7.5-minute video on what is the grid 9/19/2022 Scientific American

https://youtu.be/X2eYdAR0ka4

What is The Grid?

10/2/22

https://www.civilbeat.org/2022/10/larry-ellison-wants-off-lanais-electric-grid-that-could-be-a-problem-for-everyone-else/

The Four Seasons Resort on Lanai is one of the major properties owned by tech billionaire Larry Ellison that may go off the current electric grid system, a decision that likely would raise rates for other ratepayers on the small island.

FIG 3 New York City during the Great Blizzard of 1888. The wires are a mix of telephone, telegraph, and electricity lines. (*Reproduced with permission from the Museum of the City of New*

DC grid with
different lines for
different voltages

Maximum 1 mile

AC buried lines transmitted from northern Canada


How is Power Transported?

It's not a system that needs to be planned. No one decides which electrons will go to Los Angeles to make doughnuts and which to Walla Walla to make toast; all of the electrons are going everywhere at once. As long as there is a "sink" (of the kind caused by a toaster toasting), all the electricity on the grid will move toward it by whatever means possible. The reason your toaster doesn't explode every time you turn it on is because there are thousands, indeed millions, of other sinks on our grid where other devices are making the same kind of "hey, no resistance over here" calls to the available electric current. There are also a million little devices on the grid, and some big ones, to standardize the voltage, or push, of that electricity, so that the power available to your toaster in the first place is substantially less than that traveling along high-voltage lines from the dam to the nearest substation. Your average outlet is already offering the toaster access to one of the mildest intensities of electricity available. You still don't want to pry a burnt nub of bread out of there with a butter knife—a nasty shock greets that activity—but were you to so much as touch a low-voltage downed residential wire, it would kill you. The system, in its current form, is designed not only to protect the toaster, but to protect us from the potential force that even the modest voltage of domestic electric current delivers.

Toasters don't explode, wires function well, lightbulbs go on when the wall switch is flipped, all because the grid is kept in balance: there is enough electricity available to run our machines, but there is not so much that it rips through and destroys them.

This is our grid in a nutshell: it is a complex just-in-time system for making, and almost instantaneously delivering, a standardized electrical current everywhere at once. And though schematas of the grid tend to make it seem like there is a line out of a power plant that ends in the toaster, the whole thing is actually a giant loop that both starts and ends at the power plant, or generating station. These factories make an electric current by tearing

The Grid

-Currently almost no storage (JIT system)

-Delivery in much less than 0.1 s from production

-Not much control; source and sinks and resistance govern (distance doesn't matter much)

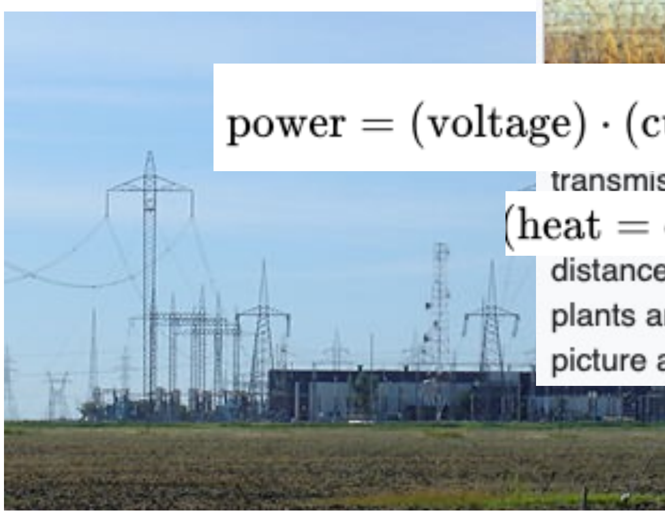
-Loss in transmission is only about 7%

- 1/5 of US power plants were build in the 1950's

-All will need to be replaced in 30 years (2050)

High Voltage DC North Dakota (Wind harvest)

3-Phase AC in Utah

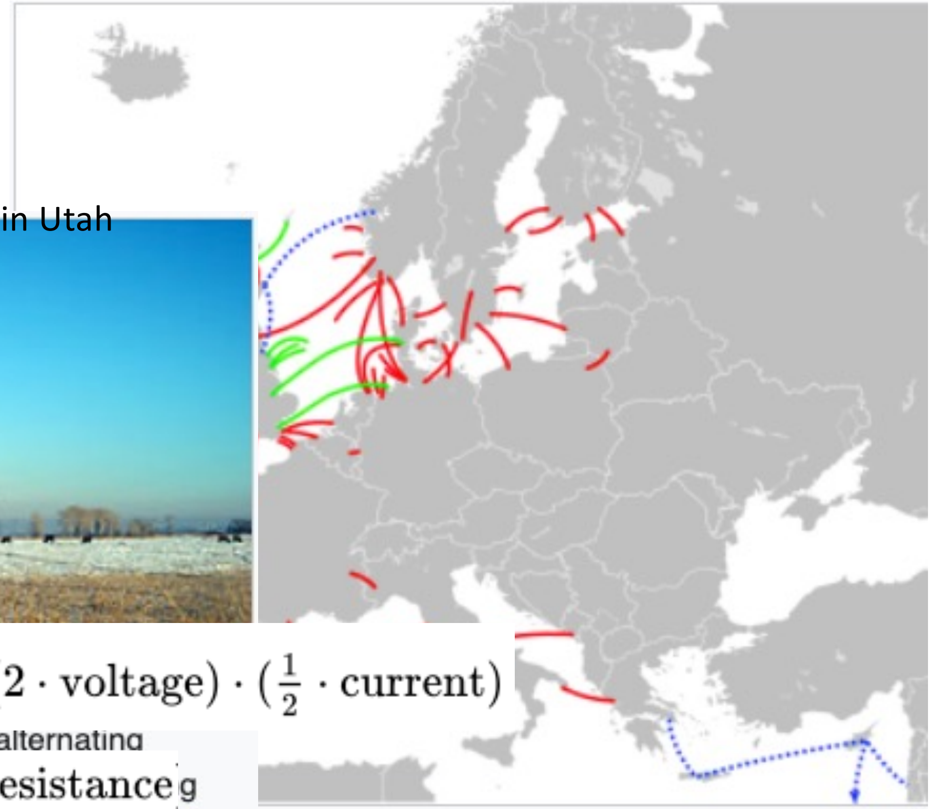


$$\text{power} = (\text{voltage}) \cdot (\text{current}) = (2 \cdot \text{voltage}) \cdot (\tfrac{1}{2} \cdot \text{current})$$

transmission lines use alternating

$$(\text{heat} = \text{current}^2 \cdot \text{resistance}$$ g

distances between electric generation plants and consumers. The lines in the picture are located in eastern Utah.



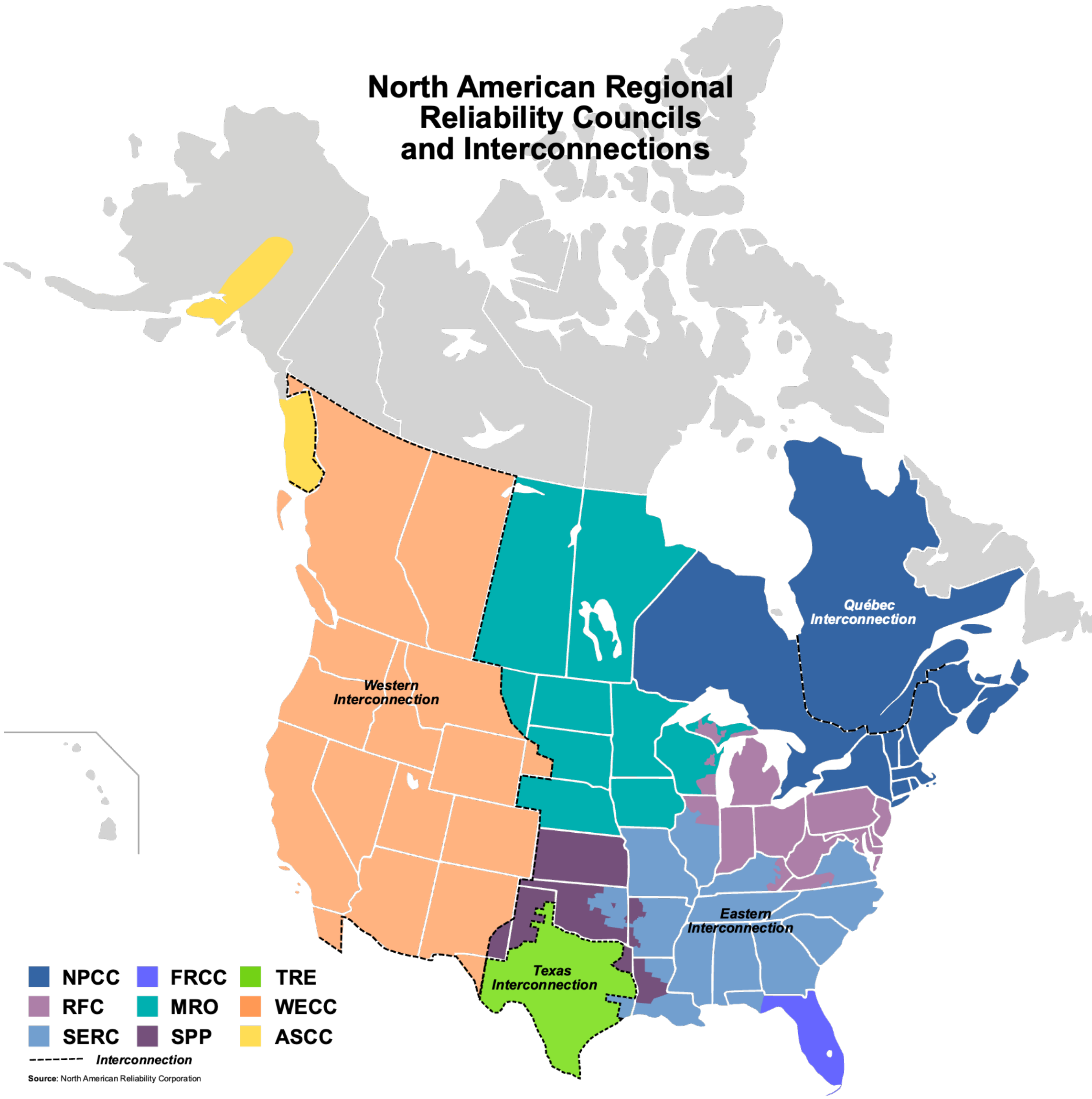
irope

uction

Proposed

Many of these HVDC lines transfer power from renewable sources such as hydro and wind. For names, see also the annotated version.[*needs update*]

Hydro Quebec High Voltage DC 1,000 kW


North American Regional Reliability Councils and Interconnections
Western Interconnection
Québec Interconnection
Eastern Interconnection
Texas Interconnection
NPCC
FRCC
TRE
RFC
MRO
WECC
SERC
SPP
ASCC
Interconnection
Source: North American Reliability Corporation

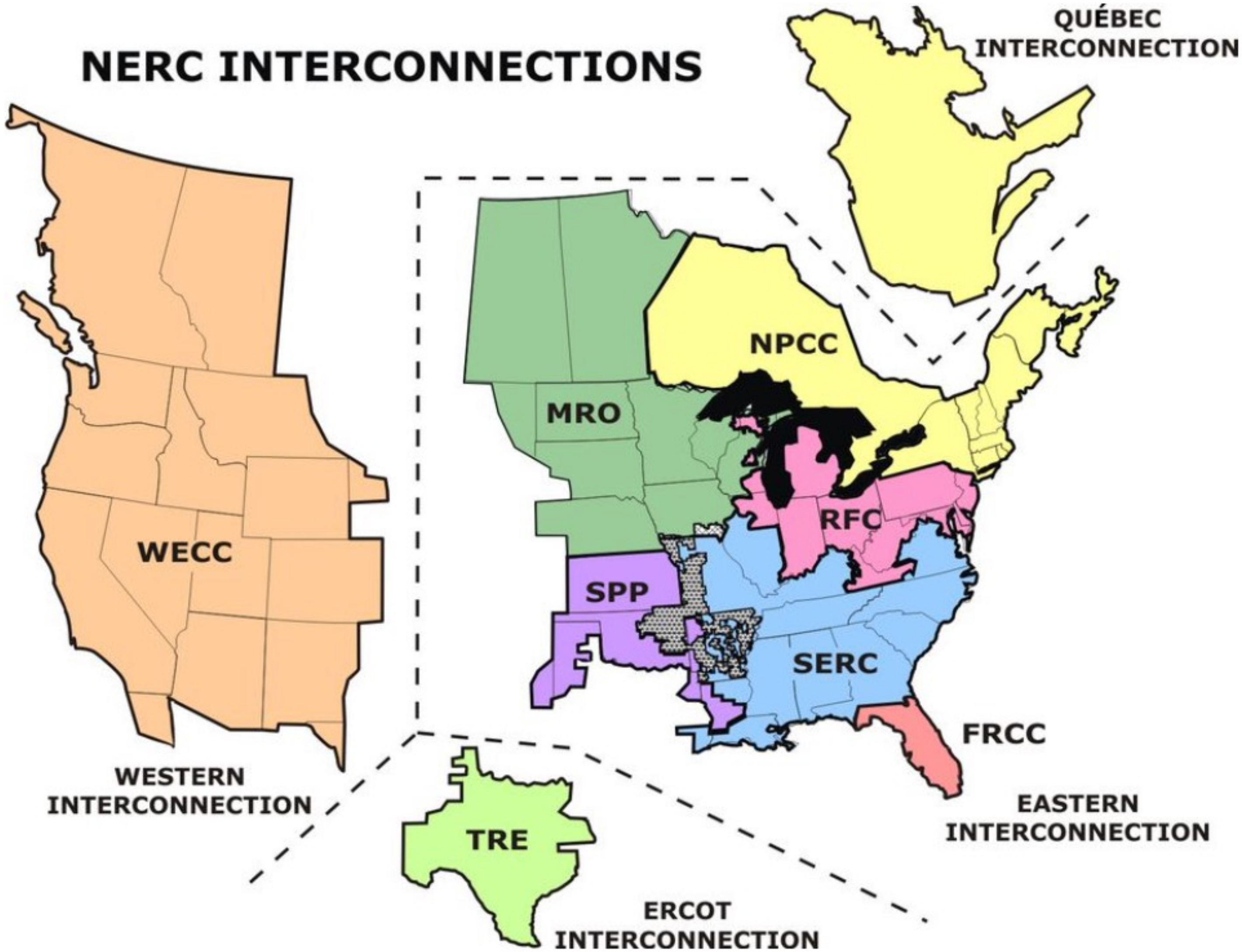
Texplainer: Why does Texas have its own power grid?

Basically, Texas has its own grid to avoid dealing with — you guessed it — the feds. But grid independence has been violated a few times over the years — not even counting Mexico's help during blackouts in 2011.

BY **KATE GALBRAITH** FEB. 8, 2011 UPDATED: FEB. 15, 2021

COPY LINK REPUBLISH

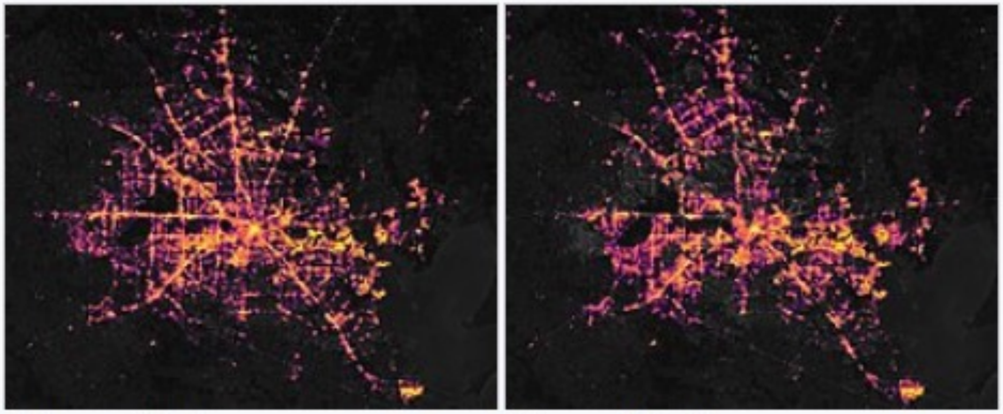
Graphic by ERCOT


NERC INTERCONNECTIONS
QUÉBEC
INTERCONNECTION
NPCC
MRO
RFC
WECC
SPP
SERC
FRCC
WESTERN
INTERCONNECTION
EASTERN
INTERCONNECTION
TRE
ERCOT
INTERCONNECTION

NERC


La Grande-1
La Grande-2-A
Robert-Bourassa
La Grande-3
Laforge-2
Brisay
Laforge-1
La Grande-4
Baie James
Eastmain-1
Bernard-Landry
QUÉBEC
Tracé de 1927 du Conseil privé (non définitif)
Tracé de 1927 du Conseil privé (non définitif)
Romaine-4
Romaine-3
Romaine-2
Romaine-1
Sainte-Marguerite-3
Manic-5-PA
Manic-5
René-Lévesque
Toulnustouc
Outardes-4
Outardes-3
Péribonka
Bersimis-1
Bersimis-2
Jean-Lesage
Outardes-2
Île d'Anticosti
Fleuve Saint-Laurent
Trenche
Beaumont
La Tuque
Bécancour
Québec
Îles de la Madeleine
ÎLE-DU-PRINCE-ÉDOUARD
NOUVEAU-BRUNSWICK
Carillon
Montréal
Beauharnois
ONTARIO
MAINE
NOUVELLE-ÉCOSSE
VERMONT
ÉTATS-UNIS
Toronto
Lac Ontario

February 2021 Texas power crisis



February 7, before | February 16, after

Satellite images of Houston before and after the storm.[1] The dark patches in the latter image depict areas left without electricity.

Date	February 10–27, 2021[2] (2 weeks and 3 days)
Location	Texas, United States
Type	Statewide power outages, food/water shortages
Cause	Multiple severe winter storms
Deaths	210[3] to 702 (estimate)[4]
Property damage	$20.4 billion (2021 USD)[5]

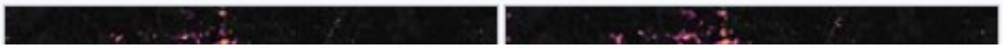
https://www.nbcdfw.com/investigations/nbc-5-investigate how-communication-failures-left-texas-unprepared-and-powerless-in-february/2588164/?_osource=db_npd_nbc_kxas_eml_shr

In February 2021, the state of Texas suffered a major power crisis, which came about as a result of three severe winter storms sweeping across the United States on February 10–11,[6] 13–17,[7] and 15–20. The storms caused a massive electricity generation failure in the state of Texas, leading to shortages of water, food, and heat.[8] More than 4.5 million homes and businesses were left without power,[9][10][11][12] some for several days. At least 210 people were killed directly or indirectly,[3] with some estimates as high as 702 killed as a result of the crisis.[4]

State officials including governor Greg Abbott[13] initially blamed[14] the outages on frozen wind turbines and solar panels. However, it was later discovered that inadequately winterized natural gas equipment contributed to the grid failure as well.[15][16] In 2002, Texas had isolated its power grid from the two major national grids in a successful effort to reduce power costs in the state and deregulate its energy sector. This disconnection made it difficult for the state to import electricity from other states during the crisis.[17]

Over one million residents in Texas remained without electricity on Feb. 16 after a historic cold outbreak and snow storm. (Justin Sciuletti, Amber Ferguson/The Washington Post)

February 2021 Texas power crisis



In 2011, Texas was hit by the Groundhog Day blizzard between February 1 and 5, resulting in rolling blackouts across more than 75% of the state.[24] Many roads around Houston were impassable, and boil-water advisories were issued in several areas.[25] Following this disaster, the North American Electric Reliability Corporation made several recommendations for upgrading Texas' electrical infrastructure to prevent a similar event occurring in the future, but these recommendations were ignored due to the cost of winterizing the systems.[26] At the time the blackouts and failures in the power grid were likened to those that occurred in December 1989, after which similar recommendations were made to the state government and ERCOT, which were similarly ignored.[27][26] On August 16, 2011, a 357-page report was released by the Federal Energy Regulatory Commission in response to the February 2011 power outage in Texas.[28]

In mid-February 2021, a series of severe winter storms swept across the United States. This outbreak was due to the polar jet stream dipping particularly far south into the U.S.,[29] stretching from Washington to Texas, and running back north along the East Coast, allowing a polar vortex to bring very cold air across the country, and spawning multiple storms along the jet stream track as a result.[30] This weather phenomenon resulted in record low temperatures throughout Texas, with temperatures in Dallas, Austin, Houston and San Antonio falling below temperatures in Anchorage, Alaska.[31]

On February 10, a winter storm formed north of the Gulf coast, dropping significant amounts of sleet and ice on many states in the Deep South and the Ohio Valley, including Texas, Georgia, Louisiana, Arkansas, Tennessee, as well as states on the East Coast.[32] A second storm developed off the Pacific Northwest on February 13 and began to gradually develop into an organized storm as it tracked southward toward Texas. It grew even more organized as it turned toward the northeast U.S. before splitting in half — one half continuing into Quebec and the other moving out over the Atlantic Ocean.[33] This storm, along with various other storms from the previous two weeks, resulted in over 75% of the contiguous U.S. being covered in snow.[34] This storm was directly responsible for nearly 10 million people losing power, with 5.2 million in the U.S. and 4.7 million in Mexico.[35][9] A third winter storm caused an additional 4 million power outages, and 29 deaths, with 23 in the U.S. and 6 in Mexico. At least 210 people lost their lives during the winter storms.[3][36]

Snow covering grounds of the Texas Capitol on February 15, 2021

Property damage	$20.4 billion (2021 USD)[5]

