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# Dealing with the Duck Curve

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Webinar Presenter

**Toby Couture** E3 Analytics

This Transcript

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**Speaker**

Welcome to the International Solar Alliance Expert Training Course. This is Session 29, looking at the issue and the fascinating complexities and mysteries of the Duck curve. I am Toby Couture from E3 Analytics and this training series has been supported by the International Solar Alliance as well as the Clean Energy Solutions Center.

This training is part of Module 5, looking at issues around the market integration of variable renewable energy sources including solar PV and focuses specifically on the issue of how to deal with the duck curve. Now for those of you who haven't heard about the duck curve or are wondering what any of this has to do with ducks, don't worry, you'll soon have answers.

So we'll start off by looking at the learning objective. We'll look at what is the duck curve and try to understand how this relates to electricity markets. We'll look at strategies for how different utilities, different companies can deal with the duck curve and we'll conclude with some concluding remarks, a bit of further reading and at the end there will be a knowledge check with a few multiple choice questions to make sure that everyone's been paying attention.

So the aims of the presentation are to understand what the duck curve is, what it means for utilities and for electricity markets more broadly, to understand how utilities and stakeholders are trying to deal with it, what kinds of solutions are being put forward, what kinds of approaches are being tested and to understand how the duck curve fits into a broader description around reaching high shares of variable renewable energy sources. Understand the relevance also of the duck curve for both developed and developing countries.

So first let's put this in the context of the background and the rise of variable renewable energy. Analyses of the global energy transition put a growing emphasis on the rise of variable renewable energy sources which effectively just means mainly solar and wind. So solar PV in particular and wind power. We say variable because the output fluctuates in real time and is not dispatchable in the conventional sense. Conventional power plants like gas plants, oil, diesel, nuclear, well, to a varying degree nuclear and hydro, can be dispatched. They can be turned on and scaled up or scaled down again to varying degrees depending on the technology.

Variable renewable technologies like wind and solar because they rely on renewable resources that are available in a natural environment and are dependent on weather are typically considered must take resources. In other words, when the wind blows or the sun shines, you take that power and if you're going to scale anything else back, you scale back other sources of generation in the mix, particularly non-renewable resources and the more flexible of the non-renewable resources, in particular gas plants. So you scale those back to make room for more of this variable, renewable generation.

Now while that often can make perfectly fine economic sense and can work in practice and can work at small levels of penetration, it becomes much more challenging to keep the lights on at much higher levels of penetration. So when we're talking about beyond say 25 per cent of variable renewable penetration and we'll start to see why as we work through the presentation.

Oh, I skipped one. So you can see here on a—from a pie chart perspective, variable renewable energy, in particular solar power, is projected to represent a very significant share of global electricity production in 2050, over one-third worldwide which means there are going to be some markets where over 50 per cent of the electricity supply is likely to be solar PV. So this creates a host of challenges and the duck curve, as we'll see in a few moments, is one of those challenges.

Using the example of Germany, you can see here quickly the rise of different—the evolution of different sources of generation in the power mix in terawatt hours over time. German electricity demand has been almost flat since the 1990s. But in the meantime what has happened is some sources have declined, in particular nuclear and hard coal while renewables have increased. You see here the share of renewables really picking up rapidly starting around 2004.

Casting things forward and looking at today, this shows May of last year and a full week of the power mix profile. So you can see onshore wind there in lighter blue and offshore wind in darker blue but particularly onshore wind playing a very significant part of the mix and some days reaching roughly 50 per cent of electricity demand. So the demand is *nachfrage* there, that's the pink line that you're seeing. And the purple line you can ignore that, that's just the emissions factor of the electricity mix. But for now focus on the pink line. You can see here that wind power during certain hours of the day is representing somewhere close to 50 to even over 50 per cent whereas solar itself is almost reaching close to 50 per cent.

So taken together on May 1st and into May 2nd, the solar—these were basically cloudless days across Germany so you have a nice smooth undulating profile. As the sun rises, PV supply increases and then decreases as the sun sets. And when you have that unique combination where the wind is blowing steadily, particularly on the north of the country where most of the wind turbines are and solar is shining strong, which is scattered across the country but also with a slightly higher concentration in the south, you get this nice profile. And solar and wind together on May 1st were supplying 94 per cent of electricity demand in the German power system. That's 94 per cent of the mix instantaneously coming from variable renewable energy sources.

