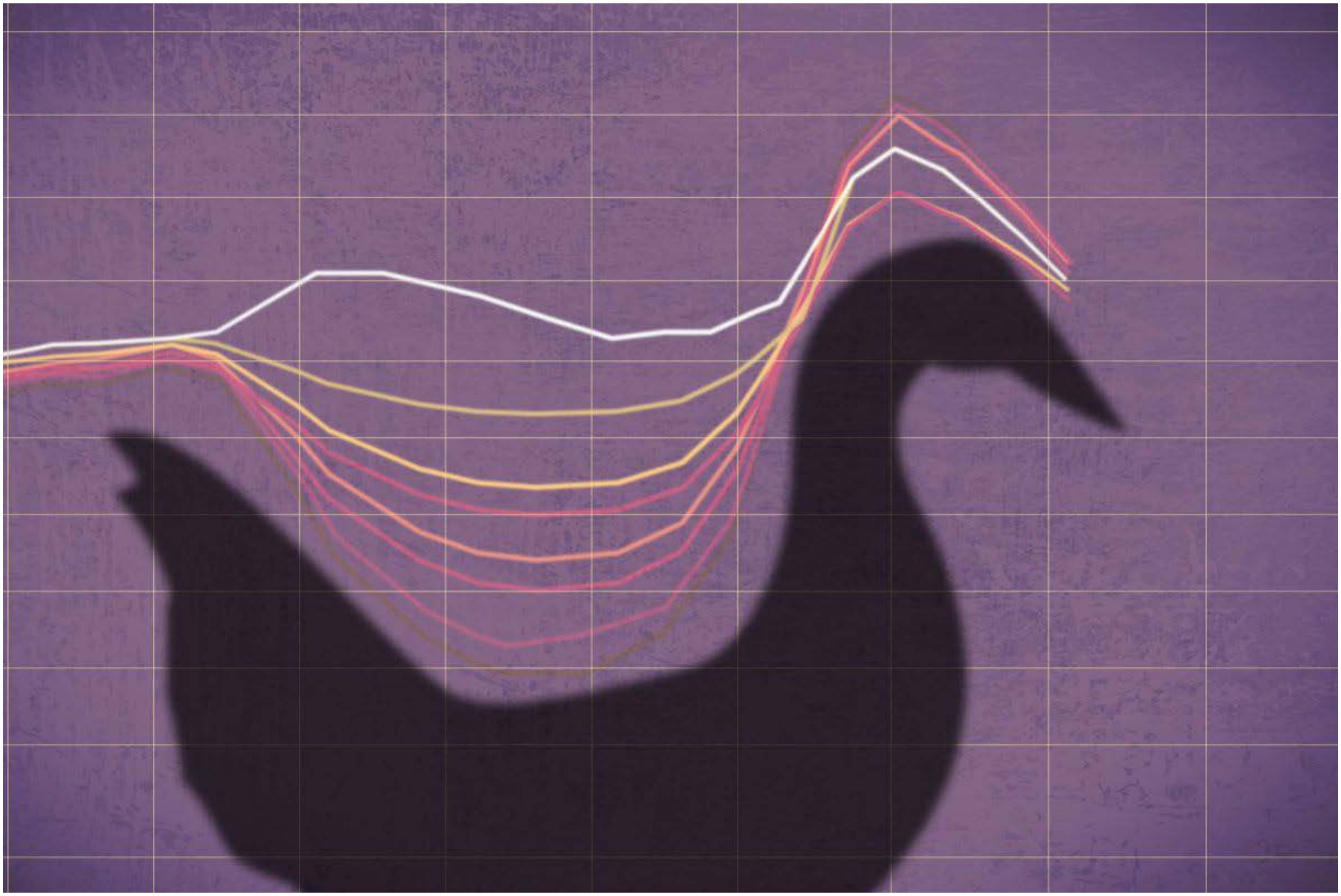
Solar power's greatest challenge was discovered 10 years ago. It looks like a duck.

A researcher discusses the "duck curve" he helped discover.

ByDavid Roberts | @drvox | david@vox.com | Mar 20, 2018, 9:00am EDT

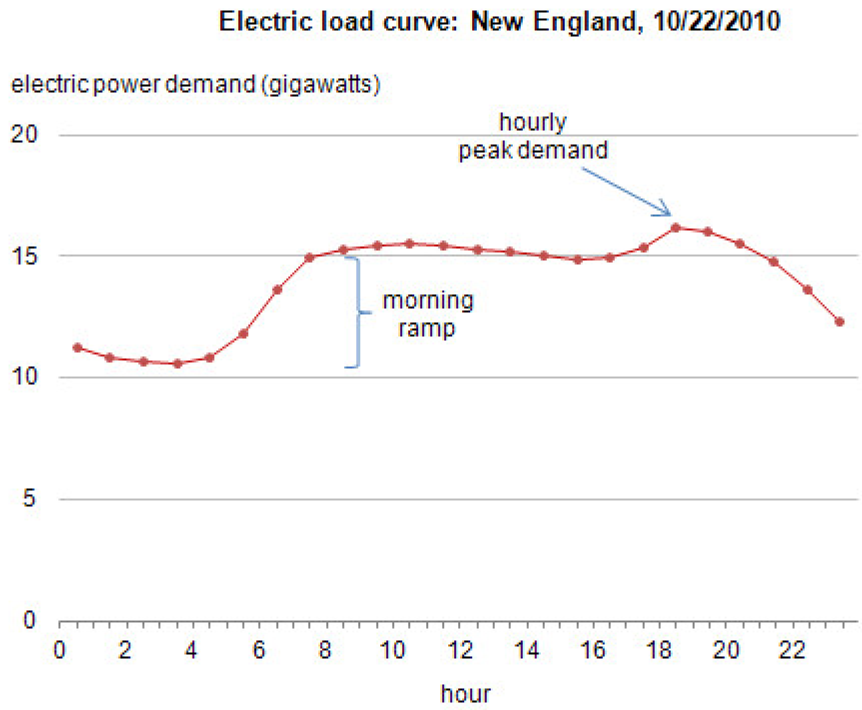


Javier Zarracina

Back in 2008, a group of researchers at the National Renewable Energy Laboratory (NREL) noticed a funny-looking shape in their modeling.