February 2021 Texas power crisis

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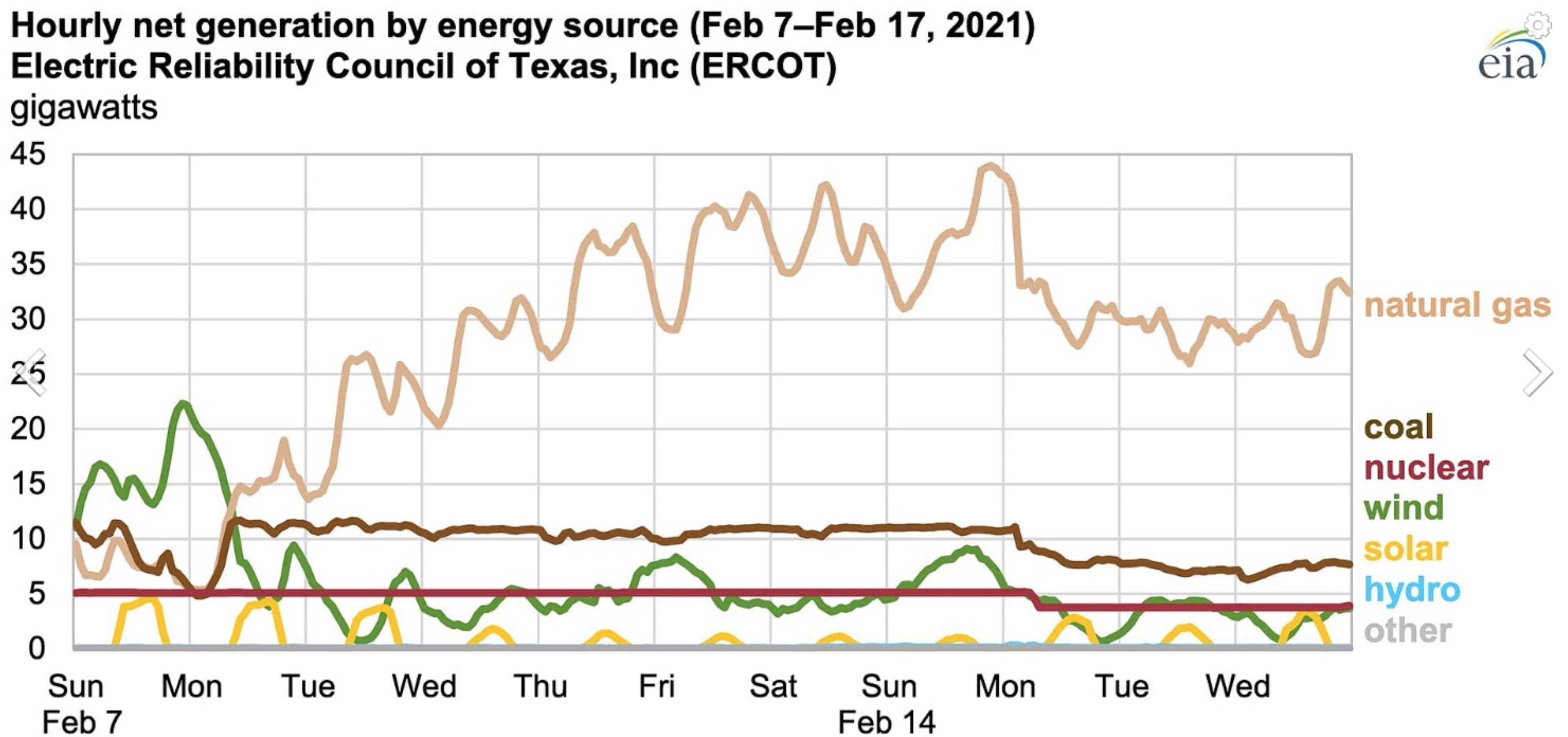
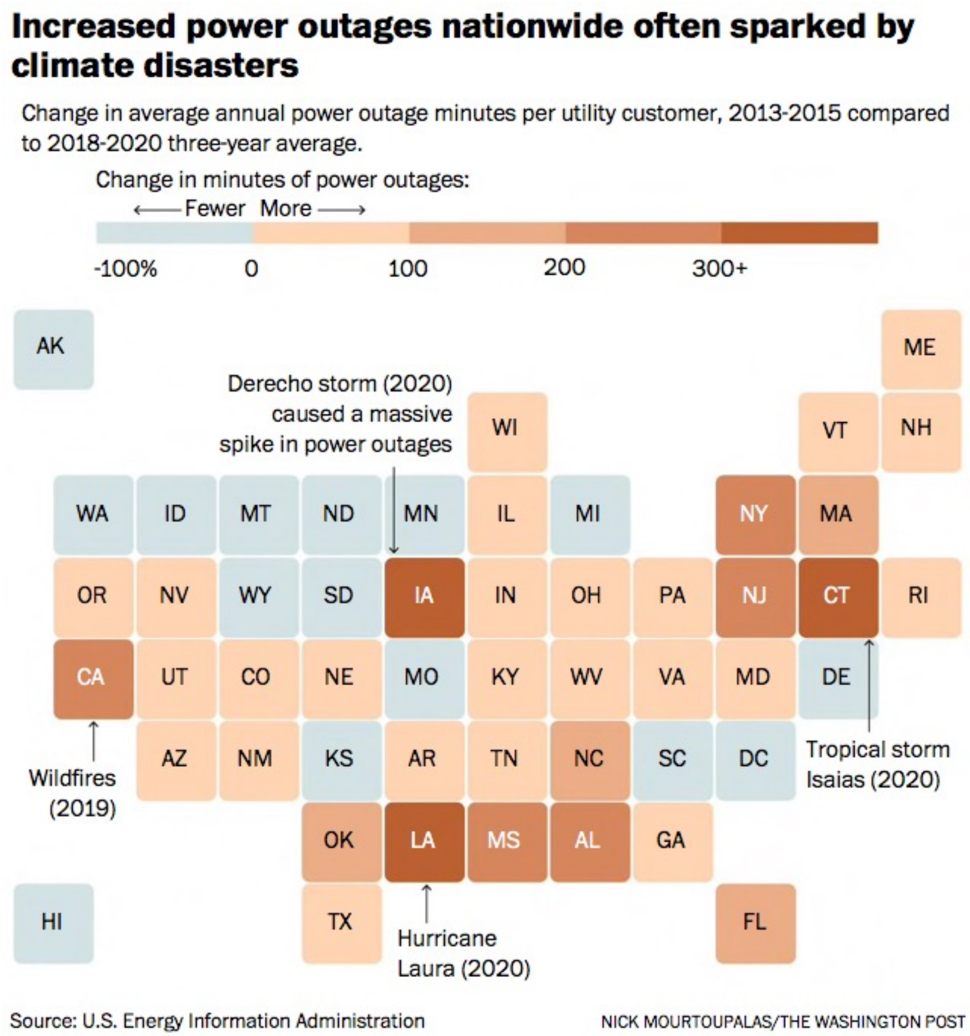


The majority of lost power generation was from natural gas sources. Reduced electricity from coal, nuclear, and wind power plants contributed to the shortage on February 15 and afterwards.[37]

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021



Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

As storms grow fiercer and more frequent, environmental groups are pushing states to completely reimagine the electrical grid, incorporating more batteries, renewable energy sources and localized systems known as "microgrids," which they say could reduce the incidence of wide-scale outages. Utility companies have proposed their own storm-proofing measures, including burying power lines underground.

More batteries
Renewable sources
Microgrids

Bury power lines

But state regulators largely have rejected these ideas, citing pressure to keep energy rates affordable. Of $15.7 billion in grid improvements under consideration last year, regulators approved only $3.4 billion, according to a national survey by the NC Clean Energy Technology Center — about one-fifth.

Nobody wants to pay for it

Problems with the grid and climate chaos exacerbate each other

Five disasters in four years

From Washington Post Article 10/24/2021

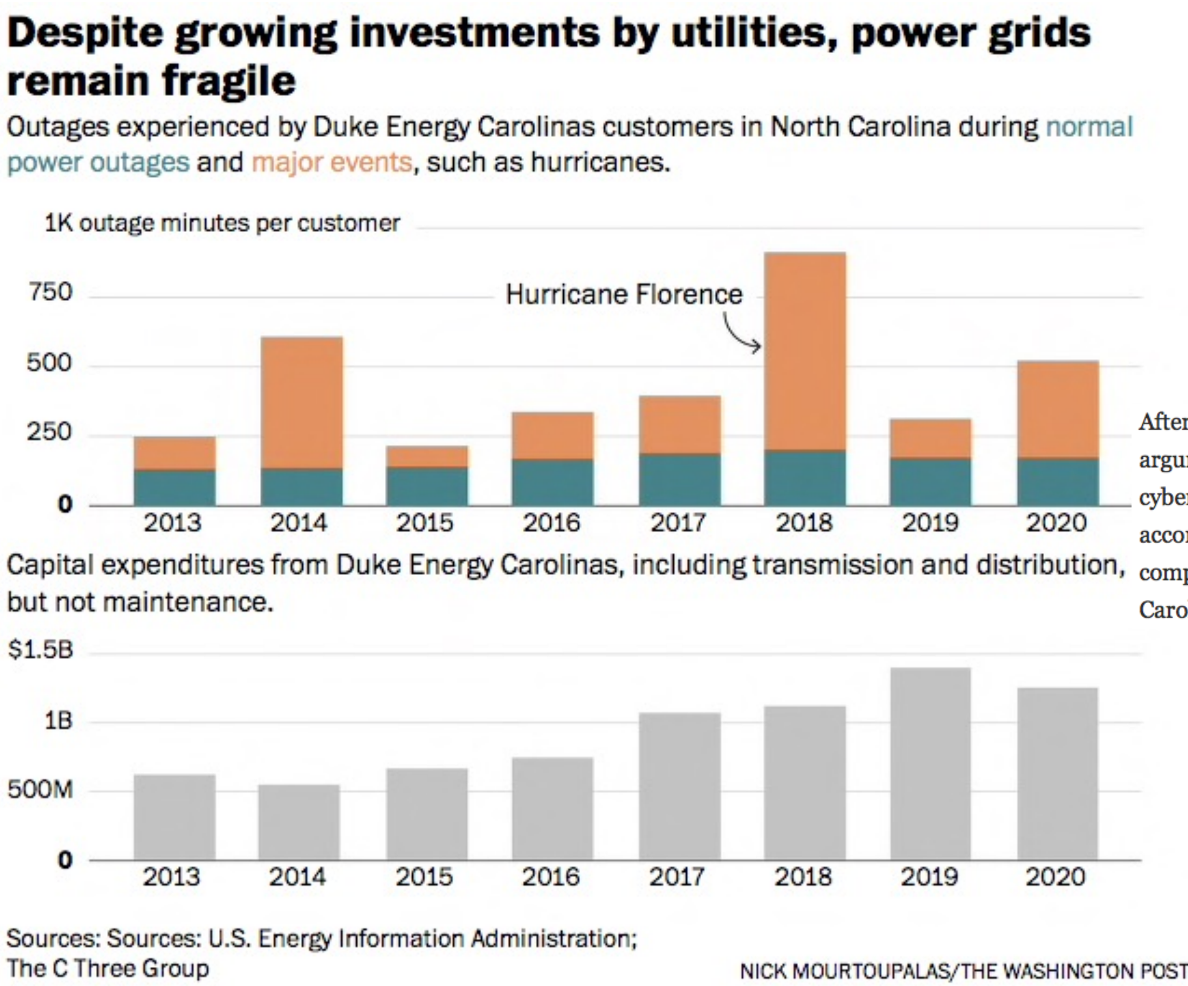
The need is especially urgent in North Carolina, a state that has declared a federal disaster from a hurricane or tropical storm five times in the past four years. Among them was Hurricane Florence, which brought torrential rain, catastrophic flooding and the state's worst outage in over a decade in September 2018.

The storm reignited debate over a $13 billion proposal by Duke Energy, one of the largest power companies in the nation, to reinforce the state's power grid. A few months earlier, the state had rejected Duke's request for full repayment of those costs, determining that protecting the grid against weather is a normal part of doing business and not eligible for the type of reimbursement the company had sought.

Nobody wants to pay for it

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021



After Florence, Duke offered a smaller, $2.5 billion plan, along with the argument that severe weather events are one of seven "megatrends" (including cyberthreats and population growth) that require greater investment, according to a PowerPoint presentation included in testimony to the state. The company owns the two largest utilities in North Carolina, Duke Energy Carolinas and Duke Energy Progress.

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

Duke Energy spokesman Jeff Brooks acknowledged that the company had not conducted a climate risk study but pointed out that this type of analysis is still relatively new for the industry. He said Duke's grid improvement plan "inherently was designed to think about future needs," including reinforced substations with walls that rise several feet above the previous high watermark for flooding, and partly relied on federal flood maps to determine which stations are at most risk.

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

The utility is now burying power lines in “several neighborhoods across the state” that are most vulnerable to wide-scale outages, Brooks said. It is also fitting aboveground power lines with “self-healing” technology, a network of sensors that diverts electricity away from equipment failures to minimize the number of customers affected by an outage.

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

In California, for example, Pacific Gas & Electric wants to bury 10,000 miles of power lines, both to make the grid more resilient and to reduce the risk of sparking wildfires. Its power equipment has contributed to multiple deadly wildfires in the past decade, including the 2018 Camp Fire that killed at least 85 people.

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

Another oft-floated solution is microgrids, small electrical systems that provide power to a single neighborhood, university or medical center. Most of the time, they are connected to a larger utility system. But in the event of an outage, microgrids can operate on their own, with the aid of solar energy stored in batteries.

Florida Approved Microgrid Test Project
Maryland Rejected for Baltimore

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

In Texas, where officials have largely abandoned state regulation in favor of the free market, the results have been no more encouraging. Without requirements, as exist elsewhere, for building extra capacity for times of high demand or stress, the state was ill-equipped to handle an abnormal deep freeze in February that knocked out power to 4 million customers for days.

Since then, Berkshire Hathaway Energy and Starwood Energy Group each proposed spending $8 billion to build new power plants to provide backup capacity, with guaranteed returns on the investment of 9 percent, but the Texas legislature has not acted on either plan.

Problems with the grid and climate chaos exacerbate each other

From Washington Post
Article 10/24/2021

New York is one of the few states where regulators have assessed the risks of climate change and pushed utilities to invest in solutions. After 800,000 New Yorkers lost power for 10 days in 2012 in the wake of Hurricane Sandy, state regulators ordered utility giant Con Edison to evaluate the state's vulnerability to weather events.

The resulting report, which estimated climate risks could cost the company as much as $5.2 billion by 2050, gave ConEd data to inform its investments in storm hardening measures, including new storm walls and submersible equipment in areas at risk of flooding.

Plug-in cars are the future. The grid isn't ready.

By 2035, the chief automakers will have turned away from the internal combustion engine. It'll be up to the grid to fuel all those new cars, trucks and buses.

Washington Post
October 13, 2021

Maple Ridge in Lewis County is New York's largest wind farm. (Kate Lovering for The Washington Post)

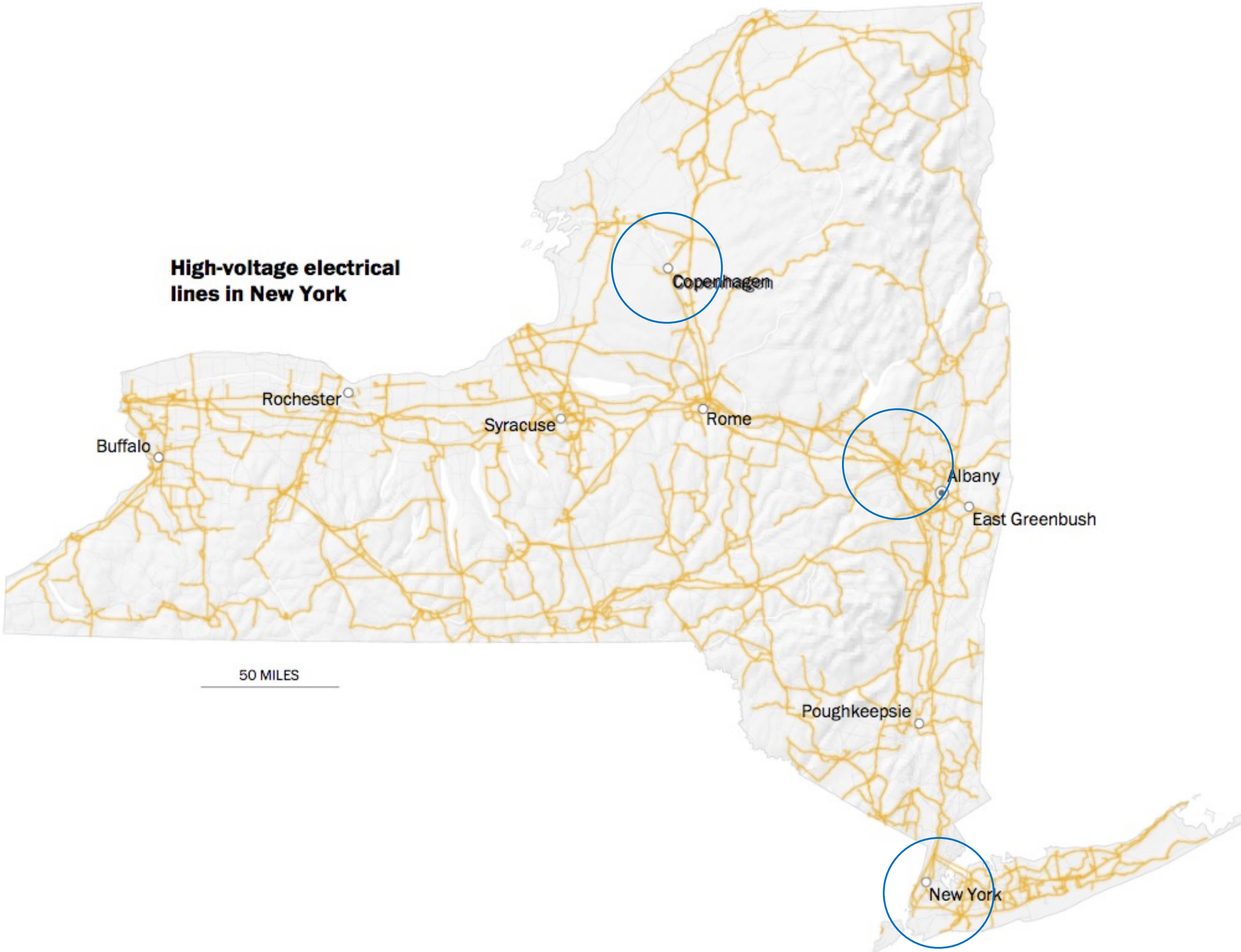
Washington Post
October 13, 2021

COPENHAGEN, N.Y. — On a good day, a fair wind blows off Lake Ontario, the long-distance transmission lines of New York state are not clogged up and yet another heat wave hasn't pushed the urban utilities to their limits. On such a day, power from the two big wind turbines in Vaughn Moser's hayfield in this little village join the great flow of electricity from upstate as it courses through the bottleneck west of Albany and then heads south, where some portion of it feeds what is currently the country's largest electric vehicle charging station, on the edge of Brooklyn's Bedford-Stuyvesant neighborhood.

Washington Post
October 13, 2021

A charging station for the car-sharing service Revel is located in a Brooklyn neighborhood. (Spencer Platt/Getty Images)

Seventy-four times last year, the wind across Upstate New York dropped so low that for stretches of eight hours or more barely any electricity was produced. Nearly half the year, the main transmission line feeding the metropolitan area was at full capacity, so that no more power could be fed into it. Congestion struck other, smaller lines, too, and when that happened some of the wind turbine blades upstate fell still.



Washington Post
October 13, 2021

Washington Post October 13, 2021

Converting the nation's fleet of automobiles and trucks to electric power is a critical piece of the battle against climate change. The Biden administration wants to see them account for half of all sales by 2030, and New York state has enacted a ban on the sale of internal combustion cars and trucks starting in 2035.

But making America's cars go electric is no longer primarily a story about building the cars. Against this ambitious backdrop, America's electric grid will be sorely challenged by the need to deliver clean power to those cars. Today, though, it barely functions in times of ordinary stress, and fails altogether too often for comfort, as widespread blackouts in California, Texas, Louisiana and elsewhere have shown.

"We got to talk about the grid," said Gil Quiniones, head of a state agency called the New York Power Authority. "Otherwise we'll be caught flat-footed."

Washington Post October 13, 2021

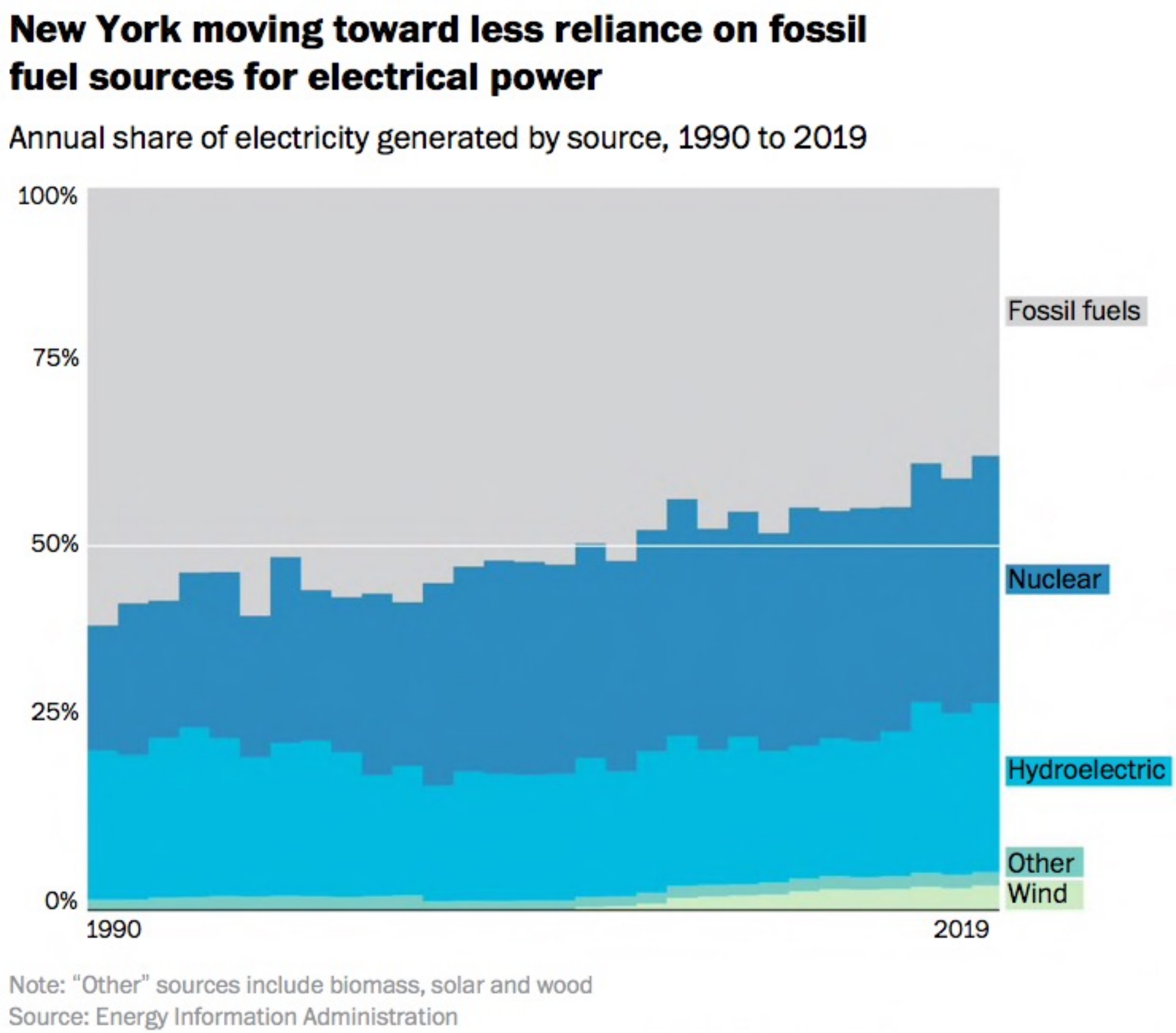
By 2050, the state projects, electric cars, trucks and buses will use 14 percent of New York's total output. That's equivalent to half of all the electricity used in New York City in 2019 — so it's like powering a new city of four million people. Overall demand could grow by as much as 50 percent.

Vaughn Moser leases land for wind turbines on his family's dairy and maple farm in Copenhagen, N.Y. (Kate Lovering for The Washington Post)

Washington
Post
October 13,
2021

“The grid of the future isn’t going to be a grid at all,” said Shuli Goodman, executive director of a Linux Foundation project called LF Energy. “It will be more like the Internet,” she said, with power generation happening all over the place.

“Something,” she said, “like a forest.”



Washington Post
October 13, 2021

Washington Post October 13, 2021

Additional growth will occur offshore, at least for the East Coast. Stronger, steadier winds and more powerful turbines in the waters from Martha's Vineyard to Virginia could reach a capacity of 20 to 30 gigawatts by 2030, according to an American Wind Energy Association report.

Linda Garrett, executive director for Tug Hill Land Trust, has pointed out the environmental concerns she has about the new Roaring Brook wind farm. (Kate Lovering for The Washington Post)

New York's share of that, probably nine gigawatts, would not be sufficient to replace all its fossil-fuel-powered generation plants, which in 2020 had a capacity of 26 gigawatts.

Washington
Post
October 13,
2021

Currently, 57 proposed wind projects in New York — on land and at sea — are awaiting a green light. Approval depends on there being enough transmission capacity to handle their output. Some have been in the queue since 2012.

If every project eventually won approval, and moved toward operation over the next decade, the capacity would be about 30 gigawatts, enough in theory to replace the fossil fuel plants.

