PROFESSOR: I promised everybody that we would have the capability of testing a multi-junction solar cell. We've been working so far with a single-junction crystalline silicon. And just to refresh everybody about what a multi-junction device is, it is a high-efficiency concept.

The efficiencies that are obtained under concentrated sunlight are above 40% now with some of these high-efficiency concentrated devices. And again, the way this concentrated device works is if you have, for example, germanium, gallium arsenide indium, gallium phosphide stack-- three different materials, three different band gaps ranging from somewhere in the range of 0.67 eV all the way up to a few eV. The largest band gap is placed at the top, because the short wavelength light is absorbed by that one, and the longer wavelength lights go through and are absorbed by the layers underneath.

So you can think about this as blue, orange, and red, if you like to see things in colors, the short wavelength light being the blue absorbed at the top, the sunlight obviously coming in through that side through the top, the middle cell absorbing the light somewhere in the middle of the solar spectrum, and the bottom cell into the reds. So the notion is to have a device that is capable of minimizing thermalization losses. So the short wavelength light, instead of being absorbed in a low bandgap material and generating a ton of heat in the process, is able to be absorbed very efficiently via that top cell. And only the longest wavelength light, the lowest energy light, makes it down to the small bandgap material underneath.

So this is representative of the stack of materials that we have. I believe what we're going to do is do a direct comparison of silicon versus multi-junction. Is that right? Yeah, so right now we have installed the silicon devices. Those are the very nicely encapsulated ones.

We had to change the light source. As you see now, we have a little bit of a flashlight there. Why is that? Why did we have to go from an LED, a monochromatic light source, to a broadband flashlight?

AUDIENCE: Well, if the point is that you have these different absorbing layers that absorb different wavelengths of light, if you only put one [? group ?] like that, the other layers wouldn't have any effect.

PROFESSOR: And it kind of defeats the purpose. Plus the current outputs of these three different cells have to be more or less matched. So because they're connected in series, if you have a poor performing cell-- or one component, one sub-cell, if you will-- that is generating a small amount of current, that will limit the combined current output of the entire stack. Good.

So why don't we go ahead and connect them to our computers. We have our tech support staff available on call-- who just walked out, conveniently, but will be back momentarily. We'll connect them to our computers, fire it up, and team up with somebody if you don't happen to have a computer with you. We'll get this demo started.

So the notion here is to first test the silicon-based device. Once we have a good working IV curve out of the silicon-based device, we'll take a pause. We'll talk about what we would expect to see from the multi-junction device when we hook that one up. So why don't we go to it and give it a shot.

So let me dive into what is effectively our last in-class lecture before we are graced with some really nice presentations. I'm looking forward to those. So global trends-- what I decided to talk the last day about-- really we have a couple of topics left, which we don't have time to cover. We won't have time to cover both. We'll have time to cover one but not the other.

And the two topics are the future of R&D in solar. And the other topic is solar in developing countries. And I think both are equally important.

I decided to pick the former rather than the latter. Global investments, trends in solar and other renewables-- what I wanted to do was to briefly walk through some of the recent trends in R&D. So energy companies traditionally are not R&D spenders. They reinvest a very small fraction of their profits in R&D, in research and development.

And solar, because it is far from grid parity right now-- factor of two or factor of three in terms of cost-- not price, cost-- we have to invest R&D to get the cost down. And this is both manufacturing innovation and, of course, engineering scientific innovation. So this right here is financial investment in clean energy, global trends by quarter. I decided to compile as much data as I possibly could into the slides so that you can go on afterward, if you're really interested in the topic, pursue it further.

And what we see is as a rise overall of investment in so-called clean energy. And by and large, by the G20-- these are countries that have access to resources, to capital-- larger GDPs on average. You also see a trend and in non G20 countries, more recently, an uptick or recognition that this is an important area. And perhaps there's room to play, niches if you will, that certain countries can adopt that would provide a competitive advantage.

This is an interesting chart as well. This shows the investment in-- I believe this is government R&D. Oh, this is financial sector investment only, excludes corporate and government R&D-- small distributed capacity in both-- so financial sector investment in the US and China. What we see in the US is relatively stable investment-- picked up in the mid 2000s, but relatively stable throughout. And in China, just a really steady increase here of a R&D funding.

Note the role of the market in the United States. Right around '05 and '06, this was when the price of PV began to plateau. The costs continue coming down, but the price of PV modules began to plateau because of the silicon feedstock shortage.

So people saw opportunity here, especially the financial sector, private capital, and said, hey, if prices are remaining high and the costs are coming down, that means our profit margin is growing. This is a good industry for us to get into-- a high profit margin industry. So there are many folks getting in because of that market condition.

Some of them saw the future in the market and said, this is trending towards commodities. We have to adopt that mentality, and really squeeze every penny out of our cost structure that we can do. And others went into it thinking that this would be a bumper crop-- a really high yield investment. And then as the margins began to get squeezed, they got scared, and some pulled out.

So it's an interesting trend, following the market perturbations in the United States and having this fluctuation. And in China, from what I can tell discussing with business leaders and politicians, a much more premeditated, long-term strategy saying this is a strategic industry for our country. We are going to invest in it. And this is of fundamental national importance.

