[SQUEAKING]

[RUSTLING]

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DAVID HSU: My name is David Hsu. This is another lecture in my series on urban energy systems and policy as part of my MIT class. I hope you're all doing well today. Today I want to talk about cities and the grid. I've been talking in this class a lot about various energy technologies. And I've said a number of times that those are basically fundamental building blocks or constituent technologies or part of your renewable toolbox towards decarbonization of the future. And over the next five classes, we're going to talk about how all these technologies fit together and why the grid is so important to pull these technologies together.

What I want to do today is frame the discussion. And I want to think, just-- first-- about what we're talking about when we talk about the grid. We often refer to the grid as one of the largest machines on the planet, one of the largest machines ever built. But that's also just assuming that we understand all these wires and power plants and users and behaviors to be connected to each other.

So why is the grid important to talk about? For the first 150 years or so of electric technology, electricity could not be stored easily. And I'm going to underline, yet, because we'll talk about storage in a few lectures from now. But the important thing for us in terms of talking about climate change and decarbonization is that electricity is going to be the basis of our clean energy scenarios going forward.

This assessment is based largely on the technologies that we have on hand, technologies that are cost effective, but also have fundamentally different characteristics than our fossil fuel-dominated energy system. It's also important to emphasize that all the reasons why electricity was a key theme in the modernity of the 1900s or 1930s or the 20th century was that electricity is relatively clean in terms of its everyday use. It doesn't emit noise like other kinds of engines. It doesn't smoke inside homes like cooking fuels with biomass.

And it's relatively safe, and I say, it is relatively safe, because, if you look at the earliest 20th century literature, you'll see quite a bit of obsession, really, with the potential of electricity to electrocute people until, of course, people learned how to use electricity and until certain devices and uses were standardized.

Another important point about electricity and the reason why it will be the basis of our clean energy scenarios going forward is that all of our clean resources, like solar, wind, and electricity, are basically designed to make electricity-- solar, wind, and nuclear-- are all designed to make electricity. And of course, as I mentioned in this class before, we're going to have to take electricity and transform it into the other forms of energy that we use, like heat and industrial processes, liquid fuels for some aviation and so on. But those things will become decarbonized by being transferred or transformed from electricity from clean resources.

Another challenge in the grid is matching electricity usage and supplies over space, and this is fundamentally a problem of transmission. In other words, because we can't store electricity, we have to match up, instantaneously, people who are far apart or power plants and people that are far apart. So we'll talk about grid architecture.

But it's important to note-- and I always note in this class-- that the grid architecture we have today is essentially a historical artifact. I say often in class that nobody would design the grid we have today the way that it actually is designed because nobody did design it. It's been developing over the last 150 years. And so we'll talk about the history of the grid today, talking about how it developed the way it did, and then we'll start to think about how we perhaps can rationalize it or change it or make it work more effectively.

And of course, we also have a problem with matching over time. Because electricity cannot easily be stored, it has to be instantaneously used, we have to match how people use their electricity when it's generated in a power plant and when people use it, literally, by turning on the switch in your house. And so this is partly a problem of storage, but we also use market prices and contracts and planning ahead and, literally, real-time management to try match the uses of electricity from supply to demand.

And so there's a system demand curve that I'll show you probably in the next lecture. But it's important to reflect on the fact that the system demand curve is a set of demands that are basically created by learned behaviors and expectations. We expect electricity to be reliable. We expect electricity to be available any time we want it.

That's not an expectation that's shared in many countries around the world, partly because those countries may not have the same level or development of infrastructure, but also simply we have to ask ourselves, is this a kind of demand we want to encourage in the future? Can we use storage to perhaps change what the demand for electricity is over time?

And finally, matching supply and demand occur through costs and prices, essentially markets. But I want to emphasize that markets, in this case, and in all cases, I would argue-- are essentially created by politics and economics. And so we want to look at some of the political and economic factors that have gone into creating markets that we have. The markets that we have were only created about 25 years ago. They've evolved in various ways. But we realize these are highly constructive markets.

But finally, if we understand all these aspects, then we can think about how to try new things in the grid. Some of those options or changes in the grid could be technological, but some might be changes in how we regulate the grid. Some might be changes in consumer expectations. And some might be simply how we think about how the grid should work.

