[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: OK, so let me just contextualize where we are. So I showed you this, we developed these screening curves in the previous class. And for dispatchable technologies, they are a way of figuring out what is the optimal technology. The first key lesson here is that it's never one. It depends on how frequently you use it.

If you're building a peaker plant, you're going to use a technology with low capital cost, but higher fuel cost, or higher variable costs. So it's steeper. That's like this brown line here. If you're building something that's on all the time, then you're going to use something that is 8,000 hours a year, for example. You're going to use something over here, which has maybe a higher capital cost, nuclear to high capital costs, but very low fuel costs.

And so it turns out, when we take the whole suite of things into consideration, that there is a role, if you will, for high capital cost technologies, like nuclear. Geothermal kind of eats his lunch. But it's not geothermal everywhere. It's not geothermal in the southwestern United States.

But we see that here, these are US prices. If we set the social cost of carbon to $100-- Yes.

AUDIENCE: So could you remind me what the y-axis is?

PROFESSOR: Oh, the y-axis is dollars per kilowatt of-- I think this is either per kilowatt or per megawatt of capacity. I don't know what I multiplied it by. So this is the amount you basically have to pay to have that capacity, even if you don't generate any electricity from that plant.

And then this is the amount that it takes, if you run the plant for 4,000 hours a year, is here. So this is the capital charge that you pay every year. We calculated it. And then this is essentially the variable cost is the slope. And that's determining your net price.

So we wind up with all these lines. And there are certain technologies that are optimized for different things. And we talked about the idea of base load. And base load is something that just means it operates most of the time.

And we reminded ourselves that base load isn't a special feature. It's actually kind of a limitation. There are technologies, like geothermal, like nuclear, that only make sense, meaning they're only low down on the plot, when operated in a base load type capacity. But there's nothing special, technically, about base load otherwise.

So what we found is this. Everyone's good with this plot? Any other questions we might need to refresh? Yep.

AUDIENCE: Could you just show this graph with no social cost of carbon?

PROFESSOR: Yes.

AUDIENCE: Thank you.

PROFESSOR: But that's less exciting. OK, there it is at zero. So, does anyone know what the current EPA prediction is? Social cost of carbon?

So during the Biden administration, they revised their methodology. Initially, the way it was done, it was a higher discount factor. So making the social cost lower. And they considered only the damages in the United States, because it was a federal entity looking at the welfare of the United States.

And in the Biden administration, they revised that procedure. And they said, we should take into account the damages done to the entire world in our calculation. And they also lowered the discount factor. And I think they went from a $22-- we should go look this up-- $22 to something like $30 for the near term. And then this number slowly rises over time. In like 100 years, I think it reaches like $100, something like that. Yeah.

AUDIENCE: 21 to 33.

PROFESSOR: 21 to 33. Yeah, thank you. It's great to have just in time fact checking. So let's just say we're way in the future, things are much worse than we thought. And so it happens earlier. So there's 35, and let's go to 100, like hundreds, something like that.

So what we see is that if we don't have access to geothermal, definitely a role for nuclear. And this was the story in the '90s and early 2000s, when people like your professors and me were getting into nuclear power, this is how we looked at the problem. But then something happened in the 2010s, and that was solar and wind just got cheaper and cheaper and cheaper and cheaper and cheaper and ate our lunch.

So I just showed you results that said, if you allow solar and wind into the equation, things sound really bad for nuclear. And it's just like it was a technology that was essential, but solar and wind, like I said, ate our lunch. But there are still places in the world where solar and wind are not very good, where there's either high latitude, or high amounts of cloud cover, or very low available land. And in those places, the situation looks more like this.

The other part of the story is that all of this is predicated on what I'm calling nuclear fast, which is to say that we can build these reactors essentially at the cost and at the timescales that the vendor says we can do it. In the United States, we didn't build any reactors after the '80s, early '80s, the last reactor was ordered in the '70s. And then we built two, and they were extremely expensive and not actually that long in their construction duration, but they were extremely expensive.

So if nuclear is actually closer to this, which I call it empirical cost, which is the average of the Western countries in the last decade, then it actually doesn't have a role. So the other part of the story is that we do have to figure out how to get nuclear cheaper. Now, if you go back to-- let me just push Play. If you go back to this, you see that there are plenty of predictions that nuclear would be cheap and somehow it wound up expensive.

And part of the variability in these predictions is because they come from Oklo and TerraPower, and companies that are trying to sell the reactor, and they've never built it, and they had no idea. And they're making very highly optimistic predictions about what things will cost. And they're going to get all this discount because they're going to order so many things.

This is exactly what CFS is currently doing with its cost estimates. I sat down with them and they're like, really? You're going to get that major discount? Oh yeah, we think we can get. OK, then. So that's to be expected.

These are sort of now more realistic numbers. We're going to talk about this one a little bit later today, The Future of Nuclear Power report. This is run by [INAUDIBLE]. They're median number of 7,520. And then this is currently what the Department of Energy is saying-- I guess-- wait. Yeah, this is the median number, 7,520, something in this kind of range of around 7,500, 7,700.

What is that? What does that mean? Now, just to remind you, these are overnight costs. So that finance is excluded. The effect of construction delays is excluded.

And so what we're really trying to measure is just the inherent cost of the technology and indirectly a measure of the complexity of the technology. Or to put it another way, the cost of the inputs, the amount of labor and the amount of goods required to build this out.

