POWER PLANT SYSTEM ENGINEERING

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Module 4

Lec 8: Energy Storage-I

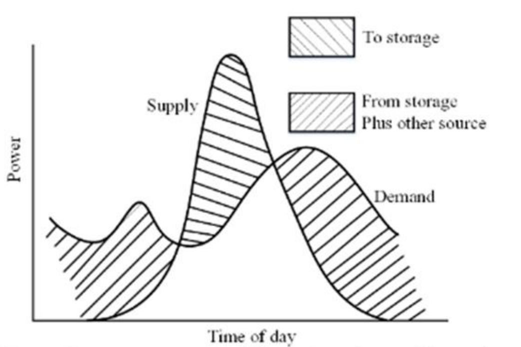
Dear learners greetings from IIT, Guwahati. We are in the MOOCs course that is Power Plant System Engineering, module number 4 and title of this module is Hydro and Renewable Energy Power Generation Systems. So, in this module in lecture number 8, our main focus would be on energy storage. And in this lecture which is the part 1 of this module, we will talk about the two basic units of energy storage systems that is pumped hydro storage systems and compressed air storage systems. So, basically speaking both these storage systems have same philosophy, but only difference is that, in a pumped hydro systems, we have the storage medium as water whereas, in compressed air storage systems your storage medium is air.

But before you start let us try to understand why we require the storage. In our previous sections and modules we have seen that renewable energy systems comprises of wind energy, tidal energy, geothermal energy, solar energy and those energies are intermittent in nature. But if you look at the energy demand in terms of electric energy in a utility systems, they vary hourly, daily, monthly, yearly and so on. At the same time the energy supplied or available for generation of electricity is also intermittent. So, it is very difficult to map when your demand is high or demand is low or when your supply is high and supply is low.

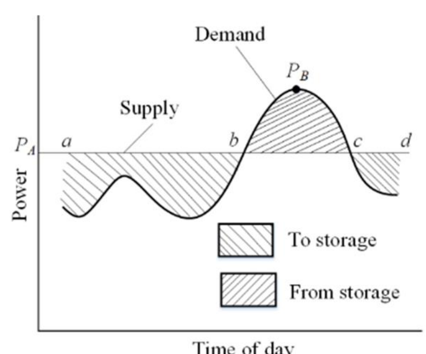
So, to counter this effect we require some kind of mechanism in which energy can be stored with a philosophy that when there is a demand, the stored energy can be utilized to cater the needs. So, the very basic need of energy storage is applicable for renewable energy systems that is solar, wind, ocean, tidal where output of the plant also fluctuates. So, to address this power intermittency which is a situations, where we cannot provide the power based on the demand, which is normally the case when the when we have a conventional plants operated with a fossil fuel or a hydropower system. But to some extent these things can be countered for renewable energy system with a mechanism of energy storage. Hence, the need of energy storage becomes inevitable for renewable energy systems mainly to counter the fluctuations in demand for electricity for assuring a steady output.

So, it operates with a fact that when the demand is lower than the capacity, energy has to be stored, when the demand is higher than the capacity, the stored energy can be released. So, through this process we can have supply of electricity in a reliable manner efficiently and in most economical way. So, in a larger sense if you see earth crust, where natural energy is available, they are also quantified in the form of fossil fuels or inner metals. And we can say earth is also the largest resources of energy. So, to give some quantification numbers, energy available or energy density in the form of fossil fuels falls in the range of 40×10^6 kJ/m^3. Whereas, from nuclear materials, the energy resources can be in order of 10^{14} kJ/m^3.

So, we have been using this energy from millions years of human existence. But at the outset you can say that in the current scenario the energy crisis is significant, so we require a storage medium. So, this is a sample plot that talks about why we require a storage system. First thing the first class talks about a case where energy or power which is available from solar incidence throughout the day.