They were starting to take solar photovoltaic (PV) panels seriously, running projections of what might happen if PV were deployed at scale. They noticed that large-scale deployment had a peculiar effect on the electricity “load curve,” the shape that electricity demand takes throughout the day.

A typical load curve looks something like this:



EIA

As you can see, demand spikes in the morning (when everyone wakes up) and again in the evening (when everyone gets home from work), before declining at night.

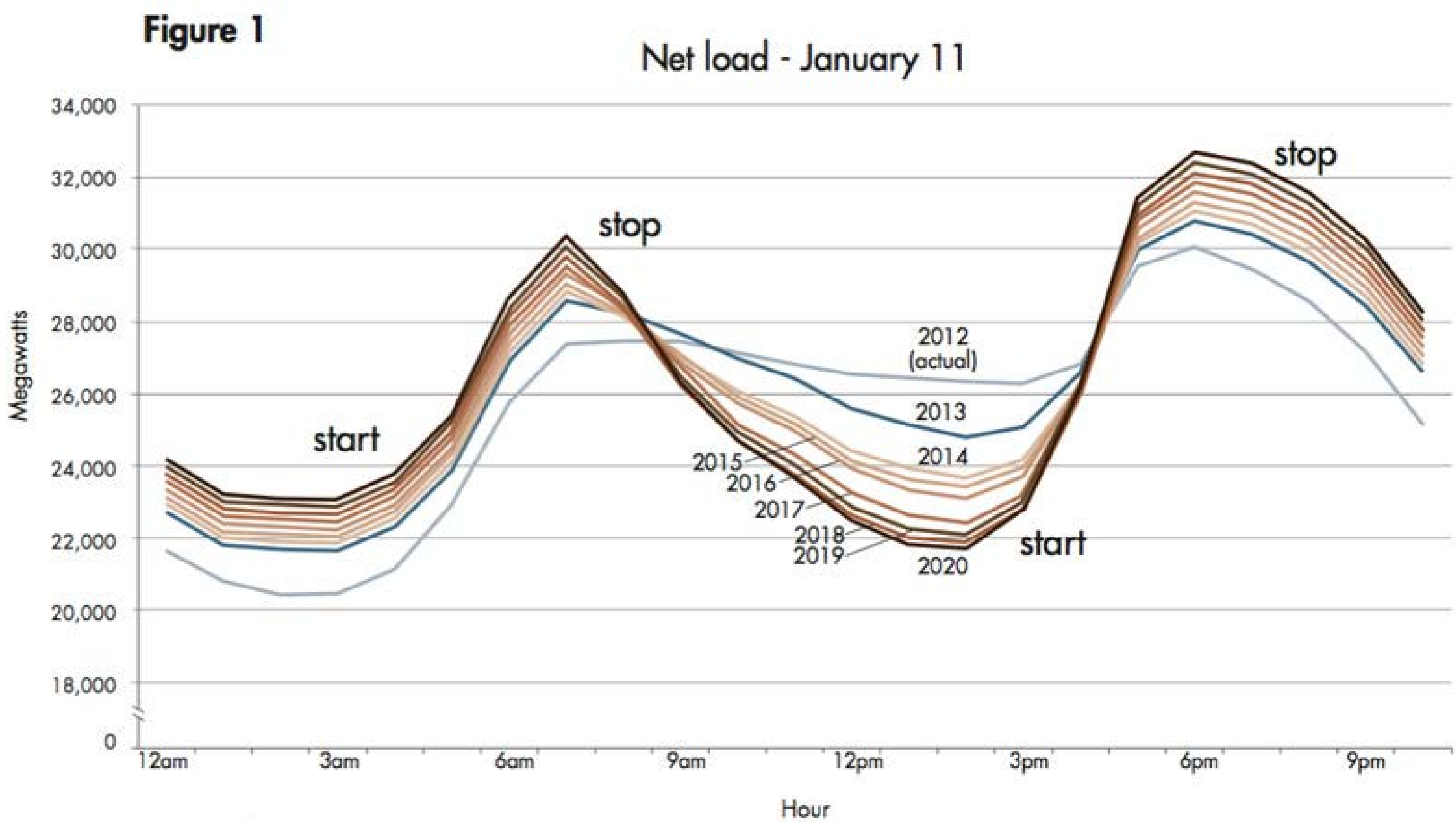
This curve happens to be from New England, in the fall. The curve looks somewhat different in different regions and during different seasons — there are different-size peaks and ramps — but it usually falls within a fairly narrow and predictable range.

Until solar PV comes along!

It may seem counterintuitive, but the people who operate the power grid don't really think of solar power as conventional supply. They can't control or "dispatch" it on their own schedule. It comes and goes with the sun; they must accommodate it. So from the grid operator's point of view, more solar (or wind) power looks like a reduction in demand for their dispatchable power.

Total load minus renewable energy is known as "net load." That's the target utilities have to hit with their dispatchable resources.

