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DAVID HSU: My name is David Hsu. Welcome to another installment of my lecture series on urban energy systems and policy. This is a class taught by the Department of Urban Studies and Planning at MIT. And what we're going to talk about today is the next installment of talking about renewables and renewable energy.

We're going to talk about solar today. And this, again, is a fundamental building block for how we are going to decarbonize cities. The readings for today are on the syllabus. If you have the PDF hard copies, you can click through to the readings in the pink links here on this page.

I'll just recap what I said in the last lecture. You have a renewable toolbox. The exciting thing is that our building blocks, like solar, wind, storage, geothermal, electrolysis, are all becoming cheaper quickly. They're all cleaner technologies. But they are fundamentally different technologies than the fossil fuel system that we've built our civilization on.

So we need to build about 47 times more solar, about 28 times more wind than we've built in the last 40 years, to basically provide enough energy to decarbonize our energy system. That gives you a very lengthy to do list, but an exciting to do list for your careers.

Your to do list includes financing, generation, transmission, distributing power, balancing power, making sure that power is reliable, making sure that the energy systems are resilient, and siting these energy resources. Last time we talked about wind basics. We talked about capacity factors as a key concept to understand intermittency.

Today we're going to talk about solar basics. And we're going to use solar technologies as an example of adoption costs, or learning curves, and siting issues. And the next lecture, we'll talk about storage and geothermal. Those are technologies that are developing new niches in the energy system, and may be critical building blocks going forward, but haven't quite developed into the same kind of competitive technology that solar and wind have become.

So just to review basically, here's a diagram from MacKay's book. This is a solar, basically converts incident light on the Earth into energy. Of course, you have to capture the portion of the electromagnetic energy in the ray. And so this diagram simply shows that at the equator, you capture the full amount of the energy landing in Nairobi with a horizontally-mounted ground panel, a panel simply lying flat on the ground.

Whereas at 52 degrees latitude, Cambridge, United Kingdom, or Cambridge, Massachusetts, are the same, you actually only capture about 60% of the energy because a 52 degree angle doesn't capture the full ray energy of the electromagnetic energy, or the sunlight falling on the Earth.

Helpfully, however, as this last line points out, 52 degrees is about the pitch of a roof angle. So if you lay solar panels flat on a roof in Cambridge, Massachusetts, and those are pointed in the direction of the sun, predominantly South, coming from the South in the northern hemisphere, then you can capture the full amount of the solar energy falling on the roof.

This is why we have different maps for solar resources. This is a map of the global horizontal irradiation. This is the amount of energy you would capture if you laid a solar panel simply down on the ground flat facing up at the sky. As you can see, around the equator, there are relatively high amounts of global horizontal radiation.

And, of course, slightly off the equator, you also get a lot of global horizontal radiation probably due to climate. This map probably incorporates not only climate, but also the level of radiation that's measured in these places.

For the direct, normal irradiation, this is how much energy you'd capture if you laid a solar panel at the precise angle to capture the maximum amount of irradiation. And you can see that it's a much more balanced view. This probably includes climate, probably includes weather conditions, but actually is based on empirical measurements.

And you can see that there, solar is actually a resource that's spread fairly well around the world, especially closer to the equator. The northern, southern hemispheres also have abundant solar potential. So if you look at the total photovoltaic power potential, again, a good message from this map is that photovoltaic power is evenly spread across the world. It can be accessed in many countries. Quite importantly, it can be accessed in parts of countries, depending on climate, depending on incident solar radiation.

And, of course, we can also use solar tracking devices because the sun tends to come low from the south in the northern hemisphere, you might have a house that's not pointed in the right direction. It may not be pointed East West. You may want a rooftop facing to the South where the sun is.

As the sun comes over at different portions of the year-- it's higher in the sky in the summer and lower in the sky in the winter-- you may want a solar collector that actually has different angles, angles that can tilt to capture this seasonal variation between summer and winter, and may even tilt as the sun moves throughout the sky. So that's a two axis solar tracking panel.