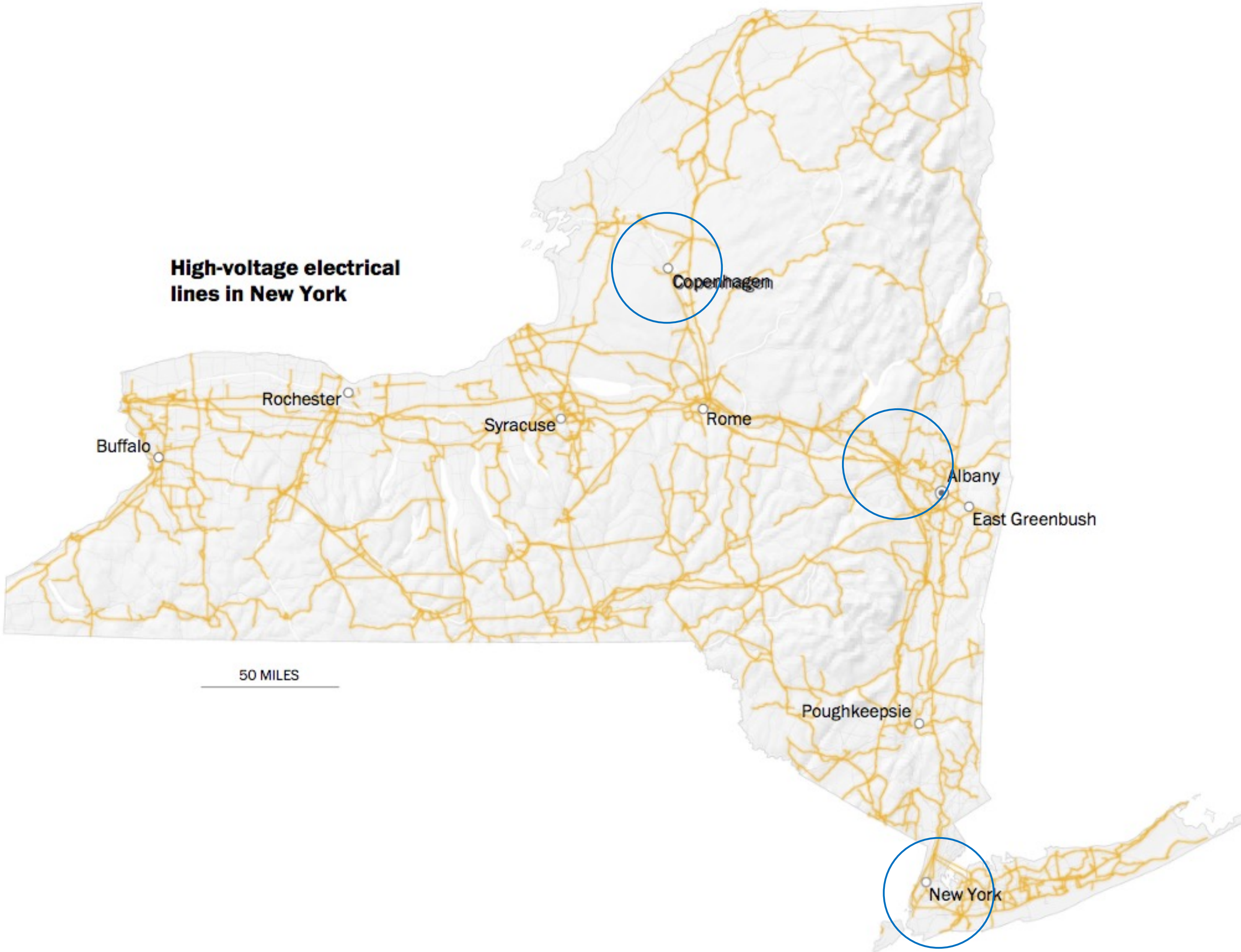
Washington Post October 13, 2021

The electricity generated in Moser's hayfield heads about nine miles to the northwest, where it joins the New York grid at a substation in East Watertown. There it falls under the control of the state's Independent System Operator and enters a transmission line that shows up as a thin yellow connector on a dauntingly complicated and huge schematic screen that dominates the ISO control room in a tightly secured building in East Greenbush, just across the Hudson from Albany. The line interconnects with other lines in magenta, blue, red, green and orange, each representing a different level of voltage.

The ISO operators like to talk about what they call the state's Tale of Two Grids: on one side, the rural north and Rust Belt west, and on the other, the Hudson Valley, New York City metropolitan area and Long Island. Both produce nearly the same amount of electricity — about 65,000 gigawatt-hours in 2020 — but one has plenty of renewable power and the other does not. One has vast rural stretches; the other does not. They operate like two nearly separate systems.

Washington Post October 13, 2021

Monitors manage New York's electric grid on June 3 from a control room at a substation in East Greenbush. (Kate Lovering for The Washington Post)



Washington Post
October 13, 2021

Washington Post October 13, 2021

One main transmission line connects the two grids, carrying power from the north and west to where it's needed downstate, which uses about two-thirds of the state's overall energy. Running roughly between Utica and Albany, that line is called the Central East Constraint, and it is congested about half the year, meaning no more power can flow along it.

And at least 11 pockets within the two regions have their own local constraints: high-tension lines that don't have enough capacity even today.

[Colonial shutdown shows how Americans pay the price of efficiency]

It is not a problem specific to New York state. Similar constraints exist in Texas, California, Maryland, Illinois and elsewhere. Across the country, long-distance transmission lines can only carry so much electricity, just the way a pipe can only carry so much water. When they're at full capacity, they can't carry any more, even if a downstream customer — a local utility, for instance — is trying to obtain some.

Washington
Post
October 13,
2021

The main transmission line from upstate to New York City comes right down the Hudson Valley, with secondary lines providing some backup. Electricity imported from Connecticut, Massachusetts and New Jersey can also feed the metropolitan area.

At substations around the region, the voltage is stepped down and the power is distributed on local lines — strung on familiar poles in parts of the outer boroughs and Westchester County, but underground in Manhattan.

Washington Post October 13, 2021

Moshe Cohen, the CEO of a start-up called Gravity, hoped this year that at the end of one of these lines would be what he needed to get his electric taxi vehicle company up and running — quickly, and at scale.

He approached major parking garage operators about setting up 50 fast chargers, which can replenish a car in as little as 20 minutes but gulp huge amounts of electricity.

Building out the equipment for such a site would be possible. "This is what we do for a living," said Patrick McHugh, vice president of engineering and planning for Con Edison. "It's nothing that we haven't done."

But it would take years. If you plugged in 50 cars at once to 50 chargers, it would draw as much electricity as a high-rise office building for as long as the cars were being refueled.

Washington
Post
October 13,
2021

But at the same time, a dramatic transformation of the grid will be necessary, experts say. Rooftop solar panels will need to be sprouting everywhere. Enthusiasts believe that microgrids could one day be powered by long-elusive hydrogen fuel, or small, next-generation nuclear reactors. All these sources would be local but deeply interconnected, supporting each other.

“We have the technology to do it,” Howe said. “The question is, do we have the will?”

Reuters
October 13,
2021

1/4 Uber driver Tim Win poses for a photo with his fully-electric Nissan Leaf, plugged into an on-street residential electric vehicle charging system developed by startup Trojan Energy, in London, Britain August 2, 2021. REUTERS/Nick Carey

Reuters
October 13,
2021

"It's really difficult to tackle on-street residential charging, so there's really not many companies that have," Hugh Mackenzie, chief operating officer at Trojan Energy, said.

Trojan has developed a charger, which is being tested on residential streets in two London boroughs, where EV owners insert a short pole into sockets sunk into the pavement and then plug in their car.

Reuters
October 13,
2021

"The biggest factor in whether kerbside charging is successful is whether you have an interested and engaged municipality," said Travis Allan, vice president for public affairs at Quebec City-based FLO, which has installed at least 7,000 kerbside chargers in Canadian and U.S. cities.

Yet even engaged local authorities like Brent, which is trying lamp post chargers and other solutions, simply lack cash.

Tim Martin, Brent council's transportation planning manager, says lamp post chargers cost around 2,000 pounds and rapid chargers around 15,000 pounds, so subsidies are the only option.

Reuters
October 13,
2021

Based on car registrations and parking permits, charging startup char.gy estimates there are between 5 million and 10 million cars in London, of which around 76% park on the street.

Government figures show the total is around 40% for Britain's 33 million cars, while around 40% of Americans do not live in single-family homes with garages.

Reuters
October 13,
2021

Char.gy Chief Executive Richard Stobart estimates Britain will need half a million on-street chargers by 2030, when around half of the country's cars should be electric. Char.gy runs a network of around 1,000 on-street lamp post chargers in Britain that cost around 1,800 pounds to make and install.

Reuters
October 13,
2021

Ubitricity, a Royal Dutch Shell (RDSa.L) business, is the British market leader, with just 4,000 chargers using lamp posts, which if they are close enough to the kerb and use LED lamps, have enough power to mostly charge an EV overnight.

Lex Hartman, ubitricity's CEO, estimates that in densely-populated areas, around 60% of Europe's car owners will need public charging.

"You will need chargers at home, at work, at the supermarket, you will need fast charging, but mainly you need charging everywhere," Hartman said.

Reuters
October 13, 2021

New York state has set a goal for all new passenger cars and light-duty trucks to be zero-emission by 2035. **read more**

But New York City currently has just 1,580 charging plugs for around one million cars that rely on street parking.

"Owning an EV in a large city like New York is a really painful experience," said Paul Suhey, co-founder of electric moped sharing startup Revel, which has launched the city's first fast-charging hub.

Reuters
October 13,
2021

In Los Angeles, which has the most chargers of any U.S. city, Blink Charging (BLNK.O) last year bought city-run EV car sharing network BlueLA, which has 100 vehicles and 200 charging stations.

Blink CEO Michael Farkas said local authorities want charging infrastructure in as many places as possible to encourage people to buy EVs, but companies cannot afford to shoulder the investments until ownership rises.

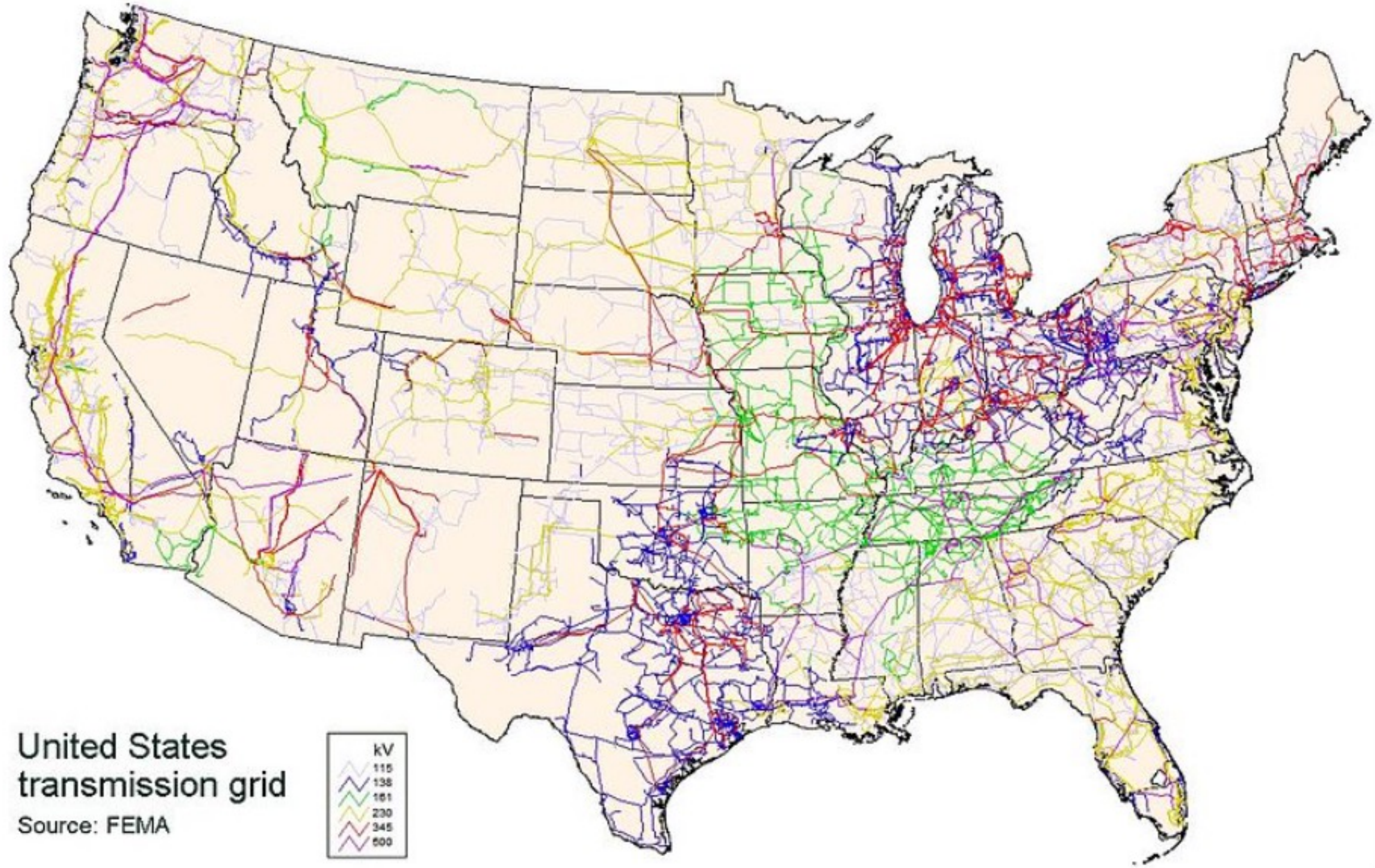
"You can't just have a field of dreams, you'll go broke unless the government wants to pay for it," Farkas said.

Reuters
October 13,
2021

Even in Norway, where state support put it at the forefront of the electric shift, rolling out on-street charging is tough.

Oslo subsidizes larger public chargers and rapid chargers, investments that pay off within three to six years, Sture Portvik, who heads up its charging infrastructure efforts, said.

But making charging accessible for the 30% of car owners who lack designated parking in a city where bans on fossil-fuel cars will start in the next few years is a major challenge.

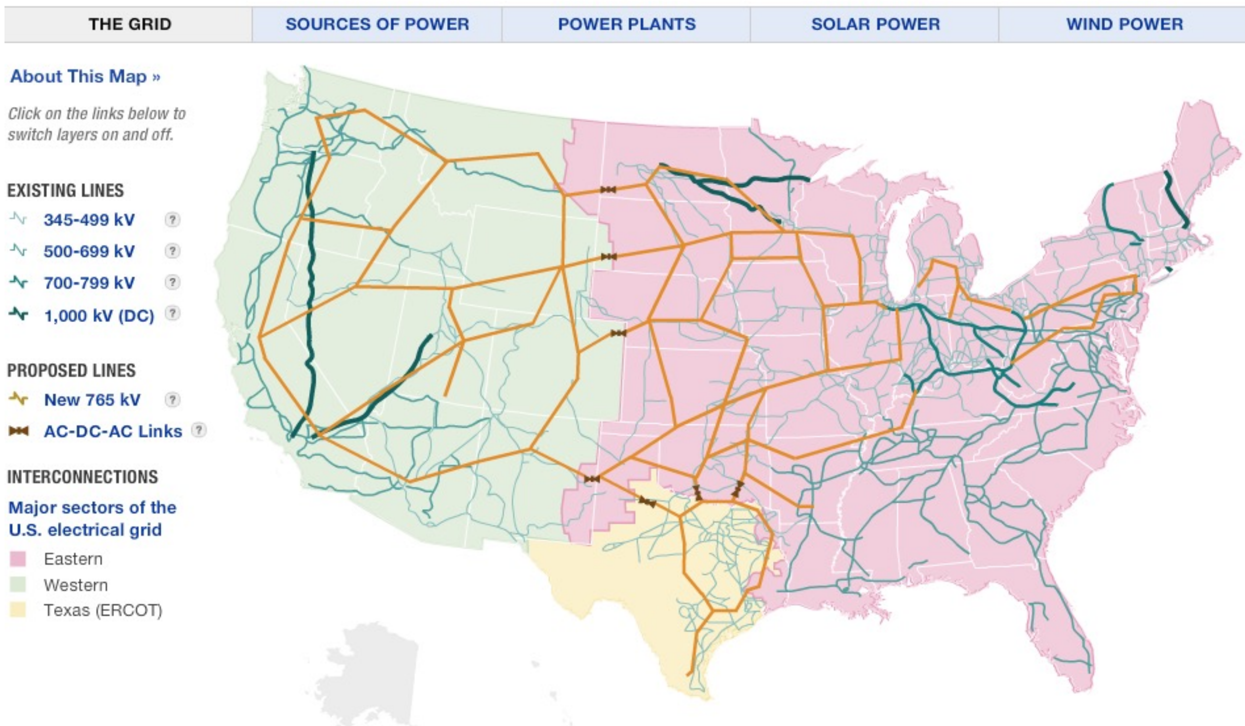

United States
transmission grid
Source: FEMA
kV
115
138
161
230
345
500

[Visualizing the Grid](#)

Visualizing The U.S. Electric Grid

April 24, 2009 · 12:00 AM ET

The U.S. electric grid is a complex network of independently owned and operated power plants and transmission lines. Aging infrastructure, combined with a rise in domestic electricity consumption, has forced experts to critically examine the status and health of the nation's electrical systems.



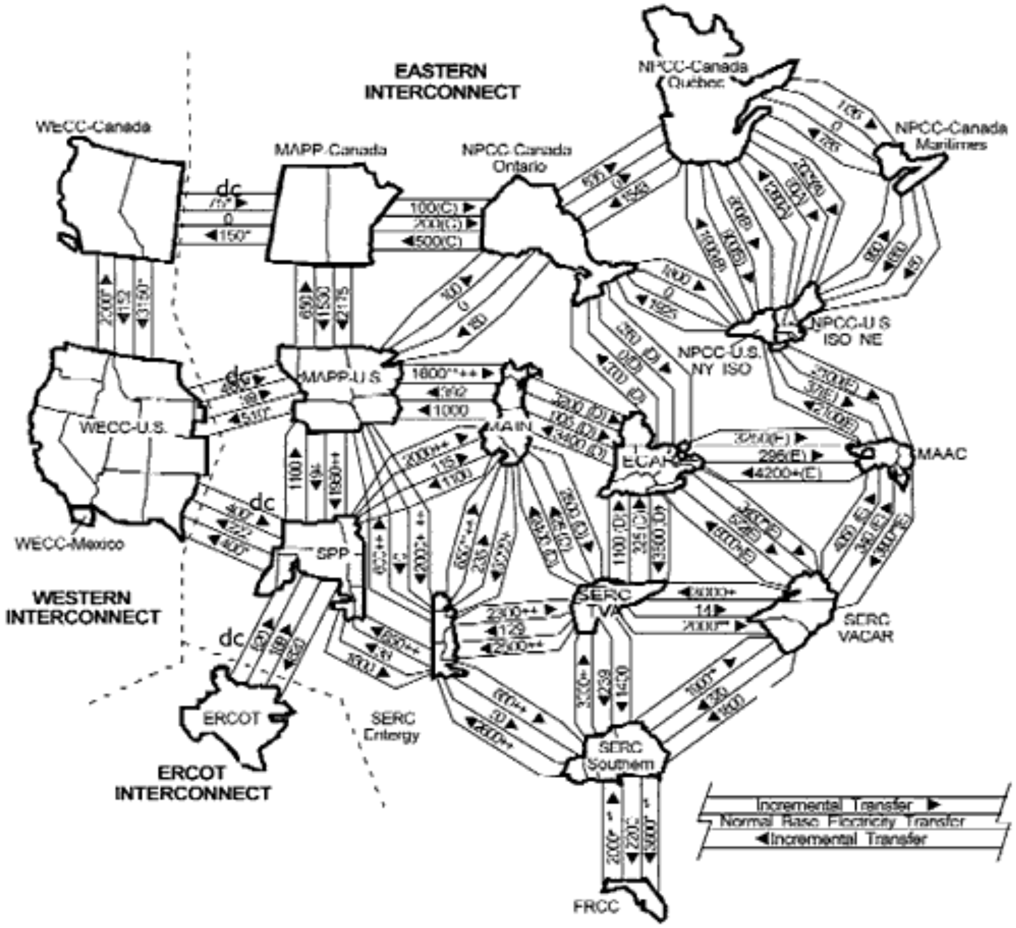
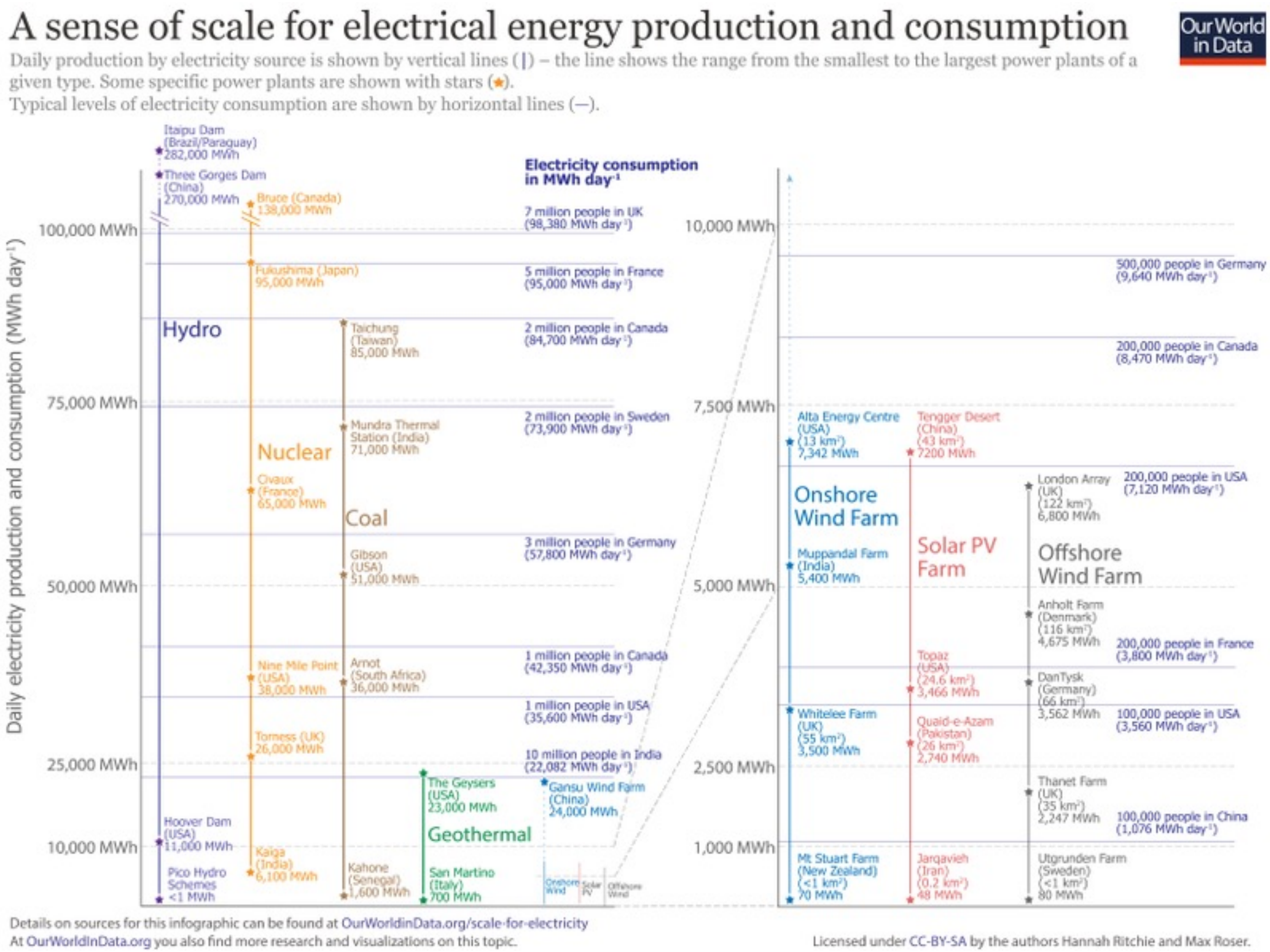


Figure 1. Normal U.S. base electricity transfers and first-contingency incremental transfer capabilities, in MW. Credit: North American Electric Reliability Council

44,0000 Ethiopia
Renaissance
Dam



Blackout August 2003

Figure 4. Blackout sequence of events, 14 August 2003

1:58 p.m. The Eastlake, Ohio, generating plant shuts down. The plant is owned by First Energy, a company that had experienced extensive recent maintenance problems, including a major nuclear-plant incident.

Davis-Besse Nuclear Plant wiki

3:06 p.m. A First Energy 345-kV transmission line fails south of Cleveland, Ohio.

3:17 p.m. Voltage dips temporarily on the Ohio portion of the grid. Controllers take no action, but power shifted by the first failure onto another power line causes it to sag into a tree at 3:32 p.m., bringing it offline as well. While Mid West ISO and First Energy controllers try to understand the failures, they fail to inform system controllers in nearby states.

3:41 and 3:46 p.m. Two breakers connecting First Energy's grid with American Electric Power are tripped.

4:05 p.m. A sustained power surge on some Ohio lines signals more trouble building.

4:09:02 p.m. Voltage sags deeply as Ohio draws 2 GW of power from Michigan.

4:10:34 p.m. Many transmission lines trip out, first in Michigan and then in Ohio, blocking the eastward flow of power. Generators go down, creating a huge power deficit. In seconds, power surges out of the East, tripping East coast generators to protect them, and the blackout is on.

