Solar Energy Engineering and Technology
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Lecture 17
Performance Analysis of a Grid Connected PV System

Dear students, today we will be discussing about performance analysis of a grid connected PV system. So performance assessment is very, very important before designing a grid connected PV system.

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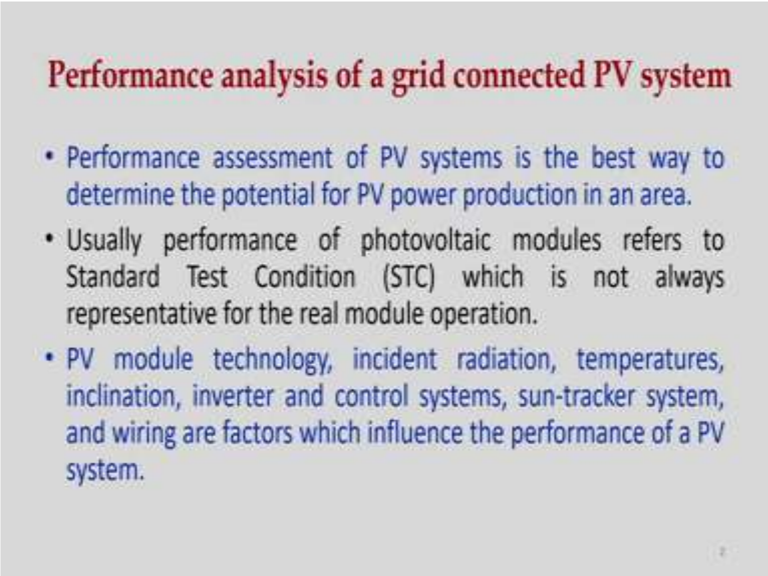

The performance assessment of PV system is the best way to determine the potential for PV power production in an area. Usually, performance of photovoltaic modules refers to standard test condition which is not always representative for real module operation. The PV module technology, weather conditions like incident radiation, temperatures, then inclination, inverter and control systems, sun tracker system and wiring are factors which influences the performance of a PV system.

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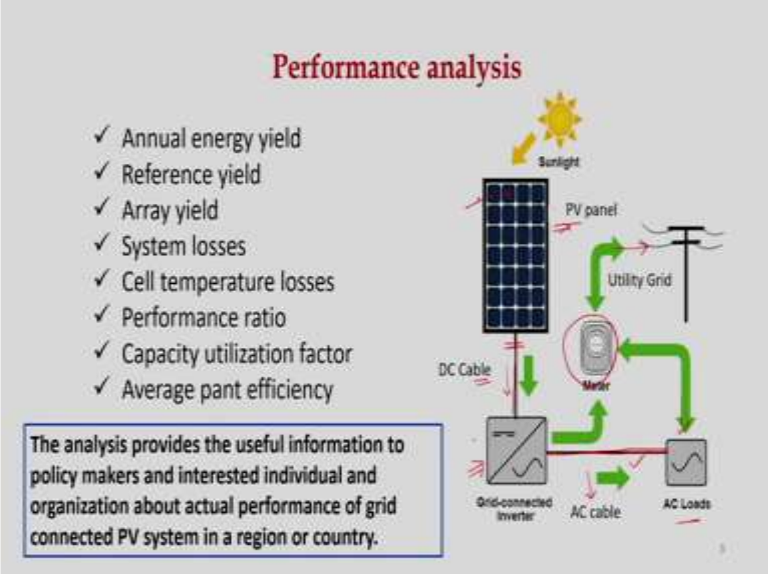

So when we call performance analysis what are the parameters includes like annual energy yield, reference yield, array yield, system losses, cell temperature losses, performance ratio, capacity utilization factor, average plant efficiency, these parameters we must know. Now, look into this grid connected PV system layout. So here what happens we will have solar PV panels, these are the modules, these are modules, there are many modules connected to form a panels and if we connect many panels then it becomes an array.

So solar radiation fall on these PV modules and then DC current is generated. So that has to be transmitted through DC cables. So this is a DC cable and if we have to convert this DC current to alternating current, we need grid inverter or inverter. And then this load is connected somewhere so we need to transfer this energy through cable and these cables are known as AC cable and also we have meter.

Suppose, we are not using the generated energy, then what we can do we can give the generated energy to the utility grid. And maybe at night when demand is there, we can take it back from the grid. So that way we can use this grid connected PV system. So when we design we need to know what will be the output here, what are the losses here in this cable what is the efficiency of this inverter, what will be losses here in this cable and then other components, like MPPT is attached here, what will be the efficiency of the MPPT.

So all those components we need to consider when we talk about performance analysis of a grid connected PV system. So by doing so what we will get, the analysis provides the useful information to the policymakers and interested individual and organization about actual performance of grid connected PV system in a region or country. So this information is very, very important. So doing analysis very correctly is very, very important for long term performance of a grid connected PV system.

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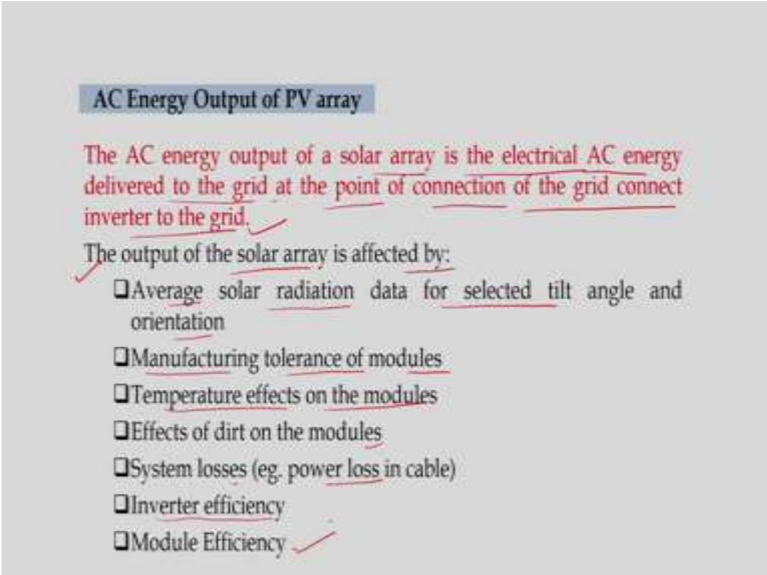

So this is AC energy, this is AC output of the plant of a solar array is the electrical AC energy delivered to the grid at the point of connection of the grid connect inverter to the grid. This output of the solar array is affected by many of the parameters; for example, average solar radiation data for selected tilt angle and orientation, manufacturing tolerance of modules, temperature effect on the modules, effect of dirt on the modules, system losses maybe in the cables, AC cables, DC cables; inverter efficiency, then module efficiency.

