[SQUEAKING] [RUSTLING] [CLICKING]

SCOTT KEMP: I just wanted to do a little review. In the last class, I had mentioned the Westinghouse eVinci kind of nuclear battery concept, and I hadn't looked back at this in a while. And Emil, who's walking through the door, had informed me that they had made progress on this.

So I just wanted to show you the progress, apparently, care of Emil. This is the reactor has gone from this concept, which was very rough, to this. So it's now, I guess, five modules-- reactor module, power conversion module, and then at least three of these control modules.

You can see here that it looked like originally the reactor was like 12 to 15 feet high based on this fence. And you can see here there's a person. So it looks like it got a lot bigger, which I think it looks like details are still being worked out.

But that's kind of illustrative of why the costs escalate. You have this idea, and then you have to actually engineer it. And reality sets in. That explains what's going on.

I also said that for the first time, I had tried to get you some numbers about how cost had come down, not depending on the number of reactors that were produced, but actually on the rate of production, which seemed to be actually where the real benefits of factory fabrication lie. And I found this. I was looking for a comparable study, and I found this study on rates of production for fixed fuel cells, stationary fuel cells, which are kind of like a battery, but a little bit more complex.

And they found a 30% cost reduction for every factor of 10 kind of, at least at the beginning, factor of 10 increase in production rate. Emil also told me that there's a study looking at this in nuclear for microreactors. So I thought this is a better example, maybe.

So here's the study. And here's their kind of final bottom line-- 20% when the cost increases by a factor of 100, or two tenfoldings. So that's instead of a 30% per tenfolding. If you back out, it's about 9% per tenfolding. So I guess my calculation was overoptimistic.

But you can see there there are people looking at this. It doesn't move in a good direction. I guess if I revise my slide, then it would look like this.

I was suggesting that maybe at 50 units per year, which is like all the nonwind and solar online, we could bring the cost down 45%. But the revised numbers are not as good. So sorry for being optimistic. I have a habit of that.

OK. So today, we're going to talk about the electric grid. So in the beginning, there really wasn't a grid. And let's do some history because it's fun.

So the first electric distribution of any kind with a central generator was in Wall Street in New York in 1882. And the price of electricity, if we inflate it to today's dollars, was about 100 times more expensive than it is today. It was a real luxury item.

And today, we have this enormous grid that actually is not just an American grid. It goes up into Canada, and it's shared. It's split into three synchronous zones.

And Texas has its own grid, as does Alaska. Texas likes this because it insulates them from federal oversight, because anytime you sell electricity across borders, the federal government gets involved. But Texas avoids that.

And so this creates a political structure that we're going to talk more about in class that has really shaped the history of how this grid operates. And there are various councils and political entities that are important in this story. The grid, in case you are not electrically engineering inclined, is something that was really made possible by the emergence of AC transformers. And before that, electricity distribution was done with direct current. But the problem with direct current is as follows.

Let's say that I have a house that wants to consume a kilowatt of power at 100 volts. And so that's something like 10 to 20 incandescent light bulbs-- not a huge amount of power.

So by Ohm's law, we can calculate the current required. And we would get 10 amps. 1,000 watts divided by 100 volts is 10 amps. OK, very simple.

Now let's imagine that house is a mile away from the generator, which is not that far. Walk across campus. And so there's going to be some ohmic losses on this line. And if you look up the resistance of copper wire-- this is a 10 AWG is American Wire Gauge.

I don't know if you know your wire gauges, but this is much fatter, a little bit fatter than what you have in your house, which is typically around 14 for 15-amp service or 12 for 20-amp service. And so this is not a shoddy, thin wire. And it has a loss of 1 ohm per thousand feet. For 5,000 feet, which is one mile, we would have-- well, I guess I did my math wrong.

I said, oh, round trip, yes, 10 ohms round trip. Because you've got to send the current there and back. Yes, so 10 ohms round trip. And so we need to figure out how much energy is lost here. All right.

So again, we use Ohm's law, and we say with 10 amps running through 10-ohm resistor is a 100-volt graph. So in order to provide the 100 volts at the house, the generator needs to put 200 volts on the line. And that means 50% of the energy is being lost in this power line.

And that's why the small DC Edison-style grids were very tiny with just very local customers. But once you can fix this problem, well, there is the original Edison plant. There's the service area in orange. You can fix this problem if you can change the voltage.

So transformers preserve power by changing current for voltage, potential energy. And so let's just do that. Let's say we'll have power transformers at each end. And instead of sending 100 volts down that mile of wire, we're going to send 100 kilovolts.

Now I send 10 milliamps of current through the line at 100 kilovolts, the same amount of power. And if I do the same loss calculation, here's my 10 milliamps times 10 ohms. I'm going to lose 100 millivolts. So the amount of power I lose is 0.1% as opposed to 50%. That was the magic-- the invention of the transformer.

And so that enabled suddenly long-distance transmission and as a result, large-scale power stations that could then power large regions. So this is the first of those stations in Schoellkopf Mills outside of Niagara Falls. And this is a hydro station. And just lots of early makeshift generators running turbines powered by this thing.

So this thing sent power to Buffalo, New York. It was 20 miles away. And it was all possible because of these transformers.

So early electric grid started out by sending power at 66 kilovolts, and then it went from there 150 kilovolts, 245 kilovolts, 375 kilovolts. Now we talk about long-distance transmission, high-voltage transmission at 765 kilovolts, I think. And people are even talking about going to higher numbers than that.