So a little bit of difference in the investment strategies of the two. The EU is a little bit in between-- a mixed bag. Again, this uptick in the middle of the 2000s, but a continued investment in PV and renewables.

This shows the investment type by sector, broken down on the right-hand side between the renewable energy types. So you have wind, solar, other renewables, biofuels, and so-called negawatts, so-called energy efficiency. And on the left-hand side, we have the different types of investment into clean tech. And interestingly, here in the United States-- this is in 2009-- venture capital is comprising a surprising total of the investment in renewable energy. And in terms of the sector itself, we can see solar here in the United States comprising a large percentage, again, of the total investment.

I want to bring caution to one data point up there-- Spain. That was a little bit of a short-term fluke. The Spanish government instituted a feed-in tariff similar to what Germany has implemented, but a little less successfully. Let me dive into the details.

Germany did a careful market analysis, was the first to move into the space, and began dominating the market for PV-- 50% of PV installed. So if Germany set the price a little differently, the PV market would adjust accordingly. Spain, a new entrant, seeing Germany's success, decided to replicate it.

The first time they attempted a feed-in tariff, their feed-in tariff came in too low, and the market looked at Spain, shrugged their shoulders, and continued installing in Germany. The second time they decided to come in, they put their feed-in tariff a little bit too high. And as a result, the market said, really, you kidding? OK, we go there and install.

And there was a slush of modules over to Spain, flooding the market. And over a period of about a year to two years, they got much more than they bargained for. In other words, they had many, many more modules installed than they had expected.

And now the government has to pay out to these installed systems. They have to pay out a certain rate based on the feed-in tariff. And it was more than they expected to have to pay out.

Then the financial crisis hits. So it was a little bit of a disaster, because they ended up killing the program, killing in the process about 10 years of work to design the program, 10 years of institution building to think about how to create a feed-in tariff for Spain, and without the desired result, which was a slow, steady increase of the photovoltaic installations in Spain and hence, the local industry. So it was a little bit of a flash in the pan-- a huge market that burst very suddenly, and then quickly extinguished itself. So it's a good example of how not to perform a feed-in tariff, how not to design a feed-in tariff.

So in 2009, that was the end of the bumper year investment. Spain also did something that was pretty nasty from a government policy point of view. They decided to retroactively change their feed-in tariff.

AUDIENCE: Ooh.

PROFESSOR: Ooh, so a feed-in tariff is a contract between the government-- or the utility-- and the installer, saying that we will pay a certain amount per year for a number of years. And to go back on that, renege on the feed-in tariff-- that's a no-no. It undermines market confidence. So the PV module prices-- I just wanted to highlight this slide once again, to highlight the market conditions that are being experienced right now. We had, in the mid 2000s, a rise in, or fairly steady prices. And meanwhile, costs were coming down.

This, by the way is price, but in thin films for solar cad-tel, these blue dots here being crystalline silicon. And the prices remained fairly steady. And then in, say, 2008 to 2011, prices have dropped precipitously. The 2011 numbers here are at or slightly below $1.

So you can see, for somebody who is being driven by market conditions, this is extremely unsettling. And it causes capital to fluctuate back and forth. Now the same thing-- what is happening here in the solar modules, the inverse is happening in the installations.

So the installers are seeing the price of their modules go down and the price of their installations declining steadily, but more or less staying fixed because of the investment tax credit staying fixed and so forth in the US, and utility prices rising. And so the installers are saying, hey, this is great. So their profit margins are really big.

Warning to anybody trying to get into the sector right now-- think carefully about these market dynamics in the United States and in Europe, and how that will affect your business. If you're trying to get into the solar absorber, as in module, manufacturing business, or if you're trying to get into the equipment manufacturing business, or in the installation side in the grid, think about how these market dynamics are going to affect your business as it grows and tries to gain a foothold in this environment. It's a great time to be a new installer company, but in three or four years, when we're in an under-supplied condition again, and prices might even go up, what then? So think about these topics.

We're talking about renewable energy R&D and the technology pipeline. So it's important to recognize the path that many of these new technologies take to go from concept or idea into full-scale manufacturing. So in general, this is the path followed in the United States. And we have technology research happening in places like this, at MIT.

The roll-out, in other words, the installations and large-scale manufacturing on the other side. And there are many funding sources available for that-- not so much this last one here in the United States, but maybe in Australia or Europe, in select regions of the US. This technology development right here in the middle has been what is referred to as the Valley of Death. Does anybody know why-- what that means, Valley of Death? What is it?

AUDIENCE: A period when it's difficult to get funding from any source.

PROFESSOR: It's a period when it's difficult to get funding from any source. Now imagine you're a group of postdocs and students in the lab. You come up with a new, fancy technology, and you can't quite get the venture capital or private equity necessary to kick off your company.

That would be one mini-valley of death. It's fairly avoided here in US. Good ideas have a tendency to get funded at that stage.

But if you don't get funded, then the postdoc gets another position over here, becomes a professor at university across the country. The student goes off and does a postdoc in another place. And all of a sudden, three, five, six months later, the venture capital swirls around to the professor, who's still here at MIT and kind of has a hollowed-out group at this point, and says, wow that's a great idea.

I'd like to invest in it. Where's your team? Yeah, poof. So that's one possible mechanism wherein technologies don't make it forward. And so keeping the team together is extremely important.

