[SQUEAKING] [RUSTLING] [CLICKING]

SCOTT KEMP: We're going to start mostly with a review of things that I've said in this course. So this is just a help keep these things in your brain. But also, this is your chance to ask questions.

Your last chance to ask questions if something didn't make a lot of sense. It's going to be the key points. We have lots of time for questions. So don't hesitate to raise your hand. Otherwise, we'll be done maybe a little bit early.

So we began the semester with the proposition that we wanted to do decarbonization, and to understand that, we needed to know how bad climate change was so we knew how much money to spend on it. And what we found out was that this is a very murky problem. There's something called the social cost of carbon, which we've talked about, but how it's calculated is just a mess. So it's to remind you that one of the inputs in the calculation is how much temperature change do you get for a certain amount of CO_2?

And over 125 years, we have not reduced the uncertainty on that number. And it's still too big to really do this calculation meaningfully. Then that number gets put into these crazy equations, which are just completely contrived and have these weird functional forms that make it so that the effect goes as the exponent of the temperature squared. So obviously, it's very overdramatic responses to temperature change. And so it's not surprising that we get very low confidence in these numbers.

And what we find is that the IPCC, who is supposed to be the vanguards of all this, to give us the truth, they have these wonderful technical reports. If you ever have the time, this working group 1 is there technical working group. It's a big document, but it is worth reading cover to cover just to understand what's going on. Good Thanksgiving weekend reading. No, work on your paper.

But the killer is this. At the end of the day, the uncertainties are all based on this expert judgment, and not in the fundamentals of the science. Totally worth reading this stuff. So where does that leave us? It leaves us in this murky morass where we know, OK, we know CO_2 has positive radiative forcing. We know it's reaching unprecedented levels in the environment.

We also know that the temperature is changing, but exactly how much of that we can attribute to the CO_2 is hard. There are other causes of that. IPCC says roughly half, but other causes are, for example, the ocean, which has 1,000 times the thermal capacity of the atmosphere and is constantly cycling heat on 1,000-year timescales into the deep ocean.

So the atmosphere is this very thin, flimsy layer that's totally driven by ocean circulation, which we don't understand. Plus, we're coming out of an Ice Age, and other things are happening. So it's really hard to know how much climate abatement we need and how bad it will be going forward. So what do we do?

Well, we say that a rational climate policy should have this principle that the benefits should exceed the cost. And some climate policies would have enormous costs. If you're going to just eliminate all carbonaceous forms of energy right now, we would triple the cost of electricity, of energy, and that would have huge and devastating cost to society, in especially in poorer countries. So the cost of that decarbonization matters.

The second insight here is that the idea that we should have zero carbon is not coming from anywhere. There's some cost-benefit trade-off. And if the marginal cost of abatement of carbon goes up, as you're trying to get rid of that last unit, which is almost always how physical systems work, then at some point, it's better to just have a little bit of carbon emissions.

So whenever you start out trying to build a policy framework around the idea that we have to have 0, you've already made a mistake. And it seems like a benign mistake because you say, well, we want to be close to 0. We don't know what it is, but close is good.

But actually, it matters when you start doing simulations and modeling because it forces extreme solutions in simulations, because it must be equal to 0. And then you get these weird trade-offs where suddenly, all right at the end, all kinds of technologies that have a little tiny carbon intensity, just get thrown in and replaced with super expensive, crazy technologies. Yep.

AUDIENCE: I have one question. I don't know if it's related to here, but it relates to climate policy. After this course, I based my career in climate, and I have become climate skeptic. And the question is based on, like everything you're telling us, would you have posed for the IRA?

SCOTT KEMP: IRA?

AUDIENCE: The Inflation Reduction Act?

SCOTT KEMP: Oh, would I have--

AUDIENCE: If you were a policymaker.

SCOTT KEMP: Would I have supported it?

AUDIENCE: Yeah.

SCOTT KEMP: I don't know enough about the details. Given the amount of graph that seems to be in there, maybe not, but I don't really know the details enough to answer that question. Yeah.

OK. So people are going to say this and nothing you're going to do about it because they're going to say it. But in your mind, you should be thinking more sophisticated. And how do we want to do this? We want to start out with technologies that have low-cost decarbonization.

We also want to do that decarbonization as early as possible to prevent the effects of CO_2 from warming the atmosphere. So we want to choose technologies that we want to choose an economic path that gets us the most decarbonization to the dollar, to get the most CO_2 out as early as possible.

If we choose an expensive technology but we have a fixed budget, then we do less decarbonization because we only have a certain amount of money. So we want to always choose the cheapest technology to start with and then work our way up to the more expensive ones. So we'll talk about that at the end of the class today.

And the other thing is we just want to choose technologies that are fast to implement. If we're going to stake the future on microreactors and it's going to take 15 years, or fusion, and take 15 years to get that built in, licensed, and then another 10 years to build the first plant. We're talking 25 years from now. That's just stupidly long.

We need to think about what we can do today. So these are just principles that guide us. They don't tell us exactly what technologies to choose, but they are what I would argue is the framework for rational policy.

OK, here's a blank slide. So the cost structure and financing of energy generation technologies turns out to be really important. And that is what we spent so much of our class talking about. The key things that you should take away from this are that costs decompose into capital costs, fixed costs, and annual fixed costs, and variable O&M. We convert capital cost into an annualized one using this equation to find essentially the cost of the loan payment required to pay back.

But what we learned is that that loan payment can escalate dramatically if the construction times are long. So quick to build is important, especially in high interest rate environments. And this is why when we have government-financed construction projects, which don't have to necessarily pay interest, it's more easy to get nuclear done.

So in countries like France or India-- in India traditionally, historically, not anymore, but they actually just had a line item in the budget. This is how much we can afford to spend this year on continuing the construction of the nuclear reactor. And it just financed each year out of the budget.

And so that fixes the problem, helps address the problem of high capital cost technologies, because you don't pay all that interest on the loan. But in a capitalist society, where we have privatized energy production and you have to borrow money from the market, now those capital costs matter a lot, and construction costs matter a lot.

Now, the problem is that nuclear has been a high capital cost technology, and there's enormous debate over this, about how expensive it is. So if you remember Vogtle, which is the reactor that has recently been finished here in the United States, if we inflate it to $2,025 cost around $20,000 per kilowatt of capacity. When that plant was pitched, they said it would cost somewhere between 2 and $7,000. And that capital cost escalation is what makes nuclear, A, unaffordable but also is B, what drives uncertainty in policy.

