GANG CHEN: Today, there are three more lectures. And we get two guest lectures on one of the reliability of the materials. I prepared this original and the last lecture. I also have to juggle a lot the schedule for everybody. So instead of what I will do is next Friday, I will be talking about the reliability of the materials. This is Professor Christopher Schuh in the Materials Department with-- has been doing research in this area for long time. [INAUDIBLE] I forget it.

And then the week after last week, we will have Dr. Ivan Simonovich talk about selective surface. He has been working on several photovoltaics. And so he spent a lot of work in the spectral control area. So help you, again, better talk to me. And then see the final lecture, we will be-- the content, come back a little bit to talk about how we combine selective surface with thermoelectrics and with also photovoltaics.

So we have learned thermoelectrics. We have learned photovoltaics also. So that's a solid state solar thermal energy conversion. And today, what I want to cover is the mechanical energy conversion, solar to electrical, solar, thermal but there will be mechanical means. So let's recall what I was talking in the last previous lecture. We talked about blackbody radiation. We mentioned a little bit on the Earth's motion and how we usually test solar spectrum AM0 or AM1, AM1.5, et cetera.

And then we define relative property, this definition, many different definitions. So as I said, I don't expect you remember all those details. The point is for spectral control, it's very important to understand the wavelength dependence of the properties. And then with that, we discuss the maximum efficiency of solar thermal engines and maximum achievable temperature.

And again, see we emphasize the silicon surface. But we do know or you do not how to do it yet, but it's important. So in today's lecture, like I said, I want to cover, really, the solar thermal mechanical part and what we'll start with is the hot water system, solar hot water. And then we'll talk about-- to bring it up to a higher temperature, we'll talk about the solar concentration. And we'll talk about the maximum, how much you can concentrate the solar radiation.

And then we look at how you could in practical to do different ways of concentration. And to do concentration, you need to track the Sun. That's one of the problem challenge. So I'll talk a little bit tracking and long tracking and then go to mechanical. If I have enough time, I'll start a little bit, give you a preview of what controls the surface properties, the action of microwave.

So solar hot water, right? It's very mundane, but I really appreciate this. As I probably mentioned before, when I was a kid, I grew up in China. I didn't have a chance to take a hot shower. And now when I go back to my parents, they still live in China and they use solar hot water. Concept, of course, is very simple-- solar collector. They absorb the solar radiation, and you heat up the water. Very simple concept, right?

And also, I want to give you a very simple backup [INAUDIBLE]. So if you're a mechanical engineer, this will be pretty easy. But I did this for the preparation of the class, also out of my own curiosity. Of course, you are from Materials, so this is probably a little bit more, say, not very familiar with you. But it's a simple energy balance. So what I want to ask is if I want to put in my own house, what's the area I live? Right? Solar hot water.

And typical household water tank is about 80 gallon. It's a larger house. If you have smaller, so ranging from 40- to 100-gallon range, I guess. And if I take a start temperature of water at 15 degrees, and I want to keep the water tank at 60 degrees Celsius-- so during the day, right? Let's suppose I deplete all the hot water during the night, and I want to store 80-- during the day, I want to heat up the water from 15 degrees to 60 degrees.

And so you want to see how much was this solar surface area, hot water surface area you want. And it's simple energy balance, right? During the day, how much solar radiation is it. And, of course, you consider the efficiency of the absorber and then that balance to heat up this much water, how much energy you need. So you do that energy balance, the area, what I want, the solar radiation insulation, and time of the day efficiency. And of course, the heat capacity that's stored in the hot water.

So I put in those numbers. Typically, when people calculate, you can say it's a little bit optimistic. If you live in Boston, you don't get the 1,000 watts, OK? And I took a standard calculation, 1,000 watts 5.5 hours. So that's an average. That's the whole day average. Typically, that's what people take when they test the solar cell. 1,000 watts, 5.1, we calculate solar cell output.

And efficiency of solar thermal hot water system ranging from-- I'll tell you how to estimate efficiency, but I take a typical number, 60%, OK? So I need a 5 meters here. And in China, I know it's very cheap. And typically, people install somewhere 1.5, 2 meters. So it's not a very big tank. Most people live in apartment, and they use less water.

OK. So I have ordered a different format. One of the format is a flat panel, right? So here, what we have is the absorber. Typically, it's a frequency selective. Meaning, they absorb solar radiation but do not or you want to re-emit a very small amount of thermal emission when it heats up. And so you can see the back side is the insulation. And this is the absorber tube, could be up on top or on the bottom.

And typically, they do not-- so if we change it here. OK? And the tank could be on the top of the absorber itself. So in that case, you don't put a tank in the basement. And you can use the gravity of the water to drive the water flow, to drive the hot water down. Let's say the problem is your water flow rate depends on how high you put the tank. So if you live in low buildings, your pressure is low.

And this is an example. Clearly, the water tank is not on the roof. It's in the basement. And in that case, you use a pump to pump the water. So it's a pressurized system. So they are pressurized. And this one is not a fossil system, just natural. And the one that-- what I thought was really interesting is this vacuum system. And this is predominantly used in China. And it's glass-- so it's a double-layer glass. Inside is a black coat. What looks black is actually inside.