So the high voltage and distances then became the standard. And the reason was because of economies of scale. So just like building a larger nuclear power plant is more economic than building a microreactor, that is also true for a natural gas plant and a coal plant. And so it was more economic to build these large plants and run transmission to customers over long distances than to have a bunch of smaller regional plants. And so this led to of hub-and-spoke architecture that we see and that has dominated the world today.

And also, as a result of this, the companies that were interested in building these plants became large, vertically integrated monopolies that built plants, built transmission lines, built distribution, built transformers, and they owned everything. And so you had these regions that run company-operated. Something-something Edison Company operated in this region, and Edison Company operated in that region. And they had total control of what was going on.

Another couple of consequences to this history-- so one is that this architecture is more vulnerable to single points of failure. If this plant goes down, you've got issues. These transmission lines are fragile. They can be taken out by natural events-- lightning, someone drives their car into the power pole. It's not great.

Another thing is because of vertically integrated monopoly, you had potential opportunities for price fixing, and there was no competitor nearby to go to. And so you had problems with pricing.

And finally, this architecture in today's world becomes unfriendly towards things like wind and solar, which are distributed generation because these power lines are all going back to one point. And unless this is where your solar farm is, it's not helping you. If you're trying to move power from different distributed solar, distributed wind generation, this architecture works against you. And so that is a situation that we're still dealing with today.

So let me just talk a little bit about this price fixing situation. So this was pretty real. The price of electricity in 1900, inflated to today's dollars, was $6 per kilowatt, which is at least a factor of 10 higher than retail price and a factor of 100 higher than wholesale price for electricity. And this was basically holding back expansion.

During the Great Depression, the US government intervened and created a regulator to prevent this monopoly pricing of electricity, and prices dropped from $6 per kilowatt to $0.88 in 1932. And of course, that meant more access to electricity for more people, which helped pull the country out of the Great Depression. And it was a great thing. And of course, we built Hoover Dam and electrified society.

So the kind of bottom line is regulation is important to prevent monopoly pricing and issues, and also that cheap power is also very important. And it's what keeps the middle class growing and the economy ticking along.

So between 1920 and 1960, the grid just blew up, expanded by enormous amounts. And here's essentially the architecture of the transmission system in the United States today.

The major generation is shown as these dots. Coal is gray. Nuclear is yellow, and hydro is blue. I don't show the natural gas because this is too much of it.

And this has basically kind of worked. Regions that were owned by different companies expanded, connected to other regions, and then they could share power and deal with power plants going out or refueling in service. And that was all well and good until 1965.

So what happened in 1965 is there was an enormous blackout. And the result is they realized that having everyone operating their grid laissez-faire and pushing power onto the grid was not a stable situation. It's kind of a miracle that this thing works. And it was basically you create instabilities.

If you push power onto the grid, you energize the lines, which then store energy as a magnetic field. So you have reactive power. So you have this sloshing of energy around between mines and transformers and generators. And you can cause generators to oscillate. And you can do all kinds of problematic things if you're not careful with how you control power flows on the grid.

And so in '65, a non-profit was created called-- oh, so I should have said that the nonprofit, the organization created to do this regulation, is FERC, which is the Federal Energy Regulation, something, something. I don't know. We have to look it up. I really should know that. And it's a government entity, and it basically just sets rules for how you compete and price electricity.

In 1965, following the blackout, a nonprofit organization called NERC, which is the National Energy Reliability Corporation, was created to set rules for not economic competitiveness, but how you actually dump the power on the grid, how you maintain the grid in a reliable state, how you can communicate power between entities, and so on. FERC is a federal entity. NERC is a non-profit. Those are the differences. N-E-R-C is NERC.

So NERC's rules are essentially voluntary. But because everyone wants their grids to operate and so they can make money, people follow the rules. And so following this time in the '60s, what emerged was a structure that was kind of a private cloud.

You had a handful of major generators that operated their local regional monopoly, and each company would individually make decisions about what generation it was going to build, what transmission it was going to build, where it was going to put the power lines. And then you had essentially state regulators and FERC working together to say, look, you can't rip off the consumer, so we're going to regulate the prices you charge. And everyone worked things out.

It may seem counterintuitive, but these regulations, both the FERC and the NERC regulations, basically cemented this system in place. It prevented, to a large extent, the emergence of independent generators. And you may say, well, why would regulation essentially create a monopoly when it's trying to prevent a monopoly, if you will?

Well, it's trying to prevent monopoly pricing, but it's not trying to prevent monopoly per se. And indeed, the electric grid is an example of what we might call a natural monopoly. It doesn't really make sense to have different outlets for different companies' power coming out of it. Is it an inefficient use of resources?

So the phenomenon was first articulated by the famous economist George Stigler, and the regulation of competition by other means. It's a famous quote. And so let me explain what he's talking about here.

Essentially, if regulations are onerous, no one likes them. But the more onerous they are, the harder it is for small startups to deal with them. So imagine you're the FDA. You're creating regulations for the safe use of a drug. You say, look, you have to run this big clinical trial. You need 10,000 people. You need all this, all these independent auditors and everything. And it's going to cost you a billion dollars to put your drug on the market.

So Pfizer and Merck assemble all this regulatory apparatus. And they hate it because they don't like to pay that. But at some small startup down the street on Albany Street that is trying to invent a new drug, those guys have no hope at all going through that process. So their best hope is basically to sell out to the big companies.