So a fairly remarkable achievement in some ways. Many expect that Germany will very soon pass the 100 per cent mark. Meanwhile, exports have grown. Germany is very well interconnected with its neighboring countries so it fortunately has the ability to export excess power but you can see here that as the share of wind and solar grows, this really becomes a dominant part of the electricity market during a growing number of hours of year and during certain days of the year it really is the bulk of the market.

It's important to underscore also that in Germany renewables have priority in the grid so they, as we discussed earlier, when the wind blows and the sun shines, they have priority and that electricity gets dispatched, gets taken first in numeric order and other generation sources have to scale back.

So this gives you a bit of an overview of the curve for a standard electricity demand profile in a market with a high share of variable renewables. Now we get to the heart of the matter, what is the duck curve and what do ducks have to do with any of this. So electricity demand in a standard electricity market follows a fairly typical pattern. Typically it's lower overnight followed by ramping in the early morning hours, so around 6:00 AM. People wake up, people start flicking on the lights, businesses start to turn on, coffee machines, the tea kettles, the showers, the hot water, all of it starts gearing up. Electricity demand increases, stabilizes over the day, typically reaching a peak sometime in the late afternoon or early evening before declining again into the evening hours. This is a fairly simple undulating profile.

This shows a simulated load profile for California from the 2000s. And you can see here this is fairly standard stuff. And here on the right you can see the different fuel sources, so CC, which is the largest, and you can see here the one that's ramping the most, those are combined cycle gas turbines. So they are basically coming up here around 6:00, 7:00 AM and are really starting to gear up and are essentially making up the majority of that daytime surge in electricity demand a company then supported by hydro. So the hydro is the blue one and you can see that also coming into gear as a dispatchable resource. So this essentially gives a snapshot of California electricity load profile by generation mix in a standard form.

Now spread that out over a week and you get something like this. Over a standard week you can see all is fairly easy. There's a tiny bit of wind here because California had developed some wind power in the 1980s and early '90s and has continued to scale up since, but it's still a fairly small part of the mix, at least when this was written in the 2000s. And you can see here other technologies on top and the same basic profile. So the first to identify and coin this term, the duck curve, was in a paper from researchers at NREL led by Paul Denholm to really identify this and give it the name we have today and that has really become embedded within the debate and is the focus of this presentation.

So if it walks like a duck and it quacks like a duck, there's a good chance that it's a duck as the old saying goes. And you can see this simulated load profile looking at what will happen. This was a forecast, mind you, in California done by the California Independent System Operator saying what's going to happen if the growing amount of solar PV continues to happen. So in the 2000s there were still small amounts of PV in the California system, but demand really started to pick up in the late 2000s and early 2010s and they started to get worried and wanted to model what the effects of this would be.

So when you look at this profile as we saw from our day, what happens if the daytime supply here, which its peak starts to hollow out and starts to come down and you see here the peak in 2012 was the actual and then 2013 updated and then you can see essentially this graph is showing the net load. In other words, the load after solar. So this is sometimes what's referred to as the residual load to be met. So the utility needs to basically meet actual power demand, but when a growing amount of that is being supplied by PV, by solar PV which is being fed into the network and accepted typically on a priority basis, it shifts then net load downwards. And you can see here they started looking forward and saying, "Well, what happens if solar continues to be scaled up?" 2014 looks like this, 2015, '16, '17. '18, '19 and 2020 going down the curve. And you can see here that the daytime net load that needs to be met by other generators in the network reduces from somewhere around 2200 megawatts capacity in 2012 down to 12,000 megawatts in 2020. So very significant decrease in effective net post solar load to be met in the system.

Now on the one hand you might say, "Well, this is fine, more solar in the system is great. We burn less natural gas," thinking back to our earlier diagram where natural gas was the largest, most dispatchable source used to meet up that gap, to meet that surge in electricity demand. So far so good. One of the consequences of this, however, and this was rightly identified by Denholm and the team of researchers at NREL is that this leads to an increased ramp in the early evening hours. And for those of you—for anybody who's traveled in developing countries or who's _____, this happens all over the world. In the early evening hours when everybody's flicking on the lights and the flicking on the air conditioning units and so on and cooking that it's common to have power outages because there's not enough electricity supply in the network to meet the surging demand.