Well, outside is another glass, clear glass. So it's a circular. And the inside glass is first coated with selective surface. And then you evacuate it. You see on the other side. So it's a double jacket. And on this side, because of the vacuum so it has a getter. The getter, what does getter do is, say, the evaporation is actually collected by this metal reacted with whatever evaporates.

And so you imagine so putting vacuum under the Sun, how long it lasts. And I actually visited some of this as a-- they really is the father [INAUDIBLE] the father of this technology in China. And he said that he put this stuff early in the '90s in Tsinghua. He's from Tsinghua University and still working. So after 20 years. And that's conceivable because if you think about in my house, I bought a TV. I remember my first TV is still working, about more than 20 years.

And that's a CRT. It's a vacuum technology, right? Say the screen of the TV, so the cathode ray tube inside is actually ultrahigh vacuum. So the vacuum is pretty high. And you can do a calculation of 5 to 1. If the vacuum is too low, the air conduction is too much heat. And so this is an evacuated tube. That's glass. This glass is really cheap.

I visited the manufacturing site and the whole tube is about this high. The diameter is 50 millimeters. And the manufacture of the double glass tube is about $1.5 per tube. So it's really cheap. This one is a little bit more expensive. It's not a glass glass. And what it has is a metal absorber. So it could be a copper or aluminum. Again, this is a cost, right?

This is really the-- see, the cost is crucial here. And this is selective absorptive coatings again. And so what it does this is a heat pipe. So the heat absorbed conducts to the heat pipe. So the heat pipe's diameter is not this big. That's too much copper, right? It's a small diameter heat pipe. And so the heat is evaporated, the liquid inside the heat pipe. And on this side, you have forced water, heat exchanger, forced water take the heat away.

So this is one of the cheap forms unpressurized. So what it has is the double glass layer. You fill the inside of the glass with water. I go back here inside, this is empty. So you fill with water. And when it heats up, the natural convection, so the hot water goes up here, and the cold water flows down. So it's a passive system-- no pump at all. And you put on the roof. And then you can take a shower.

So a typical family in China, probably, is about 15 to 20 cubes. And this one is a forced pressure, right? You put a separate tank, you put the pump through and forced cooling at the end. OK, so that's what the system looks like. Again, out of my own curiosity, I say, OK, I'm going to estimate what's the efficiency of the system, flat panel and vacuum systems.

So this is a model for a vacuum system, where I have a cylinder inside the cylinder, inner cylinder. So this cylinder, there is one-- so actually, this is a self-tracking, right? No matter what Sun direction is, there is always side wall is facing the perpendicular to the Sun. So does have some advantage here. In fact, there is a startup company called Solyndra. And they are putting solar cells like this. So circle along the circle of the cylinder.

And it's a vacuum in between. So incoming solar radiation is just the cross section area. That's like capital-- the outer diameter. And say the insulation, solar insulation. So absorbed, how much is absorbed? In terms of absorption, the first thing you have to go through is the outer glass layer. So that's a transmissivity [INAUDIBLE]. And then inside the surface is absorbed. Alpha is the absorptivity. So that's the absorptivity to solar radiation.

Now this is a disadvantage here-- the radiation loss, right? Radiation loss, because the whole inner tube is heated up, so the surface area is actually is pi times the inner diameter. It's not just the cross-section flat. Compared to flat, it's only the flat area. Now it's the whole surface area. And then that's the emissivity And I do a simple blackbody calculation of the surface.

So what I did not consider is the multiple refraction, the surface emission, I just say, OK, everything goes to the environment. And in reality, the sum of those cannot go. In fact, the glass may trap some of the radiation back. The reflection and also the glass is non-transparent in certain wavelength range. So with that, I can say this is the absorbed radiation minus loss. The difference is what I actually get into the hot pipe, and then divided by what comes in. So I have my efficiency.

So this is a simple, again, back of envelope for fun. Yes?

AUDIENCE: I have a question. So if the tube is treated [INAUDIBLE] I think only the 1/2 the total surface get the solar radiation?

GANG CHEN: That's not--

AUDIENCE: [INAUDIBLE] reflector.

GANG CHEN: That's the 1/2, right? It's cross-section area. But the emission is pi D. So that's a disadvantage. OK? And so that's an idea. I'll show you the curve later on. Now I'm going to look at the hot water flat panel type. So a flat panel type in between the air. I was actually curious whether people use double glazed windows here or not. And what I found is since they do not use it, so it's just one layer of glass.

So this is air and selective surface. And of course, if we think about heat transfer, this absorbs solar radiation and then will conduct through the air, conduct through the glass and outside the lateral convection. So you have the resistance in series, conduction air, conduction resistance, glass resistance, convection resistance. So that's one part of the heat through conduction and convection.

And backside, the thermal insulation can still leak heat. So backside, I have conduction. And then I have radiation goes through directly. So I have three parts for the heat transfer. And this is my simple circuit. The solar radiation come to the selective surface. The energy now, one part is going directly through radiation. And the other part goes through the air-glass convection outside, and then the backside, the insulation. OK?

And I put the resistance because this is assumption if you're not the mechanical engineer or didn't take heat transfer before, this is probably less familiar. But this is similar like a circuit, OK? Thermal resistance. You do the resistance calculation for air, the thickness divided by thermal conductivity. So the gap thickness divided by conductivity divided by area. And they say if you do that, why don't you use thicker?

