[SQUEAKING]

[RUSTLING]

[CLICKING]

PROFESSOR: All right, well, it's 11:05, so let's get started. So far, we have talked exclusively about nuclear for electrical markets. And the problem is that, in those markets, wind and solar have become so cheap in recent years that they've kind of displaced nuclear. That's the bottom line story.

But there's another market that nuclear hasn't traditionally been in that we ought to consider if we're thinking about decarbonizing all systems, and that is thermal markets. So thermal markets, which is to say that just the provision of heat to do some kind of industrial process, often a chemical process which requires heat, to either accelerate or initiate that reaction, endothermic reactions. These heat sources typically consume-- are responsible for about 50% of emissions from the industrial sector. So in the decarbonization effort, this is a potentially large opportunity for nuclear, which is, by its nature, a heat generator.

So here is this essentially the situation with nuclear when we're making electricity. We have some amount of energy coming out of the nuclear power plant, which is thermal energy. And then, in a way, we could price it. We know the price from all these data that we have been looking at for electricity, and we can back out the price for heat by dividing by some efficiency. And so, in most reactors, the efficiency is somewhere around 30% to 40%, something like that. And so this gives us a price for the seat.

And what is nice about that is that if we look at the other things, like wind and solar, well, they don't produce heat ever. So you can get heat, but you do it by resistive heating. So for every dollar you spend to get a megawatt of electricity, you get the heat at exactly the same price because resistive heating is effectively 100% effective, 100% efficient. So there's no economic gain for wind and solar to provide this.

And so it turns out to be fairly expensive when we compare it to nuclear. So here, nuclear on the high end is more expensive than wind and solar. This is, of course, $130 per megawatt. Does anyone remember what this is? This is the Sheiner calculation, where the whole grid is stabilized with overbuild and storage. So this is what is required if you want to reliably just plug in to your wind and solar grid and run a resistive heater. You need something of this scale to do it. We'll talk a little bit more about that in a moment. But that's why I'm assuming for the price.

And here's $200 per megawatt this is your target. This is more realistic. But even at the realistic levels, you're getting heat at a cheaper price than what wind and solar can do. And that's the real win here. This is the headline that you should take away. Yeah?

AUDIENCE: How does this compare to natural gas-based furnaces, for instance?

PROFESSOR: For pricing? So you can do the same calculation for natural gas. And it is cheaper than nuclear by a lot, but it's not carbon-free. So the whole idea is all of these options are carbon-free or nearly carbon-free. So we're talking about how do we decarbonize that part of the Industrial sector.

Of course, geothermal also produces heat. It produces a very low-grade heat that is converted at very low efficiency-- by low-grade, I mean low temperature-- to electricity. And so if you back out, given its low efficiency, you wind up with a super cheap price for heat. But the heat is a cool, a very cold of heat. And that's not necessarily useful in all kinds of resources. You can use super heating. We'll talk about that in a moment. But most specifically, it's geographically limited. And so this is not, nuclear is not. And so that's where we are interested in exploring.

So let's look a little bit more about this heat market, which on the face of it looks very promising. So it has a number of features. So the first one is that generally plants that use heat in industrial processes have a high capital cost. You have to build this big refinery or this big-- there's a lot of infrastructure in place. And the way those plants make money is to operate essentially all of the time. And so they need the heat to be always on, which makes for a baseload-like load, which is a perfect match to nuclear, which is also a high capital cost technology you want to run all the time. So this is a win-win.

Another thing is that demand in heat markets tends to be intensive in small points but distributed geographically around legacy heat sources. So you'll have a natural gas pipeline, and then you'll find that a lot of plants get built by that pipeline. But then you'll also have something else, like a paper mill in the Pacific Northwest. And it burns a lot of biomass, for example, to produce heat, make the paper. So there will be this particular kind of geographic setting, which may not be compatible with, say, a grid-based distribution system, where you'd have to bring in and build a lot of grid infrastructure to bring electricity in to do this grid renewables.

And the other important thing is that temperature really matters. And so we have to make sure we differentiate the heat market by temperature to see what we can do.

So what can nuclear do? So traditionally, for PWRs, we're looking at something like 300 degrees C as an outlet temperature. And that temperature is limited in most reactors by the departure from nucleate boiling. But there are higher temperature reactors. So the high temperature graphite reactors-- these are things like the x-energy reactors, and the FHR. These are things like the Kairos reactor and the one with the FHR that is under development for [INAUDIBLE] here.