Thermal energy storage with varying thermal input from solar incidence



Thermal energy storage with constant thermal input from fossil or nuclear fuel

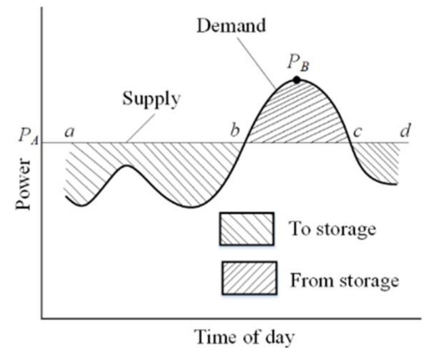
So, if you look at the supply, supply is very specific that means, in the form of solar energy which is available mainly on day time, but demand also varies in a natural way, but in some cases we can see that supply is less, but demand is high. And in some cases if you take the peak value of the supply and take an average line, then we can say that solar energy cannot continuously supply as per the demand. Another situation that can be plotted for power in terms for a fossil and nuclear power plant, we can say that the nuclear and fossil fuel based power plants supply constant power throughout the day. They are quite capable of supplying this power as per the need, but when the demand is higher we these plants cannot be in a position to cater the need for peak demands. So, for that reasons when there is a continuous generation of power we can store them and during peak demand period that can be discharged. So, that is the idea during peak demand the energy has to be supplied from the storage and during normal situations the fossil fuel power or nuclear power plants can cater the base load operation.

So, if you look at the energy storage mechanisms and you say start with a primary heat source and we want to store it, then it can be stored in an electrical storage manner or in a thermal storage manner. So, let us start with electrical storage. The conventional plants run at a base load operation and we get the electric power from its generating stations. Sometimes these plants can give a base load operation, but at this similar situation we can also have the excess electricity. So, that excess electricity can go to the storage.

Now, this storage has the possibilities like we can have electromechanical systems or direct storage and electromechanical systems can further be subdivided into the category of storing in the form of potential energy or in the kinetic energy. Now, looking at the potential energy it can be stored as a pumped hydro medium or a compressed air medium or it can be stored as a torsion bar, springs. So this is what we say potential energy based storage and it falls under electromechanical systems which is a combination of a mechanical and electrical energy. Other part it can be a kinetic energy based systems where this energy is stored in terms of flywheels. So, typical example of this flywheel is that we normally use in a conventional IC engine based plant or engine. Other kind of direct storage of electrical energy can be done by storage batteries and superconducting magnets.

Now, if you look at the thermal storage based systems, the load inputs can also go directly to the power generating stations to provide the base load and the excess heat can go to thermal storage. So, these storage can be possible through sensible heating storage, latent heat storage and chemical reaction storage. So, for all the cases there are two basic important inferences, first the primary plants run with a base load and excess electricity, which is stored energy, is used as a peak load. Now, even in thermal storage also the primary station runs for base load and the excess heat, which is stored in the thermal storage medium, is utilized for peak load.

And this is how the curve looks like, if you want to have a steady power throughout the day. So, during normal situations anyway we are getting a steady power. So, during off peak hours, energy can be stored and during the peak hours the stored energy can be released. So, if you take the average of entire day, then you can say that it is a steady state operation.



Thermal energy storage with constant thermal input from fossil or nuclear fuel

So, this is what I have explained that we have electrical and mechanical storage types and flywheel energy type and batteries & superconducting coils. So, in our subsequent discussions, we will be talking about mainly on pumped hydro storage, compressed air storage, flywheel storage, then storage in batteries in the form of electromechanical storage.

Now moving forward to the thermal energy storage systems we will talk about this sensible heat storage, latent heat storage and chemical reactions. So, we call these schemes as thermal storage schemes in the form of sensible heat, latent heat and chemical reactions. So, the first storage systems of our discussion is pumped hydro storage systems. In our first few lectures of this module number 4, we have talked about the hydropower systems, where the power is generated by converting the potential energy of water and that energy is getting imparted in kinetic energy mode to the turbine rotor. So, this is what we talk about a large scale plants. Now a pumped hydro storage systems also operate in a similar manner. We know from our previous study that it was only the power generating mode which means that turbine and generator are coupled in a hydropower systems. But in a pumped hydro storage medium, we need to store the energy in the form of potential energy with water as a working medium. So, that potential energy can be used to cater the needs during the peak demand; that is the entire idea. So, for that purpose what we require? We require a pumping unit that will be integrated with a power plant. When there is an excess power available, that excess power can be utilized to pump water from a lower reservoir to an upper reservoir. This is what we talk about a pumping mode and during discharging mode or during peak demand, that same energy can be released in a way similar to the operation of a hydropower plant and that is called as power generating mode. So, we have a pumping mode, and a power generating mode. So, that way one can say that to store the energy in a pumping mode we have head or pumping mode head available as per below expression.

