MITOCW | 2. The Solar Resource

PROFESSOR: And I think we're about ready to get started. So welcome, folks, for lecture number two of Fundamentals of Photovoltaics focused on the solar resource. What I wanted to do to get everybody in the mood of thinking about the sun is pass around a few balls. So this is really a, to limber you all up, but b-- whoop.

[LAUGHTER]

There we go. All right. Don't let it fall. There you go. I know Ashley's got solid hands. All right. Here's one. Pass that around as well. We'll get a few more there, there, and lastly, right up the middle. There you go.

OK. So today's lecture is really about the solar resource. And as we go through, it kind of helps to have a sphere in your hands since oftentimes we perceive the world as being flat-- no fault of our own. Locally, one can approximate it as a flat body. That's certainly a good possibility. You wouldn't mind passing these out to your friends as well?

AUDIENCE: Sure.

PROFESSOR: Thanks. But in reality, if we really want to understand the solar resource, we really have to begin understanding or thinking in terms of spheres and in terms of circles or, in most cases, ellipses. And so we're going to dive into the solar resource.

Before we really dive in in detail into the solar resource, I wanted to give you feedback to your surveys. So you did a background assessment survey, a census, if you will, and filled out a number of questions last class about your backgrounds. And I wanted to provide you the feedback, the consolidated information, because it's really telling about who your colleagues are.

This right here is a little bit of a snapshot of expertise and current career trajectory. So the self-defined expertise in the bottom left is really, I think, the most telling parameter. For the undergrads here, you may define yourself by your major today, but when you graduate and go on to grad school, you might, say, for example, do your undergrad in physics and then do your graduate school in mechanical engineering, but still consider yourself a physicist at heart.

And so that's why I asked this question here-- what is your self-defined expertise-- because there are several graduate students who have changed fields, if you will, from undergrad to graduate school. Most people in the audience, by and large, consider themselves engineers-- either material science engineers or mechanical engineers. Chemistry is strong as well.

And then we have about 10 different departments here represented. And that's really cool. It's going to manifest itself in the class projects. And you'll see the diversity of different inputs and perspectives from your colleagues.

The degree in progress-- undergrad/grad is about split 1/3 2/3 undergrad and grad. ASP is Advanced Studies Program, so these are folks coming in from industry who are actually here in the classroom. Some of your colleagues in the class are folks who are in industry and perhaps have real world PV experience.

Several of the people here in the class, as well, have gained-- how do we say it-- have gained expertise in solar with their hobbies, with their work. Some have installed solar panels. Other ones have done research or are doing research in solar. So it's a pretty diverse group. And some are, as well, members of the solar car team, which is rolling out its new model in a few days' time.

In terms of learning methods, it was pretty well split between hands-on labs, field trips, and guest lectures. And I'll get back to that in a few slides. In terms of class project interest, there was a strong interest in working with pre-established projects, so we've listened to that. This is pretty consistent with previous years. And so we have several pre-prepared class projects ready for you.

And a few of you had an interest in the self-design project. I'd like to talk to you. I'd like to begin developing those ideas as soon as possible so that when we start assembling teams, if you do have a strong idea for class project, we can begin crafting that and molding that starting now. So please come up and have a chat with me after class or during office hours or during recitation.

These are your learning objectives defined by you. And they range-- I tried to give it some continuum spectrum from natural sciences to social sciences and engineering in the middle. And obviously, this is more of a loop than a linear line, but bear with me.

There was a strong interest in fundamentals. And that certainly, I think, what the core of the class is about or at least the first third of the class. Going in terms of size of the bubble, these are the number of people who listed a particular topic as of great interest to them. Economics and market, systems and grid, current technologies, and emerging technologies.

And so listening to all of this, we have, or we are in the process of preparing for you some guest lectures and field trips based on this feedback right here. We have already lined up a field trip to a local PV research laboratory that produces modules like this one right here only much, much bigger and has strong collaboration with existing companies, startup companies, in the area as well as more established companies. So that'll be a lot of fun.

And we're currently in the process of arranging other field trips and guest lectures to match this feedback right here, so thank you. We'll mold the course, shape it, craft it to fit your interests. So to hop into the solar resource and without further ado, the subject of today and the motivation for wearing this tie is really the solar resource, the sun.

This is where it all starts. If we're to understand PV, photovoltaics, the conversion of sunlight into electricity, it starts from the sun. And so spending some good time thinking about the sun is really, really important. And it will avoid the embarrassing situation-- how many of you have been at a shopping center, walking along, and a little child is asking his parent, Dad, why is the sky blue? Or why is the such and such? And the answers you'll hear just make you want to tear your ears out, say, my goodness. And so part of this is just general knowledge. It's getting a feel for the world and the universe and asking those questions again that the little children will ask but we forget to ask as we move on with our lives, right? OK.

So moving forward, the learning objectives for today are these right here. By the end of the lecture-- and hopefully, you already have a good sense of this based on your readings already. I'll quiz you on that second-- verbally. We want to be able to quantify the available solar resource relative to human energy needs and other fuel sources. We want to recognize and plot air mass zero and air mass 1.5 solar spectra and describe the physical origins.

We want to describe how solar insulation maps-- these are solar resource maps, in other words, how much sunlight is available. And we want to be able to estimate a solar resource amount locally at a specific spot on the planet. We want to list the causes of variation and intermittency of the solar resource and quantify their time constant in magnitude. In other words, we want to be able to discern what are the big effects and what are the ones that don't really matter.

We want to be able to estimate the land area needed to provide sufficient solar resource for a project, whether it's a house, a car, a village, a country, a world. And a lot of this will be on your homework assignment, so we'll give you the tools here, but then ask you to address those questions. And for those of you who have already picked up your p-set number one, you'll see relevant questions.

Where is this? Does anybody recognize this right here? If I start rambling off names, what city has Pennsylvania Avenue, Independence Ave?

AUDIENCE: Washington, DC.

PROFESSOR: Washington, DC. This is right outside of the National Air and Space Museum. What this little girl here is pointing to is the sun. And then we have Mercury, Venus, Earth, Mars, and so forth. So it's essentially a solar system to scale. As you walk out of the

Air and Space Museum and walk down the street, you'll be passing the different bodies in our solar system.

And so just as a quick little review to kind of get us situated and to ask the questions that little kiddies might ask us, how far is it from the earth to the sun?

AUDIENCE: 93 million miles.

PROFESSOR: About 100 million miles. Yeah. 93 million miles. Plus or minus somewhere in the range of maybe a percent or so, a few percent depending on what time of year we are since we're in a little bit of an elliptical orbit.

Good. So that's the distance to the sun. It would be about 150 million kilometers. How long does it take light to travel that distance?

AUDIENCE: Eight minutes.

PROFESSOR: About eight minutes, eight and a third minutes, right? So it takes a little bit for the light to reach us. Good.

Some more questions-- how far are the other planets in our solar system to the sun, going in order from Mercury out? It's to get us situated here. If we are, at any point, planning on throwing up satellites and sending them with other planets, this is a good thing to kind of keep in the back of our minds.

So if we define an astronomical unit-- not in terms of our national debt, but in terms of the distance from the earth to the sun-- that's an astronomical unit. Mercury would be somewhere around 0.4. Venus 0.7. Mars 1.5. So that's all kind of in our neighborhood, right?