These things, in principle, can go to higher temperatures. There's a number of things that limit the temperatures of these reactors. So fundamentally, the TRISO particles, which are the little grains of sand in the fuel, those things are theoretically capable of 1,600 degrees C before they begin to decompose. And then because the particles are not perfectly made, you have some safety margin that brings it down to 1,200 degrees C.

But then your max temperature-- so that's your maximum fuel temperature for safety-- but your maximum temperature is not going to be the same thing as your maximum outlet temperature. So you have some kind of temperature gradient across the core. And so typically, an in-core fuel temperature at the edge of the fuel will typically be around like 950 degrees C. And that will give you an outlet temperature of around, say, 750 degrees C. And this all just because of method of resistors and so on.

The outlet temperature tends to be limited by things like the bypass gas that you use to cool the core structurals and things like this. And if you raise that temperature too much, what you find is that you begin to get creep in the structurals. So this is one of the reasons why the Kairos reactor, which is a salt-cooled FHR type reactor, is currently expected to have a lifetime of really only about four years unless they change the material. Currently, the material is 316h. And creep from that material at these temperatures basically limits the lifetime, which, of course, drives up the capital cost for the reactor. So pushing the temperature margins too high is a problematic for a variety of these reasons.

Then there are some other things in HTGRs. These are the gas-cooled, helium-cooled reactors. You have some-- I mentioned this, in helium-cooled ones, you can get these hot spots on pebble bed reactors because as neutronics is ultimately a stochastic process. So you have some excess reactivity in one spot, which disproportionately heats up the gas, which reduces its density, which reduces its cooling power. And also, helium has this effect where so, suddenly, it forms this hotspot in the reactor. And so when you deal with that kind of stuff, you have to put more margin into the reactor and limit the total temperature. And so there's additional constraints there.

You could, in principle, for the structural parts, the reactor, which undergo creep, you could start thinking about alloys that are capable of higher temperatures. There are such alloys. But typically, these alloys involve nickel. And the problem with nickel is that it transmutes in the reactor, and it makes the structures very radioactive. So typically, we try to avoid nickel. Not only does it make it just radioactive, but that radiation also causes the in-growth of helium embrittlement and things like this. So there are all sorts of structural issues. You could do isotopic separation on the nickel to try to fix that problem, but then the cost of those alloys get extremely expensive. We're talking $25 per gram or something.

So right now, the materials issues are really what are limiting these high temperature reactors. So that's just a bit of insight to say that if you really want to look at pushing these numbers so that nuclear has really high temperatures, which makes it really interesting for heat markets, it's a materials problem. And you could go do research in materials group.

Finally, there are some other things beyond materials that could potentially be issues. I mentioned that the TRISO particles are in principle good to 1,600 degrees C, but there's some data to suggest that certain fission products, particularly strontium and europium, somehow diffuse through the TRISO layers a little bit more rapidly than we would like. It's not exactly clear if that problem is solved or not. I think that it's still some open science questions on that front. So we could also run into fuel-related issues if we go too high. But for now, this issue is really an issue of finding metal alloys that are compatible with nuclear, meaning low nickel, but which also don't creep at high temperatures. And that's really what limits our ability to go higher.

People have talked about these very high-temperature graphite reactors and so on. But again, the long-term viability of these reactor concepts is very much in question. So I consider this stuff to be not-- sure, you could build a prototype demonstration, but it's not going to be economically viable because of materials lifetime. So this is kind of where I'm putting my limit for nuclear with current technologies.

So some processes, that's plenty good-- we'll talk about that in a second, how hot do we need to go. But this doesn't actually limit us all that much. And the reason is because we can still do what's called superheat. And so what you can do is here's your-- you can do it in multiple ways. You get some baseline heat, somewhere between 300 if you're PWR and 700 if you're, say, an HTGR, all coming from nuclear.

And then either you burn some additional fossil fuel and make it hotter, or you use some extra resistive heating and make it hotter. And what is the bottom one I forget? Oh, you can use heat pumps, which is a little bit fancy high capital cost. So there are these ways of making your working fluid hotter than the outlet temperature. Of course, this changes your cost and/or carbon footprint. So obviously, if you burn fossil fuel to get hotter, you're going to have some CO2. Or if you use electricity, now you need to find cheap electricity, and that can cause the cost to go up.

I said reduces cost a little, nuclear up to 2/3. Oh I see, this is to say that during versus the nuclear reduces the costs of having a pure resistive is what that means-- having a pure resistive heat of 1,000 because you provided roughly, say, 1/3 to 2/3 of that from nuclear heat, which has a lower per-heat unit heat cost. Yeah?