The second Valley of Death can happen right between technology development and manufacturing and scale-up. We've seen some of these. We've seen pictures of some of the factories. They're around here in the countryside.

These are oftentimes $10s, more likely $100s of millions investments. And venture capital funds tend to be on the order of $100s of millions to $1 billion. They don't like investing in large asset goods.

They don't like investing in factories. They'd rather invest in a small group of people with the computers set in their garage, maybe put in a couple $10s of thousands and turn around, profit of a few million. That's the type of investment that makes a lot of sense for venture capital.

When you start investing in fixed goods-- in brick and mortar-- you need other forms of financing. And some countries around the world have been very adept in providing this financing. China, in particular, has done a great job at making that type of financing available for companies that are small and looking to expand.

But in the United States, it's very difficult to access these essentially money from banks, especially, for new technology. The bank will say, well, why am I investing in you? I could be investing in something that's much more sure of a bet-- today's technology, instead of investing in something risky.

So the government has stepped in with a variety of programs to try to ease that inefficiency in the market. And so one of the means are loans-- loan guarantee program, for example, is one mechanism. There is a [? sunPATH ?] program that is coming down the pipeline as well.

So we have venture capital and private equity, but that can only take you so far, typically. They invest a few $10s of millions, in a few rare cases, a few $100s of millions. But then they reach the end of their credit line, if you will. They exhaust their ability to invest.

And what's needed to expand manufacturing is typically on the order of $100s of millions to billions of dollars to reach 100s of megawatts-- gigawatt scale. So that's the second big Valley of Death in the United States that exists. And the way some companies are transitioning across that valley-- they find a variety of means.

Some go overseas. They say, hey, the Central Bank of China is willing to invest money in me. I go there. I set up manufacturing.

Other companies, small companies, might say, well, GE, you have a big finance group within your big umbrella company. Why don't you buy us? And then we can gain access to capital and expand our manufacturing plant.

Others form partnerships with banks. It's a mixed set of business strategies. But if you look around at some of the start-up companies that are now entering small-scale production, this is where the business side of creativity comes in play. And that's where you really need a good business developer at hand to arrange those deals for you.

In terms of where the money is, in terms of clean tech in general, these are some figures in terms of 2009 data. I'm sure we can get some more up-to-date figures as well. And in terms of growth and investment, we see some countries that might be rather surprising in terms of the five-year growth of investment in renewables. Obviously, if you start from a very small number, you can grow pretty quick in terms of percents. But it's still interesting to see the development of some countries here.

This is sobering. So this is the US government R&D by budget function '55 to '97, the most comprehensive data set I could find. I'm sure that there are graphs that extend this into the future. If you happen to have one, I'd be happy to see it.

But the basic story of this graph is the following-- the lion's share of R&D is going to the Defense Department, so the Army Research Office, Office of Naval Research, DARPA-- that's the advanced research program-- a variety of night vision labs, and so forth. These are a variety of defense R&D. And there is trickle down.

There's some trickle down of technologies being developed in defence into civilian uses. And so I don't want to point to this and say it's a bogey man-- by no means. But it does indicate national priorities in terms of R&D research.

The other big one is health. So NIH, National Institutes of Health-- that's growing and expanding. It's very easy to go to congresspeople and senators who might be advancing in their years, and say, hey, we need money for Alzheimer's research, or we need money for cancer research. It resonates. It's easy to convince people of that. Energy is small, traditionally.

Let me dive forward into this going a little bit further. This is non-defense R&D funding pushed out to 2004. Again, you can see health really driving things.

Energy, traditionally-- in the Jimmy Carter years right around here, it expanded a bit. This was a renewables burst. That's where the National Renewable Energy Laboratory was founded, originally called the Solar Energy Research Institute or SERI.

And then got crimped down again and really experienced a bit of a pinch in the US right when solar was really beginning to take off in Japan. So this is when solar cell production by Sharp was really beginning to climb in the late '90s and early 2000s. And then, of course, Germany followed and the rest of the world.

So we've been a little bit behind, step by step. And the interesting thing that many people have looked into is, what sort of correlation exists between US government R&D spending and output of new ideas. And the output of new ideas, the metric that they're using for this are patents.

So you could dispute that. You could say, well, patents aren't the best indicator of new ideas. Sometimes new ideas are diffuse benefits, and they help all industries, but you can't really patent the idea.

Fine, but this is, I think, the most quantitative comparison that folks have performed. This is an interesting study where folks looked at the number of patents granted and energy R&D funding and plotted it as a function of year, and saw a strong correlation between uptick of national priority and government funding and innovation.

So this was the first wave of innovation in energy, and in PV specifically, in the late 1970s when the OPEC oil crisis hit in the United States and there was a big push for renewable energy development. Yes, question.

AUDIENCE: Just patents in energy or--

PROFESSOR: Yeah, exactly, so these are pushed down. And we can dive into patents just for PV, which is this graph right here. And this is an updated version of that earlier study by Dan Kammen. This earlier stuff study by Robert Margolis. Robert Margolis is now at NREL, National Renewable Energy Laboratory, and he works on market assessment there.

