[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: So today we're going to look at the situation with renewables. And I said that, in the '90s and the early 2000s, the nuclear was the obvious path. And then renewables just showed up and ate our lunch. But there are a lot of people who are still kind of skeptical about what renewables can do for a lot of different reasons. And we ought to have a deeper look to try to understand some of these arguments. So we're going to do that today.

I guess I'll just give you a heads up. The final answer is people aren't stupid. They're proceeding with renewables for good reasons. So we should expect something like that. Before I get there, I just wanted to give an opportunity to speak, if there's any kind of clarifying questions on previous stuff.

There are some things I've added to this lecture that people have brought up, but I'll just-- there's no other questions before I go? OK. I keep reading the reading responses and I see some ideas that have been missed. So as they come up, I'll try to add them into the lecture. All right.

So let's talk about this topic. There are a number of ways of decarbonizing. Nuclear is one. Renewables was one. Carbon capture and storage, which we aren't really going to talk about, is one. Geothermal, which you can clump into renewables, is one. Of all of these, renewables is the cheapest. And we saw this result from Jacopo Bongiorno's model. This is for the Southern United States that has good renewable capacity. And you see that they allow carbon capture and storage to be part of the model. And we had a big chunk of energy coming from renewables in this modeling simulation.

I think this is something that got missed based on, like I said, reading people's responses. This is a cost-optimized system. So for any level of decarbonization, it's telling you the optimal mix that gets you that generation without spending too much money. I mean, we could build a bunch of little wheels with hamsters in them and they would produce carbon-free energy. It would just be very expensive. There's all kinds of solutions, but these are the cost-optimal ones.

But something seems to have not dropped. Is that these are also dispatch optimized mixes. Maybe dispatch viable mixes, like the wind and solar capacity that makes up this chunk is not, let's say, nameplate capacity. This is like, I don't know what, 60% of generation. It doesn't mean that the nameplate capacity of wind and solar is 60% of the total electrical demand.

The capacity may actually be much, much in excess of that in order for it to reliably produce 60% of demand on average. So these models, despite the of non-dispatchability of wind and solar, these are models which keep the grid running. These are not solutions which are not viable. And this is an important point.

I also realized I never really talked about what dispatchability means. It's a nuanced thing. So often when we say dispatchability, we say something like, I went to your nuclear operators and said, I want you to give me a gigawatt of electricity next week. And you say, sure, I can do that. And that's dispatchability. And if I go to the solar people and I say, I want you to give me a gigawatt of electricity, they may say, well, we can't promise you a gigawatt.

Or if they have a lot of excess build, they'll say, well, we have a 99% chance we can promise you a gigawatt. And at the end of the day, the nuclear plant also has some chance of not being able to provide it. So you can get there. You get towards dispatchability with excess generation.

But there's a second aspect of dispatchability that we haven't really talked about, and that's really maybe it's better termed as flexibility. If I say to you, oh my gosh, it turns out, everyone is plugged in their cars for some reason. And I need more power now. I need it on the grid in 10 minutes to keep the grid up. Nuclear I can't help you. It takes me a day to boot the plant. And then the solar people goes oh, no problem. And they can just turn on the power.

So that is a really important element, same with taking power off. You can curtail wind and solar instantaneously. You can't generally curtail nuclear instantaneously. This thing has got to dump the heat somewhere. So variability is really important and arguably more important. It's hard to rank these things, but it's really important to keeping the grid operating, which is it's a just-in-time system where we're constantly trying to balance supply and demand, and you only have a tiny margin within which you can work.

But it's also why you don't ever see wind and solar becoming 100%, because despite the fact that it is very flexible, in order to achieve both flexibility and guaranteed dispatchability, you would need so much overbuild that it just doesn't become economically sensible. So you always see it blended in with some storage to deal with those times where you can't dispatch it, and some kind of firm resource, which in this model is nuclear. But in other models, likely that would be taken up by geothermal, if you had it, because geothermal is a dispatchable, low-carbon energy source, just like nuclear.

So those were for the areas where renewables were poor. Here in areas where renewables are not so great, you see the total renewable capacity is closer to 20% or total generation is closer to only 20%. And that's kind of interesting. That's actually just about where nuclear is today in the US grid. So the rest has to come from something else. And in this model, it's a lot of storage, and some carbon capture and storage, a lot of battery storage which I think in this model is lithium ion, and then some carbon capture and storage on natural gas.

This technology I don't really track it too closely, but you could imagine there would be reasons why this technology doesn't really reach full scale usage is, for example, I'm not certain how reliable the CO2 can actually be stored on long timescales. Does it leak out, and so on? And I'm not sure that we really have good answers to this yet, but it would be a good paper topic for people who really want to dig into that.

If this goes away, what happens is you see these other things expanding. We see more storage, more wind and solar, maybe more nuclear, or more geothermal, depending. So anyway, I just wanted to remind you that these are models that keep the grid up. They take into account the variability of the generation source. All right.

