PROFESSOR: Ladies and gentlemen, thanks for coming today. I'd like to formally start the course, The Fundamentals of Photovoltaics. That's 2.626/2.627. Why don't we dive quickly into the syllabus, and then, a few slides of motivation, why we're here, why we're studying photovoltaics. Hopefully, get you excited for the course.

The syllabus that you have before you should outline the course objectives and the course learning objectives. At the end, during the background assessment survey, we'll take the last 10 minutes of class for you to provide your feedback to us, the teaching staff, to make sure that we're addressing your needs and your interests. So take a quick moment to read over that while I describe the overall flow of the course.

The course roadmap, this little diagram right here, is essentially a three step component. We first instill the fundamentals of how light is absorbed into a material, how charge is excited, how then charge is separated and a voltage created, and finally, how a charge is collected. And that is the essence of a photovoltaic device. In 30 years time, photovoltaic devices probably will still be using that combination of physical processes. So understanding these fundamentals will arm you-- will give you the information needed to be able to assess any photovoltaic technology that might be presented to you.

Then, in the second component of the course, we'll discuss the technologies, the specific technologies that are out there in the market today, and those that are up and coming that have the potential to replace them. And as a third part of the course, we'll be discussing cross cutting themes. These include the policy, economics, and social aspects of photovoltaics that, of course, are of general interest and are particularly interesting for scientists and engineers, who spend most of their time thinking about the fundamentals, to take a step back and look at the broader picture.

A note on the fundamentals. I recognize that many of you come from diverse backgrounds, some from nontechnical backgrounds, many from mechanical engineering who never really have looked into semiconductors or semiconductor devices. Not to worry, as you'll see on page number-- page number 2, meeting times, class recitation, and office hours. We provide a number of opportunities for you to get more closely engaged with us, the teaching staff, and to work through some of the fundamentals as you might experience difficulties in the learning process.

Let's take a quick look at the course schedule just to situate ourselves. So the course schedule follows that three step process very closely. The first component of the course, the first third, roughly, is focused on the fundamentals. So we'll learn about light absorption, charge excitation, charge separation, and charge collection. And the recitation times will be used to discuss those fundamentals because, for many of you, this is the first time you're working with this material.

The second third of the course, on PV technologies-- when we discuss the industry that's out there today, how it's evolving, how the different technologies are evolving, this is when we get to experience some of the industry pain upfront, up close and personal. We'll be making solar cells. And as part of your take home quiz number two-- as you'll notice, take home quiz number two is distributed right in the beginning of October-- middle of October. And then it's due in the middle of November. So it's almost a month. And the reason it's a month long take home quiz is because, during the recitation times, we will be making solar cells with you.

And it will be a little bit of a challenge. It's not only to make the most efficient solar cell, but the most cost effective solar cell. And so we'll be making technology choices as we go along, processing our solar cells, deciding whether we do process A or process B. We'll be doing the calculations that we learned how to do during the fundamentals section to predict what the efficiency gains should be. And it will have costs associated with each of the different process steps as well. So it will be a little bit of a game, a little competition within the group, as well, to see who can make the most cost effective solar cell in terms of dollars per unit power output.

And finally, in the last third of the course, this is really when the projects kick off in earnest. We have several really interesting projects lined up as well as we're open to hearing your own project ideas. This is when you form teams of three, four, perhaps five, but hopefully three or four. And you will be addressing some of the most important questions of the day, obviously, in a very bound, well-defined way.

And some of the projects that we have lined up include looking at actual photovoltaic installer data coming from houses with temporal resolution on the order of five minutes. So you can obtain a huge database of maybe 10,000, 15,000 homes distributed geographically, and determine to what degree is the ensemble of photovoltaic systems predictable. Obviously, if a cloud goes over one home, power output drops pretty dramatically. But if you begin averaging over several homes, how predictable is the solar power output of that ensemble?

And that's going to be very important as photovoltaics scales up and assumes a greater percentage of the total grid. Another interesting project we have lined up is with the World Bank. This is with folks in Washington DC who are looking into a project called Lighting Africa. And they're installing PV on small little lights and distributing those to folks in sub-Saharan Africa.

And their big question to the MIT audience is, with some of the newer up and coming technologies out there, how will this impact their technology? How will this impact their lighting? And so the deliverable at the end will be a technology perspectus-- one page. A lot of thought has to go into it. That will be delivered to companies that will be selling their products in Africa to guide them and to inform them about some of the up and coming technologies and how their markets will be impacted.

Like those two projects, we have several others. And we're open to your ideas as well. So if you're really jazzed about one particular topic, there will be opportunities to let us know, specifically on homework number 2, when there will be a specific question there, are you interested in a particular topic of your own. We'll assemble-- begin creating teams early on so that there's some bonding going on, especially during the cell fabrication part during the second third of the course when we make the actual solar cells. But then, the third part of the course will be really focusing on the class projects themselves.

So that's the lay of the land. And I want to give you some motivation as to why we're here and why this is really a special time in the field of photovoltaics. This is not your parents' solar energy anymore. Things have changed quite a bit. And hopefully, over the course of these slides, I'll be able to convey that message loud and clear.

We'll go ahead and get started. So first question is why photovoltaics, or why solar. Photovoltaics is one particular embodiment of solar energy where we convert sunlight into electricity. And in most photovoltaic panels-- I'll definitely let you guys come up and have a look at it afterwards. In most photovoltaic panels, you have two leads coming out, basically, the equivalent of a positive and a negative. And you have a bunch of cells here that are converting the sunlight into electricity.

It's different than, let's say, solar thermal, which is converting sunlight into heat, or solar to fuels, which is converting sunlight into chemical energy. And the reason we're studying photovoltaics as a starting point is because PV, photovoltaics-- PV for short-- is the most widespread technology, widespread solar conversion technology out there today.

So the big question is why solar in general. Why are we at all interested in this? Can anybody tell me what this is a picture of? It's obviously not from the United States. Does anybody recognize the language here written on the side of the boat? It's very small.

[SPEAKING PORTUGUESE]

AUDIENCE: Portuguese.