Credit: Orbital Imaging Corp. (processing by NASA Goddard Space Flight Center)

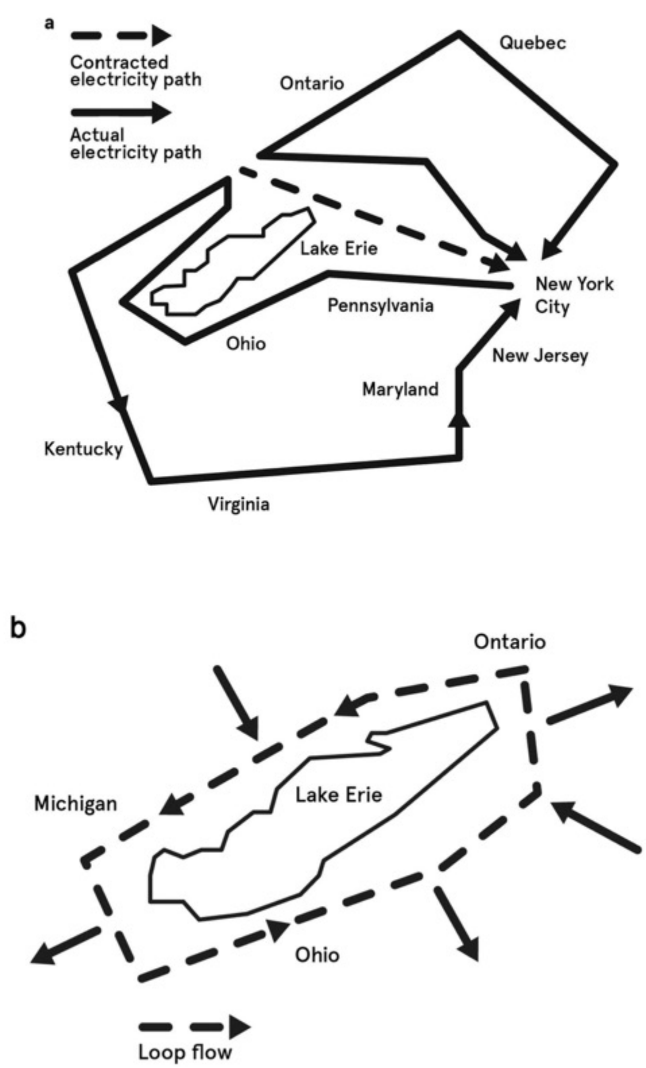
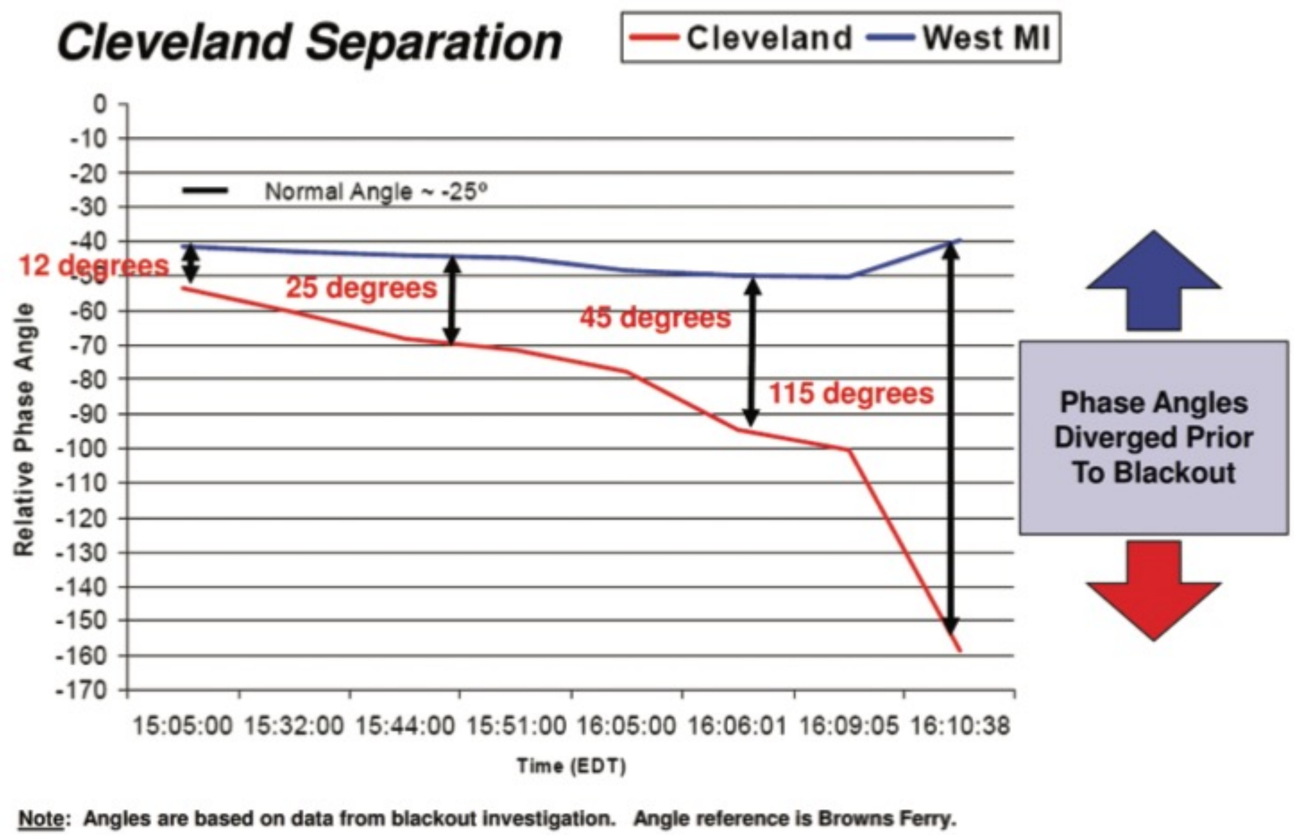


FIG 4 Electric power does not travel just by the shortest route from source to sink (*top*), but also by parallel flow paths through

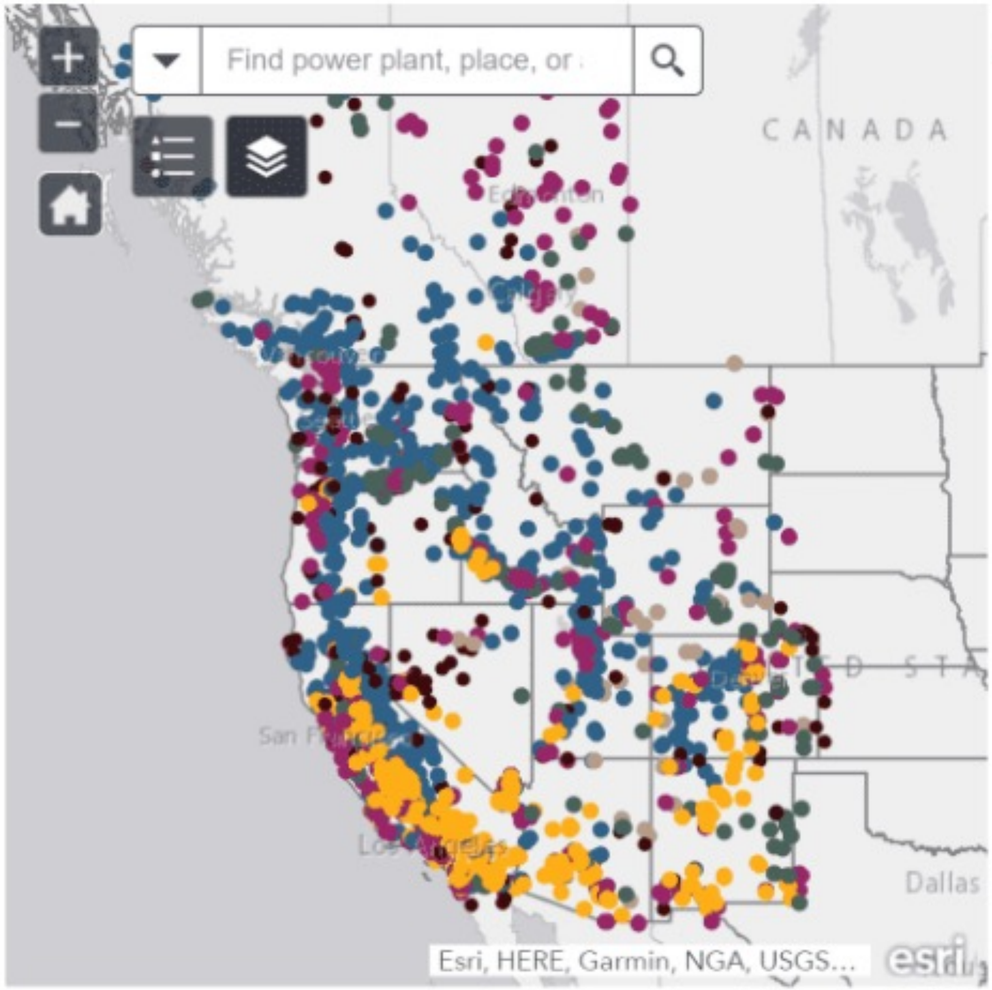
Figure 3.7 Example of Analysis using Synchrophasor Data: August 14, 2003 Blackout

Credit: North American Electric Reliability Corporation



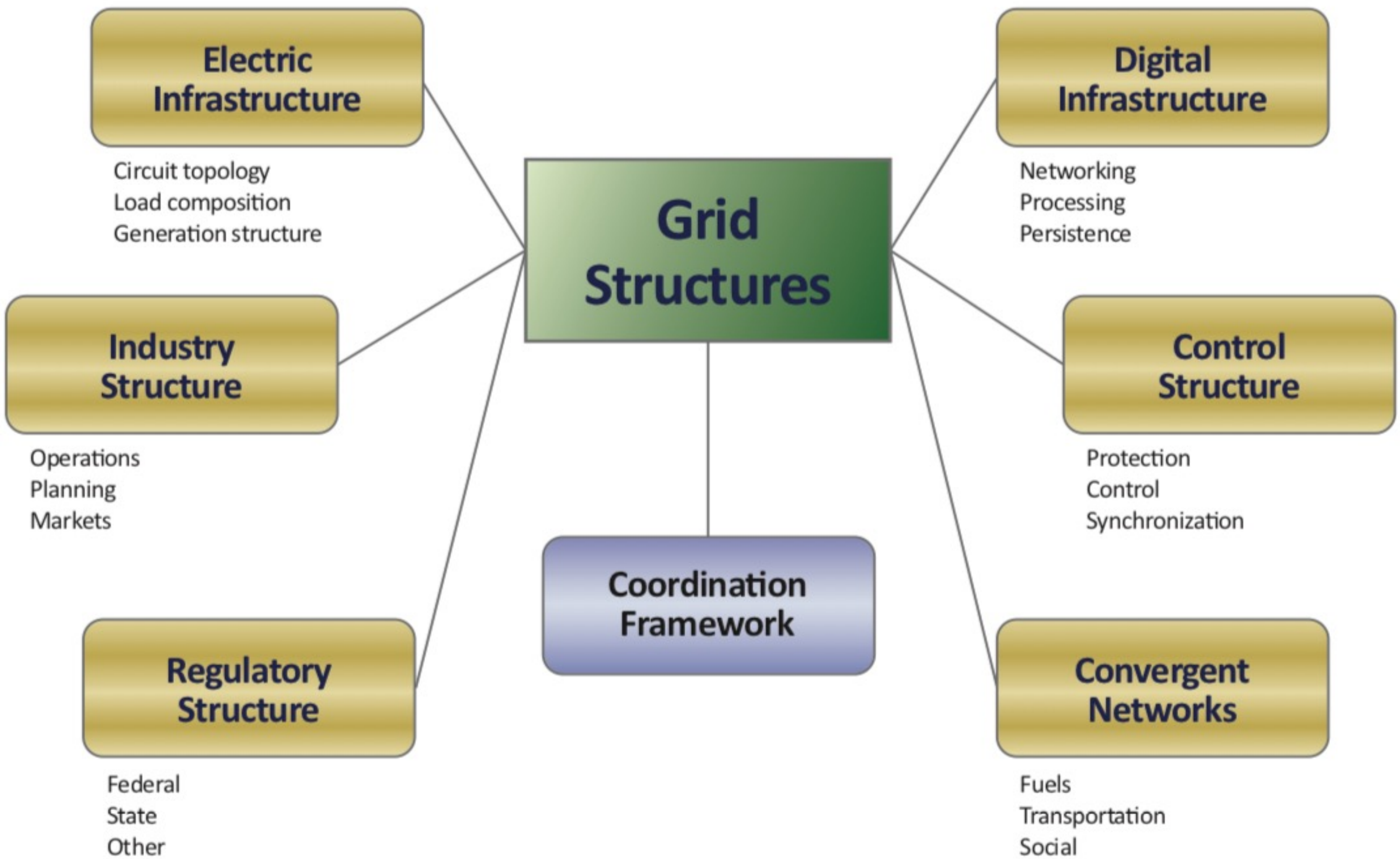
Operators may have detected the phase-angle separation that preceded the 2003 blackout had PMU technology been in place. (PMU Phase measurement unit)

Power sources and need are separated by large distances



[Western Doughnut]

Figure 3.11 Grid Architecture Structure Types



The grid can be viewed as six interrelated structures and a coordination framework to understand the needs and requirements necessary to meet the performance expectations of a digital economy.

Figure 3.12 Fundamental Changes in Power System Characteristics

Historical

Spinning generators

On demand power

Transmission and distribution

- Rotational Inertia
- Dispatchable Generation
- Passive / Predictable Loads
- "Static" T&D Infrastructure

Operator-Based Grid Management
Centralized Control
SCADA Measurements
Off-Line Analysis / Limit Setting

Supervisory control and data acquisition

Emerging

- Reduced Stability / Faster Dynamics
- Stochastic Generation
- Engaged Consumers
- "Adaptive" T&D Infrastructure
- Agile, Precise Control for Distributed Generation
- More Efficient, Reliable, and Resilient Electricity Systems

Uncertainties with renewable generation

Sensors and Data Acquisition
Faster-than-Real-Time Analysis
Algorithms and Computer Infrastructure
More Precise Control
Flexible and Resilient Systems
Multi-Level Coordination
PMU Measurements

A phasor **measurement** unit (**PMU**) is a device used to estimate the magnitude and phase angle of an **electrical** phasor quantity (such as voltage or current) in the **electricity grid** using a common time source for synchronization. ... **PMUs** can also be used to **measure** the frequency in the **power grid**.

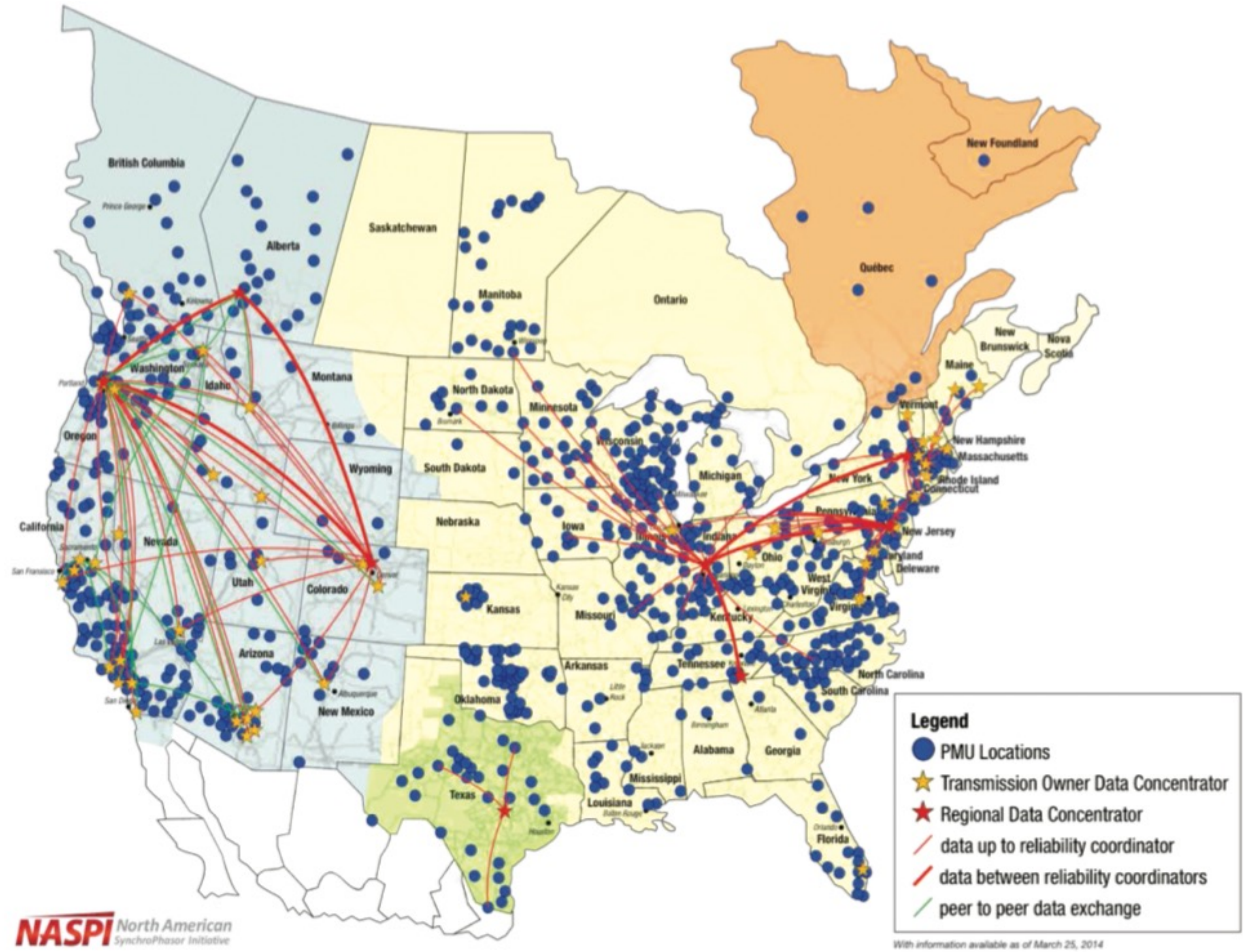
3.2.4 Moving Toward a Modern Electric Power System

The changing grid environment not only places new requirements on electric power systems, but also changes their intrinsic behavior (see Figure 3.12). Simply put, as generator and load characteristics change, the operational performance of the broader power system will be affected. Understanding these operational characteristics is integral to identifying the RDD&D needed for modern power systems.

Table 3.2 Key Monitoring and Control Attributes for the Evolving Power System

Traditional		Modern	
Observability	Controllability	Observability	Controllability
Static, slow, and local view: Weather, flows on key lines, voltages on key buses, tie flows, line status, generator status, real-power output, and predictable seasonal flow patterns	**Reactive (deterministic), high-level control:** Balancing and load following, discretized demand response, and transmission limit determination based on simulation studies **[Eliminate and/or avoid risk]**	**Dynamic, fast, and global perspective:** Resource forecasts, interdependencies, grid stress, grid robustness, dangerous oscillations, frequency instability, voltage instability, reliability margin, and field asset information	**Predictive (probabilistic), system-wide coordination:** Generator coordination (dispatch and control), topology and flow control, and demand-side coordination **[Manage risk]**

Figure 3.13 Data Flows from Transmission Owners to Regional Hubs, Between Reliability Coordinators, and Between Transmission Operators

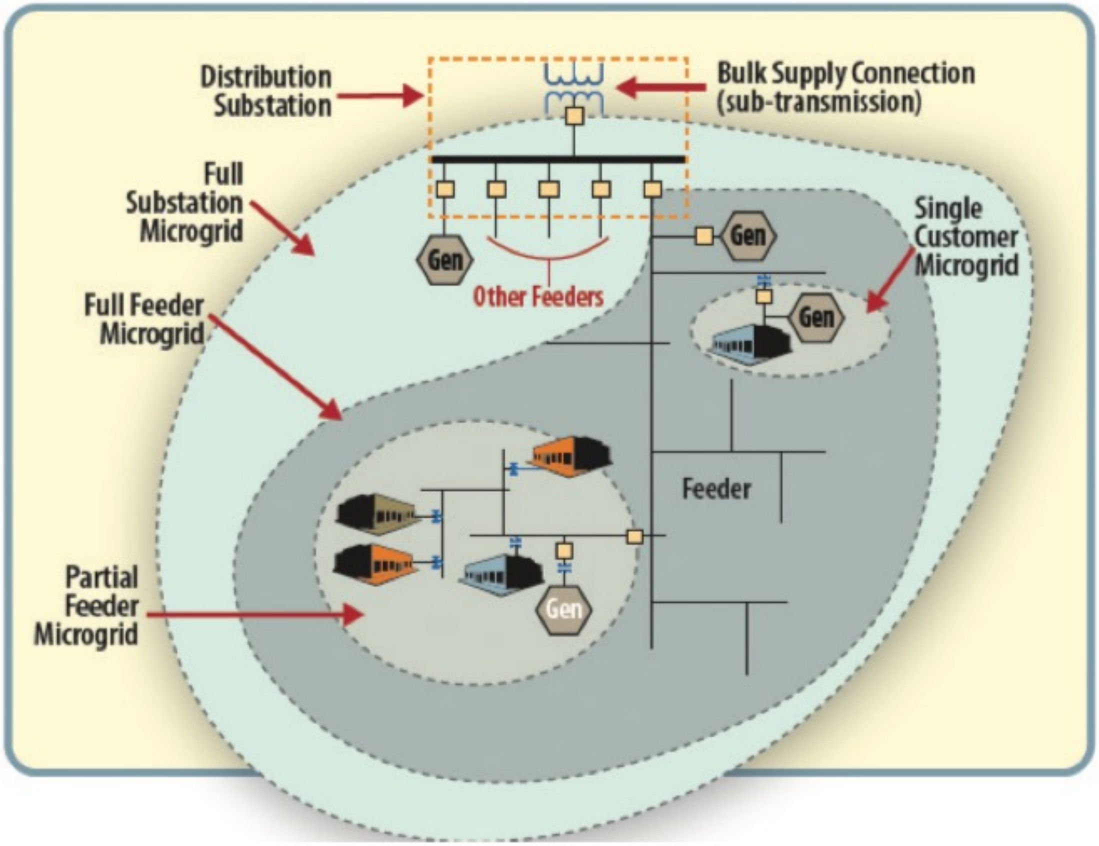


Thousands of networked PMUs now exist across the United States and Canada, sharing operational data across wide interconnections.

A phasor **measurement** unit (**PMU**) is a device used to estimate the magnitude and phase angle of an **electrical** phasor quantity (such as voltage or current) in the **electricity grid** using a common time source for synchronization. ... **PMUs** can also be used to **measure** the frequency in the **power grid**.

Figure 3.19 Different Microgrid Configurations

Credit: Sandia National Laboratories

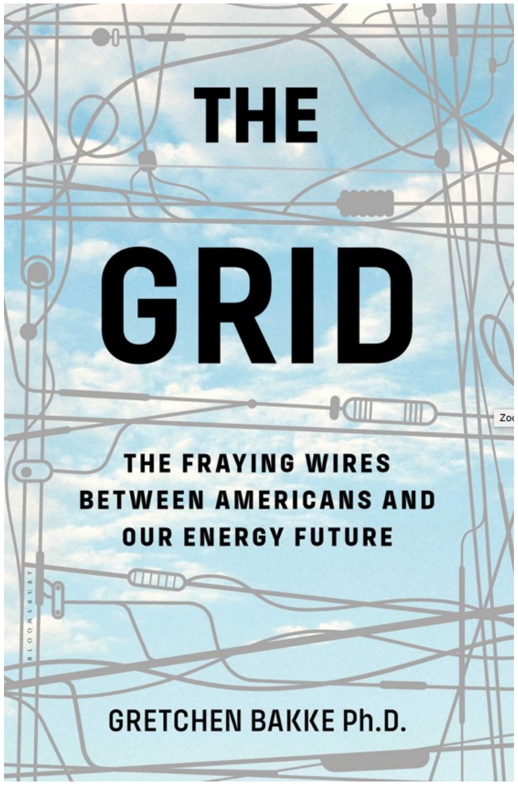


Microgrids can exist in multiple configurations: independently, networked along a feeder, or nested within another.

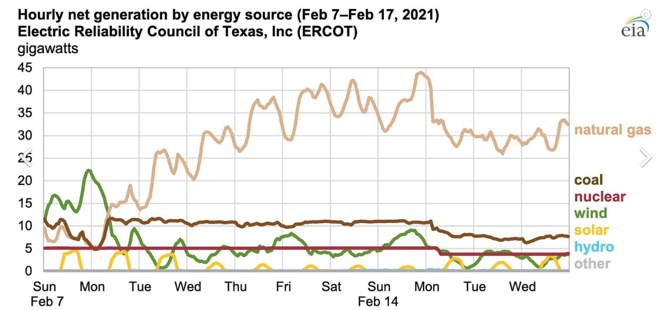
By 2050 (30 years) every power plant in the US will need to be replaced by new plants.