And the problem is once you [INAUDIBLE] start the circulation, convection starts to happen. So you look at the double panel window in the typical window, that thickness is not-- it's a few millimeters thickness. So you don't use too thick here. So here, I took a 10-millimeter. And then, say, glass, glass is a-- few weeks ago, there was a talk, somebody is going to install a flat panel system in one of the MIT building.

MIT, I don't know. Boston? OK. I was surprised. The cost per was just a surprise for me because that's like a 13-, 15-year return. I don't understand why, but let's say it looks like they use a very tough glass. This is a steel. What's the glass like? You harden the glass. You can walk on it. But anyway, but glass resistance is very small. It's really air resistance, convection resistance. Those are the resistance that cost the total. That's this side, the resistance, and then the insulation resistance on the back side.

So I put all this lumber together and did the energy loss, again, considering all the release. So I have radiation loss. I have the conduction loss in conduction/convection loss. And with this loss, I can, again, go calculate how energy comes in, absorb, mass loss divided by what comes in. And that's what I have.

OK. Those numbers, I assume, for example, in the next graph, I assume 95% absorption, 5% emission. This is what the industry can do. So we have a research group on selective surface so we can see how we can do better. Industry can do that at the meters per second, selective surface-- 95% absorption, 5% emission.

And this is how water is, of course-- the typical operational temperature is about 70, 80 degrees. So they do not operate at very high temperatures. And then when you go to higher temperatures, if you can go 500 degrees, still keep this, you will be the best in the world. It's very hard to do that. OK that's the curve I have. That's the vacuum system. And this is the big flat panel system.

And efficiency depends, of course, the temperature of the water. Essentially, it's the temperature of the selective surface there. And I went to the web, and I found this. Depends on which website they're looking at, people have different curves. But I found the one that I thought was closer to what I have. So this is one company that a vacuum system that compared to a flat panel. A flat panel goes to almost 0, I think probably, yeah, that's probably too small.

But solar thermal is efficiency compared, of course, to the photovoltaic is many times better. And so in terms of if you look at what has been used, this is a chart I got from this publication. And here is this side that's solar thermal. That's here. It's compare all the renewables. Solar thermal here is one. Here is geothermal photovoltaics, solar thermal power plant, ocean tidal power.

And you find out that the total capacity, and the red is actually produced energy. So you can see the solar thermal is actually a pretty large part of how people are currently using renewable energy, OK? Just heating up the hot water mainly. And this is in terms of technology. The vacuum tube is dominant because China-- and really China use it. And flat panel, 32%, unglazed [INAUDIBLE] collector and air collector.

So this is where it's being used. You can see that China is off the chart here. And it has about 100 million square meters installed. I don't understand why we didn't use them here. But I think I see Hawaii now has legislation, if you have a new house built, you have to put in hot water system. Tim Young from Hawaii, right? You can go back, check this.

[LAUGHTER]

So I was once talking to-- every time I have a chance, I always ask the people what-- and also, price gets very high. That's probably because in China, your typical household is $300 to put a thermal system rooftop. OK, so that's a thermal. Now we want to go to higher temperature, right? Solar thermal is 80 degrees, 100 degrees. And we want now go to higher temperature.

And to get a higher temperature, you need concentration. And now we need to look at the concentration. Let me remind you, I showed this before, the Earth itself, see the orbital is not just a perpendicular of this plane. There is a 23.5 tilt of the Earth, right? So on this side, this is tilt. On this side, the same tilt. That title is fixed. That's why we have summer and-- oh, the wrong direction. We have summer and winter. OK?

And the degree suspended of the Sun by, say, if you view from Earth, the degree is 32 second. So that's about 0.5-- so that's about 0.4, 0.5 degrees. And now the question I want to ask first is, if you do concentration, how much you can get. What's the maximum concentration, right? So we can look at theoretically, what's the limit? The maximum theoretical limit is I cannot heat up an object hotter than the Sun. Right?

AUDIENCE: [INAUDIBLE]

GANG CHEN: Now, so that, you all agree. But if I ask you, can I concentrate radiation even with the intensity hotter than the Sun? And not hotter-- the intensity higher than the Sun? Is that crazy or not? Huh? OK, you'll see later on. OK, so first, we have to look at the first or just look at energy balance. If I think about the spherical radius from the Sun and the area of the sphere times the energy flux and area of the-- see, it's a constant.

Once the energy leaves the surface, the larger you draw a circle, the less is your intensity. So the intensity of this Earth, you think of a circle here, that is the capital R 4 pi R squared times whatever insulation outside the Earth's atmosphere. So this is the insulation outside the Earth's atmosphere. This is the intensity on the surface of the Sun, radius of the Sun. So that's the energy balance, conserved always.

Now, of course, you say there are something in between scattered a little bit like-- assuming the space is pretty much all empty, right? So now let me concentrate. If I concentrate this concentration ratio and this intensity on the Earth's insulation, and this is the energy I put in onto an object that receives this concentrated light, right? So energy balance will tell me in this case, again, the object should be blackbody, actually because you want to absorb every drop of solar radiation.

