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DAVID HSU: Welcome to another lecture in my series on urban energy systems and policy. My name is David Hsu. I'm a professor in the Department of Urban Planning at MIT. And today, I want to talk about cities and future fossil fuel use, carbon capture utilization storage, and nuclear power. In short, this is kind of a grab bag of topics, thinking about how cities exist in the larger energy system. The readings for today are all in the syllabus. You can also see them by clicking on the purple links in the PDF.

And again, today, we're going to have a more philosophical discussion really about how cities exist within a much larger energy system. And the reason why we're going to talk about these scenarios for future energy use is that the context is going to decide what we try to pursue in cities. So just to take a large picture view of what we're trying to do through decarbonization, this is from 2019, the Global Carbon Project.

And their headline in 2019 was "CO2 emissions grow amidst slowly emerging climate policies." But it's important to note that even before COVID, fossil fuel CO2 emissions were growing more slowly, but did not yet decline. And of course, as you know and this red circle reinforces, CO2 emissions have to decline to net zero by mid-century to meet our Paris Climate Agreement goals, which is to keep our global temperatures less than 1.5 degrees Celsius above the previous averages, which would avoid the most catastrophic effects of climate change.

And so this graph points out that, in the last 10 years, the growth of coal was slower, relatively slower growth in the eight years up until COVID. And the 2019 projection was a slower decline still but not-- a slower growth still, but did not yet decline. If we look at the sources of global carbon emissions, natural gas and oil are now the main drivers of global emissions growth. You have gas growing about 2.6% per year, oil growing 0.9% in 2019 alone, and coal actually declining in 2019, the global projection.

Land carbon emissions also slightly increased, driving up emissions in 2019. Now, this brings us back to the decarbonization pathways we talked about in one of the first lectures. This is the reference case. This is essentially how much energy the US economy currently uses in 2020. We've talked a lot about this scenario, trying to achieve 100% renewable energy. You can see that all the fossil fuel resources in resources have been replaced by renewable energy resources.

And of course, there's the third scenario, which is the central low fuel price. This is the central scenario, where it's the lowest cost or least cost pathway to decarbonization. And this occurs in the scenario of a low fuel price, meaning that if fossil fuels remain relatively cheap. So there are still some fossil fuels, like natural gas and petroleum in this decarbonization pathway. But we should note two things about this scenario.

First, because of the central least cost pathway and low fuel price scenario, this is essentially a scenario they consider in this paper that has the maximum amount of fossil fuels that could be used that would still achieve decarbonization. And even in the scenario, if we flip back a couple of slides, you can see that we currently have coal, natural gas, petroleum around 31 exajoules of natural gas and 39 exajoules petroleum.

To go back to our central low fuel price scenario, you can see we only have about 7.4 exajoules of natural gas and 12 exajoules of petroleum. In both cases, that's about a 75% decline in how much energy we have to use from those two resources and still achieve decarbonization. So the question is, how do we go from a reference base to a carbon neutral pathway that still has fossil fuels? We need to do four things, this paper argues.

We have to lower our final energy use. You can tell, on the left-hand side of the Sankey diagrams, there's less energy use going in, in terms of primary energy. We can decarbonize our electricity sources. We should switch from fossil fuels to electricity and a lot of our energy technology or converted technologies. And we need to do carbon capture utilization and storage. That's what I want to talk about more now. Carbon capture utilization, and storage, why is this important?

Well, there's, of course, a number of cons that people will argue around CCUS. One of the first is that it's been pushed by fossil fuel interests as a way to continue emissions. If you look quite often on social media or quite often on the web, if you have energy interests, you may have been targeted by fossil fuel ads from Shell, Exxon, Chevron, and other fossil fuel companies that argue that they're investing in carbon capture utilization storage.

They're spending on these technologies with a small fraction of what they're spending on their current extraction or new exploration operations to extract more fossil fuels. So it's hard to argue that carbon capture utilization storage by fossil fuel companies may necessarily be in good faith. Another con with carbon capture utilization and storage, or CCUS for short, is that it's not economically competitive. It's simply a higher cost than existing renewable alternatives.

