Energy Conservation and Waste Heat Recovery

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Lecture - 55
Energy Storage Systems - V

Good morning and welcome back to the next lecture on Energy Conservation and Waste Heat Recovery. So, we are talking about energy storage and you remember in the last few lectures, what we covered are three mechanical energy storage technologies; pumped hydro, compressed air energy storage and flywheel. So, today what we are going to talk about is energy storage in a magnetic field.

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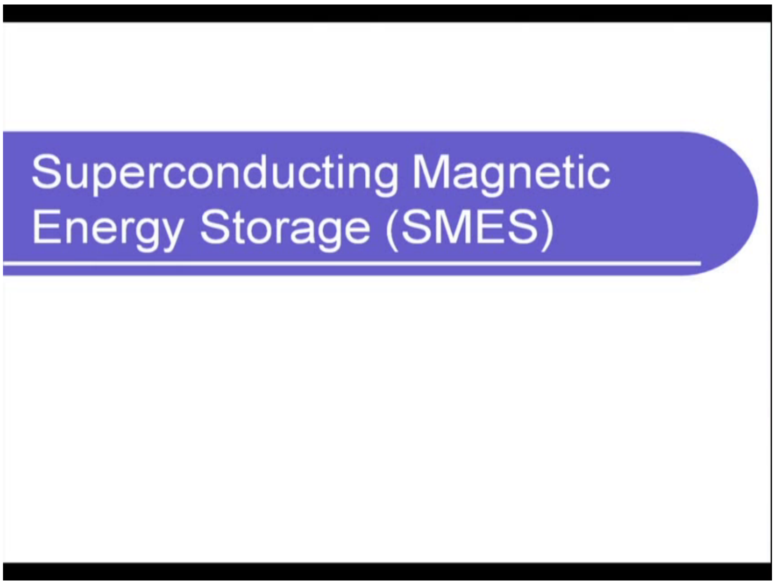

Superconducting Magnetic Energy Storage (SMES)

So, that is what is called superconducting magnetic energy storage or SMES.

So, let us talk about a little bit how a magnetic energy is stored.

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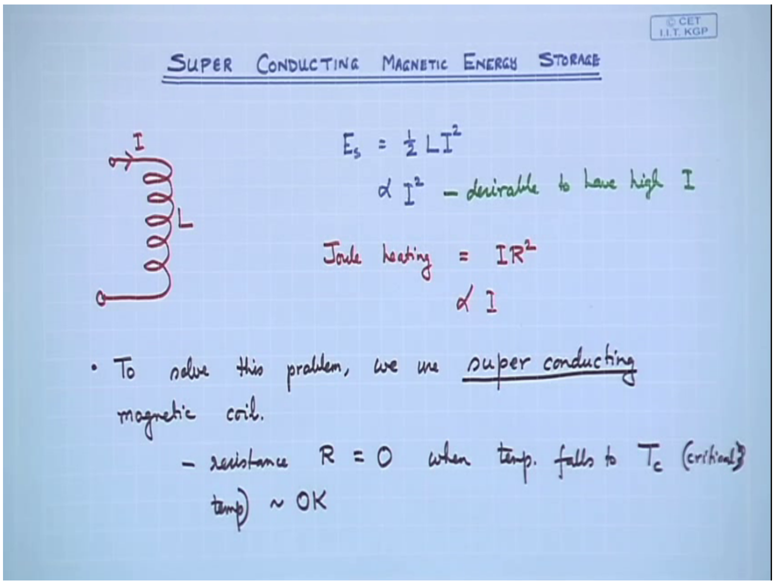

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SUPER CONDUCTING MAGNETIC ENERGY STORAGE

$E_s = \frac{1}{2} L I^2$

$\propto I^2$ – desirable to have high I

Joule heating = IR^2

$\propto I$

- To solve this problem, we use super conducting magnetic coil.
  - resistance R = 0 when temp. falls to T_c (critical temp) ~ 0K

So, let us talk about an induction coil. So, these are an induction coil, and let us say the induction is L and we have a current I flowing through it, right. So, what happens what is the amount of energy that we can store? The amount of energy that we can store is again let us say energy stored E s is half LI squared which means again it is proportional to the square of the current. Remember in flywheel it was half I omega squared. So, similar form there, it was proportional to omega square and we said that we want very high angular speed if we have to store high amount of energy.