And then from Mars to Jupiter is a bit of a jump. It goes from 1.5 to 5. Then from Jupiter to Saturn is 10-- well, sorry. 10 is the distance from Saturn to the Sun. And then 30 and then 40. Sorry, 10, 20, 30, 40.

So it goes-- Jupiter's 5, Saturn 10. Uranus would be 20. Neptune 30. Pluto 40. Pluto, planet, sort of. So it's easy to remember those numbers because it goes 5, 10, 20-- that's just essentially a sequence of doubling-- and then 10, 20, 30, 40. I'm giving you approximate numbers here, but that's something just to keep in mind all in terms of astronomical units. So in case a little kid comes up and asks you, you can spit out the answer.

Let's talk about the sun. This is just a review of our readings right here. This was a representation of the sun and the Earth moving around. And what is solstice and equinox? What do those refer to? What is the equinox?

AUDIENCE: Equal amounts of light and dark.

PROFESSOR: Yeah, equal amounts of light and dark throughout pretty much all the world except if you're really standing on the tippy top and the bottom. So equal amount of light and dark throughout the world on that particular day. So the day and the night have the same amount of length.

If you move over to this region right here, this would be a region of our northern hemisphere summer, southern hemisphere, winter. Over here, vice versa. And the solstice would be?

AUDIENCE: The shortest day of the year.

PROFESSOR: Yeah. So the shortest or the longest day of the year, depending on what side you're on. So in the northern hemisphere, the June solstice would be the summer solstice. For us, it would be the longest day. And if you're in the southern hemisphere, it would be the shortest day. Depending on what time zone you're in, there might be a variation of one day hither to. Good. OK.

And what is this? What are the seasons caused by? What is this kind of tilt right here? What is that called?

AUDIENCE: Declination angle.

PROFESSOR: Declination angle. And approximately how much is that?

AUDIENCE: 23 and 1/2.

PROFESSOR: 23 and 1/2. 23.45. Yeah, so 23 1/2 degrees. Good. OK.

And we can visualize all of this on the PV CD-ROM on the website. So this was part of your assigned reading. And here's the earth going around the sun in this representation. Likewise, if you want to take one of your balls and just kind of imagine being on one of those surfaces, you see the diurnal rotation here. It's spinning around its axis. And as well, the seasonal variation as it spins around the sun.

That's important for a number of reasons, right? That will determine how much sunlight is normally incident on the planet. If you are normally incident, if you're at this exact spot right here, you're receiving the sunlight full on. But if you're up here somewhere, your surface normal is some vector pointing out like that. You're only going to be receiving the cosine theta of that amount of sun.

So if you're an extreme example, if you're right here, you're not going to get any. But if you're in this part right here, you're going to get cosine of 0, which would be 1. So you get the full amount of sun. And likewise, as you move through the angles here.

So it's important to understand what the relative angle is between our surface normal and the vector pointing at the sun. That varies as a function of season. It varies as a function of time of day. And obviously, over the entire earth, you can define the precise amount of sunlight coming in, the precise solar resource, by a series of trig formula. It gets pretty complex. And this website will actually walk you through it if you're so interested.

Now this is all review since folks have all done the background ready, right? All done the background reading. I expect you to before class. Let me ask you a few trickier questions just to see if our creative juices are really moving at this early time of day.

When would be the shortest day of the year? Let's start there. The shortest day of the year is approximately December 22, right? In the solstice. When is the latest sunrise and when is the earliest sunset? You might need to pick up your little ball and rotate it around.

Does anybody have even just a gut sense? Would it be on the solstice? How many people think it's going to be exactly on the solstice? Let's see. Earliest sunset-- how many people think that the earliest sunset's going to be a little bit before the solstice? How many people think a little bit after the solstice? I know people don't really know.

The reality is that the earliest sunset would be a little bit before the solstice here, and the latest sunrise would be a little bit after the solstice. And it flips in summertime. It would be, let's see, the earliest sunrise and the latest sunset before and after the solstice respectively. OK.

And you can think about that in terms of what is the solar noon. The solar noon is when the sun this is directly overhead relative to our chronological noon, which is, I would say, less dependent on the specific angle of the earth relative to the sun as it moves around this trajectory. Let's get more into that in recitation. I sense since there wasn't much traction there I don't want to dwell. OK. Good, good, good. OK.

Let's think a little bit more in terms of the trajectory of the sun later on as we move through some of the introductory material. I don't want to dwell too much. I want to give a little bit of review since I'm sensing that not everybody did the readings. I expect you to do the readings, folks. So let's keep with me here.

So a touch of history, since that was asked for. It was requested. I decided to launch a little bit into a history of the study of the sun. Philosophers, going back to what I suppose most would consider early India, studied the sun. There were some writings of some of the earlier philosophers that were recorded. Some have interpreted these writings as being indicative of, perhaps, heliocentric models. These are poetry, folks. It's a very different style of communication than what we have today of technical writing, so it's difficult for us to discern, or difficult for me, at least, to discern when I read the lines verbatim if this is really somebody thinking about the heliocentric model or whether this is somebody just describing the universe in the best of their abilities.

I would say the real beginnings of heliocentric models began in the third century Before the Common Era and the notions of interstellar distances estimated in a similar manner to what we just walked through today, right? Estimating the distance between the earth and the sun and then using that as a measure or yardstick with which to measure the distances to the other planets began somewhere during that time.

Likewise, these writings of old made their way to the Middle East. And in the 10th and 11th centuries of the Common Era, the Middle East, the Arab world is really where science and technology was at. And these days, I mean, Europe was still largely mired in the Middle Ages, starting to emerge in a few places. But by and large, the carriers of civilization in the Western world were really centered and in some of the Arab cities in the Middle East. And al-Biruni, in particular, was very avid at applying methods of astronomical observation, in particular to aid travel, but in the process, discovering a thing or two about our known universe.

And of course, finally, Johannes Kepler in Europe, once it starts to emerge from the Middle Ages, with really taking observation some other scientists, who very carefully plotted out the position of the different bodies, he came up with some of the mathematical models that describe the motion of the planets through the skies and is largely credited with developing a series of laws that define interplanetary motion. So a couple of interesting things to note is that international collaboration was really essential. These ideas didn't develop in isolation. They were flowing throughout the world.

It's important to know that many of the scientists were well-traveled polyglots, meaning they spoke different languages. And that's how they were able to interpret the texts and readings of other people. And it's also to note that parallel astronomical developments were happening in other regions of the world-- the Far East, Mesoamerica, and so forth, right?

And so obviously, there may have been some communication-- I would say rather sparse-- between especially with the Far East. But there was a fair amount of communication between these regions here. And you can imagine writings or ideas traveling from word of mouth along trade routes. So there was some communication.

So back to our learning objectives. Today, we're about to quantify the available solar resource relative to human energies and other fuel sources. So let's do that. We'll jump right into one of the slides that I showed you last time.

This is in terms of terawatts av. Terawatts is a unit of power, a very big one. "Tera" is 10 to the 12. And you can see here the resource of the sun relative to the wind energy resource base relative to human energy needs. If we just consider the resource falling on the earth's surface, as opposed to that falling on the outer atmosphere, there's a little bit of a discount. But we're still very large compared to human energy use.

