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DAVID HSU: My name is David Hsu. I'm a professor of Urban Studies and Planning at MIT. And this is another installment of my lecture series on urban energy systems and policies.

Today, we're going to talk about renewable energy. And we've been talking in this class about consumption, how we consume energy in our personal transportation and our buildings and our consumption of material goods, quite often produced by industrial manufacturing processes. And I've emphasized in the class that we need to make all those uses more efficient in order for us to help decarbonize cities.

But now it's time for us to turn to talking about renewable energy, the fundamental building blocks that'll enable cities to transition from their current energy sources, which mostly depend on fossil fuels, to renewable energy sources that will help cities decarbonize and avoid the worst consequences of climate change. So today, in the first part I'll talk about wind energy.

The materials for today, if you have the PDF or hard copies, you can click on these pink links, and they'll take you to the various resources. These are the materials we'll be discussing today.

And just to refresh our memory where we are, these are, again, the decarbonization pathways from the Williams et al. 2021 paper. This is the 100% renewable energy scenario.

So on the left-hand side of the Sankey diagram, you can see that all of our primary energy sources are essentially decarbonized, renewable energy sources, solar, wind, and biomass being the three largest sources of energy. And what I want to emphasize in this class is that we're going to-- or the next few classes is we're going to talk about your renewable toolbox.

Like, I define sustainable energy or sustainable production of energy as categories of wind, solar, hydropower, wave power, hydropower, geothermal power, and MacKay gives nuclear a question mark because it's not clear whether or not-- it's not clear to MacKay and still to me whether nuclear power counts as sustainable.

But what I want to emphasize with your renewable toolbox-- and we're going to develop this theme in the next few lectures-- is that it has become increasingly cheap, increasingly clean, but these fundamental technologies require transitioning our energy system and how it works, because they work in different ways in our existing fossil fuel resources.

And so just to give a definition of renewable resources, why we are focused on particular technologies, there are technologies that derive energy from natural processes, they can be regenerative over short periods of time, and they will not be depleted. We can talk about whether or not renewables are defined as clean, net zero, or carbon-free. All these definitions or these various descriptors have slightly different meanings.

And of course, I want to emphasize energy efficiency is also necessary for us to achieve decarbonization. The 100% renewable scenario I showed you in the last slide and from the Williams et al. papers and many-- most of the decarbonization studies all emphasize the fact that we can't build renewable resources as fast as we need to to meet our mid-century goal, so it's going to be necessary to use energy efficiency.

And that can be the technologies, products, services, or changes in behaviors or expectations that reduce the energy required for certain processes or tasks or services. And we also talked about that a few lectures ago.

And the other thing I want to emphasize about your renewable toolbox is that it has different limitations. We have to think about key factors or key categories of problems to solve. First, there's the total potential of renewable energy that we can achieve in a meaningful period of time.

Second, as you may have heard, many renewable technologies may be intermittent in terms of how they derive energy from natural processes. And something I've emphasized in this class and I think is particularly relevant to cities and land use is, how much land use or how much land take is required to build renewable resources? Renewable resources are quite often less energy dense than fossil fuel energy systems.

But just to give you a sense of the intermittency or what the kind of sources of energy for wind and solar look like, there's a few kind of fun visualizations I'll click on here in a moment. If we look at the wind right now across the United States, that first link takes us to this wind map that you can see here. You can see that the wind has a directionality. It's concentrated in some places, quite clearly blowing in the Mountain West and the Midwest and Texas much more than it is here on the East Coast where I'm recording this video.

If we look at the global map of wind, you can also see something very different. You can see that the wind is much stronger over the oceans than it is over the land. This is a pretty neat little visualization. You can actually see any part of the world and see where the wind is.

And of course, these little vectors and these kind of field vectors show you that there may be a storm off of, I think, Mexico here. There may be some very strong winds in the upper North Atlantic. But you can see in almost all the cases that the wind is much stronger offshore than it is onshore, and that'll be a key theme we'll talk about today.

So just going back to our slides on wind, again, to emphasize that your renewable toolbox is going to require deploying these at scale. It's going to require us to essentially build a new energy system to avoid climate change. And so we just want to focus on this building block for a second and the challenges.

Our first building block is going to be solar. I'll talk about how solar technologies have become drastically cheaper in the next lecture. But we have to build approximately 47 times more solar in the United States to achieve our mid-century goals.