So, here also we would say that it is desirable to have very high current. So, I would say it is desirable to have high current or I. Now, what is the problem? However, the problem is there is also an energy loss due to joule heating and that is equal to IR squared, clear which means that joule heating also goes up if I increase high because you have a finite resistance R. So, on one hand if you want to store more energy in a magnetic field, we need high current, but then what acts as a detrimental factor is the joule heat which also goes up because of current or with current. So, this is where the problem is. So, the way this is solved is, to solve this problem we use super conducting magnetic coil, clear.

Now, what is the superconducting material magnetic coil? So, here materials when they come close to zero degrees absolute or Kelvin, there certain materials whose electrical resistance goes to 0, I am not saying close to 0, it is 0. Then there is no resistance. That is why it is called a superconductor. So, what is the feature? Let me write it down. It is resistance R equals to 0 when temperature falls to TC which is a critical temperature which is around 0 Kelvin. I am not exactly 0 or close to 0, it is not easy to do, but this is the material or this is the material and this is its unique characteristic of a superconducting material, ok.

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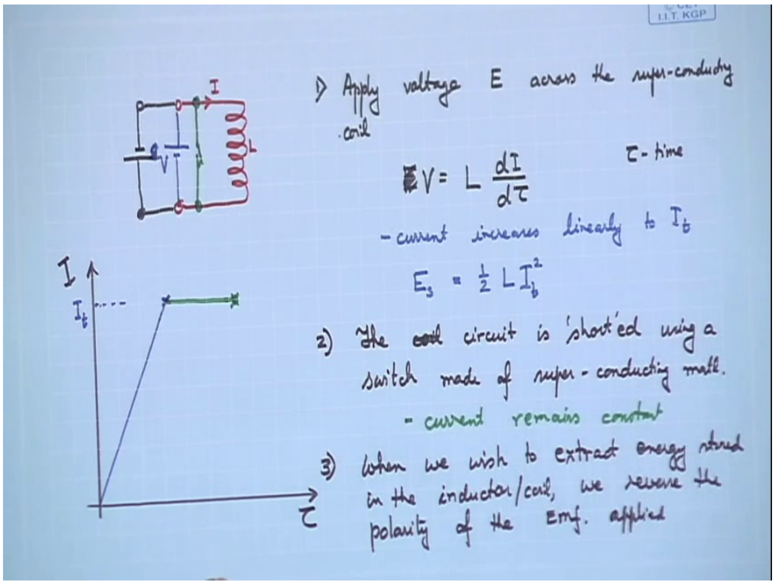

1) Apply voltage E across the super-conducting coil

$\cancel{E}\, V = L \frac{dI}{d\tau}$ τ - time

- current increases linearly to I_t

$E_s = \frac{1}{2} L I_t^2$

2) The ~~coil~~ circuit is 'short'ed using a switch made of super-conducting matl.

- current remains constant

3) When we wish to extract energy stored in the inductor/coil, we reverse the polarity of the Emf. applied

So, therefore, what happens now let us talk about it if I again draw the magnetic coil over here and I have a current i flowing through it. This is L, all right. Now, in case one what I will do is stage 1 is I will apply a voltage E across it. So, first what I would do is apply voltage E across the superconducting coil and then, what happens we know that E is equal to L dI dT or d tau where tau is time.

So, therefore, what will happen let me draw something? I am going to draw the current with respect to time. So, in the first stage what happens E is equal to L dI dT. Therefore, dI dT is E over L which is linear and therefore, the current will increase from 0 linearly to some value and we call it let say I target. So, therefore current increases linearly to L t and energy stored. What I will do is, I will just change this, give the nomenclature from E to V and here also I will write it as V. The reason is I do not want to confuse it, but I do not want to confuse this emf with the energy storage by using the same symbol E, ok.

So, the energy stored is going to be half L I t squared at this point. So, at this point what we do is V. So, I will use three different colors. At this point, I will use the green color we short the circuit. So, stage II what happens is this coil or the circuit is shorted using a switch and this switch also should have zero resistance made of superconducting material. So, it is a superconducting switch. Therefore, what happens is this current keeps flowing through this circuit, all right.