PROFESSOR: It's Portuguese. It's from Brazil. It's form the northeast of Brazil. It's a small island called Morro de Sao Paulo. It's located about an hour south of Salvador in Bahia. These are folks arriving at the island with gas cylinders. There is no underwater cable linking the island with the mainland. So they're arriving by boat with gas cylinders. They're tossing them into the salt water. They're pushing them onto the beach, rolling them on the beach, until they get to the little sandy roads-- of course, getting grains of sand embedded inside of the nozzle and so forth.

This illustrates to me the great risks that we go through to supply ourselves with energy. It's just one, what might be considered by our safety standards here, extreme example of associated risk with supplying of energy and effort, of course. But if you look at our energy supply to the United States, it's no less heroic. It just has different dimensions.

And so the energy that we use today is often produced in some faraway land, not always, but often, transported, sometimes over thousands of miles, and brought home at significant risk and peril. And the question is, why do we go to such extremes. And second question is, is there a better way.

So to answer the first question, here, why we go to such extremes, if you look at the world at night, and then look at our human development map, which I use Facebook-- what better indicator of human development is there than Facebook? This map right here shows you the number of linkages between people on Facebook. And of course, the density of the bright lights there is representing the number of users. And you can see that the two maps, the electricity consumption and the technology adoption map very closely, one on to another.

And it's almost down to the specific region once in a specific country. This is especially noticeable in some of the developing world where you see these pockets of high concentration of people, essentially capital cities. You have Lagos, Nairobi, and so forth-- Jakarta.

And you have this huge concentration of people that, of course, are using electricity. And more and more people flock to those cities, especially in developing countries, because the standard of living tends to be higher. There is a certain indicator, called

Human Development Index, that was put together by the World Bank, which pulls together a number of factors, including expectation of life, infant mortality, and so forth-- education levels.

So in some hand wavy way, comes up with a metric that indicates quality of life, roughly. And on the x-axis here, we have annual per capita electricity use-- not energy, but electricity specifically. And we see some form of correlation between the two. So one could naturally conclude from this that energy is fueling development, and energy is also fueling per capita income, as a result. This little bubble chart hear, courtesy of UC Berkeley, is showing you the size of the bubble here, indicating the size of the population, and of course, the position on this graph indicating the per capita energy use and per capita income.

The reality is that many of the up incoming energy consumers aren't quite there yet in terms of their energy use. There will be a drastically increasing demand as several regions of the world turn on as they begin plugging in and demanding more electricity. So somehow we have to satisfy that growing demand.

So to put things in perspective as well, here we have the world somewhat at night. World population in millions. And so we have somewhere around 10 billion approaching by 2050. And you can see that the majority of the growth, what's driving world population, is Asia and Africa.

Those are the two lines. My apologies for the small text. But that's the yellow line right here. And the black line right here. They're the two largest bars in that Pareto chart. And the projected human energy use is only going to go up as a result. So again, we look at the world at night.

Now instead of looking at the bright areas, we're going to focus on the dark areas instead. The regions of the world where we do have high population densities-- some of the regions, not the deserts, obviously. Some of the regions we do have high population densities, like sub-Saharan Africa, but don't have a whole lot of electricity use right now.

Then we'll take another map, which is the solar resource. Again here, the red is indicating a lot of solar resource. And the blue is indicating not so much. But still, it's pretty amazing that the entire world is falling within about a factor of two, maybe a factor of three. So even if you compare Scandinavia against-- let's say, Scandinavia against Kenya, you're still looking at about a variation of a factor of three, right?

So the solar resource is pretty well matched with the regions of the world that don't have electricity right now, where the demand will be coming online. And to put that into another nice chart, I don't think this is very common yet. You've seen the HDI versus per capita income. But this is HDI versus insulation, showing that those regions of the world that are ranked lower on the HDI scale are precisely those regions that have higher insulation, that have greater access to that solar resource.

Now the big question is, is that solar resource big enough to supply necessary energy needs. And this is a quick intro to next lecture, where we discuss the solar resource in detail. But the short answer is absolutely, yes, by orders of magnitude. The volumes of these cubes represent the volume of either energy resource or energy need. Energy need here, on the far right-- that little blue cube represents the human energy use.

Some are very small compared to the solar resource on the Earth's surface. This obviously is including the ocean as well. If we're to be realistic, instead of calling this planet Earth, we should probably call it ocean or water since oceans do comprise about 2/3. But even if we discount this for usable land area, we're still an order of magnitude greater than total human energy use. So the resource base is there. It's available. It's up to us to figure out how to use it, up to us scientists and engineers.

So the potential for solar energy is represented on this chart. I'm not a huge fan of this chart, and I'll explain why in a minute. But there is something very valuable to be taken away from here. These black dots, one, two, three, four, five, six, represent around 18 terawatt equivalent, which is total human energy use in a few years time. And you can see the total land area there is not astronomical.

The reason I don't like this chart so much is because we're not going to cover up vast swaths of Nevada, for instance, with solar panels for the benefit of the rest of the country. We're going to distribute those solar panels over larger areas. But this is just meant to emphasize the point that the land area usage does work out in our favor.

So the way we distribute solar panels typically is either on residential installations, like this one, or in large field installations. This one, the Sarnia Solar Farm in Ontario is currently the largest solar farm in the world. We call it a solar farm because it's just a massive land area comprised of solar panels. This is the covering half of Nevada scenario, right?

This here on the left hand side, on the other hand, is a residential neighborhood in California indicating the more distributed variety. And both have their distinct strengths and weaknesses. So solar isn't about those small, little, rinky dinky, 20 or 30 watt panels that are sitting on a remote thatched hut. Solar is really growing up to be a grid tied, grid integrated, renewable energy source that is now probably skirting a $100 billion industry worldwide. So it's growing up, and certainly professionalizing quite a bit.

Historical perspective. It's time to take a look back and trace through some of the technical history of how solar cells came into being. And that really will inform why it is we're at where we are today, why the industry has some of the biases it has today, and what are some of the intangible barriers that could be needed to be overcome if we are to develop new technologies.

So aside from just general knowledge and general edification, this has an important technical aspect as well. So historical perspective. We credit the discovery of the photovoltaic to this gentleman here, Edmond Becquerel, shown here in his more mature years. When he wrote this article, right here-- I'll probably butcher it, but it's "sur les effets electriques produit sous l'influence des rayons solaires." Basically, the electrical effects produced by the influence of solar rays on a contraption that looked very similar to this.