And so essentially, this is what was happening that the regulatory apparatus cemented this private cloud. And the private cloud worked on a one-on-one basis with the state regulators. And they said, look, this is the amount we want to charge. And the regulators basically say, well, it seems reasonable to us. And that's how electricity prices were set. And that was it.

The consequence of that is, well, it worked. There wasn't a lot of pressure for more efficient generation or cleaner generation, like less polluting, greener, less CO2. Because there weren't market forces in play to essentially deliver those incentives to the corporations. Then came a bunch of academics who thought they knew better.

And they started writing studies arguing that what if the electric power system were a free market, and instead of having these vertically integrated monopolies, everyone would compete and sell their electricity onto the grid? And the grid would operate in a non-discriminatory way, and they would buy power from the cheapest producers. And inefficient, expensive producers would go out of business, and prices of electricity would come down. And all of this would be fantastic.

And so this idea was largely accepted as a valid theoretical basis. And FERC issued order 888. And that required these private monopolies to establish independent system operators that would operate their electric grids.

So they still own the power plants, and they still own the grid hardware. But they could not decide who put the electricity on the grid. They had to make the grid available to any independent company. And so what emerged was a lot of what we call merchant plants, including merchant nuclear plants that decide to try to sell power.

So this is what the ISOs, Independent System Operators. There's also something called RTOs, which are essentially the same thing. And so these are where the ISOs and RTOs are located.

These ISOs and RTOs do the following things. They operate a market where you can bid and sell your electricity. We talked about bidding earlier in the class. They dispatch the generators into the market.

They say, OK, you, you, you, we want you to come online for the next hour, and we're going to pay you your money. So they decide who gets dispatched. We talked a little bit about dispatch and why nuclear plants always bid close to 0, because they always want to be dispatched.

And then they take whatever revenues they can get. They oversee operations on the transmission lines. They enforce the reliability standards from NERC. So NERC says, look, you need to have this much spinning reserve. You need to have this much voltage control.

If your frequency goes out by this much, you need to sever the link between here and here. And so all these rules, they enforce them. And in principle, they can require the transmission line owners, which are still to a large extent those vertically integrated monopolies, but could, in principle, be private transmission line companies. They can in principle require them to make upgrades, though as far as I know, not a lot of that goes on.

There are, however, some places in the United States where this system does not exist, and that's these gray areas. And so in these regions, you still have, to a large extent, these vertically integrated monopolies, and they still talk to regional state regulators and decide what the price of power will be and do whatever they want to do. It's not a competitive market. And this is actually why.

AUDIENCE: You can finish your point.

SCOTT KEMP: Oh, no. Go ahead.

AUDIENCE: I'm just wondering, in California specifically, what is happening with those little--

SCOTT KEMP: Patches? I actually don't know why Kaiser doesn't. Yeah, I'm not exactly sure what explains those patches on this map. So yeah.

AUDIENCE: On the orange, what does PJM mean?

SCOTT KEMP: Oh, I forget. I forget. It's the name of the region. Let's look it up.

AUDIENCE: Something junction manager, maybe?

SCOTT KEMP: Pennsylvania, New Jersey, Maryland-- there you go. Pennsylvania, New Jersey, Maryland interconnecting. So these regions, which are still regulated because these are deregulated. And you hear about people talking about when we deregulated power. That means creation of all these ISOs and so on.

These areas are still regulated markets, which means there's a government regulator that sets the price. And in those markets are actually where you see nuclear power being built because they can say, oh, we want nuclear power. And yeah, OK, it costs more, but we don't care.

And then they just go to the regulator and say, well, we need to charge this much. And they will say, OK. Yep.

AUDIENCE: What's the relationship between the ISOs or non-ISO regions, and in the broader interconnection

SCOTT KEMP: The broader--

AUDIENCE: It was one of the first slides.

SCOTT KEMP: Oh, the synchronous regions. Yeah. So the synchronous regions are literally just that. That's like the AC waveform is going up and down together.

And so you can have independent system operators transmit to other operators as long as they are synced up. And so they'll adjust the generation on their grid. They can control demand not easily, but they'll adjust the generation on the grid to lag the phase or advance the phase. And then they can sync up with other ISOs or with other non-ISO markets.

And so you can still sell electricity across these boundaries even though they are operated by different entities. And this is like hinting at how complex this thing is. There are like 2,000 legal entities involved in this system.

And on top of all these regional issues, you have tiny little power companies in here, which are doing end user distribution, which are all independent of what we call transmission distribution, a whole bunch of other little tiny companies who are involved with this stuff, on the power poles. So just enormous quantities of interdependency and changing things is very hard because of that. It's a very [INAUDIBLE].

So what happened when the power system was deregulated? It was supposed to save consumers lots of money and in all kinds of great things, and actually, it didn't happen. The price of electricity was basically unchanged. And it's kind of like a big economics mystery that, as far as I know, is still not really been answered as to why.

Why is it that essentially a monopoly and a monopsony independently negotiating electricity prices come up for something that is roughly the same as a complex market in which everyone is just bidding in the lowest generator rates? You can hypothesize various theories as to why this might be the case, but that's what the data seems to show is that over the long run, deregulation didn't reduce prices. It did, however, allow for more competitive generators to enter the market.

So in these regions, in deregulated regions, you will see a lot more wind and solar in these markets because they have very low marginal costs, essentially zero. They get sunlight for free. And then they can bid into the market and get dispatched. And so this is where you see these things popping up. Whereas in these regions, there is no solar being built, but it has to be built by corporate decision.

