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DAVID HSU: Hi, everyone, and welcome back to the MIT class on urban energy systems. Wherever you're seeing this lecture, please subscribe. You can either find it on the web page where you found this video or ask the instructor.

So let's get back to the topic for today, which is going to be cities and decarbonization. What is the role of cities? Again, I'm David Hsu, and if you're thinking about how cities can take action or what their role is in decarbonization, you have found the right place and your people.

So I want to cover just briefly how you're going to prepare for class this week. This is our second class. I want to make sure that everyone's caught up. First, the introductory reading from last week is fairly short and scalable. So it's easy to catch up, but you should catch up. And it's particularly important to look at MacKay chapter 2. Again, it's MacKay chapter 2.

There's the initial problem set due Monday night. You can just access the problem set by going directly to this Google form, the link on the screen.

You should do the reading for this week that's on the syllabus. I also show the reading for this week on the next page. And then you should watch the rest of this video lecture. And during the reading and while watching the video lecture, it's important for you to write down the questions that you have for discussion. And then I want you to feel free to share them on Slack, whenever, asynchronously, or in our class meeting on Tuesday.

So the material for today-- again, I won't go over them. These are all in your syllabus. But these will also be in the slides, so you can follow the links. The first four readings are the required readings, a kind of gathering of very different readings. And the last two readings are optional readings that give additional information to the articles above.

So what I want to start with is MacKay chapter 2, what he calls the balance sheet, and it's an important set of concepts simply so we can think about the energy system. And very simply, what MacKay is trying to do in his book is contrast these red and green bars. Energy consumption is on the left and red, and energy production is on the right in green.

And so when MacKay titles his book *Sustainable Energy-- without the hot air,* what we're trying to do is replace our current level of consumption with entirely renewable resources, and that's how we're going to achieve a sustainable energy system. And so a sustainable energy system would be if our total conceivable sustainable production sources, on the right, are greater than our total consumption. And an unsustainable energy system would be where our total consumption of energy is larger than our total conceivable sustainable production.

And, of course, these two bars will change over time as our expectations around consumption change and our technologies and our institutions and our markets for sustainable production change. But that's the challenge. The challenge is to try to put these two in balance and at least have total sustainable production that is enough to meet all of our societal needs, or our global societal needs, for energy consumption.

And so what that might look like is the key forms of consumption on the left-hand stack in red-- that is the energy we need for transportation, including cars, planes, and freight. It's the energy we need to heat and cool the spaces that we live in. That can wildly differ across countries. It's a basic need for lighting so we can see at night. It's a growing need for energy for information systems and our other gadgets.

The fifth point, food-- a tremendous amount of energy goes into growing and transporting and keeping our food cold. And, finally, the manufacturing-- for all the technologies or all the gadgets we need to do transportation or heating and cooling, like information systems and food, we have to make these things in the first place, and that requires a tremendous amount of energy.

On the right-hand side, our sustainable production stack has a number of categories. The good thing is-- and I'll try to emphasize this in the class repeatedly-- is that we have many sustainable technologies that can produce energy. We have wind and solar. Solar energy can be harnessed in the form of photovoltaic or solar cells that produce electricity. We can harness solar energy through thermal energy, and we can also harness solar energy through biomass, by harvesting the potential of the Earth to engage in photosynthesis, create crops that we then can use for other things, including burning in engines.

Hydroelectric power is producing electricity directly from-- or mechanical storage directly from-- hydropower. Wave energy and tide energy are two sources of energy that come from the Earth on a regular basis. Geothermal energy also comes from the Earth. The heat inside the Earth can be harnessed to produce energy.

And finally, nuclear, And MacKay puts it with a question mark because it's not clear whether or not nuclear energy or nuclear power counts as sustainable. It is low carbon, but as I said in an earlier class, we have questions about how do we handle the fuel for nuclear power plants, how do we handle the waste from nuclear power plants, and whether or not that will be fully sustainable in the long run.

And so I want to cover two physical concepts from MacKay chapter 2 that I think are basically going to be the most important physical concepts you need to understand this class. And the first one, quite simply, is energy. It's the quantitative property of doing work. Energy can be neither destroyed nor created, one of our fundamental laws of thermodynamics. Energy can be transformed into light, heat, or mass, hence the famous equation by Einstein, E equals mc squared, energy equals mass times of speed of light squared. This is a fundamental finding out of relativity.