If it's $2,000, then it's fantastic. We should be building as much nuclear as possible. If it turns out to continuously be $20,000, it's a problem. And so you all know this, but that is really, really an important number.

So another feature that we learned about, as associated with this economics, is that if you have a high capital cost technology, it's important for that plant to operate as much as possible. It's got to pay back that loan, that loan payment. That bill comes in every month, regardless of whether they make electricity or not. So they prefer to run all the time. And that gives us a condition that we learn is called baseload.

So baseload is really an economic phenomenon. It's a limitation associated with high capital cost technologies. You can run the plant in a non-baseload way. It's just that the effective price per electricity is going to scale as inversely with the capacity factor.

So it's not a feature. You hear people talk about people saying, oh, we need baseload generation. No, we do not need baseload generation. We need reliable generation. We need dispatchable generation. But we don't need baseload.

So is nuclear reliable and dispatchable? Kind of yes, but actually, not as dispatchable as people might think, because you can't ramp it up and down really fast unless you also build some kind of thermal storage that is attached to the nuclear plant. So you can dispatch it a day ahead, but you can't dispatch it five minutes from now because you can't just do this with a nuclear plant. So it's kind of there, but it is not flawless.

What about renewables? Are they dispatchable? Not normally, but if you mix them, if you do overbuild and storage, they become dispatchable.

So they both are imperfect. And they both can be fixed with more tech and more cost. But it's just important to understand the kind of quick conversation piece about baseload is really misleading.

So we learned given all these limitations of cost, how do we choose the optimal mix? And we talked about screening curves. And I'll revisit this at the end of class today. This only works if you have fully dispatchable tech because it assumes that you can choose which technology you want at will. That's not perfectly true for renewables, and it's not perfectly true for nuclear either, although we tend to avoid putting renewables on this kind of chart.

The best way to do it is actually to have a code that looks at every hour of the year and says, what is the demand. And what technologies are available, and having constraints so that they can't ramp up too fast or too slow? How much sun is shining? How much wind is blowing?

And that code that does that is called GenX. And they use this in the Future of Nuclear Energy Report. It was run by Jacopo Buongiorno here. And I'll just give this as one of the results.

This is for so-called mid-cost, according to them, cost of nuclear. And this is percent decarbonization along the x-axis. And you see in their own codes from this very pro-nuclear group that nuclear only shows up here, right at the edge, above 90%. And the amount that shows up is actually on a fractional basis, less than we have currently installed in the United States.

So this is the problem. If this would not be the case, if we could bring the cost down below their mid-cost projection. But it's just too expensive.

So we want to bring down the cost. This is the problem. So we have this narrative-- climate change, cost matters. Cost determines who wins. And now we need to bring down the cost.

So we looked globally at the history of all the builds in the United States, in France, in Korea, in Japan, in India, which I didn't put up here. All countries except for Russia and China, because we don't have reliable cost data from those two countries. And what emerges is a kind of general trend that there's basically little to no actual cost reduction apparent across all of these programs. India was the only one that showed steadily decreasing costs. But then we learned that was because India's reactors are steadily getting bigger and bigger.

So once you fix the size of the reactors, we do see in Japan this region of low cost, and in Korea, this is partly from reactors getting bigger early on in their program. And then we see this region of low-cost stability that then turns around, and the newest reactors are more expensive. And it appears that these are correlated with poor safety enforcement during construction. In Korea, we had falsified safety certificates. In Japan, we had this report by the Japanese Diet after Fukushima that basically said, we weren't enforcing the regulations during construction.

You can say, well, is that true or not true? How important was that? The evidence is in the capacity factors. If you look at the capacity factors in these countries, they are miserably bad because they have had to go back and retrofit safety onto these plants and fix the problems with the original construction. The result is because capacity factor is low, the actual cost of the electricity, rather than the cost of the reactor, is very expensive now, even more expensive than in the United States. If they had just done it safely from the beginning, they would actually have a better economic situation.

So we don't see any kind of lesson that we can learn from these reactors. We did a regression of 341 reactors in the world to figure out what the cost parameters were, and the key thing was that reactor cost decreases by 20% for every doubling in reactor size, which is why reactors got big. And we see also that if you add these two, licenses completed versus reactors built, this adds up to 1, which means on average, you get a 1% cost reduction for every doubling of the number of reactors you build in a country.

Now the error bars are highly uncertain on this kind of calculation. It will depend on a lot of factors, but the point is that we don't have a clear path on how to do this. So there are many hypothesized paths.

One thing that the DOE has said in a recent report is that we might be able to attain an on average 15% cost reduction if we bought 10 reactors at once. That's $100 billion of spending. That's not a likely strategy.

The other idea that has been all the rage for the last 15 years are small reactors and now very more recently, microreactors. And so we looked a little bit at this. And one of the things that we learned is that most of these startups are actually just recycling old ideas. Yeah.

AUDIENCE: Yeah. I have a question [INAUDIBLE].

SCOTT KEMP: Yes.

AUDIENCE: In the case of France, I heard you criticizing France's way of handling nuclear back in the '70s quite often during class. It's something I never really understood because France, yeah, they built many reactors. Maybe that was supported by the state. And maybe they overspend because it was fully supported by the state. And so nobody cared.

But since the '70s, they have almost a fully decarbonized electricity mix. And right now they have very low cost of electricity compared to many European countries. They are net exporters even though they have lower capacity factors than the USA. So I don't fully understand your--

SCOTT KEMP: Right.

AUDIENCE: Compared to the US.

SCOTT KEMP: Yes, so the cost of electricity will be driven principally by the marginal cost of production. And so those reactors are old enough that they're largely paid off. They've been paid for in large part through taxation.

So the price of electricity is not just the actual price on the bill. It's also the price of your tax bill to the French government, which has paid for a large portion of those reactors. So it's not an apples-to-apples comparison.

And as far as exporting, I don't think that tells you anything. What is interesting is that this cost was low and stable. And why is this number so high? Is this really [INAUDIBLE] effects with [INAUDIBLE] or not?

It's hard to imagine that this next one would be down here. So it seems like part of it is driven by increased concern for safety. There are issues with the reliability of some of the elements in the French fleet that they're working on.

All of these make it very difficult to do the cost comparison. I'd say, of all of these things, the cost of electricity is the most motivating factor-- the things that you raised. But you have to remember, if the costs are not fully recovered through electricity prices, then it wouldn't be a good comparison.