So, therefore here what happens is the current remains constant. So, this current will remain constant and then, what happens if I now want to retrieve the energy out. Then, in that case what I will do is, I will have a third one where I am going to reverse the polarity and make the current flow in the opposite direction.

So, at stage III when we wish to extract energy stored in the inductor or coil, we reverse the polarity of the emf applied or supplied and then, what happens is the current will reduce here. I will use a black ink only.

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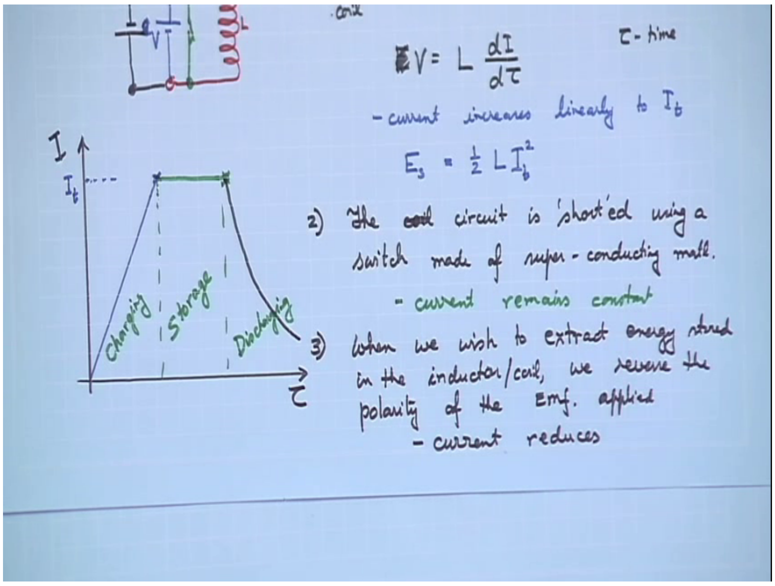

·coil

τ - time

$V = L \frac{dI}{d\tau}$

- current increases linearly to I_t

$E_s = \frac{1}{2} L I_t^2$

2) The ~~coil~~ circuit is 'short'ed using a switch made of super-conducting matl.
   - current remains constant
3) When we wish to extract energy stored in the inductor/coil, we reverse the polarity of the Emf. applied
   - current reduces

So, current reduces and how does it reduce? It reduces like this. The variation is going to be exponential and why? Please I would give it to you as a home assignment or whatever a little self-assignment. It is very easy why it should reduce or not in linear, but exponential manner should come automatically.

So, if this is the case, then what happens is I will write the three stages. So, this is charging, this is storage and this is discharging. So, this is how it works. So, therefore, when we have additional energy, we supply it. We supply a voltage and it goes up when we want to store it. We just remove it and short the circuit when we want to get it out reverse the polarity of the emf applied and then, what happens if we add. Of course, we will add a resistance through which we want to get the current out of it, all right. So, this is the case then.

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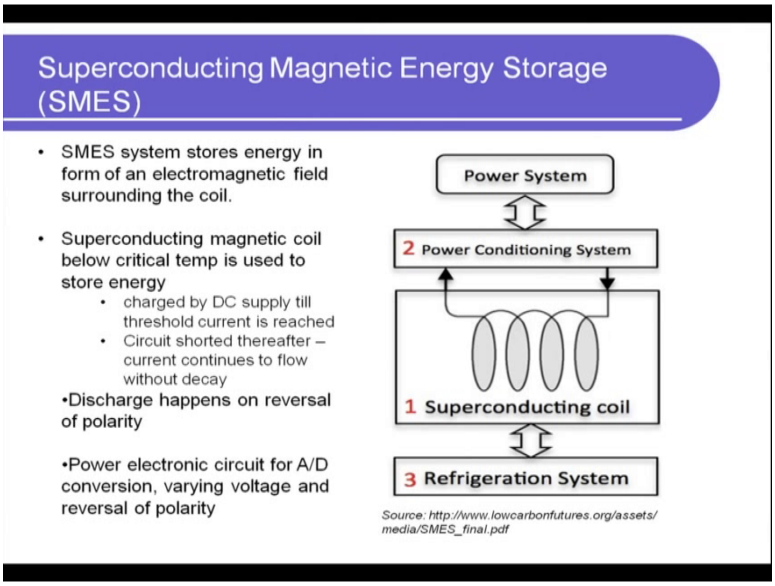