Gregory Nemet was a student at the time with Dan Kammen, produced this wonderful continuation of the study published a few years later. And again, broke it down into specific technologies, including photovoltaics, and saw, again, some correlation between the number of patents and public R&D. In the mid 2000s, this really-- the number of patents and started to grow as startup companies got into the fray.

Remember when prices stayed flat and costs continued coming down, and those margins increased, a bunch of players got into that space and said, we could make money. So a number of patents were filed. A number of startup companies got off the ground. Again, funding-patent correlation for energy in general-- I provide you the data. You can dive into it in more detail if you, not only PV but other technologies-- interesting.

Global trends in venture investing-- since venture investing is important for you specifically, it's one of the pathways to get ideas out of the university and into a startup company. We talked about this so far. And OK, so we're diving a little bit deeper here.

This is for the venture capital private equity financing by sector in 2009, looking specifically at solar in the United States, comprised a large fraction of it. Solar continues to comprise a large fraction of venture investment, surprisingly, despite the market conditions right now. Because folks, especially in the VC community, are looking at today's market as an opportunity. They think that if enough people are scared out of the market, that they'll be able to remain there and pick up the good ideas. And if they're only a little bit smarter than their competition, they can pick up the right companies and the right sections of the value chain-- maybe an equipment manufacturer, maybe an installer with a new idea-- and avoid some of the pain that's going on right now in wafer fabrication and cell fabrication upstream.

This was the VC investment in solar right here in those boom years that I mentioned. So during the years when prices started to plateau because of the silicon feedstock shortage in the mid 2000s, you saw this massive uptick of investment in venture capital funding. That scale is in millions of dollars.

You're exceeding $1 billion of VC funding in solar in 2007. And that trend continued in 2008. So still to this day, we're seeing $100s of millions plowed into solar by venture capital funds. It's interesting, really interesting.

The number of startup companies in the United States has proliferated. There are, I think, somewhere on the order of over 200 solar startup companies worldwide. There are a few that have failed.

So Wakonda, Solasta, SV Solar, Synergen, Optisolar, Solyndra, SpectraWatt, Evergreen Solar-- these are all I'd say failed companies, by the definition of failure-- bankruptcy. I mean, by that metric, so is United Airlines failed, and American Airlines failed. They're still around. They restructured under bankruptcy protection. Some have closed their doors entirely. Other ones have restructured, or are in the process of restructuring.

Why each of these companies have failed? Different reasons. You can't claim that each one had the exact same trajectory.

But you can definitely point to certain market conditions as influencing or precipitating the failure. Let me be more specific. These companies right here are all wafer or thin-film device and module manufacturers. They're the upstream components.

These aren't installation companies. These aren't installers failing. These are upstream manufacturers failing-- and a few high-profile ones at that.

So that was precipitated by the recent market conditions-- the capital crunch. It begins with some of the companies, say OptiSolar in 2009, I believe. They were a company that was producing amorphous silicon modules.

And as we studied amorphous silicon, the efficiencies are low, right? The amorphous silicon module efficiency's on the order of 6%. And they said, well, never mind that our cost structure's a little high.

We're going to scale up like nobody's business. We're going to ramp up manufacturing capacity to over a gigawatt, and do it really, really quick. And just by sheer scale alone, we'll be able to drive down costs and get us to the point where we're competitive on a cents per kilowatt hour basis with crystalline silicon.

There's a great business plan in theory. But what happened to them was, when they went out to try to raise money, they couldn't find any right around 2008. It was the beginning of the financial crisis.

So they had the business plan in mind. And on paper, it looked great. But when it came time to raise the funding to grow, they didn't have it, even though they had a guaranteed customer-- PG&E. That was the Pacific Gas and Electric, the California utility. They just could not get the financing to expand their factory.

So what ended up happening was they folded, sold the supply stream, if you will, to First Solar, who picked it up for pennies on the dollar. And First Solar modules ended up going in the PG&E field installations, instead of the OptiSolar amorphous silicon. Each company has its own story, and have failed for different reasons.

What's clear is also, there are more failed start-ups coming. This is a time of a financial pain for them. The prices are very, very low.

And there are a few people who are tracking these startup companies. I would say Eric Wesoff from Greentech Media is probably one of the most active in publishing his insights. That said, there are many promising companies among here, and some of these, hopefully, will become household names for good reasons in the future, as they have an innovation that significantly drives down cost over their competitors.

We're going to get to that in a few slides. We're going to talk about how to evaluate a company. Because it's going to be important for you-- near term because you might want a job, or you might want to form your own company, long term because you might become an investor in PV. And you have to figure out what types of companies make sense to invest in, and which don't.

In terms of startup companies in the New England area, we often think of ourselves as kind of maybe second fiddle to Silicon Valley. But there's a lot going on in the region, and a lot of good work. So if you go to cleanenergycouncil.org cluster map, you'll see a map of the local clean tech companies in the region. I'll leave this slide up there, since I see a few of you jotting notes. It's a useful map, and you can select by sector as well, if you look at solar, look at biofuels, and so forth.

Trends in renewable energy manufacturing-- this slide is a little bit outdated, but it's the Greentech Media research map of manufacturing in the United States of the different solar technologies-- again, a bit outdated. There are a few companies that have changed. But it gives you a sense of what the distribution is.