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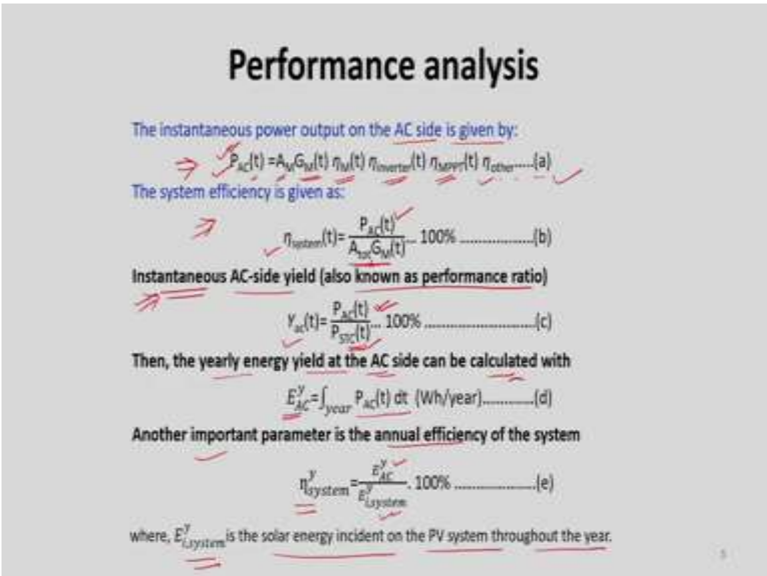

Now, if we talk about performance analysis, we need to investigate those parameters as we can visualize now. So this instantaneous energy output on the AC side is given by P_{AC} the function of time. So A_M is the area of the panel, then G_M is the intensity of solar radiation then maybe η_M is the module efficiency then we will have inverter efficiency $\eta_{inverter}$ then η_{MPPT} and many more components efficiencies need to be considered.

So this expression is for instantaneous, at any moment we can calculate P_{AC} of a grid connected PV system. And if we are interested to calculate the system efficiency then we can use this equation if we know P_{AC} that is this parameter of what we have done it and if we know the amount of radiation falling on that particular side and an area, then from that we can calculate what is system efficiency.

Now, instantaneous AC side yield, that is known as performance ratio, this is instantaneous we should keep in mind. So this will be something like P_{AC} to the STC, means standard test condition the amount of power delivered by the PV array and this is the AC output, it take care of all the losses. Then the yearly energy yield at the AC side can be calculated. So if we integrate over the year, then what we will get is in yearly energy yield.

And also we need to know one important parameter, annual efficiency of the system. So this can be represented by using this equation. So E_{AC}^{y}, that is annual energy yield to the solar energy incident on the PV system throughout the year. So this is nothing but solar energy incident on the PV system throughout the year.

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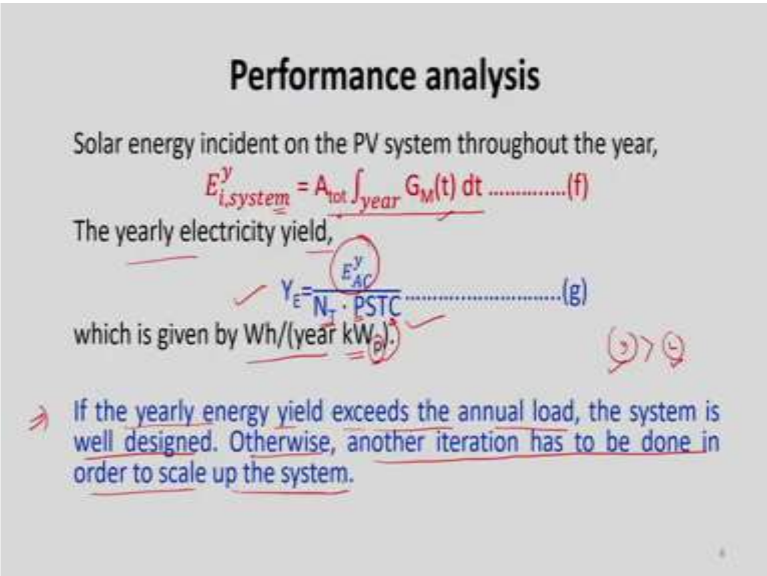

So this $E^{y}_{i,system}$ can be expressed something like this. So yearly average we need to find out and A_{total} is the multiplication. Then yearly electricity yield also we can calculate if we know this term and if we know this PSTC and number of modules, total number of modules, then from there we can calculate what is yearly electricity yield. And this expression will get in terms of Wh/kW_p. So this p stands for peak, where power is calculated at standard test condition, that means 1 kW/m^2 and wind speed of 1 m/s and spectrum of AM 1.5.

So if the yearly energy yield exceed the annual load, so we have energy yield and then we have load. So if this is something like that, so this is energy yield and then this is load, the system is well-designed. Otherwise, another iteration has to be done in order to scale up the system. So this is important condition for designing a grid connected PV system.

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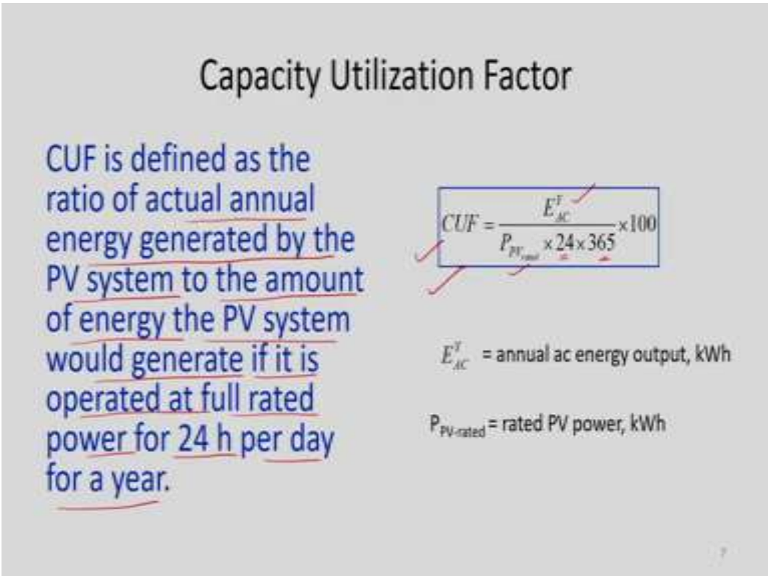

Also we need to know what is capacity utilization factor. So how do we define it. This capacity utilization factor is defined as the ratio of actual annual energy generated by the PV system to the amount of energy the PV system would generate, if it is operated at full rated power for 24 hours per day for a year.

So mathematically this can be represented by $\frac{E^{y}_{AC}}{P_{PV_{rated}} \times 24 \times 365}$,. And of course, you can multiply 100 in order to make it percentage. So this is the expression by which you can calculate capacity utilization factor.