Part of that is driven by the challenge of meeting a very steep ramp because you need lots of generation. We're talking here 14, 15,000 megawatts of capacity to scale from 12,000 up to 26, 27,000 megawatts within a span of just a few hours. And in some cases really at the steepest part of the ramp we're talking in minute intervals with demand just surging by hundreds of megawatts. So very rapid ramp requirements which creates a lot of strain on the system and is incredibly difficult to meet. Now if you had bottomless hydro dams and you could just open the floodgates, you could easily meet this rapid ramp. But the reality in most of the world is we don't have very large abundantly available, endlessly dispatchable hydro dams. We have more—we have constraints.

And one of the challenges here for the California system and for many others is, as you can see with the duck curve with that high evening peak, you have to have a huge amount of generation capacity that is only used for a few hours per day. And if that generation capacity is only used for a few hours per day, you have a problem. Because it's massively overbuilt and somebody needs to pay for that. And that's the challenge that gets into sort of peeling the layers back in a way of the challenge of the duck curve and meeting this increased ramp requirement. So that's where the duck curve comes from and you can see it here nicely modeled by the folks at the California Independent System Operator.

Solar PV generates electricity mostly during the day so obviously in equatorial countries from 6:00 AM to 6:00 PM, pretty reliably and in, depending on northern climate, southern climates, 8:00 AM to say give or take 9:00 PM. Sometimes even earlier, it can be—power generation can start even at 5:00 AM if you have really early rise. In certain jurisdictions half the panels are tilted in the right direction but basically you only start to really get significant power supply between those hours, sort of 8:00 AM, 8:00 PM to 9:00 PM in the summer.

The more solar PV enters the grid, the more it displaces other sources of generation and as we saw, this disrupts the historical dispatch order of power plants in the system, creating a trough in the midday hours. You can see here that belly down is a displacement of other generation sources and creates a host of challenges. Now you can also imagine if there were baseload supply within this, let's say everybody talks about baseload supply and we need baseload supply to compensate wind and solar. You can see this all the time in newspaper articles and coming from people who really should know better.

The challenge here is actually that the more baseload supply, in other words inflexible baseload supply you have, the more problematic daytime solar power generation becomes because as soon as you start to have more solar, you more rapidly bump into this inflexible baseload. So you have a problem. Either the baseload supply needs to be made flexible in our efforts to try to do that even to make nuclear plants flexible, coal plants flexible it's costly and it's also not easy and there are other generation sources that can provide this flexibility and there are other ways of providing flexibility that have nothing to do with generation but rather look at the demand side using demand response and dispatchable loads.

So we'll get into that in a moment but the challenge here, you can see it nicely illustrated by the belly of the duck, the more it goes down from 14,000 down to 12,000 megawatts peaking in, the more you hit into, the more you strike that baseload of supply if you have significant baseload in the system.

So at some point something has to give and that's one of the challenges and that's one of the reasons why the whole discussion around needing more baseload is arguably misleading because ultimately if we have too much baseload we're just accelerating the pace at which—or the—at which this challenge is going to have to be met head on because you can't have tons of baseload and tons of solar. It just doesn't work. At least under today, the amount of flexibility from today is system, the amount of demand response and so on—so not going to mention the amount of storage.

So put differently, rising solar output during the daytime progressively erodes what is called the residual, i.e. the post solar daytime load that was previously met by other sources on the network. And the duck curve can get even steeper as the amount of solar generation increases in the system, generating further challenges in keeping the lights on. And you can see this in a range of different markets. It's not just California. California's one of the most studied electricity markets in the world, partly because it's fascinating for historical reasons but also because it has set itself very ambitious renewable energy targets and it has a fantastic solar resource, it has terrific wind resources and it's doing quite a lot to scale up other innovative technologies in the utility sector.

So California is often focused on, but this is not just a California-specific story. These challenges are emerging are Hawaii, they're emerging in Australia, they're emerging in parts of Europe and it's very much they're increasingly emerging in China. This is very much a utility wide global challenge. And looking at California, the estimates, it turns out are already off. So we are well beyond today in 2018, 2019 well beyond the estimates of where they, California independent system operator thought they would be in 2019. So there's an even greater risk of overgeneration, in other words, too much electricity in the network, too much solar on the network, too much of everything on the network, a deeper belly net load you see here reached just over 7000 megawatts on February 18, 2018 during the daytime. So really dramatically below, well below where they thought that would be and an actual three-hour ramp of just under 15,000 megawatts on March 3rd a few days after in 2018.