2008 to 2015 wind increased by 300%
solar increased by 2,000%

The grid is rapidly changing



Renewable energy generation



Variable generation:

US 7% (but this is localized)

Texas Wind is 9%
Oregon Wind is 13%
Iowa Wind is 30% of the grid

September 2015 Price per megawatt in north Texas was $-0.64 (negative!!)
The grid had too much power input due to wind (and inability to export power due to isolation)

US Military has microgrids for all US bases
Same for most Universities
Google, Microsoft, Citibank etc.

The ”utility” is becoming just an operator of the grid and a handful of plants.

With renewables **storage** becomes a main issue.

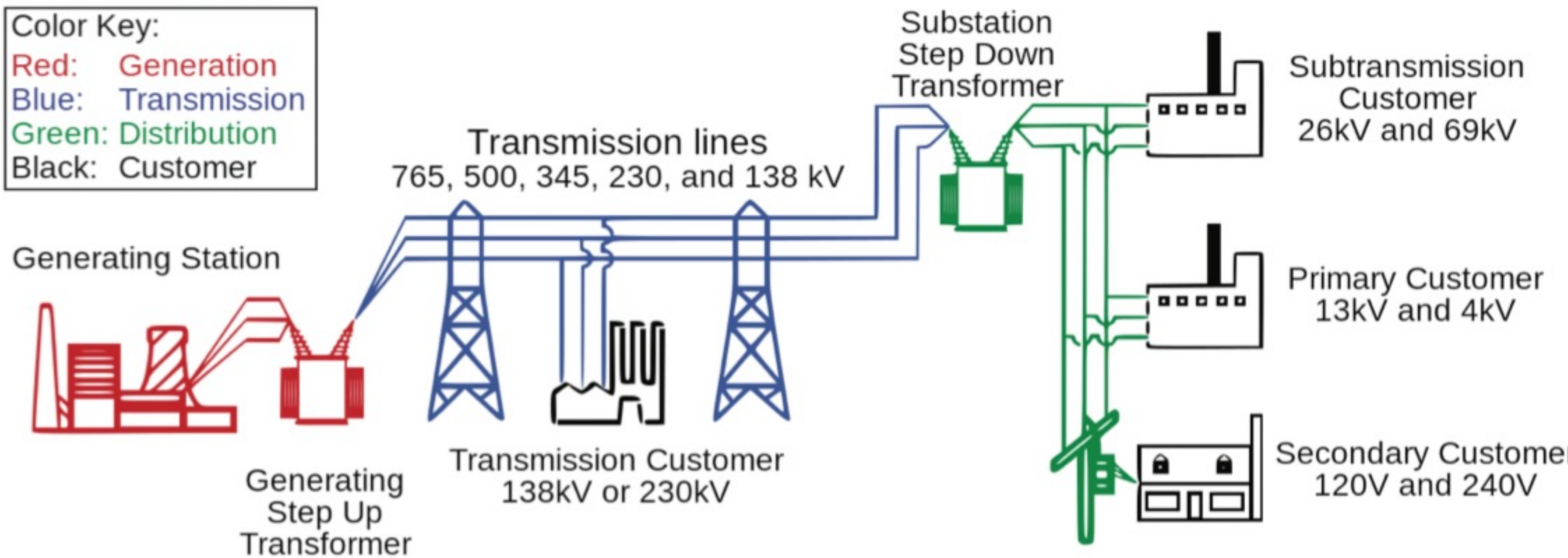
Utility death spiral

This is what is meant by the utility death spiral: "as grid maintenance costs go up and the capital cost of renewable energy moves down, more customers will be encouraged to leave the grid. In turn that pushes grid costs even higher for the remaining customers, who then have even more incentive to become self-sufficient."

DOE 2015 Quadrennial Technology Review

> "A modern grid must be more flexible, robust, and agile. It must have the ability to dynamically optimize grid operations and resources, rapidly detect and mitigate disturbances, integrate diverse generation sources (on both the supply and demand sides), integrate demand response and energy-efficiency resources, enable consumers to manage their electricity use and participate in markets, and provide strong protection against physical and cyber risks."

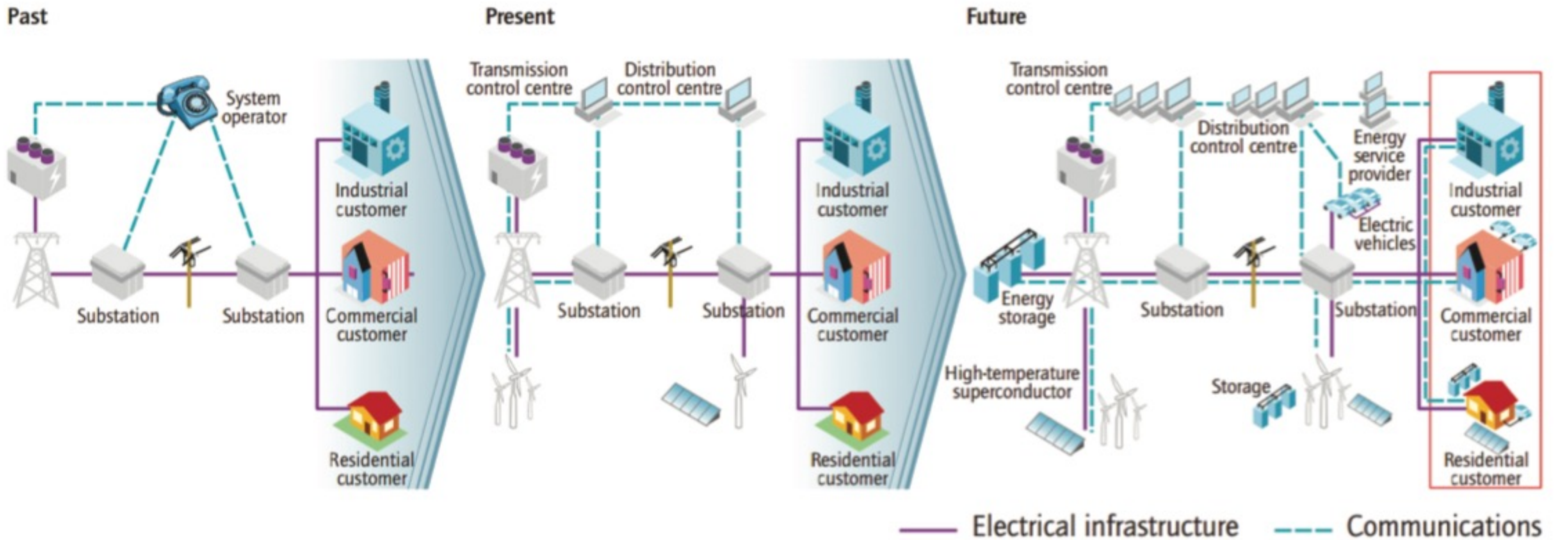
Figure 3.2 Traditional Electricity Delivery System



The traditional architecture was based on large-scale generation; centralized, one-way control; and passive loads.

Figure 3.3 Evolution of the Electric Power Grid

Credit: © OECD/IEA 2011 Technology Roadmap: Smart Grids, IEA Publishing. License: http://www.iea.org/t&c/termsandconditions/



The electric power grid is evolving to include more distributed control; two-way flows of electricity and information; more energy storage; and new market participants, including consumers as energy producers.

Your car is an under used resource

Drive to work, 1 hour, drive home 1 hour
22 hours not used

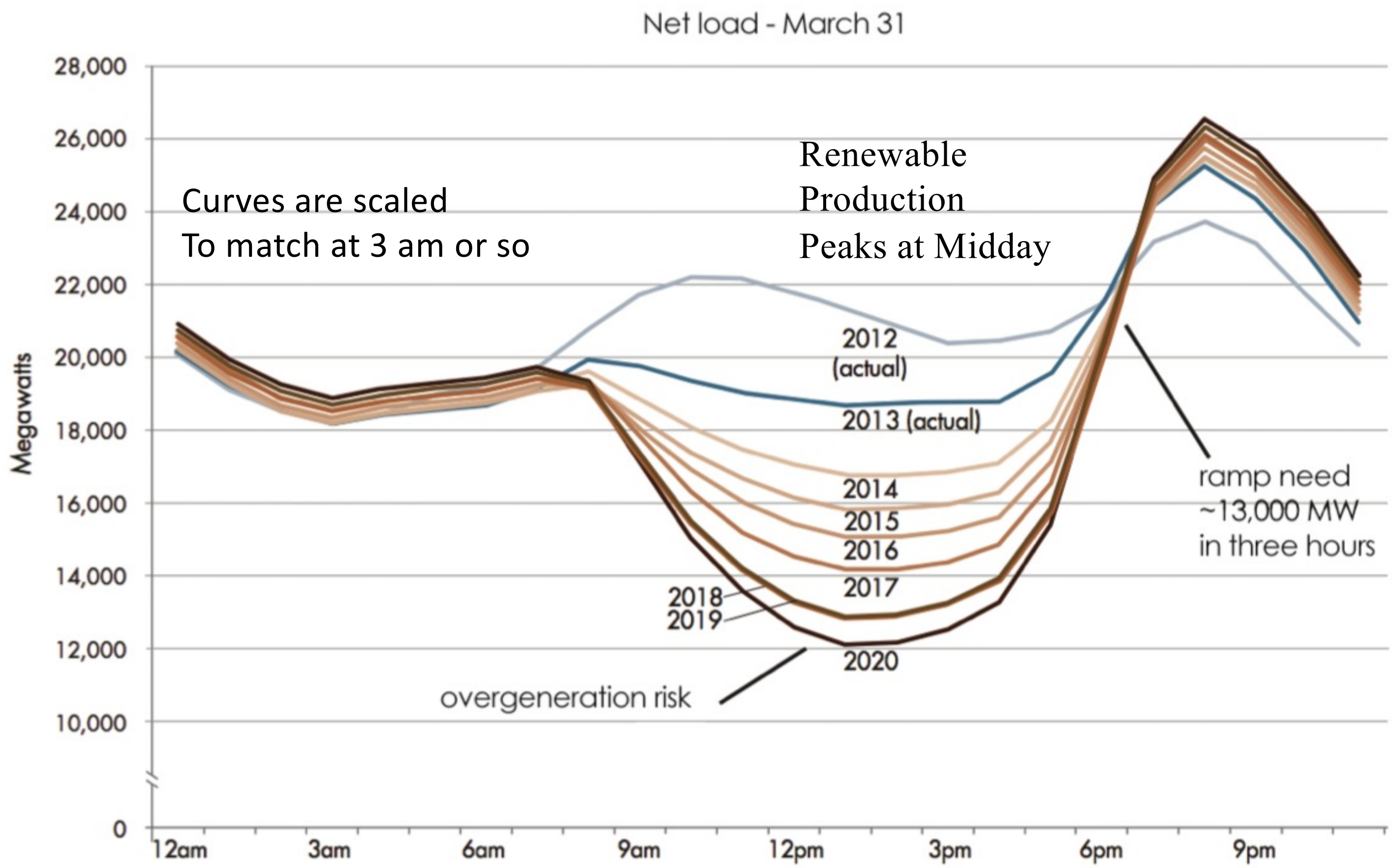
Could draw from the grid at night
(in the suburb where there is excess energy)
Add to the grid during day
(in the city where it is most needed)

Use the car as a portable energy source/sink
22 hours per day

If you get free fuel and some money
this becomes interesting

Figure 3.9 California ISO Projected Electricity Supply

Credit: California Independent System Operator Corporation



In projected scenarios, variable renewable generation is plentiful midday, but decreases just as energy demand spikes in the early evening—requiring increased system flexibility to meet challenges with steep ramps and over-generation risks. Note the offset of the vertical scale.

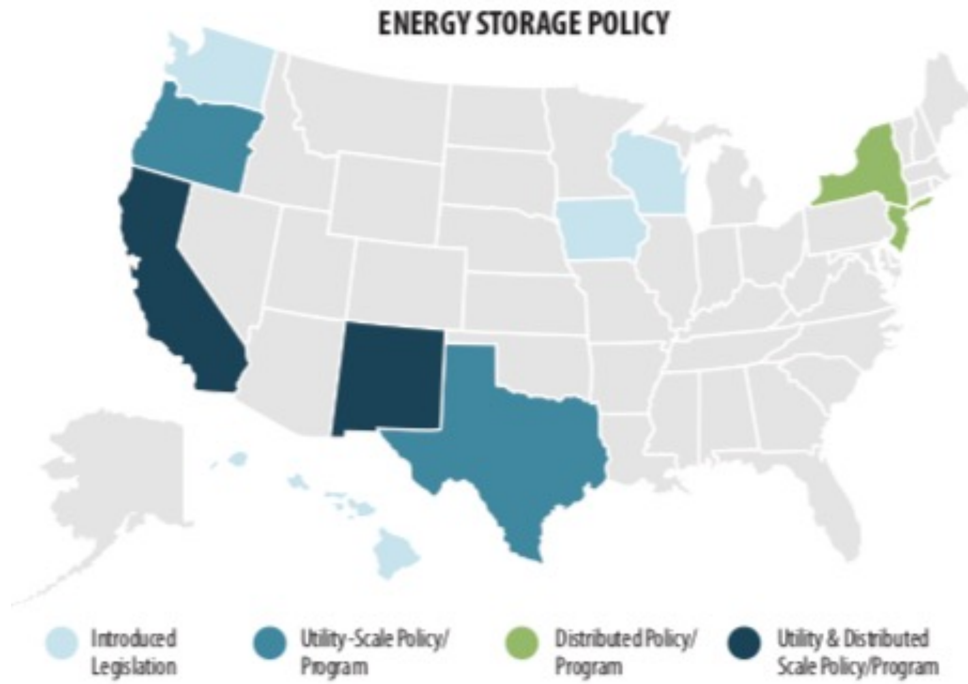
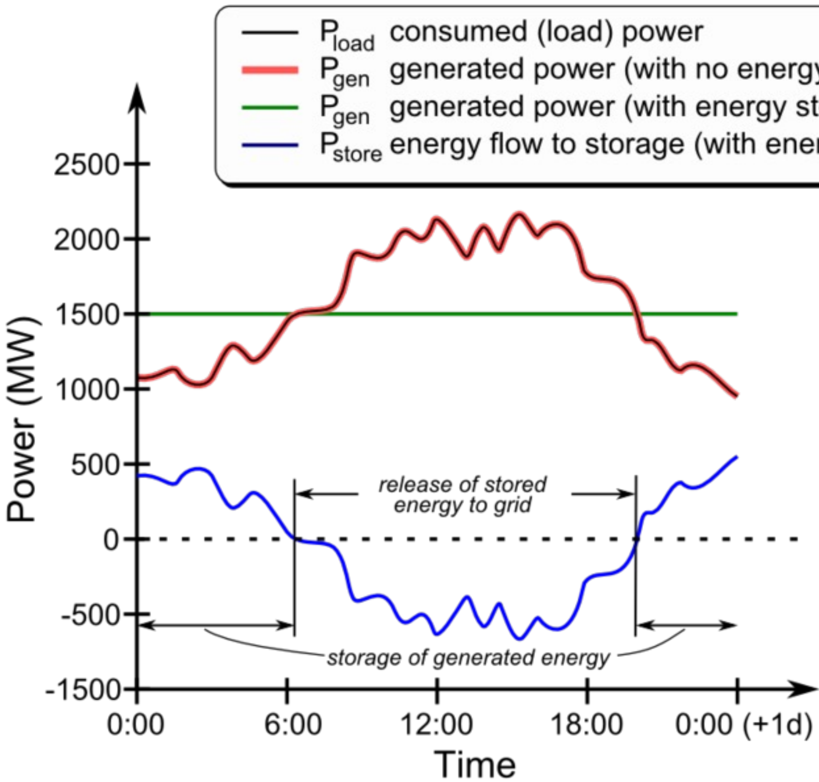
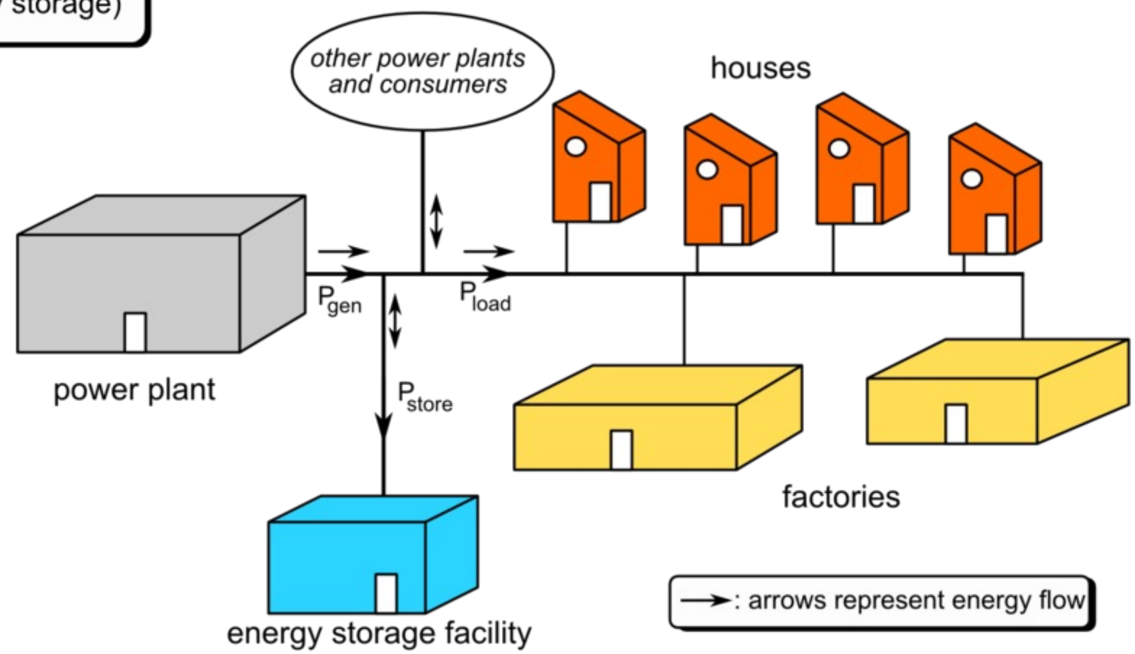


Figure 3. Between 2011 and 2014, at least 10 states introduced policies and regulatory actions focused on energy storage. Source: NREL/BR-7A40-62726

Load Balancing





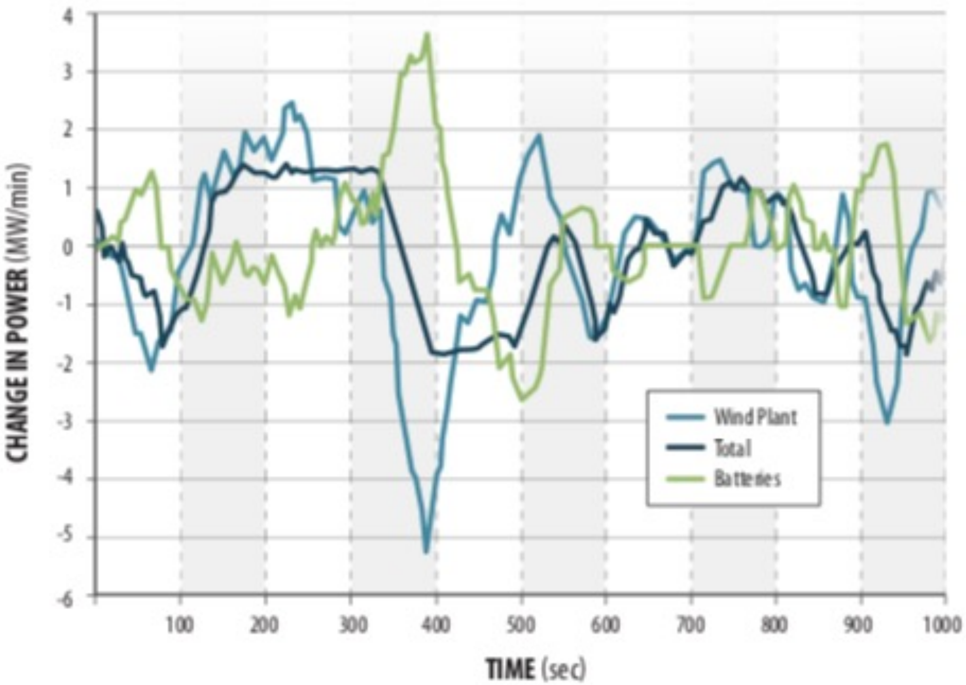
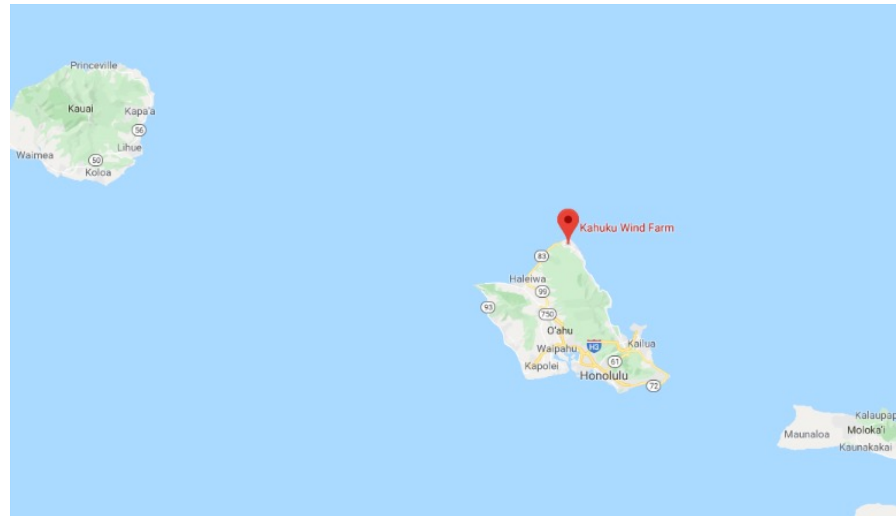


Figure 5. The 1-minute ramping operation of the Kahuku Wind Plant wind-energy battery storage system illustrates the reduction in ramping resulting from batteries being charged or discharged to limit the rate of change of wind power. These ramp rates show a more significant reduction of the total ramps (wind and batteries) than wind-only ramps. Source: http://www.nrel.gov/docs/fy14osti/59003.pdf



Grid Energy Storage

Currently used on grids

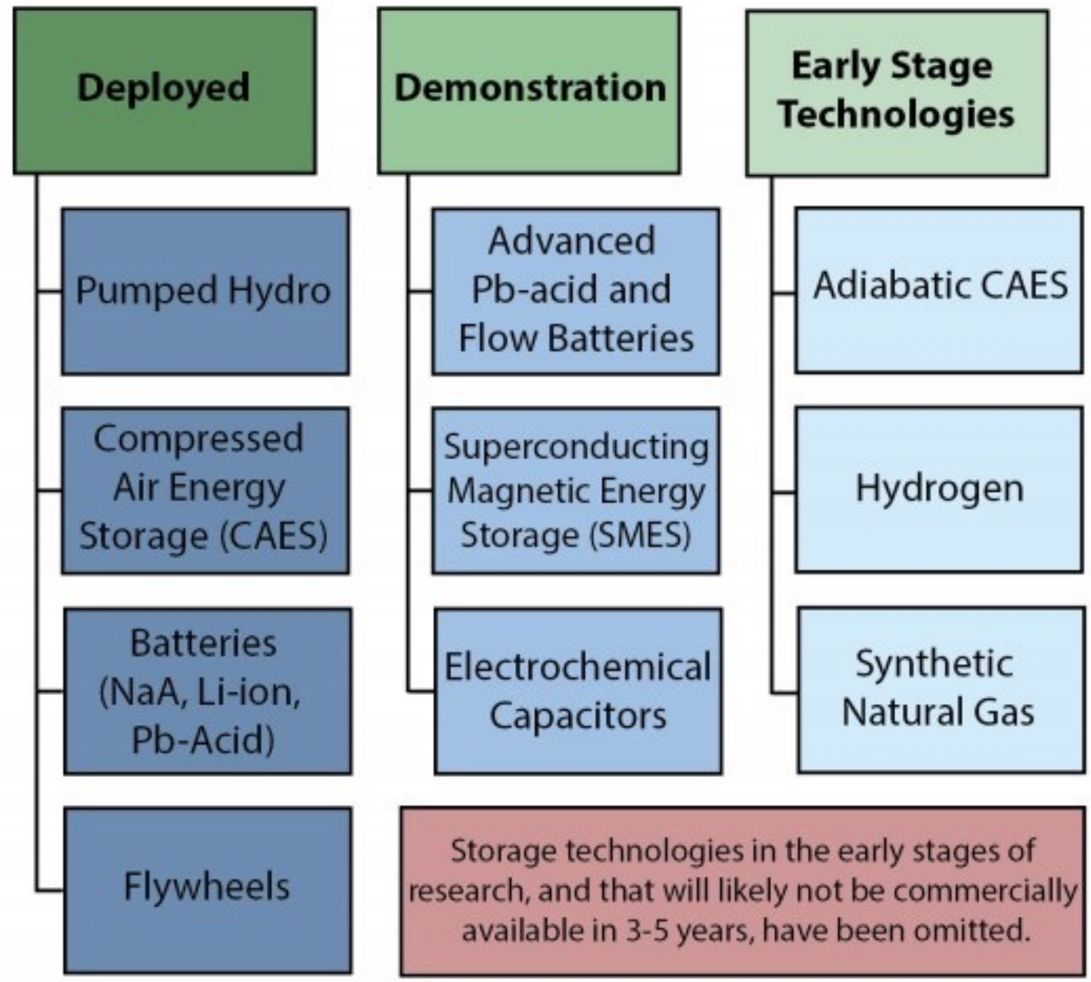
Water Storage (Ludington, MI)
Gas Storage (Compressed Air **CAES**)
Battery Storage (Iowa)
Fly Wheel (Beacon Flywheel)

Used in small scale

Electric water heaters
Electric Cars
Ice based air conditioners
Thermal Energy, Molten Salts
Hydrogen
Superconducting Magnet
Capacitors
Syn-Gas

Proposed

Liquid Air
Gravitational



Grid Energy Storage

Plant of the 100-MW advanced compressed air energy storage (CAES) in Zhangjiakou, Hebei Province. Credit: IET

The CAES power plant can generate more than 132 million kWh of electricity annually, providing electricity for 40,000-60,000 households during peak electricity consumption. It will save around 42,000 tons of standard coal and reduce carbon dioxide emissions by 109,000 tons annually.