Another argument is that there's simply no fundamental economic value to storing carbon, except for avoiding the externalities of climate change. In other words, we should put carbon-- we should store it if possible. At the same time, there's no fundamental use to get out of it, unless we simply consider the use to be avoiding the worst effects of climate change.

And because the only way that we could price externality is through a carbon tax and price, these are not necessarily proven to be politically viable in many cases so far. You will notice that the new Inflation Reduction Act does not include a carbon price, though there are still a number of politicians and policymakers who are still pushing for it.

Of course, one of the pros of carbon capture utilization storage is that, in the short-term, we use still a lot of fossil fuels. We also have relatively high fossil fuel prices. And so if we need to continue producing fossil fuels to avoid the worst short-term effects, we are going to hopefully have carbon capture utilization storage to store greenhouse gas emissions in the short-term and in the future. And one of the pros, I guess, for the idea of CCUS in the long-term is that we simply need to reduce carbon concentrations in the atmosphere.

Our current levels are 415 parts per million. If you simply stop using greenhouse gas, or rather stop using fossil fuels tomorrow, we'd still have to have a way to reduce our carbon concentration in the atmosphere to safe levels. So the latest IPCC report recognizes that we need some kind of carbon dioxide removal or some kind of carbon capture utilization storage techniques to be developed. And so this is actually to bring it back to what cities can or cannot do.

On one hand, you have the cities that are highlighted in blue-- Washington, California and states like New York, Vermont, Massachusetts, and New York are all considering natural gas bans because simply we know that greenhouse gas emissions, and carbon emissions, and methane emissions especially are driving greenhouse gas-- climate change very quickly. And so you have a number of cities and states all considering trying to pass natural gas bans, such as Berkeley, California, Seattle, Washington.

I think San Jose also considered it. And about 10 or 15 towns in Massachusetts have also proposed it. And the latest Massachusetts climate legislation allows 10 cities to experiment with this. At the same time, just to consider what cities can't do necessarily, look at all the states here in red. These are all states that have passed legislation that prohibit local governments from restricting natural gas utility service. In other words, the states are preempting what cities can do.

And so the reason why we're considering our alternatives or the possibility of how much fossil fuels we're going to use in the future is because these two kinds of states-- frankly, blue states and red states-- have fundamentally different views on what the future use of fossil fuels should be. Both consider how we might achieve decarbonization and whether or not we can consider to use fossil fuels, whether we can continue to use fossil fuels. This is going to drive what we do in cities and policy.

So there's a couple of different ways to do carbon capture and storage in the lithosphere or geosphere, essentially into the Earth's mantle. And this is a diagram from the Rissman paper that we read on Tuesday. And this shows different ways of taking-- you can basically have a pipeline up to 500 kilometers that takes carbon dioxide or greenhouse gas emissions from a power plant and brings it to a CCUS storage facility.

So you have some flexibility in disaggregating where the power plant is and where the CCUS storage facility is. You can bring in this pipeline. You might be able to bring it by ship. You can inject CO2 and store it underground. And this shows all the different ways you can store it underground. You have this impermeable cap rock that keeps the CO2 in the ground. You pump it to about 1.5 kilometers deep or more. You can put the CO2 into a depleted oil or gas reservoir.

You can put it into a natural saline aquifer. And as this little inset shows, this carbon dioxide becomes stabilized within the porous rock, forms natural compounds in the surrounding brine and minerals. Of course, that brings us to other possible ways to do carbon capture utilization storage. You might remember this figure from the Tomalty Report we read maybe I think second or third week of class. This shows Ontario's Greenbelt.

We discussed the implications of land use not only for urban growth, but for possible carbon capture and storage. So about two summers ago, I spent quite a bit of time talking to my MIT colleagues. We worked on this climate grant challenge project in terrestrial carbon. And we produced from it a series of graphics showing different ways that you might be able to sequester carbon into terrestrial or into the biosphere.