As more and more solar PV is integrated into the grid, it starts dramatically suppressing net load during midday, when the sun is out. The net load curve sags in the middle of the day (like a belly) and then swoops back up when the sun goes down (like a neck). Like so:

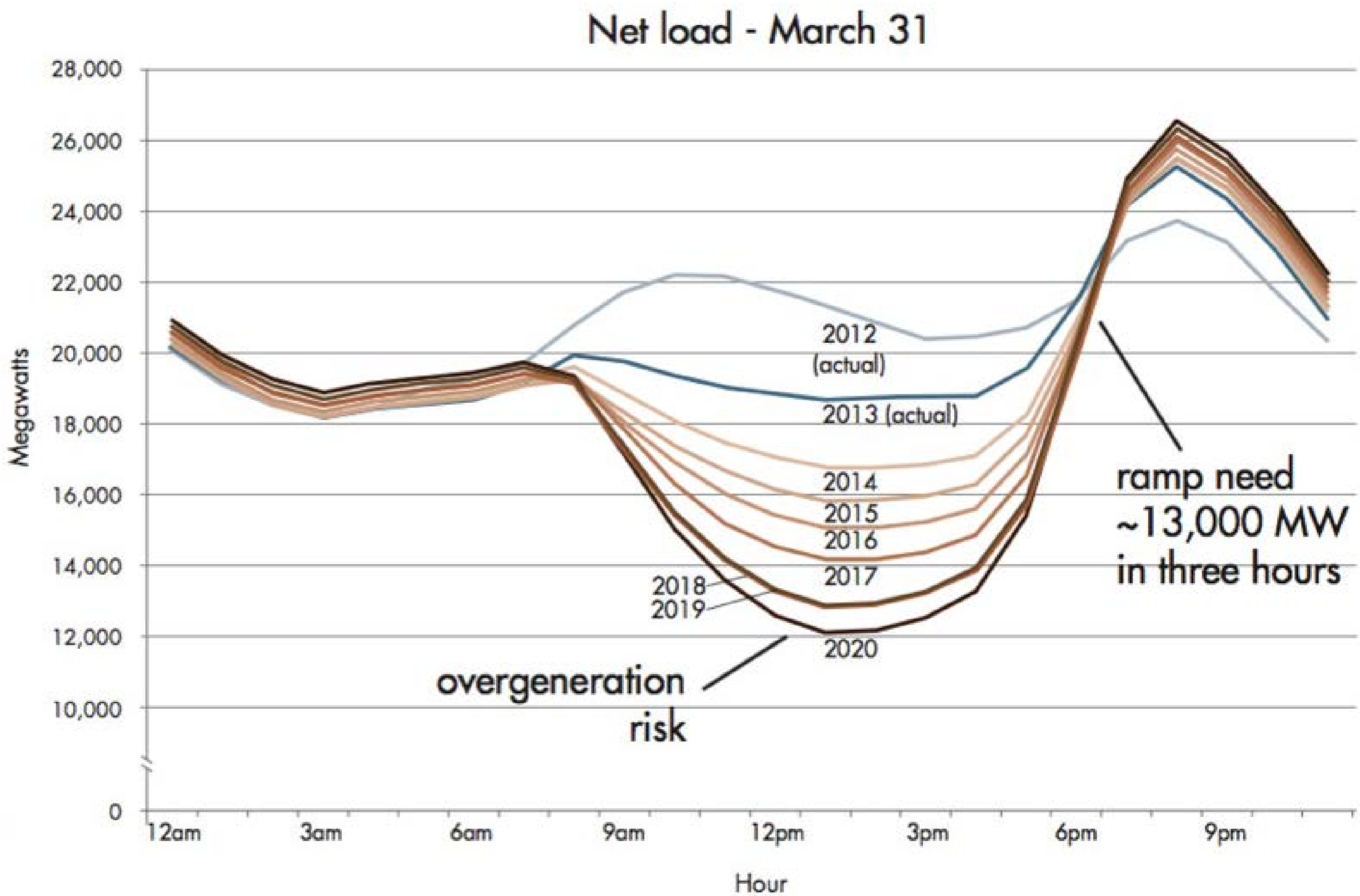


CAISO

It's just like that first load curve I showed you — a peak in the morning, a peak in the evening — only in between, there's an enormous sag that gets bigger as more solar is added.