The monopoly that all these enterprises will say, well, we'll build wind because it's cheap, but maybe we'll build it when a coal plant finally shuts down. Whereas in these regions, they're building it, and the coal plant gets shut down because they can no longer compete. So you see the movement to more efficient and greener technologies happen more rapidly in these deregulated markets.

So the bidding system that is operated by the ISO is supposed to be non-discriminatory. It says we look at the price of electricity that you offer us. And it doesn't matter if you're making that with wind, solar, nuclear, hamsters. We don't care.

And that sounds great. But in fact, it is discriminatory. And the reason it's discriminatory is because there's a interaction between the NERC rules about how the grid must be operated to stay reliable and the shape of the grid and the other generators that are on the grid.

So if the capacity of the grid as close to its max, and most of the generators are natural gas plants and is a hub-spoke kind of grid architecture, it's really hard for a wind or solar farm to go online and maintain the reliability standard that the grid operator demands. Because maybe their power is fluctuating, and they can't necessarily promise that it will be operate in a certain way. If the grid doesn't have margin, then they don't get dispatched.

And so this actually, this reality, this history of the hub-and-spoke architecture and these NERC regulations are what slows down the deployment of wind and solar today. If it were not for that, we would have enormous quantities of wind and solar. So everything will boil down to how hard is this to change. And that is going to control the speed of deregulation.

I think I basically mentioned all these things. Yeah, so if you have variable generation, you need to move electricity around more. That requires more line capacity.

And we are already, I hope, convinced that wind and solar has a major role to play according to the various economic models we looked at. We looked at Shaner. We looked at the future of MIT nuclear power study, which showed a large component of wind and solar.

I think there was a question a couple of sessions ago about the cost of storage and whether the cost of storage would be a limiting factor. In the Shaner model, they assume. And remember, the Shaner model is not an optimal model. The Shaner model is just there to illustrate whether or not a full renewables grid is possible.

The MIT Future of Nuclear Power model is more like a cost-optimal model. Shaner model is only looking at can you actually do it with wind and solar given the weather? And the Shaner model, we looked at various solutions, and we found a solution at 12 hours of storage, produced a cost of something like $150 per megawatt-hour, which was a reasonable cost, something like that. Remember that?

And someone raised a question about whether the 12 hours of storage was at all attainable. Could we build all of that storage? Now there's lots of storage technologies, but then the standard Shaner model, they kind of just assumed lithium ion.

So I went into the calculation because you probably want to know. 12 hours of storage will cost at current lithium-ion cost $1 trillion. Sounds like a lot but don't forget the whole electricity system is very expensive. And that is also the amount of money we're going to-- it's actually about half the amount of money we're planning to spend on maintaining and upgrading our 1,550 nuclear weapons over the next 10 years. So it's within the scope of budgetary probability.

And as far as production rates go, I looked at the current factories that are coming online, and we would be able to produce all of that storage within five years at current production rates. So it's within feasible. This is not beyond the pale. That's something that will take 900 years or something.

OK, so we get to these questions. Who will pay for this grid expansion? Who should pay for this grid expansion, and how much will this cost? And the current situation in the United States is that if you want to have a wind and solar farm, you get saddled with that cost. And a lot of people are interested in building these Renaissance farms just can't afford or are not interested in paying that cost.

Now the existing utilities who operate large natural gas, coal, and hydro plants, do they want to see the grid expanded? Not really. If they see this grid expansion, their businesses, their generators are going to go out of business, at least in the competitive markets, because their electricity is more expensive. And if wind and solar shows up and starts to undercut them, they're going to have to shut down their plants.

That means the vertically integrated monopoly that own coal plants, that own historical transmission lines, are going to do everything in their power to prevent this from happening. And that is what is happening now. They are keeping the grid right at the edge of the NERC stability requirement, so that if you are a wind and solar generator, you can't connect without paying enormous amount of money to fix the grid, which looks like it is for historical reasons. Yeah?

AUDIENCE: What kinds of margins do coal and natural gas companies make for per kilowatt hour?

SCOTT KEMP: Oh, I don't know. Yeah. I mean, it probably depends a lot on how old the plant is and questions like this. Yeah, so coal today, no one is building new coal because it's already not cost competitive with natural gas and what renewables there are.

So they don't make any margins. But as far as historical plants, the plants that are sunk cost, and they're only looking at the marginal cost of electricity. I would have to work it out. But you should be able to if you go back and look at these charts, these data tables, you should be able to figure it out yourself, or at least approximate it. Yeah.

AUDIENCE: Just going back to clarify, you mentioned the hub-and-spoke architecture

SCOTT KEMP: Yeah. That's a rough-- yeah.

AUDIENCE: Would the alternative be just a web?

SCOTT KEMP: Well, it is a web, but it's just that you get these centralized generators. And most of the capacity comes out, and then the capacity, the lines get smaller and smaller as you get further away from the generators. And the other architecture would be a web where all the lines are kind of the same size. And that would kind be the differentiator. Yeah. Yeah.

AUDIENCE: So the electricity market is kind of notorious for the amount of foul play, et cetera. So I definitely believe that the incumbents are kind of keeping the grid not very friendly to new players. Isn't there also something to be said for just NIMBYism against new [INAUDIBLE]?

SCOTT KEMP: Yeah. No, no, we'll get there. Yeah. Yeah. There's all kinds of problems that prevent expansion. But there are some remarkable stories. Oh, I forget the name of it.