And, of course, energy can take many different forms. And we use it in many different forms in our energy system. Energy can be kinetic. It can be chemical. We can have potential energy. We have mechanical energy, let's say, stored in the elastic properties of materials and, of course, biological energy, which is fundamentally chemical energy, but we have different modes of perhaps using that chemical energy in our muscles, in animals, in ecosystems.

And we're going to measure energy in terms of units of kilowatt-hours. You'll see energy referred to in terms of British Thermal Units, BTUs, something only used in the US and America or the United States. Therms, joules, calories, are all units for energy. They can all be converted to kilowatt-hours.

A specific category I just want to highlight below is fossil fuels are sometimes measured in barrels of oil, short tons of coal, cubic feet of natural gas. That's because that's how we measure the things we trade in commodity markets for commoditized fossil fuels. But, again, the amount of energy in a barrel of oil and a short ton of coal and cubic foot of natural gas can be converted to kilowatt-hours.

So just to give you a few examples, example 1, you may have had the frustrating experience of having gone to the gym, foolishly counting your calories, realizing you worked out for an hour on a running treadmill, and it's only equivalent to three Oreos.

You can also look at example 2. The average American household uses per year about 11,000 kilowatt hours in electricity. Each person uses 300 million BTUs total per year, which is approximately 2.3 gallons of oil, 7.89 pounds of coal, and 252 cubic feet of natural gas per day.

Now, it's just worth pointing out that the first example, in terms of the American household, is in kilowatt-hours but only counts for electricity. That's for the whole household per year. The second sentence measures each person on a per-capita basis but then breaks the millions of BTUs into different units because of the different sources of energy.

And this is to say that, when we do these comparisons, we want to be careful about the units we use, the averaging over time, and the sources of energy, because the original source of energy may not actually be how much energy we use in the end. And we'll talk about that more in a few slides.

Another key physical concept we have to talk about or will be very useful is power, and that's the quantitative rate of doing work. That is power is energy per time. It's a rate. The units we use of that are watts, or equal to joules per second. Other forms of power that you might be familiar with are ergs, amperes in terms of electrical current, horsepower in terms of the engine in your car or other motors, and lumens are the amount of energy passed off per second from an LED light bulb but measured over a sphere around a light bulb. So it's actually weighted by the area around the light bulb or what degree of area is putting out how much energy.

So to just use the same example as the previous slide, you could say, I worked out for an hour, and I only worked off the equivalent of three Oreos. But maybe it sounds perhaps more impressive if you say, "My workout maintained a steady power output of three Oreos per hour!"

Another key concept we have to cover that links energy and climate is emissions intensity. And emissions are measured in terms of greenhouse gases, usually measured in metric-ton carbon dioxide equivalent, which is abbreviated MTCDE, or mt-CO2-e, and so on. And the reason why we have to measure it in terms of metric-ton carbon dioxide equivalent is that there's a lot of different greenhouse gases, and some of them, for example, methane, CH4, has much more global warming potential than carbon dioxide.

So a single ton of methane has about 84 times the global warming potential of a ton of carbon dioxide early in its life. That declines over time to about 20 metric tons of carbon dioxide equivalent. So this is just to say that, if we have different greenhouse gases, we measure them or make them all equivalent to a metric ton of carbon dioxide equivalent during their lifetime.

We can also measure emissions intensity by the type of gas, as the example I just gave you in terms of methane, also nitrous oxide and fluorohexane, I think, are another greenhouse gas. You can measure in emissions intensity per unit of energy. This much greenhouse gas is created in terms of this much energy. You can measure greenhouse gases per activity, per dollar of GDP, or by region. People use lots of different intensities.

And the reason why I want to focus on this key concept of intensity is that, as we look at different parts of the system, we're going to look at the intensity of the different parts of the system to get a whole picture of where greenhouse gases are coming from, just like we're going to look at energy intensity in terms of how much energy do you need for different activities, how much energy do different regions of the world use.