What are the latest trends of manufacturing in the United States? The latest trends of manufacturing, if I were to point to a few of them-- Mississippi has emerged as a big manufacturing state. Why?

First off, who's from the Southeast here? Show of hands-- one, two. All right, what do you have in this region right around here that the rest of the country doesn't have?

AUDIENCE: [INAUDIBLE].

PROFESSOR: Close, coal-- you have a lot of coal. You have nuclear as well. The TVA-- does anybody know what the TVA is? Tennessee Valley Authority-- that's a big public works project, in fact, that got started. It provides low-cost electricity to this entire region right up here, including northern Mississippi, including some of the northern portions of the far Southeast states.

Bottom line-- you have depressed wages, by and large, in these rural communities, and low-cost electricity-- which if labor and utilities matter-- which it does in solar manufacturing-- it's ripe for manufacturing. And you have many startup companies-- Stion, Calisolar, Twin Creeks, and others that have moved into the Mississippi region in very recent months for that reason. You have Suniva was based in Georgia, Atlanta. Ohio still continues to be.

The Northwest as well-- cheap hydro, not exactly cheap wages, but cheap hydro. And the technologies do tend to stay closer to the places where they are born. You can see in the San Francisco Bay Area, there's a propensity to form startup companies in new technologies as well as in the Massachusetts area. So these are focusing on some of the medium-scale manufacturers.

In terms of manufacturing support, this is what local state governments are doing to help form new companies in the United States. You have, as well, a variety of mechanisms-- grants, loans, tax credits, and so forth for new factories that are trying to start up. So keep that in mind if you're going for it.

And market incentives-- in terms of the three-- Germany, US, and China-- you also have to consider Korea, Japan, India, Brazil, other countries as well in this mix, if you really want a global perspective. But this dumbs it down to three. In terms of what incentives are available for different countries, there is a plethora of different incentives which can help the market pull.

OK, so we go back and have a clearer picture of what's happening, at least in the US with its investment-- the VC investments as well as manufacturing, the next step on the state level. So we're collecting some data points there. This is interesting.

If your money is from the bank, let's say, and you're paying an interest rate on it and you want to start a new factory, but then your local inspector comes back to you and says, well, we're going to have to delay by three months because of reason x, y and

z. Now you're paying interest on the money, potentially. But you're not generating profits off of it.

So delays cost money. Project delays cost money. It's also an opportunity cost.

And so there was a study done a few years ago looking into why it is that renewable energy projects are delayed. And they came up with some interesting region-dependent conclusions as a result of this study-- whether it's transmission limitations-- Texas, there have even been cases in New York of transmission lines having limited capacity for renewables-- financing constraints, power purchase agreement weaknesses, permitting-- that could be a big slow down if that's not streamlined-- financing and permitting, and negligible local market. And again, we see the TVA popping up here as a negligible market for the renewables, because, well, you have cheap electricity.

It's hard to compete against that. But in other states with more sun and more expensive electricity, there's the potential to install it. But you may be limited, in fact, by the grid. There's a big new study released, I believe it was this week, by the MIT Energy Initiative on the future of the grid. Yeah.

AUDIENCE: Could you say again what PPA stands for?

PROFESSOR: Power Purchase Agreement-- so that's the incentive mechanism whereby you can begin putting the solar panels on your roof, and the installer pays for the panels, gets the money from the bank, installs them on your roof. You sign the contract to pay a certain price for the electricity over the next 12, 15, 20 years.

So global trends in R&D-- this is, again, a data dump of several sources, one from the NSF showing industry R&D expenditures, government, federal government, and other. You can see in the United States-- this is across all sectors here-- but really an inversion of the role of industry and federal government. So when you hear MIT, for instance, going after large companies and saying hey, you should invest in R&D here at MIT, this is one of the fundamental driving forces-- this inversion here, the decline of federal government spending. And as well, has resulted in MIT looking elsewhere for funding, not only industry.

The greatest gains in R&D intensity in terms of the R&D expenditure have been in Asia. You can see on the right-hand side of this chart, China, Japan, and Korea increasing the expenditure from 1997 to 2007. This was right before the financial crisis hit. In the US, holding relatively constant as a percentage, as a share of GDP.

Science and engineering interest in Asia-- this is science and engineering degrees as the percentage of new degrees. You can see over here we have Germany, Korea, and China. Germany makes a lot of sense. The Germans have about 44,000 engineering jobs in renewables right now that are unfilled. So they need people. They need people to go to Germany to get high-tech jobs.

China is a bit more precarious, in the sense that the supply and demand is much more evenly matched. And the growth of both are increasing at steady rates. So if the growth of manufacturing and R&D does not continue to rise in China, there's going to be an oversupply of people. And that can lead to a number of problems.

And so it's very important for China over the next several years to keep a strong, steady handle on this growth, to make growth manageable. It's a good problem to have. It's managing success. But it could also lead to some catastrophic consequences if the system gets out of balance.

In the United States, well, I believe this data came from 2005. That was at the height of financial engineering. I would hope that this number here has increased a bit since the collapse of the financial markets, and a recognition that there are productive ways of investing one's talents and mental gifts.

Global research output shifts towards Asia. This is global research R&D, share of science and engineering articles. So if you're starting from a small amount and growing, you're going to be, if you just look in a percentage basis, by necessity taking away a share of the pie from another entity. So as China grows, India grows, the rest of the world grows.

