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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 an associate professor of Urban Studies and Planning at MIT. And this week, I want to talk about cities, and buildings, and energy efficiency.

The class materials or the materials for class discussion on Tuesday are in the syllabus. We'll talk mostly about the MacKay reading today-- the first bullet point. But we'll talk about the other readings in class on Tuesday.

And I really want to start with this quote. You may have heard this quote before. It's from Winston Churchill.

It's in a speech he gave after the bombing of the House of Commons after a raid in the London blitz. And he says "We shape buildings, and afterwards our buildings shape us." At the time, they're discussing how or whether to rebuild the House of Commons after it was hit by a bomb, but I think it's an evocative quote that gets used quite often to describe what the influence of buildings on culture is.

And I've had a lifelong fascination with architecture. And so what I want to focus on today is how buildings reflect many different things. Energy efficiency is not usually at the top of anyone's list of concerns.

And at the same time, I hope to convince you that buildings are an incredibly important problem that we need to tackle for the energy transition, and also argue that there's ways that we can shape buildings that will shape our later energy-using behaviors.

And so just to give you a few arguments about why buildings are so important for energy use and climate change, in terms of operational energy, buildings are about 35% of the primary energy used in the world. They are responsible for about 38% of greenhouse gas emissions worldwide. And it's also worth noting that for cities in particular, the subject of this course, buildings are a much higher percentage of city emissions.

In New York City, buildings represent about 70% of the greenhouse gas emissions, though we also have to be aware that this is also reflective of, as I've said before, New York City being a financial center. In Singapore, buildings are only 20% of greenhouse gas emissions because Singapore has a surprisingly large industrial base, specifically of liquid natural gas processing.

But in terms of embodied energy, also, their construction represents a significant additional portion of their energy use and greenhouse gas emissions. The building construction industry is responsible for about 5% of the primary energy used in the world, 10% of emissions. And it's also worth noting that in cities like New York, many of the buildings that are already there here in 2022 are going to be there for mid-century goal in 2050.

So a key part of our challenge for addressing buildings is retrofitting the existing buildings we have. New construction may be occurring in other cities that are faster growing, but New York City is already quite dense. We actually need to figure out how to retrofit the millions of buildings we already have in New York City.

It's also important to note that buildings shape our health. And we're quite concerned about how buildings affect our health. This famous statistic from Lawrence Berkeley National Laboratory using the American Time Use Survey basically asks people how much time do they spend and where. And they find that people spend about 87% of their lives indoors and about 6% of their time in enclosed vehicles, but 93% of their time is essentially spent in spaces that could be air-conditioned or affected by air conditioning.

Of course, after three years of COVID we don't probably need to reinforce this point too much, but COVID and our concerns about ventilation have fundamentally affected our desire for real estate. Recent research from the San Francisco Fed that Paul Krugman has written about is essentially looking at inflation and the contribution of real estate to inflation. And he argued, I think quite convincingly, that there's a secular shift in what people want.

People need more space for Zoom calls, for *spending* their time at home. This ties into the remote work trend that we talked about last week. And of course, we should not forget that there's always a crisis, or there is an increasing crisis in providing affordable and sufficient housing, not only in this country and in our major cities, but in many countries also. So when we talk about buildings, we need to think about what we're trying to provide, fundamentally, is a habitat or shelter from the environment. But how we do that has tremendous implications for energy use and climate goals.

And so finally, what we'll talk about in this lecture is mostly the MacKay reading. He focuses on how much it takes to heat, cool, and use various appliances. And we're really trying to get at some underlying questions.

How much energy is used in buildings? How much more efficient can buildings be? What specific activities in buildings lead to energy use? And we will examine whether or not it leads to energy waste. And finally, how can we motivate individual users to save energy in buildings?

So just to highlight for a moment the role of buildings in the economy, this is our familiar Sankey diagram, the US energy economy being roughly about 97 quads. If you look at the final uses here, the final uses for buildings are generally categorized as residential and commercial put together. That's about 20 quads, which means it's responsible for about 20% of the total energy going into the economy, and about 30% of our final uses if you take these two as a proportion of all the various pink boxes representing final consumption.