So let's talk about what's going on in the world with renewables. I said they're kind of eating our lunch. And here is an example. This is global changes to the worldwide, not just US, in electricity generation by source. Every year, we see, so brown means is coal. We see some coal coming upline, coal coming upline, coal was built, coal was built, coal was built, coal coming offline, coal coming offline.

Actually, I shouldn't say offline. This is generation. So I just say used or not used, compared to previous years. But what you see is that basically renewables are producing more and more and more electricity every year globally. And the result is that it's rapidly decarbonizing the grid. And at least in OECD countries, developed Western world, renewables now generates not capacity, but actually produces watts on the grid more so than any other source of electricity other than natural gas.

So it's not something that's coming. It's very much here in large amounts, and it is growing very rapidly. So, I don't have data. Unfortunately, the people who published this chart rearranged their data. So they now clump coal and gas and they call it fossil fuels. And so you can't really tell where renewables are relative to these other sources. So that's just my data only goes to 2020. And I really don't know if renewables has now crossed gas or not, but it may well have.

So the result of all of this generation being built is big changes in the structure of the grid. This is just the United States. And this is for this year. This gets published at the end of the previous year, and this is what's in the queue. And these things are typically in the queue for about five years before they get on the grid. So we have a pretty good idea of what's coming online. And so it says between wind, solar, and battery storage, the United States is scheduled to add 63 watts of capacity.

To add that much nuclear at the current build rate in the United States would take us 315 years. So this is happening in one year. It's happening this year. And we're halfway done with it. That gives you a sense of how big you'd have to ramp the nuclear industry to start competing with this industry, right. A 31,000% increase in the size of the nuclear industry, just to break even with wind and solar. I can't really underscore this enough. This is not something coming. This is already here.

So our question is like, will it keep going? Is there something that will in the end suddenly stop this. And there are two basic things that might do that. One is resource constraints. OK, it's nice, but land is going to become an issue, something like that.

And the other two is when you put more and more variable generation on the grid, you have more volatility in the supply of electricity. And the question is, will we require so much overbuild in order to dispatch that generation that it becomes uneconomic? It's fine if solar that only turns on in the middle of the day, and you only have a little bit of solar, because in the middle of the day, you have a little bit of extra demand. And so it's nicely balanced.

But in the future, if you have a grid built on solar and then you need to turn on power in the middle of the night, maybe it doesn't work, right? So how much overbuild do you need to keep the grid running, and that makes the economics less and less favorable as you get more and more renewables. So we'll look at both of these questions today.

So just in the basic most basic level at the physics kind of approach, yes, there's a lot of sun on the surface of the United States. 3,500 times annual consumption, if you put solar panels over the entire United States, obviously that's not possible. How much land would you have to cover with solar panels to power the entire US electrical grid strictly from solar, which you would never do? But if you wanted to do that, how much land would you need?

Assuming 20% panel efficiency would need 0.04% of land, which is a square about 60 miles per side. And so is that a lot of land or not a lot of land? And I think we need some context to understand that. So if I put it all in one spot here, here it is. It looks enormous. It looks like it's taking up a chunk of Nevada. This, Incidentally, is almost exactly the same size as the Nevada test site, where we test our nuclear weapons, so we've devoted exactly the same amount of land to testing bombs.

I guess we could probably devote the same amount of land to building solar farms. It's also important to remember that we do already devote land to making energy. I mean, a lot of land to making energy. Obviously, every energy production takes some amount. But does anyone have in mind, like the most land intensive form of energy generation?

AUDIENCE: I'd say maybe hydro, with like the lakes.

PROFESSOR: No.

AUDIENCE: Is it solar?

PROFESSOR: Corn ethanol. We grow corn in America strictly to turn it into ethanol, to make gasoline, well, to dilute gasoline with ethanol. And this is one fifth of the amount of land that we already use to grow corn ethanol. And on top of it, the life cycle emissions of corn ethanol is about half that of gasoline.

So it's not a low-carbon energy source. This is a low carbon energy source. Right? So we could easily cut down one fifth of corn crops, replace them with solar panels, and significantly further decarbonize the system by getting rid of medium polluting ethanol and replacing it with net zero basically for CO2.

It's also about one eighth of the amount of area that we currently devote to the emergency planning zones for the 98 nuclear reactors in the United States. Now, people live in emergency planning zones, so you can do other things with that land. But in terms of just realizing that there are constraints being put on the large amounts of land for energy generation, this is something we do all the time.

It looks a lot different if I spread it out. That's the same amount of land spread out in tiny little dots. And suddenly like oh, well, that looks fine. So is there that much land available? So here's a plot that shows the amount of land that belongs just to the federal government. No one owns. It belongs to the government. It's about 28% of the United States.

An enormous amount of that land is in solar-friendly friendly regions. And so we use this land for things like military bases, and like I said, the Nevada test site where we test nuclear weapons, not in principle any reason why we couldn't also-- we granted land, federal land, to NuScale to build their nuclear reactor. We could theoretically do the same for solar.