So we are seeing increasing strains on the system and this really screams out for a solution so the curve can get steeper, the belly can get deeper and deeper and create a host of challenges for the operation of the power system. As this also started to happen in Hawaii, clever people at HECO, the main utility servicing electricity demand in much of Hawaii came up with a new term here called the Nessie Curve. They said if they look at their profile, which you can see here is sketched out, particularly the residential green profile, you can see that the steepness is even steeper than the duck's neck, hence justifying the introduction of a new species in this ecosystem, the Nessie Curve.

Very little residual demand during the daytime that's not met by solar. In other words, Hawaii during the daytime, at least certain particular regions, particular feeders of Hawaii during the daytime are met entirely by solar.

There are daytime—some parts of the Hawaii grid where solar represents over 300 per cent of residual—of daytime load effectively on those feeders. So all of that electricity is then flowing elsewhere in the network out of those feeders backwards up the substation and to other parts of the network. So very significant shares of solar because of large numbers of households with solar, large numbers of businesses with solar but also because Hawaii has a terrific solar resource and a fairly high electricity prices which makes it attractive to invest in solar.

So this is the Nessie Curve. But in many markets around the world and for those of you who are coming from other countries, it's important to take a step back. If we had version 1.1 which was the duck curve, 2.0 is the Nessie curve. If you take a step back, version 0.0 actually looks something more like this. In most emerging markets, most developing countries around the world, you have much smaller resident, much smaller industrial loads, commercial loads and the overall electricity demand profile is driven much more by the residential sector. Load shedding, in other words power outages are more common and you have less spikiness. So you still have a very high ramp in the evening but often there's not enough generating capacity to meet it because of inadequate investment in generation and you have load shedding captured here by the fin of the shark.

So you can see here imports. This is actually a snapshot of Nepal. This is Nepal's power mix in October 2016 showing the NEA is the Nepal electricity authority, basically their own national electric utility generation. Then there's IPP generation, which is mostly hydro, mostly run with river hydro and then imports in yellow. The imports come predominantly from India. As you can see here, basically much of the Nepalese mix is hydro and it just floods and goes along and imports are what are making up the—or what are covering essentially the rise and fall of electricity demand over the course of the day. That import capacity is limited because there's only so much grid capacity to import power from India which means that that peak in the evening goes often unmet. And that creates a host of challenges so obviously power outages but also unhappy customers.

So this is, in some ways, a power curve that looks much more like most electricity markets around the world in other countries. And if you were to go—if you visualize this and you start to add solar into this mix, what would solar do? Well, solar would enter in around 6:00 AM, 7:00 AM and go until 6:00 PM, thereabouts, 5:00, 6:00, depending again on the orientation of the panels and it would start to hollow out that daytime supply. And you would get again this steep curve. So you would start to get a duck curve and a way out of this, out of Nepal.

Now mind you, Nepal is in the process now of scaling up solar power. So the duck curve is on its way. And this is something that the authorities in Nepal are aware of and are trying to provision for but the main challenge remains meeting this evening load and reducing load shedding. Now if you were to shift the solar panels to point to the west, for example, so that they get later afternoon sun, you could erase a bit of address a bit more of this peak but you’re not going to get all of it. So there are some residual challenges that remain and that’s where we start to need to look at some of the solutions to the duck curve.

So the evening spike is even sharper and it’s beyond most utilities’ ability to meet. The fact that evening load is frequently unmet also has the effect of eroding utility revenues which means utilities don’t—they could use those revenues in order to generate more money, in order to invest in solutions. But because that evening shark fin is basically lost through load shedding, that revenue isn’t there and that creates in a way its own set of challenges. So there’s a bit of a chicken and egg problem. If you could build the electricity system out in such a way that you can meet that load then you can generate more revenues for the utility which could then help finance those investments but again, getting there is the challenging part.