Of course, as a proportion of electricity use, residential and commercial buildings actually tend to use a much larger proportion of the energy-- it looks like north of 70%-- because industrial uses and transportation tend to use fossil fuels like petroleum and natural gas or oil. So most of the electricity that we generate actually goes into buildings. And just to highlight what the users' uses of energy are in our buildings, this is a Sankey diagram specifically for buildings, specifically for commercial buildings.

And this is actually a relatively old report from Pacific Northwest National Labs. But I'm guessing it hasn't changed too much over time. And if you look at this, we have input coal, natural gas, petroleum, natural gas. And this is all going through electric utilities.

And these arrows here on the bottom are natural gas, petroleum, and biomass going directly into the commercial building sector. And you can see all the uses here on the right. We will focus in on this further.

And if you look at what the total energy that's delivered to commercial customers is, you can see that it's really a grab bag of many different energy uses. Half of it looks like electricity. Half of it looks like fossil fuels that are combusted directly on site.

And you can see that a significant portion of the uses are for space cooling, ventilation, lighting, refrigeration, office equipment. And then most of our natural gas goes to do space heating, water heating, and other uses-- also cooking. The petroleum or coal is still used in many countries, but less so in the United States.

It's almost all entirely going to be space heating and water heating. And then there's a portion of biomass. That's essentially wood stoves, which is this little sliver here.

And of course, the smallest sliver is unfortunately renewables now. But we hope to perhaps increase that as we have energy generation in homes occurring at a greater scale with rooftop solar. If you look at the residential sector, again, we have electric utilities here at the top. And we have the direct delivery of fuels at the bottom.

And you can see if we focus in on residential buildings from this Pacific Northwest National Lab report, you can see again that there's many different activities occurring in buildings-- space heating, cooling, lighting, refrigeration, and so on. All of these are the same. Wood solar is a larger portion of the energy use for residential buildings than it is for commercial buildings.

But this is to point out that buildings are highly integrated objects or tools that have basically been engineered for lots of different things. They provide shelter. They provide habitat. They provide home.

This is where we live, work, play, entertainment. And so we have lots of different uses we're trying to accomplish. And what we want to do is also reduce the energy use or greenhouse gas emission footprint of this sector.

Just to give you a final sense of the importance of buildings, if you look back at the Williams et al. 2020 Deep Decarbonization Pathways or Carbon Neutral Pathways in the United States, again, we have this 2020 reference case, this 2050 100% renewable case. But if we want to achieve decarbonization, or 100% renewables, we essentially need to decrease our electricity use by half. That has to become much more efficient by use of heat pumps and other more efficient technologies.

We essentially have to eliminate our use of natural gas pipelined into homes. We need to actually increase our biomass use through electricity mostly. And again, we have to make our homes much, much more efficient, or make our buildings much, much more efficient.

So the key message to take home here is that we actually have to use half as much energy. And the half that we do use has to become much more efficient.

So just to give you a sense of how we actually lose energy to the environment, and why are we continually having to heat and cool our homes, there's basically three ways that heat transfer occurs. This is how our heating energy is lost or what we call our heating load. There's three ways that we gain or lose heat from the house in the environment.

It's either ventilation, through conduction, infiltration, which is air moving in and out-- essentially, a drafty door or drafty window loses energy to the environment because our warm energy is being leaked out to the cool environment. Or if it's hot outside, we're losing the energy we use to cool the air outside and equilibrates to the environment. Or there is conduction, which is where the heat actually is conducted out through materials.

Molecules excite, basically, the neighboring molecules. This is what happens to your external sidewalls and the ground slab or the roof. And then radiation-- this is essentially a process where we do gain some heat, let's say, from radiation being absorbed by homes. But also, we know when our houses are warmer than the environment, they're radiating heat to the environment. And there's a good paper that gives a detailed breakdown for some of these fundamental physical mechanisms if you're more interested in that.

And the key point that I like that MacKay makes is that conduction and ventilation depend on the temperature difference between inside and outside temperature, while radiation depends on the area. So you have this basic breakdown of some of the factors involved. Conduction is area times a U value times the difference in temperature times time.

Ventilation is the volume times the rate, I think, that the volume is being moved out-- or sorry, the number of ways the energy could be lost times delta T times time. And radiation is area times solar intensity. Of course, the way it's written here in MacKay is to highlight the fact that conduction and ventilation both depend on the delta T, the delta temperature times time.