He noticed a current flowing, essentially a photovoltaic, a photon induced, a light induced effect current. And he was very smart to decouple the effect of heat from the light. So his experiment involved selective filters that prevented massive amounts of heat from getting through. And he essentially produced what is a spectral response. Varying the filter color, he was able to trace out the response of this apparatus to the solar light as a function of wavelength.

This was a clever experiment. He wrote it up. It's more of an electrochemical device rather than the solid state photovoltaic device, like the one we know now. But nevertheless, it earned him the credit of being the discoverer of the photovoltaic effect. Does anybody happen to know how old he was in 1839, when he discovered this or when he published this work?

It's a rather nice article. Very eloquent, very detailed. He was 19. He was born in 1820. Anyway, small aside.

The field evolved from 1839, when that first article came out. Folks began refining and-- well, first of all, discovering new elements during that period in the 1800s, refining them and then testing their properties. And this was before we really understood what semiconductors were. They were a little bit of a black box, a big mystery. Their physical, electrical properties were all over the map. We'll explain why over the course of the next 10 lectures.

And they began refining these materials and putting them in various contraptions testing them with light. And lo and behold, they would get the photovoltaic effect again, maybe photoelectric effect first, and then, the photovoltaic effect, finally, when they set up the experiment properly.

And selenium was a popular material at the beginning. So was cuprous oxide, Cu_2O. That was a very common material. And I love pointing this out. This is a little contraption, a vice. To hold the contact onto the device. And as Joe can tell you, contacting a solar cell is not the easiest thing in the world. So it's a pretty funny picture, especially in light of our current difficulties in 2011 on resolving some contact issues, especially with new materials. But that gives you a little bit of a historical perspective. And the references are there.

In 1954, the first embodiment of what we consider the modern solar cell came into being. This was driven by the purification, crystallisation, and growth of silicon, which is the second most abundant element on the Earth's crust. It was noted to be superior to germanium for electronic devices because of its larger band gap, less leakage current. We'll get to that in a few lectures.

It had superior properties. And it was engineered into, I would say, the first what we call a, homojunction p-n junction based solar cell device in Bell Labs by those three gentleman there, on the upper left. And in 1954, the paper came out in the *Journal of Applied Physics.*

And that really spurred a lot of interest in the field. Why? Because 6% efficiency was about a factor 15 higher than anything that had come before it. And now, people could see the potential of this technology to drive things. At the time, within a few years, within a decade or so, folks were more interested in sending satellites into space than they were, perhaps, powering terrestrial objects. But we'll get to that in a second.

But some of the first examples here, in Bell Labs in New Jersey-- they had a small little radio communicating with this little device, over here. And the solar cell was powering the gadget. And it's interesting to note here, the New York Times article from that time, "with this modern version of Apollo's Chariot, the Bell scientists have harnessed enough of the sun's rays to power the transmission of voices over telephone wires." And they speculate that at some point-- obviously this was written in the 1950s, keep that social context in mind. "But eventually leading to the realization of one of mankind's most cherished dreams, the harnessing of the almost limitless energy of the sun for the uses of civilization."

They saw the opportunity there. It was not lost to them. But of course, a lot of development had to come under the bridge. A lot of water had to go under the bridge before they were able to make solar really cost effective from 1954 at almost 60 years later.

The way that basic solar cell device worked-- I'm going to introduce you to the full picture now. And I will begin dissecting it piece by piece, over the next lectures, so that we really understand each component of how the solar cell works. And we'll put it all back together again. We'll actually make it, literally.

So the sunlight comes into this device. This is a cross section of a solar cell device. And today's modern solar cells are about four times the thickness of your hair. So if you can imagine 200 microns in thickness, that's the thickness here, the cross section of this solar cell device. Light comes inside, excites bound charge, and makes it mobile, so it can move around the material. There's a built in electric field, which serves to separate that charge and create the voltage. And so one of the charges goes here. The other charge goes to the back. So you have a voltage or a potential difference across these two terminals, across the front terminal and across the back one. And then, if they're connected by an external circuit to an external load, current will flow through that external load to complete the circuit. And that's essentially how the solar cell device works.

So three basic steps, there's charge generation. So light is exciting charge within the material. The second important step, up there in the upper right, is charge separation. Somehow, you have to induce a voltage inside of your material. And the third very important step is somehow you have to collect the charge coming out of it. That's why those folks in the earlier days had that big vice over here. They were trying to really make sure that the metal was in good contact with the material so they could extract the charge. And so that's essentially it.

The advantages of a solar cell devices is that there are no moving parts and no pollution created at the site of use. There is, obviously, the manufacturing of the module itself. And we'll get into detail about that, and begin quantifying the amount of energy, the cost to manufacture it.

Bottom line is that the CO_2 production per unit energy output from the solar panel is on the order of 10 times less than coal, 5 times less natural gas, so significantly less than fossil fuel. It is not a zero energy system. The reason why the majority-- where the majority of that CO_2 comes from is actually the energy used to produce the solar panel. So as we transition to solar panels made from other solar panels, as the solar industry ramps up, obviously the carbon intensity of producing the solar panels will go down, as well.

Likewise, it matters where you produce the panels. There's some active research going on at MIT to decide where in the world it's optimal to produce the solar panels and where it's optimal to actually install them. The disadvantages, which really embody why we haven't seen a mass of adoption of solar to date and why there are technical and nontechnical challenges for you here to resolve is because there's no power output at night. In other words, when the sun's not shining, it's not producing electricity. And there's lower output when weather's unfavorable.

And thirdly, today there's a high cost. We'll get to that in a few slides as well. So it's not economically competitive in most markets. In some, there are. In 1.5 out of the 50 states here in US, solar is cost competitive, today. But in the remainder, it's not.

So this is the really fun part. This is why when you pick up your phone, and text your parents, and say I'm in a PV course. And they write back, ah, PV, I've heard about that for decades. That's an old hat. That's not going anywhere. You can write back and say it's very different today than it was then. And here's the reason why.