And so to give you a few examples of the Conference of the Parties, the COP meetings that the UN Framework Convention on Climate Change runs every year-- they have reporting inventory. And when every country which is party to the Paris Agreement has to report its greenhouse gas emissions and, frankly, the actions that they're taking to reduce their greenhouse gases. They have to measure or report their greenhouse gases in terms of a specific inventory format.

So I have linked to that here. You can click on it, and you can see how countries report different kinds of greenhouse gases. It's because countries can only see the source of the activities that create greenhouse gases. So it's easier for us to measure how many barrels of oil we burned or how many short tons of coal we burned or, let's say, how much land use conversion has led to how much methane or how much carbon dioxide.

We can also measure, let's say, our greenhouse gas emissions per unit of electricity because electricity comes from a grid. The grid is a technology we'll talk about a lot in in this class that mixes different sources of energy together. And so we try to get an average intensity of greenhouse gas emissions per unit of electricity in different regions. Another emissions intensity factor that people look at quite often is air quality. You can look at how many greenhouse gases or how much particulate matter is produced by certain activities, like vehicle miles traveled or number of cars on the road.

So just to give you an example of what carbon emission intensity looks like, this is the carbon emission intensity of economies in 2018, and this is from Our World in Data. And you can see, actually, it's measured, on the bottom legend here, in terms of amount of kilograms of carbon dioxide equivalent, the carbon dioxide intensity, per dollar of GDP measured in international 2011 prices. And you can see, by that measure, actually, a lot of the developed world, such as Australia, Europe, North America, and parts of Latin America don't look very intense, if only because they don't produce that many greenhouse gases per dollar of GDP output.

Now, like we talked about in the last class in terms of population, what does this hide? Well, there's a couple of things with the map. Sometimes the area of the map distorts the actual area or total emissions. Small places don't look like they have as much impact as big places, even though that really has nothing to do with the average.

But the more important point from a map like this is that it hides the fact that the rich countries, like Australia, Europe, North America, and parts of Latin America, simply have much larger GDPs. So it looks like the carbon dioxide output per GDP is low. But if we look at the per-capita CO_2 emissions, like the point at our last class, you can see that, for a relatively small number of people in those rich, developed countries, they have very high CO_2 emissions per capita. And so your map basically changes diametrically. And you can see the difference between richer countries and poor countries. And overwhelmingly, the richer countries are more responsible for carbon dioxide emissions.

If we look at this similarly in a scatterplot, you can, again, see that it looks like, on an emission intensity basis, India and the United States are not that different. Of course, the difference is, in terms of the output of the economy on a per-capita basis, the average person in the United States produces much more and inevitably consumes much more than your average person in India or Pakistan. So even though we have equivalent emissions intensity per dollar, we simply produce and consume much more in the richer countries.

And I make this point because, after the Kyoto Protocol and after the George W. Bush administration chose to leave the Kyoto Protocol, one of their arguments was that the US actually had a lower carbon emission intensity, or at least a comparable carbon emission intensity, to some developing countries. Of course, this hid the fact that the United States is both richer and consumes much more and produces much more. So that's just a way to talk about what intensities may tell us and what they may hide also.

Now I'll get to a really key diagram that I rather love in this class. So I'll start off this class by talking about Sankey diagrams. And you can find a Sankey diagram for the US and every state at this web link at part of the bottom from Lawrence Livermore National Laboratory. What a Sankey diagram is is basically a flow chart, and it's a flow chart between the sources on the left. And you can see all of our energy sources, solar, nuclear, hydro, wind, geothermal, natural gas, coal, biomass, and petroleum. And you can see all of the ultimate uses on the right.

And the final-- I guess what we'd call final consumption is in residential buildings, commercial buildings, industrial buildings, and transportation. Of course, this final category here is also a kind of a statement about where does the energy go in the first place. Only about 50% of the energy or less that we actually burn from the original sources goes into these uses in these sectors. About, actually, looks like one third of the energy goes to what we call energy services. And rejected energy is the byproduct of that combustion, usually, that we don't capture for actual energy services.