Yes question or no? OK. OK, so what about non-US? I mean, the US is a big space. What about countries like Japan? That might be more interesting. So here's a nice way to do the comparison. Here are the land use in the United States. And you see 29% of land is pasture land, and grass, and ranges with basically nothing on it. We have some forest. But forest are not a great place for solar panels because trees tend to grow there.

We don't necessarily want to displace cropland, but we could because a lot of that is being used for corn ethanol. But we have a lot of what you would call empty land that we could use. So another potential issue with solar might be can you build all these solar panels? So if you look at the minerals required to make solar panels, there doesn't appear to be a fundamental supply-chain problem. The biggest near-term risk is over, which is used in these-- you see these traces on the front of these silicon solar panels.

It's actually so the enormous growth of solar is responsible for the current shortage in the silver market. But there are all kinds of things that manufacturers are doing because of the economic pressure, the rising cost of silver. To deal with this, they are making the traces thinner. They are making copper traces that are just silver plated. And the studies basically suggest that between this thrift and substitution for silicon-type solar panels, silver will not be a limitation in the long run.

Everything else in a traditional silicon cell, the polysilicon, the glass, aluminum, encapsulants, even the copper for the wiring are things that will require a diversified supply and expansion of supply. But there's not a critical mineral resource limitation.

When it comes to recycling solar panels, dealing with the waste problem, there isn't a toxicity issue or a technology issue with doing recycling. The problem is really just like the sheer scale of it and making it economic to do so. So by 2050, we're expecting something like 60 to 80 million tons of waste solar panels worldwide. Most of that mass is glass and aluminum. Both of those things are very recyclable. The problem is that the silicon panel itself is very thin and has virtually no intrinsic value. Once it's used up, it's not really worth recycling.

The silver content was, but as the over content shrinks, that becomes less interesting to recycle. And so for now, in most markets, it's much more economic to just trash these panels after you rip off the aluminum in the glass.

There are programs out there to deal with this. And Europe has a collection and recycling program for solar panels. A company called First Solar here in the US, which doesn't use silicon, they use cadmium telluride panels, they have a closed-loop recycling plant. There are new recycling plants in France as well to do the silicon recovery at scale.

What's missing is really policy that will make this economic to do. And we have a similar problem with dealing with the waste from nuclear. It's there and it can sit in canisters and it's not economically favorable to do anything with that waste. So in the US, what we did is we taxed nuclear power 0.1 cents per kilowatt hour is a tax for dealing with waste. And we could, in principle do the same for solar. And that would solve this waste panel problem. For solar, resources or waste do not appear to be a serious bottleneck.

All right. Let's talk about wind. So wind is more tricky because there are density limitations. You can at most fill about 1% of your area with wind turbines before you drag out too much energy from the air currents. Still, even with that constraint, the United States, cover the whole United States with wind farms would support 17 times total electricity consumption. All right. And turbines are getting bigger and much more efficient. OK, fine.

It's interesting to ask, what would wind do to-- OK, it's one thing to talk about, OK, you're slowing down the wind and the zone has only so much extractable energy. That's talking about. But what is wind doing to our climate? Like if we do extract energy from the air movements, does that affect climate? So there have been a number of studies that have looked at this.

There are studies that they start out with just a gigantic idealized arrays, and what they see is a temperature effect on the order of 1%. And what do I mean by a temperature effect? Essentially, what happens is that there's mixing between the cold upper troposphere and the warmer, lower troposphere. And the result is that the nighttime-daytime temperatures get closer together. That, on average, the air is more uniform in temperature. It also pushes around the precipitation a little bit. So there are some places that get a little bit more precipitation, some places that get a little bit less precipitation. And those changes tend to be on the order of 10%.

So let's just look at some studies in high resolution. This is a regional climate model that is probably the best one I've seen. These dots indicate the locations of wind farms. And so instead of just having wind across the whole US uniformly, they're trying to say, where would you actually build these wind farms? How big would they be realistically? And this is the result of that model.

And in this model, the wind farm, the cumulative size of the wind farms is enough to provide 100% of the electricity to the United States in terms of total production and total consumption. So it's not balanced, so that you would need a lot of batteries to do this. But that's just to give you a sense of scale. It's just a scale.

And so you can see that they see temperature perturbations of up to 1 degree, which is consistent with the large primitive studies, right in the middle. But most of the regions have perturbations on order of about 0.3 degrees. I think the technical average across the United States is 0.2, plus or minus 0.2 fluctuation.

In all the studies that have looked at this, the authors always note a couple of things. They say that the changes are well below the average or interannual variability. So one year, you're going to be a little warmer. One year, it's going to be a little cooler. These changes are smaller than that. And the other thing they point out is that these changes are way smaller than not doing anything from greenhouse gases.