And so where do these numbers come from if we didn't build any plants in the US, until we built this? They came mainly by looking at what was happening in other countries. And people saying, well, if that country can do it, then we can do it. So I want to talk about what other countries have done to see if we can glean some additional phenomenological insight and what lessons we have.

So this for reference is construction duration for all US reactors. And what you see is that it took longer and longer to build our reactors. This explains some cost increase, but not in the overnight cost. Most of these reactors were supposed to take about half the time that they actually took. And those estimates were bad. And the reason they were bad is because of safety-related considerations.

So for example, they would pour concrete and the concrete wouldn't be as strong as it was supposed to be. They'd have to rip it out and put new concrete. Or there were issues with improperly installed rebar in the basement. So then they had to rip it all out. And so this suggests, these are, if you will, measures of the complexity of the technology and all the safety versions associated with a complex technology.

So duration is a really useful measure. And the reason it's a useful measure is it's directly comparable between different companies. If someone takes five years to build a reactor, and someone else takes 10 years to build the reactors, and those reactors are comparable, then we have some sense of country-specific variation. But if you look at dollars, it turns out there's so many confounding factors about how they count, who pays what, and do they include the price of the land? Do they include the price of the engineering?

And a lot of that is opaque. They don't really issue numbers. They don't tell you what goes into that number. So I will give you both the dollar estimates, and I will give you duration estimates so that you can have some better apples to apples comparison. All right. So let's just look around and see what other countries have done.

I think the country that everyone learns about first as being a success is

AUDIENCE: France.

PROFESSOR: France. Yeah. All right. So let's look at France. All right. So I'm misbehaving a little bit by putting the DOE cost prediction on this plot. Because French numbers are not done under the same kind of accounting as American numbers. They have a state-owned utility.

They have a state-owned reactor company. They have a lot of sites. They recycle their reuse of land. Like, they're not apples to apples, but it gives you some rough estimate.

So the officially reported cost data for France stayed low for quite a long time in the early fleet, up until maybe the '90s. And then between the '90s and the 2000s, there was a little uptick. And part of the problem with having that data point on the plot is it compresses this. It's hard to see, but it's basically a 50% cost increase between the '90s and the 2000s in France. Per unit, kilowatt hour, and inflation adjusted, right? These are all overnight costs that are inflation adjusted.

So something is going on. And the most recent plant, Flamanville, is just outrageously expensive. Five times more expensive than anything the French have built previously. And twice as expensive as the DOE estimate. And part of this is that Flamanville is a first-of-a-kind reactor that was never be built. It's a gen III reactor, AP1000 Gen III+ reactor with a lot of extra safety features. And there was a lot of challenges in getting that reactor to be built directly.

Giant lawsuits, issues related to the casting of the head, the pressure vessel. It had carbon precipitates in it that may limit its life. It was a big mess. They also had the first, I think, entirely virtual control system, and it took a long time to certify all the software. And so there were a lot of issues associated with that reactor.

All right. The more interesting question is, why were these passed? Why were the earlier reactors cheap? In part, it seems to have something to do with standardization. There's more standardization in France than there is in the US.

We have [INAUDIBLE], which is running at full copies. So they kind of knew what to do. And the US, even though we had a notional standard design, like the Westinghouse four-loop, every time it got built, it was different because things had to be adjusted for the site, and the owner wanted to connect it with a different turbine than the one that was designed for. And all of these other issues. So they have some advantages on that front.

And if you look at the engineering cost for mapping out where everything goes, where all the pipes go, before the reactor gets built, France's average engineering cost is about 15% of the total cost. The US average engineering cost is about 25% of the total cost. So you can see there's a little bit of cost savings right there. 10% just from this standardization.

So given the wonderful prices for these reactors, which, again, are not really apples to apples comparisons to what the US has, we might ask, what is the cost of electricity in France? According to the French government, the price is about $70 per megawatt, if we convert it to dollars. So about $70 per megawatt hour. Which puts the price of nuclear in France in between the price of, say, wind and offshore wind, if you remember those things, right?

So it's still more expensive than wind, regular wind, onshore wind and solar. But it's not the most expensive thing. And it is dispatchable. So it fits into that role where you have some kind of low-carbon dispatchable power source that is useful for setting of variability. So I think it would still make sense in France, if those numbers are true.

The construction durations, however, tell a little bit of a different story. If France was building all these reactors, and they were all cheap, and they were learning on how to build them cheaply, why did it take more and more and more and more time to build each reactor as it went along? So far, I don't have a really convincing answer to the details. But there is a correlation that I want to talk about. I can't prove this is the cause.

And the correlation is that it turns out France's reactors are not very reliable. So at any given moment, about one in four [INAUDIBLE] reactors is down for repair. So they have about a 74.5% uptime availability-- sorry. This is probably where the noise is coming up.

74.5% availability over their fleet. Historically up until 2024. So that's pretty low. The US availability is about 99%. And so what is causing that?

Well, they have all these unplanned outages. And they've had some major issues, like stress corrosion cracking, but they just have other maintenance stuff that they do that we don't have to do. And so the kind of intuitive takeaway is that as they've built these reactors, they've realized they need to build them to higher standards. And they were cheaper, but that's why they kind of took longer and longer is they're trying to get that reliability up there.

So to put it another way, you pay either upfront or you pay later to do the maintenance. And when you pay later, you have to pay that capital charge on the reactor every year, even though the reactor is not producing electricity. And so that drives up the cost of electricity, the effective cost of electricity on the fleet-wide average.