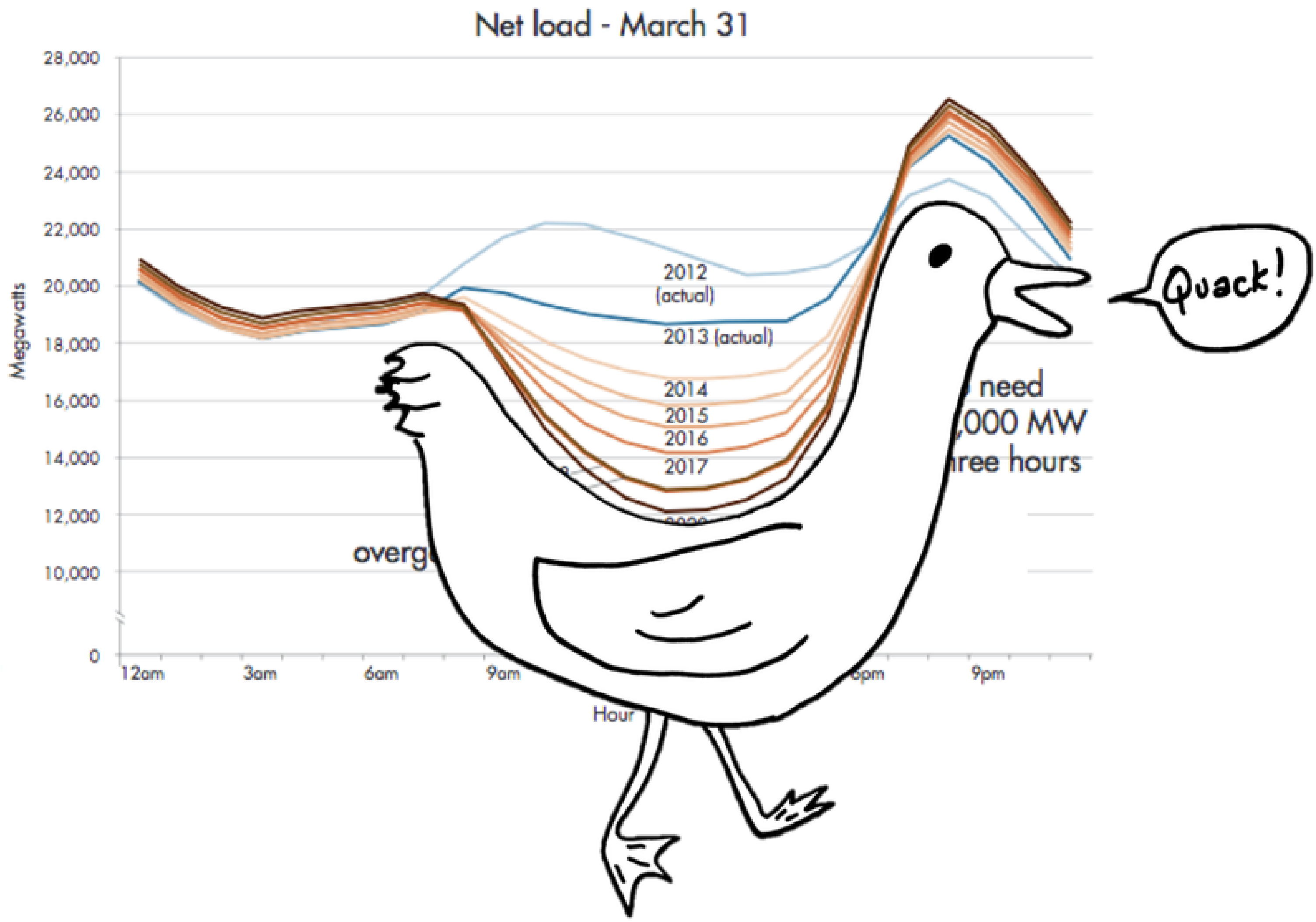
At the time, the California Independent Service Operator (CAISO, the operator of the California energy grid) was noticing the same thing. The realized that high levels of solar penetration start generating a net load curve that looks ... well, like a duck. Thus, the "duck curve."

Figure 2: The duck curve shows steep ramping needs and overgeneration risk



CAISO

Can’t quite see it? Here, let me help:



CAISO/Jordan Wirfs-Brock

It has now been 10 years since NREL's fateful discovery, and in the interim, the duck curve has become a serious threat to solar and a shared obsession among the clean energy community.

If it doesn't get solved, things could get ugly. In the near future, utilities could regularly be forced to ramp up their dispatchable plants for a morning peak, then scale back or shut down almost all of those plants while the sun is out, and then bring them all back online (quickly) when the sun goes down.

All that ramping and stop-starting is expensive and unfamiliar to the operators of many fossil fuel power plants. If the tension gets too high, solar expansion could be choked off.

Luckily, solutions to the duck curve abound — all kinds of options for making the grid more flexible and softening the peaks and ramps. In part thanks to early warnings from energy modelers, utilities and grid operators are beginning to awaken to the issue and take steps to address it.

To mark the duck curve's 10th birthday, I called Paul Denholm, the researcher who led that original group at NREL. He's been at the lab since 2004, studying electricity systems and solar integration, and has a great deal to say about how best to handle the duck — some of it counterintuitive. (For instance, he's okay wasting a little solar power here and there.)

The conversation, which I've edited for length and clarity, gets pretty energy-nerdy. But if you like puzzles, you'll like this one.

The history of the duck curve

David Roberts

Tell me a little about the history of the duck curve.

Paul Denholm

One of the first things I did when I joined [NREL] was working with Robert Margolis to model how consumers might adopt PV. When we put in the [price] projections we were getting from the [NREL] solar program, it was kind of like, wow, this actually might happen! California might actually start deploying significant amounts of solar in the 2010, '15, '20 time frame.

Simultaneous to that, the wind program was supporting some of the first-ever wind integration studies. And the solar program thought, hey, we need to do that too. If this is actually going to happen, we need to start studying solar on the grid as well.

So the next major project I worked on, we started simulating solar on the grid, performing some of the first solar integration studies. We started modeling what happens if California gets to 10, 15 percent solar. That's when we noticed these weird shapes that were happening in the spring.

We did not have the insight or artistic ability to come up with a cool name. [laughs] CAISO did that. [CAISO came up with "duck curve."] But we did generate that shape, in February 2008.