So things like demand response-- a demand response is the idea of-- instead of always trying to shape our supply of electricity going into the grid, we shape how much demand people expect. And that's by sending them signals in things like our cell phones or sending notifications. It could be an automatic communicating device in your house that simply reduces the demand at some critical times to reduce load on the grid, such as a washing machine or a dryer that knows not to turn on now during the peak but maybe turn on at night, when electricity is both cheaper and more plentiful.

It could be technologies like storage-- storage that could occur in your house, could occur in your electric vehicle, or emergency situations. It could occur at points on the grid. And finally, I want to emphasize that behavior and social change is another avenue for us to change the grid. If we always want to build a grid to meet every expectation and every need that we have, we will always be in the process of trying to build a grid with abundant electricity. That would be great, but I'll show you a lot of pictures and tell you about a lot of places in the world where this is not the current expectation. And we have to realize-- the grid we have is constructed from our behaviors and social expectations.

So just to show you a somewhat simple, perhaps dorky diagram, I like to show this diagram because I actually drew this in my last year of graduate school, about 13 years ago. And this is a really simple diagram just to show how we think about the grid. There's a generation-- a generating power plant that looks kind of like a LEGO piece in my diagram. And it goes through a transmission or a transformer yard. It goes through high-voltage transmission lines. It gets stepped down to lower voltages for local distribution. It goes through a meter and goes into your house.

If you think about this diagram, this is basically one chain of how it gets to where you are almost all the time. But what you realize-- it's also something of a hierarchical or radial diagram. This generating power plant serves probably 50,000 people, maybe 100,000 people. So these lines branch out like a dendritic network, and so there's much larger lines that carry much more voltage and current. But these step down until every single line into our house is a much smaller line. And so you think of 50,000 houses surrounding this generating or coal-fired power plant, let's say.

And I want to show you some pictures of just what the pieces of this look like because you've probably seen all these pieces before. You may never have stopped to look at them before. To talk about the historical development of the grid-- this is actually a picture of what's called the first city in the world to start selling incandescent light control station. This is a hydroelectric power plant in Appleton, Wisconsin. The reason why we look at it as one of the first pieces of the grid is that the central generating station from a hydroelectric power plant actually brought the power from a river to about 20 miles away, I think, to Appleton. So a lot of books referred to this as one of the first electricity-generating plants.

The more famous one is Edison Pearl Street Station. Thomas Edison built this dynamo plant, powered by coal. And a steam engine in lower Manhattan is used initially to power restaurants and department stores-- not homes, except, notably, the home of James Pierpont Morgan, also known as JP Morgan-- probably the richest man in the world at the time of this building. JP Morgan was actually quite interested in electricity as a technology. So he insisted on it being put in his house first.

Apparently, this dynamo was very unstable or regularly gave fluctuations in power that resulted in small fires breaking out in JP Morgan's home, that apparently singed the carpets and drapes. Apparently, JP Morgan took it all in stride, because he was a major investor in Thomas Edison's General Electric.

So this is a picture of the Pearl Street Station in lower Manhattan. You can still go to Pearl Street today, a historic district. But this is where the first dynamo grid was built. It's popularized in history and movies. This is a picture of a larger dynamo. And this is a dynamo built for Chicago Edison in Chicago.

It's a great story, actually. Samuel Insull was the secretary to Thomas Edison. He was apparently a very slight Scottish immigrant who worked incessantly or nonstop. He worked seven days a week. People say he worked almost 24 hours a day. And he left the employ of Thomas Edison to go start his own company, called Chicago Edison. It's called Chicago Edison because it was part of the Edison system or the Edison system of patenting and licensing of these technologies.

But Samuel Insull made a number of developments, which we'll talk about in a number of future classes, which are basically the assumptions we have around the grid. He realized that if he built larger and larger central power plants, that he could use the power-- or rather, he'd make the power cheaper but also use the power for multiple things.

This is another reason why electricity is so important. It's considered a general purpose technology. Electricity can be used for lots of things-- lighting, cooking, our computers, now heating, cooling, and electric vehicles. It's a general purpose technology. And so this is-- you can see how quickly the electric technology develops.