So one possibility is that you take carbon and sequester it into the soil microbiome. You may genetically engineer the soil microbiome to uptake more carbon. Another possibility is perennial crops. Perennial crops, unlike annual crops, are agricultural crops that actually can be harvested every year. So they don't require replanting. Their root systems typically grow much deeper than typical annual crops, the things we currently plant and harvest every year. Perennial crops, because the root systems go down much deeper, they store more carbon into the soil.

Another possibility is-- for terrestrial carbon in agricultural soils is abandoned croplands. If abandoned croplands no longer need to be harvested, then we could store carbon into the soil in abandoned cropland and leave it there. These are all possibilities for agricultural soils. Another possibility for carbon capture utilization or storage is forest sequestration. In many cases, you have natural carbon dioxide emissions from, say, a volcano. You get forest fertilization.

This is an ecosystem cycle that my colleagues study. You can see the CO2 is being projected into a forest. Another possibility is terra preta. This is something that Taylor Parron has studied in EAPS, how actually ancient cultures actually used charcoal and waste processes to actually create a fairly rich soil called terra preta in the Amazon, apparently resulting in much more fertile soil than the Amazon we have today.

And one simple way to sequester carbon into soil is to avoid illegal logging and deforestation. We know that quite a bit of carbon is sequestered in the Amazon rainforest. We want to avoid illegal logging and deforestation in places like the Amazon, in places like Indonesia. If we can avoid that illegal logging and deforestation, we're essentially saving carbon dioxide from being released to the atmosphere.

Another possibility for storing carbon is in the hydrosphere. This is something that Heidi Nepf and others have studied. Charles Harvey in civil engineering studies how much carbon is sequestered currently in peatlands. Peatlands are essentially decaying vegetation from many centuries before. They actually sequester quite a bit of carbon. Permafrost currently stores a lot of carbon in places like Siberia.

This is something we want to avoid, warming the Earth, because if we do have warming, they'll release quite a bit of carbon dioxide and methane into the atmosphere. And Heidi Nepf and others in MIT have studied coastal hydrosphere or coastal sequestration of carbon. I think blue carbon is what they call it, where you start storing carbon dioxide in mangroves, and salt marshes, and sea grasses. So these are all possibilities for carbon capture utilization storage.

If we think about the utilization part of it, what we might use carbon for, this is-- again, I show you a McKinsey graph because this is the marginal abatement cost curve that we've been talking about in previous classes. On the vertical axis is the willingness to pay from manufacturers for CO2. In other words, lots of manufacturers actually need CO2 as feedstock. So on the positive side, manufacturers are willing to pay for carbon dioxide.

On the negative side, they're willing to pay to get rid of CO2. Or they would actually have to spend more money to take up CO2. So if you look at it right now, there's this blue bar. This is the expected cost for direct capture by 2030. This is a typical cost of CO2 capture for high purity point sources. So right now, we can typically capture CO2 for high purity point sources. And the economic uses of that are in things like biochar or carbon, making carbon fiber in greenhouses, and food and beverages.

Right now, we can't capture CO2 at an economically viable price to use in applications like cement. Cement can actually be made stronger by adding carbon dioxide to it. You can use it to do enhanced oil recovery. You can actually pump CO2 into an oil reservoir and drive out more oil that way. But right now, it's not necessarily cost effective in many cases. Aggregates, storage, these are all things that aren't necessarily possible to use with high purity point sources right now.

McKinsey report, one interesting thing is they looked at what the viable marketplace is for CCUS now. And they also use, I, think useful graphics just showing potential industrial sources for carbon capture use and storage. There's many plentiful sources. You can see they have the sector here-- power, heavy industries, high purity industrial point sources, and diffuse and mobile emissions. And they have the number of sites here.

So we actually have 1,400 sites for power. Those are essentially power plants. Average emissions per site in terms of megatons of CO2 are 1.3. It's very hard to capture CO2 from heavy industry and from high purity industrial point sources because their emissions per site is quite low. So you have to build all the same infrastructure. Or it may not be worth building infrastructure just to capture these low emissions per site. And of course, it's very hard to capture CO2 from diffuse or mobile emissions.