So a big part of it in the NIMBYism situation is we don't want power lines. We don't want to look at them, or we're not going to give you right away to put a power line across my property, things like that. There was a plan to put a buried power line along a railroad track, and they had secured the right of way. And it can be buried.

So no one was really opposed to it. And they needed to connect that line. I think it was actually PJM. They want to deliver a wind from the Midwest into PJM's grid, and PJM basically told them, go fly a kite.

And the reason was because they said, and the claim was that it would destabilize our grid. And the wind and solar people said we're sending you. We're building a DC line, which means that we have a lot of power electronics to convert it to AC, and we can give you as much or as little power as you require.

It's not like you're on a synchronous system, and we're forcing the power down the throat of the grid. And PJM said, no, no, it doesn't matter. And then went to court. And so yeah, there's all kinds of dirty stories like this.

So here's a challenge. Is it fair to ask the wind and solar companies to pay for this generation expansion?

So on the one hand, the fact that wind and solar is variable is an externality associated with that generation. It's a flaw in the quality of the power, and they have to pay for that flaw. And that flaw requires more grid capacity. Fixing that problem should be rolled into the price of wind and solar. So that is the argument for them paying.

On the other hand, everyone else just gets access to the grid for free, and new natural gas players are just using it. And they didn't have to pay for anything. It's not that they're paying less. They just get it for free under the order 888. And so it's kind of like saying, I want to drive down to Florida for winter vacation.

And someone saying, OK, you can drive down there, but the roads are congested, so you need to build a road. And it's like, OK, but it's just me. Well, too bad. You want to go down. You pay for the road. And that's kind of the problem with this.

So one of the challenges is trying to balance these two things. And then there are other externalities that we should think about. So if you have a grid that is operating really close to margin and you have an event, like a hurricane or something. Now that grid, it has a more likely chance of going down. It's harder to recover, et cetera, et cetera.

So there are reliability and national security considerations associated with operating the grid in of traditional fashion. So especially as you see the rise of wildfires and other things in high temperatures from climate change that require the grid operators to de-rate the lines, we're seeing more and more instability and more brownouts and blackouts.

And so society is paying too for this reticence to expand the grid to allow for distributed generation and more capacity. We basically have a moral dilemma. There's no clear answer. So let's just look at what other countries have done.

So the UK, EU, most EU countries, Australia, Canada, and Korea basically say this. You need to pay for whatever local lines have to be built to connect your new plant, your wind farm, to the major transmission lines. And you're going to have to build a substation to raise the voltage and put that power. But as for the major transmission system, those costs will be paid by a regulated tariff that is socialized across all the generators. And this is socialism.

In Japan, they used to have a different system. Sorry, they used to have a system in which it was all socialized by generators, but they now have a little extra, they call a reeling tariff. That is an extra charge that they assign to the new generator to balance the two things. So you can see how the US is kind of an outlier here with this approach. And that may also explain why deployment of renewables is probably progressing maybe more slowly here, despite the fact that we have a really optimal country for renewable generation, with lots of wind and lots of solar and lots of space.

There is a new FERC order issued last year, called 1920, that is attempting to basically make us like the rest of the world. They say in the FERC order, requires long-term regional transmission planning and cost allocation to be done through cost allocation, that is, for those planning lines. It doesn't say exactly how that cost allocation will work out if it's a tariff that is applied to everyone or so on. But basically, they're saying you can't just put it all on the new generator.

New people will still have to pay for the interconnect, which is like every other country. So predictably, this new order is now suspended and being challenged in court by a bunch of lawsuits. The principal one is a coalition of 19 states being led by the state of Texas. 100% of these states who oppose this order are Republican legislature states. You can probably guess that there's probably some money behind this, getting these guys to put up this lawsuit by established corporations who own old coal and natural gas plants.

When you read the legal filing, it's pretty clear that they want to just block wind and solar. They're like, we have the right to choose our generator mix. And upstart generators should be kept off our system. And so it's unfortunate.

Earlier, I showed you this plot. And one of the things that emerged in the conversation is that, well, OK, so this plot is the amount of nameplate capacity in the queue waiting to connect to the grid. And this is wind and solar capacity. And this line is current generation. And it just shows how many wind and solar projects are just waiting to connect.

Now, it was pointed out that many of these disappear. And I got the statistics for you. Depending on if you count by the number of requests or count by the fraction of total power, something like 75%, roughly 3/4, of these projects are basically withdrawn. Now there's a question as to whether these-- yeah.

AUDIENCE: So when you say they're waiting to connect, you mean they're literally just sitting there and not doing anything?

SCOTT KEMP: Yes. Usually, I don't think they really build the capacity until they get authorization for it. But yeah, they're basically we have a project. We have an idea, or we're going to build this farm.

We have a legal entity. We're ready to go. And then they're waiting.

And the grid operator says, we have to make expansion, or you have to pay. And you have to wait in this queue. And the average time from the queue is 13 years.

So if you are an investor and you're planning to do something with your money, you want to build a wind farm, and you make money. And they said, well yeah, but you won't get your first dollar of return for the next 15 years while you wait in the queue. And then we have to build the farm.

This is the problem. So it's not really a surprise that 3/4 of these things are withdrawn and never succeed. There was some suggestion that some of these might not be real. We have no way of actually knowing that, whether these projects are real or not. But yeah, this is the situation.

I mean, this basically shows how much it is slowing things down. In case you're wondering how expensive this is, typically the point of interconnection charge is something less than $50 per kilowatt in terms of capital expenditure. And I'll have a plot at the end where we can. So just remember that.