So to give you an example, you can see how-- I said before, the electric grid mixes many different types of energy sources-- solar, nuclear, hydro, wind, all these, natural gas, and coal all feed into the electric grid. But when we feed that energy into the electric grid, into power plants, we basically only take a fraction of it. It looks like about one third of the electricity, one third of the energy in those energy sources, actually goes to things like residential, commercial, and industrial. But about 2/3 of it gets rejected, which means that it's heat energy going out of the chimney of a coal-fired power plant, or might be energy lost in the electric grid that's simply lost because of the resistance of the electrical wires.

And so this kind of graph, I actually find tremendously useful to summarize what the sources on the left are, the ultimate uses of the energy are on the right, and also some of the interim steps where we might be able to capture some of the energy back in terms of energy efficiency or at least think about how our intermediate technologies, like the electric grid, actually use energy and how much of the intrinsic energy in the fuel source are we using.

To take one example from this graph, I think it does a really good job of showing you, for example, that electricity overwhelmingly goes into residential buildings, commercial buildings, and industrial buildings or industrial activities, but you can see that there is no link between electricity generation and transportation, so a very small orange line here, 0.02 quads.

And once again, I should have pointed out is that the total US energy consumption in 2021 was at 97 quads. It's pretty easy mentally to round that up to about 100. So this is actually 0.02%, roughly, of all the energy in the US or electricity is used for transportation. You can see, overwhelmingly, that the majority of energy for transportation, 24.3 quads, or about 24% going to the US, comes from petroleum. And originally, that came from about 35 quads of-- or 35% of our initial energy sources.

And you can see some portion goes off to industrial activities. But the vast majority of the energy that drives our transportation system is petroleum. And you can see that, when we burn petroleum or gasoline in our internal combustion engines, a very small fraction-- it looks like about 20% of it-- is actually used for moving the car forward. About 80% of the energy actually goes out of the tailpipe either in the form of heat out of the tailpipe or else air resistance. That is not really what we are trying to do. We're trying to move goods and services and people around.

And so this is just, again, a way of saying that there's lots of different kinds of Sankey diagrams. This is a nice one that it has proportional flows between sources, intermediate, transforming technologies, and usages. It also shows you what efficiency level is being achieved in these different sectors. This is essentially an accounting exercise, but if you can find a Sankey diagram for a given region or a city or a country, it gives you a really good picture of where the energy is coming from and where the energy is going to.

So we want to use these Sankey diagrams to think about what our pathways are to deep decarbonization. Deep decarbonization-- I think I've said before, if I haven't said it before-- it is both a goal and a process. We know that climate science tells us-- the IPCC has told us through an exhaustive scientific process that we need to achieve net-zero anthropogenic greenhouse gas emissions by 2050. Deep decarbonization is both the goal of getting to net-zero emissions by 2050, and also, it's this process. We're decarbonizing for the next 28 years to lessen the effects of climate change.

And so the first deep decarbonization plan started in 2015. The Deep Decarbonization Pathways Project started 2015 for a number of countries to try to think about what analytical or policy or technology pathways we needed. It was updated in this paper in 2020 that you read for this class.

That was quickly followed by the White House Mid-Century Strategy, which was the Obama administration's commitment to the Paris Agreement to reduce greenhouse gas emissions by 80% by 2050. But just four years later, you have a series of reports from academics and NGOs looking at ways to get to 100% reduction by 2050, which is what the IPCC says we need to do by 2050.

And so the key thing I want to say in this class but also in the paper I referred to last time last week, the paper on deep decarbonization that I wrote recently, is that many of these plans agree what the technology pathways are. So we should focus as urban policy analysts and urban planners and people who work in cities on implementation. We should focus on geography. We should focus on the politics of it. And, frankly, as planners, we should look at the land use and built environment implications of deep decarbonization.

So look at the Sankey diagram from Williams et al., 2020. They look at the reference case for energy use in the United States. And this is a reference case I think the Energy Information Administration puts out every year. You can see on the left-hand side that, overwhelmingly, the reference case, which is usually fairly conservative, shows that we will get most of our energy from-- we get most of our energy currently from uranium, coal, natural gas, a little bit from biomass, and a large portion from petroleum. You can see renewables here are relatively small-- geothermal, solar, wind, and hydro.

And all the energy goes through the intermediate steps-- electricity generation, pipeline gas, petroleum refining outputs, or liquid fuels. It gets transmitted through the electric grid, and it ultimately goes to buildings, which are residential and commercial buildings together. It goes to industry, and it goes to transportation.