Also in most emerging markets you have lower energy efficiency and the absence of price signals that don’t provide signals during these hours of the day. Energy inefficient lighting is a major driver of this evening load. LEDs are available in many markets but they are not yet mainstream. And air conditioner units are also often less efficient and a major driver of this evening peak. So again, challenges abound.

So how can this challenge—how can the duck curve be dealt with? Let’s look at some of the strategies being used around the world today. In a follow-up paper published by the original authors of the duck curve paper in 2008 followed up I believe in 2015/16, the author suggests two basic approaches which we’re going to try to unpack a bit further. On the one hand, fatten the duck and flatten the duck. So fattening the duck is code here for introducing measures to increase flexibility of existing plants on a network and make it easier for them to ramp down. In other words, make the power system more flexible so that you can ramp down and that the PV doesn’t have as much of a disruptive effect on daytime power markets. Reducing the must-run capacity on a network, the inflexible coal and nuclear plants, for example, removing inflexible assets from the system. That could help fatten the duck and make it easier to deal with low net load during the daytime caused by high shares of PV.

A second thread, a second flank of approach is to flatten the duck as they put it, to shrink the belly of the duck by shifting supply and demand to other times of the day. So in other words, take power supply that would be there in the evening or power demand rather that would be there in the evening and move it into the daytime hours. So things that people are using at night, try to shift those loads as much as possible into the daytime or by using storage or by using power-to-x, power to hydrogen, power to gas and so on. Various options there which we’ll unpack in the slides to come further.

So visually this is how they characterize it. This is the first, fatten the duck where you see here essentially enabling the system to go down to lower, to deeper minimum generation. So the current system operates best around 12,000 minimum generation, that’s the kind of ____ threshold that if you remove some of those inflexible assets, you can make it cost effective or possible to easily get down to say 5,000, 6,000 megawatts, making it easier to integrate all that PV. So that's to fatten the duck.

Now flattening the duck. Well, flattening the duck means increasing load during the daytime and reducing it during evening hours. And you can see here the arrow net shifting load, pushing down on the evening load and shifting it into the belly so that you can better—make it better correspond with solar power output. Now some people would say, "Well, that's crazy to start to restructure electricity demand," which has always been taken as a given in electricity markets just so that we can adapt it to the daytime output of solar power. But the fact remains solar power is by far and away our largest energy source on the planet. It's abundantly available in every country in the world and it's also increasingly our cheapest source of new power supply.

So the incentive to continue using more solar power is powerful in bringing cheaper, cleaner power to all. And I think the momentum there as you look at this a bit more carefully is very much in favor of solar power which indicates that this whole discussion around shifting load around may, in fact, be necessary and is emerging as a necessary solution to again adapt the power system more to a future with higher shares of variable renewable energy like solar PV. So again, this is not something that's going to happen in a matter of days or months or even years, this is something that's really going to happen over the course of decades as the power market shifts and evolves into a new paradigm or a new configuration.

Now the obvious strategy that a lot of utilities would be inclined to use if they could is simply to curtail solar output, right. We'll just say we're just not going to buy it during the daytime when there's too much. But the problem with that is that not only would this risk undermining the economics of many privately financed solar PV projects which need that daytime power output in order to pay their loans, it would also be counterproductive because the power system would effectively be rejecting clean, locally produced power in favor of inflexible non-renewable power. So why would we do that? And that's why this growing amount of interest in looking at, okay, what can we do to address this challenge, what can we do to solve the challenges posed by the duck curve?

The aim is ultimately to use fewer non-renewable resources during the daytime and to avoid overgeneration also during the daytime. This can involve creating more load when the sun is shining so that it corresponds better or again shifting loads that currently occur in the evening to earlier in the day. And there's a range of ways, as we'll see with these different objectives, can be met.

So I've outlined here 12 basic strategies that can help deal with the duck curve. This list is not comprehensive. There are probably examples that fall outside of the examples we've used here or nuances to the existing examples that could be unpacked and turned into a standalone solution. But the attempt is to try to capture essentially the main portfolio of options being discussed. So the first is to scale up energy efficiency. Energy efficiency can help reduce the evening peak as well as the steepness of the evening ramp. So the more efficient lighting is, for example, or the more efficient air conditioning is, then the less steep the ramp because that's—it's in those early evening hours when everybody comes home that all the air conditioning units go on and all the lighting goes on, if we could make those more efficient then we could scale back the steepness and scale back the peak.