Potential energy for a mass (m) to a maximum elevation, $PE = gmH$

Static heads: Pumping mode, $H = H_P - H_{lP}$; Turbine-generating mode, $H = H_T + H_{lT}$

H_p & H_T: Operating head in pumping mode and turbine-generating modes, respectively

H_{lP} & H_{lT}: Losses during flow conditions for pumping and turbine-generating modes, respectively

Since it is a pumping mode this also talks about the losses during flow conditions of pumping. Now when that hydro storage energy runs in a turbine generating mode we have the head available in the turbine and head losses during the most operation of turbine mode. So, that losses comes by virtue of the length at which the water flows in the pipe and the pipe means it is something like a penstock.

So, what happens is that during pumping mode, the height travelled by the water is H and using turbine mode also same height is there, but main thing is that the heads are different. That means, losses during pumping mode and losses during turbine mode can be different. Further turbine may not operate continuously. That means suppose, we are doing the pumping mode for 8 hours, but turbine can operate for 2 hours. So, that way the controlling factor of H & H_T is different. So, based on this we have different flow rates, Q_P for flow rate of water for pumping mode and Q_T as the flow rate of water during turbine mode operation.

Pumping and generation powers, $P_p = g(\rho Q_P)H_P$; $P_p = g(\rho Q_T)H_T$

Q_p & Q_T: Volumetric flow rates in pumping mode and turbine-generating modes, respectively

So, in other words it means that head is converted to power for pumping mode and for turbine mode. Now, to make this concept effective we need to have two reservoir one is upper reservoir & other is lower reservoir. Now, these low reservoirs can be naturally generated or you can create some kind of artificial reservoirs. So, one case it can be a lake, river & other than that we can artificially exhibit some of the reservoir. Now, to make this effective we have two important things first is elevation height H which is defined for pumping mode and turbine mode & other is the maximum horizontal distance. So, basically H is detected by this height and L is the actual length in which the water flows in the pipe or penstock.

Favourable ratio for pumped hydro storage, $\frac{L}{H} < 2;$ L: Minimum horizontal ratio

So, when $L/_H < 2$, then it makes sense that a pumped hydro storage system can be effective at a particular geographical site. Now, to give more insight to a pumped hydro storage systems, we can have high head installations in which we can have upper reservoir and lower reservoir with a steep slope. Other case can be a medium head installations, it can be a horizontal open canal with a short pressure pipe towards this power house. So, these two things are mainly necessary to justify the requirement of a pumped hydro storage system and most importantly topography of a geographical site is also important.

Many a times pumped hydro storage systems can also be considered above ground or underground. So, above ground means your lower reservoir is on the surface and this upper reservoir will be above the surface at certain height. Now, in other way, we can say that beneath our ground we can create a lower reservoir means once we go to a depth, then we can create an underground reservoir where water can be stored and that can be easily accessible. So, that is another way we can look at the topography.

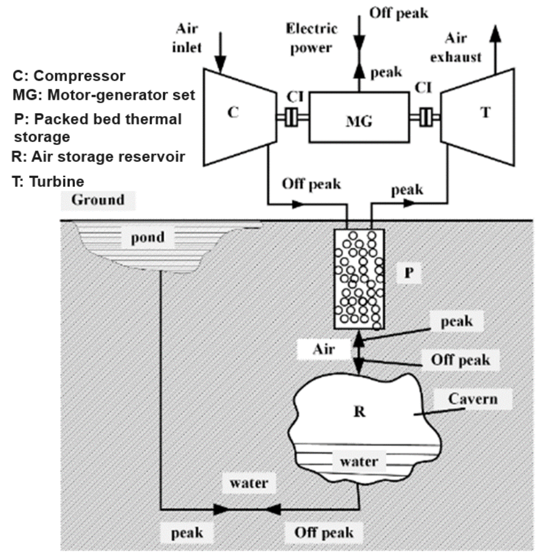
Now, there are some situations like in the earth crust we can have a natural caverns, mines or underground cavities. So, those locations can be effectively chosen to store our water. So, that is the idea of how the pumped hydro systems operates. Another important part of this I have already mentioned that the pumped hydro systems operate during storage phase as pump-motor system and during generation phase it operates in turbine-generator mode. So, which means that excess energy supplied by the primary plant during off peak hours can be used to drive a motor pump to elevate water from lower to upper reservoir and during peak demands the system can reverse the turbine generator mode for producing the excess electricity.

