storage plants I hope that kind of wraps up our discussion, let me your do one thing I had one more problem. So, I will leave it for you.

(Refer Slide Time: 28:39)



This is for thermal energy storage and what I will do is I just talk about one base flow thousand megawatt power plant it is designed with a sensible energy storage system. So, we are talking about. So, this one is about that pressurized water storage then thermal energy stored is called to produce 4000 megawatt hour of electrical energy daily. So, output is 4000 megawatt hour daily, all right and then there accumulators a series of accumulators of 4 meters in diameter each under well insulated. So, that the external heat transfer coefficient is given the storage time is given and the maximum minimum pressures are also given.

The outside temperature is given and all that stuff. So, what do we have to do we have to calculate the turnaround efficiency. So, recall here what happens is the initial the water is compressed from 200 K to 2000 kilo Pascals; 200 kilo Pascals; 2000 kilo Pascals. So, there is an amount of energy stored and we solved that how to calculate that remember rho f times h hf 2 minus hf 1 and the rho f typically we take the average specific volume all right over the 2 temperatures and these are those saturated conditions will get the properties from steam tables.

So, this part we did already exactly taking this exact same values when we were discussing next what happens it is stored I have 200 kilo Pascal, 2000 kilo Pascals and corresponding saturated temperature which turns out to be 212 degree centigrade, but then what happens is as it is stored it loses heat and to because outside temperature is 25 degree centigrade and how long is stored it is stored for fifteen hours. So, use the turnaround efficiency formula where the time constant you have to first calculate write rho C v over h a. So, v and a very nicely for a ceiling recollecting accumulator the volume is pi d squared over four times the length and the outer area is again pi d times the length.

So, we have to use this formula we will get the time constant put it in that equation and we are going to get the turnaround efficiency and then what is the total amount that we need required for thousand megawatt hour of electrical energy daily. So, from there we use that formula. So, we figure out how much is the amount of how much is accumulative volume that we need and I am using that we can find out what is the accumulative volume that we need. So, we will leave this maybe for an assignment or something and we can use whatever we discussed to solve this problem.

So, again thank you very much that times have now truly wraps up our energy storage discussions and in the next lecture we will take up a new topic.

Thank you.