AUDIENCE: Look at European landscape. Let's say maybe they pay via taxes, and maybe French has a higher taxes than other countries. But still, the standard of living in France is still good. They have a fully decarbonized, almost fully decarbonized electricity mix. And France is a big country in Europe, very big industrial one. So it seems like they did a very good choice back then.

SCOTT KEMP: Yeah, it winds up in a good place. But what have they paid for it along the way? It's an interesting question. We should maybe do a better study on it.

AUDIENCE: We have actually here a classmate of ours that is investigating that.

SCOTT KEMP: Good. Good. Yeah. Well, what is the answer?

AUDIENCE: I'm working on it.

[LAUGHTER]

SCOTT KEMP: All right, let's find out. Yeah, I mean, it's very difficult. So when we do the regression analysis, we do not use this cost data and this cost data as being treated as equal. Every time we change country, there's a floating parameter that renormalizes the cost for that country because you just you cannot take the accounting methods used in one country and apply them on a dollar-for-dollar basis with accounting methods used in another country. They're just incomparables.

So to fix that, we have what are called fixed effects in the regression to do all of that. Yeah, so it's a very tricky area to analyze. The bottom line of this was that we didn't really have an obvious lesson.

OK, so we looked at SMRs. Ultra Safe is X-energy, and they're making certain claims. Many of these ideas have been built before, not exactly the same, but largely the same.

And they had issues associated usually with availability and capacity factor and capital costs, which is basically a function of energy density. One of the principal considerations is energy density. And many of these technologies have really low energy density. So it's hard for them to compete with water. Yeah.

AUDIENCE: When you say energy density, do you mean density per volume density?

SCOTT KEMP: Yeah. Yeah. Electricity density per unit. It should really be per unit hardware cost, but as a proxy, I'm really saying per unit volume.

AUDIENCE: OK.

SCOTT KEMP: Yeah. So it's a trade-off between having more passively safe-ish stuff versus more active safety systems. And that is something that you have to see how it shakes out. But historically, it hasn't shaked out well in favor of things other than water.

The other thing that we learned is that there are these historical cost escalation trends. People have an idea. They put out a cost estimate. Here's new scale saying it's going to cost $5,800 in 2007. Then it's $11,000. Then it's $13,000. Then it's $21,000. And it's just the cost keeps going up. And the reason is they do more engineering, and they realize, oh, we need stuff. And it cost.

So this has been true for everything-- AP1000, for X-energy, for GE Hitachi's BWRs. And nothing has really been built except for the AP1000. That's the only one we have really to go on. But the historical escalation was like a factor of 6 between the early cost estimates and the finished reactor. So even if it's not a factor of a 6, even it's a factor of 4, that forecast cost escalation will completely swamp the hoped-for savings between a FOAK unit and a NOAK, first of a kind and an n-th of a kind.

So this is a reason for pause. Yes, we hope that we can bring the cost down from building multiple units. But if we continue to see this kind of escalation, it's unlikely that we'll be able to bring it down enough.

So the final idea was, well, maybe factory fabrication. And the kind of takeaway lesson from class that I tried to argue was factory fabrication might work. But it's not about just factories. It's about volume.

You get discounts when you make thousands or tens of thousands of units a year. And so you're only going to see that for very, very small reactors that have a big market. If you're building 200-megawatt reactors, it's unlikely. If you're building 10-megawatt reactors, now you can talk about tens of thousands.

But you're fighting this problem that every time you shrink your reactor, your cost is going up. So how does that shake out? We saw Enil gave us a study about how much factory fabrication could save us. And when we applied that in conjunction with this cost escalation, the answer was not favorable. So the only hope is that this cost escalation somehow stops happening.

The other issue with having tens of thousands of reactors in the world that we didn't really talk about much is that human capital. Unless these things are computer-controlled, we will need a lot of nuclear engineers-- so something like 400,000 engineers, if we're going to have 40,000 reactors out there. And that's going to be a difficult lift.

So we did find a ray of sunlight in heat markets. The basic idea here was that nuclear is inherently a heat producer. And so it will be roughly a third the cost per kilowatt-thermal versus kilowatt electric.

And that makes it very competitive with renewables, which are the same cost per kilowatt-thermal and kilowatt-electric. And so it appears if we can meet the projected-- if you look in the EIA tables for the projected nuclear cost, so they assume like $7,000 per kilowatt capital cost. Nuclear would already be competitive with renewables for heat today.

Now that's AP1000-size nuclear. And that's kind of too big for most renewable applications, because one of the things that we looked at was the average heat per site is like 60mw on the high down to 1 megawatt. And so my guess is the optimal reactor size is just like throw away these, too small, and then be like 10-megawatt units, something like that. And that would potentially have a market in the United States of like 4,000 units and globally a market of 40,000 units.

And that is a real thing. That's a real market. And factory fabrication certainly begins to make sense.

So actually, I think this is a real future for nuclear. The challenge with this market is that it's the policy levers driving decarbonization and industrial heat are very weak because in electricity, we have these incentive structures and so on that are all well established. We don't have these things for industrial heat. They just use natural gas, and natural gas is very cheap. So we have to build that policy framework to incentivize this transition to occur.

So that's where cost left is off, that the future for nuclear was in doing this non-electricity market. But then there was this question of externalities.

And so we talked in detail about the externalities associated with nuclear. And there were some. Well, I'll go through them. But we never talked about the externalities. So let's just review them.

The first thing we talked about was nuclear waste. One of the things that we learned about was that they have these incredibly stringent performance standards for these nuclear waste sites. You're talking about very improbable exposures happening at 10,001 million years after the waste is in place.

So I think there's a basis for arguing that some of these standards are a bit on the extreme side. It didn't seem like that was really what was really driving the emplacement problems. The problems are really being driven more by politics.

We heard the story of the original waste repository in Kansas and then the problems with Yucca Mountain, the senators doing late-night deals to ensure that their state wouldn't get the repository. That seems to be the issue.

One of the problems with having chosen Yucca Mountain through political reasons, this is actually a really terrible site to put nuclear waste. And that has driven the Department of Energy to stop thinking about the disposal site as providing protection against radioactive release, instead focusing only on engineered systems, a task that we will design.

The problem is that we don't really understand materials, and to be frank, geology's at these million-year time scales. And so it would be imprudent, in my estimation, to give up the defense-in-depth concepts that was driving geologic disposition in the first place. The idea that we'll put the fuel in a container that we hope will stay intact, but then we'll also put it in a geology that we hope will stay intact. And we'll put it somewhere far away from humans, and we'll put it below the water table.