The other problem with this strategy of build it cheap, fix it later is every time something fails, you have a potential safety-related issue, right? It becomes a precipitating event for a scram or some kind of valve failure or something or other. There isn't a strict one-to-one correspondence between unplanned outages and safety issues, but you can see that there would be some kind of correlation between those two factors. So arguably, France's fleet, while cheap, is maybe not super safe. And it turns out this kind of correlation between safety and cost actually shows up over and over, as you're going to see in a moment.

So another big success story is Japan. Cost and duration in Japan were exceedingly well controlled. They were building the reactors really, really fast. On average, they didn't have any increase in the duration of construction, and they were about four years to build a reactor, compared to our predicted number of around six years and actual number of around 10 years. And we can just go look at the French numbers. Just go back. You see, they were like six in the beginning and they went up to 10 to 12 later on, which is kind of what we see in the US.

So how was it that Japan was able to keep these numbers so low? And you'll see that all these reactors are just being constantly built. Prices were not nearly as low as the French reactors. They're closer to what the MIT numbers were based on or closer to the MIT predictions. And the reason is that this is the numbers they were based on initially. And then you see, of course, they stopped building reactors after the Fukushima incident.

Another interesting just upfront observation is most of these reactors in Japan were actually US designs being just being built by the Japanese. So a lot of people in the United States were saying, well, these are US reactors that we can build here. So presumably we can build them at the same speed and at the same cost. And that was the assumption that went into a lot of the estimates, like these estimates here. All right.

What actually happened? Well, it turns out they also had major safety issues. So I guess I can read it to you or you can read it. Maybe you just read it and raise your hand when you're done reading it.

Good? Yeah. So it turns out that basically the regulator was completely neutered and it had no power in Japan. And this prevents all kinds of delays during construction. You just build a reactor and you just get what you get, and it's fine.

Even with all of this, it's interesting to note that TEPCO, the company that built most of these and owned the Fukushima plant, still kept losing money because the plants were just not profitable with all the maintenance that they were having to do. Not surprising because they were so shoddily built, and that was leading to this downward spiral where they would try to cut further cost to try to make the company profitable again.

And just as an example of that, when the Fukushima accident occurred, TEPCO, the company who owned the plant, did not even have a diagram of the internal pipework of the plant for the emergency responders. They had an original draft of what they thought it might be, but no one had actually kept track of what was actually built in the plant. It was really cutting every possible corner. And so it's true that Japan's reactor fleet is kind of an economic miracle, but maybe it's just too much miracle.

And it turns out there's no free lunch. They didn't just get out of jail with one Fukushima accident card. They continued to pay the price. So we are now 14 years after the Fukushima accident, and most of the reactors are still shut down. And they are paying for all of these reactors, and they're not producing electricity. And why are they still shut down, is that they are working on fixing the safety problems associated that they've discovered after these reactors were shut down.

So when you factor in all of this shutdown time, even the ones that are operational, by the way, are only operating about 60% of the time. They're that unreliable. So when you factor all of this in, their price per kilowatt of capacity, effective price per kilowatt of capacity, it's not $5,000 per kilowatt, or $7,000 per kilowatt, or $19,000 per kilowatt, which is what it is for Vogtle. It's $44,000 per kilowatt.

So it's really easy to look at this historical data and say, look, we could do what Japan did. But unless you look at the whole picture about their availability, the safety, maintenance issues and so on, you don't get an understanding what really happened. And now they have probably some of the most expensive nuclear power on the planet, in real terms.

So it did not save money in the end. It actually cost them a lot of money. And that just goes to say that building fast and cheap probably isn't the way to do this.

There was a similar trend happening in Korea. Total investment costs and overnight costs in Korea were trending downward for many years. Even construction durations were going very slightly downwards. And then there was a turnaround, as you can see here, right here at the Fukushima accident, things turned around.

And I had a conversation. The former chairman of Korea's version of the NRC, their safety regulator, is a friend of mine. And he was telling me that they had all these unsafe labor standards for workers building these reactors. So let's see. Do I have some number here?

So it turns out, they passed a law, after somewhere around here, that said that workers cannot work for more than 56 hours a week on the reactor. So before that, their construction workers were working 80-hour weeks. Can you imagine being a construction worker working an 80-hour week, how exhausted you would be? How prone to making mistakes you might be? And this is how they were making this happen.

There were also a bunch of scandals. So in 2003, it was revealed that some 8,000 parts in at least six different reactors supplied between 2002 and 2013, which come with safety certificates, in this country we call them the N-Stamp, they were completely falsified safety certificates. They were just fake. So all of those parts had to go back and be inspected and checked. A bunch of reactors got shut down and some people went to jail because of this.

So now because of these fake parts, the reactors are undergoing retrofits which cost roughly 7% of the total construction cost of a reactor every five years or so. So they have a very chunky maintenance bill on top of their operating costs because of this. And they also have very low reliability. About 23% of the time their reactors are being shut down for maintenance and service. Again, in the US, only 1% of the time.

So then there were safety standard increases for the designs after both the Fukushima and Gyeongju earthquakes that they implemented. And all of this has basically driven the price up and the construction up, construction duration up. They've stopped publishing the prices for their reactors. So we don't know how much they actually cost.

But we do know when the reactor turns on. So you can see there's more data here in the duration time. And what you see is essentially, Korea went from being something similar to Japan, of an economic miracle, to having construction durations of about 10 years, just like the US and the French. And their costs are turning upwards. And we'll see where they come out, if they ever publish their data again.