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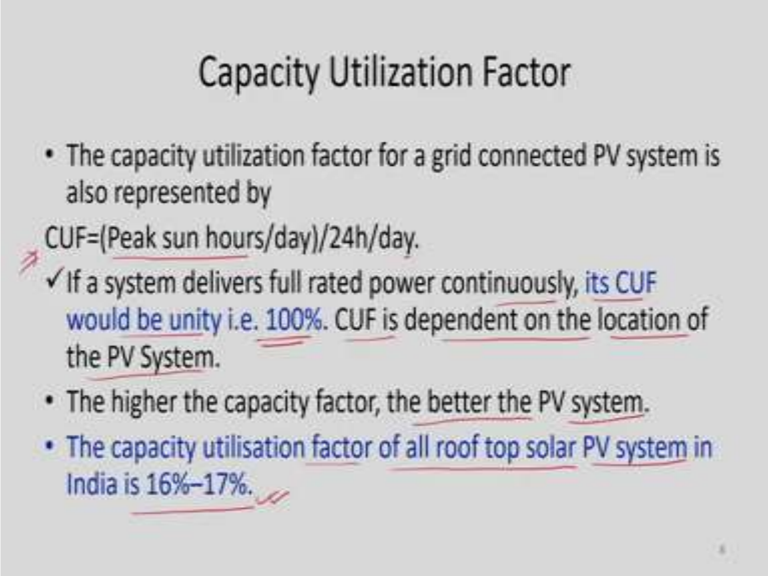

This capacity utilization factor for a grid connected system can also be know calculated or estimated by using this expression. If we know peak sun hours per day and 24 hours per day. So this will give capacity utilization factor. So if a system delivers full rated power continuously its capacity utilization factor would be unity, that is 100 percent. So capacity utilization factor depends on the location of the PV system. The higher the capacity factor or capacity utilization factor better the PV system. The capacity utilization factor of all rooftop PV system in India is in between 16 to 17 percent, this you should keep in mind.

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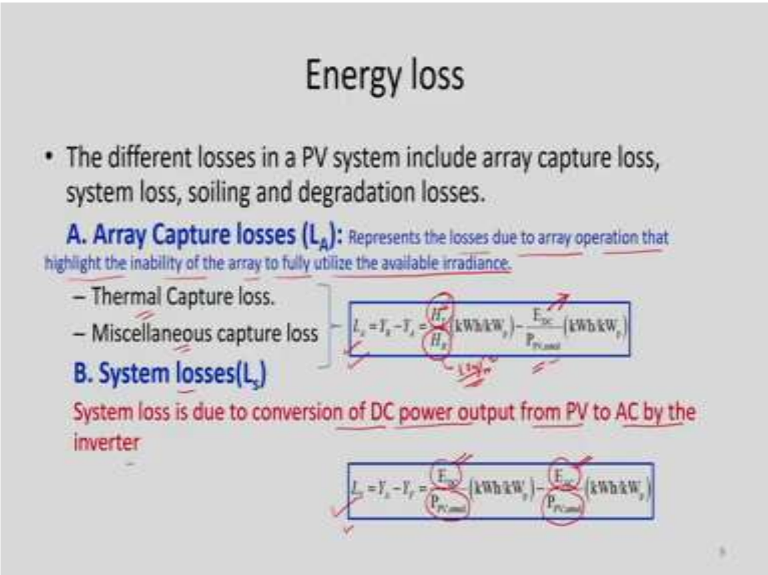

Now, what we are interested in about, energy loss. So different losses will take place in the PV system which includes array capture losses, system losses, soiling and degradation losses.

So primarily we can categorize these losses into two major group, one is array capture losses, which represents the losses due to array operation that highlight the inability of array to fully utilize the available irradiance. Which includes those two losses thermal capture losses and miscellaneous capture losses.

So mathematically this can be represented by $L_A = \frac{H_T}{H_R} - \frac{E_{DC}}{P_{PV_{rated}}}$. So this H_T is nothing but the total implant insulation or global implant horizontal insulation of the location and this is the reference. So reference is normally 1 kW or W/m^2. And this is the energy delivered by the PV module and this is the rated one. So if we know this expression and from that we can calculate what will be the array capture losses.

And in case of system losses, this loss is due to conversion of DC power output from PV to AC by the inverter. So this can be represented by $L_S = \frac{E_{DC}}{P_{PV_{rated}}} - \frac{E_{AC}}{P_{PV_{rated}}}$. So once we know this expression for E_{AC} and the energy generated from the DC side of the PV system, then we can calculate what is the system losses. So if you combine these two L_A plus L_S then it becomes the total losses.

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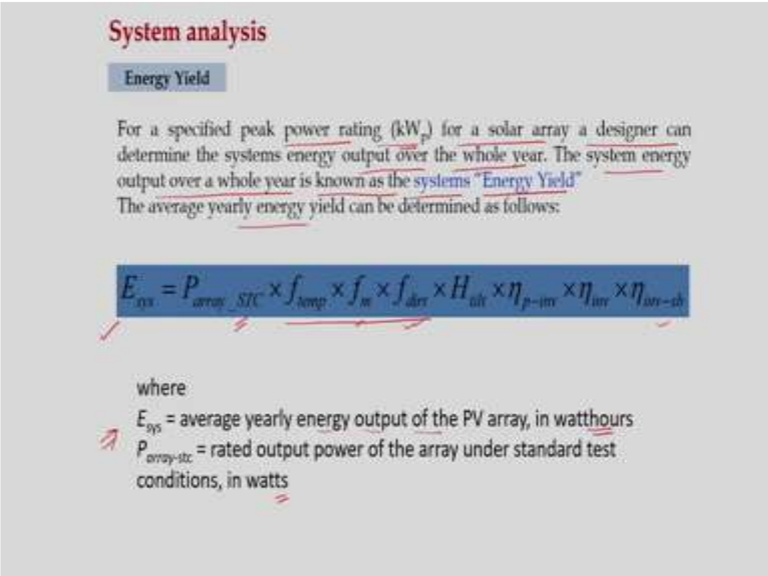

Now, let us learn this system yield and different losses in a very deeper sense. So for a specified peak power rating for a solar array, a designer can determine the system's energy output over the whole year. The system energy output over a whole year is known as the system's energy yield. So this average yearly energy yield which can be determined by using this expression, this E_{sys} is equal to $P_{array\text{-}STC}$ multiplied by these are the de-rating factors, temperature, manufacturing tolerances, then we have dirt and these values which we will discuss in the next slide.

And already we know what is E_{sys} is the average yearly energy output. So if we do not write this yearly then of course we will write Y here. So at this moment, we do not need to write and this $P_{array\text{-}STC}$ is rated output power of the array under standard test condition, for standard test conditions we represent in watt and E_{sys} will be in Wh.