And so other countries continue to do that, but the United States has been slowly abandoning it. And I hope that trend will be reversed. A small number of countries, France and Japan, maybe Korea is heading in this direction. I don't know how to get to this point.

They don't have a lot of land. They don't have good politics for this. So they have convinced themselves of doing reprocessing.

We talked about the economics of reprocessing. It was an idea that made sense when we thought that the world did not have very much uranium. Turns out the world has a lot of uranium, and it's cheap. And recycling the fuel is only economic when the uranium is like over five times, sometimes 10 times its current price.

So we looked at projections done by MIT, at when would that occur. And the answer was not in the foreseeable future.

So this is not a sensible idea from an economic point of view. It's an essential part of some fuel cycles that people talk about, like fast reactors. But remember, it may be the case, but the lesson of this class is that climate policy is going to be driven by cost, not cool tech. So what's the point of doing cool fast reactor concepts that won't help fix the climate problem?

So if you can't do this, then the recommendation is to do this. Stick this stuff in these dry cask storage until you can finally fix your politics. And this is a cheap and basically robust way of dealing with the waste.

The bottom line is that all of this, the money that we have set aside to do this, seems to be adequate. We've used up about half the Nuclear Waste Fund on Yucca Mountain. We need to find a new site. But if Yucca Mountain had been a good site, there's no evidence yet that was not enough money. And that is a tenth of a cent per kilowatt, which converts to about $1 per megawatt-hour.

So I call this the waste externality. It's small. It's not something that we really need to worry about.

Safety was a bigger issue. So it's already a major driver for the cost of reactors, because enforcing safety standards during construction is one of the most expensive drivers of cost escalation. So we decided to do a calculation to see if reactors were safe enough. And what we found was that a major accident of the Fukushima Chernobyl style, which to be clear, is an INES 7 event-- we tried to figure out what an average reactor accident was-- kills about a quarter million people. And that was a big number.

And a lot of you were like, oh my God. But when you actually then divide by the total amount of electricity, it turns out to be like something like two deaths per terawatt-hour. And that's actually pretty good. It's much less than most of these fossil fuel technologies. So it is relatively safe.

Now some people will say that, well, reactors will get safer. So maybe we can actually reduce the safety so that we can also-- this is not a bad number. And maybe we can reduce the safety enforcement during construction-- what is going on now here in the United States. And my retort to that is you don't really know how safe these reactors are until events happen. Most of the accidents that have happened, big accidents that have happened, were not in the PRA models at the time that the accident happened.

And we should remember that even though Chernobyl was bad, that if the spent fuel pool at Fukushima had did not have the leak that allowed water to leak into the pool and keep the fuel submerged, there was a risk of a spent fuel fire, which if that had happened, would have been much worse than Chernobyl. So despite the fact that these reactors are more modern, they're not necessarily more safe. So we should be careful about this.

So we did the we did the calculation. If we assume $11 million per life, then 2 fatalities per terawatt-hour turns into $22 per megawatt-hour for externalities. We also saw that after Fukushima, there's all these cleanup costs, and it costs about $5 per megawatt-hour. So the externality adds up to something like $27 per megawatt-hour and much more significant nuclear waste and also, significant relative to the cost of the energy in the first place-- a fifth, maybe. Yep.

AUDIENCE: I was going to ask-- so we started with things, I guess the carbon question is kind of murky. So fossil carbon, it's a bit murky. Then it seems like just based on health externalities, that would be the reason to decarbonize, especially for qualitative if you think like--

SCOTT KEMP: Completely on board with that. Yeah, completely on board with that idea about reducing small particulate emissions, as well as actually dealing with-- this is something that people don't talk about-- dealing with CO2 for non-climate change reasons. It's good for plants, but if your reservoir of-- OK, now I'm really on the fringe of what is widely acceptable here. But if your ultimate reservoir for air exchanges outside and the CO2 level there doubles, then ipso facto.

For given ventilation rate in a room, the CO2 level inside also doubles. And what we find is that indoor CO2 levels can easily reach something like 1,000 PPM. Now, in a well-ventilated site, it should be much less than that. But in people's houses and in rooms that are like typically poorly ventilated, especially energy-efficient places, 1,000 PPM indoor CO2 level is not uncommon.

What's interesting about that is there are measurable intellectual deficits at 1,000 PPM. People are dumber because of CO2 emissions. And some people also actually have physiologic responses-- inappropriate response to hypercapnia, as it's called-- at those levels where their bodies are literally being degraded, and their lives are being shortened because their bodies are struggling with the excess CO2.

So I'm completely on board for getting rid of CO2 for those reasons. It's just really hard to justify based on climate science. Yeah. Yeah.

So the point you raise is actually this. What we really should be doing is not focusing on CO2 or climate, but focusing on the totality of externalities, all of the harms done to society, and then choosing the best energy technology for that. And we're going to do that calculation today, or attempt it.

So just to finish up with the safety story, one of the issues that is happening right now in the United States is this trend move to something called-- is this about-- yeah.

AUDIENCE: It's about the slide. Real quick, before, you mentioned how we revise what the nuclear number was on that chart. Do you ever go back and check if the other numbers--

SCOTT KEMP: We're doing that today.

AUDIENCE: OK.

SCOTT KEMP: Yep. So OK. Yeah, so one of the things that is happening in the nuclear world, because people don't like the cost of safety enforcement, is that they are pushing for something called risk-informed licensing. And what that is is basically to move away a little bit from the traditional methods of defense in depth. And one of the challenges with that is that the major nuclear accidents, Chernobyl, Fukushima, even TMI, were-- well, I guess not TMI, Chernobyl and Fukushima, were beyond design basis accidents. So it's just to say that they were events that we intentionally chose, said, well, this is going to happen so rarely that we're not going to put this in the safety design.

But the reason those reactor accidents weren't worse is because those reactors were equipped with passive defense in depth, like containments that helped attenuate some of the release from those accidents. If we give that up in the name of smaller, cheaper reactors, then the beyond design basis accidents are apt to be worse. And that's something that we ought to think carefully about.

So what is the worst case that we can tolerate or the worst-case accident? The worst-case accident is the accident that causes the public to completely lose faith in nuclear altogether. And we are courting danger when we start to cut back the safety standards, which is happening in the United States right now. So I think, yeah.

AUDIENCE: Maybe my faith in incentives of the nuclear industry is too high, but isn't a part of the motivation for risk-informed licensing that if you want to do deterministic licensing, you have to create these design basis accidents? And historically, for example, there is a lot of focus on large [INAUDIBLE] to deal with that. It can deal with anything.