So their view is, yeah, there are some changes. They are detectable but not disruptive. And indeed, the largest changes tend to be immediately in the vicinity and downwind of the wind farms, as you can see here. And if you put these wind farms like in croplands, these changes regionally are actually favorable because it prevents your crops from freezing overnight.

So people will continue to look at this as wind farms get built. People will be doing studies to make sure that these predictions are correct because I they're just predictions, we really don't know. And it's important to keep tracking this. So there is a non-zero but probably negligible, I guess, is the conclusion effect on the climate.

What about these mineral constraints? So yeah, there are some concerns about mineral constraints for making the magnets. These magnets use rare earths. Particularly neodymium and praseodymium are the two big bottlenecks. There's also some ytterbium. And I forget, what is it, Dy, does anyone remember? I think it's like [INAUDIBLE] or something. Anyway, I don't remember.

So for one, terawatts of installed capacity, which is approximately the total which is what was actually shown on the previous plot. Total US consumption is about half a terawatt year, per year. And given the capacity factor for wind, you would need to build about 1 terawatt of wind to get there roughly. This is the amount of minerals that you would need.

If you want the global number, you should multiply this by a factor of 6, because the United States consumes about one sixth of the global electricity. So according to the US Geological Survey, this is about 0.7% of known global reserves. Known reserves used to be underlying, because there's always more than we don't know about. So it's not a huge amount. If you did wind for the whole world, that would be 4% of known global reserves. So it will make a dent, but whether it's in terms of being like an actual bottleneck, I don't see it yet.

Some more issues with blade waste, it was mentioned earlier by someone a couple of weeks ago in this class. A lot of the existing blades are glass fiber set in thermo, in epoxy, fiberglass, fiber-reinforced epoxy. The glass is in principle recyclable, but the problem is that the entropy of the mix is obnoxious. You can't get the glass fibers out. And these epoxies are not re-meltable. So for existing blades, mostly what they do is they just grind them up and put them into asphalt or concrete as filler.

But there are a bunch of proposals for making recyclable blades. So where are they? Yeah, they have either moved to do some research in fundamental chemistry to find solvents that can depolymerize these epoxies or just use different materials. And so there are things like that have been called recyclomine and others that have been developed specifically to make wind turbine blades. I don't know how good they are.

They have been used in turbines now since 2021, and whether they have the same lifetime or the same economics, I actually couldn't really tell you. But it is an issue. People are working on it. It would be bad if wind turbines was a major source of microplastics. Right? So engineering is being done and there does appear to be some path forward. But I think, again, something else that ought to be understood.

There are a bunch of other aspects about wind and solar in terms of externalities, like impact on how useful land is, or whether it's killing birds, or whether it's making noise. And we will look at those, not today, but when we do the externalities lecture, we're going to add those all up and see how that affects wind and solar.

So for both wind and solar, there are no showstoppers yet. Let's talk a little bit about geothermal. I call it a semi-renewable resource because you're digging a hole into the ground. You're sucking heat out of it and it cools off. And the way it warms up again is you have to have, essentially churn from the magma in the Earth, and that takes time. So they tend to recharge themselves on 100-year timescales. But we have something like an estimated 1,000 times US consumption in extractable renewable heat. So as long as this number divided by 100 is greater than 1, we can probably call it a renewable resource, something like that.

All right. So then the obvious question is, if this is so great and it's dispatchable and there's plenty of it, where is it? So it turns out issues faced by geothermal are not actually that different from the issues faced by the nuclear community. It's one of finance.

So here's how geothermal works. You go somewhere where you think there's a good place to drill a well, but the well that you have to drill is about 2 to 3 kilometers underground, and you're not really sure what is beneath you 3 kilometers underground. So you spend a lot of money, essentially all the upfront costs, just like building nuclear, all the upfront costs, drilling a hole in the ground. And you might find that the well is good, or you might find that the well is not good.

And it's expensive to drill hot, hard rock very deep. So investors who are looking at projects, they're saying, we want to invest in energy for private capital, for someone's retirement fund. We're going to invest in some energy projects. Would you invest in wind, or would you invest in geothermal? They invest in wind because they know it can be built and there's a lower risk of the individual investors losing their money on a project.

And so this has basically slowed interest in geothermal. It's also what slows interest in nuclear. Because if you think back to 2005, 29 nuclear plants were going to be built in the United States. License applications were filed. And of those, two got built, right?

So imagine you were an investor trying to invest in nuclear, and on average, you have a one-in-15 chance of actually making money, and a 14 out of 15 chance of losing your money. You probably wouldn't invest in nuclear. And the way we've solved that in nuclear is to have federal loan guarantees. And if we had a similar basically saying, we guarantee that you'll be able to pay your investors back, and if they did something similar with geothermal, I think we would see a lot more geothermal.

There's some other stuff related to permitting. It slows it down and makes these projects take a long time because you have to deal with a lot of groundwater issues and so on. But those are delay factors more than anything. I had one more point I wanted to make here, and it just slipped my mind.