Wind as another building block, that has been very successful. Probably our highest amount of capacity of renewable energy comes from wind right now. We still have to actually increase the amount we've built by 28 times over what we've built over the last 40 years.

And storage, geothermal, and electrolysis, that can be used to create hydrogen from renewable resources. Those are fundamentally the building blocks that are going to be part of your renewable toolbox.

But I want to emphasize this toolbox is probably the toolbox you'll be using for much of your careers. And to your credit or to your advantage, all these building blocks have gotten increasingly cheap over time, will probably get cheaper over time. All you have to figure out in your careers is-- I'll give you a to-do list for your careers.

All you have to do is figure out how to finance these new technologies, which sometimes have higher upfront costs. All you have to do is figure out how to install the capacity, the 47 times more solar, 28 times more wind to generate electricity or energy. You have to figure out how to transmit this power across-- from the places that it's generated to the places that it's needed. You have to figure out how to distribute this power within cities.

You have to figure out how to balance this power across the grid, because electricity can not very easily be stored, though we'll talk about storage. You have to figure out how to balance the system so that when you're generating power in one part of the continental US, like you saw the wind blowing in the Mountain West, it can be consumed elsewhere, like on the West Coast.

You have to figure out how to make this grid reliable. You have to figure out how to make this grid resilient in the face of increasing climate changes. And of course, you have to site all these resources and all these transmission lines.

So again, your renewable toolbox has some fundamentally really interesting, really increasingly cheap and cost-effective building blocks on the left-hand side. This is your to-do list to build a new energy system on the right-hand side.

So the agenda for our next few classes is going to emphasize a series of different technologies. And I'll try to teach you a series of different concepts that are useful to think about the nature of those technologies. So today, we'll talk about wind basics, and we'll use that to illustrate capacity factors and the levelized cost of energy.

On the next lecture, we'll talk about solar basics, including adoption costs, learning curves, and siting issues. And then the third lecture from now, we'll talk about storage and geothermal as examples of how we might develop new niches or new technologies in the existing energy system.

Renewable energy potential. What is it? There's a potential amount of renewable resource that can be generated. If you want to see maps for pretty much every country in the world or globally, you can see the International Renewable Energy Agency. IRENA has a very good resource of renewable energy potential studies.

IRENA was founded in 2009. It's the agency specifically focused on renewables. If you go to this link, you can see potential studies. And they have 10,000 studies on five major categories of renewables. And I think you can see which countries have been studied for your papers for this class.

So getting back to this graph, I touched on this a little bit, I think, in the last lecture. The price of electricity from new power plants has drastically changed over time, a lot of these arrows in 2009. Nuclear has gotten more expensive. Solar thermal has decreased slightly. Coal power has not changed at all.

Natural gas peaking plants and combined cycle plants have both decreased in the cost of electricity for new power plants. But of course, the two most drastic lines or the steepest slopes on this chart is the price of electricity from solar declining by about 90% over the last 10 years and the price of onshore wind electricity declining by 70% over the last 10 years.

Just, again, highlight that. The price of onshore, we'd love to see it decline by 70% in the past 10 years. And we have a very large installed base of wind.

So just to look at our wind basics, these are all graphs from the Mackay chapter that you all read for this class. Wind power is essentially just taking a wind. You have some kind of volume of air hits your wind turbine. It gets slightly displaced by the obstacle of the wind turbine until it blows. And you're taking some amount of energy out of the wind.

This rule of thumb in MacKay's book is that the wind turbines should be about five diameters apart. I think that's probably changed. It has gotten more sophisticated over time. Michael Howland, a new faculty member in the Department of Civil Engineering studies the operation of wind turbine blades and how to optimize them.

And of course, the important point that MacKay makes is that the wind speed changes versus the height off of the ground. You can see that the wind speed comes quite a bit higher. And the power density that you can extract from the wind goes up actually nonlinearly off the ground.

So in other words, the bigger you make the turbine, the higher off the ground, the more wind power is there, or the more wind speed is there. And the power density goes at a nonlinear function of the wind speed so more power can be extracted from this volume of air. That's going to be a recurring theme as we look at wind turbines and wind power and where it might go.