Increases in energy efficient lighting like LEDs have already contributed to evening peak shaving in most jurisdictions around the world. So LEDs have already made a huge contribution to this, above and beyond incandescent lightbulbs which were dominant in the 1980s and '90s. Efforts to boost the efficiency of other appliances like air conditioners, televisions, et cetera, can also help further reduce that evening peak. So if you bring the peak down, you bring the head of the duck down, so to speak. You flatten the overall daytime load profile, that can help again reduce the steepness of that curve and make it easier to deal with from a utilities standpoint and operational standpoint.

Second, orient solar panels to the west. Now as we saw in the case of Nepal or as we discussed briefly in the case of Nepal, if you orient your solar panels to the west, it shifts the traditional bell curve output of a solar PV project to later in the day. Because the sun sets in the west, you can measurably shift the output to those later hours so that it corresponds better with the overall electricity systems demand profile. Another way to do this is through price signals. Obviously if solar projects are exposed to market prices and market prices are higher in the evening hours then it will make sense for projects to orient their panels a bit more westward so that they can produce more power when it's worth more. So this is all part of an ongoing discussion.

This graph here shows the difference, models of the difference. And you can see that somewhat more solar power is produced after 6:00, probably twice and two and half times more in this diagram post 6:00 then under the south facing system. So again, not a negligible shift and gives an idea of some of the games there that could be achieved. A third solution is to scale up demand response. Demand response is essentially a catch-all term involving shifting load around to different times of the day in a smart and coordinated way. Price signals can help support demand response as can other regulatory approaches. Demand response can be led by the market or by the utility. And you can see here how different appliances, different loads could be made more dispatchable in the years ahead. So water heating is obviously one major candidate.

Space air conditioning is another candidate. If we can make that a bit more efficient and also there's efforts to make space conditioning iced-based. In other words, you would produce air conditioning units under new models would be used just like old models. I mean the original—it's important to remember historically that air conditioning used to be produced by storing large blocks of ice which were harvested from lakes throughout North America and Europe and basically kept mainly in hotels and other places that wanted to keep the air cool and had paying customers who were prepared to finance that using large blocks of ice which could be blown and distributed through an air distribution network.

Now we could in the future go back to that, interestingly, where air conditioning units, instead of just instantaneously producing cool air, could go back to producing ice during the daytime hours which is then again discharged, so to speak, into the air in the evening hours. So it would shift air conditioning loads, which in this depiction here are over 30 per cent of residential electricity demand use in the U.S. Much of that could be met with daytime supply. So if you take that 30 per cent residential slide, which is massive, that's a very large part of the electricity market, you could shift that more to the daytime hours and couple it again more meekly with the output of solar PV. So again, significant potential there.

But in many jurisdictions there are limits on the extent to which utilities can access behind the meter resources like appliances. So utilities don't have control in most cases over your air conditioner and water heater. And many of you may be thinking, well, with good reason. I don't want the utility controlling my water heater or my air conditioning unit. I want to control that. Now there are some pilot projects underway looking at how utilities can aggregate customer-cited resources in smarter ways to be able to use them across the network to improve the integration of their renewable energy sources. So, for example, refrigeration loads and water heating loads, residential water heaters and commercial water heaters can be effectively dispatched and controlled remotely without significantly impacting customer experience. So in other words, homeowners wouldn't even notice that the water heater's being tweaked up or down at a given hour of the day.

So it's neutral from the customer's perspective, but it opens up a new source of flexibility in the load from the utility's perspective. So there are efforts to try to open up the laws, open up the regulations to allow utilities under certain cases to own and/or control water heating assets, for example, or for supermarkets to connect up the refrigeration units, for instance, within thresholds of course but gives you an idea of where this goes. So this is where the fourth point emerges which is enable utilities to have greater control over dispatchable loads. So enabling that in the market if it isn't enabled already can help utilities better coordinate load to match abundant solar PV output during the day. This can yield a number of different benefits for good integration and can help again avoid curtailment, having to basically not accept solar because there's overgeneration in the system. So by creating more load during the daytime, you can help solve that problem.