AUDIENCE: These concepts that use heat from nuclear reactors-- how is heat typically transferred over long distances?

PROFESSOR: This is a good question that I haven't really investigated too much. Often, it's steam in many systems, but one of the challenges that we will face, and I will mention this in a few minutes, is that we might have to do more distribution than we conventionally do. So with gas, you can pump the gas right into something and then burn it underneath some vat of stuff that you're trying to heat up.

Whereas if your nuclear is somewhere else on the site, and you have to pump that heat hundreds of meters, I don't know how much the losses come into play. So I'll mention that again in a moment-- I've got a slide about that. So these are all-- we call these topping cycles. And they can be added at various costs to get us in to make use of nuclear in advantageous heat.

So let's look at how much you need at each temperature. That's kind of where we start to get to realities. So this is a plot from NREL. They have, as a function of temperature, the cumulative energy consumption. And we see that enormous amount actually does get used at low temperatures. You can see there's not really a lot of contrast on this spot, but there is a line here that you can barely see.

And this is to say that temperatures below here, which is this blue dot, this region up to about the bottom of this pink box, this is basically so cool. You can do this stuff with just waste heat. There's all kinds of industrial processes that produce heat that we just try to dump into the air that you couldn't-- you could get in a particular setup. You could reuse, for example, to drive paper coming out of your paper mill. You don't need high quality heat to do that. So that's roughly a third of consumption, something like that.

After that, you get into heat that you really need to generate. And between here and here, we get-- let's see. This pink area is-- notice, this yellow area, which, again you can't see, which goes up to roughly here, is what is good for PWR or hot geothermal, something like up to 300 degrees C. So that would be 300, something like that. And that gets you up to 800 terra BTU, which is something like 2/3 of the energy. So actually, conventional nuclear does a big chunk of that.

And then, if you can get to high temperature nuclear with these specialties, you can pick up a little bit of extra. But you see the high temperature stuff isn't-- it does buy you more, but it doesn't buy you enormous amount more of the market unless temperature losses become really important. So even without solving these material problems in dealing with high temperature, it's still a pretty decent market. And then, to go above that, you'll need a nuclear plus some kind of topping cycle. And there are some of those things. So this is what the market looks like in total.

So the consumption-- there are some caveats on this graph. The first caveat is not all of these are currently using sources of heat which produce CO2. So some of this demand will not be obtainable using nuclear, things like biomass. It makes no sense to displace biomass sources of heat because you're not getting anything from a climate change perspective.

I guess the other thing is that the market size between 700 and 1,000 is pretty small, and that suggests that people-- I've suggested using a topping cycle, but some people will say, well, why don't we just design a very high-temperature graphite reactor or something like that to do this? And if you just calculate how much extra you're getting, that's something like 13 thermal gigawatts, which would be, if we think in conventional reactor senses, as five full-size reactors. That's not sufficiently large market to justify the development and licensing of a totally new ultra-high-temperature reactor. It's just not a big enough market. So the topping cycle is almost certainly going to be the way to go.

So, as it turns out, 50% of the heat market actually uses what I would call nondebatable sources of heat. That is to say biomass waste generation and so on. But that still leaves a relatively large market size about 92 thermal gigawatts, which is roughly a third of the current electrical fleet of four nuclear reactors in the United States to be built.

Now, if we built them at full size, that means we're building something like 30 reactors, which is not that interesting, but we will not be building these things at full size. We'd be building much smaller reactors. And so there will be many more reactors. And when the numbers go up, things look more promising. Also, this heat market that uses mostly waste heat, that is typically-- a lot of that is in here, stuff that we wouldn't we weren't really talking about anyway.

I'm going too fast. I'm going to run out of lecture content.

So here is my estimate for what can be done. What I've done is I've gone through all of the-- the Energy Department, it tabulates by category all sorts of different heat users. And I've gone through all of them. And what I've done is I've calculated the total amount of heat. I've estimated the nonwaste fraction of heat used in that process. So some of these processes will have, for example, petroleum refining. They have gases that they vent. And then that can be a source of heat that they can recycle into their process.

And then I have a characteristic temperature. A little bit more is hidden behind this number. Often, there are multiple temperatures that have to be taken into account, and you average them together, and then you can back out a characteristic temperature that describes, essentially, how much of that can come from nuclear.