If we look at the work of David Keith, a professor both in applied physics and policy at Harvard, he has a firm with many people working for it called Carbon Engineering. And this is what the subject of the David Roberts article was, which is what the viable uses of direct capture might be. As he points out in this article, it may not necessarily solve climate change. It's not a silver bullet. But there are interesting use cases that are actually promising developments.

So one particular case that is just on the Carbon Engineering website, you can see that they have the solution called air to fuels and that their carbon engineering process and direct air capture is a way of delivering synthetic, ultra low carbon fuels, such as gasoline, diesel, and jet fuels out of air-- I'm sorry, jet A grade fuel out of air, water, and renewable electricity. This is the air to fuel solution that Roberts talked about in his article.

If you look at how this works, we have CO2 in the atmosphere. We capture it through direct air capture. We take the atmospheric CO2 and put it into a fuel synthesis. And we put in electricity-- renewable electricity-- and water. And we get ultra-low carbon fuels out of it. So this is not necessarily a carbon negative process. It is at least, at best, a carbon neutral process or a way of providing ultra-low carbon fuels.

And as the Roberts article points out, there are states-- or there are policy situations, like California's ultra-low fuel standard, where this may make this economically viable to produce this fuel this way. And it may make it economically viable for one large actor to sign a power purchase agreement to buy a set amount of ultra low carbon fuels. And there are possibilities for the direct aircraft technology that Carbon Engineering is developing.

It's sucking carbon out of the atmosphere directly to direct air capture, putting it in permanent geological storage. Instead of the pipeline I showed you in the previous diagram, it would just be the direct air capture technology, which they're currently piloting, I think, in British Columbia. Another possibility is what I mentioned before, enhanced oil recovery. You take atmospheric CO2, capture it in direct air capture. You can probably store this in oil reservoirs during oil production.

This is one situation that I've always been a little skeptical of, you can basically drive so much CO2 into the oil reservoir you can pump out the oil. And somehow, that still results in a low-carbon fuel standard. But if it pencils out, or if the calculations work out, there's been more than one or two startups trying to do enhanced oil recovery using CO2 or trying to show that it could be a carbon neutral or carbon negative process.

And so it would be-- just to show you the diagram from the Carbon Engineering website, in this situation, we have CO2 in the atmosphere. We capture it through direct air capture. We inject it into an oil reservoir. We actually get more crude oil out. We refine it. And we get fossil fuels to put into our existing infrastructure. This is also meant to try to meet some of the ultra-low carbon fuel standards.

This brings me to Stripe's negative emissions commitment. This is a project I've been following for a couple of years and many people have been following. Stripe, as you may know, is an online payments company. But in 2020, or 2019 I think, they announced their negative emissions commitment, which is when they pledged to pay $1 million per year at any price the direct removal of carbon dioxide in the atmosphere and sequestration in long-term storage.

They built up a small team to evaluate different carbon removal technologies. And in 2020, they announced their first carbon removal purchases. This was essentially a commitment the company made to try to pay money to start to foster or start to build the market for negative emissions or for carbon removal. And so I think this is a project I've been more interested in because they're very transparent about what the criteria are. And they're very transparent about the technology they're trying to foster.

And if you look at their website-- you can click on the purple link up here to see the website-- you will see that they actually have almost all of these submissions. And they show exactly how they've evaluated the submissions and why they've picked a certain portfolio of technologies. So their criteria, I think, are very clear. They show what their criteria are, whether or not it's possible today. The target is by 2040.

So they're very clear that they're making these purchases to try to foster these technologies. So the criteria are they want everything to be sequestered beyond the biosphere. This fundamentally shows a very different approach to the terrestrial Carbon Climate Grand Challenge from MIT in that Stripe doesn't actually believe that sequestering carbon in the biosphere is going to be effective. This is because if you store things in the biosphere, it may actually lead to-- you might have wildfires in the future.

And that would simply get rid of or obviate the effects of the carbon capture sequestration. They also typically, in a very Silicon Valley way, evaluate whether or not this technology has a path to be a meaningful part of the carbon removal solution portfolio, would allow you to achieve sufficient volume. It has to have a path to achieving being affordable at scale. It has to achieve permanent storage of carbon.