Korea does publish predicted pre-construction costs, still, for new reactor projects. And their current predicted price is $9 billion a reactor, which is slightly above what the US DOE is predicting per reactor. So they've learned that essentially they cannot do it so cheaply. Basically, the Korean industry has turned into the US industry.

All right. India is a very interesting and unusual country. The cost of reactors in India has been systematically coming down. And we will say, what is going on there? Is this evidence that India is the only country that can actually figure out how to learn? We'll talk about that in a moment.

However, construction durations are going up. And this is, if they were really learning, why do the durations go up? Also, you'll notice that they start at around eight and they go up towards 14 years. They actually take quite a long time to build.

So India is a bit of a strange case. The nuclear power in India is financed only partly by loans, and until recently, at least half of the cost of the reactor was just paid every year out of the central government's budget. So they don't have to borrow money. They don't have to worry about finance charges. And one of the effects of that, though, is that they have a certain budget of what they can spend this year, and that's all the construction they can afford to do.

And so the construction duration is going to go very methodically and plod along slowly, as opposed to in the US, where people are taking loans for billions of dollars, paying interest, and they better get that damn plant built as fast as possible. So it's a different dynamic, and that probably results in basically fewer errors during construction and better safety.

And indeed, India's fleet is one of the most reliable in the world. They're down only 4.4% of the time, compared to the 23%, 25% that you see in other countries. 40% for Japan now. So this slower method of construction appears anecdotally to be related to this high availability, high safety record that India has at the moment.

So just if we step back and look at all the countries, we see that all the major nuclear countries-- USA, France, Japan-- costs have been going up. India, the costs have been coming down. Korea had costs going down for a while, but they've turned and their new predicted costs are way up here. $9 billion a reactor.

There are still residual differences between these countries that are not revealed in the conversation we just had. For example, labor productivity in Asia is much higher than it is in the US. There, employees don't have as many safety standards. They get more done, basically.

You can look at that in two ways. You can say, oh, they're more efficient and we should do the same. Or you could say, well, they're exploiting their workers and we would never do that. And so this is not something that we can replicate. And that's up to you. But that's one of the reasons why labor costs in the US are as high as they are.

One insight that appears to emerge is this correspondence between, as I've mentioned, nuclear costs and availability. Cheaper programs have more outages in the long run, more failures, and that implies more safety risk. And it's very visible in the countries that had scandals, like Korea and Japan, where people went to jail. We also saw a correlation between reactor generation and costs. Both Vogtle, which is the AP1000-- yeah.

AUDIENCE: You can finish.

PROFESSOR: OK, let me finish this. Both Vogtle, which is the AP1000, which is the Gen III+ reactor, and EPR2, which is the French reactor, are both new Gen III+ reactors, and they both have outrageously high cost compared to everything that we've seen historically. And whether those are first-of-a-kind costs or not, or are they something related to the technology, we won't know unless we build a bunch of them. But there does seem to be something going on, because the first copies of older reactors were not nearly as expensive.

So an important question for us as a class will be, is there too much safety? So we saw that when they tried to cut costs, they paid later on with reliability that potentially leads to more safety issues down the road. But then when we designed really safe reactors, like the French and the American reactor, the price went through the roofs. So we need to do a calculation to estimate the true safety of nuclear power in order to make a decision about what is the right technology to build, in order to make a decision about whether nuclear has a future to address climate change. And so we will do that. Yeah.

AUDIENCE: What's your perspective on engineering safety versus operations safety? So for commercial reactors in the US, we typically rely on more engineering safety. But for naval reactors, the theory is basically you just have a bunch of very overqualified reactor operators who are always on shift.

PROFESSOR: Oh, I think there's lots of engineering safety in naval reactors.

AUDIENCE: There is a lot, don't get me wrong.

PROFESSOR: Yeah, no, there's a lot. But we do have a better safety culture in the US industry than in other countries. And that's driven by a whole lot of things. Liability drives that. It's driven by the supporting structure set up by INPO, which is Institute of Nuclear Power Operators, INPO. It says, essentially, if there are small issues at your plant, you can share this information with others and without it becoming public.

And so people learn from each other without being embarrassed, which is not something that necessarily happens in other countries. And it also turns out that the insurance that the plant operators have to purchase, the price of that insurance is related to how many safety incidents they have. So that drives them to have a lot of pressure for safe operation of the plant. For state-owned enterprises, where it's just person showing up to their government job, and they don't give an F, that might not be the case. So questions, questions, questions? Yeah.

AUDIENCE: Are there any insights on the other countries, like China and Russia and all that, or is the data just--

PROFESSOR: There's no good data. And that's largely because the plants in those countries are built entirely outside of the free market system. So they have Institute of Machine Building 44 making this part for the reactor. But that Institute of Machine Building would exist anyway. And its budgetary costs show up somewhere that is unrelated to the nuclear plant. And so there's no good way to actually price it.

China does publish prices for their reactors, but you basically just can't trust them. It's not even clear they really know what they cost. So, yeah.

AUDIENCE: It's like approximately 20-year gap between us building a reactor and also France that plays into that trend of the heavily increased costs?

PROFESSOR: Yeah, I do. I think there's definitely some component of that. We have certainly lost a lot of industrial capacity in the US and probably in the West as things have been offshored. Korea has fantastic industrial capacity. Again, their predicted prices are higher. So I do think it's a combination of all of these things. Yeah.

AUDIENCE: Is the Indian technology different? Are they also using US designs?