And so this is how MacKay basically breaks down how his house lost energy in 2007 and how he tries to tackle this problem of energy efficiency. It breaks down the horizontal surfaces to the roofs, the floors, vertical surfaces to the walls, thin walls, glazed doors, windows, double glazed windows, and then calculates the leakiness-- that is, the number of air changes per hour. So you can calculate the meters squared in terms of area.

The U value is an indication of the power transfer depending on difference in temperature. So it's watts per meter squared divided by degrees Celsius. And that gives us the leakiness if we multiply area times U value of watts, which is the power being lost for every degree Celsius difference. And with the ventilation, we have the number of air changes per hour.

So we have a volume of 80 meters cubed in the bedrooms. We want to change the air in there half every per hour or change the entire room volume once every two hours. And that gives us the leakiness in terms of watts per degrees Celsius.

What MacKay calculates is that the main ways that he loses heat in his house in Cambridge, the UK, which is similar to the climate of Boston, is that he's losing about 78% of its energy through production and about 22% of its energy through ventilation changes. And so what he does to try to reduce the energy loss of this house is to add cavity wall insulation. He increases the roof's insulation.

He adds a new storm door and replaces the back door and window with double glazed windows. I want to emphasize here that energy efficiency is not necessarily a high tech endeavor. It can be a high tech endeavor, but at the same time, all these things that he does in 2007 are fairly simple things. This is essentially a technology that you can acquire from your hardware store.

Having said that, there are startups that actually drive cars around, like the Google cars that do street view. And they actually measure the conductive and radiative losses of houses using infrared cameras or guns. And so you can basically drive around and map out the city from the street, and see where people are losing energy. And there's a number of energy startups I think that are trying to use that technology to try to identify homes that might be-- to essentially acquire customers for energy efficiency.

So just to give you a sense of what's possible with energy efficiency measures now, this is from an old report. I think it's from one of the national labs. And this shows, actually, we have an R value, which is the resistance value, or 1 over the U value, 1 over the weakness. And you can see that the technologies here are basically net energy losers, but they are increasing amounts of resistance over time starting in 1970, going to 1990.

We have very poor single pane windows. We get a much better improvement from double pane windows. But we're getting to low E windows, super windows, and super windows that are essentially net energy losers, but we're decreasing how much we're losing. And projected time, I guess, in the last 10 years-- we're expected to get to a very high resistance super windows. And so I'm not quite sure of the current state of technology, but I suspect that we are well above where we were with double pane windows.

Just to give you a sense of some of the R values included in a model building code, one area that I've said to you that local governments and cities can actually do a lot of work, or implement policies that actually change the building stock-- are their building codes. All of our buildings have to be built to a fire code, an electrical code, and in the places that have earthquakes, a seismic code. These are the fundamental codes that govern how our buildings are built.

In Florida, after Hurricane Andrew in 1992, it actually developed some of the strongest building codes in the country because the hurricane revealed that relatively simple interventions in the building code would result in much better and stronger homes. But this is also a key area where local governments and cities have jurisdiction. They're allowed to actually implement building codes in a way that the state and federal governments cannot.

So just to give you a sense of the R values in model buildings based on what two International Energy Conservation Codes require, there's a code from 2000. There's an upgraded code in 2012. And there's proposed changes further.

This has been a key area of research in the last 10 or 12 years. The federal government, since the ARRA stimulus in the Obama administration, has pushed building codes very hard to improve very quickly. So you can see that the R values of ceilings have essentially doubled from 2000 to the proposed code from this Golbazi/Aktas paper because see that above ground walls have essentially tripled in their resistance to heat losses.

Basement walls have essentially doubled. Floors have doubled. Roofs have doubled. And mass walls have developed a code value for the first time.

These are all ways that when the local government simply specifies you have to build to this standard that the local development industry and contractors have to respond to that. So this is why I had you calculate heating degree days in the problem set. If you look at MacKay's house, he shows that in Cambridge, which again is similar to the climate of Boston, for most of the year, you can see that he's doing heating in his house.

He has 3,200 degree days of heating and about 91 degree days of cooling required. If you look at, I think, what happens after his energy efficiency installations, he goes to about 2,200 or 2,300 degrees days of heating and is unaffected by cooling. So this is to say that if you simply change the base temperature, which is what I did, which you did in the problem set, you can actually reduce how much time is heating, which is to say that we measured everything against the temperature we'd like to keep our indoor temperature at.