And because you absorb the solar radiation, you also reradiate. So you want to absorb maximum. You also reradiate maximum. So it's a blackbody. So actually, I put the-- so the energy absorbed, the balance the energy reradiated, I do perfectly insulation. So this is per unit area based. This is per unit area based. So that's the energy balance for the object that receives the concentrated light.

And of course, as I said, my condition is that this object cannot be hotter than the Sun. Right? So this is the concentration. And from here, I get my maximum concentration happens when this is equal. And that's the solar flux intensity divided by whatever [INAUDIBLE] in the Earth. So that's R over small r based on my energy balance.

And if you look at R small r, and this theta here, it's half angle sustained to Earth. So that's a sine theta squared. So that's my maximum concentration. And if you plug in the number, I said the 2 theta is a 32 seconds. So you plug in a number, that's about 46,000 times. It's the maximum you can get. It's not the maximum. People actually have achieved higher than this one.

OK? This is because the emission inside the object is proportional-- I have one mistake here. Should be proportional to n square, not proportional to n. OK? So the emission inside object is proportional to n squared. So if I have a medium like a water or glass, the intensity inside could be higher than the vacuum. Blackbody intensity, n squared. n in glass is 1.5. So square is 2.25.

And if you use a silicon, the n is about 3.5. The square is about 10, right? So if you do that again, your limit is the temperature limit is not the intensity limit. Your temperature of the concentrated surface cannot be higher than the temperature of the Sun. You do that, you get your maximum is n squared sine theta squared. So that's higher than the previous one. And indeed, this was achieved in the lab. This is Roland Winston. I'll talk about this in more detail. This is a compound with the focus and non-focus, and they have achieved 56. So there we go. OK?

So that's from the second law perspective, your absolute upper limit. And now let's see how we can get there. OK? And I think I'm going to use a lens. And this lens, if I think about a lens, so all parabolic trough, we know that you have [INAUDIBLE] comes in, you focus on one point. So the question is, What's the concentration limit if you-- those are the image formation, right? Using a lens or using a parabolic trough, you have a focal point. That's a focal point. This is the image.

So the image forming optics. And remember, the Sun sustained angle. That's the k, right? Even though we say solar radiation is a part of light. But when you want to do focusing, that angle becomes important because previously, you've already seen. So what I want to think about is if I have either lens or parabolic trough, say the opening here is D, and the focus here is a small d-- why is it big D, the other small d? And I want to find the ratio.

OK, let's look at it. So if I do 2D, this one is a flat panel. So if you do two, you have a different result. But here, I'm a flat panel, and this is the half of it. And now I look at-- this is a vertical-- I say perpendicular line here. So R times sine-- see that here is 2 theta. So this is really-- if you think about parallel line comes in this way, and that's my reflection here. And this one is my this line reflection. So that's the edge of the solar cone there.

And so R times sine theta gives me this one, right? Perpendicular line. And D over 2-- so that's here-- times, this is phi. And here is phi. So here is also phi. So D over 2 times cosine 5 is all giving me this segment. So I have an equation geometry here. Geometrical relation. And then I have this R, and this R is about the same. So R times sine theta gives me D over 2, the opening there.

And then from here, I can get my relation, how much focus I get, capital D over small d. I have sine 2 phi divided by 2 sine theta. So this is the maximum you will get. This is the concentration you get. And you will see the maximum happens is assigned to 2 phi equals to 1. Right? So 45 degrees. So when phi equals 45 degrees here, I have the maximum here. And that maximum is 2 sine theta. That's 107, my calculation. Maybe you can go back to check.

And if you 3D axisymmetric, you square that. And that's 4 sine theta squared. The problem is now you can see this is a factor of 4 smaller than the limit, right? Thermodynamically, it's 1 over sine theta. Here, if you form an image, your limit is a factor of 4 smaller. And how you can reach the maximum number. OK. So imaging optics is a little bit too constrained. Ideally, you want everything goes to one point, right?

And you want to form an image. So this is a-- here, there's another slide that I just copied from Winston's book. And if you want to focus on the cylinder, that's 1 over pi smaller than the previous slide. Now there's another way to do it. That's a lung image method. This is Roland Winston's baby. And if you read, his rationale is starting from this 1 over 4, how you can get to the maximum thermodynamic limit.

And here is one where there is no simple mathematic in terms of the shape of the concentrator. But this is how he would explain it. So this is where the area you want to-- this is a flat plate example. You want to focus on a flat plate and B prime to D, OK? And this is the angle of incidence, right? So that's the maximum angle. Let's suppose this is the maximum angle that you accept the radiation coming in.

If you have another angle higher than this, you will not get in. You will be blocked. So this is the maximum angle. So you take the string here. At this point, you take a string. This is the opening limit A. So you draw-- you keep this string fixed. Let's fix, and you draw the curve down. So this one will slide. So the angle of incidence equals reflection. That's what it's following.

This surface gives a surface such that the angle of incidence equals angle of reflection. Of course, it's a specular surface that's being assumed. And at the limit, this one when it's here, the reflection angle as [INAUDIBLE] goes to D prime. OK, so that's the image surface. This is the image method he developed. And now we can check whether this one gets to maximum or not.

So this is, again, simple geometry. I have AC, this section, plus A B prime-- that's the [INAUDIBLE] length, right? And the outer limit-- so this is the edge. You look at the edge, you'll need A prime to B plus B B prime, right? So this is the [INAUDIBLE] length. This is the [INAUDIBLE] length, and the same [INAUDIBLE]. So it's actually a very convenient and simple way to do the geometry, whether the surface is harder to express analytically.