Whereas a network upgrade would be something like $200 or $300 per kilowatt of capacity. So it depends on the project, but it's somewhat of an addition to the cost of these things. I think the killer is not really the cost. The killer really is the queue, the wait time.

If you're a new project and you want to connect to the grid, how much does it cost? So it turns out that the permitting and right of way costs, as I mentioned a moment ago, which turns out to be something like 25% to 30% of the total cost of the project-- an amazing amount of money being spent negotiating legal agreements with various entities. Sorry, this is for transmission, not for wind and solar.

The towers are something like half the cost to put up these large transmission towers. The conductors and wire are about 10%. Substation is about 15%, 20%, and it's a contingency.

What is interesting is that the towers determine the voltage. The voltage determines how far apart the lines have to be, how far apart they have to be off the ground. And that is the most expensive part. The number of conductors that you run on the tower determines the ampacity of the circuit, how much current you can send. So you can triple the amount of power by tripling the amount of wires as long as you have room on your towers to put more wires.

So sometimes you'll see all these wires hanging in a row. And that's why. And that doesn't cost very much to increase the ampacity, but it does cost if you want to change the voltage. So you have this weird phenomenon where the voltage is actually the determining factor in the cost of transmission, not the power that you're sending, where power is, obviously the thing that you're using.

So it's notable that since 2010, we have installed-- I think it's 70. Yeah, I think I have this on another slide-- 70 miles of 765-kilovolt lines. And the average time for one of these projects is something like 13 years. We've installed in the same time 100,000 miles of natural gas pipelines.

And one reason might be that for power lines, the company that is trying to build the line has to go out and negotiate with each federal entity, state entity, local government, landowner, et cetera and secure all these rights themselves. And it takes a long time to do that. For going across federal lands, and there are lots of federal lands, they still have to deal with the EPA and FERC and the Department of Energy and the Bureau of Land Management, or a bunch of different entities have to have a licensing process. And they have to go through all of this with all these different federal entities.

For natural gas pipelines, there's a law on the books that says, when dealing with the federal government, there's a single point of contact that authorizes the transmission. And you don't have to go to all these different agencies and do all of this permitting. As a result, the average time to get a natural gas pipeline permitted in the US is two years, instead of 13. And you can understand why 100,000 miles of gas pipelines have been installed. It's just much, much easier to do.

So of course, there is a proposal for a law to revise permitting on federal lands of transmission lines and make it identical to that of a natural gas system. But predictably, the Republican Congress is not interested in that law. And it has just sat there, and no one has ever put it up for a vote.

So you can see how these politics are kind of holding back decarbonization. So is this expansion that is required to enable all of these wind and solar projects that are waiting in the queue? Is this thing going to be expensive?

So I did some statistics on the 13 most recently completed construction costs, and I developed this little regression formula-- some fixed costs associated with running your operations and then $100,000 per mile, plus $8,000 per kilovolt per mile. Remember, the voltage determines how big the towers are. And so that there's a strong dependence on the voltage.

Say this is maybe typical today. If we really have a lot of wind and solar, we need to go to higher voltages than this. But for typical contemporary line, 500-kilovolt line, that's something like $4 million per mile. I asked last night, ChatGPT, to go through and look at all the data and do its own regression, and here's the formula it gave me.

So it came up with a $5 million per mile. And since I did my regression some years ago, it came out pretty good. It has this really nice dependence on the voltage, and it normalizes. And it has the number of conductors. It's a fancy result. So something like $4 million, $5 million per mile is a good rule of thumb.

Of course, there are lots and lots and lots and lots of entities-- academics, NREL, Berkeley, Berkeley Lab, all sorts of entities who are interested in increasing the amount of transmission. And they've done all kinds of studies on what it would cost. And here are their results.

And these lines are slopes of constant costs. So this is a million dollars a mile, $2 million a mile, $3 million a mile, $4 million a mile. And I said it costs $4 million a mile. And ChatGPT says it costs $5 million a mile. And the studies all predict that it's going to cost less.

So I think this is basically the same thing-- microreactor vendors telling you that things are going to be cheap, and then they're never cheap. And so I tend to think that whenever you see these transmission studies, and if you look at the real historical data, it's more expensive than they say it's going to be, not double or triple, but 20% more, some 50% more or something like that, depending on where they line up. So I think I will use this scaling factor when I talk about the cost of these systems. Let's just look at some costs.

Here's a line that goes from the Great Plains to California, 1,500 miles. This thing would cost like $9 billion. Here's something that brings hydropower from Quebec down to New York City, something like $6.2 billion. It's basically the price of a nuclear power plant. And they can carry, depending on remember how many lines you string on the tower and the ampacity of the system, something on the order of maybe 4 to 6 gigawatts of power continuous, which doesn't seem like a lot.

But you have to remember that they're also really dealing also with excess generation. So there will be a lot of local generation that is locally consumed and just how much excess generation do we have to move around to stabilize the grid? That's their principal interest. So they're only taking the cream off the top. So six gigawatts of transmission capacity might support a much larger installed base of variable generation.

So there is also a new study. This is the 2024 National Transmission Planning Study. It's a multi-year study that was run out of NREL. And I'll just tell you what they found and how they market it. And I think they're very optimistic. But here's what they say.

They say that for every dollar spent on building transmission, we will save somewhere between $1.60 and $1.80. And in other words, it pays for itself. And so that comes out to something like $270 to $490 billion between now and 2050, half a trillion dollars of saved money between now and 2050.