Superconducting Magnetic Energy Storage (SMES)

- SMES system stores energy in form of an electromagnetic field surrounding the coil.
- Superconducting magnetic coil below critical temp is used to store energy
  - charged by DC supply till threshold current is reached
  - Circuit shorted thereafter – current continues to flow without decay
- •Discharge happens on reversal of polarity
- •Power electronic circuit for A/D conversion, varying voltage and reversal of polarity

Power System

2 Power Conditioning System

1 Superconducting coil

3 Refrigeration System

Source: http://www.lowcarbonfutures.org/assets/media/SMES_final.pdf

Let us look at this slide now and it is going to become a quickly clear you have a power system and a power conditioning system. So, all these things that we talked about which is supplying the voltage reversing the polarity shorting, these are all done using a power converter circuit.

So, that is what is shown here that the power electronic circuit does the analog to digital conversion. It varies the voltage, it reverses polarity and everything. The discharge happens on reversal of polarity. I am going down up here because we have discussed all these and the first two of course we see that the other thing to note is the superconducting coil has to be maintained at a very low temperature. So, as the result we would need a cryogenic system rather I have written it or the figure over there which I have borrowed from the source says it refrigerated in refrigeration system, but I would say actually it falls in the cryogenics range.

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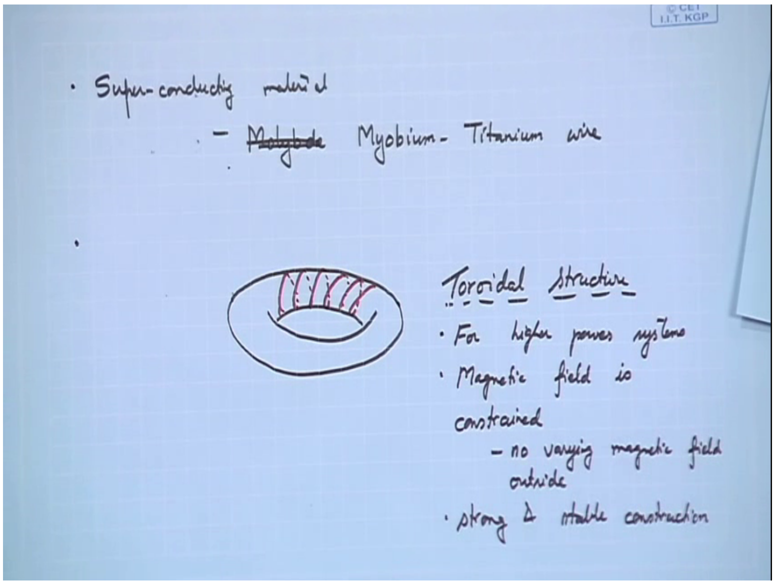

- Super-conducting material
  - ~~Molybde~~ Myobium- Titanium wire

Toroidal Structure

- For higher power systems
- Magnetic field is constrained
  - no varying magnetic field outside
- strong & stable construction

Now, what is the material that is used? What are some of the materials? So, superconducting material the one that we most commonly know is actually molybdenum, oh sorry myobium titanium wire.