The dynamo, I think, in Thomas Edison's Pearl Street Station looks like this. I think, within a decade or two, dynamo would start to look like this. Apparently, it was so big that it shook the building. Samuel Insull encouraged Westinghouse, I think, to keep on building larger and larger dynamos to supply his growing utility in Chicago.

About 10 or 20 years later, by 1929, Samuel Insull actually is supplying more electricity through his companies than most of Europe is supplying its customers. This is another reason why we talk about electricity so much in the United States. It was the grid. Utilities were essentially invented here, and we're rather proud of that. But also, this is the first fairly democratization of this technology. This is when electricity becomes cheap enough to use for many different things and starts to penetrate different uses beyond restaurants and department stores, first, factories, but also, increasingly, homes in cities.

If you want to see a dramatization of this story, this movie came out about three or four years ago. It's called *The Current War.* You can see that it features many famous actors like Benedict Cumberbatch, Michael Shannon. Tom Holland is here, now the current Spider-Man, as well as-- I think this is Nicholas Hoult. He plays Nikolai Tesla, the original Tesla namesake-- the electric vehicle company is named after today.

The Current War dramatizes this early kind of battle over the future of the electric grid. That's why it's *The Current War.* The metascore on Metacritic is 55, so your mileage may vary. I've been trying to see this movie for a number of years. Maybe this, year I'll finally get around to seeing it.

Another reason why electricity is so important, though, is that shortly after Insull's empire implodes with the stock market crash in 1929, partly because Samuel Insull's ousted by JP Morgan-- it's a good series of stories. In 1932-- I want to note that FDR is probably one of the last presidential candidates to talk quite often, on the campaign trail, about electricity. He campaigns against large utility companies that he considers to have-- considers to be large corporations abusing American consumers and citizens.

And so in the 1932 speech on the campaign trail against Herbert Hoover, he actually says in Portland, Oregon-- he says, "Let us consider for a moment the vast importance of the American utilities in our economic life. The utility industry in 1931 went to over $4 billion in one year from the users of electricity, gas telephone, and telegraph. That means an average of $133 from each and every family in the United States."

There's just a few things worth noting about this. $4 billion in one year may not sound like very much to us now-- about 90, 91 years later. But $133 from each and every family United States doesn't sound like a small amount of money, necessarily, for most households. And in fact, we should realize that $133 from each and every family in the United States is based on a vastly lower number, or vastly smaller number of households using electricity than we currently have. That's why it only adds up to $4 billion in one year.

So we know we spend much more on electricity and other utilities like gas right now. But we should also realize that prices have become much cheaper over time. Energy and electricity have become much more plentiful. But it still adds up to a lot of money, and this is why I've emphasized, a number of times in the past in our discussions, that we're going to focus on utilities, where utilities are the kind of institutions and mechanisms by which we provide electricity or we charge people for electricity or we sell electricity but that this utility industry is still present. It was very important to FDR in 1931 and 1932, but also still important to us today.

So just to show you a few pieces of what the electricity system looks like, in terms of physical pieces. These are high-voltage transmission lines. There's many different kinds of structures or transmission lines engineered differently, depending on the wind or snow loads that may occur, the weight of the cables and how far they have to span.

This is a transformer yard. You've probably seen these in city neighborhoods and never looked very carefully at them. This is one in Australia. But typically, in a transformer yard, you have a high-voltage transmission line coming into the city. These are transformers that step it down to a lower voltage. And then your utility company distributes it locally.

Quite often-- I like this picture as a representative picture because it also shows pictures taken through a chain-linked fence. Transformer yards are places that are quite often distributed through cities and within neighborhoods. They're close to where utilities distribute electricity and where people consume electricity, but there are also security vulnerabilities.

A number of years ago, there was actually an incident in California, which has never been quite adequately explained. Somebody actually deliberately took a rifle and shot-- shot bullets into one of these oil tanks to see-- and people think that it was basically a test of the ability to take down the electric grid. Whether or not this was another state actor or if it was a terrorist group, nobody knows, but it's been investigated quite heavily, and it's considered a major vulnerability in the electric grid.