And if we redefine our units from terawatts into HECs, which are Human Energy Consumptions, defined in, say, 2050, where one HEC is the average, let's say, energy burn rate of 2050, you can see here that these numbers are a few orders of magnitude larger than what our human needs are. So if you were able to capture only 1% of all of the solar resource falling on the earth's crust, we would be actually in pretty good shape. And 1% of the total land area on the earth's crust-- I believe somewhere between 1% and 2% of the United States is covered in asphalt right now for roads. So this could be on houses, on rooftops, on buildings, and so forth. We wouldn't necessarily have to exclusively repave virgin farmland with solar panels.

So going back to quantifying the solar power, we have our sun. We're going to start by quantifying the solar resource by assuming that the sun is a black body. The same way that hot objects emit light-- say, for example, when you turn up your stove and you have a very warm glow coming out of it-- the sun is as well a hot body, a black body, sorry. Very hot as well, somewhere around 6,000 Kelvin. And the total radiated power is given by Stefan Boltzmann's law here in the following way where we have temperature to the fourth and the temperature is somewhere around 6,000 Kelvin.

And so we have this power being radiated out at the surface of the sun. And then, as it travels outward, it becomes, you could say, diluted in effect. Because the total surface area of that sphere is increasing, obviously as r squared. And so by the time that that light reaches the earth, it's only a very small cross section, or very small solid angle to be more precise, of the sun's surface that is radiating directly at the earth right here because this, in the absence of scattering centers in the universe that might reflect or bounce the light back toward the earth.

And you can calculate the total power incident on the earth by that simple formula right there. What is the radius of the earth? Again, one of these simple numbers you should kind of having your head. 6,370 kilometers, somewhere in that order, right? And so you can begin estimating here the total power and the order of magnitude. It's going to be tiny compared to the total power that the sun is radiating thankfully, or else we'd be pretty hot right now.

So the average power coming from the sun on the surface of the outer atmosphere is around 1,366 watts per square meter. Who's heard of 1,366 before?

AUDIENCE: Yeah.

PROFESSOR: Yeah? You've heard about it? All right. You know where the number comes from now. It's pretty wonky. 1366 is a startup company, a spin-off of MIT focused on solar energy.

OK. And so that's at the equinox, which we just learned is occurring somewhere around March 21, September 21-- coming up soon. Celebration. The ratio of the surface areas of the spheres is really something to keep in mind right there. OK.

So we've quantified the available resource relative to human energy needs. Now we have to come up with some language that we use to describe the sunlight moving through the atmosphere of the earth and reaching the surface of the earth, right? So we're going to use what's called the air mass convention or AM convention. AM stands for Air Mass.

Even without knowing much about how the light is absorbed or how to quantify it mathematically, we can assume that our atmosphere contains molecules. It contains particulate matter. And that's going to interact with the light in some ways. Probably either going to absorb or scatter it. And so as the light passes through our atmosphere, there's going to be some absorption.

And the greater the distance, the greater the optical path length through the atmosphere, the more absorption and more scattering there will be. And so we use air mass, or AM convention, to define the path length or the path distance through the atmosphere. AM0 would mean the outer atmosphere. AM1 would be essentially just going straight through, normal incidence so that the direction of the trajectory of the light is parallel to the surface normal of the earth at that location.

And then air mass 1.5 and so forth is as we increase the angle of the entry of light relative to the surface normal. So in other words, as we go further from the equator to northern latitudes that air mass number is going to go up, up, up. OK. We'll explain it with a few graphs and figures and a few slides.

So we have our atmospheric absorption. When we just glance at the earth in these beautiful pictures taken from outer space, we can see very obviously the clouds present. And more importantly, if we were to zoom in on one of these regions right here, we would see this bluish hue coming from our atmosphere, which is scattering preferentially the shorter wavelengths of light. And more importantly, this radius right here is somewhere on the order of 6,370 kilometers. And this thin atmospheric shell in on the order of 30. Right? So that's why you don't really see too much of a ring around the planet from this distance.

So the atmospheric effects, let's try to bend them into discrete buckets. This is a simplification, but it helps us gain a foothold in understanding. And then from there, we can make our understanding a bit more complex.

So we have incoming solar radiation coming from here. We have a number now that's 342 watts per square meter. Why is that number so much lower than the 1,366 that we were just talking about?

AUDIENCE: Particles in the air and pollution in the atmosphere.

PROFESSOR: Yeah. So this is meant to be an average over the entire day at one fixed point along the ground, right? So as we're rotating around, we have at least half of the day normally when we don't have sunlight. And then there's, I would say, the cosine theta angle is not 1 at all times. It's very rarely 1. And so this is a bit of a discounted incoming solar radiation, essentially a time-averaged solar radiation for a given patch of the planet over a typical day.

And so we have a variety of processes here. We have reflection off of clouds. That's pretty clear to see from here. It looks nice and white.

We have some absorbed by the atmosphere, typically in a rotational or vibrational modes of molecules up in the outer atmosphere, sometimes by particulate matter as well. And then we have the amount that's absorbed here by the surface, of course, reflected as well.

And so the amount that's incident on the surface or coming down to us is what we can actually use to make solar energy. And this is an average, right? Because sometimes the cloud cover is a lot greater. And for that particular day, we will have a lot less resource striking the ground at a given time.

This over here, this is all mostly infrared, right? Where this is visible coming in, once the light gets absorbed and then gets re-emitted, it usually gets re-emitted in the longer wavelength light or the infrared light. And this is the stuff that gets blocked by or absorbed by greenhouse gases and then re-emitted equiangularly. And some of it makes its way back to the earth, right? OK.

So air mass, let's define that so that we have a common language that we can use to describe the solar resource from place to place. So again, this is the sun. This is the surface right here. And let's imagine that the angle between the incident sunlight and the surface normal is 0 such that the cosine theta term is 1.

Air mass here at this point, at this point on the surface of the earth, is going to be AM 1. So we call it air mass 1 if the sun is literally directly overhead. What did we learn about the declination angle of the earth? It's about 23 and 1/2 degrees, right?

How far north are we? What is our latitude here in Boston?

AUDIENCE: 41.

PROFESSOR: 41, 42ish, right? So let's for simplicity say that here in Boston, our latitude of Boston Logan Airport is approximately 41 degrees north. And let's say that the declination of our planet is approximately 23 and 1/2 degrees. So what would be the angle of the sun in the sky if you were to lie on your back in the middle of the summer solstice and the middle of the winter solstice and you're lying straight on your back looking up at solar noon, what would the angle of the sun in the sky be relative to the surface normal? How far south would the sun be?

Imagine that this is 0 degrees and that's 90, right? So relative to this angle right here, where would the sun be in the sky? Why don't you turn to your neighbor right now and discuss? On the summer solstice, the winter solstice, come up with some set of angles there.

All right, folks. What do we come up with? This is our little human being, you, in Boston. This is south, and that's north. And we're at the solar noon in the winter solstice in the summer solstice. So here's you. This is directly above.

So I would say if you're lying on your back and looking straight up, that's the surface normal of the earth. In the summer, at solar noon, the sun would be at what angle relative to the surface normal of the earth?