And you know, say, the symmetry A B prime, A prime B from symmetry, they're equal. So you get rid of two variables in the above equation, and your AC is this 1 times sine theta. So A A prime times sine theta, and your concentration then is 1 over sine theta. Remember, before is I'll say sine 2 phi over 2 sine theta. Now you got rid of that factor of 2 in the two-dimensional geometry.

And then you go to 3D. You actually reach 1 over sine theta square. So if you put your theta angle of acceptance, right? If you just say I only accept the solar cone, theta S, when that's your maximum, you have to accept those solar within that 32 arcsecond. So that's the maximum there. But this isn't convenient because let's say if you think about your design, you don't need that high concentration, but you want a large angle acceptance.

Particularly when you have also streetlights, right? If you think about you don't always have parallel light, you also have the scattered light. And typically, people take 80/20. It depends on where you live. And so scattered light is actually approximate isotropic in all directions. So tracking, if you track only the solar part, maximum concentration, anything beyond that angle, you can't capture it. So that's an AD-- that 20% is gone.

And so with this, these are the other examples. And if you read the paper, it's interesting. This is when you concentrate to cylinder using the same string rule. You can even do this, and the effect, those curves show different acceptance angle theta and the concentration ratio, and also the height of the-- height versus the aperture. So this height, aperture, right?

And if you look at it, if you want 3 times concentration, that's about the 21 degrees, and the height, the aperture is about 2 to 1. And also, what's important is you can never make a perfect surface reflector. So every time a light bounce once, you lost a fraction of a light, right? So this surface is never perfectly reflecting, 100% reflecting. So you want to minimize that level of bounce because every time it bounced, it's absorbed, a fraction of it.

And let's say aluminum is-- you can get about 97% reflection, but that's 3%. If you have 10 bounces, 97 10 to the power, you'll get some more numbers, right? So you want to minimize it. So this is the average number of bounces we calculated for these geometries. OK, so this is the conservation, right? Now, you concentrate it, particularly when you go to higher concentration, you have to track it because only certain angles are accepted, right?

So you have to go track it. So let's think about how we would-- typically, how you should track it, right? Again, think about the Earth has this 23.5-degree tilt. And in fact, I haven't figured out all this a little bit detail in the Earth's motion yet. That tilt of 23.5 is an average number, which it turns out the Earth is actually wobble a little bit. So that wobble happens between 22 to 24.5. OK?

And this will be important when you do the high concentration ratios and the acceptance angle. So if you think about the-- so that's what I listed. In the summer, Northern hemisphere, and in the winter they come from-- so in the winter, Southern hemisphere get their share of the sunlight. And now let's think about the why it's easy to think of why you need the packet.

So [INAUDIBLE] let's say your radiation coming perpendicularly. And when you come at an angle, the [INAUDIBLE] energy you get is times sine theta. So you don't get all the energy you could get if you make this plane perpendicular to the ray direction, right? But see this installation not only just a sine theta change. Also, if you think about the departments through the atmosphere, different angle of incidences, the departments going through the atmosphere changes called 1 over cosine theta thickness derived cosine theta direction relation.

So your insulation also changes. And if you combine all this together, those are some of the places people measure per square meter how much energy comes in. And so this is the Northern latitude, 45 degrees. Anyone remember Boston latitude? I thought I was going to check, but I forgot. OK.

AUDIENCE: I think 42.

GANG CHEN: So we're close around this number. You can say this, not very good solution. So my calculation was too optimistic. I need about 7 or 8 square meters for my household. OK, so which direction is your track? If you have a solar-powered or a solar panel, should you render the source loss East-West? So first, this is the East-West. This is the rotation, the angle of rotation in the East-West direction. So of course, if you do only one x tracking, you want the maximum amount of energy received be your solar cell area or your aperture.

Then you want to do the axis in the south-north direction. And then your rotation is the-- so that it's the East-West direction. And then say in the other direction, you remember the Earth is the tilt during the summer and winter, that degree will go from-- go back here, right? So this angle will fix your solar cell here this on the summer.

And then when you go to the winter side, this side your angle changes. So ideally, you want to track both directions, OK? There is one case people have done before that I think it's interesting where you do not need tracking, or you do seasonal adjustment. And this is when you have a low concentration and people use a weight ratio. So these are the-- you put a solar cell here.

Those surfaces are reflecting surfaces. It's a wave group. And now if you read weight in the East-West direction, if you think about East-West direction, those groups in the East-West, so you will use this one means you can do light here. You don't need to put the solar cell. So you can actually increase the flux here by a factor of 2. You use less-- 2 times less of area.

So typically for this geometry, this group geometry, you can get, let's say, concentration ratio is 2.5 to 3 times. So you can operate in that range, low concentration range. And if you do a little bit, what they needed here is a seasonal change because the acceptance angle in the south-north direction will change.

But there are also people now developing this local. I will check in there, people actually do tracking, a little bit tracking. So there are even people doing south-north direction tracking. But in theory, so for this low concentration looks like you put it in south-west direction. You still don't capture that sine theta, the solar installation. That's still will change because your angle coming at an angle, you project area. You're not tracking perpendicular there.