In the 1970s, when PV really started to take off for civilian purposes-- obviously, they had put satellites up into space. They had proven that it worked. It was robust. In microwave relay stations up in remote locations, that they didn't want to service, they also would place PV panels. But in terms of civilian purposes on houses and so forth, really late 1970s, early 1980s were where things were beginning to take off.

And driven by the oil crisis. The OPEC oil crisis of 1970s. This is a New York Times article describing the state of the art of solar. This is taking a look some 20 years later at solar and saying how far have we come.

And one of the interesting things of note in this article, right here, is that it cost upward of $10 a watt for the solar panels, in that day in 1979. Meaning it would take, roughly, $12,000 to run an ordinary household toaster. So that was the impression that folks had of solar in the 1970s. And for good reason. This is the cost of electricity produced of solar versus time.

In reality, the x-axis, if you look closely, it's cumulative PV electricity production. That means for each new panel we make and for each new unit of energy that that panel is producing, the cost of electricity is coming down. That's because we learned how to make panels better. We learned how to make cheaper panels faster, with less cost.

So the cost of the electricity reproduced, over here, is showing going down with time. And this is a little bit of apples to oranges comparison, that's why they're two different colors for the two different dots. The black dots represent the average retail electricity prices. Not costs, but price. This is going to be a repeating theme throughout the entire course. I'm going to emphasize it now. Can somebody tell me what the difference between cost and price is?

AUDIENCE: Price is going to be more than cost because the company wants to make a profit on the product.

PROFESSOR: Yeah. So let's see I make a gizmo-- this is a great example. I make a gizmo that costs a certain amount, x, let's say. And now, I sell it for 3x. And I make 2x profit. So the price would be 3x. The cost would be x.

And so the cost of solar is shown here in the white dots. And the price of retail electricity price is in black. Why is this comparison made right here? Why would somebody do that sort of apples to oranges comparison? What point are they trying to make?

AUDIENCE: Because we need to bring down how much we need to put into PV to be at to compete with the price that electricity is at, as opposed to cost.

PROFESSOR: Exactly. This is a substitution play, right? You're looking at PV substituting what is, in that case, the base load and peaking price of electricity-- probably more driven by the peaking price of electricity. And so what they're doing here is they're saying, OK, how much does it cost to manufacture this panel, and how does that compare against the grid if I were to plug into the wall over there and extract electricity from the grid.

How much would that cost me? How much would I have to pay for that electricity? And that's really the comparison that they're trying to drive right here.

AUDIENCE: Does that adjust for inflation?

PROFESSOR: Yes. The details are in this paper, right here. Again, you can access all this information online. But it is adjusted. These are, I believe, in 2002 prices. I can't remember the exact-- yeah.

AUDIENCE: What are some of the assumptions used to compute the cost of PV and electricity?

PROFESSOR: Great question. So the higher density of data points, over here, is in part because they get closer together. It becomes harder to drive the cost down. And of course, we were looking at it in a log scale. But also, the quality of the data is much better in recent years because we had access to-- greater number of companies were able to average values coming from multiple sources.

Some of the earlier data, especially 1957-- those were some of the first solar cells produced. If they had access to good primary data, those numbers would be highly accurate because it would be one company making it. And that's it. Very little error bar. But if they were making guesstimates based on material cost of the day, then there would be some error bar associated with that data point.

These curves are very difficult to produce when you're in academia. But I can say that when we were in industry, we did this for our company just for hahas one day. And it fell on a very similar slope-- with a similar slope and a similar value. So somehow they were getting the numbers right.

AUDIENCE: In terms of insulation, what numbers are you using to assume-- like you said, do you use values for Nevada or do you take an average of the summation of the entire US-- US average for the retail electricity prices.

PROFESSOR: And so the retail electricity prices in the United States vary quite a bit. You have some coal rich states, like Wyoming, that get $0.05 per kilowatt hour. You have states like Massachusetts at the end of the energy pipeline. If you look at the natural gas pipeline, for example, we're at the very end. We get some of our natural gas even shipped in by boat. $0.18 per kilowatt hour is residential prices.

And in California, which has a tiered structure, if you're one of the highest consumers of electricity, you're going to be paying somewhere around $0.30 per kilowatt hour compared to some of the lower use folks down around $0.12. And so, it varies quite a bit. Typically, when you're looking at these sorts of charts, if the chart is produced, say, by the USDOE or some solar promoter, let's say, they will typically be choosing a rosy scenario of the American Southwest because that is-- well, not only do the numbers look better but, more importantly, that's where a lot of the solar is being installed, today, but not all of the solar.

Because it is a substitution economics situation, two parameters are really of interest that drive the cost competitiveness of the solar installation. One is the retail price of electricity. How much are you paying out of the wall? What are you substituting it with? And the second is how much sunlight you get locally. So our break even point in the state of Massachusetts is not too far off from Arizona because they have a lot cheaper price of electricity even though we have a lot less sun.

So I wanted to emphasize a couple more points. So when Gregory Nemet put together this chart, it was within the context of a really interesting paper in which he attempted to decouple the effects of scale from innovation. Let me emphasize that. So if you are making a widget-- let's imagine a razor, like Gillette does here in South Boston, or if you're making some other high tech product-- razors by the way are very high tech.

How many times have you cut yourself by a defective razor? I certainly haven't, and I've probably used tens of thousands in my lifetime of individual blades. And that's because they're examined using laser technology. They're really manufactured in a high tech way. And they get better and better every time they produce one razor blade.

And so they follow a learning curve, just like photovoltaics does. With cumulative production, the cost of producing one widget goes down. And likewise, microwave ovens and other high tech products.

And so the big question is, how much of this learning curve cost reduction is driven by innovation and how much is driven by scaling-- just learning how to do incremental improvements, tweaking the manufacturing line to make it a little bit more efficient. So Gregorian Nemet, the author of this paper right here, in which this figure appears, looked into that question and came up with some answers. Some of those learnings were incorporated onto this beautiful chat here produced by 1366, a spinoff from MIT focused on commercializing really cool next-gen PV product.

They took that learning curve from Gregory Nemet's paper, plotted in a slightly different scale, and showed several of the technology innovations that drove down that learning curve for crystalline silicon. And so those, in the fine text there, represent specific technologies. And we'll be getting to know some of them over the course of the PV course.