All right. Oh, the point was that investors' decision to invest in wind and solar, which is obvious given like I showed you these charts of how much is actually being built, that's all being paid for by private capital or mostly private capital. There will come a point where the value of building the next wind or solar farm decreases because of so much capacity already on the grid, that these projects, these geothermal projects, will start to look more attractive.

So it's exactly what the economics predicts. You're going to see basically natural gas and wind and solar. And that's what you're going to see. And then at some point, you're going to see these dispatchable technologies show up because the economics force the situation to go there. So that's when we're going to see the geothermal.

All right. So how much can we do or how much will be done on the grid? I guess the answer is it appears from what I just showed you, that wind and solar can heavily decarbonize the grid. It's cheap. Why aren't we decarbonized already? It's cheaper than natural gas. Why hasn't it displaced natural gas?

The answer is it's doing so, but it's rate limited by something exogenous. And what's rate limiting the deployment of wind and solar in the United States, is not economics. It's actually connecting to the grid. So this is a plot which I've extended for two more years, showing you the total amount of generation capacity from wind and solar waiting to be connected to the grid every year.

And you can see that by 2023, the amount waiting to be connected to the grid is twice the amount of electricity that we actually use. That's the black line. That's the existing generating capacity. Now remember, this stuff has 30% to 40% availability capacity factor. And this stuff has closer to 100% capacity factor. So this amount of capacity waiting to connect still it's not going to provide all the electricity, but it's getting close to providing all the electricity.

It's a really staggering amount, 2.7 terawatts of capacity in 2023. It's down a little bit since then. So the bottleneck is basically getting access to the grid and the average time that you are stuck in this queue is about five years right now. And there's an order from the Federal Energy Regulatory Commission, I guess, that says that it's a first-in, first-out queue. So the people who signed up first will come out first and so on.

So why are these things taking so long to connect? Well, if you just dump all this generation on the grid, that is variable, the people who run the grid won't be able to keep running the grid, because the grid is not designed to handle all of this variability. And there's a couple of different problems with it. So one is related to predictability and controllability. Yeah?

AUDIENCE: I have a question. So about what you mentioned that the queue is first-in, first-out, I heard this a few times, but I haven't looked into it a lot myself, is that developers will put projects in, even though they're not really sure if they're actually going to follow through because of the queue, so they might as well put it in and that the actual percentage, so let's say commitment on what's in the queue, is relatively low. If you have an idea of how low that is--

PROFESSOR: That's a very interesting point. I don't. That would be a really good thing to look into. I am aware of the alternative situation where essentially people have made real investments in projects, and the grid operator has basically denied them access, and they start suing for access and so on. I really don't know. Yeah, that's probably a hard number to come across, but something worth looking into for sure. Yeah.

Yeah, I guess we can't really tell anything from this data. Yeah, I will look into that. That's a very good point. Let me just make a note here. We might not really be able to tell. I mean, I guess if people put in connection orders, they're not going to say publicly, we don't really have the money to do this, but we're just putting in a connection order just in case.

AUDIENCE: Yeah, I mean, it sounds from when I was talking to people from the MIT Energy Initiative, et cetera, that in more of the, let's say grid modeling community, this is somewhat of a known thing. But I never heard them mention any numbers about oh, we think half of them are fake, but it seems to be a somewhat known thing.

PROFESSOR: Interesting. I had never heard of this, but I will look. It makes sense that this would be done. So OK, even if we say half of them are fake, that's still a lot. All right. So, let's just talk about the problems, why these things can't be connected right away, which, despite whether they're real or fake, I think are our real problems.

So one is this forecasting what is going to be actually available, how much wind you're going to have, how much sun, you're going to have. And the weather models and ability to do that forecasting has gotten a lot better, but the integration of that information into the running of the grid has not yet happened. Traditionally, the grid was designed to basically dispatch most of your generation, and then you would have these small, tiny, near-term capacity markets to do the little adjustments.

And now we would need to redesign how that happens, so that the dispatch is more just in time to deal with the large amount of wind and solar. So basically it's a control theory and software problem. And there are people working on this. But it is a major limitation.

The other thing that has been raised is ancillary services. So traditionally you have one thing is just putting watts on the grid. But the other thing is that you need to do voltage control. You need to have regular up and down regulation, frequency stability. These things come generally from synchronous spinning generators, which are basically large moving masses that are synchronously linked to the grid. And they provide an inertia against unwanted change and they stabilize the frequency, and so on.

Traditionally, the inverters used for wind and solar or particularly for solar, don't do that. However, there are now fancier inverters called smart inverters, that have software to simulate the effects of being a rotating machine. And I think it was this last year, CAISO, the California grid operator, gave a large-scale test of these smart inverters, a 300-megawatt megawatt electric solar farm, using them and to see what they could actually do on a real grid in terms of providing these ancillary services. And according to their report, they performed comparable to or better than conventional units. So it looks like the smart inverter technology will solve the ancillary services problem.