PROFESSOR: No, they use completely their own designs. Yeah, it's a fascinating history for a nuclear program. The original design was they stole a CANDU design from the Canadians, and then they just couldn't build it because they didn't have the industrial base. So they said, OK, well, if it has some fancy, let's say, root style pump or some kind of fancy pump, we'll just replace it with a propeller pump because we can make a propeller pump. And then they just systematically went through and changed things.

And they have a really weird regulatory process also. They have these people who are kind of gods in their little area. So they'd be like the god of pump safety, and whatever that person says, goes. But the result is that there's these high concentrations of expertise in different areas in the regulatory structure. It's a really interesting system, completely different from the rest of the world. Yeah. Yeah.

AUDIENCE: So how does someone become the god of--

PROFESSOR: I have no idea. Yeah. Yeah. It's not at all like with computer codes in teams and stuff. It's just like-- yeah.

AUDIENCE: They seem to be experts, by training or-- it's like political appointee?

PROFESSOR: No, no, no, no, no, no. Yeah. Yeah. No, they are people who have spent their life, being the Indian expert on pump design for reactors. And then they become-- yeah, it's a very interesting kind of model.

All right. So we do need to figure out what the situation. Any other questions on this or other countries? Yeah.

AUDIENCE: You may be about to cover this, but how does nuclear accident rates compare to other energy sources? Is there a socially acceptable accident rate when it comes to coal spills or oil spills?

PROFESSOR: We will cover that, but weeks from now.

AUDIENCE: OK.

PROFESSOR: Yeah, we will get to that. So yeah, we do need to do that calculation of what is acceptably safe. And that is going to be based on a comparative analysis with other technologies. So yeah, and we'll do the deaths per kilowatt or terawatt hour calculation, which is floating around on what-- yeah.

AUDIENCE: You touched on it for India. Could you discuss what the regulatory structure looks like in France, and Japan, and Korea, and how that might contrast with the US?

PROFESSOR: Oh, OK. So if you're really interested in this, go read on DSpace. Everyone know about DSpace? DSpace is an MIT website where all your theses are stored and people can put papers up there. You'll probably find on DSpace a PhD dissertation by Aditi Verma, who did a comparative study of the French, Indian, and US regulatory histories and how they came about.

The French regulator has-- they're kind of like the NRC, but they work more intimately with the designers. So in the US, you design your reactor, you're a private company, you design your reactor, and you pay $1 billion to the NRC, and they run all of their codes and they check to see if your reactor is safe. And it's like going for a test.

And in the French system, the regulatory safety people work with the designers as they're designing the reactor. So well, we think this should be improved here. And then they say, well, but then we're going to have to do this. OK, well, then why don't we do this other thing? And there's like this back and forth all through the process.

So it seems like a good way to more efficiently make trade-offs between safety and cost. But unfortunately, this number doesn't back it up. So it is what it is? Yeah. And then I think the Japanese and Korean regulatory structures, but I'm not 100% sure of this, but I think they're basically just modeled on the US NRC. But they are much disempowered relative to the NRC, or historically were disempowered. Further questions?

OK. So a big part of this is, we would like to get the cost down. And people talk about learning. And there hasn't been a lot of evidence of learning here. Oh, I want to answer the mystery before I go on. OK.

So it turns out, India-- this will come up in a moment. I'll just tell you what the answer is. Why did India's costs come down? Because their reactors got bigger. Dramatically bigger as they print. And so their cost per unit of electricity came down. And their times to build those reactors got longer because the reactors got bigger. So that turns out to be the answer.

And the fact that wasn't obvious from these data is an important point. There are all these unobserved variables. And people looking at these data, trying to draw conclusions about what things cost, but without looking at all of the parameters, are often drawing the wrong conclusions. And so we are going to try to measure this in a more robust way.

So let's look at how we would do this rigorously. How we would look at the potential for bringing the cost down through learning. So there are various ideas for how learning occurs when you build things. Probably all of you have heard of Moore's law. Moore's law basically says that the cost, beta is minus, comes down as a function of time. Or you could say that the number of transistors per unit cost goes up per, or something like that.

The problem is that if you don't do anything, there's no reason for the cost to come down. If you don't practice making reactors, they're not going to magically get cheaper. So it's a poor correlation where time is correlated with output. But it's a bad measure. It's a bad model. Unfortunately, NREL, the National--

AUDIENCE: Renewable Energy Laboratory.

PROFESSOR: Yeah, Renewable Energy Laboratory, has a giant cost model that they use to predict the future cost of all kinds of generation technology, including reactor. And in fact, if we go back to this number, this 2018 number, this came from NREL. That is NREL's number. That's where they got it.

And the problem is that, if we don't build reactors, we shouldn't expect them to get cheaper. But the NREL model just magically lets them get cheaper with time. So we shouldn't do that. And we can't trust the annual data for that reason.

So there are other cost models that are based on something called Wright's law. This was developed by TP Wright in 1936 to predict the cost of airplanes. This is not the Wright brothers. This is a different Wright, but it was also associated with airplanes.

And there have been a number of statistical analyzes of different cost models to see which cost models actually fit historical data best. And indeed, these cost models, this capacity-based cost models, or units built, or capacity kilowatts built, or hours of time spent building, are the best models.

All right. The problem with just having a simple cost model that looks like this, the cost is number of units that I built to some exponent, which is to say, if the exponent were negative, we would be like, the cost comes down for every doubling by the same amount for every doubling or every tripling of capacity is logarithmic. Problem is that you have these, you can't really solve this equation because of something called collinearity. So let me just show you what I mean.