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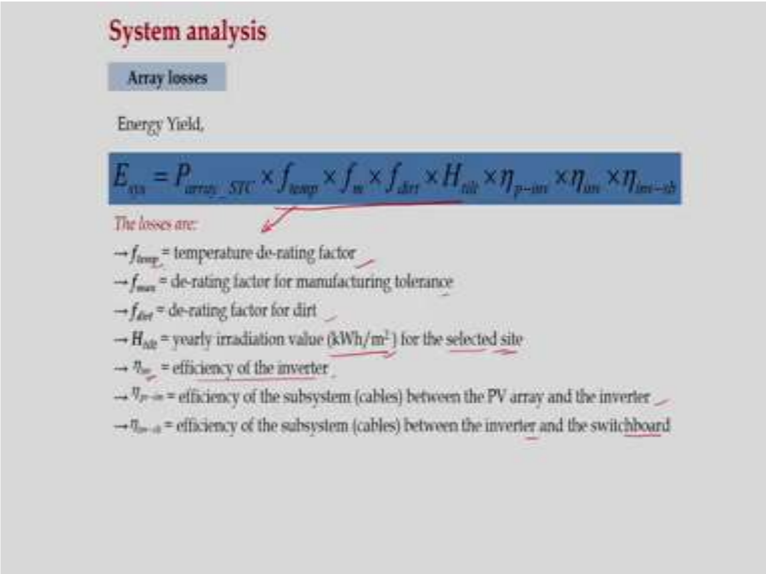

Now, if we include this, so what are those f_{temp} means temporary de-rating factor f_m or f_{man} is de-rating factor for manufacturing tolerance and f_{dirt} is de-rating factor for dirt and H_{tilt} is yearly irradiation value, which is represented by kWh/m^2 for the selected side and eta inverter is the efficiency of the inverter, then η_{PV-inv} is the efficiency of the subsystem between the PV array and the inverter. And η_{inv-sb} is the efficiency of the subsystem between the inverter and the switchboard. So we will analyze one by one and then finally, we will estimate all those derived parameters.

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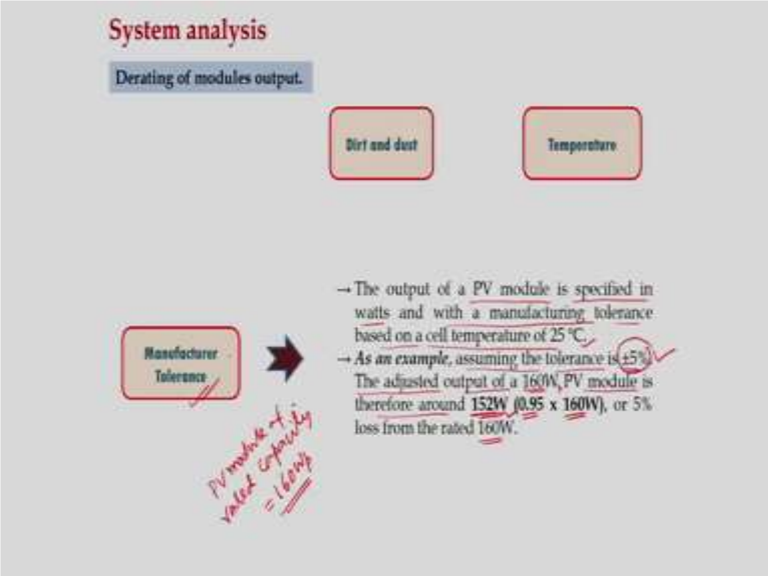

So de-rating of module output we will consider here. So three primary de-rating factors are manufacturer tolerance, dirt and dust and temperature. So we will discuss one by one with a workout example. So when we talk about manufacturer tolerance, when a module is when manufactured, it has got some kind of tolerances. So they has to be considered when real PV module performance is estimated or analyzed.

So the output of a PV module is specified in watts and with a manufacturing tolerance based on a cell temperature of 25 °C. So, if we take an example, assuming that tolerance is 5 percent, the adjusted output of a 160 watt peak, I can write to watt peak also here PV module is therefore around 152. So here we have considered a PV module, PV module of rated capacity is 160 watt peak.

If 5 percent is the manufacturer tolerance, then if we consider it then what will happen? So it will be 0.95 into 160 watt, that means 5 percent loss from the rated 160 watt. So if we multiply this 0.95 into 160 watt, it will be 152 watt, if we compare 5 percent manufacturer tolerance.

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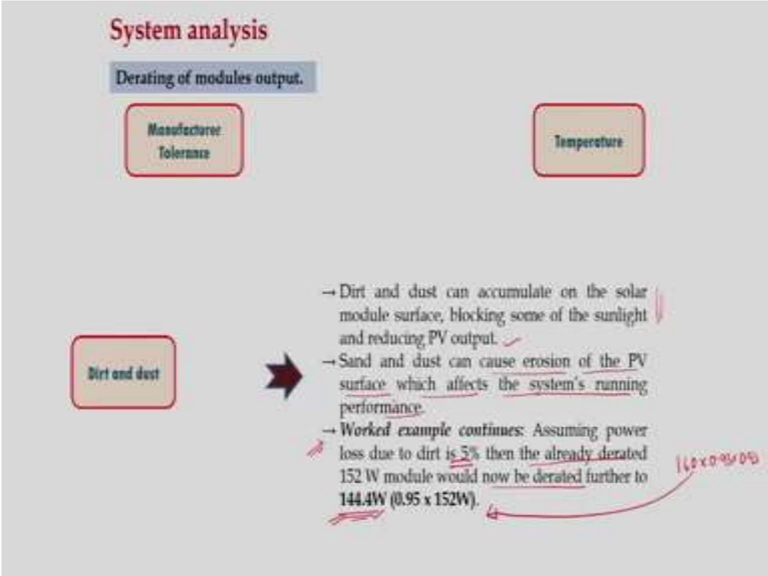

Now, let us discuss about dirt and dust. So dirt and dust can accumulate under solar module surface blocking some of the sunlight and reducing PV output. This phenomenon already we have studied, what happens when we block some of the modules or cells with some elements like dust, maybe leaf or maybe other unwanted foreign materials. The same then dust can cause erosion of the PV surface which affects the system's running performance.

So if we consider 5 percent losses in this case and if we continue with the problem what we have initiated in the last slide, then what will happen, we will get a value of 144.4 watt, because already so if we already that module is de-rated because of this manufacturer tolerance. So $160 \times 0.95 \times 0.95$. This is something like 144.4 watt.