So this looks like around 65 degrees. And this is about 2 degrees Celsius lower. And if you simply change the thermostat setting, what you're trying to target for maintaining indoor temperature, you can actually significantly decrease the amount of heating or cooling required to make up the heat loss. Remember that we looked at conduction and radiation dependent on the delta T times time.

If we change simply the delta T that we're trying to heat or cool to, then we can reduce a lot of our heating and cooling energy use. This is also why there's a very large push on heat pumps. This is a diagram from a book from Randolph and Masters. And they basically have this very simple diagram that I like.

It basically shows how a refrigerator acts as an air conditioner, but it heats the world. We're air conditioning the space inside a refrigerator. And the back of your refrigerator is rejecting heat.

Of course, we can flip this thing around. And we could actually cool the outside world and heat the inside of our house. This is essentially how a heat pump works. It's the same thing as a refrigerator.

It's the same thing as an air conditioner, but the key difference in a heat pump is you can operate it in both directions. I think I told you the story before of research I did in Brazil that looked at electricity use in informal settlements. In informal settlements, a lot of people don't pay for their electricity use. 40% of all electricity in Brazil is unpaid for or stolen from the grid.

And so people actually have very little incentive to save energy. So people use their refrigerators not only to store food or to even cool their home because they can just leave the doors open, but people actually use refrigerators to dry clothes. They put dry clothes on the hot condenser on the back, or the heating coils, or the radiating heat fins. And those actually radiate heat.

And they use them to dry clothes sometimes. So there's been a very large push in policy now to use heat pumps because unlike burning fuels directly, you actually get about four times the heating or cooling effect for the same unit of energy in a heat pump. And so the MacKay book explains why heat pumps are what we're talking about in terms of why we're generating more heating and cooling energy has to do with entropy.

The MacKay book goes into more detail if you're interested in that. Emphasize why we are trying to treat our climate-- I think instinctively, we know that the United States is defined as quite different climate zones. We have a marine zone, or almost Mediterranean zone on the West Coast. We have our very hot, dry, or mixed dry environment.

We have cold or very cold environment in the upper Midwest, Upper West, and New England. We have a mixed humid climate. And we have a hot, humid climate.

The reason why this matters for building design or building engineering is that engineers actually use charts that are called psychometric charts. And those are charts that actually detail how comfortable people feel in mixes of humidity and temperature. So the reason why we look at these different climate zones is that we know our energy use is closely related to the humidity and temperature of the outdoor environment.

And that's what our buildings are trying to correct for. So we know that in hot, humid environments or hot, dry environments, we use much more air conditioning. We may use dehumidifiers, or our air conditioners may have to work differently to account for this humid environment.

The US EIA also defines these climate zones in slightly different ways, but you can see here on the bottom, they define their zones in terms of how many cooling degree days and how many heating degree days our buildings use. These numbers actually factor into how we measure Energy Star ratings on buildings because we rate buildings according to how effectively they're heating or cooling relative to the environment, but we also know that our commercial buildings for Energy Star are located in many different environments. So we try to score them differently.

So just to show you, the reason why I had you look at your appliances briefly is that MacKay estimates the loads from various electrical appliances. And you can see it's a pretty simple calculation, OK? We have these different categories-- cooking, cleaning, and cooling. They have a power use, which is kilowatts or joules per second.

We simply multiply times a unit of time-- here hours. And then we get kilowatt hours, which are a measure of energy per person per day. And so we just multiply it in a spreadsheet.

You can see that the largest users of energy are the tumble dryer, the freezer, the electric oven, and the electric cooker. You can see, on an annual basis for two people, you get about 4,500 kilowatt hours per person per year. That's actually relatively low. I think in the US, the average household uses about 14,000 kilowatt hours per person per year.

So you can see the average electricity consumption in the United Kingdom. It tends-- are relatively lower. One reason for that might be that MacKay's house has a party wall, it's built quite densely. It's a relatively small home by American standards.