SCOTT KEMP: Which is not true.

AUDIENCE: Well, if it works. Whereas if you would have just started with what can happen, you would have caught at the small break. Local is actually worse.

SCOTT KEMP: In expectation value.

AUDIENCE: Yeah, so wouldn't it also be-- I don't know.

SCOTT KEMP: So I think there's a role for both. The warning is just don't give up defense in depth as a principal. What we're doing now, which is to say we have defense in depth, but we use PRA models to inform our design choices. I think it's a perfectly valid choice. The problem comes when you take the outcome of the PRA model, and you say this is the true safety risk.

And we can then therefore throw away all these other backup systems because you can twiddle those numbers to give you whatever you want. And that's the problem. We should maintain some humility in our engineering design to say, what if these numbers are wrong? And we'll have a second layer of backup. And that's all I'm suggesting.

So I think in terms of safety, the US operating experience is the best. We run a fleet that is very well-built, very safely run. And as a result, is economically optimal compared to most countries because we get really good capacity factors. Yeah.

AUDIENCE: Back to the thing you said just a minute ago, where you said like the worst-case scenario is essentially an accident that would make the public lose faith in nuclear. I don't believe that because I feel like we've already hit that point, like with Chernobyl historically and Fukushima in some places. But we have sprung back in public opinion.

Obviously, it hasn't been a linear pathway. But I do feel like there's generations that dislike nuclear, and more recent generations are more pro-nuclear. And it just kind of cycles around.

So I think that there's humans love forgetting things on generational cycles. So I feel like that's not borne out in the actual experience. I would argue that the accident that we're trying to avoid is something that kills so many people, that sticks a bit more.

SCOTT KEMP: So first of all, I agree that human memory definitely has a half-life. But I would say, from an energy policy perspective, what happened at Fukushima was disastrous for Japan. And that's kind of what I mean, that basically a whole bunch of the fleet goes offline, and it stays offline for a decade. And we're paying premium, basically paid.

We could have done wind and solar. Instead, we chose to pay four times more for nuclear, and then we have to also buy natural gas to back that up. And it just becomes this enormous disaster. That's kind of what I meant by that. Yeah, whether the public will ever permanently lose faith in nuclear and say, never again-- yeah, I'm doubtful. Marketing forces will always be sufficient to overcome that.

AUDIENCE: I think we should have lost faith in coal by now.

SCOTT KEMP: We absolutely should have. Absolutely. Yeah, we'll look at the externalities on coal in a minute. All right.

So not a small consideration. Not a lot of room for making the reactors less safe. I think that's my bottom line. The externality at $27 a megawatt-hour, unless the other externalities turn out to be way higher safety externalities, which they might be for coal, there's not a lot of room for motion here.

The last one we talked about is something that you never see calculated. This is the only place you'll ever find it calculated. And that is nuclear weapons. And this is a very controversial calculation. I acknowledge that.

We use Bayes' to estimate the probability that a civil nuclear power program helps give rise to a nuclear weapons program. We estimated that to be about 63%. It's very hard to predict who the good guys are.

You want to say, well, this is only fundamentally an issue with exporting nuclear power. It's fine if you don't export it. This externality goes away. But if we're exporting it, then we have to deal with this externality. And so it's a very on again, on or off type of thing.

We had lessons from Iran and Iraq, both of whom were our friends, both of whom later turned and used their civil nuclear technology to build weapons programs. Iraq, we actually were selling them enrichment technology at the time. Iran, we were selling them enrichment technology at the time. So it's very hard to know where the politics will take us.

And one of the ways I tried to drive that home is to point out that the average age of a constitution in the world is about 43 years before there was a major government reorganization. Not all of these turn out to completely change the character of the country. Many of them don't, actually. But it just goes to show you. You don't know who you're really negotiating with.

Reactors are lasting 60 years. Plutonium is lasting tens of thousands, hundreds of thousands of years. So you're creating a risk that you can't necessarily manage into the future. So this is something that has to-- oh, there's a little friend's picture. It's something that we have to think about, and we tend not to think about.

The externality range is all over the place-- 20 to 300. The number that I like, which was sanctions policy, debited only against US power production is 60. So that's the number I'm going to use going forward-- $60 per megawatt hour. So this is very large.

So getting back to this, we want to verify what the situation is with all of these other things so that we know how to read the number on nuclear-- this plot, actually. I want this plot-- yeah, that's better-- with the adjusted externality.

All right. So let's just talk. So any questions about this historical stuff? No? OK. People have been asking, so that's good.

So what other what other externalities have we not discussed that might apply to some of these other technologies? Well, there's a lot. So we really, really need to go beyond just deaths.

You talk about things like the effect of SO2 on galvanized steel, decomposition of buildings, acidification that affects crop yields, ozone that affects wheat, barley, rye, oat, and potato yields. You have PM10 that produces congestive heart failure, which is a big thing for coal plants. Accident risks from transportation transporting fuels, noise risks, eutrophication, which is deposits of phosphates into lakes and streams that causes algae blooms, all kinds of phenomena, mercury from coal causing IQ changes in children. This is not an easy thing to do.

One of the problems with attempting to find all of these externalities is that they turn out to be very specific to the region or country in which you are operating. Yes.

AUDIENCE: PDF.

SCOTT KEMP: PDF? Oh, PDF of species.

AUDIENCE: Probability distribution function.

AUDIENCE: Yes.

SCOTT KEMP: I have no idea. It also has a little apostrophe, which suggests to me that this might have been an accidental paste where you delete a word.

AUDIENCE: That's what you said-- land use. I imagine it's like you had--

SCOTT KEMP: Oh, PDF of species. I see.

AUDIENCE: Yeah, it's got to be probability, correct?

SCOTT KEMP: No.

AUDIENCE: No.

SCOTT KEMP: I'm not sure what it stands for. I have forgot. It's a problem when you make slides years and years ago. So it turns out that these calculations vary dramatically by region.

Is that coal plant next to a field of barley or not? Is an extra city full of children? We talked about transportation risks. Well, that matters. There's different risk if that oil comes in a pipeline versus being shipped in a container ship or in an oil tanker ship.

So it turns out that these are all very difficult things to do. Health risks, which are some of the biggest, are also some of the most difficult. So it turns out you calculate it in days of labor lost. Well, that depends entirely on what the value of that labor is, which depends on who's being affected and in what country, and what economic scales-- so not easy.

So how do we do all this. So one idea-- yes, it's blank-- is that we could try to get a whole bunch of scientists together and say, let's look at all the negative effects.