Certain appliances are obviously better suited to this than others so water heating is a classic example and the potential to aggregate those together into not only thousands of individual units but potentially millions opens up the possibility again of shifting more load to the daytime to correspond to variable renewable energy availability. The fifth is to require major loads like air conditions to integrate thermal storage. This comes back to the ice example that we discussed earlier. Air conditioners represent a major component of the evening ramp in many countries around the world, but traditional air conditioners are not only inefficient, they're also a huge weight on the grid and are a leading cause of power outages in electricity markets around the world.

So trying to create new ways, innovative ways or even just using older ways of producing thermal storage can enable these cooling units to be charged up, so to speak, during the day by either producing ice or some other glycol type fluid that can be dispatched later on in the evening hours which alleviates the stress on the grid. And you can see here that although this matters in the commercial sector and in the large and industrial sector with air conditioning loads growing here on the far right, the major driver here is the residential sector. And again, this is mostly late afternoon, early evening when people come home. And this is a challenge across almost every emerging country, emerging market in the world from Bangalore and Mumbai in India to major cities in China to Manila, Lagos. I mean this is a huge challenge. So there's a major call, a major need for re-envisioning how we do air conditioning. And these alternatives can really provide a powerful alternative to current air conditioning technologies with a number of benefits for the grid and for customers.

The sixth pathway is to apply these time-of-use rates or variable pricing for the ramping hours. So higher demand charges, for example, during the critical ramping hours could help trigger price-driven changes in electricity demand. So people could say, "Oh, electricity demand is so expensive in the evening hours, I think I'm going to buy myself one of those new ice-producing air conditioning units so that my electricity demand is during the daytime and not during the nighttime. Similarly businesses could start shifting their usage profiles in different ways using different dispatchable loads that are not as time sensitive. Houses could avoid washing clothes or turning on their dishwasher during that critical say 5:00 PM to 9:00 PM timeframe. A range of different possibilities, but pricing can be one driver and one important driver of behavioral change.

The seventh is to increase the use of power-to-x. In other words, electricity can be converted into a wide range of end-use of applications, including fuel cells, storage, hydrogen, among others. Scaling up the ability of the system to do this can create more daytime power demand. Again, corresponding nicely with solar PV. To use up that solar PV and produce other forms of energy, other storage or hydrogen and so forth, they can be used and dispatched in different ways and at different times. So potential there for again shifting more load to the daytime in a more flexible and controllable way.

The eighth is to expand balancing areas and allow more transmission. If you can import and export power, as we saw with the example of Germany in the beginning. Germany is a very highly networked electricity market. It benefits from strong electricity import-export ties to the Netherlands, to France, to the Czech Republic to Poland and Austria and that interconnectedness is a major asset and it can help again mitigate the duck curve and make it easier to maintain higher liability and in the case of Nepal, as we saw, it can be critical to help meeting that evening peak as Nepal imports predominantly to meet its evening peak demand.

Another one is to remove inflexible power plants from the system. As we saw earlier, this is similar to fattening the duck in the original characterization. The inflexibility of existing generators on the network is a major part of this challenge because that produces essentially a bottom on the minimum load at which electricity system is comfortable operating at. And if you can reduce some of those or remove some of that inflexible load, you can make it easier again to integrate more variable renewables and more solar PV in the process. So the presence of inflexible loads is a major challenge, is a major barrier in some ways to the continued scale up of solar PV. And that's why this old argument about needing more baseload supply to compensate for variable renewable energy is dead wrong and that's why we really need to shift the conversation away from the need for baseload because that's exactly what a solar heavy electricity market does not need. A solar heavy electricity market with high penetration of solar PV does not need inflexible baseload. It needs flexible load following dispatchable rapid response resources, including demand response and we'll discuss that more at the end.

Another one is to expose solar PV to real-time market prices. Often solar PV projects had PPAs or Power Purchase Agreements or guaranteed feed-in tariffs which basically create an incentive them to produce at maximum output all the time and make them fairly time of day agnostic. If—when solar power projects get out of that contract period and are exposed to market prices directly, then there's more of an incentive to produce power during the evening hours which may lead to future projects actually being built to orient westward. And we're starting to see that in Germany. Germany has seen some of its first westward facing solar systems growing up in recent years.