Looking-- the Department of Energy in the United States produces a land-based wind market report in 2022. Here, they just map the wind speed at 100 meters off the ground. They map it against these different regions, which are tracked along different regional transmission or intersystem-- interconnected system operators. These are all different regions of the electric grid. It's relevant because wind is going to plug into regions of the electric grid that are governed in different ways.

But the most important thing is that you can see that most of the power, wind power, or the wind speed in the United States is concentrated here in the middle part of the country. That's concentrated in Texas. This is the region of the Electric Reliability Council of Texas.

The Southwest Power Pool constitutes much of the Midwest here. And the Midcontinental Intersystem Operator operates much in this part of the Midwest. So our wind power is clearly concentrated on land in the middle of our country.

And if you look at the wind market report, it's been exciting to track it over the last few years because you can see over the last few years, these are the cumulative total capacity added. And the cumulative total capacity has, of course, gone steadily up over the last 22 years.

But if you look at the capacity additions, you can see that every single year we're adding much more capacity of wind power. In fact, until this last year, until 2020, for four straight years the capacity had increased.

And you can see that almost quite regularly we're starting to break records for how much capacity we're adding in any given year. 2021 slowed slightly, but you can see that a lot of this capacity is being added in certain regions, and those are those three regions I showed you the map before. Texas, the Southwest Power Pool, and the Midcontinental Intersystem Operator.

If you look at where wind stands in our capacity additions, another exciting part of the story is that this is from the Wind Market report. It shows over years, well, how much capacity? How much capacity are we adding to the grid to generate electric power? You can see overwhelmingly it is coming from wind, solar, and storage over the last few years. Natural gas in light blue has had some years of growth, but is steadily becoming a smaller part of our capacity additions.

Our capacity additions to our electricity system are almost entirely wind, solar, and storage. Wind for the first time has, I think, fallen in the second place from solar. It used to be-- a few years here, it looked like solar was actually larger, but now wind is clearly in the second position. Solar is the biggest capacity addition being added to the grid.

This is the capacity, the ability to generate power in gigawatts. That doesn't necessarily mean that capacity is being used all the time, which we will talk about when we talk about intermittency.

But finally, if we look at the different regions, again, wind is quite dominant in the middle of the country, in the Southwest Power Pool, in the Electric Reliability Council of Texas, and the Midcontinental Intersystem Operator. You can see all of these areas are quite dominated by wind. Other parts of the country are more dominated by solar and natural gas.

So just to give you an example of what these offshore wind turbines look like, this is actually a plane picture I took out of a plane window when I was flying, I think, over the North Sea in Europe. This is, I think, off the coast of Holland. And this just gives you a sense of what you can see from a plane. There's a little ship, probably not a little ship sailing between these wind turbines. But these wind turbines are simply offshore where we know more wind is blowing.

I have to give you another picture. This is a picture of offshore wind turbines in Europe, which tends to have shallower waters than the US. But you have-- it looks like a ferry and you have a sailboat sailing through.

And the reason why it's exciting to talk about wind offshore is that if you look at the average wind speed above North America, you can see that there is this concentration of wind power in the center of the country. But very importantly, you actually have very high wind speeds off the coast of the US. This probably doesn't go all the way out into the ocean. This is probably just mapped along the continental shelf. But you can see the concentrations of wind are just as high, if not higher than the middle of the country.

But also, quite importantly, these wind towers or wind potential are located very close to the population centers of the US. We know most of the population of the US is actually concentrated along the coasts, and so it's important to be able to generate renewable energy close to the populations because it minimizes our need to transmit the power through the grid. So we will need more transmission lines for the grid also.

So just to give you a sense of what these floating wind turbines would look like off the shore of the US, here's three different ways of anchoring a floating wind turbine to the ocean floor. You have one that has this big kind of counterweight to keep it upright. You have this kind of tripod system with three anchors. And you have a different tripod system, all meant to anchor wind turbines offshore.

Of course, just to give you a sense of where this technical potential is located, according to the NREL study, if you look at places that have greater than seven meters per second wind speed, less than 1,000 meters in depth, less than 60 meters in depth-- the Great Lakes-- and if you try to avoid conflicting use and environmental exclusions, you can see that they break each of these bars into the places where the water depth is greater than 60 meters and less than 60 meters.