So they looked at hundreds different scenarios and they go through 2050 as their time horizon. They also say that it will offset somewhere between 10 and 11 billion metric tons of CO_2 emissions. So that's about 3,000 gigawatt-years of natural gas. So over that time period, one way you could look at it is we would have to build 115 nuclear plants and run them between today and 2050 to save as much CO_2.

So the question is, where does all this cost savings come from? Where does all this CO2 abatement come from? And it's kind of not exactly intuitive. What they say is that for the next 10 years, between 2025 and 2035, most of the cost savings actually comes from avoiding fossil fuel use-- natural gas that will not get burned and carbon and coal that will not get burned because the existing wind and solar installations can now use more of their nameplate capacity and put more power on the grid. That's basically the offset.

And as a result, they say that the capacity factor for wind and their model goes up to 40% is pretty high. And for solar, it goes up to 28%. You might remember we typically think of solar as having a capacity factor of around 20%, maybe 15% in the north. And they're saying they can actually operate at 28% because they can shift all that power around.

So that may all be so. I don't doubt that physically that's possible. But in the process, they're also making certain assumptions about capacity expansion, about people building wind and solar, and also assumptions about people building all this transmission.

And I think we have to evaluate whether any of this is realistic. So for example, they assume that 770 gigawatts of nameplate capacity of wind and 1000 gigawatts of nameplate capacity of solar are going to be added, which is something like the equivalent of 300 gigawatts of nuclear generation between now and 2050. That's a lot. And I think there's some extreme optimism here.

Despite the extreme optimism with these numbers, the study is good for potentially one thing. And that is if a very sophisticated study that looks at, sorry, the mapping of the transmission requirements onto a future world with a lot of renewables generation. Whether that happens by 2050 or not, that is still an interesting relationship. And that gives us a price that we can use to estimate the additional cost that we should burden on solar and wind, because we choose a technology that requires a bunch of new generation.

So they don't give us that price explicitly, but you can back it out of their calculations. And it comes out to somewhere between $80 and $200 per kilowatt of capacity. So this goes on the front of the overnight cost. You're going to build your wind farm.

It's going to cost you $2,100 per kilowatt, and you're going to have to add $200 of grid penalty because of its variability. And that's kind of their takeaway conclusion. So that's something like 4 to 14%, depending on whether you're applying it to wind or applying it solar and which one you choose.

And remember I said that I think they're optimistic on the pricing. Most of these pricing models are optimistic. So multiply that by a factor of 2, something like that.

But at the end of the day, it's still not that much money. Even if it's 30%, the price difference between $2100 and $7,000 is not killed by this 30% transmission tariff. And when I did the Shaner calculation, and I came up with $130 per megawatt, do you remember what I used for this number? I used 25%. This is why I used 25%.

So I think it doesn't really change anything with respect to the competitiveness of the technologies. But it does show how much has to be done if you want this world of wind and solar to emerge. Yeah.

AUDIENCE: So do these studies look at electrification as well? Because I know back home in Belgium, a lot of the grid expansion now is just from EVs. It's not really related to a big renewable expansion.

So today, this study, are they looking at you meet current demand with wind and solar-- I mean, current demand plus-- I don't know 2% per year or something? Or are they also looking at the same time we assume this many EVs are coming online, et cetera? I could see it working for or against wind and solar, to be honest.

SCOTT KEMP: Yeah, so three comments. A, the detailed answer, I don't know. We have to go dig in a study. My general sense is NREL does have a model for increasing demand that includes transportation sector as part of it, so that for transmission purposes, total capacity, there is some EV-related kind of effect.

And the third comment is that I believe most of the expansion for dealing with that will probably actually be distribution rather than transmission at this level. It's the more regional stuff that really is where that's a sticking point. So that's a different entity. But all this could be looked at in more detail. And then there's a whole issue with it you kind of pointed out. EVs can go both ways. They can suck up excess solar capacity in the middle of the day and therefore reduce the amount of transmission that you need.

And so it's complex. People have talked about coming up with dynamic models so that people can use their EV as like on storage. And there's none of that exists yet. But people are looking at it-- on-grid storage to deal with the problem.

So here's my kind of final slide. Is this major expansion of the grid that is required for this world of wind and solar realistic? So I think the biggest criticism is that it's institutionally optimistic.

If over the last decade, we've installed just 70 miles of 765-kilovolt lines. And this study, we're going to need to says we need to install 170,000 miles of 765-kilovolt lines. There's an institutional growth there that just is not realistic, I think. We're supposed to do this in the next between now and 2050.

I think it's a very high level of optimism. It comes from various things. For one, there's a long lead time on equipment, such as power transformers, is unlikely to be the manufacturing capacity for all the transformers that would be required here in the United States. Some of them can come from China, but even that probably not enough.

Where's this capacity come from? Same for transmission towers, insulators, wire, switches, all that stuff.

It also presumes that all these ISOs will have planning capacity to operate this grid. This is a level of operations and of inter-regional transmission that has never before been demonstrated, especially the high-voltage DC lines. We just don't have any experience operating all of this kind of power transmission. So I think these things are going to be major barriers.

On top of that, none of this is going to get built. If all the costs of building it is just going to sit on the next solar generator who wants to add their plant, and then they have to pay for another line and so on. There really has to be something like FERC order 1920 that socializes the cost of being major lines over all of the generators. But of course, that thing could be held up in court for years, maybe a decade.