We'll get some ecologists. We'll get health experts. We'll get economists, and we'll look at every single plant and where they're located and who's affected by the emissions from that plant. And we'll do this for every country, and we'll add it all up.

And that sounds crazy. But in fact, this was tried.

So there was something called the ExternE Project that was founded in 1991 jointly by the US Department of Energy and the European Commission. They employed 100 scientists for 15 years, and this was their job. And they tried to come up with externality measurements. It's still one of the most significant studies of externalities has ever been done.

But the problem is that now that the data are 20 years old. And we've learned a lot about health effects that we didn't 20 years ago. So this is also woefully outdated, despite the magnificence of the effort.

Another way we could do this is we could look at individual studies. But the problem with individual studies is that the study author brings a lot of bias into their calculation. Is the study being funded by the gas lobby? Did they really do a good job of counting up everything?

So the only fair way to look at individual studies is to look at a meta-study that basically looks at all of the individual studies and does summary statistics. I think this is a more modern way of trying to measure the externalities. So here's the answer.

All this has been inflated to be on a constant dollar basis of $2,025 per megawatt-hour. We've been talking about the nuclear ones in megawatt-hours-- coal, oil, gas, nuclear, hydro, et cetera. The boxes are the 25% to 75% quartile, quartile 1 to quartile 3.

The dot is the median, not the mean. We choose the median because these have large outliers, and we don't want to overrate them. They're also kind of like a lognormal distribution because they're bounded at 0. And then they go as high as they want.

And you see coal goes all the way up to $1,448 per megawatt-hour, completely blasting away anything to do with the actual cost of the coal plant. So if that highest number were true, yeah, that's crazy. Here's the same data shown. And then I put the ExternE where they have data here.

And one of the things that you see is that the ExternE numbers are all much smaller than the other ones. And that's for a number of reasons. So one is the early nature.

There's a lot of effects they weren't aware of. Two, they used a bottom-up approach. They were going to each plant and trying to add them up.

And there are two consequences of that. One is that. They may be missing things as they're trying to add it up because they're literally counting from scratch. So they don't really know what the PM10 was from that particular plant because they don't have a measurement. They might just omit it.

The other thing is that they might actually do better in incorporating selection effects that are associated with that's a dirty coal plant and people who live near it. If a larger number of people, they don't want that coal plant nearby. So it turns out only the dirty plants are in rural regions, and that means that actually the impact of those emissions might be smaller. That kind of NIMBY effect would actually drive down the externality value.

And finally, this is all just public health. There are no climate change effects here. Whereas these numbers from the meta-analysis do sometimes include climate effects-- whatever the author thought the climate effect should be. Yeah.

AUDIENCE: Where is geothermal in this?

SCOTT KEMP: Geothermal is not reported in either study, so can't tell you. So I would guess around here, six, but it's not reported. So we did our own calculation of externalities for nuclear, which I just reviewed with you. And that is the yellow diamond. And the big difference between the yellow diamond and this is almost entirely nuclear proliferation.

So my externality calculation, which we did in class with deaths and all that. For nuclear, just doing deaths and waste, came out to $28 per megawatt, and this is, I think, $21 per megawatt for the median value. So they're basically in agreement, which is good to see.

So overall, actually, nuclear does very well compared to all the fossil fuels, which is not a surprise. When the world didn't have renewables, we should have been doing nuclear unquestionably. Yeah.

AUDIENCE: Are these numbers representative of the total cost externalities and the cost of electricity and everything?

SCOTT KEMP: No, this is just the externality.

AUDIENCE: Yeah, because it seems to me that a lot of these are just 0 on the minimum. What kind of studies are they doing?

SCOTT KEMP: No, it's not LCOE. It's just the externality. So there are people who say, oh, wind doesn't have any externalities.

AUDIENCE: And people will say something that is close to the externality.

SCOTT KEMP: Yep.

AUDIENCE: What about birds?

AUDIENCE: What about birds?

AUDIENCE: What about this?

SCOTT KEMP: This is why you don't choose one study. And this is the problem. The nuclear people are fond of doing this with learning studies. They're like, oh, according to such and such study, nuclear can come down in cost.

That was one study. What do all the studies say? So this is why I don't present you a single study. I want you to look at all the published studies. And this is where we wind up.

So the only problem is that wind and solar are so small that we wind up in the same place as we were when we were just looking at cost. Yeah.

AUDIENCE: So this is a little bit outside of the scope of this discussion. But knowing that different parts of the US government put a different literal dollar value on human life. Would any organization do that for different like animal life? Because there's a lot of creatures that we would not be able to live with, like pollinators for food to actually grow, et cetera.

There's a lot of animals that we eat or use for different purposes, but shouldn't we be actually worried if, for example, we did just kill off one of a certain bird. If they all love running into wind turbines and then suddenly, a certain ecosystem collapsed around that bird going extinct--

SCOTT KEMP: Yeah, we should be worried about things like that. So I mean, that's much more something you see people thinking about in the context of climate change, where, for example--

AUDIENCE: And not externalities.

SCOTT KEMP: Well, I mean, you never really see it like in the calculation because the climate change externality is calculated traditionally, using this totally bullshit equation, which is not serious.

AUDIENCE: An issue fundamentally, but if we were going to be like, what is the cost per life of one be that we would end up with just such bullshit numbers that they would--

SCOTT KEMP: Well, I mean, there are always these cliff-edge effects. So the example I was about to give is beetles. When winters were colder, beetles would die off in the winter, and forests would flourish, like bark beetles. But now that the winters aren't as cold, they are ravaging enormous forests, which not only reduces the availability of timber but just destroys whole ecosystems full of all kinds of things.

And so what are the downstream consequences of that? So yeah, it's very hard to know what those connections are. I'm not aware of any agency that attempts to monetize the value of every flora and fauna out there. But it would be an interesting idea. It would be a very hard calculation to do. Yeah.

AUDIENCE: Have you done any estimate independently for wind and solar? I guess it's the point of the study is you look at everyone or all the studies try to avoid bias.

But I feel like societally, there is just so much bias to renewables are good. If you look at regulation, identity, everything is set to 0 for renewables. And then we take into account scope 3 for nuclear, but only for fuels, so that renewables and wind is 0, even though they would be higher than nuclear. So I don't know if you--

SCOTT KEMP: I haven't attempted to do a study. But I agree with you that the academic community has these systemic biases. So for example, on climate change, if you were to publish a paper that says, oh, climate change might not be so bad, you probably wouldn't get tenure. So yeah, there are these problems in the literature. There's no doubt about it. I just don't know how to do better than that. Yeah.