This is the history of construction of US reactors. Starting in the 1950s, these were called small modular reactors-- I mean, these early reactors, they were basically the same size as our small modular reactors that we're talking about building today. And they got bigger and bigger and bigger. And they got bigger because you had better economies of scale.

And to keep the cost per unit kilowatt down, we made the reactors large. But here's the problem. There's almost perfectly linear correlation between the number of reactors built and the size of the reactor. So if you look at the historical data and you attribute the cost reduction to the number of reactors built, you may accidentally be measuring the cost reduction associated with the change in reactor size.

So you have to control for this. And there are a number of other variables that people should be controlling for. So this is what explains the India stuff. Here is the Indian reactor size. And you can see that the reactors are getting larger. And this basically accounts for the cost trend.

OK. Also describes some of what was going on in Korea. The reactors were getting larger, the costs were coming down. And then the better safety standards pushed the cost back up. So it's kind of rough, because you have to remember that these are not points. These are the durations of construction are large and so on. So it's hard to see the correlation.

But the problem. So organizations like NEI have published all kinds of statements about the ability to bring the cost down based on the slope of these curves, but they are ignoring the slope of these curves when they make those statements. So here's a generalized cost model. Let me just explain to you why it has the shape that it does. I guess I'll write right over here.

So we have the idea that the cost is equal to something like A, some factor, some input B to some power alpha, some input C to some power gamma, and dot, dot, dot, dot, and so on. And this is called a Cobb-Douglas production function. And the reason why people like this shape of production is that you can take the first partial of cost with respect to any input. So let's say the partial with respect to B. And then, of course, we get B times alpha times B to the alpha minus 1, C gamma, dot, dot, dot, dot.

And then we can do the following math. Partial cost, partial B times B over cost is equal to-- and we'll just write out-- the denominator is A, B alpha, C gamma, dot, dot, dot. And the numerator is-- let's write it as alpha-- numerator is B, times alpha, times A, times B to the alpha minus 1, C to the gamma, dot, dot, dot. And of course, this B joins up with this B to make this alpha. And then this whole base cancels this. And what we're left with is this equation where this is proportional.

So now I just rearrange this side, and I get partial cost. Sorry, I'm blocking the board here. Over cost is equal to alpha times partial B over B. Did I do that right? Yeah.

So what does that mean? How do we interpret that? That means a change in the cost of some input B, and say a 1% change in the cost of input B, will have an alpha percent change, a constant effective percent change in the change of cost in the reactor. And so that idea that there's this constant percent for percent change is a nice assumption that seems to more or less hold and is independent of scale. And so this is why people use this type of model.

So there it is just written out. And there's the B, and the C, and the D, and the E. All these controls will be in here. And then there's the key one that we're interested in is experience.

And another nice thing about this is you can take the log of the whole equation. So you take the log of cost. And then all of these exponents come down, right, when you take the log of something. So you get this format. And the nice thing about this format is it's a linear equation. And that means it can be solved with least squares regression.

So this is how people essentially do the fitting to estimate these parameters. So what kind of controls are we interested in? So controls could be something like, is it the first of a kind for that reactor design? Is it the first reactor built at a site or is it the second or third reactor built at a site?

What country was it built in? What labor cost is showing in that country? Was it built before Three Mile Island when we didn't care about reactor safety or after Three Mile Island? You have a binary variable? Yep.

AUDIENCE: It's just a kind of weird question regarding the equation. What actually are we measuring for experience? Is that literal years spent in building reactors?

PROFESSOR: You can do it in different ways? I think ideally it would be, man years in reactor construction, but these data are hard to come by. So the way most people do it is just by number of reactors built. Yeah.

AUDIENCE: Cool.

PROFESSOR: Yeah. Some people have proposed looking at kilowatt of capacity built, but I think that's probably sub-ideal. But you could do that also. All right. So if we control for-- oh, OK. So let me just give you some more terms of art.

You can basically solve this equation. And then you get these betas out when you solve. When you do the linear regression, you get betas for all the inputs. And we have this thing called 2 to the beta is the progress ratio. Or we have the learning rate, which is 100% times 1 minus 2 to the beta.

And so the way to put this into words is, the cost reduction in percent terms for every doubling of experience, that is the way we talk about it. If we double the number of reactors built, a beta of 0.2 means a 20% cost reduction for every doubling of reactors built. All right.

So let's look at some historical estimates of learning and critique them. And then we'll do our own. So the early ones-- actually, these are not organized by time. The first two found that, indeed, if you build more reactors, the cost would come down. 4% per doubling or 12% per doubling. But they made no attempt to control for reactor size. So their models confused the fact that reactors got larger with the cost coming down.

These second two focused on construction firms rather than on the cost to the utility. And they concluded that actually, construction firms were bringing their costs down. They were actually building reactors faster, but the costs were not coming down. And they concluded that might be because of what they called rent capturing, which is to say, they're now the company that builds reactors.

And so they give you the first one at actual cost, but now they want to make some profit, and they're just squeezing the utilities for profit. That may be true. And there's some evidence that one of the big construction companies in the US, Fluor, has been doing that with the NuScale reactor.

But the other explanation that would produce the same effect that these people observed is that, yeah, so 7% learning to firm to construction firms at minus 49% industry. The other thing that would explain this would simply be that there's a lot of extra regulatory crap going on. So while the construction is maybe becoming more efficient, there's more to do, build the same reactor because of regulatory pressure.