Now, there is a method in which the efficiency or efficacy of this pump storage system is defined and this combined efficiency for pumped hydro systems is called as turnaround efficiency. So, basically there is a charging period and discharging period and turnaround efficiency talks about how much we have charged, but how much we have actually discharged. So, taking into account the power produced during discharge phase and power produced during charging phase the turnaround efficiency falls in the range of 62–68%, which is quite a reasonable number for any energy storage device. But main issue here is that when you talk about storage their energy densities are less. So, you cannot supply continuously for a long run. So, it is only used for peak demands.

Now, we will move on to next segment of our discussion that is compressed air storage systems. When you say pumped hydro storage it takes the advantage of hydrostatic pressure to increase the potential energy of water through its elevation. And the analogous mode in the compressed air storage is that energy is stored in reservoir, aquifer or caverns. And this stored energy is released during the period of peak demands by expansion of air through an air turbine.

So, essentially in a pumped hydro we require a hydro turbine, but in a compressed air storage we require an air turbine and water is liquid phase and air is gas phase. So, in the first case we are storing the water in a potential form and in the second case also we are storing the potential energy by compressing the air in a compressed form. Another additional feature that we have during this compression of air, temperature of air also increases & that part is gives an additional advantage. Now, looking at the storage, compressed air storage systems can be of three types one is salt caverns, aquifers or hard rock systems. Salt caverns are more stable compressed air storage systems because of its loading for entire duration of the plant life. Aquifers are naturally occurring formation of porous rocks that has capability of air water interface movements. So, that pressure difference can be utilized as a storage. Hard rock systems maintains air pressure above its surface, but main difference is that this system is not stable when we have large temperature fluctuations. However, our main intention in this compressed air storage systems is to talk about salt caverns system which is a more stable system and simple in its operation.

Now, let's see how a compressed air storage systems in salt in a cavern mode looks like. So, what we have shown in this figure is a hybrid mode of system. Hybrid mode means when we compress the air, pressure increases as well as the temperature increases. So, which means the stored energy is in the form of pressure as well as thermal energy. So, that way it is a hybrid mode. And the system is mostly adiabatic because we are taking out the heat from this compressed air after its compression and we are not allowing this heat to go out of the system. Let us see this figure how it operates. So, what we see here is that a motor-generator set (MG) is coupled with a compressor on one side and turbine on the other side. And this turbine is an air turbine. Now, during off peak hours that means, when we have excess energy or there is there is not much demand, we run this unit that is motor-generators unit as a motor mode. So, when it runs as a motor mode, it runs this compressor. So, when the compressor starts running air gets sucked into this compressor from atmosphere. During this process of compressions its pressure, temperature increases. Now, we are storing this in an underground reservoir (R) which is called as air storage reservoir. Now, before entering this air reservoir we allow this compressed air to pass through a packed bed storage material. So, here we have some materials that can absorb the heat from this high temperature air. So, by absorbing heat the heat is retained within this packed bed. And during this charging phase what happens is that the thermal energy is captured through the packed bed and through this process your pressure does not change, but temperature drops. So, normal air gets stored in a reservoir & we call this as an air storage reservoir. Now, this can be underground as well or it can be kept in a balloon or some cavities in an underground systems & we call this as a cavern.



A Single-stage Adiabatic Compressed-air Energy Storage System

Now, during discharge phase or during peak demand we allow this MG set that is motor generator set to operate through turbine mode. So, it means that compressor mode is switched off and side by side we start the discharging mode. So, through this process the compressed air by virtue of its own pressure again passes through this packed bed. Now, during this passage through the packed bed it absorbs the heat which is stored inside this packed bed material and its temperature increases. After that we try to expand the high pressure and temperature air in the turbine. Now, why do you require this? Because we expect that during expansion phase air should not condense. So, that is the idea that it should not condense. That means, when you allow this air to enter into this turbine its temperature is reasonably high enough, so that during its expansion phase, it does not condense. So, through this the system operates. So, this is how the system operates and it is a single stage adiabatic compressed air storage system that operates during a charging phase and in a discharging phase. Now, typically since this system operates in adiabatic manner and we are talking about a very high pressure and temperature storage, the conventional system of γ, C_p values change. So, for that case, instead of assuming an isentropic system, we call this as a polytropic system and if this polytrophic systems operate in an adiabatic manner.