The temp fraction is a variable that is 1 if the temperature required is under 600 degrees C, which is to say all of it can be serviced by nuclear. And as you go above 600 degrees C, it goes down depending on the amount of superheat that needs to come from other sources. So this gives you the amount of heat-- when you multiply it by the fraction, it gives you the amount of heat that you can service with nuclear. So that's how you get to nuclear gigawatts possible, and then here's the number of sites. And then I divide the heat from nuclear gigawatt thermal by the sites. And I get the average heat per site in megawatts.

So I've also removed a couple of big source users of heat in this chart. This adds up to 104 gigawatt thermal. But if you google around and you ask, what is the industrial heat usage in the United States, you'll find it's closer to 180 gigawatts [INAUDIBLE]. What have I removed? I removed refining of petroleum solely for purposes of producing liquid transportation fuels because, in a decarbonizing world, arguably, that all goes away. So you'll still have petroleum refining for plastics, but that's in here under petrochemicals. So I've taken the transportation fuels out. Now we are interested in replacing that with biofuels, but we're going to talk about that separately.

And I removed the production of corn ethanol as a 10% additive to gasoline, which also uses a lot of heat, and almost all of that ethanol, like 98%-99% of it, is used for transportation fuels. So that has also been taken out. When you take that out, this drops from 180 to 104. There's also a few tiny categories that are just not in here because it's too small to matter.

So what do we see? Well, iron and steel is the most interesting. It particularly is a high temperature process. But we could have some kind of super heat, electric super heat maybe. And it's also an industry that is fairly well-consolidated. So these are ordered by which ones have the highest per-site usage and, therefore, are most compatible with a nuclear reactor being on site. And you go down from there-- ammonia, paper, nonethanol corn milling, glass products, chlor-alkali, cement/lime production, and so on and so forth.

And many of these things are in the tens of megawatts. So you might imagine designing a reactor that is, say, 10 megawatts thermal. Equivalent would be about three megawatt electric, which would be basically a nuclear battery size thing. And you would probably have-- if you had this plant that needed 12 megawatts, you probably have two of them there. And you would take the excess energy, and you would produce electricity with it, sell it back to the grid. But you would have two so that if one of them went down, you would always be able to keep that plant running, something like that-- two or three, something like this.

Now one of the problems with doing this division is that it's not the case that plants have the average size. There's some power law distribution. There's some plants that will use [INAUDIBLE], some glass plants that will use way more than 25 megawatts, hundreds of megawatts because they're the largest producer. And there will be tons of tiny little glass plants that use just a little bit. And those are not really available using nuclear.

So the size of the optimal reactor size will probably be a couple of reactors, maybe one in 100 megawatt range and one in the 10 megawatt range, something like that. But you can have too many reactors, otherwise you don't have enough reactors being made. So at the end of the day, we're still talking about about 60 gigawatts of power that can be potentially abated with nuclear. And if I divide, say, 60 gigawatts of nuclear, but I was going to propose that we ignore these 60, 50--

So in a prior calculation, I'm not actually sure if this is recently updated-- I'm not sure. In part calculation, what i did is I said, well, let's put a cutoff here and say that these industries are maybe too small in terms of per site usage to justify nuclear. And then when I did that previously, I got 24 gigawatts of heat that was actually used in sufficient intensities that you could probably put a reactor at the site. That's just a rough estimate. Let's say it's somewhere between 20 and 60, something like that. But we're still talking like 2,000 to 6,000 10-megawatt reactors, which is a lot of reactors.

And now we're talking really about factory fabrication. I have large numbers at reasonable rates. And that's where things start to really look promising. So I think this is a real market for nuclear, for small kind of battery-style nuclear, especially if they can get a little bit higher temperature and so on. Yep?

AUDIENCE: Whenever you adjust for nomenclature purposes, whenever you refer to nuclear battery, you talk about microreactors? Are you talking about just pure decay?

PROFESSOR: No, I'm not talking decay heat. I'm talking microreactors. Yeah, sorry.

AUDIENCE: Oh, you're good.

PROFESSOR: Yeah, I'm talking little microreactors that are basically remotely-operated or automatically computer-operated that you can drop into a site and you don't need to have a whole infrastructure to run the reactor. Yeah?

AUDIENCE: --sites tend to be distributed, or do they tend to congregate in an industrial park where you could have higher usage per site?

PROFESSOR: Yeah, so industrial parks are an idea that have been proposed. The idea, the reason for this is because if you have a large industrial park, then you could actually use larger reactors. And so now your economies of scale that we talked about earlier are solved. The problem with the industrial park idea is you have to ask questions like, could you really colocate a paper mill that is taking wood pulp coming out of, say, the Pacific Northwest, United States, and colocated with an oil refinery? So that takes crude coming out of the Gulf of Mexico. Maybe you could, but now you have to move those plants, and there's a lot of transportation involved, and we'd have to look into it.