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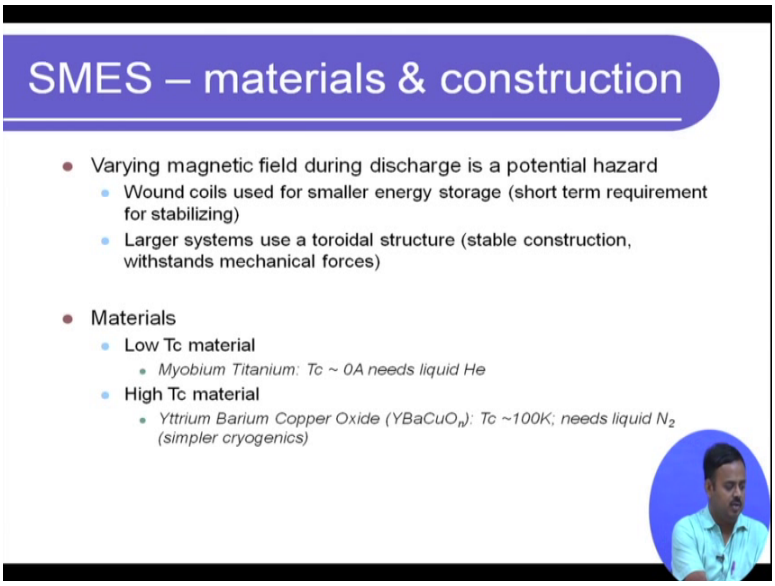

SMES – materials & construction

- Varying magnetic field during discharge is a potential hazard
  - Wound coils used for smaller energy storage (short term requirement for stabilizing)
  - Larger systems use a toroidal structure (stable construction, withstands mechanical forces)
- Materials
  - Low Tc material
    - *Myobium Titanium: Tc ~ 0A needs liquid He*
  - High Tc material
    - *Yttrium Barium Copper Oxide ($YBaCuO_n$): Tc ~100K; needs liquid N_2 (simpler cryogenics)*

However, what is happening is these days the myobium titanium as is shown in over here, the critical temperature is close to 0. So, it requires liquid helium, but what has happened is new development is that recently we have been able to or some labs have been able to develop materials which have super conduct which show superconducting behavior at higher temperatures that like 100 Kelvin. They are still below 0 degrees, still need refrigeration, but here you can use liquid nitrogen instead of liquid helium. The simpler cryogenics nitrogen is available in abundance. We have established technologies to liquefy nitrogen.

So, the cryogenics are much simpler compared to liquid helium. So, that is why this high tc material is also being used, however typically what has happened is the high tc material is still under development. So, small units, small energy storage has been shown to work, but if you go to slightly higher values of energy that you need to store, it is still molibium myobium titanium that we are using. What else? The other thing that I want to show is about the construction. So, we drew a simple magnetic coil, all right and we say that at one point we will discharge at one point we will charge, then during discharging again we will reverse the polarity.

So, what is going to happen? What is going to happen is as the current changes during the discharging cycle, let us talk about the charging cycle, right. Now, as the current changes, the magnetic field stream will also change. So, now think of me as a person or any living person or even that most what is happening around it. There will be a magnetic field that is generated whose intensity will be varying, ok.

Now, let us say I stand and human body is a conductor, then what happens I will be a voltage established across my body which is going to be fatal, right. Correct it is a varying magnetic field in a conductor, conductor in a varying magnetic field. So, therefore, what is typically done is we use a toroidal structure as I am showing here in the slide that for wound coils for smaller energy storage. The regular coil is froley short term requirement for stabilizing a cycle of stabilizing a circuit. It is for the larger systems. What we have to do is instead of just having a regular magnetic coil, you have it in the form of a toroidal structure this way and what happens here is the coil is boon round this structure, all right.

So, this is the toroidal structure. So, I would say for higher power systems and what this does is the magnetic field is constrained, so no varying magnetic field outside, clear. This is also a very strong and stable construction because you will see I do not know how many of you have had the experience of going through an MRI scan. In MRI scan what happens is you have these large magnetic coils which is continuously magnetized and demagnetized and as a result of that I mean if you have gone through it or if any of your friends or relatives have gone through it, you ask them. MRI scan is a very painful experience because there is a tremendous deafening hammering noise that the patient has to withstand for the duration of the scan which is typically around 20-25 minutes.

It is extremely painful because you first go into that tunnel which gives you a claustrophobic feeling and then, you have this hammering noise all around you. The reason this happens is because of the repeated magnetization and demagnetization. There are mechanical forces that arise which are known as the Lorentz force and that leads to this. Lorentz force happens between two adjacent conductors and in this case maybe two of these windings, adjacent windings, all right.