Another technology that could be used to capture solar energy is called concentrated solar power. This is a CSP plant, or a solar thermal tower. This is Crescent Dunes in the American West. This is actually 10,000 heliostats. These are those tracking mirrors I showed you.

But instead of tracking the sun directly, what these mirrors are doing are actually tracking the sun, reflecting the sun to this one point, and super heating up a fluid here that's used to drive a steam turbine. So these 10,000 mirrors are moving in concert, are all moving differently, all concentrating the sun on this one point to superheat the site and create superheated liquid or steam to drive a turbine to create energy.

Of course, what we're going to talk about mostly today is much humbler, smaller technology. It's the solar photovoltaic panel. A utility-scale solar array is composed of many of these modules, a rooftop on a residential installation, or in a, let's say, camping cabin would probably be based on one standard panel. This is a solar panel installation on top of a big box store.

But solar panels are fundamentally modular. They can be deployed in different ways. And we're going to spend most of our time talking today about why solar photovoltaics, that modular technology, has gotten cheap much faster than other technologies.

And so if you look at the fundamental cell efficiency, this is how efficiently a solar cell converts incident energy to electricity. This is what's called the champion graph that NREL does. Every year, they update this graph. And you can see steadily, there are these different trajectories of different technologies.

The technologies are all in upper left. They range from multi junction cells to crystalline silicon cells, to emerging photovoltaic technologies. You can see these technologies have all developed over time and gotten better. The best research cell efficiency is 47% conversion of incident sunlight into electricity.

But your average solar panel that's deployed on most solar arrays ranges from 20% to 25%. What MacKay says in his book, that he'd be shocked if there's better research cell, or better efficiencies. Efficiencies have gone up over time.

But that's not the key story I want to focus on today. It's the fact that solar panels have gotten much cheaper much more quickly, even though the research efficiency, or the efficiency of most solar panels sold has stayed relatively constant, around 20%.

So if you look at-- this graph from the BP Statistical Review of World Energy. It shows the share of global electricity generation by fuel. And you can see that oil and coal and hydroelectricity are all relatively flat. Natural gas has trended up.

But the one that's quite remarkably trending up is renewables. And renewables is trending up both in terms of wind and solar. If you look on the right-hand graph and renewables as a share of power generation by region, in every single region of the world, renewables seem to be on this very steep, increasing curve.

That curve is reminiscent of this putting of what's called a cumulative distribution function. And this is basically simply a sum of a bell curve. And you get this S curve by summing up the bell curve. So using different parameters for the mean or the standard deviation, you get different steepness of S curves between this mustard-colored curve and this green curve.

And so just to point out how that is the sum of these bell curves, those S-shaped curves come from these green, and mustard, and blue, and red bell curves. The reason why this is important is because this is an idea about how innovations diffuse, that you may have seen this famous curve called the diffusion of innovations curve that was coined by Everett Rogers. And you may have heard this phrase, "innovators and early adopters."

And he adopts this idea of a bell curve of different people or different organizations willing to adopt technologies in different ways. There's innovators and early adopters who are first. There's an early majority, late majority, and there's laggers. And if you take this bell curve of behaviors and add it up, you get this distribution, this S-shaped distribution of adoption.

And that's really what we want to talk about today because if you look at this S-shaped curve, this is a curve from a *New York Times* article by Nicholas Felton. And you can see that our adoption of different technologies over the last century have essentially followed this S-shaped curve.

We have electricity which has a kind of bump here in the 1920s, but looks roughly S-shaped. You see rapid adoption of refrigerators. You see rapid adoption of color TVs. And the point of this column by Nicholas Felton a number of years ago was that these curves get increasingly steep over time.

Of course, we can't assume that this is a causal process, or this is a inevitable or ineluctable process. Obviously, some of these technologies like clothes, dryers, microwaves, color TVs, cell phones, computers, VCRs, could only exist if electricity existed beforehand.