So in short, it's basically software electrical engineering, grid permitting, and software and software and software that basically has to be worked out to get large amounts of solar. And it's coming. A of people are working on these problems.

All right. So I just thought to go back to our first slide or early slide, there doesn't appear to be issues in category 1. So let's just look a little bit at category 2. Now, we saw something that looks like a category 2 result with this, which just says for localized grids, this is the answer. But what is the situation, if we really said, let's look at across the whole United States? We might also be interested in let's look at all across Europe.

So I wrote a paper on across Europe. It's in the readings. There's another group, Shaner, who's the author of the paper. They wrote one on across the United States. Theirs is a little bit different than mine in that they don't have particular technologies substituting. But I thought, who read Shaner's paper? Not many people actually read it yet.

A lot of people in nuclear love it because if you read it, it sounds like wind and solar are really going to fail. But I think it's just worth like looking at it carefully. So let me just walk you through. These are the solution sets from their model. So what this plots is on the left axis, the mean solar and wind generation normalized by the electricity demand. And so one indicates that the wind and solar is providing exactly the same amount of electricity as demanded.

But, of course, because it doesn't produce electricity at the right moment in time, that's not enough. You need to build more wind and solar to deal with that, or you need to load shift it with storage, one of the two. So if storage were free, then you could just build this, right? But storage is not free.

And so this is a fraction of the electricity demand that is met with wind and solar plus storage, and they have zero storage model, 12-hour storage model, four-day storage model, and a 32-day storage model. Four days and 32 days of storage is awfully expensive. I don't consider those things to be viable. So I'm only interested in the 12 hours of storage model. So we're only going to look at this light green curve here, light green curve.

This graph and this graph is the exact same graph. It's just that this goes from 0 to 20. And this graph is rescaled to go from 0 to 99.99/ So it's focusing on what's happening here, which is the area of interest because we're interested in questions of can you produce 99% of the energy from wind and solar?

So if you are interested in running the entire grid just off of wind and solar, and have the same grid reliability that we have today, you would be somewhere around here, 99.9, maybe in here, depending on how many hours of blackout you're willing to tolerate a year.

So what my proposal is, we'll just look at the 12 hours of storage, and we'll look at 99.9% of electricity demand being met by wind and solar, which is to say, essentially the same reliability, and basically no other technologies. This is not an optimal system.

We know from these results, which are optimal systems, that for a lowest cost system, you need some kind of dispatchable stuff to make it lowest cost. But that's not the question we're trying to answer. We're not asking what is the optimal system. We're just asking, is it even feasible at a reasonable price? That's the question I want to answer right now.

So we'll look at these results. And he has these results that are 100% wind, 75% wind, 50% wind, 25% wind, 100% solar, different mixes between these two renewables. So let's just pick the 50/50 mix, half wind, half solar, and see what we can do with 50/50 mix and 12 hours of storage.

So the first thing I want to do is note for you that if we take the left axis, which is mean solar and wind generation divided by demand, and we divide that axis by the right axis, installed capacity by mean demand, we get generation per unit capacity, which is capacity factor. Does that make sense?

So if we look at this intersection here, the 99.9%, we have 1.7 divided by 6.5, which is about 25%. Is that right? So they're basically saying that as you move up to these very high penetrations, the capacity factor for the blend will be something like 25%. And this gets to this earlier question that someone had, because right now the capacity factors are 41% and 30% But if you have this much, the average capacity factor is going to drop. So that makes sense.

So the first thing we need to do or the next thing we need to do is to calculate the cost. So this is now a couple of years out of date, but the numbers are close to the same. This is the EIA's table of cost, which remember, comes from actual survey data of real plants, real installations. So this is not a forecast. It is for nuclear, but not for solar and not for wind.

So they have here some prices and they have here a total cost and a transmission cost. And so the first thing we want to do is subtract out, again, I wish I had a laser pointer. Subtract out the transmission cost just to get the cost of the generation. And so if you look here in this top plot, you'll see I take this top right there, I take the price of wind, which is $40.23 and I subtract out the transmission component $2.63 That's the cost of the wind farm, not the transmission line.

And then I multiply it by 0.41 divided by 0.25 in order to rescale the cost for a lower capacity factor, because the capacity factor is going to go down from 41 to the 25. Does that makes sense? And so that tells me the new, whatever that number is, that's the new, I guess the $62 per megawatt hour is the price of the generation at the reduced capacity factor. Same thing for solar, it's $29 per megawatt hour at the reduced capacity factor for solar.

Now I need to add the transmission back in. If we looked at these transmission costs, they're about 6% and 10% of the total cost. But I happen to know from other studies that if you have this much wind and solar, your transmission costs are going to be higher. And a reasonable number, which I used to give the grid lecture first, but now I'm going to give it later. So you're just going to have to trust me on this for now. A reasonable number is about 25% of the cost will be transmission. So we're going to add 25% to deal with transmission required for this generation. That gets us to this number.