Currently, we can start for greater than 1,000 years as that's their target in 2040. Their target for cost is less $100 per ton. Their volume has to be a minimum of 0.5 gigatons per year. And their criteria are that the carbon sequestration has to be scientifically rigorous and transparent for verifiability. It has to meet standards for quality and safety and be globally responsible. And it has to have a net negative lifecycle.

So currently, we have a negativity ratio-- this is reducing net atmospheric CO2 expressed at a ratio subject to appropriate boundary conditions. This is currently a negative activity ratio of less than or equal to 1. And of course, in the future, they want a negativity ratio of less than 1. They want to get a net negative lifecycle, or showing that we have net atmospheric carbon removed. So this is what Stripe is paying for. In the first year, they picked four technologies, I think ranging from about $60 per ton to about $600 per ton. Simply because they had a portfolio, they're trying to venture capital their way into new technologies for negative emissions.

And I just do encourage you all to consider this in the context of your future careers. They say it's a call to action. Their goal is "not only to remove of the atmosphere, but to create a ecosystem of funders and founders that will invent ways to solve the world's largest collective action problem. We continue to search for great projects, partners, and experts. Reach out to us to work together on this effort or give any feedback. And if you're an engineer or a designer who cares about climate impact, consider joining [their] team."

This has, in the last two years, advanced even further. You see this new movement called Frontier, led by Stripe but joined by Alphabet, Shopify, Meta, and McKinsey company. These are not small companies. This is essentially taking Stripe's negative emissions commitment and expanding it even further.

What they have said this basically negative emissions commitment is is called an advanced market commitment to accelerate carbon removal. It's an advanced market commitment because you're making the market by pledging money going forward. By pledging the money is what's going to get people to enter the market with a long-term commitment to develop new technologies. So scaling up from Stripe's original $1 million purchase in 2020, Frontier is an alliance between all these companies led by stripe, which has advanced market commitment to buy initial $925 million in permanent carbon removal between 2022 and 2030.

Tens of thousands of businesses have joined Stripe because Stripe quickly realized they're building a platform for negative emissions commitment, and other companies wanted an easy way to try to do negative emissions in a way that was verifiable-- perhaps more verifiable than a lot of our discussion around offsets. So this brings us to another alternative future for energy is this kind of question of nuclear. And there's this, I think, silly question, and I think it was discussed recently in a podcast by David Roberts and others, which is "Are you pro or antinuclear?" is essentially a silly question.

You can make pro or anti arguments, and we'll talk about those, but there's maybe other ways you should think about it. On the pro side, the Sepulveda et al. 2018 paper that I assigned for today makes a convincing argument that it'll be more expensive to achieve decarbonization without "firm" resources. And just to add another reason why they don't consider in this paper-- land use. We know that solar and wind are less energy dense. We'll talk about that next week. And we know land use and permitting may be a serious problem for renewables.

Having said that, land use may also be a problem for new nuclear power plants. But the con arguments against nuclear are will nuclear power ever get cheaper. And we'll go into that argument in a little bit. And, of course, there's other reasons why we might not want to use nuclear power-- nuclear waste, proliferation of nuclear technology. Our concern has always been around nuclear technology.

The reason why I guess we can argue that this pro or anti-nuclear stance may be silly is because there's a more useful way to think about some of our problems with nuclear power and whether or not it is a viable alternative going forward. First, there's the problem of operating and maintaining the existing nuclear fleet. A Lyman 2022 article about Diablo Canyon talks about some of the problems with keeping Diablo Canyon open. Having said that, the state of California and the governor just recently reversed his position on trying to close Diablo Canyon because Diablo Canyon has to stay open to essentially provide a large portion of the state's renewable energy or clean energy resources to meet their low carbon goals.

So we know we can operate and maintain the existing nuclear fleet we have with some modification. We know there's some existing risk. But more recently, a lot of environmentalists and policy analysts have come around to the idea of operating and maintaining the existing nuclear fleet.