And you can see surprisingly that one of the largest states for practical energy potential is Massachusetts. And then Florida, and then Texas, and so on. So these are all offshore wind potentials for different states, but this is also to give you a sense of why it's so important that Massachusetts is pursuing offshore wind energy. This is the chance that Massachusetts has to develop renewable energy resources.

In a highly dense area of the country, a highly populated area of the country like Massachusetts, we're not going to build-- we're not going to be able to build as much solar as other parts of the country. And frankly, it's not very sunny in Massachusetts compared to Arizona or Hawaii. So offshore wind is probably going to be our biggest opportunity for building renewable energy.

Now, what's really exciting is if you look at the DOE, the US DOE also does an offshore wind market report. Every year, I've been updating this. And so actually, it's interesting when you look at the graphics in this report, every year they change because offshore wind is growing, and in fact, basically exploding in its potential.

So last year, I think when I looked at this map they had the entire Atlantic coast was on one map. And there was, I think, about 20 planned projects. Now there's about 20, 31 planned projects in the North Atlantic alone. They also-- actually, sorry. 32 because they show Lake Erie having a offshore wind project, a freshwater wind project. There's one all the way up in-- off the coast of Maine.

And you can see on this graph that there's about 32 planned wind projects. They all are in different areas off the coast. You can see they occur at different bathymetric depths. They are-- some of them are leased. Some of them are dormant areas, but these are all areas that have been explored for offshore wind.

If you look the Pacific Coast and the South Atlantic, now they have separate maps broken out just for these areas. You can see that on the West Coast off of Oregon and California, there's a number of offshore wind projects planned. There's offshore wind projects planned off of Hawaii now and these in the South Atlantic. These are all areas in the Gulf of Mexico. These are all areas that weren't even mapped in the last offshore wind market report from just last year. So clearly, this is an area that is growing very rapidly.

If we look at the pipeline for offshore wind, the striking thing about it to you should be this classification from what we actually have operating, from what's under construction, from what's financially closed, what's been approved, what's waiting for permitting, areas that are under site control, and areas that are being planned. If you add all of these parts up, you get the total pipeline of offshore wind expected.

What you should notice about this is that we have about 40,000 megawatts of offshore wind that's in the pipeline. That's up from about 35,000 megawatts just last year alone. But the really striking thing to you should be that of the 40,000 megawatts we have planned, we only have 42 megawatts operating. That's actually, I think, exactly seven offshore wind turbines in the US right now, five off of Rhode Island and two off of Virginia. That's all we have operating.

When we go to under construction, we're going to effectively, I think, increase that by a factor of 20. A lot of that looks like in Massachusetts. And we have very little that's been financially closed and financially approved.

But if you look the states that are permitted offshore wind, it's New York, Massachusetts, New Jersey, North Carolina, Virginia, Maryland. All up and down the East Coast we have a lot of permitting, a lot of permits that need to be expedited or need to be achieved or approved for these projects to go forward.

In terms of areas that have people, developers have achieved site control, a large majority of that is in New York and Massachusetts. And then in terms of planning, we have quite a bit of planning for offshore wind in California.

But again, if you add this whole pipeline together of the 40,000 megawatts we have in our total pipeline, we only have 42 megawatts operating, which is 0.1%. So we obviously have big ambitions for offshore wind, but we haven't realized 99.9% of the actual wind capacity yet.

If you look at the states and the wind pipeline by state, you can also think about how this fits into the energy policies. Currently, quite a bit of New York's potential is under site control, and quite a bit is being permitted, and a very small portion is under construction. And Massachusetts has less total wind offshore pipeline, but has less under site control, more in permitting, and more under construction. New Jersey is almost entirely in the permitting phase, and so on and so on.

But just to give you a sense of how big these wind turbine blades are, this is a graphic of the Haliade-X turbine, a new turbine introduced by GE just a couple of years ago. And just to give you an example, this is the Statue of Liberty at 305 feet, the Empire State Building, the Eiffel Tower.

The average onshore turbine is 466 feet tall. The tallest US turbine, the tallest turbine you've probably seen onshore, is 574 feet tall. The new GE Haliade-X is 853 feet tall. The current-- the five wind turbines we have operating in the US off Rhode Island are only 590 feet tall.

So GE can build these turbines. They've introduced this as a product. But clearly, these turbines are very large. I think each of those blades is one or two aircraft wings long.