Everyone's good so far? All right, now we need to increase the storage because Shaner says that we need 12 hours of storage in order for this green line to be valid. But this plot is if you read the footnote, footnote C, which I did not put here, it's four hours of storage. So we need to rescale the storage. So how much does storage cost?

So what we do is we say we have to go back here to Sergeant and Lundy's. This used to be a part of your homework which I'm no longer assigning. So you don't have these numbers in your head. So we go to the Sergeant Lundy table, which is produced for the Department of Energy, and they tell us how much it costs to build all these different technologies. And we see here they have solar and solar with storage. And this is about four hours of storage.

So the capital cost difference is 1755 versus 1313. So the amount of cost is roughly 25% of the capital cost of a solar farm with storage, roughly 25% of that cost, which is to say 1755 divided by 1313, is 25%. Roughly 25% of that cost is going to be for the battery.

All right. So 25% of the initial cost of solar, so it's this number minus the transmission costs, which is that, gives you $6.70 per megawatt hour for four hours of storage. We need 12 hours of storage. So we're going to multiply that times 3. And that comes out to $20 per megawatt hour for storage. And we're going to add that back to not only the solar but we're also going to add it to the wind. So we need storage for both.

So here's your wind, plus transmission, rescaled for lower capacity factor, add back in the storage. And you get these numbers for each generation technology. Yep?

AUDIENCE: Do I need to assume that the cost scales linearly with storage?

PROFESSOR: It does assume that, yeah, because this storage is lithium ion battery. Yeah. Yep?

AUDIENCE: I actually wonder. I feel like I don't care about wind and storage as much. Is it equally cheap for solar? You have one battery pack and it's big, but all your turbines are kind of scattered around.

PROFESSOR: Is it really cheap? No, it's the same. Yeah, and ultimately that all is going back to one node where you're putting it on the grid. Yeah.

And we need a 50/50 blend of these technologies. That's what we chose, the 50/50 mix. So we just average the two together to find the 50/50 mix. It gets to $77 per megawatt hour. And we need overbuild. So I go back to this plot. We chose the 50/50 mix. And it says that mean generation divided by mean demand where it's somewhere here, 1.7, we have to generate 1.7 times the amount of electricity in order to deal with the variability.

So we're going to take that number and multiply it times 1.7 to deal with the variability, where you get to $131 per megawatt hour. So this is a grid run entirely by renewables with 12 hours of storage and excess generation to deal with the variability that operates 99.9% of the time. So it's basically just as reliable as the current system. And the cost is $131, which is essentially the same price as base load nuclear or much cheaper than load following nuclear.

So there's the AP1000 load following number. And there is the MIT. future of nuclear nominal cost estimate with 50% load on schedule at 180 megawatt. So it's just too cheap. That's the problem. If you have good wind and solar, it's really hard to see how this becomes a problem. So that's the bottom line. In order to keep nuclear in the mix, you have to find a way to get nuclear price way down.

And there are ideas and we're going to talk about microreactors next week. Any questions about wind and solar? Or microreactors? Yeah, next week. Yeah. Yeah?

AUDIENCE: On the study that you assigned talks about the fact that building this amount of storage might be unfeasible, at least with the current capacity that there exists in the US. Do these prices for storage for $12 storage account for that?

PROFESSOR: So I didn't do anything to account for that. I don't know what would affect the feasibility. Was it a lithium resource?

AUDIENCE: It was just the sheer amount of batteries that needed to be produced in order to supply the demand. They argued that with the current, for example, like gigafactories, it would take something like 900 years to get the amount of energy that they need. And I'm also wondering, how this accounts in terms of the laws of capacity over time for these battery packs, which is what happens with lithium batteries.

PROFESSOR: Yeah, so I believe-- I mean, this is a good question. So these numbers, they call this four hours of storage. I don't know how much this declines over the lifetime of the battery packs. So if they're calling it four hours of storage, but on average it's really one hour, then this calculation is not correct. And I don't have good information about that. So we'd have to dig into what the EIA assumes four hours of storage is.

In terms of the making of the batteries, I think first of all, I would say that using lithium ion is a worst-case scenario. There are lots of other storage technologies coming. I think [? mion ?] is here, but it's expensive. In terms of battery production, if there's a market demand, capacity will emerge. That is not something that particularly worries me. What would worry me is something that I haven't looked at in this study, which is there a lithium resource constraint?

The reason I didn't look at it is I'm assuming that we will probably not use lithium. We will use some kind of flow battery chemistry, or lead battery, or something else that is cheap and abundant but is not yet being deployed. So I assume that this is a conservative calculation because it uses lithium ion cost numbers. But to answer these questions in an intelligent way would require someone to really undertake a study on battery technology.

I guess my final comment on this is part of the reason why there is so much storage in Shaner's model is that he doesn't have anything other than storage. That's a problem in his model, and that's why I signed the version that I did because what we do is we say, OK, well, why don't we have 1% dispatchable, like we do natural gas just because it's built and it's there. And we figure 99% decarbonization is probably just as good as 100% decarbonization.