AUDIENCE: 17 and 1/2.

PROFESSOR: 17 and 1/2, somewhere around there. And how did you get that number? Subtract those two, right? So you get 41 minus 23 and 1/2. You're somewhere around 17, 18, somewhere around there. So we'll call it 18 degrees in summer, again, relative to the surface normal.

And in wintertime, what does that work out to be?

AUDIENCE: 64 and 1/2.

PROFESSOR: 64 and 1/2. Similar logic, right? So we'll call it 65 degrees in winter. Good.

So what does that work out to be in terms of air mass for winter and summer? Quick engineering approximation, I'm going to say that, in summer, it's approximate air mass 1, but you can calculate it real quick. Somebody with a calculator want to plug those in?

AUDIENCE: And roughly 2 in winter.

PROFESSOR: And roughly 2 in winter. All right? OK. We're going to get into scattering of light in next lecture actually. And we'll see why that matters in terms of especially of getting sunburned since the shorter wavelengths, the ultraviolet, are more sensitive to the path length. OK. Good. Very good.

So we have pretty much a gut sense now of where the sun is in the sky. And as it moves from summer to winter, from our perspective, it follows a little bit of a, I would say, sinusoidal path, right? It stays in summer for a long period of time up here. And then it moves pretty quickly down here and stays here. So versus time, the angle of the sun in the sky is following a sine curve, or cosine curve if you will. Right?

And so right now, the sun is actually close to the middle. We're in September 13. The solstice is coming up in a week's time. And so the slope of that sine curve is at a maximum right about now. And so that the amount of time that the day will change in length is changing at its greatest point right now in the year. And so you really begin to notice it if you start paying attention or if you go to weather.com and start looking up how long is today's day going to last, when is the sunset tomorrow.

I don't know about you folks, but I like to cycle. And when I'm doing my evening rides, I'm noticing it now that I have to start earlier and earlier if I want to put in, say, 30 or 40 miles. I'm not going to be able to make it home in time. So that's the sun and how it relates to you in your daily lives. We're going to get back to this in a minute, so keep this in mind. Don't let it out of your RAM.

Let's talk about the actual solar spectrum for a minute. This is the sunlight intensity in some very real units. We'll get to that in a minute. But think of this in terms sort of like the total amount of power in a given bandwidth. So the wavelength right here-- or the power density in the bandwidth. The wavelength is the wavelength of light.

Shown for your convenience here is the visible spectrum. That's what our eye-- mostly what our eye-- is able to detect in this wavelength range right here. And the sun is emitting over a much broader range of wavelengths. It's emitting following a black body emission source at 6,000 Kelvin. And that's in this very difficult to see green line right there.

Air mass 0 spectrum looks like this, this red line right here. And again, let me remind you that the air mass 0 is the light that's falling on the outer atmosphere. There is no earth atmospheric absorption yet. Why do we have these little lines here?

Do you see it's not a perfect black body. We have some-- I'll give you a hint-- absorption lines. Where is that light being absorbed? Is it the ether between the earth and the sun? No. There's no ether between the earth and sun. Where is that light being absorbed?

AUDIENCE: Hydrogen ions and stuff?

PROFESSOR: In the sun itself, right? So these are absorption events occurring in the solar atmosphere. And now, if we do air mass 1 or 1.5-- let's push it up a little bit from air mass 0-- this is now passing through an angle of somewhere around 60 degrees. Now what do we have? We have several absorption lines occurring, right?

And these correspond to absorption events where?

AUDIENCE: In the earth's atmosphere.

PROFESSOR: In the earth's atmosphere. Exactly. And so we can attribute each of these little absorption lines here to a particular-- usually it's a molecule in the earth's atmosphere. Note the sensitivity of the human in black right here and how well-matched it is to the air mass 1, air mass 1.5 spectrum. That's pretty cool. That's pretty cool. OK.

So there you have the spectrum. Let's get to these units of power density per bandwidth for a second. The way to think about those units is as follows-- kilowatts per meter squared. OK, I get that. It's the amount of power falling on a unit area.

Per micron, the reason it's normalized per micron is because the wavelength units right here is in microns. And if you take the product of the two, it makes it pretty easy to calculate the total power density, right? So if you want to calculate the power density, the total watts per square meter, falling on the earth, say, between 0.5 and 1 micron, you can calculate the total amount of power by multiplying one versus the other.

So that's why they're in this weird unit right here. It's to help you perform calculations like the ones you'll do in your homework, like the ones you'll do for your class project and so forth. And it strikes a little bit odd the first time you look at it, but it begins making sense. And you're appreciative of it after a while.

There are standard spectra. They're standard reference spectra. Sure, you can go outside and using some form of spectrophotometer. You can measure the incident solar radiation and map out the spectral irradiance as a function of wavelength. In terms of the planning or communicating with other scientists, we typically refer to standards. We use common yardsticks, common metrics. And that facilitates communication, avoids ambiguity, avoids misunderstanding.

And so these standards right here, these ASTMs, refer to the particular standards that are used for those solar spectra. And in your supporting online material, at the very end of the lecture slides online, we go into some more detail regarding that for those who are interested.

So again, these little absorption lines here correspond to specific atmospheric events, interactions of that particular wavelength of light with some molecule usually in the atmosphere. We can, as well, have generalized attenuation due to other scattering mechanisms. Notice right here in the short wavelengths what's happening.

From the red to the blue, this light is particularly effective. We have a sharp drop in the shorter wavelengths. And it grows sharper the shorter in wavelength you go. So the attenuation due to passing through the atmosphere grows or increases the shorter in wavelength you go.

And this is a process generally called Rayleigh scattering. And there's a wavelength to the fourth dependence. So as you go shorter and shorter in wavelength, the likelihood or probability of scattering will increase.

Why is that pertinent to us? Well, now you can answer that little child who walks up to you in the shopping mall and says, why is the sky blue? You say, well, there is this elastic scattering mechanism of electromagnetic radiation whereby in a broad spectral event, such as the sun, black body emission, we have the shorter wavelengths that are scattered more. And that's why when we look away from the sun, in the other direction, we see those shorter wavelengths that are scattered back to us.

That is pertinent for two reasons. A, it makes the sky look blue. Secondly, it's not only the short wavelengths in blue light that we're worried about, but also the ultraviolet radiation. Right? So even on a cloudy day, if there are a few open patches and you can get scattered light coming in, you can still get sunburned.

And secondly, there is a very strong dependence on the path length, the optical path length, the air mass, right? So if you go further north in latitudes, where your air mass increases, right-- because now, if you think about the atmosphere as being kind of a flat. Just giving you an approximation for minute. If you think of the earth being flat and the atmosphere of being flat, now the path length in winter is much, much greater than the path length in summer. Same sun, just different path length. You're much more likely to get sunburned in the summer than you are in winter because the path length is a lot shorter and the amount of short wavelength ultraviolet radiation that will be scattered away is going to be less in the summer than in winter.

That's also why if you go south latitude, for example, from here to, say, Miami, your incidence of getting sunburned is a lot greater, a lot more than the total increase of the visible portion of the spectrum. So the sun might not look that different to you, but your incidence of sunburn events goes up quite a bit. And that is due to Rayleigh scattering.