So just to give you a sense, the total height of the new Haliade-X wind turbine is three times the Flatiron Building. The diameter is equivalent to the Golden Gate Bridge tower height above the water. And the surface of the blade sweep is equivalent to seven American football fields. A single one of these turbines can generate 67 gigawatt hours annually, which is-- I guess that's enough for 16,000 European households per turbine, which I guess is maybe about 8,000 American households.

The key point, though, is that because of the map I showed you before, wind speeds are higher offshore. The wind is steadier offshore. If you put one of these turbines offshore, it'll generate much more power than onshore turbines.

But again, we have yet to realize the technology. American waters are deeper and stormier than European waters. Europeans, I think, have deployed something like 5,000 or 6,000 offshore wind turbines. We've only deployed seven in the US. We have a lot of obstacles and barriers to overcome such as the right kinds of ships and the right kind of workforce and the port capability that are all necessary to build these offshore turbines, let alone the undersea wiring required to transmit the power from offshore to onshore and connect it to our grid.

I'll skip over more GE marketing literature. One key point or kind of elemental concept I want to talk to you about is the idea of intermittency. You've probably heard that renewable energy technologies are intermittent in that the wind doesn't always blow. The sun doesn't always shine.

But what we use to measure the output of these technologies is a calculation called the capacity factor. The capacity factor is defined as the ratio of actual power produced divided by the maximum possible power over a period of time. So the key point I want to make is that it's a unitless. It's a percentage.

This is the number or percentage that's empirically determined in real-life operation, and it changes seasonally. The wind blows differently in different places in the summer than the winter. Obviously, it's determined in real-life operation. Seasonally, solar operates-- has different intermittency or different capacity in different times of the year. So we measure the capacity factor, and we use capacity factor as kind of a general ratio that we use to calculate how much energy we're going to produce from a given technology, given that the resource that is harvesting the wind or the sun are not necessarily always there.

So just to give you a few other kind of key terms, the nameplate generation capacity. This is what the manufacturer says the technology can generate. That's what the GE diagram in the previous few slides showed you. That's the nameplate generation capacity. And the nameplate generation capacity varies for different technologies. Just to show you two fossil fuel technologies, a coal-fired power plant or a natural gas turbine.

If we skip to the tables put out by the US Energy Information Administration, when I clicked on the link from the slides for the EIA tables from the Electric Power Monthly, what you're looking at here is a table of capacity factors for utility scale generators primarily using fossil fuels. So just look at the kind of aspects of this table.

You have the annual data. This is annualized data. You have the various fossil fuel-generating technologies. Coal, natural gas. Natural gas is broken into combined cycle, gas turbines, and peaking gas turbines. And you have petroleum steam turbines, gas turbines, internal combustion, and so on. These are all categorized in different ways.

But then the important thing to note is that there's a time-adjusted capacity, and it varies across years. And here's the capacity factor. It's a percentage of the time that the resource is actually producing power.

So you can see that coal has a relatively high-capacity factor, I guess, around 50% or 60%. But that's still much lower. When we talk about coal as a base load resource, a lot of advocates will say, well, we need coal as a baseload resource because it's always providing power.

This capacity factor could be relatively low at 50% to 60%-- 50% or 60% of the time, it's only providing resources or energy for a couple of different reasons. It could be because it's coal power plants are actually frequently down for maintenance. It could also be that coal-fired power plants are simply outcompeted in certain seasons of the year.

For example, if you at the year 2020, you look at the capacity factor, coal-fired power plants look like they have a capacity factor around 50% or 60% still in the summer because in July and August, we have peak electric demand. But the capacity factor gets as low as 25% or 30% for these kind of shoulder seasons and the winter seasons, probably because coal is simply not as necessary as for, quote, unquote, "baseload power" in those seasons of the year. And it's probably being outcompeted by natural gas power plants.

And if you look at combined cycle gas turbines, capacity factor has been relatively steady over the previous years, let's say around 50% to 60%. And you can see, again, that they're much more utilized in the summer when we have electricity demand very high because of air conditioners. But it actually dips also in the spring and fall simply because there's not as much electricity demand when it's not very hot or very cold.

If you look at another kind of gas turbine, natural gas gas turbines, these are probably peaking plants that are used to meet electricity demand for certain peaks or for regulation of the grid, keeping the grid at the right frequency, you can see that the demand utilization for these technologies is relatively low. It's like 15%, 16% in July and August. It dips as low as about 9% or 10% in the rest of the year, simply because these turbines are mostly used to meet kind of the peaks or the reserve or the regulation of the grid itself.