So just to show you what some of the technologies are that might help us understand how we use energy in buildings, I'm going to show you some of the devices I use to manage my own home, mostly out of interest and because I like to show students every year what some of these different technologies look like. OK. So just to show you what some of these technologies I use to manage my home look like, I'm going to show you-- this is a Sense monitor.

This is actually a small monitor that I installed in my electrical panel box. And it basically measures the entire energy use going from the electrical grid into my house. You can see this is a typical day from 6:00 AM to about midnight.

And you can see several different things happening. First, energy use is pretty low in the morning before we wake up. What it measures-- you can see what I'm moving here is the current meter. This measures 500 watts going into the house.

You see these occasional small cycles. That's probably a refrigerator cycling to keep the food cool. And then we wake up, and we start running a lot of our appliances. Things go very high. That could be the tumble dryer coming on in the morning.

It could be a hair dryer coming on. And then this is probably a dishwasher load that we set when I leave for work. You can see throughout the day when we're away at work or at school, our energy is quite low. Again, these are refrigerator, cycling, going through.

And then you can see we get home around 6:00 PM. And then we start turning on lights, turning on cooking devices. And our energy load goes up quite high again. And we probably run the dishwasher or the tumble dryer at the end of the day again.

This is a small box that goes into the electrical panel. It gives me a handy dashboard. It tells me how much energy I'm consuming relative to my bill.

Much to my frustration, it shows I'm totally average in how much energy I use compared to other similar homes. I use less than other Sense homes in Massachusetts. And I use less than most Sense homes all over the country, but it gives me some useful ways to manage my energy use.

It shows me when pumps or heat goes on off in my house. And it also shows me when certain appliances are on or how much they use. For example, "always on" represents the vampire load. These are all the chargers that are plugged into all the walls all the time.

This is a point that MacKay makes. But it also shows me how much each of the AC units use. It shows me how much that applies on a bill basis. It shows me which appliances use the most.

And it shows me ways that I could possibly reduce my energy consumption. Here you can see that my clothes dryer cost about $41 per year, 6% of my electricity use. And you can see how many times or how often I put it on.

Another device that I use to manage our home electricity use is a Nest thermostat. You can see right now, the downstairs is set for 65 degrees. Upstairs is set for 63 degrees because we're not upstairs during the day very much.

If I click on one of these, you can see that I have a schedule that changes throughout the day. Obviously, I want it to heat it while we're awake. And I like to have the house cold when we're asleep.

But also crucially, it's useful that when you go, let's say, to the airport and you're on your way to a trip, you realize, oh, I left the thermostat on. I can actually turn the energy down in my entire house remotely. Finally, I have rooftop solar panels. You can see here in the middle of the day one set of panels that are facing the east are still getting a lot of power.

But slowly, as the sun moves over the top of the house or the roof line of the house, all these panels here on the right are going to get more energy. And it's cool. You can actually see on a weekly basis how much energy, how much energy is being used.

And you can actually see throughout the week, I got a nice sunny day with lots of solar energy, maybe a cloudier day with less solar energy, and more solar energy throughout the day the last few days of the week. There are fancier setups for people. A lot of electrical energy engineers like to calculate how much solar is coming into the house, and how much they're using.

I clearly don't have all these systems integrated. But this is to point out that all the data we need to manage our energy efficiency uses is much easier to get. It involves installing one device on my electrical panel, and involves managing my thermostats, communicating through Wi-Fi. This is my solar panels communicating to the internet and sending information to my computer or web app.

OK. And the last point I want to point out, the last point I want to make is that a lot of this information that you need to measure your energy use is actually on your electricity or natural gas bills. I know we talked in class about only 1/3 of you get your bills because the 2/3 of you live in dorms, or let's say shared apartments. But if you look at your electricity bill, for those of you who get them, very carefully, you can see a number of policy implications on your bill.

There's various charges for energy efficiency, whether or not you access energy efficiency services. There's a delivery charge. There's a fuel charge.

We know all these different charges are changing over time because of our changing energy markets. And so I'll probably show you some bills in class. If only because there's privacy implications, I don't want to show them on this video. But let's just think about why buildings, again, are important in a global sense.

The International Energy Agency did a report in 2020 called "Tracking Buildings." And they point out that building energy use is not on track to meet our Paris Climate Agreement goals. So we focus on different aspects of the report.