This is just to show you a picture of what local distribution looks like. This should be pretty familiar to you from wherever you grew up if you grew up United States. This is a pole and a wire. This is the distribution line coming in from the utility-- from that transformer yard or substation that I told you about. And these are all the various lines going off the houses. You can see that these lines go to all these houses.

But it's also worth noting what the vulnerability of this is. These are poles and wires, above ground, in most American cities because it's very expensive to put wires in the ground. And second, American cities tend to be more spread out than in other countries. For example, if you go to European cities or a dense American city-- let's say, the center of the city-- you often will not see poles and wires because those will be underground already.

But there are certain vulnerabilities to having above-ground poles and wires. For example, you can see the wires go down my street, through this tree. I've seen the utility out a number of times trimming this tree. If we have a Nor'easter-- a Nor'easter storm in New England, then when the leaves are still on the tree, you get heavy rain and wet snow, taking down branches. Then you lose these wires, and you lose power.

So quite a number of times, when I'm teaching this class in October and November, I will show pictures or utility estimates of the numbers of thousands of people who've lost power because branches have taken down these local wires. And it's actually quite remarkable how quickly sometimes the utility is able to restore power and also surprising when the utility is not able to restore power quickly.

If you look at another waypoint on the grid from that diagram I showed you before, this is my meter. I actually have three meters in my house because I live in a two-unit condominium. This is my neighbor's meter. This is my meter. And this is a third meter for our solar panels.

I also find it somewhat amusing that there's a box on the side of my house that has On or Off, where people walking by could just turn on or off the solar panels. And this is amusing to me because we just take for granted-- this is the kind of thing that's bolted on the side of our houses. We almost never notice. But this does tell you something about how electricity is used and distributed inside the house itself.

Now, to go to a really different situation, just to show you how electricity use can vary in different countries-- this is an example I want to show you among a number of different examples from different countries about how electricity distribution and use changes in different cities. This is an informal settlement in Rio de Janeiro called Santa Marta. It's got this really beautiful paint scheme in the main square.

You can see a number of things. There's this busy street in the center. There's a porta potty. Somehow the truck got behind it. A number of stores along the side. So informal settlements in Brazil and Rio de Janeiro aren't necessarily unplanned settlements. You can see, obviously, it would require some level of planning to build five or six-story buildings.

Quite often, informal settlements start on steep hillsides in Rio de Janeiro, outside of, let's say, allotted lands or lands that are zoned for development. And informal settlements will occur when migrants come into dense cities and just start building homes because they can't afford homes elsewhere. So Rio de Janeiro is an unusual city because rich and poor neighborhoods are actually very close together, and poor neighborhoods quite often creep up the hillsides and actually have amazingly good views.

But what I want to emphasize in this informal settlement is not only the fact that it requires some level of planning to build five or six-story concrete buildings, to have economic uses and commerce here, mixed very closely with some settlements that may have been built over time. But let's look at the electric distribution grid here. This is a typical street lamp. This has about-- looks like hundreds of wires going off of it.

And a lot of these wires may not actually be paid for or metered from the utility company, simply because about 40% of all electricity in Brazil is stolen. It's not paid for. It's taken from by users, quite often in informal settlements, for their use, and not necessarily paid through a meter. Just to show you another informal settlement, this is Rochinha, also in Rio de Janeiro. It's this informal settlement creeping up the hillside.

But it's quite organized. You see that there's a pretty large road. There's multistory concrete buildings. There's a lot of city planning and city development occurring. It doesn't necessarily look like traditional city planning or city development. And again, in the middle of this, you have this pole with hundreds of wires coming off of it.

Quite often, residents will hire what they call a *gato,* which means, cat, in Portuguese. And a *gato* is based on an electrician who will go to an existing power line and essentially drive a nail into it with a wire. And they'll tap the electric line and use that for individual households. So you get these proliferation of these small wires, very similar to the wires that come to my house in my neighborhood. It's just that there's hundreds of them, and they aren't necessarily planned. And at the same time, the grid and the utility has to accommodate hundreds of users taking electricity from points like this.