Again, you can see here from buildings that, overwhelmingly, about half of the energy comes from the grid, and half the energy comes from pipeline gas. Transportation, almost all the energy we currently use comes from petroleum. And industry uses a variety of energy technologies and fuels.

Now let's contrast that with the Williams paper on what a 100%-renewable-energy future would look like. There's a couple of things to notice here. First, all of our renewables, the 100% renewable sources we are going to need, have taken over completely-- geothermal, solar, wind, hydro, and biomass. There's no coal, no natural gas, and no petroleum. Overwhelmingly, about 2/3 of the energy will go through the electric grid. It will be generated as electricity, either goes through the grid or be used to produce hydrogen. Hydrogen will produce various liquid and gaseous fuels.

And if you look at what the future looks like in 2050 according to this paper or this technology pathway, you can see that buildings have to overwhelmingly get their energy from electricity. Industry will still use a variety of inputs, but all those inputs will be from intermediate steps that have transformed our renewable energy into the kinds of fuels we need to drive industrial processes.

And you can see that transportation is going to come overwhelmingly from electric. About 50% of our energy in transportation will come from electric. Some of it will come from, I think, liquid fuels, and some will come from compressed gases, such as hydrogen and maybe natural gas or methane produced from renewable resources.

And let's just look at the implications from this, and this is to read the numbers off those previous two graphs. And then you look at the power sector. You can see that petroleum, natural gas, and coal, as I said, have to be eliminated completely, 100%. Biomass has to grow by 3 and 1/2 times. Nuclear power, in the 100% renewable case, is actually eliminated completely because I think Williams et al. do not define nuclear as a renewable energy source.

But the key things, the most dire, I think, or most challenging things we have to deal with are growing our solar energy share by about a factor of 46. We have to grow our share from wind by a factor of 27. Hydro and geothermal are going to be relatively small players in this forecast. And that's just for the electric power sector.

If you look at buildings, residential/commercial, you can see two things. Not only does electricity have to decline in total use, but we have to completely eliminate natural gas. And we have to increase our use of biomass just slightly. Now, the key thing is that the reason why we're declining our total use of electricity is that it's more efficient. But at the same time, the electricity we do use is going to be used to do things that natural gas currently does, like we're going to get heating and cooling from electricity rather than from natural gas as we do now.

And so this is one important point I want to highlight from Sankey diagrams. If you look at the total primary energy in buildings, it actually has to go down by about 50%. And this is the point I think I made in the last class, which is, if you look back here, the total amount of energy-- it looks like, I think, roughly 100 quads, also 100 exajoules I think is how this paper measures it.

And if you look at the next slide, you can see that the width of these flows have gone down quite a bit, which is just to make the point that I think I said to you last week, which is that not only do our uses have to become more efficient, we also have to simply reduce the total amount we're using. And the remaining 50% have to become renewable. So we actually need a complete transformation of our energy system both on the consumption side and the production side.

If you look at the Tong paper, this is going to shift a little bit to this question of existing energy infrastructure. This is a paper written in 2019 in *Nature.* And in this paper, they say our estimates suggest that little or no new CO2-emitting infrastructure can be commissioned, and that existing infrastructure may need to be retired early or be retrofitted with carbon capture and storage technology in order to meet the Paris Agreement climate goals.

So this paper is basically going to show us that we have existing infrastructure-- obviously, the energy infrastructure that we use every day-- and if we want to meet our Paris Agreement climate goals, which is keeping, preferably, global average temperatures less than 1.5 degrees Celsius higher than pre-Industrial era, we actually need to build no more fossil fuel infrastructure, which is CO2-emitting infrastructure. And we may have to retire some of the energy infrastructure that we have early before it's planned lifetime.

This is part of the struggle. This is why you have activists trying to retire coal-fired power plants and avoid building new pipelines and natural gas plants or having, let's say, gas bans for new appliances in parts of Massachusetts and California and other states.

So just to show you what this looks like, all these categories in the legend here-- commercial buildings, residential buildings, international transport, road transport, industry, electricity-- these kinds of technologies have a natural lifetime in terms of they have a committed CO2 emission from existing and proposed infrastructure.