You see the track of the telephone has a much more mixed, not S-shaped curve. So we shouldn't assume that a S-shaped curve is inevitable or ineluctable, we obviously have to do things to adopt these technologies. The progress of our technologies may not be completely predictable or linear.

But the point I want to make about solar power is that solar power has declined by price by about 90% in the last 10 years. This is, again, that graph from Our World in Data. And the key point of this being part of your renewable toolbox is that you want to work with technologies that are getting cheaper and also happen to be cleaner.

So if you look at all the energy or electricity generating technologies on this graph, again, nuclear's gotten more expensive. Coal stayed relatively flat. Gas has gotten cheaper, but not as quickly as solar power has gotten cheaper.

Solar thermal towers, the concentrating solar technology I showed you a few slides ago, that kind of awesome installation in the desert, though it's awesome in how it looks, it has not necessarily gone cheap as quick as the humble solar panel.

And, also, of course, onshore wind has declined rapidly over time. And, again, if you look at these curves, you can see that lithium ion batteries since 1992 are also steeply decreasing in price. And I think I said in the last lecture that this is called the learning rate.

For every doubling in cumulative capacity, price has declined an average of 18.9%. Solar technologies, electrolyzers, are also following a very rapid curve. And, again, the key point is that, yes, coal is a dirty fuel. But nuclear is also a low carbon or clean resource.

I would argue that nuclear will probably be a critical or important firm resource for the future. But the problem is, our existing ways of building nuclear power plants have only gotten more expensive over time. They've not demonstrated any learning rate, whereas solar photovoltaics have a learning rate of 36%.

Offshore wind has a learning rate of 10%. Onshore wind has a learning rate of 23%. And lithium ion batteries, which are crucial to electrifying vehicles and all of our electronic devices, have a learning rate of 19%. You can perhaps, if not count on it, assume that some of these learning rates will continue in the near future that will only make these technologies more competitive in the near future.

And so a key question is, why have the solar prices declined? This is a topic that my colleague Jessika Trancik at MIT has studied. And she studied in a 2016 paper all the various factors leading to these declines in solar prices, or this learning rate.

And it's also important to point out that, as the Nicholas Felton graph I showed you a few slides ago, it's not necessarily ineluctable, or inevitable, or fated for all these things to happen. But it is a little strange, and it is a little weirdly wonderful how they follow a fairly consistent pattern, even if different factors are leading to these price declines.

For example, in Jessika Trancik's paper she decomposes the sources of price decline from 1980 to 2001, from 2001 to 2012, and the overall effect. And so she finds that the overall effect, the biggest contribution to solar prices declining is the efficiency.

Nonsilicon material costs have also improved. Silicon prices themselves have improved. The usage of silicon has improved. The wafer areas have improved. Plant sizes have gotten bigger. The yields have gotten better. And there's been slight impact on price.

But you can see from 1980 to 2001, and 2001, 2012, a lot of these different factors play in at different times. In other words, for some reason, we have these fairly steady declines in solar, though they're not completely linear when graphed on a logarithmic graph.

But it's also weirdly wonderful how all these different factors play together. And when one part of the industry improved in one part of the technology, other parts of industry were then able to, let's say, improve others. For example, Germany was a pioneer in solar until China pioneered large-scale manufacturing of solar panels.

If we break down some of these changes and attribute them to larger categories, you can see that there's an overall effect of public and private research and development funding. There are some effects of learning by doing. The more you do something, the better you learn how to do it.

Economies of scale-- the more of something you build, it actually gets cheaper if you build it in large volumes, and other factors. But, again, between 1980 and 2001, and 2001, 2012, you actually see the really different contributions from these different factors.

And so another question is, will solar prices continue to decline? And this is that learning rate graph showing solar actual asset costs by year. This is from a recent paper by Way, Ives, Mealy and Farmer. And what's really entertaining about this graph to me is that you can see the different projections for solar costs.