Zimmerman, Cantor and Hewlett both have really good statistics. I can't remember which one, maybe Cantor and Hewlett, one of these guys is on the board of the Fed. He's like a real econometrician and knows what they're doing. But they did not fit the traditional Cobb-Douglas style function.

They instead found that the data was better fitted by a hyperbolic-learning function. So instead of a logarithmic decrease in cost, they have something that basically looks like this. And then the cost savings asymptotes to basically zero instead of continuously going down, down, down, and down.

AUDIENCE: That makes sense, though?

PROFESSOR: It does kind of make sense.

AUDIENCE: Because you're going to reach a minimal cost at some point.

PROFESSOR: Well, that's what people thought. But the whole learning literature actually shows the opposite. It's amazing how things just keep getting cheaper, more and more and more slowly. But they seem to get cheaper, almost like in perpetuity. But this says it very quickly after there's three or four reactors, there's no more learning to be had.

And that model, I think, is a good model that describes the difference between first-of-a-kind and Nth-of-a-kind. The first time you build a reactor, oh, you didn't realize, this pipe is not going to fit through this doorway. And so you make some changes. But after a while, you debug it, and then there's no more construction based learning to be had.

And so I think that is a good model for the first-of-a-kind, Nth-of-a-kind. The question is, though, that does not give you the long-term steady cost reduction that we would want to see to bring the cost down. So unfortunately, while these are very good models, they don't tell us anything about long-term learning potential.

This Grubler and Escobar both focused on France. This guy is accused of using bad data. And so Escobar, Rangel, and Leveque-- or however you say this name-- redid the study using better quality data. So initially, Grubler was saying, prices going up by crazy amounts, negative learning. And they said, oh, this is not fair.

And so they redid it, and they said, something in this range. And basically there was no statistical significance in their data set. So it's like approximately zero.

And then Buongiorno, along with Eash-Gates, did this study of a few different kind of reactor types, looking at particular key components, and found, depending on what they were looking at, somewhere between minus 115% to minus 31% learning. So again, costs are going up and up. But basically, they did not do any of these controls that we talked about. They just looked at the prices and didn't control for things.

So we need to do-- none of this, this is all the entire literature on cost, and it's all crap. So we need to do a better job. And so for this class, I have produced a regression with 428 reactors. Painfully data collected.

The eight largest nuclear countries. Extensive controls on experimental reactors have been removed. Heteroskedastic and autocorrelation robust estimation model. And the various models are selected based on the Akaike information criterion. We can talk about that at some future point. But basically this is a very robust way of attempting to estimate the learning potential.

And I will just show you some results. This is the screenshot of the output. In the end, only 341 reactors are in the model because of the, what, 428 we started with, yeah, we removed all reactors that were one-offs, for which that particular design was not built multiple times, and therefore, we can't measure learning. We do this by reactor design. I guess that's principally the cause. Experimental reactors are the same.

Everything is statistically significant. What is this? Unless you're in Canada, so is Canadian, is German, is French, is British. So these are different controls for different countries. Log of capacity factor. First at a site. Number of reactors that you've completed, whether or not the reactor is built before or after Three Mile Island.

Also we control for the total number of reactors in the project and the number of total projects that the country has built or licensed, so they did some separate measure. So just let me just put the results in a way that is easier to read the data table.

So if your reactor was built before Three Mile Island, this says it will cost 40% of what it would cost after Three Mile Island. That's basically the cost of the safety improvements that evolves. Again, get back to this question. Is there too much safety? Because if we can drop the cost by that much, basically 50%, that would have a big impact.

Reactor size. No surprise here. For every doubling of reactor size, there's a 20% cost reduction. So this is why reactors got big in the first place, as you saw in the data.

But here's the problem. Now we're talking about making reactors small. So what that do to the cost? So we can just do a quick calculation. The NuScale reactor is about 77 megawatts electric. And the AP1000 is about 1,100 megawatts electric. So we can ask, how many doublings are there to go from-- inverse doublings-- to go from the AP1000, where we have cost data, to the NuScale?

And so we can do this by taking this, log base 2, which will tell us how many doublings, which, of course, is equal to, what? Ln of 77 over 1,100 divided by ln of 2, which I believe is minus 3.84. So with minus 3.84 doublings, and so then we want to know, what is the change in cost?

So the new cost will be 20% reduction. So 1 minus 0.2-- or 0.8-- to the minus 3.84. Because for every doubling, we have a 20% cost, and we have minus 3.84 doublings. And this turns out to be 2.35.

So on a per kilowatt capacity basis, the fact that we've gone small, we would predict we'll increase the cost by a factor of 2 and 1/2, roughly. And so NuScale has to make up, these small modular reactor concepts, have to make up that loss of cost reduction somewhere else. And the place they hope to make it up is in factory fabrication. And we'll have a lecture on whether they're getting there or not. All right.

So this comes out of the data. That's a 95% confidence interval. And you'll see that it's pretty good. Reasonably tight. If you build it first reactor at a site, it will cost you 12% more because you have to deal with this site purchase and issues like that.

If your project size is larger, two reactors instead of one reactor, your cost comes down by 4%. If it's four reactors instead of two reactors, your cost comes down by 4%. So it's a little bit of savings, but it's one of the reasons you see that we never build one reactor at a time now.

And this section is a weird phenomenon. It's not a weird phenomenon. It's kind of an expected phenomenon. Let me just explain what's going on.