And so, we're approaching this very interesting point. If you haven't noticed from this chart right here, this ended in 2003. And boy, these two are getting very close to one another. We're entering a very interesting point where the cost of producing PV electricity is rapidly intersecting with the US retail electricity prices. And that is represented in a very broad brush strokes by this DOE chart that was produced in approximately 2006 with the Solar America Initiative, where you have the system price range for PV systems. Again, broad range now, instead of finite data points.

Residential and commercial rates and utility generation. For those who have already dealt with electricity markets, the residential commercial rates-- this is the price or the retail price. And the utility generation, this is more the wholesale price over here for utility scale. So again, just showing you the range of substitutions that could be going on.

And we're entering the regime now where, finally, solar is starting to be cost competitive. And when you start having this sort of interaction, you can imagine two Gaussian curves, one curve representing the price of solar and the other the price of electricity. And as they begin overlapping, as the price of our electricity goes up-- it went up 15% over the 2000s here in Massachusetts, the retail price of electricity in residential.

And as the price of solar comes down, those two Gaussian curves begin moving against each other. And at the edge of a Gaussian, you can model that using an exponential. And so you have two exponential curves overlapping. You have, effectively, an exponentially growing market penetration. In other words, the solar adoption on the grid is following a hockey stick curve. And that's why you hear a lot of interest in solar these days.

We had a solar system installed in our house in 2007. And now, our neighbors put them up last year. The folks across are putting them up, actually, just last week. And there's another family down the road. So our little neighborhood is representing this little hockey stick, right here, as is Cambridge as a whole and some of the places in the United States where it does make economic sense. You're beginning to see that take off. And that's why it's such an exciting time right now.

This is a much busier chart. There's a lot going on. But to sensitize you, this is the PV residential. In other words, it's either the cost or the price to install PV on a residential home. In other words, it's a smaller system. So there's a larger overhead per system. The architect needs to spend more time per unit energy produced to design your system because it's a smaller one. A lot of people go out there per panel to install it.

Whereas PV utility, those large fields filled with PV panels, it's cheaper per unit panel to install. One architect can sit down and design the whole thing-- maybe a team of architects. But the overhead costs are lower. And you can bargain with the module manufacturers to get a better rate on your modules. So get a better price.

And as a result, the PV utility costs and prices tend to be lower than PV residential. And the blue and the red, here, just represent the wholesale and retail electricity costs-- what they're substituting here in the United States. So a bit more detailed chart, again, showing the grid penetration down here at the bottom.

Also, in terms of percent. So back here, a few years ago, the 0.2% of total worldwide electricity was generated by photovoltaics. And projections are that by 2020, we'll be at around 1%, by 2030 around 5% using these just two overlapping Gaussian curves.

And it's interesting to note that this is global. On a local level, Germany has already well surpassed 2% in Bavaria. I think it might be up 3% or 4% now in photovoltaics, in the southeastern region of Germany. There's a small island in the Hawaiian chain that has, I believe in peak days, around 40% of its electricity produced from solar. So there are regions that already, you have a very large percentage of the total electricity being produced by solar because of that distribution of prices.

And lastly, this is a really exciting chart. This is the convergence between PV and conventional energy-- essentially, what this chart over here was attempting to capture in its percentages. This is explicitly laid out, now. And I took data going back to the 1970s, and plotted the average terawatts installed of new PV installations versus total primary energy-- new primary energy installations.

So for those energy wonks here in the audience, what is the primary energy burn rate in the world, right now, in terms of terawatts average? Around 15, right? And so the average new energy installed each year is represented here. It's somewhere between 100 gigawatts and a terawatt, typically.

And this is the new PV installs. You can see that we're within about two orders of magnitude, now, of total new energy installs. This is primary energy. For electricity, it looks even rosier. And so we're rapidly approaching the point where substitution will begin. We're going to start replacing, not only we're going to take a larger share of total new installed energy, but we may even start putting some existing power plants out of business. And we'll get into that in the economic section in the third part of our course.

Interesting to note, these three distinct phases of growth of the industry over time. Phase one was right at the beginning, when we had the OPEC oil crises, when people were really interested in solar, but it was really a boutique thing. And solar cute, great PR, but not really impactful.

In this regime, right here, where most of you were born, solar went kind of through a down cycle. So while the price of oil was really high, right back here, it crashed in the early 1980s. And symbolically, Ronald Reagan ended up taking down the solar panels from the White House some time in '86, '87. And big oil companies were the ones who kept the solar industry going, interestingly enough. It was Mobil-Tyco. It was BP Solar. The largest companies that were producing solar panels in the world were ones that were small divisions of larger oil companies, which viewed themselves as energy companies.

And then finally, this phase three, this really rapid growth here. Again, a cumulative annual growth rate somewhere between 40% and 50% average. That took off when generous government subsidies, whether it be for the manufacturing or the installation.

In the case of the United States, it's mostly been on the installation side. In the case of China's, it's mostly been on the manufacturing side. Japan and Germany had a bit of both, but more heavily toward the installation. And we saw a massive growth of the PV industry because, now, the government's realized, well, wait, the cost is coming down, and we will need new electricity coming on board.

And our oil supply is a little unreliable. So let's invest in this new technology and see where it takes us. And I think the Germans, now, are paying somewhere on the order of a euro, maybe a little over euro, per month on their electricity bills as a result of having financed a lot of this growth right here in the PV industry, which allowed the costs to come down for the entire world. So it was a successful program.

And as a result, many pure play companies saw the financial opportunities. The case Q Cells, which is highlighted down here, is not unusual in those days. In the late 1990s, a group of executives at McKinsey got together and said, wow, the numbers look really promising in the solar business. Why don't we form our own company and only do solar instead of being part of a much larger one where they have their interests dispersed among many different product lines and technologies? Let's focus exclusively on solar, burn our bridges behind us, and just go for it.

And they went for it. And for a while, for a few months Q Cells was the largest solar cell producer in the world. It was, I would say, a poster child of this new generation of PV companies coming in this third phase here. And as we'll learn over the course of this semester's course, many of the leading solar producers today are now located in China. So this is, basically, the history of PV development.