But you could also have 1% geothermal, something like that. And you see the enormous cost reductions that come about when you substitute battery for dispatchable generation. So again, this is not a cost optimized scenario. This is not how it would actually be built. This is just saying that wind and solar, in theory, could do it. Right? That's all it's saying.

You wouldn't do it this way. It would be foolish to do it this way. You would much rather do it like this. Yep?

AUDIENCE: When you discuss the rare earth metals as far as the mineral resources for wind energy, you mentioned, a total percentage of global resources. Do you know that percentage of US resources or perhaps not?

PROFESSOR: I was looking for it, but I didn't actually have time to look it up. So one of the problems is the US Geological Survey does not actually import by mineral or just report total rare earth oxides. And then you have to break it down by what the average rare earth ore is. But then that data is only available for the countries that currently produce the rare earth. So it turned out not to be an easy thing to do. So I didn't have that data for you. Yeah.

Anything else? Yep?

AUDIENCE: Something really quick, if you go back to the slide before--

PROFESSOR: Slide which?

AUDIENCE: The one with all the transmission costs that you did the calculation on. Transmission costs was rather low. If we were actually to scale up in solar to the levels that you're describing, wouldn't you expect it to be higher? I mean, you said that 25% transmission to add. I guess that kind of answers.

PROFESSOR: That is the answer. Yeah, so I estimate that for nationwide transmission that is needed to deal with renewables is about 25% of the cost. And that's based on historical transmission project costs. I'll show you when we get to the grid talk. I have a little regression model that tells you how much it costs to build transmission.

AUDIENCE: And then just one more from before, you were talking about the case when we had one gigawatt of capacity of wind for the entire country. You have an idea of how many wind turbines that would actually take to do, the number, just roughly?

PROFESSOR: 1 gigawatt of capacity in terms of number of turbines? We'd have to--

AUDIENCE: What the typical power of a turbine is.

PROFESSOR: Why don't you just Google what is the average power of a current turbine? Yeah, I mean, they've gotten very big and I don't know enough about the mega-sized turbine turbines, if they can be deployed anywhere. So I don't know what the average size is. But that's a very quick google. You can do that yourself. Yeah.

AUDIENCE: Let me show--

AUDIENCE: Could the expansion of solar or wind turbines lead to deforestation, let's say, or whatever other similar concerns about this?

PROFESSOR: I think I missed the first part.

AUDIENCE: The large scale expansion.

PROFESSOR: Of solar?

AUDIENCE: [INAUDIBLE] solar wind designs of adverse effects on the environment, for example, deforestation, et cetera.

PROFESSOR: Yeah. So when I did my preparation for this talk, I read a whole bunch of papers that have analyzed these things. And the things that I talked about are the things that the academics have investigated. There are also-- and I mentioned these minor issues like noise, and killing birds, and ecosystem repurposing, and land use changes. And there are people who have tried to calculate the externalities for that.

So the way I think about these things, and they're not limitations. They're not technical feasibility limitations, so I didn't put them in this talk. But there are things that might raise the effective social cost of wind and solar. And so when we get to our talk on externalities, where we're going to talk about, the safety externalities from particulates, the safety externalities from nuclear accidents, the safety externalities or the social externalities from noisy wind farms, we will come up with numbers for all of these things and see if things change dramatically. Yeah. Yep?

AUDIENCE: Is 12 hours of storage on a massive scale really feasible, because my understanding is that it's quite hard to get big batteries to hold a long charge and discharge them every day without-- my understanding is 12 hours storage is actually a pretty difficult technological line for us to get to.

PROFESSOR: Sorry. Why would that be?

AUDIENCE: I mean, I don't know too much electrochemistry, but there are some trade-offs in terms of how big you want the battery to be, how quickly you want it to discharge, and how long you want it to hold the charge. So the longer duration storage battery you want, it would either degrade very quickly, if we want it to discharge at 0 to 100 every single night, or it would be able to dispense energy at a very small--

PROFESSOR: So first of all, let me first remind you that 12 hours of storage is not how it will actually happen. This is a hypothetical study that is just to take Shaner's results and do something with them interesting. You wouldn't build all that storage. You also wouldn't necessarily build it out lithium ion, so those things aside. So yeah, so the thing you're talking about is basically a series parallel problem. How many cells you put in series, how many cells you put in parallel? And if you want high intensity discharge, then you wind up with the scenario where there's a lot of internal resistance, and you have more self-discharge.

I still think 12 hours is not that bad from a self-discharge perspective. That's my sense of the matter. I think if you want to store for weeks, yeah, your self-discharge is an issue. I mean, this does 12 hours of storage. But I think this is a niggle on a fake scenario. So, I'm not worried about it. Yeah.

All right. Anything else? All right. I will see you Wednesday.