10/5/22 https://www.inceptivemind.com/china-worlds-largest-compressed-air-energy-storage-plant-connected-grid/27685/

Grid Energy Storage

10/4/22
https://www.inceptivemind.com/china-connects-worlds-largest-flow-battery-energy-storage-station-grid/27631/

Batteries at Dalian Flow Battery Energy Storage Peak-shaving Power Station. Credit: Dalian Institute of Chemical Physics (DICP)

The 100 MW Dalian Flow Battery Energy Storage Peak-shaving Power Station, with the largest power and capacity in the world so far, was connected to the grid in Dalian, China. It will be put into operation in mid-October and will eventually be scaled up to 200 MW.

Grid Energy Storage

Currently used on grids

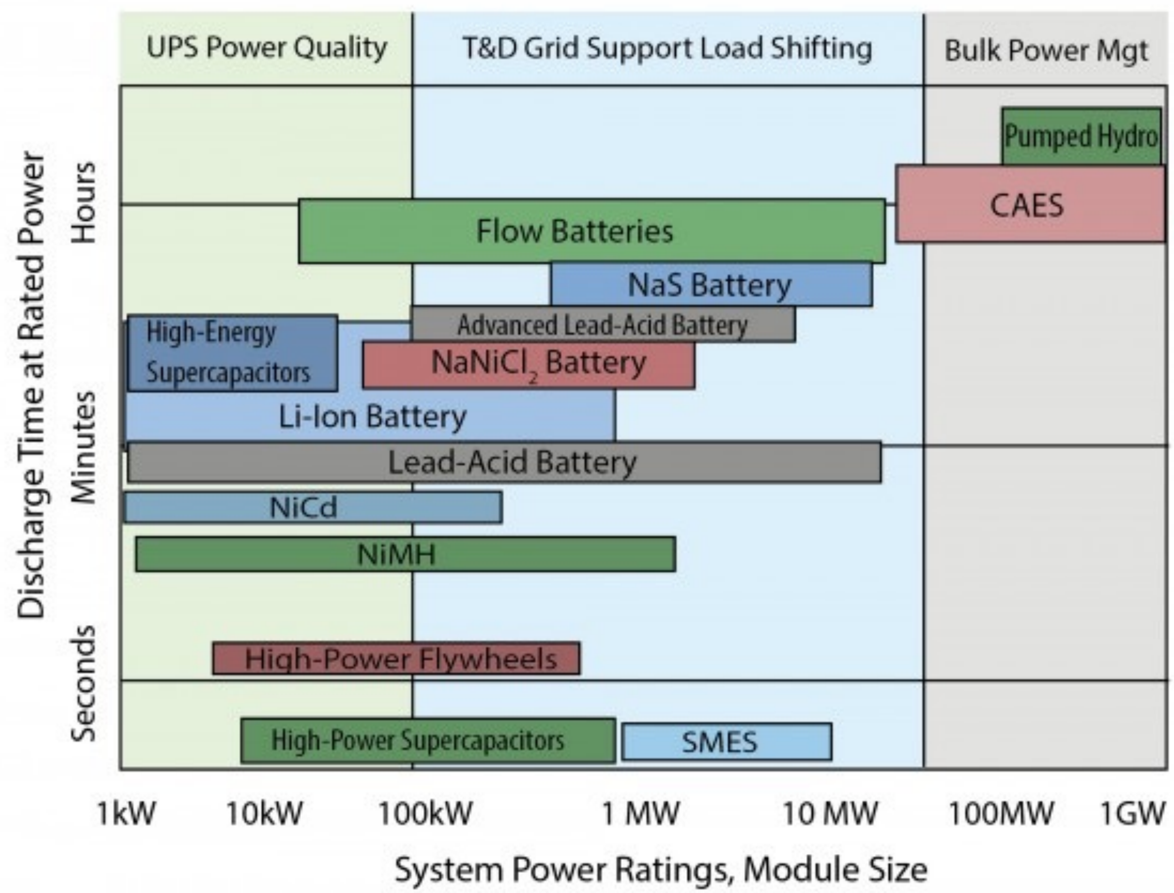
Water Storage
Gas Storage
Battery Storage
Fly Wheel

Used in small scale

Electric water heaters
Electric Cars
Ice based air conditioners
Thermal Energy, Molten Salts
Hydrogen
Superconducting Magnet
Capacitors
Syn-Gas

Proposed

Liquid Air
Gravitational



Grid Energy Storage

Currently used on grids
Water Storage
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Battery Storage
Fly Wheel

Used in small scale
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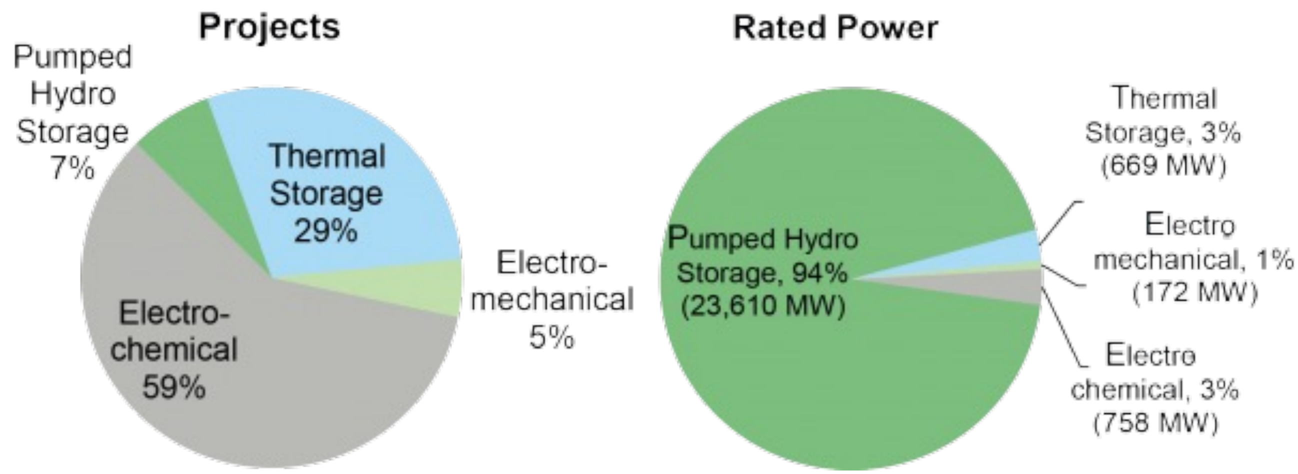
Ice based air conditioners
Thermal Energy, Molten Salts
Hydrogen
Superconducting Magnet
Capacitors
Syn-Gas

Proposed
Liquid Air
Gravitational

In the US 2018



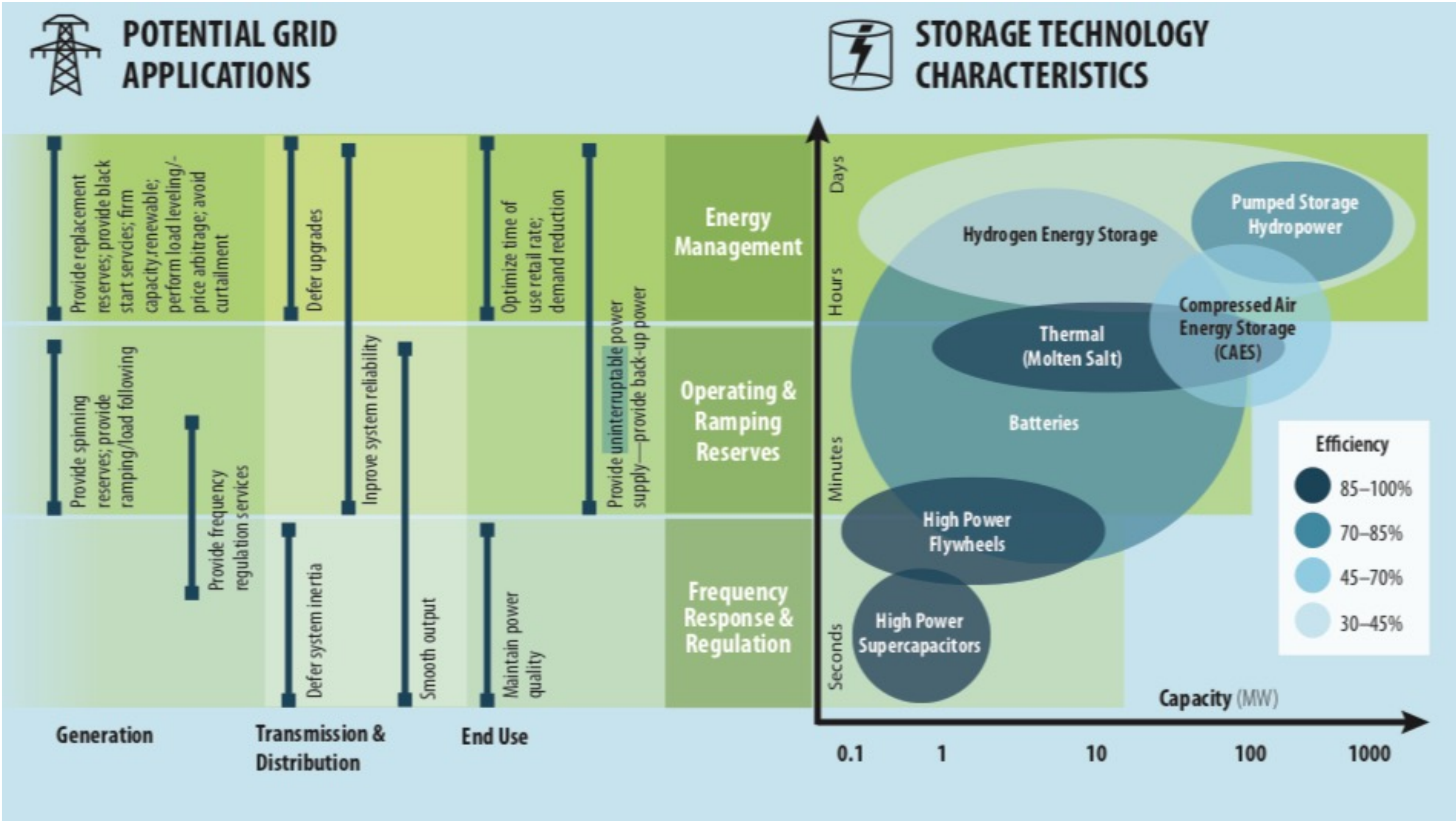


Figure 1. "Storage" is a broad category of technologies and applications that can help utilities balance power supply and demand by holding energy for later use, like a bank account for energy. Storage technologies are distinguished primarily by capacity and discharge time. Different storage technologies can be used for each of three main electric sector goals: energy management for daily/hourly scheduling, operating and ramping reserves for load following, and frequency response and regulation to maintain power quality.

Load leveling [edit]

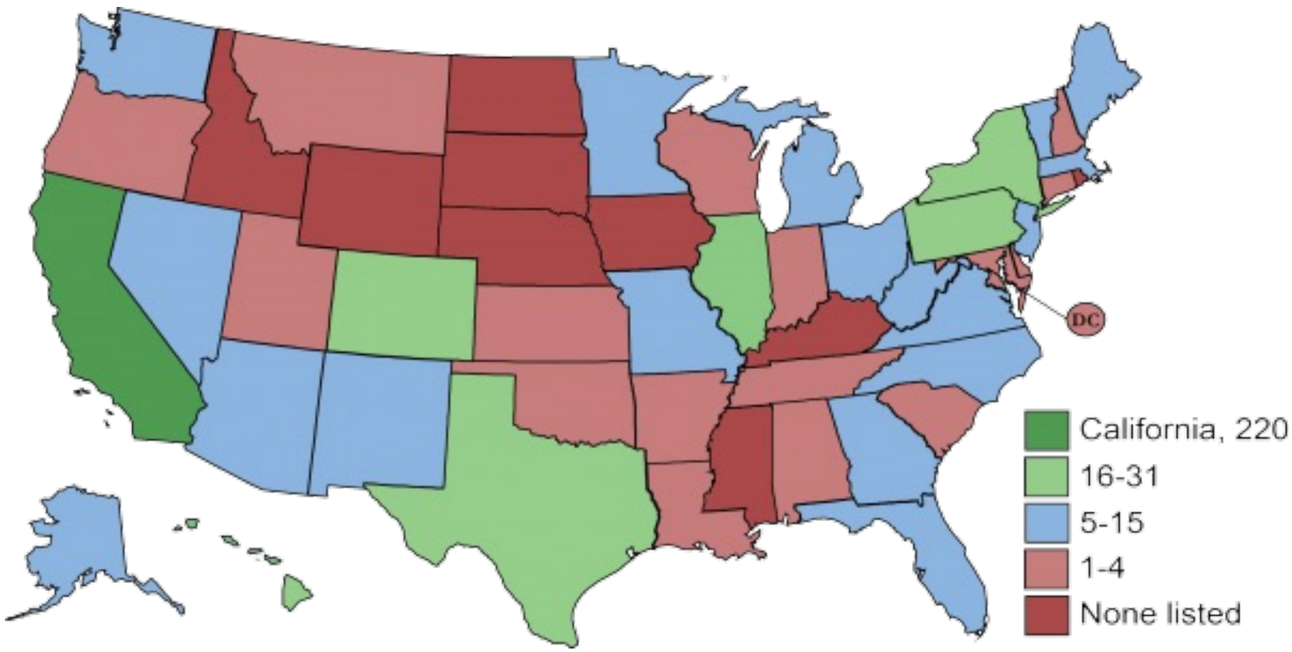
The demand for electricity from consumers and industry is constantly changing, broadly within the following categories:

- Seasonal (during dark winters more electric lighting and heating is required, while in other climates hot weather boosts the requirement for air conditioning)
- Weekly (most industry closes at the weekend, lowering demand)
- Daily (such as the morning peak as offices open and air conditioners get switched on)
- Hourly (one method for estimating television viewing figures in the United Kingdom is to measure the power spikes during advertisement breaks or after programmes when viewers go to switch a kettle on [88])
- Transient (fluctuations due to individual's actions, differences in power transmission efficiency and other small factors that need to be accounted for)

There are currently three main methods for dealing with changing demand:

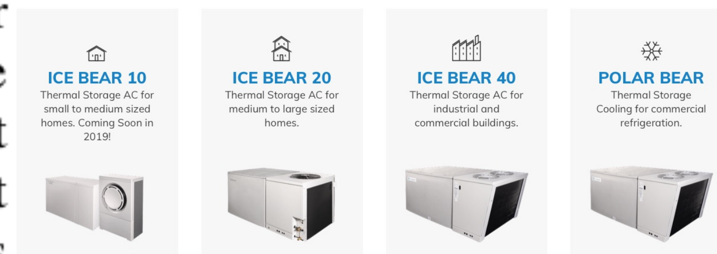
- Electrical devices generally having a working voltage range that they require, commonly 110–120 V or 220–240 V. Minor variations in load are automatically smoothed by slight variations in the voltage available across the system.
- Power plants can be run below their normal output, with the facility to increase the amount they generate almost instantaneously. This is termed 'spinning reserve'.
- Additional generation can be brought online. Typically, these would be hydroelectric or gas turbines, which can be started in a matter of minutes.

Grid Energy Storage
Number of Deployed Storage Technologies



Everywhere, and often inefficient, air-conditioning is finally being replaced in some places by an ingenious, if old-school, energy-storage device—an icebox that uses electricity during the middle of the night to make ice and then blows hot daytime air over that same ice during peak demand hours. Where an electromechanical air conditioner, the kind most of us use, employs electricity to move hot air over a refrigerant to be cooled and dehumidified the icebox uses a fan to blow hot outside air over ice. By this means the air is "conditioned," as the ice melts and returns to water (ready to be refrozen the next night) and the edifice to which the unit is attached is kept at a comfortable temperature during even the hottest hours of the hottest days. All of this is accomplished using about the same amount of daytime electricity as a ceiling fan. It's an icebox and, effectively, also an electricity box—nighttime electricity stored in the form of ice.

Ice Bear



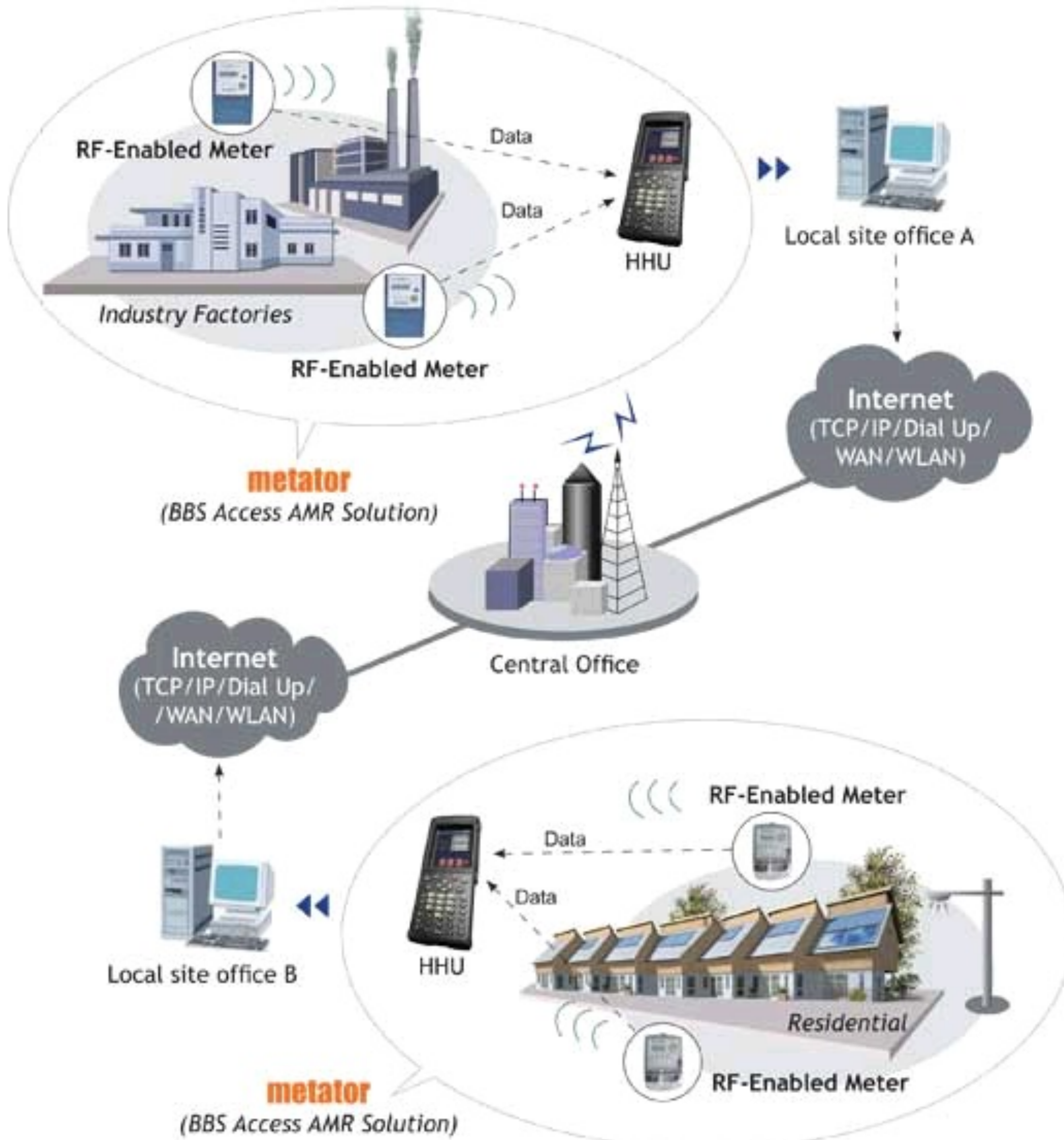
https://www.theatlantic.com/science/archive/2022/09/electric-cars-help-california-electricity-grid/671420/

"The car won't charge between 3 p.m. and 11 p.m." unless you override it, he said. "The reality is either you charge at work, and then you're done by 3. Or you get home, plug your car in, and it doesn't draw from the grid until 11 o'clock. But you don't care because you're having dinner with your kids, then you go to sleep, and it charges."

More and more appliances may soon work like this, especially if, as in California, time-of-use electricity rates become the default. (Under these plans, electricity is usually slightly more expensive in the early evening, when power demand is peaking but solar is beginning to fade.) Yesterday, Apple announced a new "Clean Energy Charging" feature that allows users to set their iPhones to charge during the parts of the day when the grid is most likely to be dominated by renewable sources.

Xcel has launched a plan that addresses renewable energy goals and also involves testing new technology that will pave the way for an interactive, intelligent and efficient grid. (Denver Post file)

SmartGridCity
Boulder CO
2008-2010
XCEL



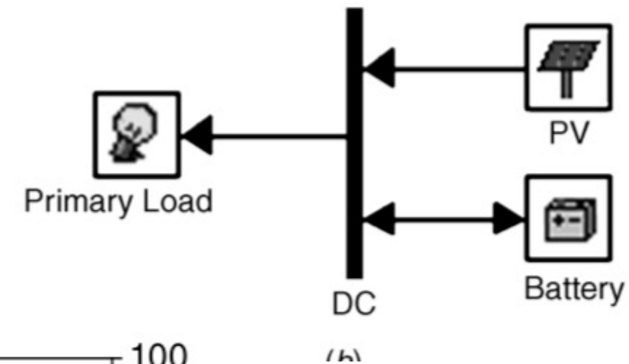
RF-Enabled Meter
Data
Data
HHU
Local site office A
Industry Factories
RF-Enabled Meter
Internet
(TCP/IP/Dial Up/
WAN/WLAN)
metator
(BBS Access AMR Solution)
Central Office
Internet
(TCP/IP/Dial Up/
/WAN/WLAN)
RF-Enabled Meter
Data
Data
Local site office B
HHU
Residential
RF-Enabled Meter
metator
(BBS Access AMR Solution)

Said Val, "I pretty much get on my computer, tell my house and my car what to do and then I walk away. My solar panels are talking to my house, are talking to my car, are talking to my house. It's a beautiful system."

Said Xcel, "Since the Petersons started the program, they have been able to produce 590.7 fewer pounds of carbon, saving enough to microwave 154 pizzas. Multiply that by fifty thousand customers—the number currently expected to install the system—and it can make quite an impact."