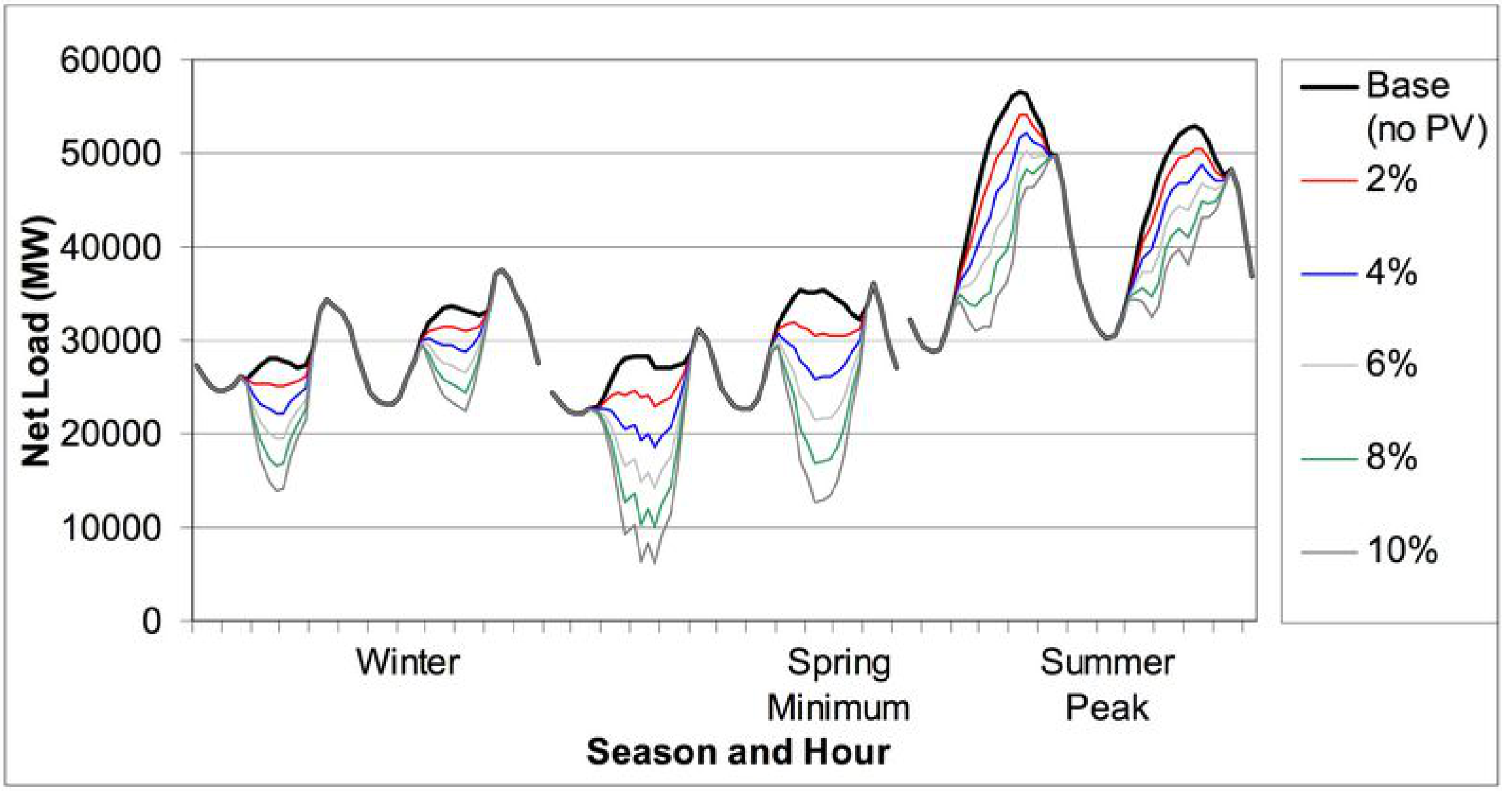


Figure 8. Load Shapes in California with Various WECC PV Penetration Scenarios

The earliest known representation of the dreaded duck, from 2008. | NREL

Learning to make "baseload" power plants more flexible

David Roberts

When you look ahead 10 years to a really severe duck curve, what do you see as the most effective solutions?

Paul Denholm

A lot of people in the industry use this concept of a "flexibility supply curve," which is you deploy the most cost-effective flexibility option first.

Thinking back to the early part of the 2000s, when wind people started worrying about this, storage was nowhere near cost-effective. There was a lot of strong disagreement between the storage people and the wind people, with wind really resisting storage, I think legitimately. They said, wait a second, there are way more cost-effective measures to deal with wind curtailment and integration challenges.

So for the first eight years of my time here, I was
focused on more cost-effective measures. A lot of them are pretty boring and don't get a lot of attention. "Learn how to ramp your coal and gas plants better" — that's a real thing, it's really important, but it's not sexy.

David Roberts

You mean ramp them better technically or economically speaking?

Paul Denholm

Both. You've got coal or gas plants that were designed as baseload, or intermediate load with a little bit of load-following capability, and the operators just weren't used to moving these plants over a large range.

They technically could. You look at the spec sheets, what the manufacturers say they can do, and they say the plants can comfortably ramp over 50 percent of their range. But the operators were never forced to do that, so there were a lot of institutional issues, quite frankly.

Work by NREL and others has promoted the economics, saying hey, if you ramp your plant an extra 10 points per day, yeah, it's going to impose a little bit of extra cycling cost, but the benefit of avoided curtailment vastly outweighs those costs.

If we'd had this conversation five years ago, I would have said the institutional culture needs to start changing. But that's underway. There's a lot less resistance now. These utilities talk to each other now, learning what they can do and what the challenges are.

Ramp faster. | Shutterstock

David Roberts

You're probably aware of the heated debate about just how flexible nuclear power plants can be, whether they can be "load following." What's your take on that?

Paul Denholm

Look, the French have been ramping their nukes up and down for years. They do it every day. I've talked to people from Électricité de France multiple times and they say it's no big deal. It's part of the institutional culture.

But I've talked to some nuclear folks here in the US and they have legitimate concerns. We haven't done [load following] here. There are safety issues, thermal stresses on the plant, and some of these plants are reaching the end of their life.

So in general, I'm gonna give nuclear plants a pass. There aren't so many nuclear plants in this country that they're the highest priority. The higher priority is maximizing the inherent flexibility of the fossil thermal fleet.

Covering a wider geographic area with renewables and energy markets

David Roberts

Faster ramping can't keep up forever, though, right?

Paul Denholm

That's right. It's not any single solution; it really is a suite of options.

One thing we talk about is spatial diversity [i.e., spreading renewables out over a larger geographical territory] and the role of larger footprints [i.e., larger connected energy markets] — things like the energy imbalance market (EIM), where California can sell surplus energy to its neighbors.