There's the question of should we try to build new nuclear power plants with our existing technology and mechanisms. We have two new nuclear power plants under construction in the US, both in the South. Currently, I think one is $9 billion over budget, and I'm not sure how much the other one is over budget. There's the Vogtle power plant, and there's one in South Carolina also. That's also considerably over budget.

The paths of nuclear power plants-- the path of building nuclear power plants under budget or at least within budget has been terrible with our existing technology. Of course, a third possibility is to build new nuclear with new technology. And this is the alternative of small modular reactors that are quite often touted by nuclear enthusiasts.

This is something that needs to be researched. It needs to be proven out. These are all different problems we need to solve with nuclear power. They're all possible solutions. For example, the first one is probably the easiest to achieve. The second one we have a terrible history with. The third we would probably need to research to see if it's actually possible to build new nuclear power plants with new technology in a more cost-effective way.

But to give you a sense of my skepticism about nuclear, I'm open to the idea but skeptical because of the past history we have with nuclear power plants. Let me show you some of the problems we've had with nuclear power plants and why they may be outcompeted by new renewable resources. If you look at this fairly nice set of graphs from Our World in Data, it shows the price of electricity from new power plants. This is expressed in terms of levelized cost of energy-- something we'll talk about in a few lectures now. And it shows in 2009, on a per unit basis, gas peaking plants declined from $275 to $175, gas combined cycle plants declined from $83 to $56.

The problem is coal-fired power plants essentially stayed stable in terms of cost over this decade, and nuclear power plants actually increased by 26% to $122 per unit of power from $55. Which is to say that basically these two natural gas-based technologies got cheaper, coal stayed the same, and nuclear got more expensive over the last decade. Obviously, not making nuclear power nearly as competitive as before even though nuclear power is cleaner in many ways than natural gas.

What the article is about mostly though is the fact that the price of solar modules has decreased by 99.6% since 1976. This essentially shows a steady march. You might notice the vertical axis and the horizontal axis are both logarithmic scales. So every time you go down one of these blocks is basically halving the price. And as this graph points out, with each doubling of capacity along the horizontal axis, the price of solar modules dropped on average by 20%. This is called the learning rate or learning curve.

So the learning curve is essentially every time you double how much you make of it, the price goes down. This is also referred to as Wright's law, which has been studied quite a bit by Jessika Trancik especially, my MIT colleague in IDSS. And some of the theory around why this occurs is that as we have more deployment, there's more competition, or there's prices fall because there's more deployment. It becomes competitive and new markets and that increases demand. And it becomes a virtuous circle where more deployment makes things cheaper on a per unit basis.

The more you make, the cheaper it gets. And Jessica Trancik has written another paper about why the modularity of these systems across not only the solar cell but the balance of the system has made these things cheaper. And she analyzes the different policy drivers, ranging from German feed-in tariffs to Chinese investment in large photovoltaic cell factories and policy drivers from the US, Spain, and other countries.

But the important point to take home from this is that we have a learning rate of about 36% here in this graph for solar PV. We have an aggressively, not-as-fast learning rate for offshore wind-- steady decreases in the cost of offshore wind. You can see we're currently at low levels of deployment of offshore wind compared to the other technologies. Onshore wind is much larger at deployment and much cheaper than offshore wind. That learning rate has also been comparable or in the same ballpark as solar PV.

A lot of coal has no learning rate. Coal has not gotten significantly cheaper over the last decade. And as we pointed out in the previous graph, nuclear power has actually gotten more expensive over time. And so, what I want to encourage you to think about is this in a competitive market. Which is to say that nuclear power is getting more expensive, and everything else-- solar and wind-- are getting cheaper and faster.

The new target for nuclear is no longer simply declining. It actually has to decline at a rate at a comparable price that could compete with solar and wind. And so, the Sepulveda et al. 2018 paper argues the cost of the system will be much higher if we don't have firm clean resources such as nuclear energy or natural gas power plants that include carbon capture and storage or large reservoir hydro resources. But this picture is going to change over time, and they do a lot of modeling in this paper to show that we need nuclear energy to keep the cost of decarbonization low, anywhere from 10% to 60% lower.