Now, during the polytropic compression we can find out this temperature ratio that is

$$\text{Temperature ratio,} \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{\frac{n-1}{n}}$$

Subscripts 1 & 2: Before & after compression; p & T: Pressure & Temperature, n: Index of compression

Then to get the efficacy of the system, we also have to consider the storage capacity of the reservoir and this has to be quantified as storage efficiency and that storage efficiency operates in an adiabatic manner and we call this as an adiabatic storage. That's the First thing. And second thing is that the system is also a hybrid system because we talk about thermal as well as pressure energy which is tapped simultaneously during this compression phase.

Now, if you look at a typical workable model for a hybrid adiabatic system, one can say about a cavern size or talks about the storage volume. And first thing we need to quantify is this cavern volume and based on the cavern volume, the size of the packed bed thermal storage will be 10% of that value volume. So, for a typical situation of a peak unit capacity of 1500 MWh, an expected storage would be 2000000 m^3 of storage capacity to store 10 bar pressure. It means that if you want to store air at 10 bar pressure for producing 1500 MWh energy, then you require 2000000 m^3 storage area, which is huge. So, this is not a feasible option. So, we have to look for a higher storage medium. We have to store the air for same capacity at higher pressure, so that our volume reduces or storage capacity reduces drastically. So, 2000000 m^3 comes down to 64000 m^3, which means at higher pressure the storage volume is less & hence your cost of developing the system will be less.

Hence it is concluded that a compressed air storage systems becomes effective when we are exploring high pressure storage system. Now additionally what happens is that there are techniques like we have already told about like the single stage compression, single stage expansion, multistage compression and multistage expansion. So, instead of compressing heat in a single stage, we can think of multistage compression. So, this is a case of three stage compression and this is a three stage expansion in the turbine. And everything what we do is similar to air compressor and air turbine.

Let us try to see if there is any workable model which is available in a compressed air storage system. So, the first compressed air storage system was designed and built at Brown Boveri in 1978. So, it is a hybrid gas turbine plant which is built at Huntrof, Germany for a capacity of 290 MW. This is shown in this figure. Now to cater this need, the cavern requirement is 300000 m^3 storage volume. Storage volume capacity is close to 300000 m^3 and this is created by leaching salt dome. Because normally we keep this salt in this thing because its density becomes higher and higher. So, in the leaching salt dome air is stored to increase its density. And this is stored at a depth between 650 m to 800 m below this ground & it is not under water rather it is underground. This is what we do in a charging mode.

So, in a storing mode compressor pumps the atmospheric air into caverns and stores at 50-70 bar and in generation mode we do not operate at 50 bar rather we operate at a reduced pressure to maintain the constant pressure in this storage volume. So, it is operated at lesser pressure that is 46 bar. So, this is a case where atmospheric air is taken at 10℃ and it is a 3 stage compression and 2 stage expansion. So, additionally we have other units like intercooler, after cooler at various locations. So, this particular figure is just to give you a feeling that such a compressed air storage system do exist and it has to be integrated in any one of the power plants. In fact, this particular unit is a hybrid mode with a packed bed and it is a gas turbine plant.

So, other point is that for this particular unit the storage occurs for about 8 hours, but generation is done only for 2 hours. So, thereby we maintain a constant pressure in that air storage reservoir. So, this is all about this compressed air storage system which is a very fundamental requirement for any kind of power plant operation. And it falls as a renewable energy because we do not spend any extra cost for developing the systems. So, we are just taking the excess amount and try to store it and this unit only gives the peak requirement of demand. Now, with our discussion today we will try to solve a numerical problem which is a simple numerical problem just to know the feeling of the quantitative numbers that we are talking about.