AUDIENCE: This kind of goes back a little bit. But so a huge part of the nuclear disaster or accident externality are the deaths from cancers.

SCOTT KEMP: Yeah.

AUDIENCE: How would that change if we cured cancer?

SCOTT KEMP: Yeah. It would go away.

AUDIENCE: Would that be the only externality? Could we think about other--

SCOTT KEMP: No. There are other health externalities. I didn't compute them explicitly. And my suspicion is that they're small relative to the fatalities.

AUDIENCE: You just got to cure cancer first.

SCOTT KEMP: Yeah.

AUDIENCE: Maybe on that note, as a little bit of a tangent to my research, which is the introduction of health. What if you take into account all health effects like cancer, et cetera, also discounting morbidity? And it ends up being predominant like the DALYs, which is essentially a metric used for discounting mortality and different types of other health effects. It ends up being like 90% cancer [INAUDIBLE]. So I was like, oh, what if we look at all the rest, but all the rest is [INAUDIBLE].

SCOTT KEMP: This is why we do it the way we do it. Yeah. OK, so let's add this to LCLE and find out where we land. So here I have included on this chart wind and solar. And in order to do that, I have assumed 1.7 times over-build, and 12 hours of battery have to be added to both of these.

So that bumps the cost way up. And that's because otherwise you can't call it dispatchable, and you can't put it on this chart. So here's where we wind up.

These numbers are the current cost data from the 2024 Sergeant and Lundy Report that was done for the US Department of Energy. And then I've just used the median externalities from the meta-study. And then for the nuclear, I used our calculated externality. And there it is. It's like nothing changed.

Geothermal is still very attractive, natural gas if you're a peaker. You remember how to read this chart? If you're operating the plant for this many hours per year or more, then you prefer this purple technology. Otherwise, you prefer this. You always prefer the lowest line for whatever duty cycle you need-- so otherwise natural gas.

Wind and solar actually are interesting in that they are actually, according to this, not yet quite justifiable-- still a little too expensive. The reason why they're justifiable is that this is on the scenario with the overbuild, which we're not doing. This is to say a full overbuild case is not yet justified. This includes a climate externality, but it's whatever the median estimate is. And who knows what the reality of that is.

And then there's the promised nuclear. This is what they say it will cost. And then this is what it'll cost in case you're wondering.

So we don't really know what the climate externality is, but the effect of a climate externality is to take the fossil fuel lines and pin them at the left axis and just make it more steep. And so the takeaway from this is no matter how steep you make this natural gas line, even if it goes up like this, because you put an enormous climate externality, it will always have a point where it was below the rest of these. So it will never make sense to get rid of natural gas, which is the incarnation of this. Zero-carbon systems never make sense. Question.

AUDIENCE: Explain how you get to 1.75.

SCOTT KEMP: Oh, we did that in class. That number comes out of the study. What is the name of the author?

AUDIENCE: Shaner.

SCOTT KEMP: Shaner. That found that 12 hours plus 1.7 times overbuild plus national transmission could meet the reliability standard in the United States. So that's where that comes from. Yeah.

AUDIENCE: A question on the slope of nuclear versus gas. The slope should be the cost of ONM and variable costs of fuel?

SCOTT KEMP: It's actually just the variable cost.

AUDIENCE: So fuel.

SCOTT KEMP: Fuel and maintenance.

AUDIENCE: So here it seems like the slope of nuclear and gas is kind of the same. Shouldn't it be much smaller?

SCOTT KEMP: It should be. But this is what Sergeant and Lunday reports.

AUDIENCE: But what's the basis for that?

SCOTT KEMP: I don't know. Yeah, I feel like it used to be more flat, and then it has been getting steeper. And I don't know if it's because they actually survey reactors, and they find that maintenance costs are going up because the reactors are getting older. I don't know what it is.

AUDIENCE: With a 95% capacity factor, seems like there's not much maintenance to do, at least in the US.

SCOTT KEMP: You would think. You would think. I'm going to pull up the report and see. Can I do this in real time?

AUDIENCE: It would not change, of course, the argument for which--

SCOTT KEMP: Yeah. Yeah, it doesn't change that. Maybe I'll do this after class because I think it's going to take me too long to do it in real time. But we can look at the numbers. Yeah, I am surprised it is as steep as it is. There's another question. Yeah.

AUDIENCE: So a while ago, I think you were saying that geothermal isn't entirely clean energy.

SCOTT KEMP: Isn't entirely carbon-free. Yeah.

AUDIENCE: You're not worried on that?

SCOTT KEMP: I don't know too much of the details, to be honest. I have a feeling it has something to do with either fossil fuels being used for pumps or something, or it has something to do with some kind of methaganic leakage from the wells. I don't know where it comes from. It's just there's published data, and it's not zero.

AUDIENCE: And on that note, are there arguments against wind and solar as being carbon neutral?

SCOTT KEMP: Yes. So there is an endogeneity in any computation of the carbon intensity of a technology. So if you have a bunch of coal plants in China powering a plant that makes fossil fuels-- sorry, that makes solar panels-- then that is not a carbon-free solar panel. But it comes down to what is the energy that goes into making it versus the energy that you get out of it. So is there some kind of efficiency factor?

So I don't think that the geothermal is the cost of the carbon footprint associated with building the geothermal plant. I think it has to be something more to do with its continuous operation. Otherwise, it doesn't make sense.

But it may also be one of those situations where geothermal plus some renewables could actually bring this down. And that they're assuming that there's some kind of other fossil fuel being used at the plant. It's a good question. I've never looked into it. Yeah.

AUDIENCE: So just to make sure I understand. What this is saying effectively is that based off of this dispatchable solar wind assumption, even if nuclear were cheaper, it could never be a baseload because the slope is higher.

SCOTT KEMP: Well, it could be a baseload if-- oh, yeah. Let's see. Yeah, that's right. It would be like a peaker. Yeah, and in fact, when we see that when we run the GenX model, nuclear becomes a peaker technology. Yeah. It just turns on when the renewables are bad and deals with the variability, or becomes like an intermediate peaker.

AUDIENCE: Would it in reality just stay on and then charge zero during times? How would that work? Would they actually shut down the plant?

SCOTT KEMP: So I think if the model is correct that they actually shut down the plant. I mean, the model has in it assumptions about the temperature, ramp rate, and cycle, things like that. So I mean, the French do load-following with their plants. It increases the O&M because you have more pellet-cladding interaction, more leakers, more cleaning up the primary coolant and dealing with that kind of stuff. But beyond that, it can be done, just changes the cost structure a little.