Number 11 is deploy storage. Obviously storage can play a role for reasons that we probably don't need to get into too much detail. Storage can be a part of the solution and is definitely one of the portfolios of options being discussed here. And that doesn't necessarily mean battery storage, that can mean any of a number of different storage technologies. And finally acquire renewables. Other sources of renewable generation that have complementary production profiles. So some sources like hydro or wind power have important complementarities with PV. So wind blows mostly in most markets at night, hydro is relatively flexible so there's ways you can integrate these to make it easier to deal again with the duck curve. So summary of the options here. I've put them all on one slide just for ease of reference and to go back to, summarizing effectively to 12 main options.

The impacts. Now if you were to do all of these things in California, to come back to our original duck curve diagram, what would it do? So some analysis undertaken in California tried to do just that. And you can see here in a section of the California grid, this is not the entire California grid, you can see here the impact of the post-strategy net load so versus the original net load which is the dotted green line on the bottom basically maps the red one on top. That green one, the green dotted line is where the load used to go and now if you shifted, if you did all of those things, you could significantly shift more again power supply to the daytime or power demand rather to the daytime and significantly flatten the overall net load. And by flattening the overall net load, you make it a lot easier to be met with by any other range of other generation technologies, including inflexible baseload sources.

So if you do all these measures in a way, you make the power demand curve flatter, again, which makes it easier to be supplied all around from whichever sources the power mix happens to have at its disposal, either from imports or from sources within the network. So again, a much more utility friendly and much more system operator friendly load profile and you can see here the quite dramatic impact that that could have, can have through the implementation of a portfolio of measures.

So a few concluding remarks. As I've said it a few times throughout the presentation, renewables need flexible backup, not baseload. This chart shows the differences between a week in May 2012 and a week in May 2020 and you can see the dramatic differences in the power profile and the net residual load in gray that's effectively unmet by renewables. So in some days like on the Saturday here in this depiction on the right, there's effectively zero unmet load from beyond renewables. Everything is met with renewables pushing out everything outside of the network. On Sunday it's even worse. On Sunday you have a situation of overgeneration where basically you need to export that power or again store it or use it up in different ways or boost demand so as to use that up.

So again, if you imagine the addition of a baseload flank of power supply into this, it really doesn't make sense. Baseload and variable renewables like solar are, for the purposes of the power system, effectively like oil and water. There are four main challenges that define—four main factors that define the challenge of integrating variable renewables: the geographic spread, how distributed over the landscape is, the solar power or the wind power, the existing flexibility of your power system, whether you have hydro, open cycle gas turbines or other highly flexible resources demand response. The third is a level of interconnection with neighboring jurisdictions and fourth is the overall size and mix of your renewable energy portfolio.

Now this is really what defines how challenging it is to deal with the duck curve. And as we saw with the various strategies that we just went over, there are solutions available. There are ways to fatten, flatten a dress, deal with the duck curve in a way that we can continue to increase variable renewable energy shares and push forward towards a cleaner and more sustainable power system.

As I mentioned at the outset, this list of strategies and solutions is by no means comprehensive. There are and will be new innovations emerging that will help further address the duck curve, potentially more cost effectively, potentially even more smoothly than some of the technologies discussed here and solutions discussed here, but at least this provides a concise overview of some of the main portfolio options available.

In sum, the duck curve does entail, however, a fundamentally different approach to operating the power system and as the share of solar power grows, again, because solar is our most abundant renewable energy resource, our most abundant energy resource on the planet and because it's increasingly the least cost resource, we urgently need solutions to tackle this challenge. And hopefully this has provided a helpful overview to further catalyze this important discussion. So thank you very much for your time.

A bit of further reading for all of you who've paid attention all the way through. The original paper here from Denholm as well as the follow-up paper, both from NREL. An excellent report from which many of the examples here in this presentation are drawn by the Regulatory Assistance Project, Teaching the Duck to Fly is also provided here. And then a short piece that I wrote last year on the shark curve and the duck curve and all of that, trying to put this into context specifically for developing countries, drawing on the experience of Nepal.

So with that, I'd like to thank you very much for your time. I'm Toby Couture from E3 Analytics. I'd like to thank the International Solar Alliance as well as the Clean Energy Solutions Center for their generous support of this training series and we'd like to invite you now to stick around for the multiple-choice questions and a quick knowledge check. Thank you very much and I wish you all a great day.