And just to show you where some of those uses go in informal settlements, which are also called *favelas* or *comunidades.* These are settlements that are built incrementally. You can see that this is an unoccupied space built with cinderblocks. It looks somewhat precarious on this very steep hillside. But almost all of these homes have satellite television. There's another satellite dish there. You see water storage tanks. These are the places I think I mentioned in class discussion, where quite often, you'll have a lot of uses-- like refrigerators and lights and televisions. These are actually well-serviced electric grids. They're just not necessarily planned electric grids.

Again, to emphasize the point that this electricity is not always metered or paid for in the same way that we pay for it, this is actually a informal settlement or *favela* that the state moved into to try to regularize or try to bring governance or a different kind of governance or formal governance to this community. So they've actually put this box here to stop tampering with meters.

Again, if I go back to the picture of the meter for my house, you can see that there's these little blocks that stop tampering so people can't change their electric bill. Also, meters in the United States quite often read by what's called the automated or automatic meter reading, which means a car drives by my house and they pick up the signal from this meter.

It used to be meter people would go look at the number on this and record the number, and my bill was based on that every month-- based on a meter reading. But automatic meter reading is the way a car driving down the street, probably communicating, in many cases, with these meters by radio signal.

So if you look at this house and this meter, they've actually built the plastic box to stop any tampering with it. You see the electric line goes into this box, but there's no actual physical meter inside this box. This is the informal settlement that the government at the time was trying to bring formal governance to. They may not have actually put a meter into the box yet.

To give you another picture of what this distribution grid looks like in an informal settlement-- again, you have remarkably high five or six-story buildings, mostly built out of concrete. They may have been built in successive stages. And again, you can see this pole with hundreds of wires coming off of it, probably tapped by *gatos.*

If you look inside these informal settlements, this is what a local distribution line looks like inside the settlement. It's clearly not undergrounded. It's barely suspended by poles and wires. It's basically a whole tangle of wires overhead. Quite often, you will have electrocution incidents-- electrocution occurring inside *favelas.* You have water or weather events interfering with electricity sometimes. But again, there's a different expectation of how people pay for it, how reliable it is, how they expect to get their electricity.

And of course, we should point out that these*favelas* actually have quite a bit of electric uses and loads. You can see that there's a small store here selling [PORTUGUESE], flip-flops. It's a bar that probably sells cold drinks and ice cream and other condiments. It probably sells some basic groceries. You can see there's an air conditioner built into this informal settlement. You can see streetlights built along this informal settlement. These are places that use quite a bit of electricity, not relative to richer neighborhoods, but it's not like they have no electricity needs at all.

If we look at a really different place, this is a hardware store in Jamshedpur, India, alongside the highway. And you can see that as people build their homes and villages, they often recreate their own infrastructure. You can see that there is plastic tarps overhead to keep this store dry. You can see that these are all watering cans and perhaps water gas cans to store water.

You can see that there's nylon and rope here to secure or build homes. And most importantly, you can see all these electrical outlets are just simply hanging in the string. If you want to build electricity in your house, you can hire a builder or perhaps simply do it yourself by just pulling up to the roadside stand and buying yourself these outlets and switches.

Another example-- one of my colleagues pointed out when we were doing a research field trip in India-- was that quite often in developing countries, we don't have the same information about how and how not to use electricity. He pointed out that this is one of the exact problems we have in developing countries. This is a light bulb on during the day in India. This probably came from a coal-fired power plant. And yet, this electricity is essentially being wasted during the day in India because there's no need for this electric light.

At the same time, it's incandescent bulb. You can see the filament there. So it's actually using a lot more electricity than a LED light bulb would. But it probably runs all day and night because the person who gets the bill gets a bill very rarely. This is a farmer we were talking to a number of years ago. They had a very large electric bill.

But at the same time, they never knew what their electric bill was. It seemed to continually keep on simply growing. They didn't necessarily get it on a regular basis. And they didn't necessarily pay their electric bill, also. It's not like every country and every city has regular mechanisms of enforcement and payment and bill collection or collection for energy used.