And you can see that our existing infrastructure is overwhelmingly dominated by industry and electricity. And road transport is this blue wedge, and buildings are actually relatively small. And those are all things that are going to phase out naturally over time because infrastructure gets old. If you don't maintain it, and you don't rebuild it, then it wears out, and you can't use it anymore. We've had more proposed infrastructure, but that proposed infrastructure cannot be built if we need to try to meet our Paris Climate goals.

At the same time, in the B panel here, we have the committed emissions from different countries. And you can see the lifetime of infrastructure in China is relatively long and a large portion of the future problem because so much of it has been built fairly recently. You can see the rest of the world is actually only about 2/3 of the problem that China poses.

And, actually, the US has a relatively small future committed emissions because the nature of our technology. Of course, there's been many more proposed projects, but the point of this paper is that we cannot actually build the proposed infrastructure, and we may have to retire some of those existing infrastructure early to avoid going over our climate limits.

So another kind of interesting graph in this paper which I like quite a bit is a population pyramid, but it's a population pyramid showing the proportions of the population of people by age. It actually shows the age structure of our global electricity-generating capacity. And I want to simply make a point about what the different nature of the problem in China and the US are.

You can see on the left-hand side-- this is the rest of the world, in some ways, dominated by the US. You can see around 15 or 17 years ago, we've built quite a bit of natural gas or oil infrastructure. You can see the rest of the world has more recently been building gas and oil infrastructure, these yellow bars. And you can see on the right-hand side-- this is electricity generation from coal, and that is overwhelmingly dominated by coal-fired power plants built in China mostly in the last 12 or 14 years.

The reason why we use this graph is to look at the nature of the problem and what particular sectors we're going to have to tackle or which particular power plants we have to tackle to avoid creating more greenhouse gas emissions that, again, will put us beyond our Paris Agreement targets, that will then finally jeopardize the climate of the planet.

So this brings me to cities, which is-- numerous recent studies show that most US greenhouse gas emissions or global greenhouse gas emissions in some of these studies are from cities. But the key point of this literature I want to highlight is that the exact proportion depends on how and where you count.

The Jones et al. 2018 paper and the Goldstein et al 2020 paper both find that higher incomes and lower population densities are highly correlated with higher carbon footprints and energy use. The Gurney et al 2018, 2020, and 2021 reports and papers find that a majority of road and fossil fuel infrastructure or use can be associated with cities.

The Moran paper is quite interesting, and it finds that, both in China and the US, the largest 10 cities plus 5%, or the top 5%-- of suburban residents by income are responsible for more than a majority of the greenhouse gas emissions from both countries, China and the US, which is to say that, if we focused just on the largest 10 cities and the most carbon-intensive suburbs, now we could actually make a significant difference in the greenhouse gas emissions of the countries.

It is also kind of recapping the moral argument I made to you in the last class, which is that the richest people in both countries have a disproportionate responsibility to lower the greenhouse gas emissions just in the same way that the US has a disproportionate responsibility to lower its greenhouse gas emissions relative to the rest of the world.

Finally, the Seto in the 2021 and the Wiedmann et al. papers, 2021, show different research and planning frameworks for how do we really count these greenhouse gas emissions. And so there's debate about how you count it, but there's this emerging consensus in the literature that cities are responsible for a large proportion of greenhouse gas emissions in many countries, including China and the US.

Just to highlight a few of the key issues why it's hard to get an exact proportion, depends on different definitions of cities or what an urban area is. It depends which emissions you count, upstream emissions, like things that you import in the form of fuels or goods; downstream emissions, the things that you export out of the city or waste energy or waste products that go outside of the city; and goods and services. There's all different ways to count the emissions from all of these things. The C40 annual report that I assigned in the reading gets to some of these issues.

Finally, some interesting questions that are not always accounted for-- cities clearly shape local microclimates. Do we count that as part of climate change, because that actually changes how people subsequently use energy in cities? And there's this kind of fundamental question-- how do you measure affluence? Do you measure in terms of wealth or income? I suspect if we measured these in different ways, you'd find different places responsible for different levels of greenhouse gas emissions.