If there's a way you can share the sun with places that don't have as much sun, that helps everybody out. The wind folks have been talking about that for more than a decade.

There are limits to spatial diversity. We've only got three or four hours of solar spatial diversity across the entire country, east to west — when it's 4 am in Maine, it's midnight in California — so you're only going to get so far.

But let's do all these things that don't cost very much. Implementing markets is a pretty darn cheap solution.

David Roberts

To what extent are utility regulatory models a barrier to solving this problem?

Paul Denholm

[laughs ruefully] The spread of [deregulated] ISO/RTO markets has provided a lot of benefits to system operation. We've got more efficient economic dispatch of the system, much greater transparency.

But this is one case where vertically integrated utilities do have a slight advantage. They can look at the system as a whole — not just this individual power plant, but 12 power plants, plus their fleet of wind and solar. They can look at the total cost of all of this. There are challenges when you have a single-plant owner.

More ways to fatten or flatten the duck: flexibility, EVs, and demand shifting

David Roberts

What about reducing inflexible baseload capacity [coal and nuclear plants] to make more room for renewables?

Paul Denholm

We talk about "fattening the duck" or "flattening the duck." Fattening is doing all the things that let the belly of the duck grow, and reducing inflexibility is one of those things. If you're talking about existing nuclear plants, it's a little weird to back them off to increase solar — you're trading one carbon-free resource for another.

David Roberts

How big of a role will demand shifting play in flattening the duck? Can we move a lot of demand over underneath the belly, to soak up some of that power?

Paul Denholm

Obviously I would love to have super-flexible demand. There needs to be planning around that, as well as socially acceptable methods to empower people to use electricity in the most economically efficient way.

I want to know, when we start exposing customers to some kind of varying price, what are we going to get? The preliminary numbers I've seen are disappointingly low. It will be really interesting to see how much demand we can shift.

David Roberts

What about electric vehicles (EVs)? Intuitively, it seems like having an enormous, dispersed fleet of batteries could help soak up renewable energy during times of excess.

Paul Denholm

[NREL has] done quite a bit of work on that, looking at how you send the right price signals, so people are incentivized to charge the right way.

Doing it right? | Shutterstock

The general idea is, you get home, you plug in your car, and your intelligent car is sending signals. It's saying, don't charge right now. It's 5, 6 pm, now is the worst time to charge. The car is going to know that most of the time, its person doesn't need the car until 6 in the morning, so it will hold off [charging] until midnight or 1 in the morning, hopefully mostly or completely from off-peak wind.

You drive to work and plug in, it's 8, 9 am, there isn't quite enough solar yet, so [the car] is going to hold off again until 11 am. It's going to know prices are low and charge until 2, 3 pm.

If you do that math, EVs help a lot. Fortunately, the way that people use their cars fits. We're just going to need the right intelligence in the system, sending the right economic signals [i.e., charging varying rates throughout the day, more when power is expensive, less when it is cheaper].

Wind is complementary to solar, but not quite enough

David Roberts

Is there any kind of analogous animal curve caused by wind power?

Paul Denholm

Wind is just different. The thing about solar, which makes it harder and easier at the same time, is that it just has a big blast in the middle of the day. Wind is a lot more spread out, and you don't see a characteristic pattern from one day to another.

The biggest challenge with wind is it tends to blow more at night, off peak, which does lead to this synergy between wind and solar — wind covering more of your nighttime load, PV covering more of your daytime load.

That is true to a certain extent, but I don't want to oversell that phenomenon. We have so much wind in the spring, and so much solar in the spring, when demand is low [because of milder temperatures], so yes, they are complementary in some sense, but the seasonal nature of the wind and solar means it isn't as awesome as a lot of people would like it to be. But I'll take it!

David Roberts

So wind and solar are complementary, but not enough so to solve the problem or cover the gaps.

Paul Denholm

We're not going to get to 100 percent [renewable energy] with just wind and solar, without doing something else.