But you use less. In this case, if you do this concentration, you use two or three times less solar cell. So you cut the cost. OK, so this what we talked about is the concentration and tracking. And in terms of PV, People do [INAUDIBLE] concentrated PV. There's effort, there are some companies, start-up companies-- I'm not sure how successful they have been in deploying.

This is particularly when you think about the high efficient solar cells, like gallium arsenide, the maximum here you can get about 40%. That's very expensive. So what you want is to use a high concentration ratio to reduce the cost per unit area, so income and cost. But see, I'm not sure how successful they are commercially. And I know one of the problems is actually the heat transfer is a problem.

And the other is it's very-- I think it's very important to keep the light uniform. So if the higher the concentration you have, if you're tracking is not accurate, you light goes off your cell, then so you're screwed. So that's the tracking accuracy becomes very important. Now I'm going to shift next to the energy conversion system and the mechanical energy conversion.

And the most popular in use is the trough. So the absorber is a tube, and you concentrate the light. And so this concentration could be either by parabolic mirrors or the Fresnel arrays. In this Fresnel, so you can see the mirror is individually adjusted. So this is not a one, say, parabolic, but the angle of each mirror is adjusted so that the light focuses to the pipe there.

It's called the Fresnel, but I think the Fresnel-- my understanding of Fresnel [INAUDIBLE] real object that's a diffraction side. But anyway, and this is a dish where you concentrate-- you track 2D. Here, you could just do 1D daily tracking, or I'm not sure if people do a seasonal adjustment or not. And here, you need a 2D tracking is a dish structure.

Or you tau. You have, say, station the mirror reflecting and to the power. And trough is the most common use to look at the more cost structure where you have a parabolic mirror. And you have the pipe inside in the focal plant. And this is a typical pipe, the solar collector pipe. Again, it's a vacuum. So the vacuum is a pretty high vacuum here, 10 to the minus 3 millibar, right?

And you can imagine the challenge there because the pipe itself is a steel pipe. Steel pipe. And then outside is coated with selective absorber. So typically, you can see the absorptance is larger than 95. Emittance is less than 14% at 400 degrees C. And the outer clear glass is also coated so that it's under reflection coating. So the typical glass transmission is about 93%. I'll get to 96%.

And the watts-- if you look at this, what's important, how you make the seal, right? High-temperature seal is really-- so you have a tube, 100-meter long, and thermal expansion and seal. Those are the really critical technologies. So tubular trough plant, you've got collectors. You have the steam turbine, and you also have-- very often, you have to have the gas fired. So you have to do cogeneration.

What do you do in the light? Or what happens if you have clouds come in? That's actually a big headache there, particularly for PV. Solar thermal actually slightly better because the thermal inertia, thermal heat capacity damping them. That's one of the advantage that solar thermal has. And you could also do some storage, I'm not sure here as storage, but you could, you could do storage.

And the solar thermal plant here, the fluid itself, you can see there's a closed loop. The fluid through the pipe is closed. Or steam generation, steam turbine, similar if the water-based steam turbine. So this is the outer loop, the steam loop here. And in fact, in the pipe, they use oil. And the oil is one problem. You can't go to too high temperature. You go to too high temperature, you decompose.

And so the oil has a stability. This is a steel area where people are doing research, stability problem, and how you can develop a higher temperature oils. You can get to higher temperature, but your oil will not unknown. OK, and this is another just a picture here. If you look at it, they typically installed and typical size of the plant is around 100 megawatts. 100 megawatts is small in terms of if you compare it with the coal-fired.

Coal-fired plant, typically one steam turbine is one gigawatt. OK. And this is too small. You can read your handout. So those are examples, and what I want to point out here are the concentration here. It's typically, those concentration is between 60% to 80% Stirling. That's the concentration ratio. And they look at the cost of the solar thermal, that's the one case where different generations, 30 megawatts.

This is a US dollar megawatt hour. So if you do kilowatt hour, you divide it by 1,000. So that's about $0.19 per kilowatt hour. Coal fired is about $0.05. power plant. So here is the $0.16, and there's some projection to scale up that will go down to $0.10. The efficiency, again, I'm not expecting to read it. Just let me just quoted the fuel efficiency numbers.

The collector efficiency here is 50%, receiver efficiency, 82%, and the cycle, that's a steam turbine cycle efficiency here, 45%, right? So right now, it's a 38%. So at the end, if you combine all this efficiency here, this is about between 13 to 17%. The collection efficiency is not good. Collector efficiency, here it's only about 50%. You lost a lot of light in the collection.

So there, you want to minimize the number of reflection. The other problem is your street light. If you design a high concentration, if it's not parallel, you don't fall into the focal point. Interesting to look at the cost. The cost here, if you look at it here, we have 58. That's the collection system, 58. And structure, this one does not include the engine. So you have the storage. Thermal storage is here.

And we have 14% is the power block. I do not know what exactly is that. OK. And now here is the-- so this is the parabolic power plant. And again, this is a breakdown different materials, the cost of structure. And so that was kind of fun. I thought I saw it before. Where is the cycle?

AUDIENCE: [INAUDIBLE]

GANG CHEN: Huh?