Just again, to kind of make this argument about how we measure things matters and also how intensity may show us a different picture, this is from the Gurney et al. 2020 paper. The left-hand panel shows absolute emissions. You can see the absolute emissions in this country basically almost identically mimics the spatial or urban spatial structure of the country, where all the red areas and the left coast are high concentrations of absolute emissions.

Of course, if you measure on a per-capita basis, you might say, OK, out West, people are relatively inefficient. But we should also highlight the fact that there's these interrelationships between these two areas. Places out here in the West is a high concentration of fossil fuel production/generation. But where is that energy going? That energy is going to cities.

And so we think back to MacKay's left-hand bar of consumption. I would argue to all the urban planners in the room-- and I've said this to my colleagues in city government-- that we should not be complacent about the fact that we think we have relatively low per-capita emissions in cities. We have to be responsible for the fact that energy is being used elsewhere, that we consume in the form of fuels, goods and services, food, and we export our waste also. So that is the place where cities can have a big impact on greenhouse gas emissions.

But it may be a different kind of efficiency. We might have to think about how much we consume, why we consume energy, and how do we do it more efficiently, and, hopefully, ultimately reduce our consumption to meet our decarbonization goals.

Finally, I'll just flash through the readings quickly because we'll talk about them more in class. The Hsu et al 2019 paper-- this is actually not my paper. It's written by a colleague, Angel Hsu at University of North Carolina. It is a research roadmap for how do we spend more time or how do we spend more thinking about quantifying the climate mitigation actions that nonstate or subnational governments could take. And this is getting at that measurement question. How are we going to measure greenhouse gas emissions? And how are we going to measure what action those entities take?

And just to give you an example, there's different ways to count how cities take climate action in comparison to state targets. And those targets may be different still than national-level targets. And so there's a question-- are we going to double count? In some cases, or, actually, most cases, cities are more ambitious than their states. Cities are often more ambitious than national governments. We want to avoid double counting. We want to assume-- we want to count cities considering how those cities are going to act relative to cities without targets. So this paper will get at that. We'll just talk about more in class.

And this brings me to this optional reading by Markolf et al., which is "Pledges and Progress." This is a Brookings Institution report. It looks at the 100 largest cities across nine states. They find that number of cities, these 100 cities, have all set fairly ambitious goals, everything on the blue here on the right. The parentheses shows you when they set the goal.

And you can see Boston, where we are-- actually, Cambridge is also in the graph somewhere. But Boston, Massachusetts, in 2005-- so they're going to have an 80% reduction by 2050, as all of these cities did, also meeting the White House's targets in 2016. It's commensurate with the national targets in 2016.

You can see a number of these cities here in the left have set less ambitious targets-- 50% reduction, let's say 40% reduction. But they may have more closer targets. So this might be an interim goal on the way to a more ambitious target down the road.

But the take-home from this Markolf report-- and I'll let you look at your leisure because I think some of you will be quite interested in particular cities-- you can see what the difference is between their current emissions inventory and their target emissions. And you can see in the case of Chicago, Illinois, they set a 2015-- they had a 2015 greenhouse gas inventory. They had a target emission in the year of that inventory, and it looks like Chicago is emitting about 50% more emissions than they targeted in 2015.

I actually find this report quite hopeful because it takes a serious look at all these cities and says, well, we should take cities seriously in terms of the climate action goals we're studying. But in order to take them seriously, we also have to hold them according to the plans that they're setting.

So it looks like Boston is closer to its target of 10% higher inventory emissions than it had planned for in 2016. That 10% hopefully gives us-- or that inventory difference gives us a good place to target our actions. Other places, let's say, Los Angeles-- looks like it's actually ahead of its goals. It's actually 10% less in terms of greenhouse gas emissions than they planned for in 2013.

So cities-- looks like almost overwhelmingly temperate cities except for Minneapolis, but all of these fairly temperate-region cities are doing better than they expected. Some of these cities here-- I guess Chicago is a cold climate city, and Tucson is the opposite. But for different reasons, Tucson and Chicago are wildly over the goals they set in 2014 and 2015.

And so I'll just stop here, and I will talk more in class this week. We'll talk the results of our carbon calculators that you did for homework. We will put some questions for discussion on the board, and we'll just start our discussion. And we'll have some news items to talk about in class. Thank you very much. I hope you guys have a great rest of your weekend--