Now, I'm going to show you a different slide. One moment. If we go back to the slides, the handout, and I click on this table for Electric Power Monthly Table 6.07B for nonfossil resources, what you now see are capacity factors for utility-scale generators primarily using nonfossil fuels. So we should just note right off the bat, this is for utility-scale generators. This is what the US EIA, the Energy Information Administration, collects. This doesn't include necessarily rooftop solar.

But if you look at the different types of technologies-- geothermal, hydroelectric, nuclear, biomass, other kinds of gas, solar photovoltaic and solar thermal, and wind and wood-- these are kind of what I've referred to as our renewable toolkit. If you look at the capacity factor for geothermal, it's actually quite high. It's around 70%. Geothermal, because it comes from the heat from the Earth, is quite steady.

Hydroelectric is actually surprisingly low from 30% or 40%, probably because hydroelectric technologies often require water to be behind a reservoir, and then it flows through a turbine and generates electricity. So hydroelectric plants may not be run all year, or they may be run certain times of the year. Again, let's say in July and August. Actually, it's relatively low here.

But you might imagine hydroelectric power plants being run for various reasons in different times of the year. For example, where there's more spring runoff or snowmelt in the spring, it might actually have higher capacity factors.

Nuclear power plants look like they have very high capacity factors, around 90% consistently. And then solar photovoltaic you can see only has a capacity factor of 25% over many years. That doesn't seem to change a whole lot, though you can tell in the year 2020 it does change throughout the year, because obviously some parts of the year the days are longer, notably summer than they are winter.

Wind, you can see the capacity factors are around 30%, 35% over the years. And you can actually see the capacity factors go down slightly in the summer. They're slightly higher in the spring and the winter and the fall.

So this is just to give you a sense of even though certain technologies have a nameplate capacity like GE markets their Haliade turbines, it's not necessarily the energy or the electricity that we derive from these technologies. That's a percentage of the possible capacity.

So going back to our slides, just to show you, again, the capacity factor changes. You can see that nuclear has relatively high capacity. Hydropower, wind, solar PV, solar thermal all have lower capacity factors. And of course, our landfill gas, our biomass, coal, and natural gas power plants have higher capacity factors, so geothermal is also quite high.

A noticeable thing I want you to observe in this graph is that offshore wind has no capacity factor because we haven't empirically determined it yet, or we haven't observed this technology in action. As I said to you on the earlier slides, there's only seven offshore wind turbines operating in the US. Even though we are planning to build about 100% or 1,000 times more offshore capacity, at the moment it's a unproven technology that we still need to understand what the actual capacity is going to be so we can plan to build our grid or forecast how effective this technology is going to be in the future.

So another key metric for the cost of these technologies is the levelized cost of energy. In a simple way-- I just call it here the simple levelized cost of energy-- it's taking the fixed cost, the fuel costs, and then variable operations and maintenance and dividing it all or amortizing it over the length of life of the technology. In other words, taking the average cost of technology averaged over its full lifetime.

To show you in another way, you have the capital cost times recovery factor plus the fixed cost. This is the fixed cost term. You divide it by 8,760 hours in a year and multiply it times the capacity factor because you're not getting the full capacity of the technology all the time.

You can add on this additional fuel costs. This is kind of the cost you're incurring throughout the life of the technology. So you take the fuel cost to average over time and multiply times this heat rate, which is the exact amount of energy you're actually getting out of the heat energy of the technology. For example, with a coal-fired power plant if it has a low heat rate around 30% or 40%, the heat of the technology may actually be going out in the smokestack and you wouldn't factor that into the energy of the fuel that you're getting.

And then you might add on some variable operations and maintenance costs. I think a more exact way or a better but more complicated formula for the levelized cost of energy, Wikipedia actually has a surprisingly good article on this. They call the levelized cost of energy the sum of costs over the lifetime divided by the sum of electrical energy produced over the lifetime.

So you have various terms like the investment expenditure in year T. That's this term here. Plus the operations and maintenance expenditures in year T. That's the MT here. Plus the fuel expenditures in a given year T here.

You add it up across all the years and starting at T equals 1. But the more complicated formula has a discount term, 1 plus R over T where R is a discount rate. That's a way of taking all the financial costs and discounting it over the discount rate.