And now, by this point, the little child has already run crying back to the parent. But you have a full satisfaction of knowing how the universe around you is put together. And that actually was a pretty deep problem. It took a long time for at least European scientists to crack that nut and figure out what was going on.

Describe how solar insulation maps are made and use them to estimate the local solar resource. So we have metrology. We have techniques that we can use to measure the amount of sunlight that is out there. And now we want to apply those in some systematic fashion to measure the average solar resource around the planet, including the oceans, and then use that information to estimate later on the land area needed, or the size of the array, or how many cells we're going to have to string together based on the solar resource locally.

So how are these insulation maps made, these maps that we'll use as engineers to size our systems? First off, let me define insolation. This is not insulation, as in stuff you put around the house to keep the heat from going out. This is insolation with an "o," a shorthand for incoming solar radiation. Insolation at the top there.

It's typically given in units of energy per unit area per unit time, so kilowatt hours-- that's energy-- per meter squared per day. And it's helpful when designing or projecting these PV systems. And it's affected by a bunch of stuff, which we'll get to over the next few slides.

So we can measure insolation from the ground. That's a surefire way to do it. This right here is a pyranometer. Pyro, fire, sun. Ano, on top of. So anode/cathode. Cata, under. Ano, above. Catatonic, under. Right? OK.

So pyranometer. So it's basically measuring the sun above, right? Measuring the sunlight above. This is a full hemisphere measuring the sunlight coming in from all angles. There's a small little sensor right here. It's lying flat. And that glass is essentially allowing the light from different angles to get into the sensor.

And this is a very narrow, solid angle of the sky. It's probably just looking at the sun, or in a particular direction rather, plus or minus 2 and 1/2 degrees in either direction. So it's a very limited solid angle of the sky.

This one over here would be more appropriate, say, for a flat panel that's receiving scattered light coming in at all angles. This one over here would be more appropriate for a tracking system, especially a concentrator system that has optics that only accept light in from a very limited solid angle. So imagine you have a lens that has to have like incident to it to focus it on the right spot.

And if the sun moves in the wrong spot or the-- put it another way-- if the lens is in the wrong position relative to the incident solar radiation, the light is being focused off of the solar cell. And it doesn't produce any power. So this is a system that's used for measuring the direct solar spectrum, which will be useful for calculating the total output from concentrator systems. And this pyranometer over here is useful for flat panel systems.

And we can also measure the total amount of incident solar radiation, total amount of insolation, from the sky using satellite imagery. This is an example of a measurement. And this right here is insolation, average insolation, from 0 to 550 watts per square meter taken from a NASA satellite with the NASA Earth Observatory. Very cool website, great place to spend a Friday night if you don't have plans. Just log on here, and bunches of maps from snow cover, to population density, to CO2 being emitted, to wildfires around the planet-- anything that a satellite can measure, they're measuring. And the insolation value is one of them.

And so we have data from various points. This is the insolation in January. So in January, it's the Southern Hemisphere's summer, the Northern Hemisphere's winter. And as a result, we have less insolation up north. We're in the blues. And the Southern Hemisphere is more in the reds.

And of course, the tide turns in July. We have our summer and the Southern Hemisphere has their winter. And the poor folks here in Antarctica have nothing.

So a couple of things to note just already straight off the bat, we're noticing that there's, in general, higher insolation near the equator, the equator passing right through here approximately. Fun fact-- small city up there in the north of Brazil, there's a soccer field that is half in the north and half in the south. That's neither here nor there.

We have rainforests up here in the north of Brazil, Central Africa, and here in Southeast Asia. And even when the sun is directly overhead, those clouds are preventing some of the sunlight from getting in. And that's why right at the equator itself, we typically have less insolation than we do in the tropics, say, Tropic of Capricorn, Tropic of Cancer. Tropic of Capricorn running straight through Sao Paulo, Brazil, Tropic of Cancer running through Key West. Just to situate yourselves.

And the Tropics are how far away from the equator? Right. OK. 23 and 1/2. Good guess. Good.

So what we're going to do is now launch into our next learning objective, which is to list the causes of variation and intermittency of the solar resource and quantify the time constants in magnitudes. This is really, really, really, really important. The other stuff is very useful from an engineering point of view from answering certain questions in your homework. This right here is the singular reason-- one of the singular reasons-- why solar doesn't behave like a regular fossil fuel source, why solar does not produce power all the time.

It is variable in terms of its power output. Variability generally refers to the fact that we can predict it's coming. It's going to vary, but at least we can predict it's coming.

Intermittency, while not a strict definition, the understanding when somebody says "intermittency" or "intermittent power source," the impression that it gives is that it's unpredictable in terms of its variability and its variation. So we've talked a little bit about the variation so far and about the predictable nature of the sun. We've talked about how the sunlight, the solar resource, varies from summer to winter. We've talked about how the solar resource varies as a function of latitude, right?

But now, we're going to talk not only in a little bit more depth about that and have a few fun in-class exercises to get us really grasping that concept in its entirety, but also talk about some sources of intermittency, which if you have a large amount of solar contributing to the grid and it is intermittent, and you have no way of dealing with that, you're going to have fluctuations of energy level on the grid or power levels here as a function of time. And that's not going to be good.

So in terms of the seasonal variations, in terms of predicting the amount coming from the sun at a given point-- I told you it looks a little bit like a sine, a cosine wave. And indeed, it does. You can calculate those values based on this website right here. Just to show you how nifty and cool it is, our friends at Arizona State University, Stuart Bowden and Christiana Honsberg, really put in a lot of time to make this. You can vary the time or the day of year right here for instance. Right?

And you can see how the solar resource-- this is the direct radiation, kilowatts per meter squared. And this is the time. So if you take the integral of the curve right here, you're going to get what? Units of--

AUDIENCE: Power.

PROFESSOR: Power. Power times time is?

AUDIENCE: Energy.

PROFESSOR: Energy. Energy per unit area, right? So you're going to be able to calculate the total amount of energy falling on a given area per day, let's say, right?

So if we look at the size of this little curve in winter, the total area under this is going to be very small. And that's because the solar resource is very small. And the sun rises late and sets early in winter.

And as we move towards summer, obviously, the total amount of the solar resource increases. Not only it increases because of this that we have at solar noon. We have less of a path through the atmosphere. We have more sunlight reaching the earth. We have a total increase of the amount reaching the earth.

We also have that cosine theta term here dictating the cross-section incident to that sunlight coming in increasing. And so that's driving this going up. And we also have a second fact that the time of the day, the total duration of the day, increases, at least in northern latitudes here at around 40, let's say, 41 degrees north, here in Boston.

And we have because these two effects a much larger area underneath that curve. And so as we go through summer and now finally to September 13 and back to winter, our solar resource goes back down again. So you can calculate it. You can visualize it. That's cool.

And we can plot the total amount of energy per unit area per day, essentially the integral under that curve, as a function of location around the US, around the world per month let's say, right? So this is January. This is kilowatt hours per meter squared per day. So it's just taking the integral of the curves measured. So it's accounting for cloudy days, which kind of has a depressive effect.

This is an envelope function, if you will, the maximum you could get. And then, of course, local weather patterns will suppress that, drive it down. So this is the real map of the United States.