Why we may have to throw away some solar power

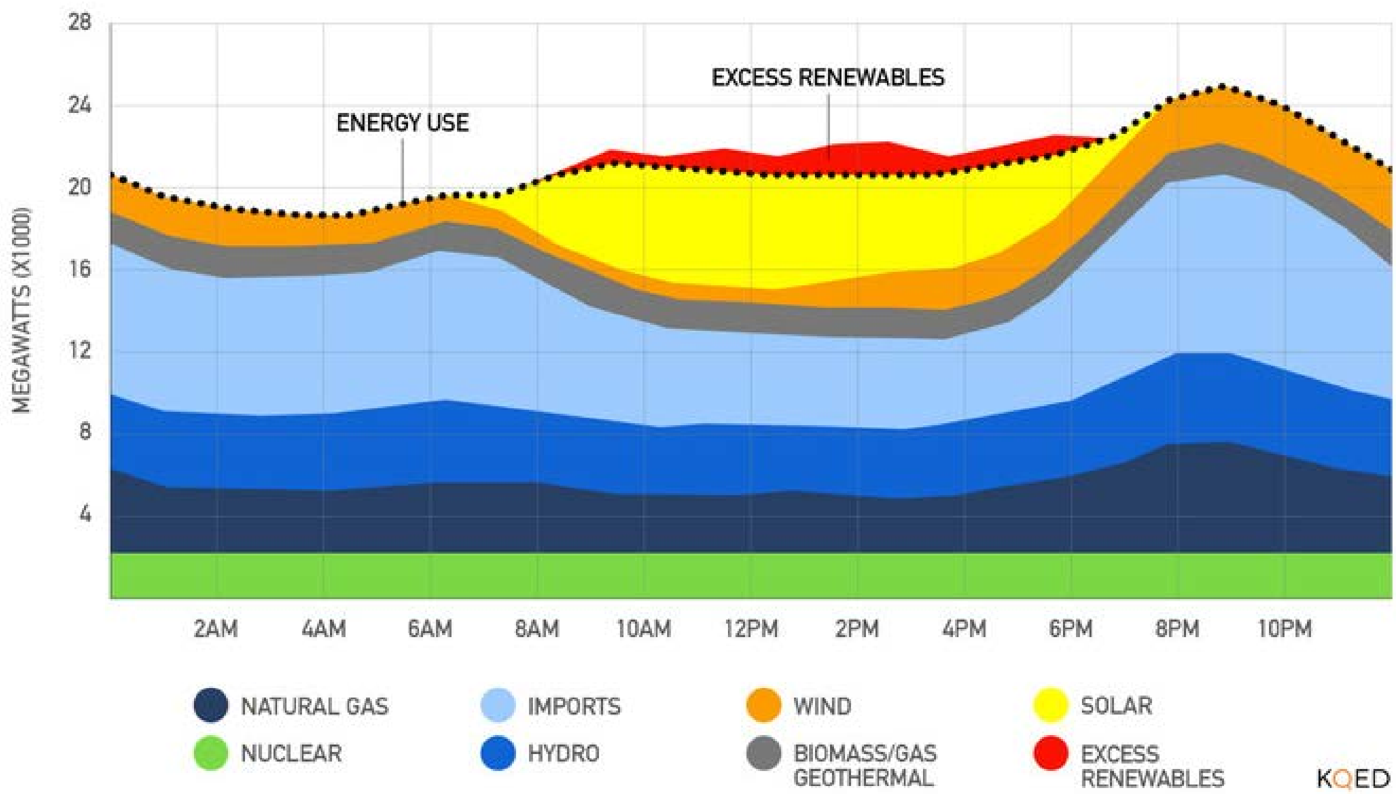
David Roberts

The duck curve is only going to get worse, and it doesn't seem like solutions are coming online nearly as fast as solar, which is continuously falling in price. Is something going to break?

Paul Denholm

We have to be really careful when we talk about something breaking. The only thing that's going to break is the economics of solar. The lights are gonna stay on. All it comes down to is more curtailment.

If it was all rooftop solar, it would be a huge problem, because the ISO can't control that. Fortunately, a large enough fraction of the solar is utility scale that the ISO ultimately has the ability to turn off. And that's just what's going to happen, more and more curtailment until people say enough is enough [and stop building solar] or economic solutions are deployed.



KQED

That's where I'm glad to be an optimist about the price of energy storage. I want to see all these things happen, improvement on the flexibility side, growth of the energy imbalance market, all of the semi-boring things I was talking about. But ultimately, the biggest hammer in the toolbox is energy storage.

All the projections I see say that by 2020, four-hour batteries should be competitive with peaking resources in much of California. Then you potentially have a multi-megawatt or even multi-gigawatt sink for at least some of this curtailed solar energy. That's — fingers crossed — the solution that looks like it might come into play.

But we are going to have to get used to the world of curtailment. As we move to a renewables-rich world, large amounts of curtailment in the spring is going to become the normal operating mode.

David Roberts

Curtailment seems crazy to me. Surely any use of solar power is more economical than throwing it away. Do you see curtailment as a sign of failure?

Paul Denholm

I have a sign over my desk that says, "Don't be afraid of curtailment." [laughs] I've been dealing with this for so long.

Is it an indication that something's not quite right? Yeah. If you expose the average consumer to the real prices of electricity — say that it's going to be dirt-cheap at noon and $0.50/kWh at 6 pm — then yeah, you're going to see a shift in consumer behavior.

But what fraction of the nation's consumers of electricity are exposed to actual, wholesale, real-time prices? If you're not a large industrial consumer, it doesn't matter.

I've got a button on my dishwasher that lets me delay the start by two or four or six hours, and I have no incentive to push that button [because rates are "fixed," unchanging throughout the day]. Here in Colorado, I know we're curtailing wind, but I have no way to know when. One night [the utility] could be throwing away wind; another night it could be coal on the margin. I would rather do something with that free wind, but I have no idea when my local utility is throwing it away. Let me push that button!

Throwing it away. | Shutterstock

Still, you have to think about how much curtailment there is and what it means. If we're curtailing 2 percent of the wind or solar and 98 percent of the time we're not, the world is fine.

We never talk about "curtailing" coal or gas plants. A mine-mouth coal plant, some of those plants used to be able to generate for $5/MWh and they'd still have to ramp because there wasn't enough demand. Instead of having a 95 percent capacity factor, maybe they'd run with 80 or 85. Nobody was screaming about that, even though we were "curtailing" the capacity of a coal plant.

David Roberts

When you curtail the coal plant, though, you still have the fuel. You're not wasting it.

Paul Denholm

But what fraction of the LCOE [levelized cost of energy] of a mine-mouth coal plant is the fuel? It's a small fraction. The cost of the plant is the major component of the LCOE, so when I curtail generation from that coal plant, I'm losing the opportunity to recover the cost of investing in that really expensive asset.

That's one of the reasons I say don't be afraid of curtailment. It can be part of the economics of the power system. It's when you start curtailing 30 or 40 or 50 percent, that's a problem. But these small amounts of curtailment here and there, I'm not too worried.

They are indicators that we need to do something about it, it's gonna get worse, so let's be intelligent, let's get the economists to design appropriate markets and rate structures, let's get the engineers to come up with solutions, let's let industry come up with interesting and new ways to use electricity.