The share of science and engineering articles in the US and in the EU begin to drop-- essentially the dominant players-- and in Japan as well. Now, that's not necessarily a bad thing if the quality of the articles is maintained, and the total number of articles continues to expand, and we have the capacity to keep up with the information. So there's a threshold, or a limit, to how much we can absorb-- how much new information we can absorb per unit time. So people are working on more sophisticated ways of gathering and assembling this information, especially using computers nowadays, that can help expedite R&D. So a number of trends happening on the scientific side-- you're involved with that.

High-tech trade balances continue to widen. This is the trade balance in high technology goods, US and China. And so obviously, Chinese economy is trending away from-- still heavily invested in raw materials-- but trending away from that toward high-tech manufactured goods. And the US entering a region of trade deficit as a result of purchasing those products. So these are all trends that have policymakers, in particular, concerned, and looking at the future of global competitiveness.

Technology evaluation-- let me spend a couple of words bringing all of what I've just said, and everything over the entire course, home to you. So far we've talked about these things in very ethereal terms. It's useful information. It will prove useful once you begin applying it.

But we want to run through a quick, little scenario right here, where you're asked to evaluate a new PV technology. Why? Well, you might be applying for a job at this company, and they say they have the greatest thing since sliced bread. And you want to put on your thinking cap, and evaluate whether that's true or not.

You might have a new idea or new innovation. And you're trying to make the tough call-- do I go forward and establish a company off of this idea? Or do I have to go back and turn the crank a few more times to come up with the next better idea that's more worthy of investment?

You could be an investor. You could have money at your disposal, and you could decide what company to invest in or what not to invest in. So how do you go about this?

I'd say three fundamental components. And venture capitalists might disagree with me, or other people who have different skill sets might disagree with me. But me, from this perspective as an engineer, I say first analyze the physics. Figure out how this technology works.

Because if you understand how the technology works, you can understand some of the fundamental limitations. You can understand efficiency limits. And you can predict, based on pattern recognition, how hard is it going to be to obtain or to approach those limitations?

Analyze the cost scale potential, meaning the potential to scale up, and manufacturing. This is really more in the engineering science side. And we've been getting more into this during the second and third parts of the course. And analyze markets-- this is definitely the third part of the course. So this begins to pull it all together.

Let's start with analyzing the physics. We talked about conversion efficiency being a strong lever for cost. That's way we're analyzing conversion efficiency. The way I would recommend analyzing any PV technology that they throw at you would be thinking about conversion efficiency in terms of output energy versus input energy. And think about losses along each step of the way.

If you have time with the R&D department, sit down with them. Sit down with some of the chief engineers and walk through each of the steps, going from a light photon entering the device to charge being collected on the other side with a certain current voltage characteristic. And keep in mind that the total efficiency is going to be limited by whatever the worst performer is. And keep that picture in mind, too-- [INAUDIBLE] big advice.

Customer needs-- the next is analyzing what makes your product special. So where is it going to fit into the big picture? Is it going to run with the big dogs? Is it going to be an on-grid application, in which case cents per kilowatt hour really matter-- the price for the electricity for a power purchase agreement? If you're just selling the module, maybe dollars per watt would be an important metric as well.

Or are you going to one of these other niche markets right over here? And are you going to be a player there? How big is that market? These are some questions to ask.

Cost-- all right, so now we know what our intended market is. We know what our product is going to look like. We know the physics behind it. In a bit, we'll know more about the manufacturing.

We think about cost. And we talked briefly about this during class. We had more of an in-depth discussion with Doug.

That Excel spreadsheet, by the way, will be available to you so you can look through it, and see how a cost analysis was done for crystalline silicon, and how you might adapt it to your technologies. But it's really important to perform a cost performance model for your technology so that you can understand what levers to pull, what levers need to be pulled, to increase your parameter of merit, whatever that parameter of merit happens to be for your potential customer need. Manufacturing technologies and scale really do play into this quite a bit. And for many technologies, or for many companies at least in the Silicon Valley area, there might be 50 companies working on the same material-- copper indium gallium diselenide, let's say, CIGS.

But they each have their own deposition process, and they're each trying to develop their own pieces of equipment to manufacture this material. So understanding the basic differences between the different deposition systems is important. And we walked through that during our thin-films lecture. So again, you have access to this information, and you can parse through it in greater detail should you need to.

Scaling of manufacturing-- we talked about resource availability. We even had an in-class debate about it, about cadmium tellurium. There are reports out there which you have access to, like this APS report on critical energy materials.

And we understand that the manufacturing and reserves of these elements are not equitably distributed. In fact, they're concentrated in certain regions of the world. And so that might influence the ultimate potential of a certain technology to scale. And again, this is another intelligent set of questions that you can ask.

We understand a bit about the market dynamics now. We understand this is price. We understand that there was a bit of a plateau in price in the mid 2000s, a precipitous drop over the last three years, and that's really changed the way that investments and equity look at the solar market.

In the mid 2000s, it was all gangbusters. Everybody was really happy to throw any money they had at solar. Now people are a lot more selective in terms of what they invest in. And this trend of oversupply undersupply is probably going to continue for some time if the integrated circuit industry is any example and model. So we're likely to see this continue.