And the important thing to note is this closing gap, right here. So when folks are saying solar, it's the same old, same old. It's been gimmicky. It's been around for a long time, but it's not going anywhere. You can point to some of this data and, say, no. Actually, it's on the cusp. It really is beginning to take off. And these are some of the data you can point to if you care to do so.

Let me spend a few minutes talking about the broader picture beyond just solar photovoltaics into some of the other solar technologies. We won't be addressing too many of these over the course of the lecture because we have to focus and we have to become very good at something, otherwise we spread ourselves to thin. But I did want to give you a sense of what's out there so that you can situate solar photovoltaics within a broader context.

And so this is a solar energy technology framework that encompasses all conversion technologies from sunlight into energy. And so first off, I start with a rationale for framework. Why invest the time to come up a the framework? I'll explain why.

There are several hundreds of technologies out there that can convert sunlight into energy. And to make sense of the technology space and to provide some meaningful technology assessments, there have to be some performance driven, technology neutral performance metrics that you can use to evaluate one technology against another. And that's why coming up with some sort of framework is very helpful.

So the three criteria that I chose together with Vladimir Bulovic when we put the together, to design a technology framework was an exhaustive categorisation. In other words, our framework had to encompass more than 90% of all technologies out there. The 30 years challenge. Again, in 30 years, the PV technologies should be able to fit into this framework still. And it should be a useful analysis tool. It should be able to give insight into the complex space that's out there, and allow folks, like yourselves, to make sense of it, whether you're trying to develop cost models or if you're trying to develop technology prospectus. This should allow you to gain a foothold in it.

So we have solar energy conversion technology. And we chose an output oriented rationale for dividing the solar energy conversion space. So the output would be either electricity, heat, or heat which is then used to power, say, a turbine which generates electricity, or fuels. And those are the four primary outputs of solar energy, today. Yes, there are technologies out there, for example, that convert sunlight and store it in some way and convert light on the other end. But we're not including those in here because, again, the 90% rule. We're focusing on the major ones.

And then, we do a further subdivision between the non-tracking and tracking. Tracking means if the sun is moving through the sky over the course of the day, your apparatus is following the sun so as to maximize the cross section between the incoming rays in your device. The reason we chose tracking non-tracking is because tracking requires motors, which will add cost and reliability questions to your system considerations. And that's why we chose this further division right here.

So on to the assessment. Let's look at the technologies that are out there and try to bin them. Solar to electricity. There are a few embodiments. There's the photovoltaic device, these ones. There's the thermoelectric device as well, which convert solar energy into heat, really, and then heat into electricity. So maybe it should have been in the other category. But it is a device that converts solar energy into electricity.

So we've seen a solar cell device. We've learned the three steps, charge generation, charge separation, charge collection. And we look at the existing technologies that are out there, today, and say, all right, let's start to bin them. We have non-tracking systems that can be non-concentrating, like these panels right here. Essentially, they're just flat panels that are receiving the sun's rays. Or, you can have cheap, mirror-like materials that bounce the sunlight off of them into the solar panels and concentrate sunlight.

So let's imagine we put a set of mirrors on either side of this panel, right here. And when the sunlight bounced into the mirror, it would reflect back into the panel. That would be a concentrating, but non-tracking, system.

And these are common on barriers along the highway in Germany. They're sound barriers. They're preventing the people who live on the other side of that barrier from hearing the noise of the cars going by on the Audubon. They're not meant to be crash barriers. Those are separate, closer to the actual road.

But these are examples of concentrating and non-tracking photovoltaics. There are ground mounted and roof mounted systems. So again, another way to split the pie. In the concentrating non-tracking system, there aren't only these types, there are a variety of other species of concentrating non-tracking devices as well.

There are so-called sliver cells-- which the light comes in, bounces around a little bit, and then eventually gets absorbed by the device. And that even happens, to some degree, in these modules, too. Because the light comes in-- make sure I don't reflect this into your face. There we go. Point it up.

The light can come in sometimes and reflect off of this white back skin. If the light is coming in at an oblique enough angle, total internal reflection by the glass. It'll get a second bounce and go into the device. We'll talk about how that works in a couple of lectures.

So internal reflections. And this is particularly timely. Does anybody know-- does the word Solyndra ring a bell for anybody? Yeah. What about Solyndra?

AUDIENCE: It went bust.

PROFESSOR: It went bust. So it's one of the three photovoltaics start up companies in the United States that went bust over the past few months over this past summer. And that's a really interesting market dynamic, which we'll get to in the third part of this course. And we'll discuss that head on because it's an interesting, and very important dynamic in the evolution of the solar industry.

We have some technologies under development at MIT. Marc Baldo's lab and Vladimir Bulovic and others are working on devices that absorb sunlight, reemit the light at a different wavelength, trap it inside of some high index medium, like glass, and then, ultimately, concentrate it on to the cells that are on the corners. So you can imagine a window that absorbs some of the incoming light, bounces light off, and eventually concentrates the light in the corners where you have your solar cell devices. The advantages, or the potential advantage, here is that you can have a very high efficiency, expensive device, but a very small area of it. Instead of covering this entire area right here, you've now reduced the total area.

And then, if this is a very small percentage of the total system cost, you can just switch it right out when a new and better technology comes along, almost like you switch out your computer. So if a better solar cell device comes along, you can take this one out and put the next one in. It's almost like an upgradable system because the majority of the embedded cost is in the concentrator and not the solar cell device itself. Again, just really drinking out of the fire hose this morning. We're drilling you with data, but it's meant to begin to sensitize you to some of the terms and some of the ways of thinking here in the field.

Tracking. So when we're talking about tracking, there's a rise in the number of tracking systems in the United States. It is shown with high efficiency modules that it can be more cost competitive if you have a large field installation to do one axis tracking. One axis tracking and two axis tracking. Why would you want one or two axis tracking? What are you tracking?

One axis tracking. What would make sense to track with a one axis? If you had one axis to choose, would you rotate east west? Would you rotate north south? Would you rotate northwest to southeast? Where would you go?

AUDIENCE: East to west.

PROFESSOR: East to west. Why is that?