Having said that, there's also other reports and other analysts looking at the idea that solar may get so cheap so quickly that we simply need to build twice as much capacity as we need. In other words, for the times of year we don't have that much sun, we simply build twice as many solar panels in order to try to meet that winter load or winter demand.

There's different possibilities. There'll be different forecasts going forward. But for nuclear energy it's a moving target. Not only does the price of nuclear energy have to come down, it has to meet targets of offshore wind and solar that are getting cheaper all the time. Batteries are also getting cheaper. Electrolyzers which is the technology by which we take electricity and create hydrogen is also getting cheaper. So these are all kind of fluid technologies, and this is why we need the technological forecasting to show us how much more expensive it may be. Having said that, because we know there's other ancillary effects, we have land use obstacles, we have rate of electrification of some of our technologies, we have policy barriers, it's not clear necessarily if cost is simply going to win out for some technologies or others. But we know that the technologies that are getting more expensive over time are going to have a hard time competing with the technologies getting cheaper over time.

So just to reinforce the point about electrification, the price and market size of lithium ion batteries since 1992 also exhibits a very fast learning rate. The prices have declined by an average of 18.9% for every doubling in capacity of batteries. This shows you the steady march of battery prices going down, which is why we're getting successively cheaper generations of electric cars and pretty much lithium ion batteries in everything.

We all know that our phones have gotten more powerful, but now you can buy power banks, flashlights, pretty much everything has a lithium ion battery that can replace a small combustion engine like leaf blowers very easily or electrical appliances very easily. Bringing us back to just the idea of cost and nuclear, this is a paper written at MIT also in 2020. It's about sources of cost overrun in nuclear power plant construction calls for a new approach to engineering design. And this is written by a student I had in this class, that Philip Eash-Gates, Magdalena Klemun, who is also a postdoc and grad student at MIT, and also Jessika, working with James McNerney, Jacopo Buongiorn, and Jessika Trancik here at MIT.

This paper essentially studied why cost overruns have been occurring in nuclear power plants. It finds that it has a negative learning rate. Nuclear construction in the US has gotten steadily more expensive over time as capacity has gone up. This is a negative learning rate that shows for all these different technology types that overnight construction cost has steadily increased. The analysis of why these prices have increased-- they showed it's almost an across-the-board increase. And all the different components of a nuclear power plant, the blue bars are the direct cost of, let's say, the nuclear steam supply system. The indirect cost is essentially the soft cost of labor-intensive components around building these technologies.

You can see that this is pretty much a steady increase across the board. Everything costs more. Partly everything costs more because of these indirect costs or soft costs. It is not clear, necessarily-- again, if our current way of delivering nuclear power plants is going to be effective, we obviously need to rethink how we deliver nuclear power plants. And this is another paper by Arnulf Grubler, a fairly famous [INAUDIBLE] analyst. This is written about 10 or 12 years ago, but this takes the French nuclear industry, which is basically always touted as the most successful nuclear industry in the world, and again essentially looks at data from this program and finds negative learning by doing.

It reviews the history and economics of the French PWR program, which is considered the most successful nuclear scale-up experience in an industrialized country. But drawing on largely unknown public records, the paper reveals, for the first time, both absolute, as well as yearly and specific reactor costs and evolution over time. The most significant finding is that even in the most successful nuclear scale-up is characterized by substantial escalation of real construction costs.

In other words, we still don't have very much evidence over the last 40 or 50 years that nuclear power plants get cheaper over time. They seem to get more expensive over time. So again, while I'm open to the idea of nuclear, I would like to see it become cheaper before we actually think that it's going to be a viable part of our future energy system.

That means we should research it. It does mean we should subsidize research into it to try to bring it into a more cost-competitive stance versus alternative or existing alternative and renewable energy resources. But again, we should recognize that our current costs don't make it economically viable to use nuclear power plants for the things that it's been touted for. So thank you very much. I look forward to our discussion in class on some of these themes.