AUDIENCE: [INAUDIBLE]

GANG CHEN: Yeah. OK. So that's where it is. Yeah. So the cycle itself is not the--

AUDIENCE: Bottom one is just the soil so it's just so.

GANG CHEN: Yeah, this is-- yeah, this is-- so the first one is the overall. The bottom one is the field component breakdown. So the cycle itself is not a big part. The collector-- look at-- I think it was interesting. Look at this here. Metal support structure, 29%. All right. This is a big stuff here. The steel used a lot of steel. And receiver, 20%. Mineral, [INAUDIBLE] 19%. Mass support is the big one. So if you can cut that cost, that's good.

AUDIENCE: Where's the engine?

GANG CHEN: The engine is here. 14, that's nothing compared to the solar side. OK. So if you were in Jacob Carney's talk a few weeks ago, he gave a mature-- he does a lot of the [INAUDIBLE]. So you have mirrors tracking inside each one and reflect to the power, the center there. So it's like a big array of mirrors reflecting the light. So there you have the solar tower.

And what's interesting is that this is what I learned from Jacob Carney is that the finger size-- and you put a question mark, but I think the [INAUDIBLE] size is actually smaller than 12. The tower, you don't want to build too big. OK? And a lot of-- but the temperature is much higher. So the [INAUDIBLE] side there, efficiency should be higher. And the problem is the focus. And he showed some very interesting pictures.

You don't always hit your target. You have a lot of missing light. So if you look at around the focal point, you see a lot of white light that missed the scatter. And so this is the absorber, two different absorber ways to absorb the radiation. And what in this cases-- so I showed I think the last lecture, once you get a higher concentration, your absorptivity is more important. The emissivity is less important.

So I think those are pretty-- it's not a really spectral control surfaces. There are really not-- I think there are only one or two [INAUDIBLE] probably has. But in the US, there are the [INAUDIBLE] junction mostly is 12, but it does have a tower system. And so here, it gives you in terms of the cost, they feel they sell 40%. Power is 14%, p2p storage, 11%, and the engine is 32.

And so here is a structure, reflector. Structure, 10%, reflector, 36%. Drive for the tracking is 30%, and the foundation. So that's the tracking system itself. OK. The car efficiency-- this is from the number here-- is not much better than the-- this one is not power, I think. Sorry for that. This one is not power. This is a steel car. So that was going to delete this one.

OK, the other form of the generator is a dish. So dish, you make smaller. This one is, say, tracking. And the problem is the generator here. So you have how you can make a small power generator. And here, it is a Stirling mechanical system, so Stirling engine. And if you're a mechanical engineering student here, the second year, they always do the Stirling engine. It's a burner Bunsen based Stirling engine.

So the Stirling engine is very different from an internal combustion engine that's used in the car. You can heat up one side of the Stirling engine from external-- so external heating. And then you generate the mechanical motion to generate power. The cost is much higher, I learned. So I do not know anybody who is using this. It's not mature. The most mature is the 12th.

And so we have an efficiency number here. Right here is the efficiency. This efficiency is the-- I thought I would try this. I don't know. It's a pretty high efficiency. I see. But I can't believe this number is 29%, 30%, 39%. And so this is the Stirling. And that's all I have in terms of the thermal mechanical systems. Any questions? Now I will go back. So this is a big stuff, and I'll go back to a simple-- question?

AUDIENCE: Are these technologies too immature to talk about in terms of [INAUDIBLE]

GANG CHEN: I think the last two-- well, at least the Stirling, I don't think it's mature enough to talk about dollar per watt. And I don't have exact number. I asked the people around. This is 10 times more expensive than 12. But the heliostat, I have not looked at how many deployment-- I see there was one running together with I think the Kramer junction, the 12th system.

So what I want to do in the rest of the time now is coming back to-- we have too many simple [INAUDIBLE] stuff now. Now I want to come back to a little bit more math. And the reason we want to do next is, What are you going to say is a selective surface? And it's important to have the-- in the case of concentrating parabolic mirror, it's important to have less reflection. Each reflection, you lose very small amount of energy.

So you want a high reflectivity. You want a high transmissivity going through glass. And once it gets onto the surface, you absorb solar radiation. You want to spectrally absorb the solar radiation, but do not reradiate. So now this is in terms of technology, some of the key technologies. And for those technology now you have to come back to the basics, how you can understand what people have and develop further.

So the basics is maximally efficient. And I'm not going to spend much time on the Maxwell equation. If you want to really learn, you should take a course. But you all heard about Maxwell equations. It's a set of four equations for electric field, for magnetic field edge, and displacement and magnetic induction. Right? So I gave you the definitions of those symbols-- electric field, magnetic field, displacement.

And j is the current. And they are considered relation related displacement, electric field, magnetic induction, magnetic field. And those constants, the material properties, electric permittivity, magnetic permeability. Yeah, Maxwell equations. And it's a wave equation. It's describing electromagnetic waves. So if you go to solve those waves, and because that's important, what's important-- say, when you do the particularly selective surface, very often, it turns out they are based on controlling the phase of those waves.

So if you look at a simple solution, a wave has a direction of propagation with vector. And it's an electromagnetic field. So electric field, magnetic field, turns out the solution tells you they are perpendicular to each other. And in fact, they form a right-hand rule. So you go from the electric field to magnetic field to some point to the propagation direction. And to describe a wave, we have wavelengths, and here in time.

