The electric grid in a decarbonizing world

Jefferson County Library

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Why emphasize electricity as an energy source?

Someone asked an excellent question in Session 1:

Why concentrate on electricity when discussing de-carbonization?

I apologize for forgetting who asked it, because it's important.

Answer: Because electricity is one of the few ways to deliver energy without emitting CO_2 at the point of consumption.

Since electricity can't always be made at its point of use, a transport system is needed to deliver this energy

A CO_2-free energy economy will be mostly electric

The currently feasible sources of large amounts of CO_2-free primary energy all generate or require electricity

- Wind
- Solar
- Nuclear
- Hydroelectric
- Hydrogen (energy delivery)

Energy has to be safely, dependably and economically delivered to end users. That's the purpose of the grid.

Outline of today's discussion

- Background: power system organization
  - From the 1930s to the 1980s, electricity was delivered by vertically integrated, regulated, publicly traded utility companies.
  - Since the 1980s, companies have been generally split into three generally unregulated parts: generation, transmission and distribution
  - So grids today are run by a so-called independent system operator, or ISO.
- General structure of grids
- Description of the main grid components
- Discuss grid control and operations
- Note issues caused by the increasing amount of renewable generation
- Speculate about future grid structures—e.g. microgrids
- Raise some issues for decarbonization of the world economy

Historically, energy had to be produced where consumed

Water powered underground mine ventilation

A—Hollow drum. B—Its blow-hole. C—Axle with fans. D—Drum which is made of rundles. E—Lower axle. F—Its toothed wheel. G—Water wheel.

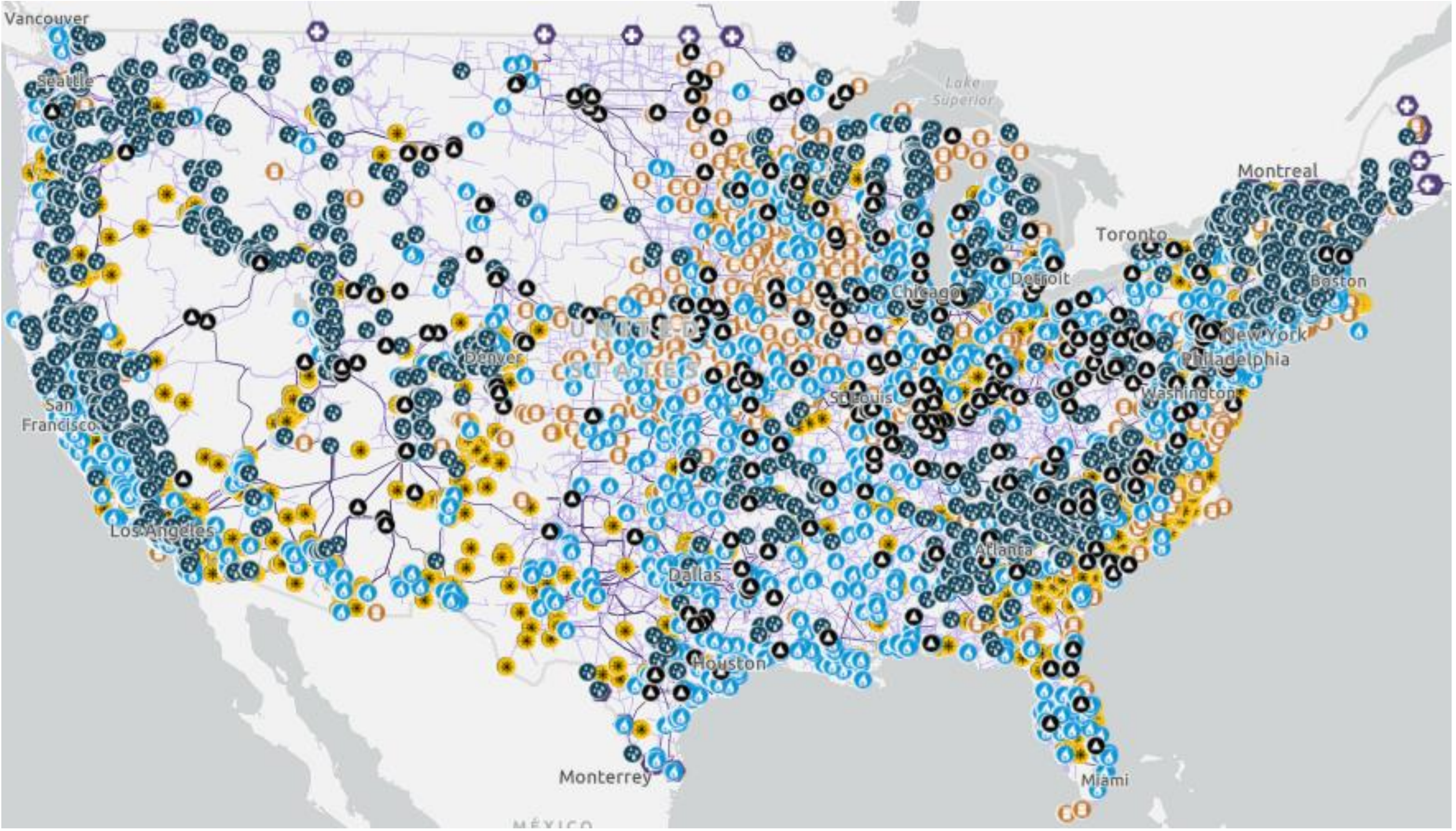
Geothermal heat for extracting salt from saline water

A—Pool. B—Pots. C—Ladle. D—Pans. E—Tongs.