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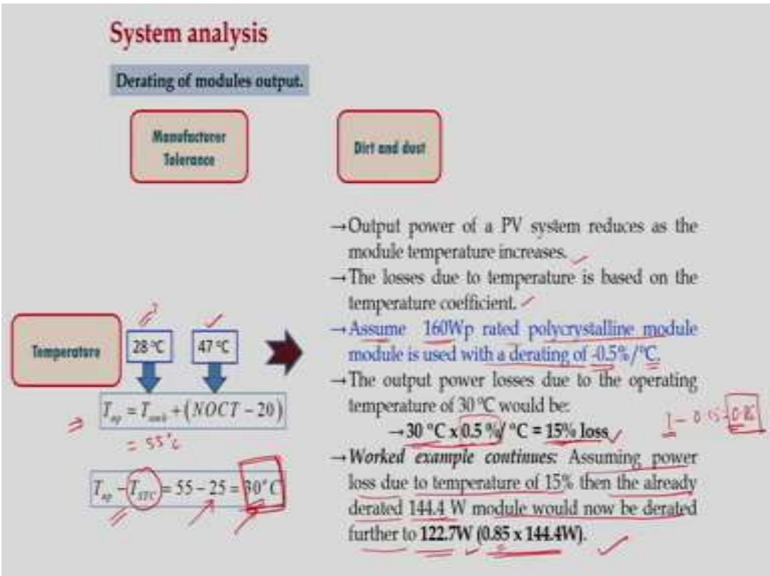

Now, consider the case for temperature. As you understand this output power of PV system reduces as the module temperature increases. The losses due to temperature is based on that temperature coefficient. So behavior of these losses will be different for different cell material. Assuming 160 watt peak rated polycrystalline modules with de-rating of 0.5 percent per degree increase in temperature.

So for that you need to know some of the information, say ambient temperature is 28 °C where the modules or panels are installed and NOCT for that module is 47 °C. So by using this expression we can calculate what will be the T_{op} or operating temperature. So if we substitute this value, then what we will have, 47 minus 20 becomes 27 plus 28 it becomes 55°C.

Now, if we have to deduct this T_{STC} from this operating temperature then what will be the effective temperature, 55 minus 25 is 30. So what does it mean? These modules are tested at 25°C or cells are tested at 25 °C. Now, we got a temperature rise of 30 °C behind 25. So how this performance will vary? As you understand per degree increase in temperature, there is a reduction in efficiency of something like 0.5 percent.

So if we multiply this 30 with this 0.5 percent then what we will have about 15 percent losses will be there. So if we continue with that problem what we have initiated assuming this power loss due to temperature of 15 percent, then the already de-rated 144 watt module would now be directed farther 122.7 watt. So this will be something like 0.85×144.4 watt, so 85 means 1 minus 0.15 it becomes 0.85. So this is the losses, so if we deduct this loss from 1 what we will get is an efficiency. So that way we can calculate how much energy will be de-rated.

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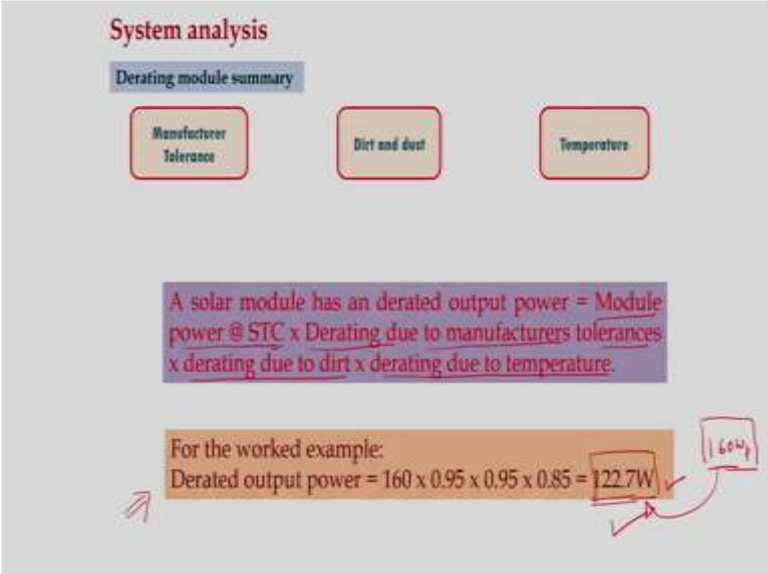

So now, if we compare all the three de-rating factors, then what we have done solar module under standard test condition, then de-rating due to manufacturers tolerance, then de-rating due to dirt and then de-rating due to temperature. So if we substitute all those values, then what we will have, we will have the de-rated power output of 122.71. You just see we have initiated 160 watt peak, now, just we have considered 3 de-rating factors like manufacturer tolerances, they we will have dirt and then temperature. So this 160 reduces 122.71. You can see this is a significant reduction of power or power output.

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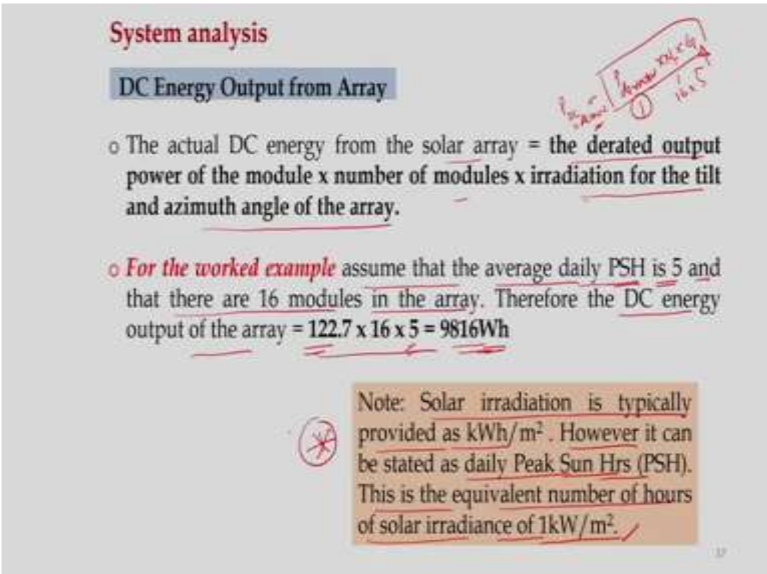

So now we will move to the DC energy output from array. So the actual DC energy from the solar array is equal to the de-rated output power of the module, then we need to multiply with number of modules, then multiply with irradiation for the tilt and azimuth angle of the array. So this is $P_{de\text{-}rated}$, $P_{de\text{-}rated}$ multiplied by number of modules, total number of modules, then we have G maybe the irradiance or maybe I you can write. So this is something like actual DC, P_{DC}, this will be actual, actual.

So if we continue the same problem assuming the average daily peaks sun hour is 5 hours and that there are 16 modules in the array. So it is assuming that 16 modules are present in that array. Then the DC energy output of the array will be already de-rated power. What we have done here is 122.7 And number of modules are 16 and then how many hours is the 5 hours. So it will be 9816 Wh, we will see what is G.