In 2014 the people of Boulder voted to municipalize their electrical infrastructure. They simply bought the wires and all the rest from Xcel and bade their digging, meddling, poorly communicating, investor-owned utility good-bye. Their main complaint: the utility had not given them enough choice; in poorly realizing their SmartGridCity, Xcel had failed to offer customers anything like real control. Mostly the people of Boulder wanted the utility to ensure that more renewables and less coal was being used to generate power for the town. A

Software to simulate micro grids (Homer)



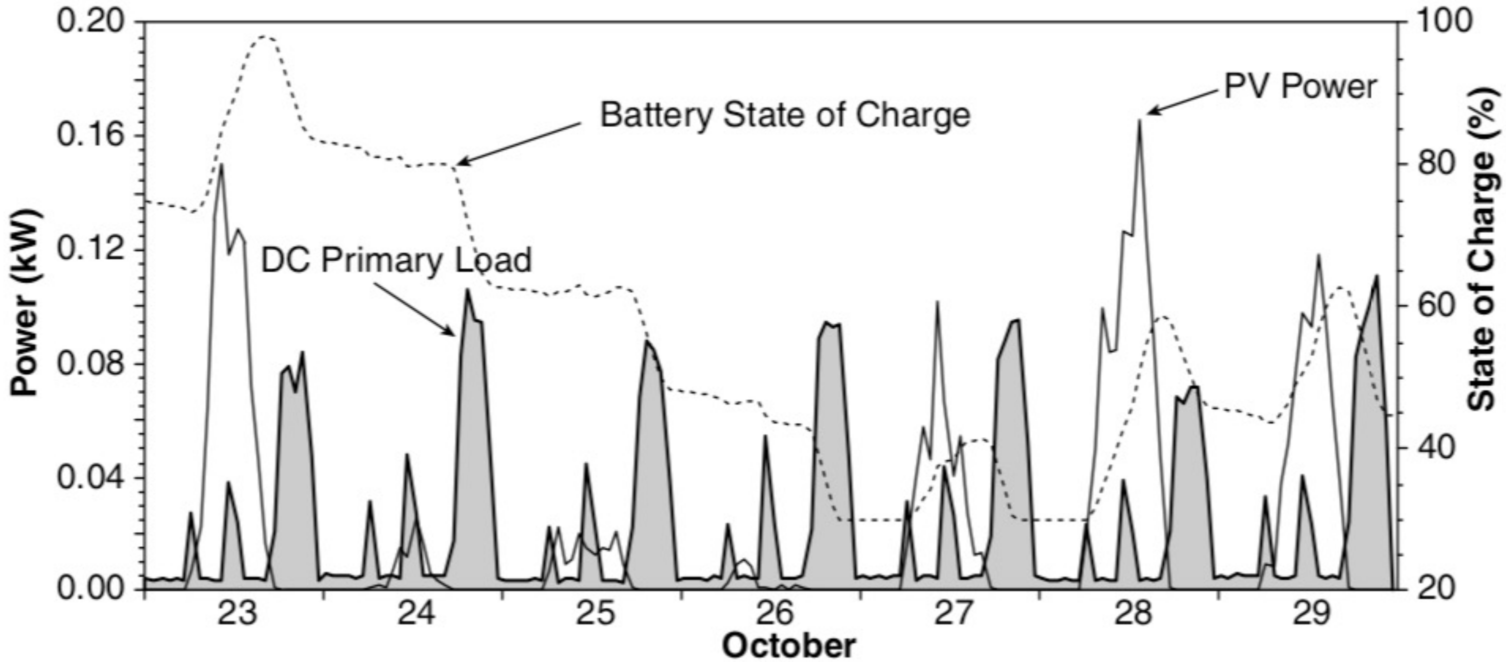
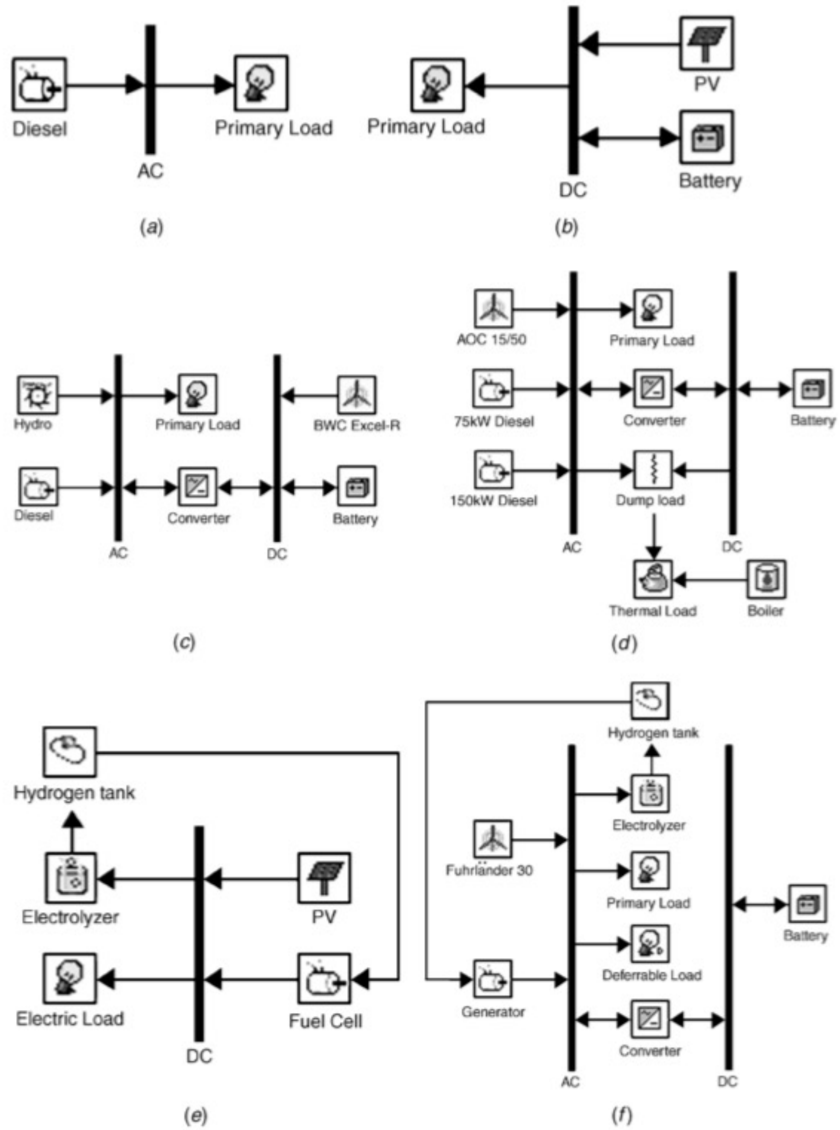


Figure 15.3 Sample hourly simulation results.



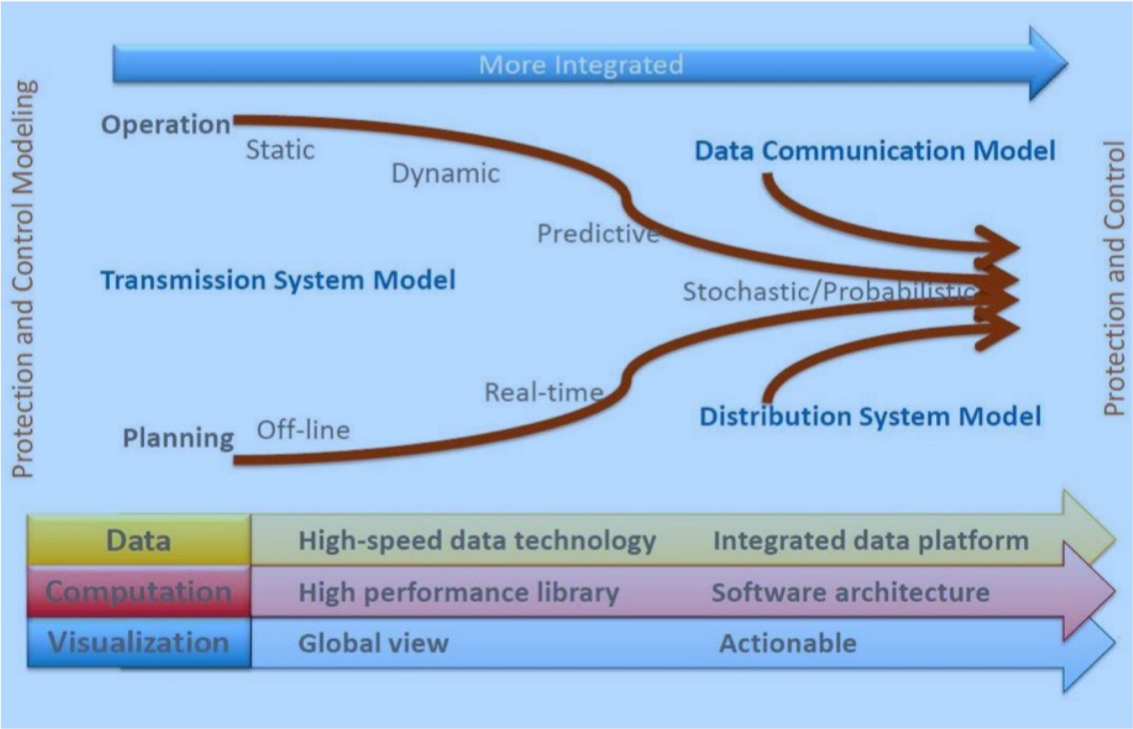
Diesel
AC
Primary Load
(a)
Primary Load
DC
PV
Battery
(b)
Hydro
Diesel
AC
Primary Load
Converter
DC
BWC Excel-R
Battery
(c)
AOC 15/50
75kW Diesel
150kW Diesel
AC
Primary Load
Converter
Dump load
DC
Battery
Thermal Load
Boiler
(d)
Hydrogen tank
Electrolyzer
Electric Load
DC
PV
Fuel Cell
(e)
Hydrogen tank
Electrolyzer
Fuhrländer 30
Primary Load
Deferrable Load
Generator
Converter
AC
DC
Battery
(f)

An Example

- Modern power systems are moving toward a stochastic environment due to increase in random forces that modify the system behavior (variable generation, demand-side management, congestion, system load, outages, and market).
- The existing deterministic operational practices are based on established dispatches and flow patterns which are becoming inadequate to deal with this uncertainty problem.
- This could potentially result in an increase in the system failure and outages.

Modeling and control of the grid

An Example (Courtesy of PNNL)



A Flexible Power System Operations Simulation Model for Assessing Wind Integration

Preprint

E. Ela and M. Milligan
National Renewable Energy Laboratory

M. O'Malley
University College Dublin

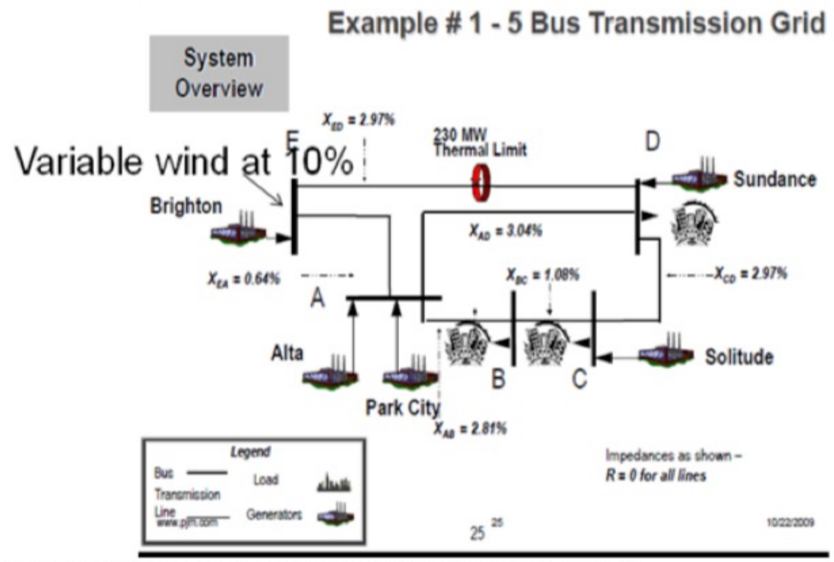


Fig. 4. PJM 5-bus system with variable wind added to bus E.

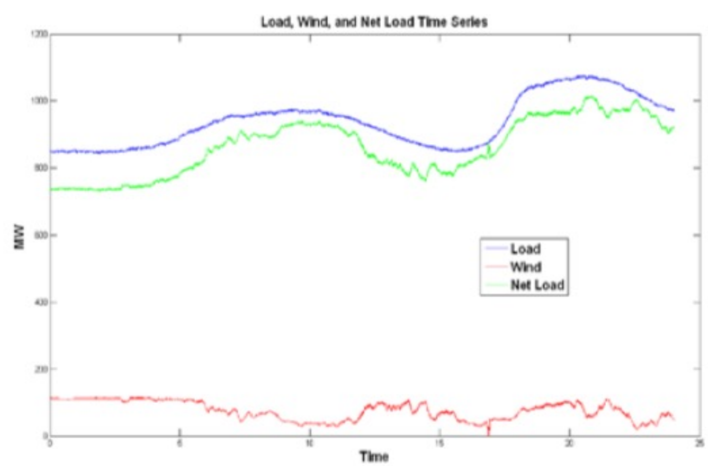


Fig. 5. Wind, load, and net load used in test system.

The grid will play a larger role in our lives

Getting off the grid and having grid independence seems to be a growing issue after Sandy and other storms

There are jobs in this sector, but it is difficult to define where they are, nobody is an expert right now (that is a good thing for a job seeker)

In the developing world there may be potential to build it right or to skip the gird altogether and leapfrog to a new microgrid future based on alternative energy

It is important to consider who is benefiting from technical advances, monitoring and control

ETHIOPIA
ADDIS ABABA
Hydro-electric power plant:
in operation
under construction / planned
possible future development
Power transmission line:
in operation
under construction / planned
Kilometres
Miles
RED SEA
GULF OF YEMEN
INDIAN OCEAN
SUDAN
ERITREA
DJIBOUTI
SOMALIA
Somaliland
KENYA
UGANDA
YEMEN
SAUDI ARABIA
KHARTOUM
ASMARA
DJIBOUTI
MOGADISHU
Mekele
Gonder
Bahir Dar
Dire Dawa
Harer
Jimma
Nazret
Jijiga
Kombolcha
Debre Markos
Debre Birhan
Asayita
Yabelo
Moyale
Dolo Odo
Negele
Gode
Warder
Kismayo
Eldoret
to Nairobi
TEKEZE
TIS ABAY I
TIS ABAY II
FINCHAA
KARADOBI
GILGEL GIBE I
GILGEL GIBE II
GILGEL GIBE III
GILGEL GIBE IV
KOKA
AWASH II
AWASH III
MALKA WAKENA
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ABUJA
Overhead lines:
33kV – 3,312km; 11kV – 3,804km; low voltage 3p – 3,520km
Cables:
11kV – 355km; low voltage – 262km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 2.1 GWh/yr
Turnover (2005): $62m
Expected investment: avg of $20m/yr for the next six years to improve efficiency and keep up with the growth in demand
Distribution losses: 35% (technical & non-technical), expected to reduce

KADUNA
Overhead lines:
33kV – 1,533km; 11kV – 1,614km; low voltage 3p – 6,535km
Cables:
33kV – 5km 11kV – 145km; low voltage – 93km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 1,522 GWh/yr
Turnover (2005): $31.2m
Expected investment: estimated $12m for initial six years, then likely to fall
Distribution losses: 25%

KANO
Overhead lines:
33kV – 3,583km; 11kV – 1,253km; low voltage 3p – 2,351km
Cables:
33kV – 4km; 11kV – 156km; low voltage – 17km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered (2005): 1,228 GWh/yr
Turnover (2005): $28m
Expected investment: est $15m/yr for initial six years, then likely to fall
Distribution losses: 40%

JOS
Overhead lines:
33kV – 3,930km; 11kV – 1,395km; low voltage 3p – 12,152km
Cables:
11kV – 20km; low voltage – 56km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered (2005): 438 GWh/yr
Turnover (2005): $9.5m
Expected investment: estimated $15m for initial six years, then likely to fall
Distribution losses: 22%

YOLA
Overhead lines:
33kV – 8,761km; 11kV – 1,407km; low voltage 3p – 21,489km
Cables:
11kV – 2km; low voltage – 29km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered (2005): 438 GWh/yr
Turnover (2005): $9.6m
Expected investment: estimated $15m/yr for initial six years, then likely to fall
Distribution losses: 22%

PORT HARCOURT
Overhead lines:
33kV – 6,109km; 11kV – 9,747km;
Energy delivered: 1,163 GWh/yr
Turnover (2005): $32.2m
Expected investment: estimated $15m/yr, then likely to slow down

IBADAN
Overhead lines:
33kV – 8,088km; 11kV – 4,594km; low voltage 3p – 11,401km
Cables:
11kV – 462km; low voltage – 407km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 2.8 GWh/yr
Turnover (2005): $77.2m
Expected investment: average of $31.4m/yr for the next six years, then likely to fall
Distribution losses: 8%

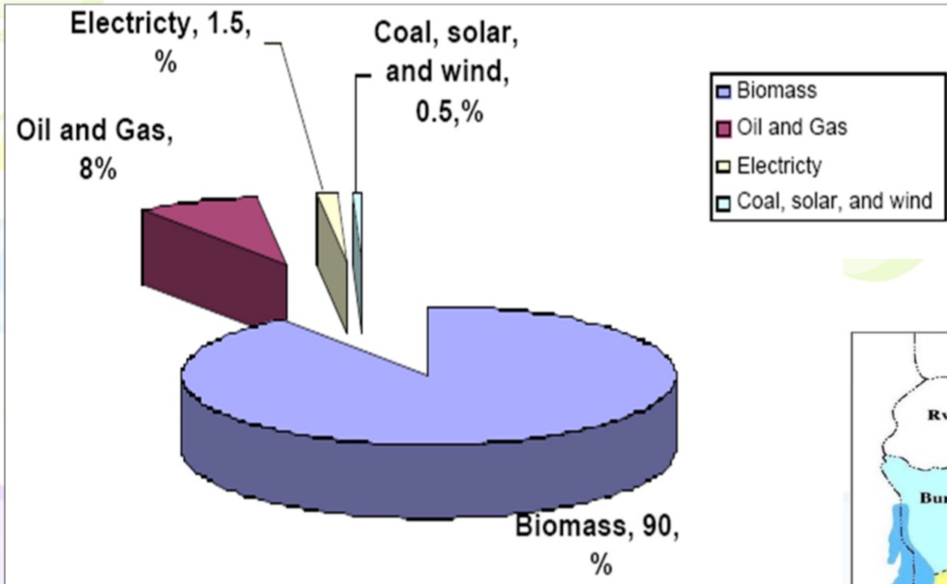
IKEJA
Overhead lines:
33kV – 7,711km; 11kV – 2,730km; low voltage 3p – 25,742km
Cables:
33kV – 12km; 11kV – 110km; low voltage – 262km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 3,520 GWh/yr
Turnover (2005): $117m
Expected investment: estimated $15m for initial six years, then likely to fall
Distribution losses: 18%

EKO
Overhead lines:
33kV – 545km; 11kV – 2,347km; low voltage 3p – 3,980km
Cables:
33kV – 317km; 11kV – 462km; low voltage – 262km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 2,629 GWh/yr
Turnover (2005): $103.1m
Expected investment: avg of $17m/yr for the next six years, then falling
Distribution losses: 18%

BENIN
Overhead lines:
33kV – 4,133km; 11kV – 5,168km; low voltage 3p – 12,876km
Cables:
33kV – 11,346km; 11kV – 132km; low voltage – 150km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 438 GWh/yr
Turnover (2005): $9.6m
Expected investment: avg of $18m/yr for the next six years, then likely to fall
Distribution losses: 21%

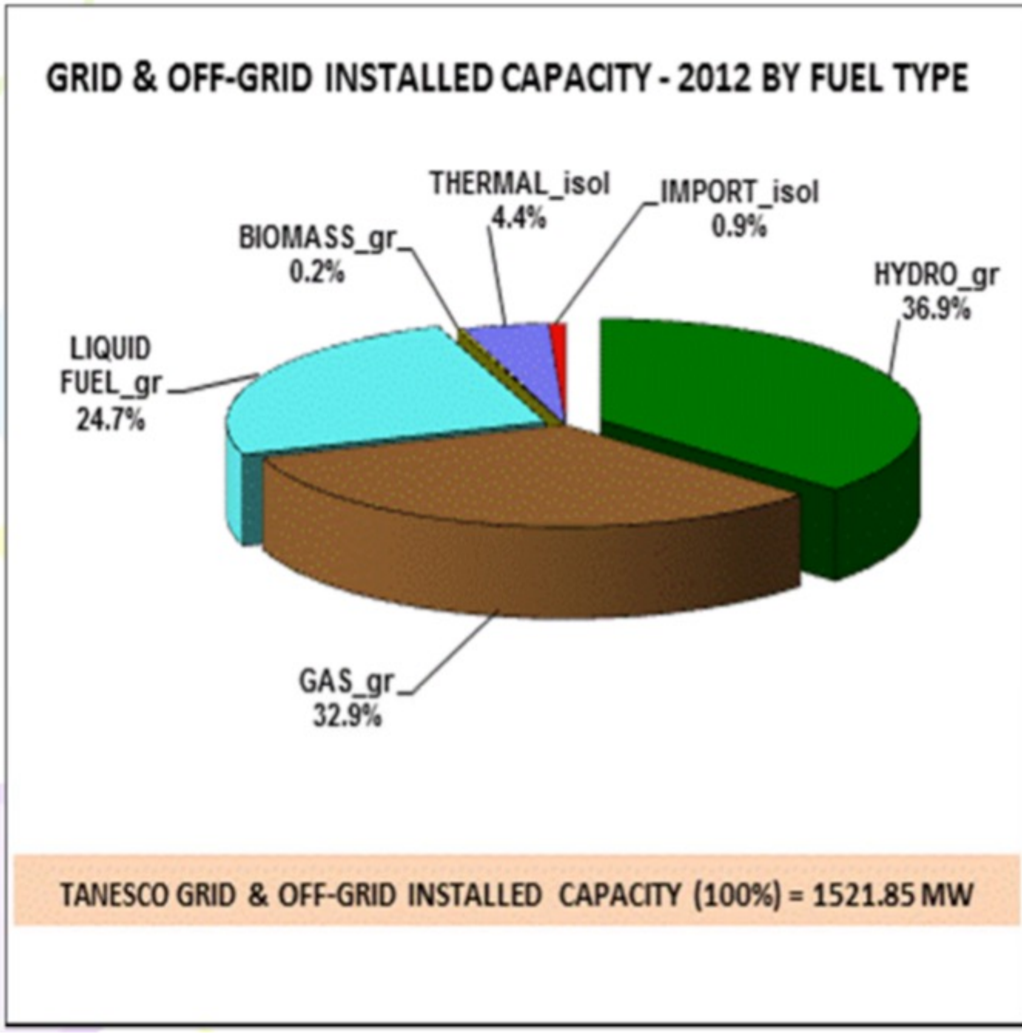
ENUGU
Overhead lines:
33kV – 4,092km; 11kV – 3,210km; low voltage 3p - 20,558km
Cables:
33kV – 4km; 11kV – 178km; low voltage – 213km
Ground mounted transformers:
33/11kV; 33kV/415V
Energy delivered: 2.2 GWh/yr
Turnover (2005): $57.8m
Expected investment: avg of $21m/yr for the next six years, then likely to fall
Distribution losses: 6%