And you can see in sunnier areas that are less cloudy, over here, for example, in Arizona and New Mexico, there's a large solar resource even in January. Atlanta, which has half of the number of sunny days per year as Phoenix does, even as it's at the same latitude, is getting about half the solar resource. They got a short end of the stick.

Again, this curve right here is the envelope function, right? And off of that, you can only go down. You can only decrease the amount of solar resource actually arriving at our feet here.

And so this is in January. And this is all in the same color scale here as we move through the months. So we'll move from January, to February, to March, April, May, June, July, August, September, October, November, December. So you can see across the United States how the resource is distributed geographically. The general trend that as you go from south to north you have a decreasing solar resource holds. You can also see the influence of local weather patterns as well for the same latitude. So that's pretty nifty.

And another nifty fact, if you look at the year average value, annual-- this is the annual average value-- here in Boston, we're averaging around 4.5 kilowatt hours per meter squared per day. Phoenix, Arizona can be upwards of 6 somewhere in the outskirts. It's not that bad. It's only a few tenths of percent. It's not that bad, I tell myself. I don't believe it myself either, but I try to convince myself of that during winter.

All right. Let me show you the seasonal and diurnal variations. We're increasing the level of sophistication as we go along, right? We've assumed you've done your readings. We've started with some simple examples, and now we're really taking it one step further, which is to introduce the full 3D model.

And I'm going to do that by use of this really cool app that's available here. Right here. This is you standing on the earth. And you can drag and pull this around. You can see there's north, south, east, and west. So I'm going to pull it up a little bit just to give us a little bit of perspective.

Still, south is facing toward us. North is away. The sun will rise in the east and set in the west. Now, let's say I pull the date back to September. So this little tool is so cool because it recognizes your IP address and situates you at the proper latitude, so we don't have to touch that at all. It's approximately right. We're at 40, yeah, about 41 degrees.

We're right here in September. And in terms of time of day, we can pretty much just cycle through the time of day if we like. We could, for example, start animation. Let's see, this is going very fast right now. I'm going to slow it down so you can see the time of day moving right over here. And you can see that relative to our vantage point on the surface of the earth, this little yellow dot here and this yellow line is tracing through the path of the sun in the sky from our perspective.

And so as we go through the seasons, I'm going to speed it up just a little bit so that we pay more attention to the position of this yellow line and less attention to the diurnal variations. We're paying more attention to the seasonal variations. I'm going to vary the seasons by force here. I'm going to go back to July or June if I may. Here we go.

AUDIENCE: What's the blue line? So you can see it?

PROFESSOR: Yeah. So there's a number of other lines right here, and they're all explained very carefully. There is the hour of ascension, which would be prime hour circle. Yes. I'd have to go back and double-check all of this, but I believe they relate to would be the sunrise and sunset of that given day. Let's see if our hypothesis is correct. No, it is not.

That would have to be, since it is varying in a systematic way from January through the summer and then back to the winter, I'm imagining this has something to do with the direction of the sun relative to the earth, right, as it traces that ellipse through the sky. So let's pay attention to that yellow line for a minute. That's the one I want to attract everybody's attention to.

Now we're in June, so in the height of summer. And relative to this observer right here, the sun is further up in the sky just like we traced out right there. And now, as we go to winter, that line drops close to the horizon.

So a couple of things happen. If we look like this for instance, now we're looking straight down on the observer. In wintertime, the sun will rise in the southeast, and it will trace this arc through the sky and set in the southwest over here. In the summertime, the sun will rise almost in the northeast, slightly north of east, just slightly north of east.

And that's why if you have a north-facing window and you put your little plant on the window sill, it'll get a little bit of direct sunlight early in the morning and late at night. Because when the sun is tracing this part or that part through, it's tracing the sky. So it's worth sitting down with one of these plots, toying around with it, getting accustomed to it, and understanding really how the sun traces its arc throughout the sky relative to our position right here on the earth.

If we shift this further up north, really interesting things begin to happen. So for example, my wife is in Sweden. If we go to her hometown right here in the middle summertime at the solstice, you can see the sun traces this awesome route from north to north barely leaving the horizon. If we look at, again, from the perspective of the little creature here, that yellow arc is really close to the horizon. Maybe it goes up about that high, but it continues going all the way to the north.

And if you keep going north, it will never set during the middle of summer. It'll just be light all the time. And you can see here it just traces that orbit right around there.

It's all trig, folks. We can do it. We can sit down, and we can work through the equations by hand. I did that once. It took me a long time. I didn't learn that much.

I would instead advise you to go to one of these simulations right here, but to understand all the inputs into it, all the different components, the fact that the earth is moving around the sun as a declination angle, seasonal variations, and so forth. Very useful tool. You have the website link right here. And yeah.

So from this tool-- actually, one last tiny, tiny thing. From this tool right here, we can understand why-- OK, this is a real stretch. And forgive me, social scientists in the room, for doing this, but I have to project a little bit of science onto human behavior. How far west is Madrid from GMT? Madrid, Spain? It's 3 degrees west of the Great

Meridian.

So the line that divides the East and the West Hemispheres is 3 degrees west. But it is one time zone earlier than London, so it's in the same time zone as Germany and all the other cities that are east of London. And this is just for convenience factor.

If you're traveling from one continental European country to the other, it just makes sense to have everything be on the same time zone. You get to work at the same time sort of. Pick up the phone, call somebody, you're doing business.

Now relative to everybody else in Europe, though, is the sun setting later or earlier if you're that far west in your time zone?

AUDIENCE: Later.

PROFESSOR: Later, right? So the sun is setting later if you're there. So if you're eating according to the sun, not according to what your watch is saying, but if you're choosing to eat dinner when the sun is setting, when will your watch say, oh my goodness, it's really late when you're in Berlin or when you're in Madrid?

AUDIENCE: Madrid.

PROFESSOR: When you're in Madrid, right? So again, I'm not saying that this is the sole reason for social behavior being a little different on the Iberian Peninsula, since Portugal also eats very late and they're in the same time zone as London, but it could be a contributing factor. The sun is still up in the sky when it's 5:00 PM in winter, let's say, where in Germany, it's set a long time ago.

So these are just little things to keep in mind. An easy way to calculate, when is the solar noon, you look at the earth more or less like we're looking at this right now. We have 360 degrees. We divide that into 24 time zones. And then we say, OK, about 15 degrees each. And then we can begin counting from there.

If in Boston, were 41 degrees north, but we're 71 degrees west, we can say, OK we should be for GMT minus 5. We should be at around 75 degrees. And so we're a little earlier, so we do things a little earlier around here than what the solar noon should be telling us to do things-- wake up a little earlier, go to bed a little earlier. And that's why students are like, dang, there's no night life around here. I'm not saying that's the only reason, but it could be a contributing factor. Whereas the opposite happens when you're far west in your time zone.

OK. So again, just trying to wrap our heads around the solar resource and around the world around us so that we can answer that little child in the shopping mall when they come with questions. What are these?

AUDIENCE: [INAUDIBLE]

PROFESSOR: Solar trash compactors, right?

AUDIENCE: At the Student Center.