This solar irradiation is typically provided as kilowatt hour per meter square, it can also be stated as peak sun hours. So this is the equivalent number of hours of solar radiation of 1 kW/m^2. So that is why we have multiplied with 5. So it will be 9816 Wh, so this is important.

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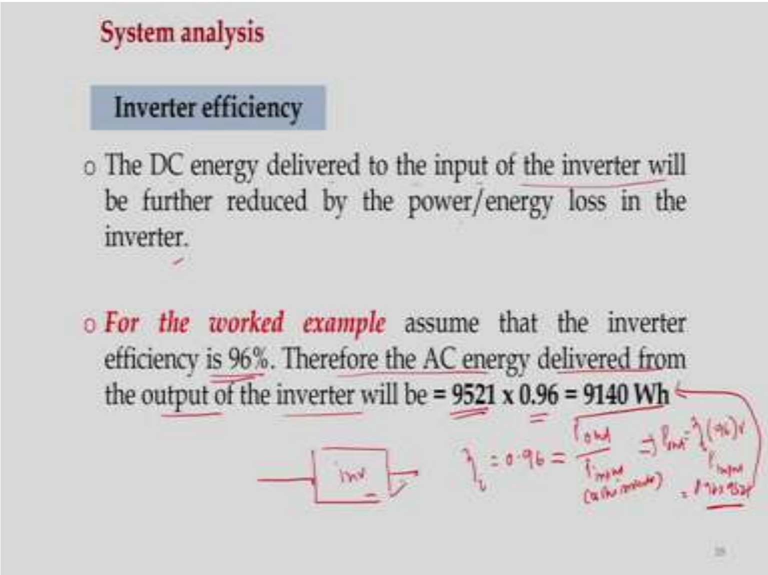

Now, this DC system losses if we are concerned, then DC energy output of solar array will be further reduced by the power loss in the DC cable connecting the solar array and to the grid connect inverter. So this need to be considered. So if we continue with the same problem and we add this loss about 3 percent for this DC cable then DC subsystem efficiency will be 97 percent. Therefore, the DC energy from the array that will be delivered, to the input of the inverter will be 9816×0.97, it will be 9521 Wh, because this one already we have calculated.

So if we draw it, we have this PV panel and then this is the cable maybe, this is the cable, this cable loss is 3 percent. So here before entry, so this will be inverter, next we need to know about inverter what will be the efficiency of the inverter. So up to here what we have calculated is this much of energy.

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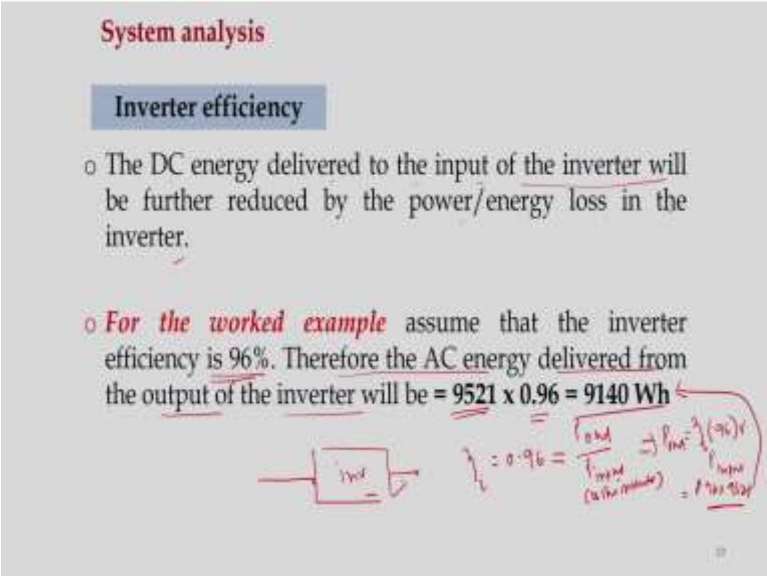

Now, this DC energy delivered to the input of the inverter will be further reduced by the power loss in the inverter. So if we consider the inverter efficiency is 96 percent then the AC energy delivered from the output of the inverter will be 9521 multiply by 0.96 because now we will draw this inverter here, inverter, so input is known then output you need to calculate.

So inverter efficiency is known to us what is given as 0.96 is equal to output, power output by power input to the inverter. So this power output you need to calculate that means P_{out} is nothing but η_i which is nothing but $0.96 \times P_{input}$. So P_{input} is 9521. So this is 0.96×9521. So, once you do the calculation what we will get is 9140 is the value which is delivered by the inverter.

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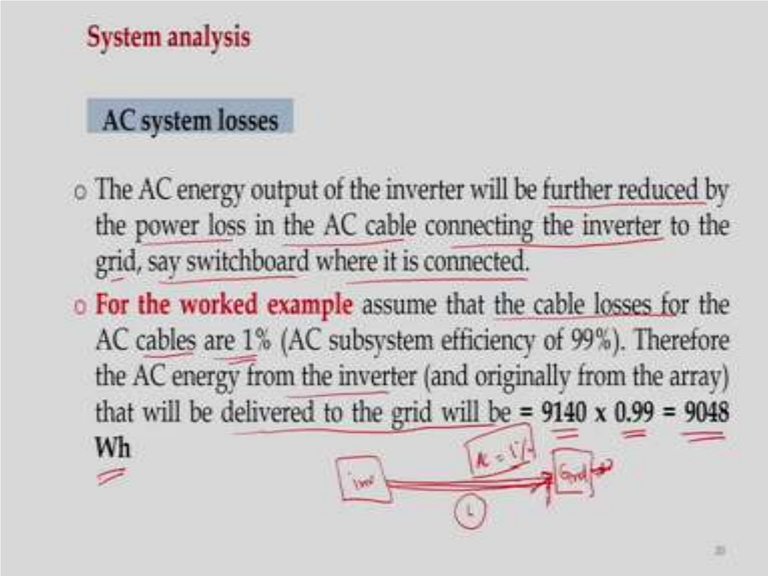

Now, this AC system losses. So once this inverter is over then we need to transmit, so we need to consider this cable, cable length. So it is proportional to the length. So length is very long means losses will be more. So this AC energy output of the inverter will be further reduced by the power loss in the AC cable connecting the inverter to the grid, say a switchboard where it is connected.

So if we continue with the same exercise, so assuming the cable loss for the AC cable, 1 percent, so AC cable loss is 1 percent. Then the AC energy from the inverter that will be delivered to the grid will be 9140×0.99. So this is the grid. This is the grid, this is the inverter. So in between this efficiency 1 percent, so energy which will be given to the grid the here at this point, not this here, at this point. So this will be 9048 Wh.