Or could you take concrete production of limestone, which comes out of the Northeast, and combine it with corn milling that makes corn syrup, which comes out of Iowa? These are the types of questions you would have to be looking at.

There are two problems with the industrial park idea. One is, in principle, it could be done, but you'd have to get all these plants to move their base of operations. Even if the transportation costs weren't problematic, you'd have to get them to move their base of operations kind of simultaneously. And that's going to be tough because there's large capital investments there and infrastructure and people and everything, and they're not going to easily move.

So this might be something that works on something like a centrally-planned economy, where China, which has so much capacity and so much growth, or India, which has so much growth, can say we're going to build an industrial park for the reactor and paper milling and all these things, limestone calcination, and so on, and do it from scratch. But in the US, I think it's probably not a good starter.

The other problem with the industrial park argument is that if you really can move all of these things to one site, then why don't you just move them to where there's geothermal? And so now you have geothermal becomes more of a competitor. And so these are the two considerations that you're up against. Yeah?

AUDIENCE: But you were saying-- but then you were saying geothermal has low grade.

PROFESSOR: It has low grade, but it also can produce a lot of electricity. So if you use a big super heat line, and you have to work out the ergonomics, but yeah. Yeah, so that becomes the challenge. So I don't think this is a US approach.

Let me show you what is happening in the US right now. So this is the first nuclear process heat operation that is being looked at here in the United States. This is Dow Chemical. This is their seadrift plant, where they make plastic precursors, and their plan is to buy four 200-megawatt thermal HTTR reactors from x-energy. So that's a total of 800 thermal megawatts, of which they plan to use 300 thermal megawatts for their plastic production process and then convert the rest to electricity to sell back to the grid.

Now, part of the reason why they are doing this is because they are getting those reactors for almost free. They're so heavily subsidized by the government and by X-energy and others that for them, it's kind of just the retooling of their processes and what the electricity sales on top of that, they get some income. So it was interesting. Whether this becomes a sustainable model is something that we have to see.

Now of note is that they've purchased 2.5 times their heat demand in nuclear capacity. And they've done that because this is a very expensive plant to operate and takes days to get this plant up and running if it shuts down. They cannot afford an outage. They have to have absolutely reliable electricity. So the consequence of that is that you wind up having to build a lot of excess generation. The same is true for data centers. If you want to have nuclear power and data centers, but you need it to be on all the time, you wind up needing extranuclear reactors. And that would seem fine if nuclear reactors could sell electricity on the grid at competitive prices. But when they sell electricity at noncompetitive prices, what it does is it effectively raises the effective price of the heat.

So one of the things that you have to work out is what are the reliability demands for each particular application, and what is the backup generation going to be? Is it going to be nuclear? Or could it be, say, natural gas or something else that would be a cheaper emergency backup option so you don't have to buy all this extra capacity, which would make the nuclear option less attractive? But there are ways of engineering your way out of all of these sorts of problems, but it's just something to think about, that reliability is a big cost factor in doing this.

And then the point that was raised earlier-- look how big this plant is. If I'm putting my nuclear reactors over here, and now I need to use the heat over here, how much temperature loss am I going to sustain in this transmission? What does that mean for temperature loss and heat loss? What does that mean for the viability of centralized heating. So all these details are obviously very process-dependent, site-specific, and temperature-specific because the heat loss is proportional to the temperature. So my little previous calculation kind of ignores all that. But even if we cut out 50% of these things, we're still talking order 1,000 reactors or more. And so I think there is still a market here for heat, even with all these things that I'm glossing over.

But also, this is where there's huge opportunity to really start doing studies to understand where the nuclear heat is best deployed, which types of sites, what are the size distributions of these types of sites in each of these categories. If I'm going to look at corn milling, what is the size distribution of corn milling? Is it tons of little small operators all throughout Iowa? Or there are a couple of big, giant mills that could be easily nuclearized? And what fraction of the total heat is available for dealing with this kind of nuclear decarbonization? So that kind of market analysis hasn't really been done in the level of granularity that we need it to be done at. But it is something that the data that we have thus far look good, I'll just say that. I think there's a real opportunity here.

So let's just look briefly at the costs. This is your bottom line cost. This is what your brain should be thinking. The renewables option is something-- order 130. I have to build this microreactor that produces 10 megawatts thermal. And it needs to produce it at some cost less than 130, which is what the renewable cost. And I'll just put these numbers back on. Here are the same cost estimates for microreactors, except I changed the number from dollars per electric megawatt to dollars per megawatt, assuming a 33% efficiency conversion, which is roughly probably roughly right.