The holy grail: affordable energy storage

David Roberts

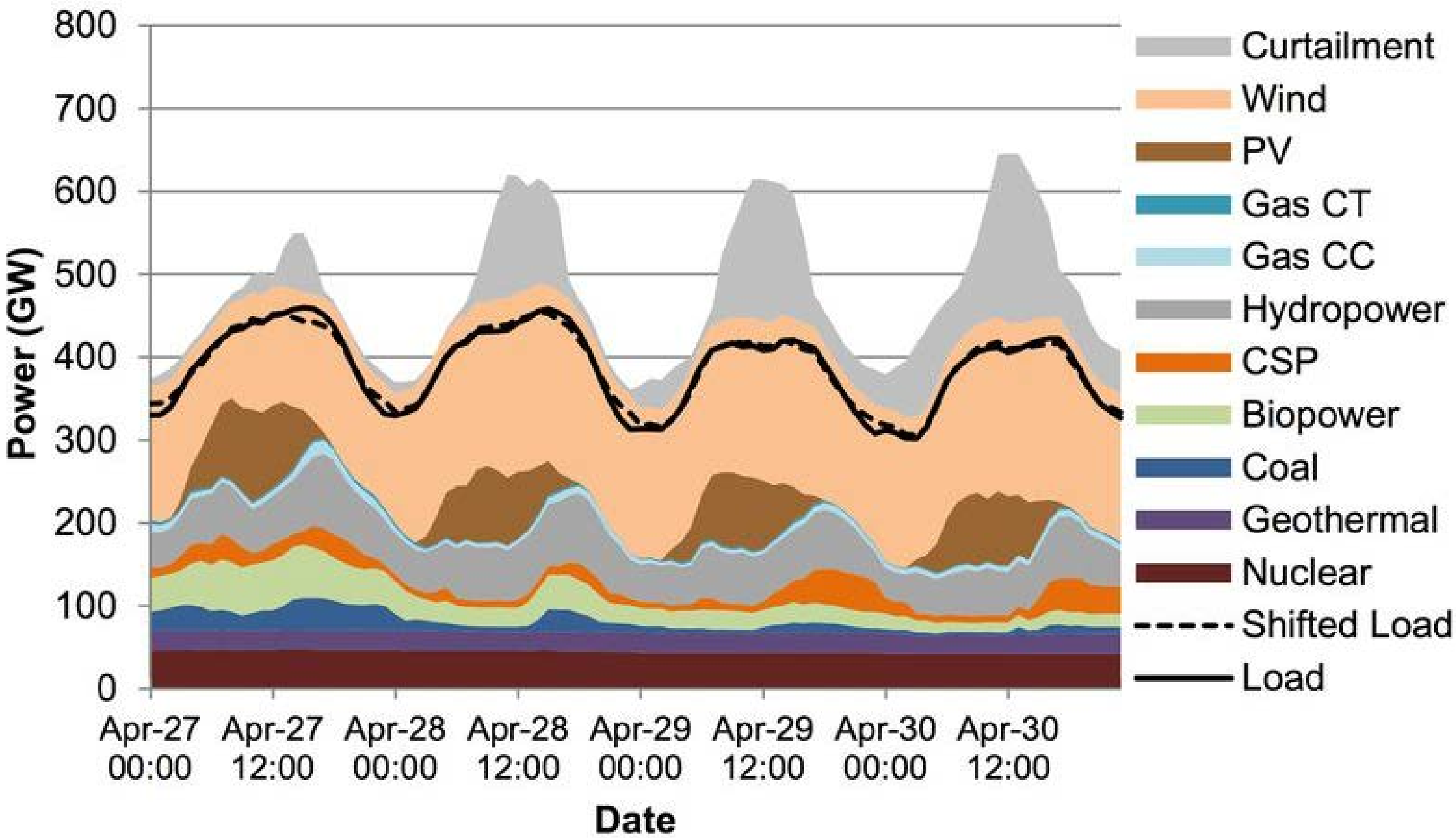
It is frequently argued that a system based on wind and solar will need an enormous amount of storage — not just hourly, but daily or even seasonal storage — and that batteries aren't up to the task. So we'll either have to limit the scale of renewables or find some other cheap, large-scale, long-term storage. What's your take?

Paul Denholm

We spend a huge amount of time talking about this topic here around the lunch table — a lot of calories are spent on it. So I'll tell you what I'd say is the informal general consensus about ultra-high-penetration renewables scenarios.

The consensus is emerging that we can probably do 80 percent [renewables] with some combination of spatial diversity and short-duration storage.

We can deal with diurnal shifts with short-duration storage, and not too much of it. When we did our Renewable Electricity Future study back in 2012, we got up to 80 percent renewables with only about 100 GW of additional storage. It's not *that* much.



(b) Lowest coincident load in 2050

The load curve in an NREL 80 percent renewables scenario. | NREL

So what's the last 20 percent?

Some people might say, well, why isn't 80 percent good enough? Eighty percent renewables and 20 percent gas, you've largely decarbonized the electricity sector, you've electrified the transportation fleet, everybody's happy. But what if that's not good enough and we need to go even further?

For 100 percent, I don't think we actually know what the right cost-optimal solution is. The seasonal nature of wind and solar is a problem.

David Roberts

But even getting to 80 percent requires a nationwide transmission grid, right?

Paul Denholm

We did build a lot of transmission. We did do some cases where we didn't allow as much transmission, and we just built more PV and more storage. Obviously, the social concerns about new transmission really worry me. I'd like to see more transmission.

But yeah, the seasonal nature of the problem will require something. Maybe it is [synthetic] fuels production, maybe it's seasonal storage, I don't know. If I had the answer worked out, I probably wouldn't have a job anymore.

We're not at 100 percent yet. We're not even at 80 or 50. Let's keep going with what we know, continue development of solar and wind and batteries, other no-regrets strategies. I think we can continue on this pathway, and I'd like to think we'll get there.

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