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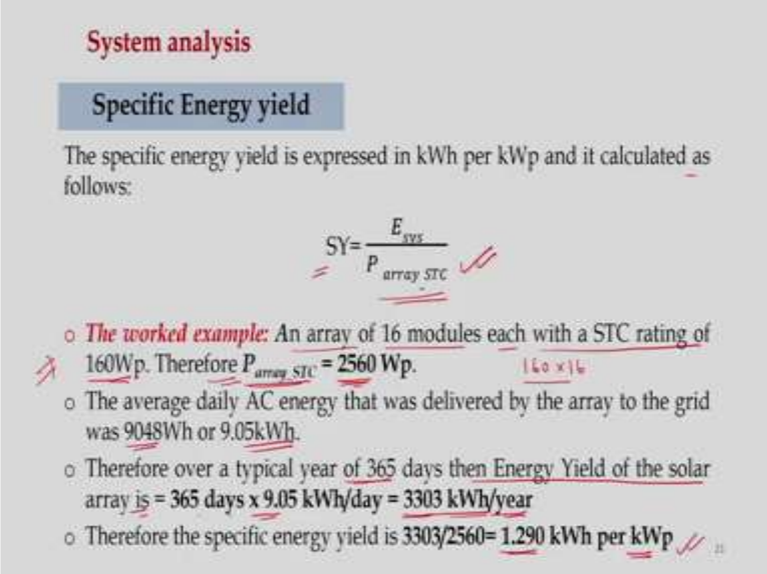

Now, we will calculate what is specific energy yield. This specific energy yield is expressed in kWh per kW_p and is calculated as follows. So this $SY = \frac{E_{sys}}{P_{array\ STC}}$ SY is nothing but E system this is yearly, since I have written here, so this was not included and P_{array} under standard test condition. So in the same problem if we continue, an array of 16 modules is which has STC rating of 160 W_p.

Therefore, $P_{array\ STC}$ will be 2560 W_p. So this will be something like 160 multiplied by 16. So this will be 2560 W_p. So the average daily AC energy that was delivered by array to the grid was 9048 Wh, that is 9.05 kWh. So over a typical year of 365 days, then the energy yield of the solar array will be 365 days multiplied by 9.05, So it will be 3303 kWh/year. Therefore, the specific energy yield will be 1.290 kWh/kW_p. So this specific energy is very, very important. So in this problem what we got is 1.290 kWh/kW_p.

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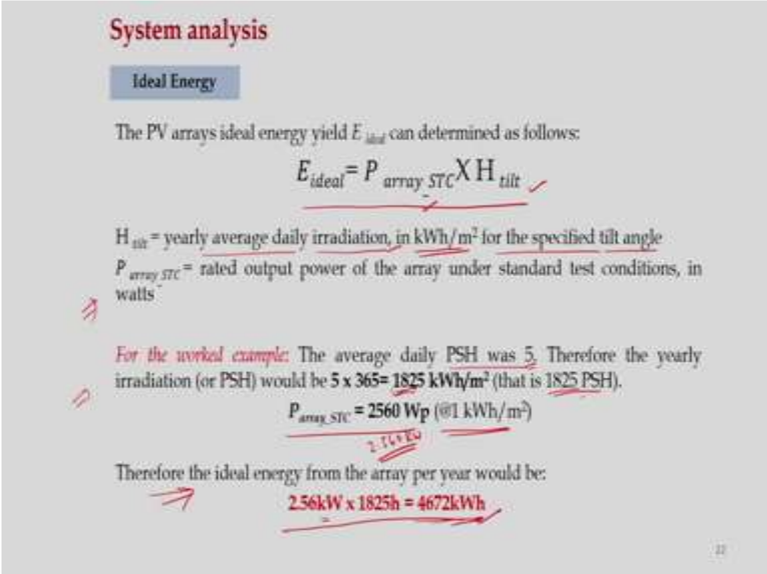

Now, let us calculate the ideal energy, that is the PV array ideal energy yield. Which can be determined by using this expression. So $P_{array\ STC}$ is known to us because we know the rating and than H_{tilt}. What is H_{tilt}, it is the yearly average daily irradiation. So that is average irradiation data and which is normally represented by kWh/m^2 for a specified tilt angle.

And already we know $P_{array\ STC}$ is a rated output power of the array under standard test condition. So in this problem, if we consider PSH, peak sun hour, is 5 hours therefore, the yearly irradiation would be 5×3655 which is nothing but 1825 kWh/m^2 that means 1825 peaks sun hour. So P_{array} will be 2560 W_p at 1 kWh/m^2. So we can calculate now what will be the ideal energy from the array per year.

So this will be something like 2.56 kW multiplied by 1825, it will be 4672 kWh, because what we have done, this is watt peak, so kilo will be 2.560, so that will be kilowatt. And then 1825 is known to us, that way you can calculate the ideal energy from the array per year, which will be equal to 4672 kWh in this exercise.

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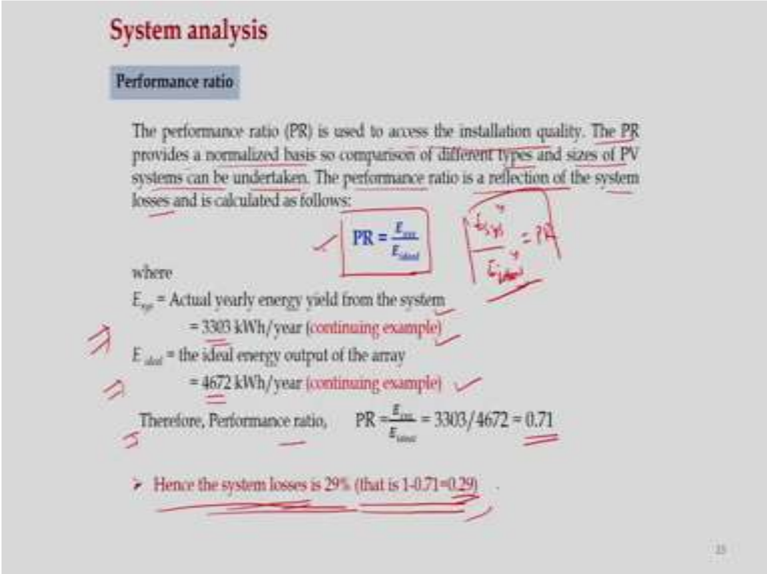

Now, we are very much interested about the performance ratio, this is one of the critical parameter of a grid connected PV system. Once we can calculate this performance ratio, from that we can confirm that the amount of losses are taking place in the design PV system. This performance ratio is used to assess the installation quality. The performance ratio provides a normalized basis, so comparison of different types and sizes of PV systems can be undertaken.