We can see that lighting has actually been a relative success story. We had other forms of lighting and fluorescent lighting, but light emitting diodes, LED bulbs, have shot up remarkably-- almost to about 50% of lighting sales from 2010 to 2018, and about 50% of lighting sales. And they're headed for about 80%.

That is on track for us to meet our sustainable development scenarios or our Paris Climate agreements. LEDs are a success story because they're essentially developed with government research funding, but they required subsidies in the beginning. And then as they are produced in scale, they became much, much cheaper. I actually bought LED light bulbs in graduate school for, I think, about $50 a bulb.

And now, these bulbs have the exact same light quality as incandescent bulbs or fluorescent bulbs. But now, they cost $1 or less. So LED bulbs are an energy efficiency success story.

If you look at building envelopes, all the things that Dave MacKay did in his home to try to reduce induction, ventilation, and radiative losses, you can see that the IEA says we are not on track. Almost 2/3 of countries lack any mandatory building energy codes, meaning that many buildings are not built with any kind of code or any kind of energy efficiency at all.

This is similar to the number of buildings that are built with architects, which is only a small fraction of buildings built in the world. We know we have a lot of construction that people do themselves, either do it yourself, or in informal settlements. But those places are often not governed by energy codes.

So therefore, they're not energy efficient. And therefore, they're not using energy very efficiently in a way that is going to help us reach our Paris Climate Agreement goals. In terms of heating, you can see that we have fossil fuel based equipment, conventional electrical equipment, heat pumps, district heat, and other renewable sources of energy.

In order to meet our sustainable development scenarios, we need heat pumps to expand by a factor of probably four or five. And we need our use of fossil fuel based equipment, like the natural gas coming into our homes and spaces now, to decrease. We need conventional electric equipment to decrease because it's relatively much less efficient than heat pumps.

District heat is not actually predicted to expand very much. And the use of other renewables and perhaps hydrogen is expected to expand. But the problem is to meet our 2050 goals, or 2030 goals, sorry, we are not on track according to the IEA.

In terms of heat pumps, we need more efforts. Many households purchased heat pumps in 2019. If anything, that's probably expanded rapidly with the explosion in natural gas prices because of the war in Ukraine.

We know heat pump sales are going up very quickly. Some people have said that one of the biggest things we can do to try to reduce Europe's dependence on Russian gas is to send in heat pumps. We need to manufacture heat pumps as quickly as possible, but I can tell you from personal experience-- my home uses natural gas-- it is difficult to retrofit a relatively old home with a heat pump.

Or rather, it is not inherently difficult, but right now, even as somebody who's very interested in this problem, I have a hard time trying to figure out how to retrofit my 1925 home with a heat pump. So this is an area where contractors, architects, engineers, small businesses have a tremendous opportunity to increase the adoption of heat pumps. And this is an area where the Inflation Reduction Act gives a lot of tax incentives for homeowners to increase their use of heat pumps, which is why I included that ACEEE report for you to read.

If you look at cooling efforts, cooling is actually a big area of concern because we know that not only is the world getting hotter, but lots of places in the world that are getting richer, like sub-Saharan Africa or Southeast Asia, India, essentially, are relatively hot and humid climates. As those places get richer and more urbanized, there will be greater demand for cooling.

So the energy demand for space cooling is actually going up quite a bit. There's a space cooling intensity index in a sustainable development scenario. And we'd like our space cooling intensity index to go down, which is the amount of energy we use for cooling. The good news is if we're going to install air conditioning, we can simply install a heat pump and get both heating and cooling benefits.

And they're relatively more efficient. But the problem is in order to increase the use of heat pumps, again, for cooling, we need to make more policy efforts or more efforts need to be made across industry and government. And if you look at appliances and equipment, Energy Star, Energy Guide-- those yellow tags on appliances you might buy in the store-- equipment has become much more efficient than before, partly because of changes in technology and partly because energy efficiency codes have pushed the technology to become more efficient.

But in order for us to reach our sustainable development scenario in 2030, we still need to make more effort. Demand is being driven by rising ownership of connected plug load devices-- those are devices you plug into the wall-- especially in developing countries that are becoming wealthier. So we need to try to pass performance standards that govern how much energy all of our devices use.