And what you see is that, remember, the CAREM reactors, that small PWR, 25-megawatt PWR are being built in Brazil. This is based on a real reactor under construction. It looks like it just barely but does indeed make it. And certainly, this reactor could be cheaper if we built it on a better schedule and built more of them. So little PWRs look promising.

Then we go to microreactor concept, batteries. We talked about Bongiorno's estimate. This was $85 per megawatt, which he said is too low, but this would be $28. Here's the NEI estimates. These all look favorable. These, again, were based on nothing.

Now, this is the one that is based on the MARVEL reactor, which is an actual microreactor design. It is not good enough for a first of a kind. We don't know what it will cost for an n-th of a kind. Remember that they got their n-th of a kind cost estimate just by asking people, what do you think it should cost? So let's not trust this number. But this number is definitely too high. So what will mass production do to this number? That's the question. And here's the Project Pele thing, which is not a relevant reactor for this case.

So if these numbers are even close to being real, it looks promising. Many of these numbers are under the $130 limit. Now, on one side, there's also the caveat that when we tend to price things at this early stage, we are typically low by factors of, say, 2 to 5. Remember, I showed you how the price escalation for all those different reactor concepts went up as the reactor became more mature. So that's working against us. But on the other side, these reactors are really capable of being factory fabricated if they're at the 10-megawatt thermal size. And so that's working in favor.

So all of this has to be worked out. And designs are needed. And realistic economic modeling is needed both for demand and the manufacturing. So we don't really know, but it looks promising so far. Any question-- yeah?

AUDIENCE: For a design, like eventually where it's particularly low outlet temperature, at that point, is it pretty much out of the game because then you'd have to, I guess, do a lot of [INAUDIBLE] electricity [INAUDIBLE]?

PROFESSOR: Yeah, probably.

AUDIENCE: Because it's only like a couple hundred Celsius I think.

PROFESSOR: As below PWR temperature?

AUDIENCE: Yeah, I think it's like 150 Celsius.

PROFESSOR: Is that because of heat pipe limitations? Yeah. Yeah, so the cool heat pipe concepts, I guess, might not work unless you have fancier heat pipes. So I think this is-- I think this is a market. In fact, this is what I think the future of nuclear is about, personally, because I don't think it can compete with wind and solar for electricity. We talked about electricity markets. I just want to show you-- I mean, industrial parks.

I just want to show you where that heat is currently being used in the United States. And this kind of shows you here enormous heat users in the Gulf of Mexico, where, of course, you have a lot of oil coming in. And so a lot of this is going to be actually petroleum refining. But there's other-- there are some heat users over here. I think this is mineral stuff, like calculation of limestone maybe, things like this. This is in the region where there's good geothermal-- may or may not be addressable by nuclear. And then you have some in the Pacific Northwest, which is mostly paper production, and then bits and bobs scattered around. But really, the story is that there's some concentration, but there's also opportunities elsewhere in the country. Yeah?

AUDIENCE: So I guess since a lot of that concentration is in the regulated parts of the market, would that make it easier for someone like Dow to sell that electricity at a more reasonable price since, at least in those areas, it's quote unquote easier for nuclear to compete? I just think that-- that's Louisiana? Or no, that's part of Texas. But I was just wondering if that was--

PROFESSOR: --an interesting question.

AUDIENCE: And a lot of those states are red states, so they wouldn't be as excited about putting in solar.

PROFESSOR: So in both cases, they're going to be able to sell their electricity without issue. The only question is whether they can get better rents off the price of the electricity in regulated markets. So I guess they become utilities, and then they probably negotiate their price with the regulatory board. So probably, they could get more money in those markets. But I'm not 100% sure how it works when you're doing two things at once. But it would make sense. Was there another question over there? No?

So all of this is heat sans petroleum products for transportation fuels. Let's talk about making transportation fuels. So this is what we call the hydrogen economy. So right now, 10% of our gasoline in the United States, roughly, is biofuels-- comes from corn ethanol. And to produce that 10% of gasoline substitution, we use 45% of our corn cropland area. Obviously, this is not a scalable process. It's also dubious levels of carbon neutrality because of all the energy that goes into doing this conversion. In fact, much of that is actually not that carbon neutral. It's not a scalable process.