So I think for all of these reasons, it's not likely to happen. Then there's also the rights of way issue. 30% of the cost of this transmission line was rights of way.

It takes 13 years for the average transmission project to be permitted versus two years. It just shows how hard this is going to be unless those policies change. And yet, despite the bills being written, there's no indication that these bills are going to be passed.

So there's a lot of legal, regulatory, and political issues that are in the way of this transmission fantasy from coming into place. The most recent blow, the Trump administration used to have a loan guarantee program for companies that wanted to build large-distance, high-voltage transmission, just like we have a loan guarantee program for nuclear. And the Trump administration last July just decided to cancel all those guarantees so that they can basically stop transmission from being generated. They're doing their best to prevent wind and solar from being built. On the finance side-- yep.

AUDIENCE: Why isn't this is a problem also for nuclear and just for wind and solar? You would expect [? nuclear. ?]

SCOTT KEMP: So it will be eventually a problem for everyone. As long as your nuclear plant isn't needing to deal with the variability, then you can very reliably say, OK, I need this size line into this region. I don't have to send it long distances. I'm going to take this coal plant offline.

I'm going to put this nuclear plant online, and the total transmission costs are going to be small. It's when you've got a lot of wind in the Great Plains, and you need to move it to Los Angeles. That's the problem. Otherwise, you just build your nuclear plant in Los Angeles. And so that's kind of difference.

So it turns out there's a lot of money available for new nuclear startups, as we've seen. Some money may be smarter than other money. But there's also, predictably, a lot of money available for transmission. And there are basically private capital people waiting to help build mines.

So despite the Trump administration's best efforts to cancel federal loan programs, the money to build these things is there. That may not be enough. We need these timelines to come down if we want to build this capacity. And that means dealing with the regulatory frameworks that are holding everything back.

So the short answer is we can decarbonize the grid. We have all the technology we need. According to these studies, we will save money if we do it-- $1.70-ish for every dollar spent on this technology by not having to buy fossil fuels.

We'll save enormous amounts of carbon. But there is a political battle that is backed by a lot of dark money by the fossil fuel industry working to stop this from happening. And in the meantime, nuclear is benefiting because it's the alternative that doesn't require all of this legal architecture. And so there's a storyline that says, all this wind and solar is great, but look, it's not getting done.

And then the question is whether nuclear can actually be cheap enough and whether it can actually happen fast enough. We talked about 20-25-year timescales to bring a new reactor online and whether at the end of the day, that's really the path we should be taking or not.

So a lot depends on what happens in the next election, 2026, and for the midterms, whether we can get some bills passed that help reform some of these things and in 2028, with the new administration to reinstate executive-level programs to help streamline and incentivize transmission production. I am not terribly optimistic that policymakers will move the needle on this very quickly. I think it's probably going to be the case that we're going to see a lot of business as usual and more of the same and continuing to see more fossil fuel generators be built and so on. And then this transmission and renovation will happen very slowly over the next 30 to 40 years in bits and bobs as becomes practical for entities to do it.

So climate change is not a technological problem, or dealing with the electric grid is not a technological problem. It's a legal and political problem. And that's where we stand. Yeah.

AUDIENCE: Do you think the potential international competition, like seeing China build out like extremely fast solar, could then potentially become a motivator in terms of the US, just like the Republican Party becomes jealous in a sense more so than it being a decarbonizing technology, and more so just being China's doing it better than us?

SCOTT KEMP: I think all these arguments will be brought to bear on the politics. But at the end of the day, I think that the argument that will win is who is paying for your campaign? Yeah.

AUDIENCE: [INAUDIBLE] talk about financing and interest costs as a portion of cost for nuclear. If wind and solar farms do have to end up paying for their own transmission, we know what that cost of transmission will [INAUDIBLE] against the actual [INAUDIBLE] cost?

SCOTT KEMP: Well, that's the I think if I'm understanding your question, you're asking, what is the fractional increase in capex? Yes,

AUDIENCE: Yes.

SCOTT KEMP: Which is this number.

AUDIENCE: Given the amount of time it takes to actually build the transmission.

SCOTT KEMP: Oh, like the IDC, the Interest During Construction?

AUDIENCE: Yes.

SCOTT KEMP: So the actual construction times, once you get through the rating period, I'm not sure. They're probably not very long. Yeah. Yeah. You look it up. But I would guess a couple of years or something. So any other questions? Yep.

AUDIENCE: Do we expect the unregulated and regulated map to pretty much stay the same?

SCOTT KEMP: Yeah, I don't think there's any momentum to change that.

AUDIENCE: So then I guess in a lot of those states that won't be changing to unregulated markets and that might potentially be a place where nuclear could thrive. I mean, assuming that you're able to build a not Nobel Prize, though.

SCOTT KEMP: There have been people in the nuclear business that have obviously self-interest at least said, oh, we should get rid of deregulation and go back to regulated markets. And I don't know if there's anything there. It's a mumble I hear, but I don't think there's a lot of people waiting to jump on board like, oh, let's get rid of regulation.

The regulation is still right for corruption, and it doesn't serve the public interest. This is why the Vogtle plant was billing its customers for years and years and years for the cost of the plant, well before it ever was built. And these poor people are basically footing the bill and avoiding the interest that really the corporation should be paying. So it's not a great--

AUDIENCE: Necessarily a great system.

SCOTT KEMP: But markets are totally acceptable. That's a whole Enron scandal too. Markets, you can do all kinds of bad things to. So I don't know, maybe. Yeah. Anything else? All right. See you next Wednesday.