And finally, there's also behavioral interventions we can make. This is an important thing I want to touch on today leading into next week's discussion. This is a paper by Tyler Marghetis, Shahzeen Attari, and David Landy that was published in *Nature* in 2019 or *Nature Energy* in 2019.

And the headline is simply that simple interventions can correct misperceptions of home energy use. And the reason why I had you look around your apartments and homes at how much energy things use and try to calculate it, and the reason I wanted you to look through Dave MacKay's home is that people don't have a very good sense, actually, of how much various appliances use. And if you look at this graph, this is the estimate that people give on a survey, a logarithmic scale on the vertical axis, and the actual energy use of these appliances on the horizontal scale, also a logarithmic scale, which means if people perfectly predicted the amount of energy use all of these different devices used, they'd be right on this dotted line.

But you can see for small devices like LEDs, they actually estimate they use more than they actually do. And for large devices like a central air conditioner, they actually estimate it using less energy than they actually do. Or else, they would be on this dotted line.

And so the key point here is that they actually do an experiment where they target the use of energy use. And they try to develop two interventions. First, they try to target how people respond by just giving people quantitative information about the extremes of electricity.

They tell people how much a phone charger uses, how much a clothes dryer uses. And they predict that this is going to help people understand or translate their beliefs into energy use into explicit estimates without necessarily changing their underlying beliefs about energy use. And that's relevant because we know we have very different beliefs about energy use and climate. The second thing they do is they target systematic understanding by supplying a simple, explicit, heuristic rule.

They say people underestimate the energy used by appliances that change the temperature perhaps because heat generation and heat removal may not be as noticeable as movement or lighting. So therefore, they give this explicit heuristic, this rule for people to judge energy use. They say large appliances that primarily heat or cool use a lot more energy than people think they use. That's all they say.

And they give people these two interventions and see how well they can estimate energy use. The reason why that's important is because our underlying beliefs about energy and climate may actually shape how well we can actually perceive energy use. These are all graphs that show the understanding of appliances' relative energy use on the horizontal axis, and to see how they're correlated with behavioral choice accuracy-- behavioral choices people make to change their energy use.

They see if it correlates with pro-environmental attitudes. They see if it correlates with climate change beliefs. And they see if it correlates with climate policy support.

And you can see that behavioral choice accuracy is actually relatively the same among liberals, moderates, and conservatives. But you can see that pro-environmental attitudes, climate change beliefs, and climate policy support all diverge. And so their point in this paper is that if you actually supply people with both this scale use intervention-- telling people how much energy appliances use-- or giving them an increased understanding of appliance energy use, they have different implications for who may be listening to this message and how they might act on these beliefs.

So they argue in this paper that if you increase people's understanding of appliance and relative energy use, you may be able to not necessarily affect their pro-environmental attitudes, or their climate change beliefs, or their support for climate policies, but at least you can correct their misperceptions of home energy use.

Finally, just to touch on the health aspect of decarbonization, this is a project I'm working on in indoor air quality in New York City. It's an interesting project because we're working on a low income or affordable housing building-- a subsidized housing building. And what the developer or the owner is doing is essentially retrofitting this building to be decarbonized.

They're upgrading it to passive house standards, meaning that they're wrapping the whole building in a highly efficient envelope. And they're decarbonizing the building by taking the water heating and the space heating out and installing basically heat pumps to the roof that will push air down to each of the apartment lines through these blue ventilation shafts. And of course, when the ventilation or the exhaust air comes out of the apartments, it'll come up back to this blue line and go through a heat exchanger, meaning that all the heat will be captured in the building even if we need to push in new fresh air for ventilation.

But we also have to think of the implications this has for ventilation and for health. We know that gas appliances produce combusted methane, but also particulate matter, and have a gas or chemical-- they release chemicals into living spaces. So what we're hoping to see in this project is by decarbonizing and removing the gas of the building, we improve air quality inside this building.

And so we put these air quality sensors in all these points in the building. What we are hoping to show is that not only can we decarbonize a relatively inexpensive or low income building, if we can decarbonize it, we also improve people's air quality inside their homes. So we're hoping for a triple win.

And that is applicable to any building. It is relatively cheap. It eliminates the greenhouse gas use in these buildings, and also improves people's health.

We've been doing a two-year field experiment, and we're almost done with it. So I'm looking forward to sharing the results with you soon. And that concludes our lecture for today.