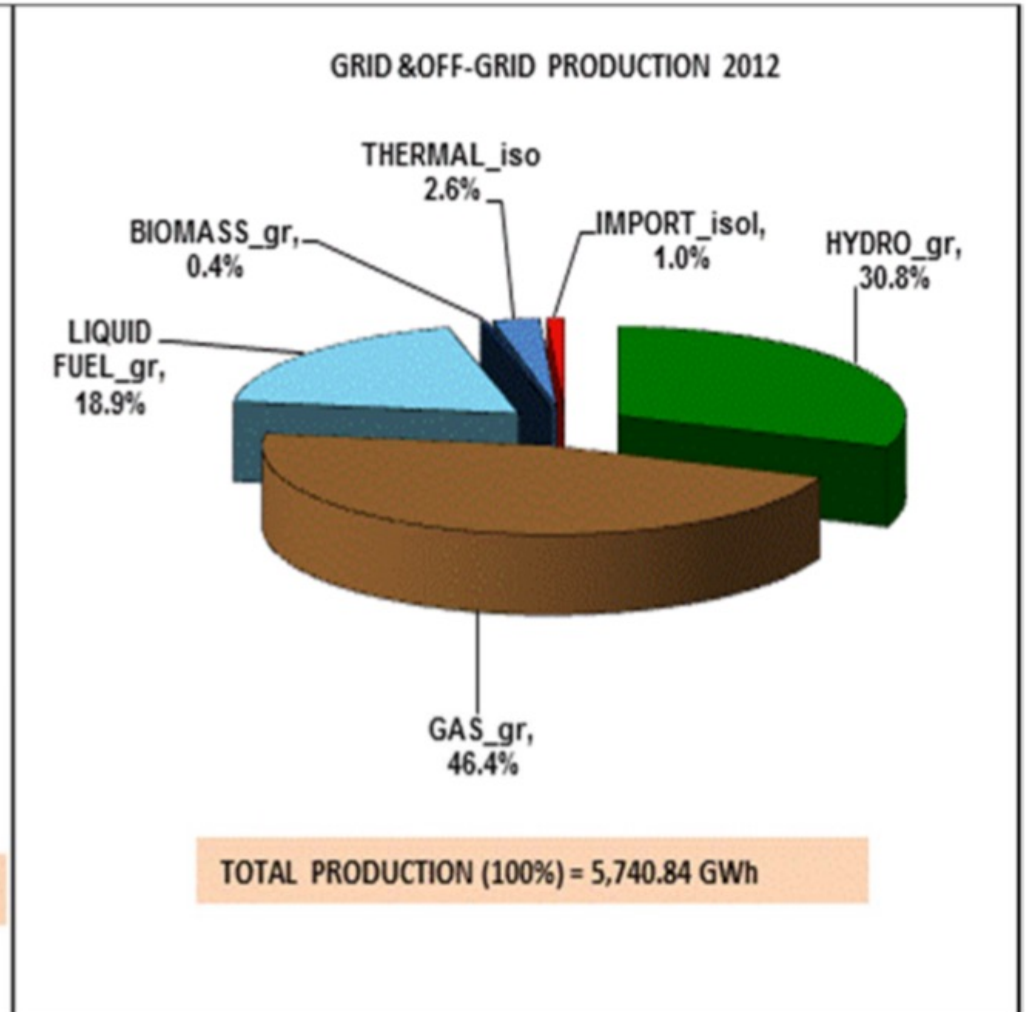
Energy Sector in Tanzania

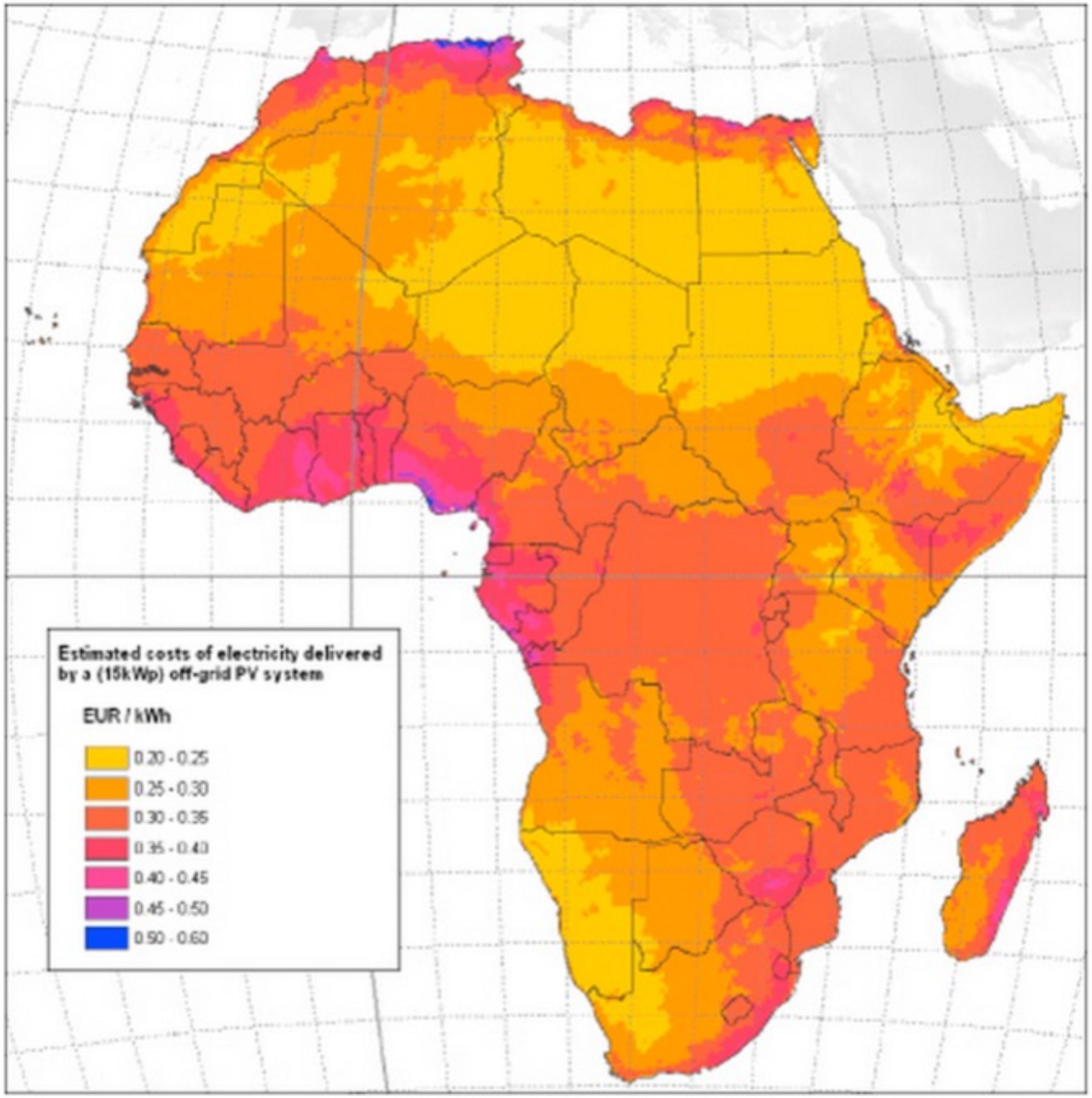


TANESCO's Grid Power Network

Tanzania Grid Electricity Source







[Comparison of Grid/PV/Diesel in Africa]

In the developing world the issue is partly no grid
The answer may be microgrid or off grid
An economic assessment of the advantages of the grid is needed

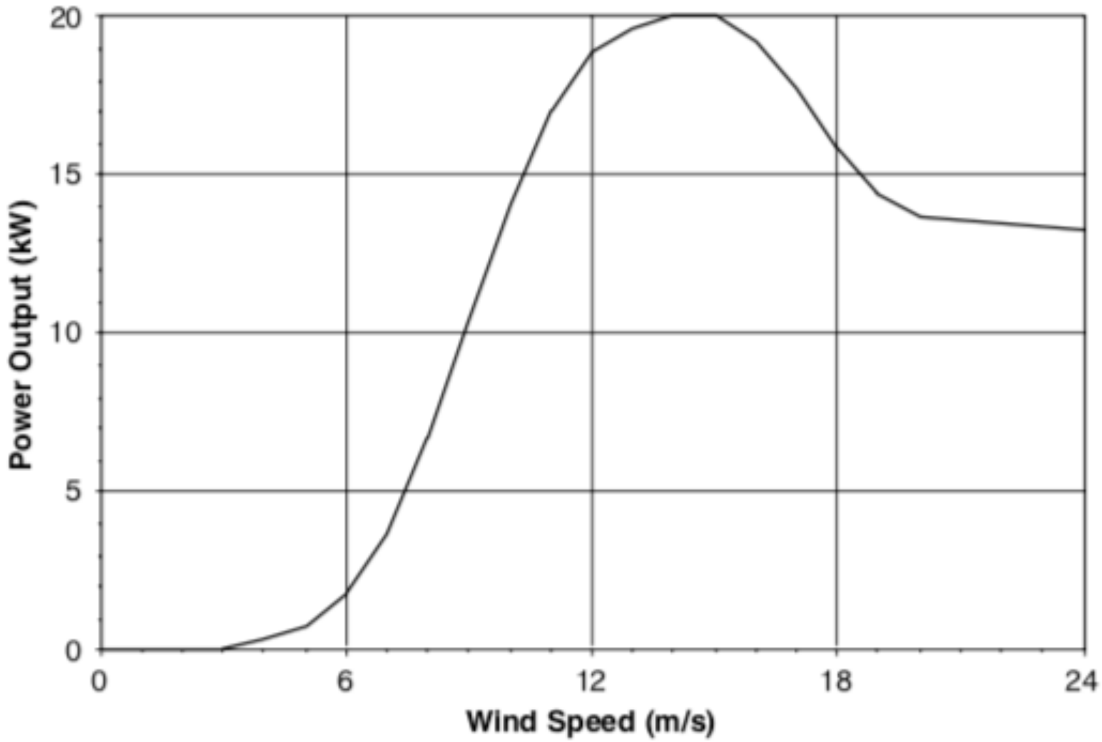


Figure 15.13 Sample wind turbine power curve.

him. And though they are getting faster, they are just not very adjustable. Coal-burning plants, at 50 percent in five minutes, are one of the fastest; natural gas (from a cold start) takes about ten minutes to get up to speed, while nuclear takes a full twenty-four hours to turn up, though it can be shut down in seconds.

In human time, five minutes might seem pretty quick, given that we are talking about moving a mechanical system as massive and complicated as a coal-burning power plant, which pulverizes and combusts, on average, 125 tons of coal every five minutes.

But in electricity time, which is what matters to grid stability, five minutes might as well be infinity. In five minutes, electrical current generated by a power plant outside Muncie, Indiana, can go to Mars. Even in the decidedly imperfect conditions of electrical transmission more characteristic of life on Earth, the wind power generated in the Columbia River Gorge that is not used by the relatively sparsely populated states of Oregon, Washington, and Idaho can be easily transported along a long DC (direct current) line to the good people of Los Angeles County, where it is gobbled up by air conditioners well before its sixty seconds are up. This is one of the reasons the grid is big. Big means that power plants can be built in places with not too many people but still provide electricity to large population centers as distant from one another as Seattle is from San Diego.

Their balletic capacities to the side, the utility companies do find themselves trapped in an increasingly tight spot between a rock (variable generation) and a hard place (keeping the lights on). If in 2009, when Chu gave this presentation, there were twenty-five wind farms in the Columbia River Gorge; today there are four times that many, most containing hundreds of turbines, each turbine producing well over a thousand kilowatts of power. Some of the largest wind developments in the nation sit nestled into this single slash of land. All that power, currently estimated at 6,000 megawatts (or enough electricity to power 4.5 million households) depends solely on the way the wind blows.

You can't just turn the wind down. When it blows hard, those turbines spin and spin and the output is tremendous. The young control room operator with whom I sat watching the weather as it approached and moved through widely scattered wind farms told me with a note of awe in his voice that you can actually see a gust of wind as it tops the Rockies and then hits one set of turbines after another all the way to the coast. You can see it in the power spikes —*bang*, *bang*, *bang*—of wind farm after wind farm shooting electricity into the system. It floods the grid; it crashes through the infrastructure much like a wave crashing against a sea wall on a stormy day. Even Los Angeles can't absorb all the electricity made on a seriously blustery day in the Pacific Northwest. Even the Western Doughnut, as the high-voltage DC line that carries electricity from the Gorge to the people of Southern California is called, with its 3,100 megawatts of transmission capacity (or half of L.A.'s peak capacity), cannot carry it all.

"On the afternoon of May nineteenth, 2010," he might have said, "in a single chaotic hour, more than a thousand wind turbines in the Columbia River Gorge went from spinning lazily in the breeze to full throttle as a storm rolled out of the East." Here he would pause, to see if his audience understood what was about to happen, what all of this wind was about to do to all those turbines. "Suddenly, almost two nuclear plants' worth of extra power was sizzling down the line—the largest hourly spike in wind power the Northwest has ever experienced."

A massive uncontrollable, unmanageable, unstorable, undumpable electricity surplus. Chaos on the lines. And what is worse: it's May.

In Oregon in May it's still raining. It's been raining since November, and it will continue to rain for another month or so before things begin to lighten up. In the Cascades, the mountain range that bifurcates the state, all that rain is snow, and in May all that snow is meltwater—pure, chill runoff. The rivers are very full, and they are sloshing their way down the sides of mountains and hills into the man-made lakes that sit behind, and feed, each and every dam on the mighty Columbia. In May these reservoirs can't hold another drop. They are full up. And the turbines on every dam up and down that mighty river chug along at a fearsome rate, because if they don't there are only two options. Either the reservoirs flood up over the homesteads, highways, and towns that dot the river's edge, or the dam operators let the water out through spillways.

Though the second might sound like a good option, sadly for them, it also happens to be illegal. Because, in May, the fishlings are running, tiny silver slivers that will,

The only option is to let the dams operate at close to maximum capacity. And if the dams are going to make all the power they can, they are going to need all available transmission lines to move that power out of Oregon to anyone and everyone who looks like a market. It can't be stored, it must be transported and used immediately, or the land will flood, or the grid will crash. This is every day in May. There is water, there are fish, there are laws, there are power lines with a finite capacity to transport electricity, and there is a market that just might not be big enough to use all the power they are being fed.

This was the situation into which the equivalent output of two nuclear power plants was suddenly poured that mid-May day back in 2010. The only real option was to shut down the wind turbines. Switch the beasts off. Still their spinning. Clear the lines. Let the storm blow itself out. Leave all those electrons unreaped.

At the time, that's exactly what the local balancing authority—the Bonneville Power Administration (BPA)—mandated be done. They called up the corporation that developed, built, and still manages most of the wind farms in the Gorge, the Spanish-owned conglomerate Iberdrola, and asked them to pretty please, and yes, immediately, turn off their many hundreds of wind machines, whipping around just then at absolutely ferocious speeds in the onslaught of wild air.

But what does Iberdrola care for the grid? They are in the business of making electricity, not of moving it to market. Transmission is the utilities' problem and balancing is the balancing authorities' problem, regulation is the regulators' problem, interregional cooperation is the ISO's problem. Iberdrola's problem, as the second-largest wind company in the world, is maintaining a profitable bottom line. Turning off their turbines at a moment of maximal productivity? Well, it's just not a sensible course of action. Most especially because the federal subsidies that have helped them to build and maintain their almost three thousand American-sited turbines only accrue if those machines are turned on and running. It's not just that they only make money from these beasts' ceaseless rotation, it's also that they have to *pay back* money if their turbines are ever off. Even the agency that Chu headed didn't imagine as it wrote up its guidelines for subsidies that sometimes the best thing anyone could do with a wind turbine is turn it off; that sometimes, in America, we can have too much of a good thing. If Iberdrola switches off even one turbine just to be nice, this has very real ramifications for their profitability. From their point of view, if the grid isn't up to the task of moving to market the power they make, then the grid needs to be better.

In West Texas, the largest wind farm ever planned on American soil was abandoned in 2008 because the utility refused to build a high-voltage line out to the site. And the developer, the local oilman T. Boone Pickens, thought it was a travesty given how much he was investing to build the farm itself that he would be expected to also build the transmission infrastructure. He shelved the project after having installed just a thousand turbines, a fraction of the total.

Add to this a second outrage. Pickens had already been obliged to use turbines that were small by international standards, just as was every other wind farm developer in America at the time. The grid's fragility demanded it. If a wind storm can turn a field of "small" wind machines into the equivalent of a nuclear power plant in a period of minutes, you can only imagine what would happen to a field of the really big ones. Germany's Enercon makes a 7.5 MW model (only slightly smaller than the largest offshore turbines, which come in at 8 MW), whereas in the United States the most common turbines remain the 1.5 MW GE model and the slightly bigger 2 MW Gamesa. This has nothing to do with how fast the wind blows across American plains versus German ones; it has everything to do with the wires these massive machines feed into. It is the system that stands between the point of generation and point of consumption that delimits productivity. The grid is the weakest link. It isn't made for modern power grid's known woes: use smart grid technologies, curb customer demand, end peak demand, develop grid-scale storage, add a nationwide extra-high-voltage DC/AC transmission network, reduce line congestion, encourage interregional cooperation, develop interoperability standards, increase government investment, train a new generation of grid operators, and integrate large numbers of electric vehicles.

Renewables and their scattershot siting are not what make America's electricity difficult to manage in the second decade of the twenty-first century. They just bring to light a problem that has been characteristic of our grid for more than half a century: it was made to be managed according to a command and control structure. There was to be total monopolistic control on the supply side of great electric loop—which included generation, transmission, and distribution networks—and ever-increasing yet always-predictable consumption on the customer side of things. Electricity would move from one to the other, while cash would move in equal measure in the opposite direction.

Those heady mid-twentieth-century days of massive, secured investment in big power projects are over. As a result, in 2005, a full fifth of America's power plants were over half a century old and reliant upon technology that

was state of the art in the 1950s. More important, as complicated and old as these massive electrical generating factories are, they are but one aging and difficult-to-maintain bit of the older and even more complicated grid that binds them all together. As rightly afraid as we have

There is nothing unusual in the story so far: a hot day, an overtall tree, a sagging wire, a flashover, which, while bad for both the tree and the line, was hardly a harbinger of the violent voltage swings—and resultant blackout—to come. This kind of death of a wire happens all the time in the United States. A tree, a wire, a bang, a short, followed by the automatic shift of the dead wire's "load"—this is the technical term for the electricity it is asked to carry—to another, duplicate wire, heading in the same direction. This kind of redundancy on the system, which has been intentionally increased since 1968 after the Northeast's first big blackout, is today de rigueur. Even most rural systems have some duplication of duties on their higher voltage lines. This doesn't, however, mean that there is an indefinite number of available lines; there are more than we need for everyday power transmission and distribution, but this doesn't always add up to enough for exceptional events.

All of this redundancy absorbed the loss of that first line in northern Ohio. Its failure was mostly a nuisance. The problem came later. And when speaking of a product that moves at nearly the speed of light, later came on very quickly indeed.

A second wire also sagged into a tree, waiting there, too tall, its branches stretched skyward to catch every ray of sun and channel every drop of rain downward to its thirsty summer roots. This wire, like the first, was warm and sagging low with the heat of the day; it was, like all conductors, apt to stretch longer in hot weather. This expansion is a molecular property of metals that is exacerbated, but not caused, by the presence of an electric current. All the lines in Ohio, in the Midwest, in the East, were hanging low that day as they were on any day in any August. Had the tree not been there, or had it been trimmed down, both it and the line would have survived the limpid afternoon, rather than a *bang!* and a fizzle and the smell of charred wood. And a second line was out. This one, the Chamberlin-Harding line, ran just south of Cleveland. Its load, too, was transferred to yet another set of wires, headed yet again in the same direction. And thus did the cascade begin. A load easily borne by one wire or two proved too much for the third duplicate.

The first line that met that first tree out there in Walden Hills, Ohio, was a 345-kV line. This is a midsized long-distance transmission line carrying AC power, as was the second, as was the third (this outage, too, was caused by a tree—you begin, I hope, to see the trouble with trees). It is here, about an hour into what was not yet but was fast becoming a blackout, that automation began to get seriously involved. Within ten minutes of the third deadly tango between line and tree, a fourth 345-kV line was lost—this one because it was being asked to carry more current than it could safely transport—followed almost immediately by fifteen 138-kV lines shutting themselves off automatically. This is a self-preservation technique designed into electrical conductors ("conductor" is the technical term for an electric transmission line) when giant waves of unstable voltage threaten to fry, melt, or otherwise disable them. At this point, 3:41 P.M., about thirty minutes before the actual blackout started, trees ceased being the problem. Line failures were fast becoming commonplace because circuit breakers had begun to trip.

To travel around Lake Erie, an electric current made just outside Toronto will simultaneously take the shortest path to New York City (about five hundred miles) and it will take the longest path, winding its way through Michigan, down to Kentucky, over to Virginia, back up through Maryland and New Jersey to finally arrive in New York. It will also take every single other path, with a decided preference for low resistance routes.

So long as resistance is equal on all paths the electricity that takes a longer, more confused or circuitous route will arrive at the same instant as the one that took the shorter path. Distance is irrelevant to it, only resistance matters.

But FirstEnergy didn't react. One line went down, a second, a third, a fourth, a fifth, and then simultaneously fifteen more. Twenty high- and medium-voltage lines down and no word is coming out of FirstEnergy's control room. They aren't doing anything. They aren't calling anybody. They are hardly reacting when others call them. All because of a problem of a different sort. They have a software bug—a tiny, fairly innocuous, incompatible line of code that slowed, perhaps even halted, the refresh rate on their computer screens while also silencing their alarms. They didn't know they'd lost all these lines; they were blind to the blackout that was coming. And because they didn't see it, neither did anyone else.

The first critical difference is that with a perfect, future smart grid, electricity might be made everywhere. Flows of power would be multidirectional as rooftop solar met backyard wind met big nuclear or hydro, and the output of all these types of generators would intermingle "intelligently" on the wires. Second, information would also travel freely between utility, customers, and the various machines that populate the grid, including both those that used electricity and those that produced it. The movement of both information and electricity would be monitored because meters could run both forward and backward, keeping perfect track of electricity outputs and inputs from even the smallest sources. Smart thermostats would form the hub of home-based networks of smart appliances that altered their behaviors without direct human intervention to take into account real-time, variable pricing of electricity. Since the lines necessary to carry radically distributed, uncoordinated, and small-scale generation to market also needed to be smart (which is to say to have some basic digital computing capacities), it made sense to build the two functionalities into the same set of wires. Information and electricity finally, in Boulder, becoming one.

In a perfect world, the various component parts of the Boulder smart grid would have functioned like distributed, systemic thought. The grid would make simple decisions from the dishwasher level all the way up to that of the power plant; it could communicate both to and between people and machines while balancing its load, all while avoiding the electrocution of its linemen, What this means (and here I'm just translating) is that twenty-five years ago, in the early 1980s, we as a nation could increase our electrical consumption by about 30 percent at the drop of a hat, and the utilities had all these power plants sitting around primed for precisely this kind of sudden increase in load. They fired them up, blasted some fuel in, set the crankshaft a-spinning, and the electromagnet too, *fwamp fwamp fwamp* (but much faster than that at 3,600 rotations a minute) churning out a flood of electrons. As these electrons bumped one into the next the force of their serial desire flew down the wires and out to the switchyard, where its voltage was ramped way up and then shot down America's electrical superhighway at 60 cycles per second. A second or so later it is in your home helping your air conditioner cheerily blow its cool all over you and yours.

With such systemic "shock absorbers," as Amin calls them, in place, no day was ever too hot, no peak load too pointy, for the grid's infrastructure to absorb. Granted, there were fewer people in the United States twenty-five years ago, fewer air conditioners, and even fewer disastrously hot days. But even given these changes, had utility investment in infrastructure kept pace with population growth and GDP growth, peak-load days would simply not be the sort of panic-inducing and blackout-causing affairs that they are today.

In a way the utilities are right in paring back. Having 30 percent of one's power plants just sitting there 359 or so days a year, and 30 percent of the carrying capacity of one's lines equally left unused "just in case," is wasteful in all kinds of ways. The issue was not the tightness of the ship, or even the desire to shave and shave at the margin of the system. The problem is peak load itself. The phenomenon is what needs to be done away with, and without a viable means to store electricity the only way to control it is to control the part of the system that creates it—us.

Remember Samuel Insull's point: it is costing the utility the same amount of money to keep all their plants basically idle between eleven P.M. and six A.M. as it would be costing to run them full bore. They prefer that wind farms in Wyoming and then, using an existing high-voltage line from the more southern installation, to send power to Los Angeles—a line that is becoming available because the last coal plant it was designed to serve will be retired in 2027. The line will be serviceable but empty; the salt caves, prepared and treated to hold natural gas, will also be empty (the shortages of that substance proved a fleeting fear), while the fierce bluster of wind across Wyoming will at long last be harvestable for an urban population dense enough to make use of it. This project shimmers with the future-possible. It is practicable, like the basalt land plug, but far further along in the permitting and funding process. It will gather its monies from a mix of private investors, government subsidies for kooky but viable ideas (called ARPA-E), and state and federal funds set aside for infrastructural upgrade.

Nano-grid
Micro-grid

Peak Load
Load Shifting