Q1. In a compressed-air storage unit of 1500 MWh is to be designed for charging period of 7.5 hr. The air inlet pressure and temperature for compressor are 1 bar & 20°C while the exit pressure is 100 bar. The polytropic efficiency for compressor is 70% and the peaking turbine efficiency is 60%. Calculate the following parameters: (a) temperature of air after compression; (b) polytropic exponent for compression; (c) storage volume; (d) average air flow into the cavern during charging

So, this problem is about a compressed air storage unit which is supposed to be designed for a charging period of 7.5 hour. That means, we need to charge this thing for 7.5 hour. The initial condition of air is 1 bar, 20°C and exit pressure is 100 bar, polytropic efficiency for compressor is 70%. Here you will not use the word turbine here we will use the word peaking turbine because the turbine runs during the peak demand. So, we need to find out temperature of air after compression, polytropic exponent, storage volume and average air flow rate during charging. Now, to solve the problems, let us first understand what all data has been given.

Polytropic efficiency of compressor, $\eta_C = 70\%$; Peaking turbine efficiency, $\eta_t = 60\%$

Initial case, $p_1 = 1$ bar; $T_1 = 20°\text{C} = 293$ K

Exit pressure, $p_2 = 100$ bar

Taking this η_C as adiabatic efficiency: $\eta_C = \dfrac{h_{2s} - h_1}{h_2 - h_1}$

Had this polytropic efficiency been an isentropic efficiency, it would have been the ratio of isentropic enthalpy difference to the actual enthalpy difference.

$h = C_p T$. Since the working medium is air. So, C_p gets cancelled.

$$\eta_C = \frac{h_{2s} - h_1}{h_2 - h_1} = \frac{T_{2s} - T_1}{T_2 - T_1} = 0.7$$

Now, here T_1 is known. And T_{2s} can be calculated by using isentropic relation

$$\left(\frac{T_{2s}}{T_1}\right) = \left(\frac{p_{2s}}{p_1}\right)^{\frac{\gamma-1}{\gamma}}; \text{Take } \gamma = 1.4; \ \frac{p_2}{p_1} = 100; T_1 = 293 \text{ K}$$

$$\Rightarrow T_{2s} = 1090 \text{ K} = 817℃$$

But we do not require T_{2s}, we require T_2.

$$T_2 = T_1 + \frac{T_{2s} - T_1}{\eta_C} = 1159℃ = 1433 \text{ K}$$

For Polytropic compression, $\dfrac{T_2}{T_1} = \left(\dfrac{p_2}{p_1}\right)^{\frac{n-1}{n}}$

$$\Rightarrow \left(\frac{1159 + 273}{293}\right) = (100)^{\frac{n-1}{n}} \Rightarrow n = 1.53$$

So, we get the first two answers. The temperature after compression is 1152℃ . Index of polytropic compression is 1.53.

Now, next part is to find the storage volume. To find the storage volume, we need to use the equations which is called as equation of state.

$$pV = mRT$$

So, in this equation we know pressure and temperature. We do not know mass and volume. For mass calculation we have to look into the requirement for turbine.

$W_t = 1500$ MWh; Turbine efficiency, $\eta_t = 60\%$

$$\Rightarrow \text{Storage power}, P_s = \frac{1500}{0.6} = 2500 \text{ MWh}$$

This 2500 MWh has to be stored through heating. So, for that reason you can write

$$mC_p(T_2 - T_1) = P_s$$

Now, here we are talking pressure is about 100 bar and expected temperature would be around 1200°C. So, for this case we say

$$C_p = 1050\frac{J}{kg.K}; R = 284.75\ \frac{J}{kg.K}$$

This data can be obtained from any of the conventional thermodynamics books.

$$m = \frac{P_s}{C_p(T_2 - T_1)} = \frac{2500 \times 10^6 \times 3600}{1050(1159 - 20)} = 7.5 \times 10^6 \text{ kg}$$

Now, once you know this mass then we can say what should be volume.

$$V = \frac{mRT}{p} = \frac{7.5 \times 10^6 \times 284.75 \times 293}{10^7} = 62575 \text{ m}^3$$

So, for storage of 1500 MWh at 100 bar we require a storage volume of 62575 m^3.

And last part of this analysis is to find the average flow rate of air into the cavern during charging. So, basically our charging period is 7.5 hour.

$$\text{Average flow rate}, V_{avg} = \frac{62575}{7.5} = 8343\frac{\text{m}^3}{\text{hr}}$$

So, this is all about this problem which is based on this compressed air storage unit. So, with this I conclude this lecture today. Thank you for your attention.