AUDIENCE: I thought that France had basically like one or two reactors that were load-followers so that the rest could function more steadily.

SCOTT KEMP: Yeah, my understanding is that they--

AUDIENCE: I don't think like all of them.

SCOTT KEMP: Yeah, I don't think, but I also think that they do something where they use multiple plants to change the effective ramp rate so that they can something. They do something fancy, but I'm not 100% sure how it works.

AUDIENCE: So does [INAUDIBLE] making all of your nuclear reactors be peakers with from a materials perspective, would put a lot of stress and strain on the system so it's a bad--

SCOTT KEMP: Yeah, economic choice. Yeah, I would definitely agree with that.

AUDIENCE: Actually, two more questions. So first one for geothermal-- in the previous slide, you mentioned that these externalities are not calculated by the meta-study. So in here are you assuming basically--

SCOTT KEMP: Oh, I mentioned I added six.

AUDIENCE: You just assumed.

SCOTT KEMP: Yeah, I just assumed six.

AUDIENCE: And my second question-- I was wondering if the studies talk about, for example, the health effects of battery or solar panel recycling as externalities to solar.

SCOTT KEMP: I have never seen a study on that. And so I'm almost certain that none of these studies include. I haven't looked at every one, but I would be surprised if some of these solar studies actually included battery health effects. That would be an interesting issue. Whenever questions like that come up, usually the answer is it turns out not to be a big deal, but this is a perfect student paper topic if you weren't already done. Yeah.

AUDIENCE: And so, just for clarity, are we including any land use externalities for solar, wind, or no? I know those are obviously incredibly difficult to quantify.

SCOTT KEMP: They're incredibly difficult to quantify. If they're in the studies, they're in there. And if they're not, they're not. It's a challenge.

AUDIENCE: I feel that the sensitivity, like we were talking about the collapse of the ecosystem. It's kind of like if you start nuclear war, then the externality becomes just almost--

SCOTT KEMP: Infinity,

AUDIENCE: Infinity. It can almost be like a similar thing. We don't know what it looks like to use up that much land. So I don't know. It feels a little bit. Obviously--

SCOTT KEMP: It's not all that much land.

AUDIENCE: Locally, though? Because we've industrialized so much of this country. We kind do know what it's like to just pave over.

SCOTT KEMP: Yeah, I mean, it's small compared to the amount of land that is paved over. Yeah, yeah.

AUDIENCE: So it seemed like the only hope for a second was deep markets. But then if you take a factor of 3 off of nuclear here, it's still more expensive. So is it then also not market or--

SCOTT KEMP: Relative to natural gas?

AUDIENCE: Yeah, I mean pretty much everything.

SCOTT KEMP: So you would be talking out here. And a factor of 3 would put you here.

AUDIENCE: Yeah. So for nuclear, if you bring it down by a factor of 3 per megawatt-hour of heat. So is it in conclusion also heat markets now, or is there something--

SCOTT KEMP: Wait. I don't see. Why it isn't the conclusion yes?

AUDIENCE: I mean, conclusion as in no nuclear.

SCOTT KEMP: No, because natural gas stays here. You're talking in heat market. You're talking basically 100%. So you're on the right side of the scale. And if I take nuclear and I divide this into three, I would say that one-third of the height is somewhere around here, slightly under natural gas.

AUDIENCE: The nuclear products occur though.

SCOTT KEMP: That's what I said. If you could build nuclear at current projected AP1000 prices. Yeah.

AUDIENCE: How about natural gas bill? Wouldn't that also come down [INAUDIBLE]? Because this is accounting for converting the natural gas heat to electricity.

SCOTT KEMP: You don't do that in process heat.

AUDIENCE: You don't? OK.

SCOTT KEMP: Oh, you're saying. Oh, yeah, yeah, yeah. No, no, no, no. Yeah, right. You're saying that this is the electrical cost. Yeah, you're right.

AUDIENCE: But it does become the lowest-cost carbon. Oh wait. This is accounting for that.

SCOTT KEMP: It does become the lowest carbon-free source of heat. It does become the lowest carbon-free source of heat. But you're right that the cost of the natural gas also comes down by a factor of 3. So it goes down here.

AUDIENCE: [INAUDIBLE] If you just get the combined cycle, that's maybe 70% efficiency. So it goes down by a lower amount.

SCOTT KEMP: Is it 70% efficient?

AUDIENCE: [INAUDIBLE]

SCOTT KEMP: OK, let's say, a factor of 2. Yeah, factor of two or something like that. Yeah, so it'd be like where the geothermal number is.

AUDIENCE: These externalities include climate externality.

SCOTT KEMP: Whatever the meta-studies say were the climate externalities. So yes, you could imagine that if the climate externality were a lot larger, this would be a lot steeper.

In fact, we looked at that. Do you remember that variable? I could find that one just to. All right. Well, I can't find that variable plot. Anyway, that is not the end.

So the question-- we go back to the original question. How do we deal with climate change? Oh, are we out of time? Let me just leave you with this.

There are these ideas of these. Have you seen these marginal abatement curves? How these things are generated is very kind of inaccurate. But the point is that there are lots of places where you can deal with CO2 abatement. Some of them are, have very high intensity, but not very much, not a lot of opportunity. Some of them have low intensity, but there's quite a lot of stuff to deal with. And this is the cost of dealing with it.

And the point is that there are lots of things that you can deal with CO2 emissions for free. You actually will save money if you deal with those CO2 emissions. So this is where you start. And then you walk down this until you get to more and more and more and more expensive options. And this is how it ought to be done.

There are lots of people who have attempted to come up with these numbers. This one, the data actually closely matched what is in the DOE reports. But LED lighting, smart grids, crop rotations, forest management, a lot of forest management, electric vehicles-- you get more and more expensive. And we seem to do a lot of these really expensive things, electric vehicles and stuff.

And we don't do a lot of this stuff, which isn't sexy but actually has potential for significant decarbonization. Co-generation, we do do livestock feeding, residential energy efficiency. So there are programs. These things are difficult to have big policy levers. So they get somewhat neglected.

Anyway, this is just an idea of a way to think about these options before you start going out here to your super-expensive electricity options. So you want to deal with climate change. You need to look at the system in the totality. And that's it. Happy Thanksgiving from Turkey Point.

AUDIENCE: Is that real? Is that a real plant?

SCOTT KEMP: That's a real plant.

AUDIENCE: Oh, I didn't know that.