And the important thing about this graph is that, in every single case, the empirically-observed capacity cost has been lower than the projected costs. In fact, for some reason, a lot of integrated assessment models keep on projecting that solar is not going to get cheaper faster. They have a shallower curve.

But in reality, solar has gotten much cheaper much more quickly than anyone ever projected in the first place. The authors of this paper argue and forecast that solar prices will continue to get cheaper because they look at other empirical cost declines over time.

If you look at wind, wind has been on a similar trajectory of decline. And in all of these cases, many models keep on predicting that wind is going to cost more than it actually has. So this leads to the question, if solar and wind continue to get cheaper more quickly than we expect, what might happen in the energy transition?

The authors of this paper actually argue that there could be a fast transition between clean energy and fossil fuels, a slow transition, or no transition at all, where fossil fuels remain in our energy system. And clean energy simply adds to it.

But they actually argue that based on the probability of technical and technological process, which could be low, medium, or high, we'd actually save quite a bit of energy if we had a fast transition to renewables. That would actually result in less costs in this scenario than it would if we continue to use fossil fuels.

And that's assuming that solar and wind prices continue to get cheaper. If we have a slower, medium transition, then we will still save money over a no transition scenario. It just won't be as much. And it won't be as fast.

If you look at some of the price breakdowns of solar installation costs, this is, again, the cost to actually install and get solar running, you can see that NREL did a study in 2015 looking at benchmark prices and price breakdowns. And you can see in a lot of these cases, that residential, small installations are much more expensive than commercial large installations, or utility-scale installations.

But when I point out to you is that the actual hardware, the solar module, the inverter, the rack, and the balance of system, are actually not much different between residential and commercial and utility-scale installations. The panels are basically the same panel.

It might cost different amounts to mount them and put them in a rack. But the costs are not very different between even a single solar panel on a residential house versus utility-scale solar. The big difference is between the soft costs.

The labor is slightly higher to install on a residential house, probably because we haven't achieved economies of scale or large volumes. But the soft costs are a big difference. Why residential? Rooftop solar is much more expensive than utility-scale solar.

And so if I had to urge urban planners in cities to work on one problem, I would argue that if we were to-- if we were able to decrease the soft cost of installation, then rooftop solar could be competitive with utility-scale solar installations.

And so NREL also did a study in 2018, showing a road map to achieving cheaper solar electricity. This shows the 2017 real levelized cost of energy, something we've talked about in this class before. This shows what the goal is, $0.05 per kilowatt hour for a residential PV system.

And it shows that the roadmap for cheaper rooftop or residential solar goes entirely through soft cost reduction. This is a waterfall diagram again. You can see all the things you can do to get to the goal. But, obviously, the bulk of the savings comes from reducing soft cost.

That's reducing permitting. That's reducing design costs. That's reducing design complexity. It's making permitting easier at city hall. If urban planners and policy makers were to focus their attention on this, we could have equally cheap rooftop solar. And that would probably not have the same land-use impacts as utility-scale solar.

Now, let's go to the MacKay graphs for a second, MacKay papers for a second, because I think they usually show points about the energy density per area required for renewable technologies. This brings us into talking about siting.

This is a graph of a vertical axis and energy consumption per person the population density of people per square kilometer. And you can see, the world has generally in the last two centuries, both consumed more energy and gotten more dense.

The United States had higher energy consumption at the beginning and lower population densities than the world. Developing countries tend to have lower energy consumption and higher population densities. England, over the last four centuries, has gotten to very high energy consumption per person, though not as high as the US, but much higher population densities than the US.

And what MacKay does is graph simply where we are currently. This is the United States. And he uses this graph to show that if you multiply these factors together, you can get these kind of isoclines, or these gradient lines.

And you can see that the energy consumption of the US and the size of the circle is the population of the country is basically approaching what can be provided by energy crops, which is to say, given this energy consumption per person for the US, and given this population density, we could supply all of our energy needs with energy crops, assuming we use the entire United States for energy crops.