Here, the inverse is the frequency. Angular frequency is 2 pi times period, say, 2 pi times frequency. Wave vector has a direction, but it also has the-- it's numerous wavelengths. So wave number is 1 over lambda. 2 pi over wave number gives you the magnitude of the wave vector. And the direction of the wave vector is the unitary vector here. And then if you solve the equation, turns out at the end that epsilon and mu combined give you the refractive index of the material.

This is a property. You can look at different materials many times people have measured. Sometimes it's called the optical constant, but it's not a constant. It's a frequency-dependent quantity. So you have the real part and your measured. And since it's a wave, so the planned wave, simple solution of this wave is the electric field is a function of location time. This is the direction. It's a vector, direction of the field, right?

And the wave vector frequency, complex refractive index. So that's your solution for electric field, similarly for magnetic field. And these two, e and h, perpendicular to each other. And so that's your plan with solution. This one, you can substitute back into Maxwell equation. You find this satisfies Maxwell equation. So this is the field. What's the energy? Energy is the product of e and h.

And particularly, this time area average. This is time dependent, but to do time average, you can simply calculate the e cross h complex conjugate. If you do complex conjugate, you see this i omega t cancel. There's no time there. So that's your Poynting vector. And if I do that, I will get-- for propagation in a homogeneous medium, the Poynting vector is the real part of the refractive index [INAUDIBLE] exponential decay function.

So this exponential decay, that's the problem silicon we said, right? Silicon photovoltaics takes the alpha is a problem. It's too small. We have to use a very thick one to absorb. And this alpha is the absorption coefficient we mentioned before, and that's related to the major part of the complex refractive index [INAUDIBLE]. OK. So this is the, see, [INAUDIBLE] inside the one medium.

Now, what I can control is really with the interface to control. So you've got the interfaces. When you have light comes in, reflection, refraction, right? High school, you will learn that. And because the light can actually have two-- see, you decompose it into two directions, it's a transverse wave which become the two directions. One is your electric field is independent of incidence. So direction of coming in norm form the plane of incidence, right?

So if your electric field is within the plane or your electric field is in the other direction. So we have the electric field. If it's in the plane of incidence, the magnetic field is perpendicular, right? It's always perpendicular to electric field. So we'll be in the perpendicular plane. So in this case, we have transverse magnetic wave or parallel. That's for electric field, different lengths. I can remember this. I always just say TM, then I say, ah, transverse magnetic. That's more intuitive.

OK. Edgefield. OK, that's if the magnetic field is a plane of incidence, the electric field is perpendicular. That's TE. And so perpendicular and [INAUDIBLE]. So you have expressions when you look at or calculate the interface. You have to calculate for both solar radiation. It's a typical combination of 50/50. We say we calculate, and we say, oh incident is 50 TE, 50 TF.

OK. Now, what happens? First thing is reflection and if you have a smooth surface, right? Angle of incidence equal angle of reflection. So that's the reflection rule. And then refraction is the angle change based on the refractive index. And then you can actually calculate the magnitude of the field reflected and refracted. And again, I'm giving you the solution. The point is, I want to tell you, those could be calculated.

OK? And if you want to learn how to calculate, you need to take a course or pick up the book, read yourself. Let's say it depends on-- what it depends on is the refractive index of the material on both sides. And so you need to know the property very often, although, you think people should list it. You go-- when you need it, you don't find it. That's one.

And even people list it, you do solar thermal, you want a high temperature, you don't find it. So there are a lot of things you can do. Find them. And so when we want to design, the first step, we say, oh let's design-- let's deposit a film and try to measure properties. So those are just a few of the reflection. And the energy, that's reflectivity, transmissivity. So you do reflection coefficient squared. You get reflectivity.

Transmissivity, you have to plug in some factors in the front. But again, those all depends on the complex refractive index. So the final one is just one example, where it's a calculation given the refractive index is between vacuum or air, which is one. And let's say dielectric to the constant, gold also to the constant. But remember, it's not a constant. It's wavelength-dependent. So each wavelength, this can change.

But here, it's calculating only the angle dependence. So if it's a dielectric, so copper is, say, 0. And here is for the TE wave, transverse electric. And here is for the TM, transverse magnetic. And then what's interesting is this crystal angle, and there are certain. So that's how people make the polarized glass coatings. And you can choose the polarization, the certain angle. You can get, let's say, no reflection at a closer angle.

Gold is a very good reflector. You can look at that. Reflectivity is almost close to 1. So when people do selective surface, very often, they start with aluminum metal. It's a good reflection in the infrared. The problem is reflected up to about 0.2 micron or 0.5 micron or 0.4 micron. But you don't want that. You do not want to reflect the solar radiation. You want to absorb it.

So you try to put materials on the surface to make them absorb between the solar radiation up to 2 microns. And then you still keep the old-- say, infrared is very reflecting, which is good because that means emissivity is small.

So people have developed, like I said, let's say, the different coating even for the solar thermal. Solar hot water, I said they're very cheap, right? $1.5 per two. You go through the factory, you will see their vacuum deposition. I saw one vacuum deposition is about 100 meters long. Continuously deposited in different layers and do it at that low cost. It's amazing. OK. OK, so I'll stop here.