[CLASS MURMURS]

PROFESSOR: Because you're tracking the sun over the course of the day. And you're tracking, pretty much, every day of the year. So 365 tracks per year. The two axis tracking, what is this other axis? Presumably, it's orthogonal to the east west. In other words, north south. Why would you want to track north south?

Seasons, right? Yeah so from winter to summer, you're tracking. So you would always want your solar panels facing south, I guess, right?

AUDIENCE: In the northern hemisphere.

PROFESSOR: In the northern hemisphere. Exactly. So if you're in Australia or in Brazil, your solar panels are facing north. So let's accustomize ourselves with that. And the two axis tracking, of course, would allow for that adjustment.

The reason one axis tracking is taking off as the most common field installation tracking system is because the seasonal adjustment, if it really needs to be done-- it's not a huge energy benefit, but if it really needs to be done, you can probably just crank by hand instead of using a machine or a motor that can break down. And the adjustments still need to be made very often.

Non-concentrating and concentrating PV. Tracking. So these are one axis trackers, right here, tracking over the course of the day, but not concentrating. In other words, they're flat panels like this, but just mounted a one axis tracker that follows the sun over the course of the day. The system over here is a two axis tracker that includes little lenses that are focusing the sunlight onto tiny little cells. And again, very similar idea that the solar cell itself is high efficiency, but it is a low percentage of the total system cost.

Non-concentrating and tracking. Again, several examples of that. You have fancy systems, two axis trackers, again, most common. Can anybody guess what this little gizmo is, right here? We're going to get to that in next lecture but--

AUDIENCE: A solar sensor that finds the position of the sun?

PROFESSOR: Exactly. Somehow, you have to have a measuring device if you have a tracker. It has to tell you where the sun is. So this little gizmo, right here, is just making sure that the panels are facing the right way. Awesome.

So concentrating and tracking. Here's a closer look at some of the Frenel lenses that are used to concentrate the light down. On some cheap microscope-- or sorry, cheap magnifying glasses they also use Frenel lenses. And so this is an example of a low cost apparatus here to concentrate the sunlight onto your high efficiency cell.

Solar to heat electricity. We're not going to talk too much about this during the course. But just to sensitize you-- that there are technologies out there and some pretty exciting once. There are heat engines. In other words, sunlight heats a fluid, which moves a turbine or a piston, either directly or by heat exchanger.

Heat exchangers. Thermoelectrics. Long wavelengths photovoltaics. These are devices that convert the heat portion of the solar spectrum into usable energy. And there are hybrids that are possible with these. So if you heat up a fluid, say, a salt or a glycol solution, then you can store the energy in terms of heat.

And if the stored energy begins to decay with time because of poor insulation, you can augment that heat with natural gas or with some other fossil fuel. So you get these hybrid, renewable solar and natural gas power plants that are possible with the solar to heat electricity.

And there are some really fancy designs out there. And I'm happy to dive into these in more detail. The most common one are sunlight coming into some sort of reflector, and then concentrating the sunlight into a thin tube that contains your high heat capacity material, liquid usually-- so a glycol based liquid or even a salt, sometimes.

It has to have a high heat capacity. In other words, it has to be able to absorb a lot of heat and retain it. But it also has to have, ideally, a minimum amount of corrosion so that the longevity of the parts is sustained.

And you can see, here, these tubes that are running along here and going down these fields of collectors all the way to the other side. And somewhere off in the distance is the heat exchanger. So that's solar thermal for you.

We have parabolic dishes concentrating sunlight into Stirling engines. That's kind of neat. And so your T high is basically that of generated by the sun. And you T low is the ambient. So typical mechanical engineering there.

And you also have solar power towers. There's some work being done at MIT in this as well with Alex Slocum and others that are using fields of mirrors to concentrate the sunlight into a tiny little spot, right here, in a big tower. Say, for example, that spot right there, it's dark. It's not in operation. But if it were, the sun would be concentrated onto that little spot. It'd be really, really bright, indicative of it's very high temperature, on the order of a couple thousand Kelvin.

And then the sunlight would either be absorbed up here, with some molten salt, or reflected down underground to a heat reservoir. And that would be your T high running your engine. So your Carnot engine. And then the T low would be the ambient temperature.

Solar to heat. This is really important in developing countries. Not to be overlooked, the very simple, low tech conversion of sunlight into heat. You can heat water. This is very, very common on rooftops all throughout the sunbelt of the planet. You'll see these on the roof, painted in black. They contain potable water, typically used for either, say, for example, showers or kitchen use.

And the fancier versions that are really marvels of engineering. These materials all have to be coefficient of thermal expansion matched. As it heats up, the glass tubing has to match the expansion of the metal around it. So it is quite a feat of engineering that they make these so well. There are a few companies in Germany that really pioneered this effort right here.

Of course, you have tracking versions, like solar ovens. Not too common. You typically find more still in developing countries. Unfortunately, you find a lot of wood burning, which isn't good for the cook, which, unfortunately, most often is female.

And so this illustrates some of these societal questions that solar involves. It's not just the technology. This involves gender equality. This involves societal development. This is a much broader topic than just the fundamentals of the physics of how the solar cell device works or how sunlight is converted into energy. And that's why we have the three segments of the course.

Lastly, solar to fuels. The way I've traditionally broken it down-- it's a little bit wishy washy-- is into enthalpy and entropy in the sense that, in enthalpy, you're storing the sunlight in bonds-- in chemical bonds. The bonds are forming-- more complex, higher energy molecules are being created. So you're taking water and splitting into the gases.

Or you're taking CO2 and water and converting it into hydrocarbons. And those can be used to store the fuel and, ultimately, release it in the form of burning the fuel. So it's a closed loop cycle.

And what I refer to as entropy, which I get some flack from the folks in chemistry for, is the separation of phases, in other words, desalination. If you separate your salts from your water, then you're increasing the energy of your system. You're doing a physical separation. And it is a form of energy storage.

So this right here is the example of the renewable fuel cycle where you have sunlight coming into your starting compounds. Using some catalyst, typically, you're creating the intermediate compound, which is a solar fuel. Then you burn your solar fuel. Then you have your final compounds. In the ideal world, 5 equals 1. The final compounds are identical to the beginning compounds. And you have a closed loop cycle, a renewable cycle.