If we add other possible technologies, you can see the limit for wind power is further out. Of course, that would require us to use much of the US for wind power. And the US has enough energy density. So we would have to use the entire country for wind power.

But you can see countries like Germany, the United Kingdom, and Japan, are already at the limit for what wind power can provide. South Korea does not have enough land to provide all of its energy through wind power. If you look at these other technologies that MacKay discusses, solar PV parks in sunny locations or northern Europe are concentrating solar power.

You can see that they have lower energy-- the higher energy densities or lower land take. So the frontier gets pushed further out. So for one of the students from Singapore, he asked how much, what technologies could we use to supply Singapore?

You can see that it's possible to use the UK sun before conversion-- sorry, and the desert sun before conversion. Those are things that the population and energy consumption of Singapore would fit into. Obviously, it's not entirely possible to convert all of Singapore into energy production. But this gives you a back of the envelope estimate of how much energy, or how much land you need to provide that energy.

And so this brings me to the paper by Carley et al 2020, which focuses on energy infrastructure and NIMBY-ism. And let's just start with what is a systematic literature review. A systematic literature review is a paper where you set particular search terms and parameters.

You extract the relevant academic literature. The reason why you do this kind of literature search is that there's just too much literature to read. So we occasionally write papers to summarize what's been written. And then you code and analyze and summarize all the papers you find. And you categorize the vital data they use, what kind of methods and findings they come to.

And so the findings of this particular systematic literature review is that on page 1 they say, knowledge, trust, and positive perceptions of the benefits of projects are positively correlated with support for projects with variation across energy types.

They actually say that we don't focus on the positive aspects of energy projects enough. And our study of energy infrastructure and often NIMBY-ism were often focused on some of the drawbacks of these policies. And people ask, or asked in survey literature, much more about the drawbacks.

And so, and also they find in this paper that in our assessment, it's not clear that NIMBY-- which stands for "Not In My Backyard"-- traditionally defined is often being evaluated. At best, we have a set of inconsistent findings regarding the weight that people give to the proximity of energy infrastructure.

And, finally, they say on page 13 the high rates of support or found literature may seem to contradict what is often portrayed as significant opposition. And so this leads us to the question, how much opposition is there really to energy infrastructure?

Do we actually have significant opposition to energy infrastructure? We have a million anecdotes about this happening in many places. But this paper is trying to get at the existing survey literature, summarizing a lot of papers, trying to understand, what is the actual opposition? Does it actually fit into our definition of "not in my backyard" sentiments?

And so I like this graph. Actually it's in this paper quite a bit. It's a way of summarizing the papers. They look at these independent variables, whether or not they're considered in the literature, terms of knowledge, gender, trust, benefits of energy, and drawbacks of energy infrastructure. And they look at the total portfolio of energy types.

Total portfolio-- and then that's composed of wind, solar, nuclear power plants, fossil fuels, and transmission and distribution lines. And the red, yellow, and blue columns represent percent of papers that include this factor, the percent of papers that find it to be statistically significant, and the percent of papers that find it to have a positive effect.

So what's important to note from this graph, what I want to point out, is that wind, solar, nuclear, fossil fuels, and transmission lines have very different profiles in terms of who supports it. Not many researchers have considered asking people about their actual knowledge of wind projects.

But if you include a gender variable, you'll often find that one gender, I'm guessing female, is actually quite supportive of wind projects. Not all the papers find this as statistically significant. But almost all the papers find this support of gender to be a very strong factor in supporting wind power.

If you look at a different technology, let's say, nuclear technology, only about half of the papers asked people their actual knowledge of nuclear power. Only about 50% of papers find it to be statistically significant. And, actually, they find that knowledge of nuclear power is quite positively correlated with support for nuclear power.

At the same, time if you include gender, almost 100% of the papers include gender. 2/3 of them find to be statistically significant. And they don't find a strong positive effect of gender sentiment about nuclear power. What I'm trying to point out this graph is that all of these factors, knowledge, gender, trust, benefits, and drawbacks, have different profiles.