PROFESSOR: At the Student Center. Anna's Taqueria is right over there. Dunkin' Donuts is there, right? So these are solar panels mounted on the tops of those. And what the solar is doing is charging a battery inside. Once the trash reaches a critical lever, a sensor is triggered. It stops you from opening this bin, and it compacts the trash and then releases and allows you to open and put more stuff in.

And what it does is it minimizes the number of times between trash pickups. If labor is a large portion of the cost of trash management, of refuse management, then it eliminates some of the labor, transferring it instead to the technology. And so installing these at the Student Center, I had a little bit of a pet peeve.

[LAUGHTER]

So you have angle of the sun right here, which we just walked through, 18 degrees in summer. And it just so happened to work out that-- and these numbers were approximate. This was me going with my kind of engineering sense. That's about 45 degrees. Count the number of paces. Equilateral triangle. Estimate the height of there.

But in the middle of summertime, when you are at the solstice, there is no so direct sunlight hitting this trash can because of that overhang way up there. And it's not a problem for this particular trash collector, since those panels are way oversized for the amount of energy that the trash collector actually needs. And there is a fair amount of what we call diffuse sunlight, meaning sunlight being scattered off of other things. That's why this portion of the image looks white. It wouldn't look white if there was no diffuse scatter. It'd look black, pitch black, if there was nothing to scatter the light off. Like an outer space, there's nothing to scatter this way. It looks like a black night.

But instead, there's a large amount of diffused light. There is some sunlight reaching it. And since the panels are way oversized and the system is over-engineered, it still manages to acquire enough energy to compact the trash. And it doesn't have a catastrophic stop. But it was an example of somebody not really thinking much about the direction or the angle of the sun in the sky. They probably installed it sometime around March when the snow started to melt and the sun was right around here. And the angle was around there, and it made it into the trash collectors.

But as the summer came along, it got shaded. So it's something to keep in mind when doing a solar installation. It is important to calculate these things. And I just pick out once more example. I'd encourage you to walk through. I was going to have that be a small little in-class example, but since we're running short on time, I'll just give it to you like that.

OK. Fixed versus tracking systems. So if the sun is moving as a function of season and as a function of time of day throughout the sky-- and we can see that very nicely, again, through our demo right here-- so if the sun is actually moving, one embodiment would say, OK, I know more or less what the sun is going to do as a function of season. Forget the diurnal variations, but just the seasonal variations.

I know that the sun is going to be on average somewhere around here, somewhere around my latitude. So if I point my panel at latitude tilt, since this angle was-- what was it-- 41 plus 23. This angle was 41 minus 23, so this would be right around 41 latitude. So if I aim my solar panels at latitude tilt, then I'm going to get, on average, some pretty decent power throughout the year.

I'll have a little lesson in winter, a little more in summer because, well, just because of the amount of solar resources available. But all in all, I'll be all right. At most, I'll be off by 23 and 1/2 degrees.

You can do that. And that's called fixed latitude tilt. And typically, you'll face the panels south approximately. We'll get to that in a minute. It depends on local weather patterns. If you have fog in the morning, for instance, you want to face them a little to the west. But we'll face them south and at latitude tilt.

Or we can decide, no, let's actually track the sun throughout the sky throughout the day. And so we'll start in the east in the morning and have it rotating through on one-axis tracker throughout the day. Or we can have a two-axis tracker where it rotates to follow the sun throughout the seasons as well, a kind of a north/south tilt.

And that's what's plotted right here. This is a quick approximation of the fixed one-axis and two-axis trackers for a given system in Boston using a simulation tool called PVWatts. There's a link to that. It's based on the National Renewable Energy Laboratory website. There's a link to that at the end of the slides.

But this shows you the total system output in terms of kilowatt hours in terms of hours per day. I think, yeah, it's a little bit of an odd units there on the one-axis. But it shows you the relative gain that you would get by going to a one-axis and then, finally, a two-axis tracker.

So in many places, it makes sense to go to one-axis tracker, since especially you broaden out the peak near the peak hours of the day. And that's really good. But not always does it make sense financially to go to a two-axis tracker. You're adding another motor onto that thing. It's really not gaining you that much. Obviously, you have to calculate it out yourself for that specific location. But by and large, a generality, one-axis tracker makes sense for a flat panel.

Now if you have a concentrator lens in the front and it has to be looking directly at the sun, then you're kind of forced to go to two-axis tracker. OK. And there you have your total system output, which is just the integral under the curve over the entire year.

So definitions-- I should have done this before. But direct sunlight, looking directly at the sun, and then diffuse sunlight or scattered light coming off of other things. So diffuse sunlight would be coming from the other angles in other directions in the sky. The direct sunlight would pretty much be at the sun plus or minus a few degrees.

And we have different ways of measuring the-- this would be flat plate. Up there on the upper left it says, flat plate facing south latitude tilt. Just like we said, it's facing south. In the United States, that's good.

Latitude tilt, meaning it's tilted at our latitude. So if we go from the southern tip of Florida and Texas up to the northern tip of Minnesota, we'll be tilting it more and more toward the south like this, going from Texas to Minnesota. From Texas to Minnesota. And so latitude tilt facing south flat plate. This is essentially accumulating all of the sunlight, the direct and the scattered light, because it's all being collected by the flat plate there.

This map, on the other hand, is for a two-axis tracker. And it's looking at the sun plus or minus 2 and 1/2 degrees. And so it's really only picking up this right here out of the sky. And when it's sunny all the time, you're golden. You're tracking the sun. You're actually getting more energy than you would if you just at a flat plate because the cosine theta angle is changing throughout the day if you have a flat plate.

When the sun is in the morning time, you have a flat plate like this. So if my sunlight is coming in like this and I do cosine theta of the angle, I'm only getting a very small amount of the incident sunlight projected onto this plate right here. If I was in the middle of the day, now cosine theta is 1, I get the full sunlight.

But if I have, for instance, a tracker, I would be able to face this panel due east and then track it throughout the day. And that's where I'd get this additional energy boost here in the mornings right there from the tracking system. So if I have a tracker, I get a big gain in the places that have a lot of direct sun. And if I'm only looking at a very small solid angle of the sky, if I'm only looking at, say, this little portion the sun, on cloudy days, most of the sunlight is coming off of the diffused light, not from the sun.

If I have a flat plate, I win. If I have a concentrator, I lose on a cloudy day. And so that's why, in some of the regions of the United States that are notoriously cloudy-- I won't point to any one in particular-- it's actually better for non-concentrating solar in terms of total energy output. And in other regions of the United States where we have a lot of sunny days, you start having two-axis trackers making sense. And it's just really the ratio of these two maps-- whoopsie-- this one, which is flat plate, and that one, which is concentrator.

You see over here, we win if we go for the concentrator. And over here, we get more energy out-- oopsie-- more energy out if we use the flat plate. Now that's just energy. Obviously, cost and economics factors what it takes to install it. OK.

And weather patterns, I promised I'd get back to this. Interesting to note that for right near the equator, we have this drop of the insolation. And there are these beautiful maps put out by, again, NASA Earth Observatory that show you the cloud fraction coverage of particular spots around the planet.