What is your market timing? It might be a really good time to found an installation company right now, if you can scale, and grow quickly, and you have the right niche. But if you have a new idea for a thin-film absorber, it's important to think critically about where the market is going to go over the next few years, and how that impacts your strategy as a company.

You might decide, well, the market's kind of cold right now for modules. So why don't we hold back on building that large-scale manufacturing plant until, say, 2014, and invest really heavily in R&D right now, and stay small, without the financial obligations of a big manufacturing line, until we really nail the technology, and have something good to go. And plus, think about our exit strategy.

Maybe we won't ramp up to be a gigawatt or two gigawatt company. Maybe instead it's more important to form partnerships with companies that are manufacturing cad-tel or CIGS right now. So our business developer's going to spend more time chatting with the business developers of First Solar and other companies.

We also know a bit about the financial incentives from Germany and some of the largest PV markets in the world. We know that China is going to ramp up significantly in terms of installations over the next few years. We know that the United States will, as well, as the prices continue to come down.

These are the PV feed-in tariff rates shown in blue and red for different types of installations, blue being the large, freestanding systems, the red being mostly rooftop mounted systems. So we saw that the feed-in tariff rate in Germany has come down versus time. And the average electricity price has gone up. So we can begin predicting what the role of market subsidies will be when we try to roll out our technology onto the grid. And we can plot this, and see how that will impact our business model as well.

And lastly, we know that about 99% of the solar panels have yet to be made. 99% of the solar panels have yet to be made. So there's a lot of potential here.

This, again, going back to the very first lecture, where we had new energy installations, new PV installations growing significantly. Convergence is coming. Who's going to comprise-- who's going to the bridge that gap? Who is going to be the maker of the technology that will ultimately bring PV to a massive scale in the grid? That's for you to decide.

So other intangibles in terms of evaluating companies would include the team, especially the leadership team. What is their track record? What is their philosophy of running the company? The financing that's available-- how much cash is at hand-- the patent portfolio, how protected are they, and so forth.

Patents, by the way vary in importance from the US to certain other regions of the world. It's very important in the US and Europe, less important in China. But it depends.

If a certain idea is patented, you will have difficulty accessing that market. You will have difficulty selling product into that market, even though you can continue to sell a product into markets that value patents less in IP.

So let's go through a few examples. I'm going to throw a couple of examples at you real quick, and just spout off the first ideas that come to you. How would you analyze this company? Solar paint.

All right, so I have my big spray paint system here, and I go to the side of the house, and I go shh. And that saves me a bundle on installation costs. It's easy. You can do it yourself, and you just connect a few wires and voila, you have solar electricity. What would be your first instinct?

AUDIENCE: How does it work?

PROFESSOR: How does it work? [CLAPPING] Bravo, bravo. What is the physics behind it? How do you separate charge?

If you go back to this right over here-- light absorption, charge excitation is important. What's the [? bang-up ?] of the material? How does it excite charge inside of the material?

Where's charge separated? How do carriers reach those separation points? You're just spraying on one homogeneous layer? Did I get that right? There's not two layers?

Does it phase separate? How does that work? And in charge collection, how are you collecting the charge over that massive area? What are your resistive losses? And so forth.

You're equipped now to ask those questions as a result of this course. That's pretty awesome. You think about it, you're pretty empowered.

So it could work. Solar paint could very well work. So it's important not to ride into this discussion on a high horse and say ooh, won't work because of x, y and z.

It's important to keep an open mind, because new ideas are really quite startling, and they can be game changing. But it's important to have a critical yet respectful approach to this. A critical mind is always a good thing to have on your shoulders.

Wundermaterial-- so I'm arriving to you, and I say, this is the wonder material. It's all earth abundant, totally scalable, but I'm not going to tell you what it is. So you're going to have to invest in my company because I have this great team right here-- a great team coming from Intel.

I used to be a head manager at a national laboratory. I know my stuff. I really know my PV. I can wow you with a few presentations about PV device physics, and talk all this fancy stuff.

But you're going to have to invest in my company based in a few SCM images, plain-view SCM images of the material structure, just to prove that I can actually deposit it. But I'm not going to tell you what the material is, because US VC's could run off with my idea and go sell it to somebody else. So I'm going to hold that very close to my chest. Do you invest in me or not?

AUDIENCE: Depends on what you're asking for.

PROFESSOR: Depends on what you're asking. Depends how much you're asking for. That was a real situation. I was in that room.

I was evaluating that company. And as a scientist in that room, I was, like, are you serious? You can't be serious.

The venture capitalists, however, thought differently, and said, look, the team is really good. And for reasons that were described-- I can't get into all of them without giving the details away-- there were reasons for investing in that particular case, in that company. And even though the physics was not understood, and even though the ultimate efficiency potential was not understood, the VC firm made an investment.

So far it's been going OK with that company. So just to point out that this is a base, a foundation of which to make decisions. It's not a prescription upon which to make decisions.

A lot of things factor in. Use your best judgment. You're the one best equipped to make those decisions.

Path forward-- this is kind of my last few words on the soapbox before I hand over the microphones to you. The path forward, from my perspective-- the markets are going to drive a lot of the public story. But you know that cost matters more than price.