Some of these technologies like solar have extremely positive correlations with the benefits of solar power, whereas the drawbacks are quite often asked about and have very little difference in how people feel about solar power. What I encourage you to do is just look at this graph. Look at these different factors on the top. Look at the energy technologies. And think about how you might appeal to different people to support different technologies.

Obviously, the profile for fossil fuels is quite different than the profile for transmission and distribution lines. And so we should think about this research, and think about how to use it to get people to support these different technologies that we do need.

So another paper I want to talk about is written by my colleague Larry Susskind at MIT. It's just written this year about sources of opposition to renewable energy. And to summarize this paper, a team of students-- many students I know from our department-- helped build this database of opposition to renewable energy projects.

And they did this by reviewing open access media reports and published scholarship to identify instances in which conflict or opposition paused, delayed, or canceled a utility-scale renewable energy project. There were media reports on projects that had been defeated, including some concerns about these projects that did not lead to stoppage or delay. They did not include these in their study.

So essentially what they did is they went and looked at media reports, and looked for projects in which there actually had been delays or opposition. What they find in this database, they find 53 projects equivalent to 9,586 megawatts that were affected.

They find that 34% of the projects were delayed. 50% of the projects were canceled permanently. And 26% of the projects were resumed after being stopped for several months or years. In terms of the energy transition, this is a very concerning finding because we know we need to build solar and wind much more rapidly than in the past to achieve our decarbonization goals.

And they have seven distinct hypotheses regarding the sources of opposition and barriers to renewable energy development. First, communities could be expressing concerns about possible environmental impacts, including impacts on wildlife. There could be challenges to project financing and revenue generation.

There could be public perceptions of unfair participation processes or inadequate inclusion in light of regulatory requirements. There could be a failure to respect tribal rights, including the right to consultation. There could be health and safety concerns. The intergovernmental disputes. And there could be potential impacts on land and property value.

In the paper, one of the notable findings, I think, is that they find that most opposition to projects is not composed of a single source of opposition. As they characterize it, only 20% of the sources of opposition have one rationale or one basis for opposition. Most projects represent multiple concerns or multiple sources of opposition, or a collision of different groups that may be opposed to the project.

Now, this is a very concerning finding in terms of what we are going to be able to site in terms of our future renewable energy projects. But one thing I actually noticed about this paper is that I actually thought back to other studies I've seen.

This is a graph from the US Energy Information Administration. And this actually shows how much generation capacity we've added over the last 22 years. In 1990, you can see that our energy, our renewable energy generation is actually dominated by hydroconventional and hydropumped storage.

Even by 2005, we had very little wind and very little solar. And by 2021, 16 years later, we basically had this massive explosion of wind, and this very rapid explosion of solar that is probably only increasing this year also. But what I realized when I calculated this is that you had this question about whether the findings of this paper are generalizable.

The Susskind et al paper finds 53 projects over the years 2008 to 2021. And that basically is 9,586 megawatts, which is 9.6 gigawatts. But from that graph I just showed you, the Energy Information Administration finds roughly over the same period of time 2005 to 2021, that we added 185 gigawatts.

So if you calculate the percentage, essentially the Susskind paper is looking at 5% of the projects. And so there's three perhaps stupid questions that we need to ask about this question of permitting and sources of opposition to renewable energy.

First, how big is the problem of permitting? If these opposition sources are expressing themselves through denying permits for projects, we can find 5% of the projects have been blocked or opposed, does that mean that our other 185 gigawatts of projects that were built, could we have had another 185 gigawatts of projects if 50% of the projects were canceled?

Or do we find in this case the projects that were canceled or opposed, and the vast majority of projects are actually built without as much controversy? And so this brings me to the question of permitting reform, which we started the class, which is discussed quite a bit in Congress, and we in class. How pervasive is this problem?

And, finally, are the future problems we're going to have around sources of opposition or permitting similar to the past problems that have been found in this database? Those are all open questions for us to consider in class discussion. I look forward to seeing you in class tomorrow.