If you want to produce all the transportation fuels, gasoline but also diesel and also jet fuel, from bio sources, you need something like cellulosic feedstock instead of starchy feedstocks. And you're going to need a lot more hydrogen to protonate all of those carbons to make the liquid fuels that you want. So we need to find a way of making that hydrogen, and heat is involved.

So just to give you a sense of the scale of this industry, this is roughly one third of all CO2 emissions. There are some sectors which can be easily decarbonized just through electric vehicles and so on. But the NREL folks figure we need 70 billion gallons of gasoline equivalent-- this is GGE, Gallons of Gasoline Equivalent-- for the hard-to-electrify sector. So this is like interstate trucking, people who use vehicles for long distance driving or in areas where there's not easily access to charging stations and, of course, jet fuel and possibly train transportation and things like this.

There are many, many different ways of making this stuff. All of them, basically almost all of them, require some source of hydrogen. So here are some of the biofuel production processes. Different feedstocks-- oilseeds, starches, woody crops and [INAUDIBLE] residues. This is where you're getting into cellulosic materials, which are interesting. Municipal solid waste, which is the stuff that is happening over at that-- is basically poop-- sewage and algae. Oh, I guess this is trash. There are various ways of converting these things.

But the ones that are interesting are the woody ones. And you need 62 grams of hydrogen per gallon of gasoline equivalent, essentially. So that gives us our baseline hydrogen feedstock requirements. So we can do that calculation. They said 70 billion gallons. At 62 grams per gallon, we would need 5 million tons of hydrogen per year.

So where do we get the hydrogen? Well, there are these named sources of hydrogen, which you probably heard about-- pink hydrogen and green hydrogen and blue hydrogen, gray hydrogen. So right now, most of the hydrogen is produced by gray hydrogen. We basically do it on steam methane reforming of natural gas. So you have natural gas. You combine it with hot steam, and you get CO2 out, which is what we're trying to avoid, and hydrogen molecules.

And so one proposal is to turn this into blue hydrogen by taking that CO2 and doing carbon capture and storage. Now there's an important difference between carbon capture and storage on steam methane reforming and carbon capture and storage on, say, a natural gas plant. In a natural gas plant, what you're doing is you're taking the flue gas, which is water vapor and CO2 and some other residues.

And you're trying to extract the CO2 using amines in various chemical processes and store the CO2 underground. This is just giving you pure CO2. So it's much cheaper to capture that CO2-- is not an entropy process that you're trying to undo. You still have the problem of whether you believe that once you pump it underground, that CO2 will actually stay there. So that's the issue is whether carbon capture and storage can decarbonize. This hydrogen production is-- so I still think an open question, but it is cheaper to do it than with natural gas for electricity.

Then you get to water hydrolysis, which is powered by electricity, which could come from renewables. This makes green hydrogen. So there's your hydrolysis process. And we could also do it with nuclear. So let's just look at what these things cost. So it depends a little bit on the cost of the feedstocks. If you're doing steam methane reforming, then you need to know what methane costs, natural gas costs. And so the price fluctuates. But it's roughly currently we're paying basically under $1 in the United States per kilogram of hydrogen at current prices. You can see, if you try to do this carbon capture and storage, it increases it by 50% to double to triple hydrogen. The green hydrogen more than 3 and 1/2 times more expensive. And so green hydrogen must be pretty expensive.

And this pricing assumes the 1.7 times overbuild required to have this process running all the time. It does not assume-- one of the things that you could do is that the fact that you have a 1.7 times overbuild to keep your renewable grid running all the time is take some of that excess capacity and use it to make green hydrogen. Does that make sense? Have you built extra rain and solar to keep the grid on all the time? That means sometimes you have too much.

The problem with that idea is that that means your capital utilization of your electrolyzers, which are the things which are converting the electricity into doing electrolysis for you, will go down if you're not using them all the time. And so there's a trade-off to be made there. So it's not so simple.

Let's look a little bit at what is happening in that space. So right now, you can see electricity cost is the dominant factor in the production of green hydrogen. But NREL believes that there are ways of bringing various costs down-- improving efficiency, improving the lifetime, reducing the capital costs. And so they have these mid-term targets where they would bring the hardware costs way down. But some of these things, like increasing lifetime, are essentially capacity factor issues. And so if you undo that by using only excess generation on the grid, then you wind up looking more like this.

So even though they say they can bring the cost down, it's not clear how much of that will actually come from cheaper versus better utilization of that capital. And only cheaper to capital gets you into a place where you actually can use the extra generation. But then, nonetheless, they believe that there's an ultimate target for green energy that is competitive with current gray hydrogen, or making green hydrogen can be made the same price as gray hydrogen in the long run. I think TBD because a lot of optimistic assumptions baked into this calculation. And we'll see what happens.