Price is the short-term market pull. During the mid 2000s-- actually, down here when the price was still very, very high, solar was kind of this hippie, tree-hugging group of nerds that would get together at the Muddy Charles and come up with the facts-based analysis, which formed the MIT Energy Club-- really small thing. And then right when the prices began to stabilize and there was this view that energy was a huge gold mine waiting to be explored, a massive amount of interest came into the field-- and growth, accordingly.

And it was good. But in the 2008 and so forth, we had this precipitous drop in prices, as well as the collapse of finance to allow these technologies to scale up. The Valley of Death widened and deepened a bit, if you will. And suddenly, energy looked a lot more precarious.

I started having students come into my office doing interviews, saying what sort of career can I have here? Tell me, seriously, are their jobs waiting for me when I exit? The reality is, there are jobs waiting for bright, smart people regardless of the market condition.

There were jobs back here. There will be jobs in the future as well, if you're good at what you do and you ask the right questions, conduct good experiments, and know how to disseminate your work. But this is kind of a return to the roots now, where we have people who are in solar and interested in solar who are really there for the long run.

And so knowing the market conditions really helps you put everything into perspective, and see how the situation might evolve going forward. In terms of tipping point, it's largely agreed upon that $1 a watt system installed is really where we want to head to. So we know the cost right now of manufacturing a PV module of crystalline silicon is on the order of $1 per watt. And if you're inventing a new technology, you have to do half of that. And crystalline silicon has a roadmap to get to about $0.50 per watt peak by 2020, 2025.

And so if you're developing a new technology, you have to undercut that and some way, shape or form. And you can do that in a variety of ways-- improving the efficiency. There's a lot of headroom in efficiency-- lot of headroom there-- maybe at manufacturing scale and so forth. But if a technology, some technology by 2020, can get to $1 a watt installed, we're looking at, by 2030, a pretty massive, good penetration of PV across the United States.

And that's just the start of it. The US is just the drop in the bucket. This is the world. There's a lot of people-- 1.6 billion of them, approximately-- without electricity right now. They're coming online. And they're driving the majority of the growth in CO2 emissions. Majority of the growth comes from two points-- one, we're outsourcing our CO2.

If you look at the amount of CO2 the United States contributes to the world, it might be 1/5, but if you look at all the manufactured goods, all the clothes we're wearing right now, all of the apparatus that we're using, these were manufactured probably not in the US, but they're here for our consumption and use. We own that carbon. That's our carbon. We're responsible for it.

So our footprint increases further. So we're outsourcing the carbon. It's growing in certain developing regions that are exporting to us.

And secondly, they're also growing. They're also consuming. They're also getting cars, and computers, and so forth.

So there's an overall growth of consumption around the world. We agree that climate change is an issue. And we look at the solar insolation map, and we say, wow, compared to certain minerals, or rare earths, or petroleum, this is fairly equitably distributed. Even regions, say in Patagonia or up in northern Europe, compared to the Equator-- we're looking about a 3x, maybe 4x delta in solar resource, not a million to 1.

We're looking at a 4x delta in solar resource, which is not that big of a spread. And furthermore, if we go back and look at the countries that are really coming online, just using this loose parameter of human development index that we referred to on the first day of class, we can see that the countries with the largest solar resource base-- several of them also happen to be countries that are on the path toward development, on the path toward consumption. And solar can really have an impact in those countries to improve the quality of life, and also reduce carbon emissions overall in the world.

So what role can you play? I mean, I think important things to keep in mind is, we're really at the beginning of solar. We have a lot of headroom to grow.

I think the amount of venture capital investment loss so far due to failed companies is a drop in the bucket compared to GDP. It's a drop in the bucket compared to military investments. It's drop in the bucket to things that we consider important, and especially the quality of life in the world. So it's important to keep that in perspective.

We need to maintain momentum in capital innovation culture. That's what we have here. It's growing in other places around the world as well.

It's important to foster that growth, and evolve into a global society where we have connections and shared connections with groups around the world, shared interests, and can leverage each other's strengths. The rest of the world is catching up fast with increased competition. That's why isolation won't work in this case.

We do need increased R&D efforts on key targets. I think better investments and smarter choices of technology is important. And hopefully, over the course of the class, you're equipped with several of the tools to make those types of decisions yourself.

We also need to change the way we innovate. Pooled resources, collaborative efforts, improved industry-university lab relations-- which in the US are somewhat at a precarious state because of differences in priorities between publications and IP protection and so forth. Direct to manufacturing innovations-- instead of always thinking that startup companies are the only route, thinking in terms of how do I get this technology into a large established company in the US? That's a route that we don't think about very often, but could have a huge impact, and certainly has an impact in Germany.

The need for a steady predictable market-- all right, I think I might be asking too much in this bullet point. But it would be nice. And certainly policy can play a large role in that.

We have enough unpredictability with oversupply and undersupply. We don't need the politicians getting into it as well, and changing their minds every two years. And investment in education as well-- the right type of basic education-- so you can get involved a number of ways. And I encourage you to do so.

I thank you for your attention. And I wish you the best of fortunes going forward. Please feel free to call me whenever you have a need. And I look forward to your presentation. So be well. Thanks.

[APPLAUSE]