And you can see that right near the equators, typically we have these beautiful tropical forests. The high cloud cover in those regions is blocking out some of the sun. And likewise, you can see the dichotomy between Phoenix and Atlanta. Same latitude again, but Atlanta having a higher cloud coverage than Phoenix and, hence, a lower solar resource, a lower insolation.

So you how all this kind of ties together. That's all predictable in a sense. This is unpredictable at a local level for one system.

If the sun is tracing its route through the sky, and you have that envelope function that you've just spent so much effort calculating out with all your trig functions in the computer simulation, the code that you've just been given here. And now, a cloud comes over, some random cloud that was very hard to predict. And you just have one panel, one tiny little thing like this. And the cloud goes over it. Boom, all of a sudden, you get a drop in your instantaneous power output. Boom, drops again. Another cloud, drops again. And then a thunderstorm in the afternoon.

So a meteorologist could have told you that this thunderstorm was coming, but a meteorologist would be hard pressed to be able to predict the evolution of a tiny little cloud over your system. And so the question is, to what degree are these local weather patterns predictable and unpredictable? And hopefully, some of you, over this class, will be able to help answer that question by analyzing data from tens of thousands of systems that have been installed throughout California in local geographical systems, for example, in the Los Angeles region, San Francisco region, and so forth.

If you start averaging the curves, the energy outputs as a function of time, from a variety of systems throughout a neighborhood, you can probably average out the small tiny clouds. You probably can't average out the thunderstorm. But you probably could have predicted that the thunderstorm would've come along. And so this is a hot area of solar research at the systems level. It's trying to understand, to what degree are PV systems predictable? To what degree can the power output of a PV system or an ensemble of PV systems be predicted in advance so we don't wind up in a situation where all of a sudden we have this catastrophic drop of a cumulative PV system output of, say, 30% and meanwhile, it's a hot summer day, everybody's air conditions are going, and we cause failure of the power grid? Kind of worst case scenario.

So this boils down to intermittency with a short time constants tend to be less predictable. Cloud cover. And it's relevant for predicting power supply reliability. And the longer time constants tend to be more predictable. The diurnal or seasonal variations-- and these are relevant to calculating total energy output annually. And oftentimes, when we just work off of these long time constant variability issues, we're assuming we have access to easy storage.

Right now, the solar panels on top of my roof, they're producing in excess of what we're consuming right now because neither my wife or I are at home. And they're injecting that power into the grid, and the grid is serving as our big battery, as our storage unit. And I'm riding free. I'm a free rider right now. I don't pay for that service necessarily. I do to NSTAR. But they're not charging extra for the service of using the grid as my big battery.

Another thing to keep in mind is that we're calculating all this on the basis of engineering and scientific principles. We're calculating the solar resource, which is a good, important first step. Now if we look at the actual solar installations by year and by country-- this is a big table, but follow me on the two underlined red lines here, DEU, that stands for Deutschland, Germany, and USA. We'll see that Germany has about seven times more solar installed cumulatively than the United States does.

And yet, if we look at the solar resource in Germany relative to the US-- this is average annual, same scale, going from 900 to 1,200 kilowatt hours per kilowatt per year-- we can see that there's a lot more sun in the United States than there is in Germany. So there's something else going on than just the solar resource. And that's economics. That's why we talk about the policy and economics later on in class. That's why we dedicate a sizable portion later on talking about that.

Lastly, our final learning objectives before we halt for questions and for comments, we need to estimate the land area needed to provide sufficient solar resource for a project. And this is really where your homework picks up, and we'll spend some time in recitation walking through this. But it's important to get your units right.

And so I want to do a quick quiz right now. Think in your minds which of these properties corresponds to which units or are described by which units over here on the right. So do a kind of a linkage in your mind one to one, connect, connect, connect, connect, without looking at your slides. And then we'll do it in three, two, one.

Those are your answers. So the ones that usually get confused are power and energy, kilowatts and kilowatt hours. I'm not saying it's easy, but the way to remember it, the easiest way to remember it, would be to remember that the power time product is equal to energy. So if you have power instantaneous energy burn rate versus time, some plot that looks like this as you take the integral of that curve, that's your total energy.

So in terms of units, current voltage power and energy, a hair dryer versus a fridge, which is more likely to blow a fuse and which is more likely to blow your budget?

AUDIENCE: A hair dryer is more likely to blow a fuse.

PROFESSOR: A hair dryer is more likely to blow a fuse. Why is that?

AUDIENCE: High voltage.

PROFESSOR: Yeah, high voltage. Well, high current, really. Because everything's running 120. It's a higher current. It's pushing the wattage up to around 1.5, 1.7, 1,500, 1,700 watts. And so it's running close to the 15 amp limit.

And the fridge, on the other hand, is probably an order of magnitude lower. But the fridge is running all the time, and your hair dryer is only running a few minutes a day. So in terms of blowing a fuse, it uses a large amount of power for a very short amount of time. Whereas, the fridge uses a small amount of power for a long amount of time. And the integral under that curve winds up being more, typically, then your hair dryer.

That's the total amount of energy. And you pay by the energy. You pay by the kilowatt hour to your utility company, and that's why it would blow your budget. Yeah. Oopsie.

So the numbers work out to somewhere around 1 kilowatt hour per day for the fridge and about 1/2 a kilowatt hour for the hair dryer. A kilowatt hour is how much in here? $0.18? Most people pay about $0.18 per kilowatt hour. And so you can calculate how much it costs to keep things running in your house. Most of us don't usually think about that.

And last, last, last, last point, in your homework assignments, you're going to be asked to size out systems, PV systems, photovoltaic systems, in different parts of the world. And the easiest way to do that is if we take a panel and we say that this panel right here is rated at a certain amount of power, so under peak illumination conditions. When the panel is seated at incident sunlight, so the cosine theta term is 1, and the incident solar resource is 1,000 watts per square meter, so around AM 1.5 conditions, this panel right here would be producing-- this one is tiny. It would be producing 6 watts peak. But most of these panels over here are producing somewhere around a few hundred watts peak.

And so the panels are rated in terms of watt peak because the panel manufacture doesn't know where you're going to install them. You could decide that you're going to install it in Alaska, in which case, it's going to produce about half the energy than if you installed it down south in the continental US in, say, Arizona. Maybe a third of the energy.

And so it doesn't want to rate the panel in terms of the energy output. It's not going to guarantee that you're going to get a certain energy output off of the panel. But it will guarantee that the panel was rated at maximum power of such and such under standard testing conditions.

Now that's good because you can generalize it, which you'll do for your homework. But it also has a downside because standard testing conditions aren't real world conditions. The panel isn't always operating at 25 degrees Celsius. The panel isn't operating always at incident sunlight normal, right? And so the gap between actually knowing how much the panel is going to output in terms of its energy for a specific location and what our calculations, the back of the envelope calculations, will give us, that gap is, from an economics point of view, there's a lot of money to be made there.

If you understand really well how much of a given panel will output, you can then predict to a much finer degree what you should be charging your customer for installing panels in a particular location. So there's a lot of work being done right now, more on the business side of pulling the systems engineers along and trying to increase the accuracy of predictions. And so with that, I will leave off on this slide. We can get to it during recitation tomorrow at 4:00. I welcome your questions here at the front if you have any. Otherwise, I'll see you tomorrow.