And so a lot of work is going on here at MIT. This is a recent paper we published together with Dan Nocera. His group is looking to special types of catalysts. Our group makes solar cells. So we work together to make these nifty little devices that convert sunlight into storable fuels. What you see here are little bundles coming up from the water in which the solar cell device is embedded.

The water is near pH neutral. Then it's converting that sunlight into gas, into hydrogen and oxygen, which can then be stored. On one side of the device, you could be creating oxygen. On the other side, hydrogen, for instance, if you have a physical separator, you'd be able to store that electricity.

This is an example-- a very simple example-- of desalination driven by solar. There are much fancier examples, as well. But that gives you an idea. You have contaminated or salty water. And you're evaporating the water. It dribbles down into this little collector over here, and finally out into your collecting pot, leaving the salty, brine behind.

And then in the broader perspective, we have many other issues beside just the conversion technology itself. We have how do we use the electricity and how do we store it. Is the solar power generation centralized and all the users distributed, similar to how we produce power today? Do we have one big solar field that's producing electricity for all of Cambridge, or do we have the individual solar panels in each of our houses that are producing the power locally, and they're all interconnected? In case a cloud goes over one region of Cambridge, there's still coverage.

That's a really big question. And the economics are what's driving this right now. These large field installations give you a sense. This is a road right here. These little green specs are trees. These are huge field Installations of solar. The economics are driving it right now. But there are opportunities with commercial buildings. This is the Moscone Center in downtown San Francisco. It's like the Heinz Convention Center equivalent there.

This is an example of a house in Rochester, New York. That housing development in Rancho Cordova in California. So you have examples of residential installations as well.

Are we just going to let economics drive this? Is there going to be some policy involved? Is there a smarter way to do it, not only from a cost perspective, but from a societal perspective or an energy grid robustness point of view? What are the right choices here? There's a lot of open questions right now in the field.

And what about energy storage? Are we going to store it in terms of batteries and fuel? Centralized storage? Are we just going dump it into the grid and be free riders? Let the grid handle it, somehow.

Hope that the grid a stable enough that when a lot of solar is being produced and when no solar is being produced, it'll just be able to accommodate. I guess the resistance in the turbines of the fossil fuel plants will either increase or decrease depending on how much energy we're pumping into the grid.

And so at the end of the day, we have this very complex space of conversion technologies. The solar electricity, solar to heat, and so forth. And the system itself, whether we have centralized generation of electricity distributed generation, and whether the storage is centralized or distributed, whether you have storage inside of our house on the inverter, let's say, or in the basement, or rather the storage is some centralized storage facility in the center of Cambridge that serves as a buffer.

And we have all of this space to play in. We're going to be focusing on solar to electricity. So we'll be focusing on these two columns right here. And specifically, the technologies during the first two thirds, and then, the broader, system level impacts in the third of the course. So that puts it all in perspective,

I'm not going to get too much into this. I'm just going to say one quick word about CO2, energy, and climate change. You hear a lot of talk about, at least from the political sector, that scientists are, shall we say, in a lot of debate whether climate change exists or not.

That is patently false. The majority of scientists, upwards of 96%, believe that there is strong evidence to support the fact that human energy consumption, especially the high CO2 intensity of our energy consumption, is driving some form of climate change.

What the magnitude is and what the impact is-- obviously, that is still under discussion. But the reality that our emission of energy-- our emission of CO2 as a result of energy use, our fossil fuel energy use, is driving some form of climate change that there is widespread consensus among the established scientists in the field.

Now if you want to do some back of the envelope calculations just to convince yourself that we, tiny, puny, little human beings are having an impact on our world, do this for me. Take the total energy consumption rate. This is the energy burn rate. So it's the average power-- average rate of electricity use.

Look at just the fossil fuel based energy sources. Or if you prefer, take the average CO2 intensity of our energy mix, which somewhere around 600 or maybe 800 grams of CO2 per kilowatt hour. And then look at that amount of CO2 emitted.

You can calculate how much CO2 is emitted per unit time from our energy mix knowing the carbon intensity of our energy mix. Then do a quick back of the envelope calculation. Assume that our atmosphere is 30 kilometers thick. It's a generous assumption.

The density of the atmosphere dwindles pretty quickly above 10 kilometers. But assume it's 30 kilometers thick. And then dissolve all of that carbon that we're creating from this energy mix into that thin shell surrounding our earth. Our earth is on the order of 6,370 kilometers in radius. And it's only 30 kilometers thick, the atmosphere.

That's why those beautiful photos from the space missions, when you see that thin blue shell on the planet, right-- that's the atmosphere. It's really, really thin. Just do a quick carbon density analysis. And you'll see that we're adding hi tens of parts per million of CO_2 to the atmosphere. And then you look at the total CO_2 in the atmosphere, which is in the order of 400 parts per million, and you'll see that we're adding an appreciable amount, just given the carbon intensity of our energy mix and the total volume of atmosphere into which we're dumping that carbon.

And so the question of whether or not we are adding carbon to the atmosphere, I think, is indisputable, based on some quick back of the envelope calculations and, of course, the more in-depth models. The only place where you can have some wiggle room to argue is whether or not CO_2 actually influences the climate. And for that, there are a number of studies discussing that point. I would refer you, specifically, to these here, published in Science in 2005, that discuss historical correlations over the last 600,000 years, correlating CO_2 and mean global temperatures based on oxygen isotope ratios containing gas bubbles, for example, in ice cores.

So I would say if you're arguing whether or not we're having an influence on our atmosphere, I would say that is a difficult position to take. The only room that I would give you some room to maneuver would be if you said, well, you know, CO_2 really isn't that bad in the atmosphere, despite what our infrared absorption data seems to indicate, that it really does absorb infrared light and reemit it.

So that's what I have to say about the climate, which is a huge motivator for a lot of people taking the course. And you're welcome to talk about that in more detail, but I'd really love to keep this focus on the technology, by and large.

And for that, I'd like to hand out these background assessment quizzes for each of you. Please take a few moments to fill these out-- just pass them back-- so we can learn more about your interests. And what I'll also do is pass around this little solar module, right here, so you can get a sense of what a small little solar cell looks like up close and personal. Once you're done, feel free to come up and take a look at the solar module, right here, as well. And thanks.