Another example of local distribution or I guess the lack of local distribution I saw in India, in Gumla, India-- these are concrete electric poles lying by the side of the road. When I was traveling there with my research team, I asked a villager, how long have the electric poles been here? And they said, these concrete poles have been lying here in this field for about five years. So they'd been promised electricity in the village. The utility had gone as far to pile up the utility poles or the poles and wires in a field but hadn't come back in five years to actually build the electric grid.

One research paper my colleagues and I did in this village in India was to ask villagers about their expectations for electricity. A lot of these households have some electric uses. Some is based on local solar panels. Some are based on highly unreliable electricity coming from the grid.

So my colleagues, who are both trained as architects, and I developed these cards that basically enabled people to express-- if you survey or interview people about things they may not have or not have seen, like reliable electric service or, let's say, electricity storage or appliances they don't necessarily own, you don't actually, I think, always get a clear response. And it also wasn't clear if individuals would be able to respond or groups would respond to this.

So my colleagues, who are trained as architects, developed a card game, and we used this card game to structure our interviews and ask people, what do you prefer, or why did you make certain choices about how you use electricity at certain times? We saw, quite often with household transitions, that some people used propane for some things, go to electricity, find the electricity was unreliable, go back to propane, or find a different technology to supply electricity, like a solar panel or an LED light.

Just to give you another example, this is somebody's DC converter. It probably is used to convert a DC power from a lead-acid battery, maybe charged by a solar panel or by a diesel generator. And they convert this direct current to other uses, such as AC uses like fans and appliances and refrigerators and laptops. Another example in the background here-- these are LED lights handed out, probably by an NGO. These are powered by solar panels, but they can be charged and they provide light here.

Another example is the research we did in Tanzania with a small electricity company there, or small provider of electricity meters and service. This is a new neighborhood actually being built in Tanzania. And you can see-- again, similar to the neighborhood we saw in Brazil, there's a water tank on the roof. There might be a satellite dish coming. And you can see these lines go up this pole and down these wires to different households.

This is another view of the same neighborhood. But truthfully, I was there with a company called My Power or Zola, and what they do is they actually have meters that supply electricity from leased solar panels. Crucially, because solar panels are expensive for these households-- they may be the second largest thing that people bought after the house, what you do is lease people solar panels by putting a solar panel on the roof and putting access to the power of the solar panel on a keypad that you pay through cell phones.

A large portion of GDP in Tanzania and Kenya is transacted through cell phones, so you can rely on the financial infrastructure of cell phones to enable payment. So people lease the solar panel. And in order to access the power from the solar panel and make regular payments, they text their company-- text money to their company. The company sends them back a code. They punch the code into this panel. And they access electricity from solar panels and batteries.

If they aren't able to make their payments, then people repossess the solar panels and batteries. But this is basically just-- I want you to think about this as an alternative system of finance and collection for electricity. It has financial aspects of, let's say, a car loan wrapped up with it to enable people to buy a large asset. But you also need to encourage-- or rather, this company's business model is encouraging people to make regular payments for this, and it's been very successful. Solar leasing has taken off quite a bit in countries like Kenya and Tanzania, if not outright ownership of solar panels attached to households.

So taking us back to this idea of grid architecture, this, again, is another diagram I drew about 13 years ago. It greatly simplifies what we want to do. But we want to have renewable resources like solar and wind. We want to connect it to the grid. And now, on the end of the grid, we may have many different possibilities, such as smart meters.

These are meters that communicate to the utility through the internet or through cell networks instead of a car driving by to read your electricity use. Our homes may have distributed solar. That can either send energy back to the grid or directly supply uses in the home. We may have home energy management, like I've shown you with thermostats and phones. And at the time, I thought we might have plug-in hybrid-- maybe now electric vehicles.

The most amusing thing to me is actually the size of the phone I drew in 2009. It's a truly ginormous phone with huge icons for apps. Obviously, our cell phones have developed much further since then. This is all just to frame our expectations around the grid. I've talked to you a lot about the historical development of the grid and the architecture of the grid. But obviously, the future architecture of the grid is going to depend on technological changes and, frankly, behavior changes occurring at a lot of different levels.

So thank you very much. We'll go into the technology, politics, and market organization of the grid in the next few lectures, I'll see you soon.