The model is attempting to apportion the variability that it sees between the number of licenses granted, or projects completed, if you will, and the number of reactors built. But there's an almost perfect one-to-one correlation between these things. So it doesn't know exactly how to apportion that variability. And this is a big, big uncertainty in how that does, they call it "horse racing" when you do regression.

So basically, if you just want total number of everything's, licensed and built, we would add these two numbers together and we would get 1% as the learning per project license and completed. Does that make sense? OK. So that's interesting because a 1% learning per every doubling kind of is consistent with the data we've seen.

The data is all over the place. We don't see dramatic learning. And what it says is that you can build a lot of reactors and they will come down in price, but it will happen very, very, very slowly. To get to the cost that we need, we're going to have to double and double and double and double and double. And we're going to go down 1%, go down 2%, go down 3%. It's going to be really slow.

Building a lot of reactors is not going to be the answer to getting the price down. It's got to be something else, like reducing safety or switching how they're built from stick-built to factory-built, or something else. And so that's kind of the result of this. And that's also, if you will, consistent with all of this.

Basically, the person who was the economist and really knew what he was doing said there's basically no learning. These people said there's basically very little learning. And it's consistent. We don't see any really good studies that show there's lots of learning.

All right. So that's kind of the end of this. Will nuclear power be cheaper if we just build more? Yes, but insignificantly. So we have to fix it somewhere else.

While I have this license and built story up here, I think I will use the next few minutes to tell you about the combined operating license. In the United States, we used to have a process where you would go to the NRC and get a construction permit, and then you would tell them what you were going to build. And then after you built it, and it will never be built in the way that you thought it was going to be built, they would come back and they would give you an operating license.

The problem there is, I don't remember when it was, there was a shorthand nuclear plant built in New York. And they were doing this and they built the whole plant and they were going for their operating license. It was built in Long Island. And the local community, anti-nuclear activists got all activated.

And they said, if there's a reactor accident and we're on the far side of Long Island, there's no way for us to evacuate except to go into the radioactive plume. And this led to a lot of public pressure to delay the issuance of the operating license. And eventually they just gave up.

So there's a whole plant that was built, ready to go, never operated. So the industry said, never will we let this happen again. And they went to the NRC and they said, we need you to change the rules so that this can't happen. And so the NRC said, well, our obligation is to make sure that the plant that is built is a safe plant, and we need to know what has been built.

And so they came up with this agreement called the COL, Combined Operating License. And it works like this. You tell us what you're going to build, and as long as you build exactly what you say, then you can operate it. But if you make any changes, you have to get a license variant exemption, basically.

So that is how plants have been built since. But now what happens is, inevitably they have to change something during the construction, and then they have to go back and get NRC approval for that change as they're doing the construction, which then slows down the construction, which then causes the interest payments to accumulate, which increases the cost of nuclear power. And so this is what happened in part with the Vogtle design.

There were something like of order 100 license modifications during the construction. And it's not a surprise that pervades everything and pushes up the price. So we have not yet figured out how to modify stick-built construction to make it so that this won't happen. Yeah.

AUDIENCE: So given the obvious risk, I don't know that this ever would happen. But does the NRC still allow you to do the construction permit and then the--

PROFESSOR: I think it's still on the books.

AUDIENCE: OK, I'm curious as to if there's any marginal savings there, if you have a community that's very down to have nuclear power. So you don't have to worry about.

PROFESSOR: Yeah, so I think the sociologists who study nuclear energy would probably say, if you do more consent-based siting, where you get everyone to buy-in before you start building the plant, then you could go back to the other model and it would probably save you time. Yeah. So I mean, the way the new model works is, they get their construction permit. Nobody in the community really is paying attention.

And suddenly there's a nuclear power plant being built and people are like, wait a second, we're opposed. You're like, oh, sorry, too late. You should have come to the meeting before-- now the COL has been granted, nothing you can do. And it's honestly not fair to those communities, but the better way would be just to do as you say. Do the consent-based siting first, and then build the plant under the old licensing model. Yeah.

AUDIENCE: It sounds like the COL that reinvented the French system. Your company has to be in constant conversation with the NRC. You know, it would like. And they'll be like, I don't know, maybe try this instead. And then if you do that time after time for the whole period that you're building, is it-- I guess, do we know that the French system isn't the worst?

Because maybe this is better long term if we actually have the NRC more involved at each stage rather than if they actually-- Well, these would be, I can't imagine a time where someone would actually just build a whole plant and then everything would be perfect, and at the end of the day, ah, great job. No notes.

PROFESSOR: So your analogy is apt. It's not exactly the same as the French system because the French regulator doesn't work with them during construction. Well, they probably do, but it's more during design phase. And what's happening in the US is it's back and forth during construction, and that's where then the interest payments are accumulating.

And then remember, the French reactors are being built by state-owned enterprises. So they notionally pay interest. But it's basically like their bond rate to the-- at the rate at which the state issues a bond. They don't have to pay the bank's profit. So delays in France do not cost anything like they cost in the United States.

So there's all of these system-specific things that go in. Whether in the end you get a safer reactor or whatever, what is better, I don't think anyone has really studied it. It would be a wonderful PhD thesis to try to undertake. It would be hard to pull off, but yeah.

All right. Any other questions before we wrap up? All right. So that's the international situation and the learning situation. And we will now move towards-- we're going to look briefly at whether small modular will fix the problem. We'll look at what wind and solar has done. And then we'll look at safety. All right.