What's the situation for nuclear hydrogen, or it's pink hydrogen? At the moment, it's more expensive. It can technically be done. And there are actually three ways of doing it. So one method, which is you have very hot nuclear, and just because it is so hot, it breaks up the water at these high temperatures. But this requires these very high temperature reactors, which have low lifetimes. And it doesn't look really promising.

The second thing you can do is you could make electricity, you make green electricity from nuclear and do the traditional just green hydrogen, just do water electrolysis. But we already know that electricity from nuclear is probably not going to be cost competitive with renewables, and therefore, this is probably not the strategy.

So the real way you would use nuclear is that you would preheat water using nuclear heat, and then you would use electric, probably actually from renewables, to do the electrolysis. It would be a two-step process.

So why do I say preheat the water? Well, it turns out that the efficiency of electrolysis is a function of temperature. And you can see here this maximum theoretical efficiency. And this is more like where things actually operate. And the blue line, you see the efficiency goes way up as you heat the water. And so, actually, in these electrolysis plants being run off of renewable energy, they're heating the water anyway. And instead of heating it using resistive heating, we would heat it using nuclear heat. And that's where you would actually get the gains from nuclear because, remember, nuclear heat is cheaper than renewables heat.

So that's the idea. So here's the kind of calculation to be done. Your target temperature is something like 700 to 800 degrees. 777 is kind of like our target temperature to operate our process. So let's just look at this plot. 777, and you're here where the curve is turning over.

So this is just a way of calculating how much nuclear we need. So we're going to start with room temperature water, which is 20 degrees. And we're getting heated up an additional 800 degrees to get to boiling. Now it turns out you can obviously change-- you could change the amount of heat you have to put in to get it up to boiling by, say, putting it under vacuum. But it turns out, then, what happens is that this number goes up when you're at lower than atmospheric pressure, and you don't really gain anything.

So basically, this is your number to get it up to boiling, plus the heat of vaporization, plus to take the steam from 100 degrees up to 777, use another 677 degrees C of heat in the steam, and if you add that all up, it gives you 4,000 kilojoules of heat per kilogram of water to get it up to 777. No, that is your water feedstock.

And for 5 million tons, which we previously calculated for 70 billion gallons, at 26 grams per gallon, you have five million tons of H2. That gives you 45 million tons of water. And then you multiply that number times that number, and you get 6 gigawatts of thermal heat needed to produce all of the hydrogen for all the transportation fuel production that is difficult to decarbonize with batteries.

So the bottom line here is that, yes, nuclear could contribute, but 6 gigawatts is not that much in terms of a market size. So I don't think the transportation fuel story is actually the thing for nuclear. It's actually all the rest of those industrial processes. Sure, you could use your nuclear batteries to help with this, but it's 10% perturbation on the existing market, something like this, despite the fact that this is one third of transportation. And that's because, really, the principal energy consumer here is just electricity, which is just cheaper coming from renewables. So that's the kind of bottom line for the transportation story.

Everything that I've shown you so far, the industrial processes and the transportation, are both for the United States. The industrial processes are the ones that are interesting. So what happens if we're looking at a global market? So here it is. Here's the distribution of emissions, which is in my proxy for CO2 abatable sources of heat. And you see around 2014, which is essentially when all the data I showed you were-- it takes them a long time, satellite data. So that data was all-- basically, in this region, the US is about 10% of the total industrial heat emissions.

So my kind of global estimate is that potentially up to 10 times what we estimated for the US. So we were talking a couple thousand mini microreactors in the US-- we might be talking something like 20,000 microreactors globally. And so that really just underscores that there is really a potential there in the heat market.

So bottom line, globally, around 600 gigawatts of thermal heat potential-- majority will be at these tiny sizes. There is a strong preference to get to higher temperatures. If we can do it with keeping the capital, we're keeping-- microphone going out-- keeping the lifetime of the reactor good. We don't want to harm the reactor lifetime. That affects the capital cost by pushing [INAUDIBLE]. It still depends on economics. We still need to build these things cheap, and we don't really know how is it going to be. And so we have this rule of thumb, under $130 per megawatt, which we should bear in mind. This is a problem worth working on.

So that's it for the heat markets. If there are any other questions? Take care. Yeah?

AUDIENCE: With transportation of heat, I know it depends on a lot of the factors. But just first order estimate, how far can you translate it?

PROFESSOR: I have no idea. Good paper topic. So any other questions? All right, get out early.