And this performance ratio is a reflection of system losses which can be calculated by PR is E_{sys}, of course it will be yearly, since I have written yearly, so this Y we have not included here. Of course, when we not define of course, we will write E_{sys} yearly then E_{ideal} yearly. So this is nothing but performance ratio. So this E system actual yearly energy yield from the system which is nothing but 3303 kWh/year, already we have calculated.

And E_{ideal} is the ideal energy output of the array. So this is equal to 4672 kWh/year which has already been calculated. Therefore, the performance ratio will be $\frac{E_{system}}{E_{ideal}}$ which is nothing but 0.71. What does it mean? The system losses will be 29 percent that is 1 minus 0.71 is 0.29.

So what we can conclude here, by knowing this performance ratio, we can estimate the kind of losses taking place in the entire plant. This is not individual, so this will tell you the entire losses taking place in the plant. So this is one of the very important parameters for a grid connected PV system performance analysis.

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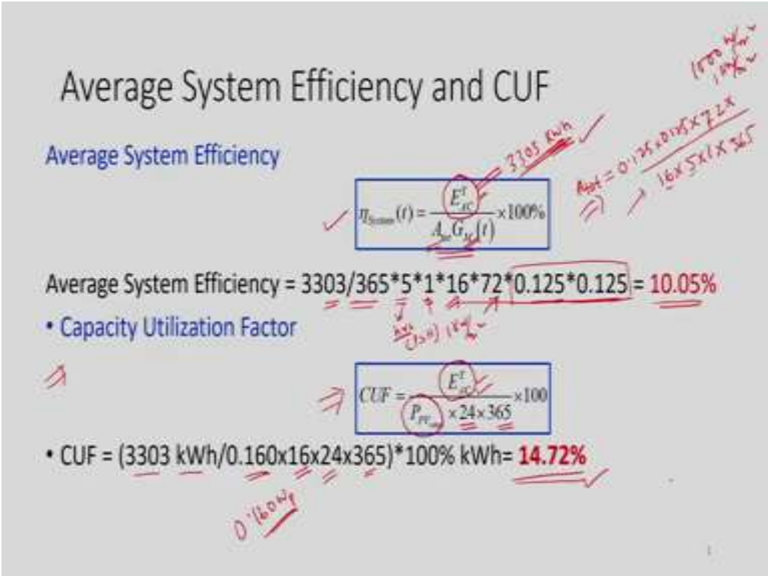

Now, we will calculate average system efficiency and capacity utilization factor. So how we can calculate average system efficiency, this is the expression by which we can calculate this efficiency this E^y_{AC}, this yearly energy yield in AC side already we have calculated and we know the area of the panel and G_M is the amount of solar radiation received by the panel. So here this is calculated to be 3303 this is kilowatt hour and this has to be in kilowatt hour.

So how to calculate A_{total}, A_{total} is something like we will have first consider 0.125 by 0.125 is the cell area. And then for this kind of module, what we have considered in this case is 72 number of such cells are there and then we will have 16 modules. And it says peak sun hour is 5 and then solar radiation is 1000. So 1000 W/m^2, so in kilo it will be 1 kW/m^2. So what I will write in 1 because here also is in kilowatt, this energy, yearly energy yield in the AC side is also in kWh.

So this has to be in kWh. So this $16\times5\times1$and how many days, it is 365 days. So it becomes yearly amount of radiation received by the solar panel. So that is how this is $365\times5\times1$this is 5 hours. So this is peak sun hour, peak sun hour was 5 in this continued problem and this 1 is 1 kW/m^{2}and then this part is nothing but the area of the panel.

16 number of modules in that panel then 72 cells and then every cell has an area of something like this. So if we calculate it, then what we get is something like 10.05 percent average system efficiency. Now come to the capacity utilization factor. So we know this expression, how to calculate this capacity utilization factor. So this yearly energy yield in the AC side we

already know and then PV rated power is known to us. And then it is for 24 hours then 365 days.

So if we substitute these values like 3303 kWh and then here is 160 is the rated power watt peak. So it is in kilo, that is why it is 0.160 and then 16 number of modules, 24 hours, 365 days. So it comes around 14.72 which is the value close to the recommended for India.

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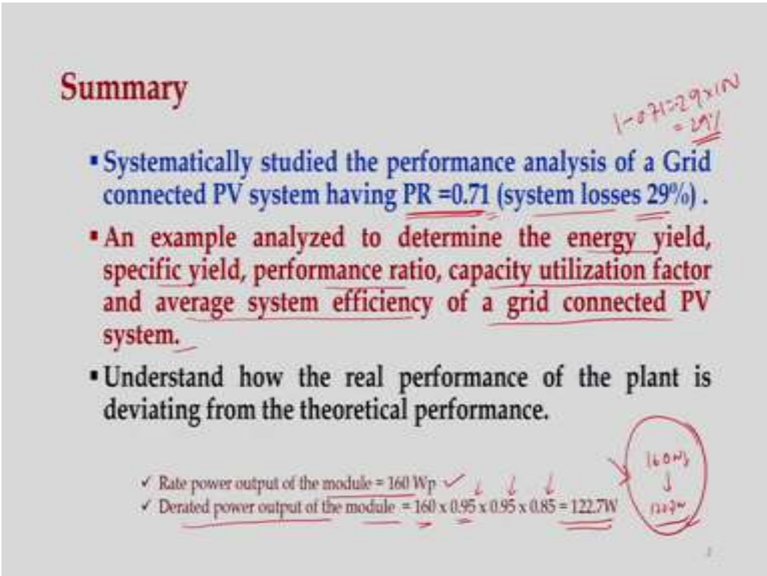

Now, let us summarize what we have discussed in the today's class. We have systematically studied the performance analysis of a grid connected PV system having performance ratio of 0.71. So what does it indicate, it directly indicates the system losses, which is about 29 percent. It is something like 1 minus 0.71 will be 29, it is 0.29, that means, if you multiply by 100 it becomes 29 percent. So this performance ratio is an important parameter to know the system losses.

We also solved an example to analyze and determine the energy yield, specific yield, performance ratio, capacity utilization factor and average system efficiency of a grid connected PV system. And also we understand how the real performance of the plant is deviating from the theoretical performance. As you can see, that rated power output of the PV array or module is about 160 watt peak, this is for modules.

And if we consider a single module, this de-rated power output of the module will be, if we multiply by 0.95 for manufacturer tolerance, 0.95 for dirt and 0.85 for temperature. So it becomes 122.7 watt. You see the difference, so we have started with 160 watt peak and what we got is 122.7 watts. So that is how we are getting very reduced amount of power generation. So these parameters are very, very essential while designing a grid connected PV system.

Of course, we need to consider the other losses like cable losses, which includes DC cable loss, AC cable loss and then inverter efficiencies and other factors like MPPTs and other components which is important for a grid connected PV system. Hope you have understand the aspects of analysis of a grid connected PV system. So thank you very much for watching this video. Thank you.