And then what you do on the bottom is you have the energy. So this is the cost per energy. And you take all the energy over each-- the periods T. Again, sum it up over n terms and discount it. So you discount it because the value of the energy or the cost of the energy may not be the same in the future as it is now. Like the time value of money, you're valuing the energy and the costs upfront more than you are the energy and cost in the future.

And of course, this note down here is useful. Some caution must be taken when using formulas for levelized costs as they often embody unseen assumptions like neglecting the effects of taxes or maybe specified in real or nominal terms. In other words, other versions of the above formula like the previous slide do not discount the electricity stream in the way that the Wikipedia formula discounts it.

But this is why we look at the Lazard levelized cost of energy analysis. I think all the assumptions are stated upfront in the report. This is a fairly industry standard report that gets reported every year. Last year, it came out in this week in October, so we may get a new version this week. You can see the cost of renewable energy up here in the top boxes and the cost of conventional, quote unquote, "conventional" or fossil fuel technologies at the bottom.

And the reason why I say your renewable toolkit is getting cheaper and cleaner all the time, look at the relative costs of each of the technologies. Solar PV on a cost in dollars of a megawatt hour is the same thing as the cost of cents per kilowatt hour. That's $147 per megawatt hour at least for solar PV in the rooftop residential.

But it's much cheaper for a commercial industrial rooftop installation. It's actually about 2.5 times less. A solar PV in a community solar installation is even lower, but none of these other solar installations are as cheap as solar installed at the utility scale using different technologies like crystalline, photovoltaic panels, or thin film photovoltaic panels.

If you look at solar thermal tower, that's also called a concentrating solar tower. This is like out in the desert in California. This is still relatively expensive and has not gotten cheaper over time. Solar PV is the technology that's gotten cheapest most quickly, and we'll talk more about that in the next lecture.

Geothermal is relatively cheap, but it's also important to note in the context of this class that wind is the cheapest resource among the renewable technologies. It's at least at the lowest point $26 per megawatt hour. That can vary and be as much as $50 per megawatt hour, probably for an older wind farm that has smaller wind turbines.

The important thing to note is that wind at $26 per megawatt hour on the low end of the scale is actually much cheaper than our other technology. It's cheaper than a gas peaking natural gas plant. It's much cheaper than a nuclear power plant. It's cheaper than a coal-fired power plant. And it's basically cheaper than a combined gas cycle turbine power plant.

If we look at the sensitivity of these various costs to federal tax subsidies, these levelized cost estimates from Lazard clearly include federal tax subsidies in some of the calculations. You can see that federal tax subsidies make solar PV on the rooftop cheaper and make solar PV on the commercial industrial buildings cheaper. It makes community solar cheaper and makes utility scale cheaper by about 25%, 30%.

It makes solar thermal towers cheaper. It makes geothermal technology cheaper. And it makes wind much, much cheaper. At the low end, $26 per megawatt hour to $9 per megawatt hour. If you compare that to all the conventional or fossil technologies in the previous slide-- and none of these things compete because we don't offer as many overt federal tax subsidies for these technologies in terms of energy production, even though these technologies or these industries do receive a lot of subsidies in other ways.

But Lazard doesn't calculate those levelized costs. Just to show the sensitivity of this because the federal tax subsidies for renewable energy have been much more debated and are, frankly, sometimes a little less secure or less entrenched than the fossil fuel subsidies.

But if we do this comparison again, the key point from a lot of energy analysts and a lot of renewable energy advocates is that if you compare the levelized cost of new billed wind and solar versus the marginal cost of selected existing conventional generation-- in other words, the right-hand side here for coal, nuclear, and combined and gas cycle turbines, we already have that fossil fuel system. It's already built.

What we're trying to compare is, should we continue to operate the fossil fuel system that we have, or should we new build wind and solar? And so the point of this graph is to show that onshore wind, if you subsidize it, it's cheaper to build a whole new onshore wind turbine or farm and provide power that way. Subsidized wind outcompetes all these fossil generation technologies.

And unsubsidized solar PV, unsubsidized wind, and subsidized solar PV are getting to the point where they're starting to outcompete coal and nuclear, and will probably soon outcompete gas and combined cycle-- combined cycle gas turbines also. Thank you very much.