So, such things even here also you have a varying magnetic field. It may not be you know from 0 to a certain magnetic field in a step function or close to a step function. That is what happens in an MRI scan scanner, but here also there is a varying magnetic field. So, there will be Lorentz forces and these Lorentz forces have to be withstood. So, for higher power systems, this toroidal structure also helps in withstanding or the mechanical forces which are the Lorentz forces, all right.

So, again to summarize I will just take help of this schematic. On this slide what we have is a superconducting magnetic coil. What is the superconducting magnetic coil? A superconducting magnetic coil is made of a material whose electrical resistance goes to 0. It just does not exist below a certain temperature which is this critic corresponding to which is a critical temperature corresponding to that material. So, we make use of that. So, we have a superconducting coil.

So, this material has to be refrigerated and cooled down to below its critical temperature. If we now have that, then what happens is if you now apply a voltage across that coil first, what happens is there is a charging cycle. During the charging cycle, the current through the coil increases linearly and till it reaches a certain target or threshold value which is the amount of energy that I want to store and what is that energy that I am going to store is given by half L i squared and here i is the target current where I have stopped.

So, at that point I stopped charging the circuit anymore and instead short the coil by using a superconducting switch. The wire and the switch has to be made of superconducting material again. So, therefore what happens is we have a superconducting coil through which a current flows or keeps flowing and therefore, the energy equal to half L i squared and in this case, i is a target current where I had stopped is now stored. It does not discharge; it is stored. So, that is the energy storage system that we have. When I want to take energy out of that, what we do is we have the current flow through in the reverse direction and the way to do that is again attach an emf source with reverse polarity and then, attach and then, in the same circuit, you put the resistance across which you want to flow current or you want the current to flow and thereby extract that energy out, ok.

So, if you do that then the current in the discharging cycle falls from the target value to which I had charged it and it falls down as it flows through that or as the discharging cycle continues and we we are able to extract electrical energy out of it which we can use for some useful purpose that we want to wear or use it where I need additional electricity. Now, keep in mind these are all DC. We need a power converter circuit which will convert DC to AC during generation if I want AC power or during the charging also if the supply is AC, right. So, all that is done using a power converter circuit which takes care of everything which has a superconducting switch in between which does 2D conversion and which also does the reversal of polarity and so on and so forth, ok.

So, this is the whole principle of how a magnetic energy storage system works or superconducting magnetic energy storage system works. Next what we talked about was the magnetic construction we say that for small energy storage systems.

If you want to just use it for stabilizing circuits' short term requirements, then a regular coil the way we described is, but if you want to go for larger systems, the problem is during the discharging cycle. You have a varying magnetic field across the outside which can be fatal. If a human or a living being comes in contact our bodies do conduct electricity and then, that can be fatal. Therefore, we use a toroidal structure as I drew it on this picture over here. The toroidal structure the way it helps is it number one contains the magnetic field and does not let it go outside Secondly, it also adds strength and it is a stable construction. It is able to withstand the mechanical forces, the Lorentz forces that we talked about and another thing that we discussed is about the materials.

So, meibum titanium has been traditionally used, but its critical temperature is close to zero absolute which is you know one can never third losses one can never achieve that.

So, we use liquid helium and we go close to that right. So, high tc material the recent developments have been four materials one of them yttrium barium copper oxide this has a critical temperature of about hundred Kelvin which is much easily attainable and where we do not need liquid helium helium itself is a is an inert gas its a rare gas it is not very abundantly available, but with high temperature or high critical temperature materials high dc materials we can use liquid nitrogen which is abundantly available where we have established techniques for liquefaction and therefore, the cryogenics is going to be way simpler.

So, that kind of brings us to the end of our discussion on superconducting magnetic energy storage. So, with this what we have studied so far under energy storage are three mechanical technologies; pumped, hydro compressed air and flywheel and then, the fourth one is magnetic energy storage. So far we have learned about in the last I think 5 lectures, we have covered four different technologies for energy storage. All of them very interesting exciting and all of them are used especially like pumped, hydro, flywheel are abundantly used, compressed air superconducting magnetic energy storage is also used, maybe not so wide. Application is not as widespread as others, but still it is used.

So, what we will do in the next lecture, we will continue this discussion on energy storage systems and we will start with something called thermal energy storage systems where the energy is stored in the form of thermal energy.

Thank you very much, and see you in the next lecture.