Wind powered underground mine ventilation

Delivery of renewable energy to industrial sites in late Medieval times, from Georg Bauer's treatise on mining, mineralogy and refining, *De Re Metallica*, 1556

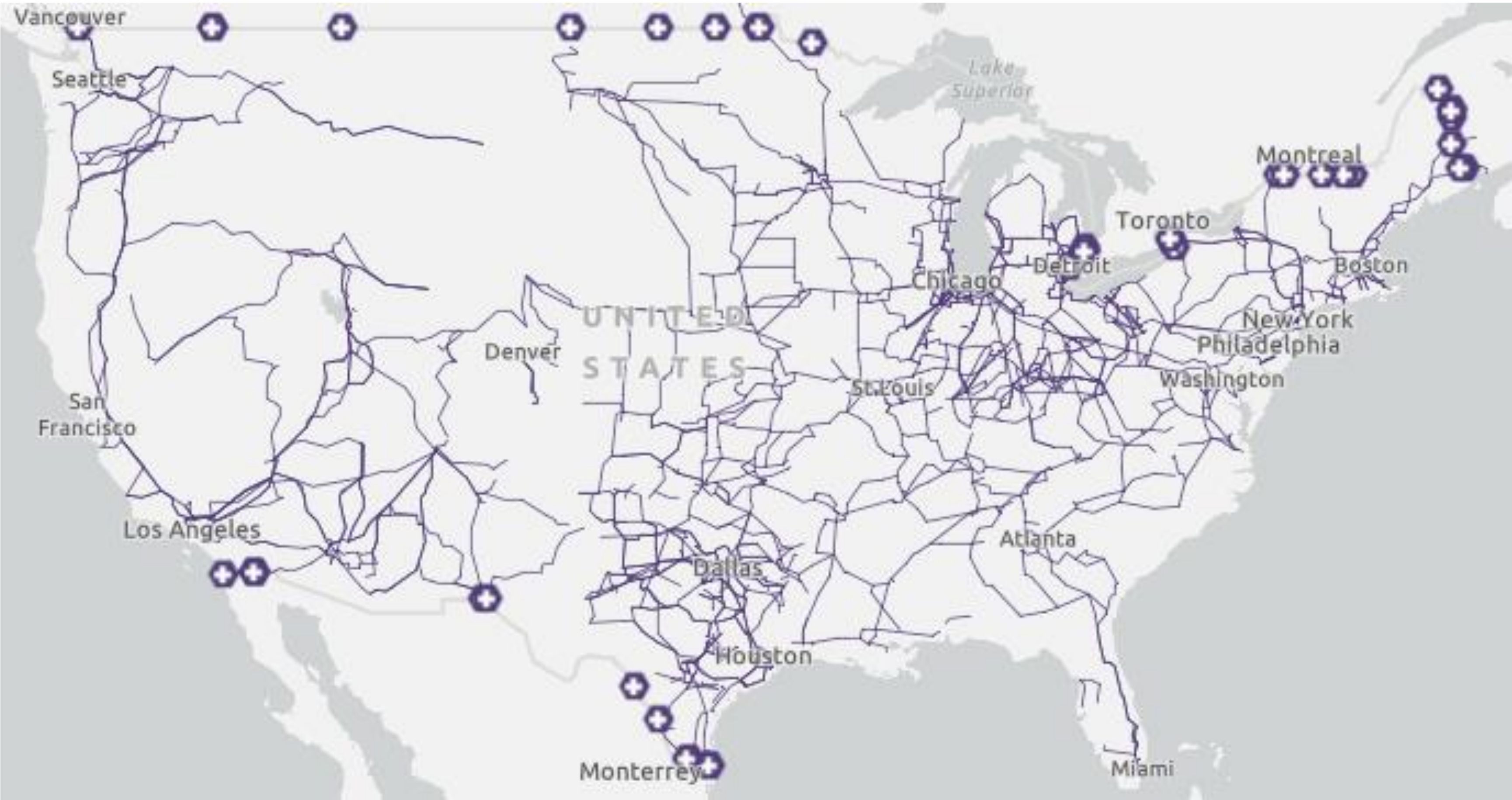
Now, energy sources are widely dispersed



A complex network is necessary to deliver power produced in these widespread locations.

https://atlas.eia.gov/apps/electricity/explore

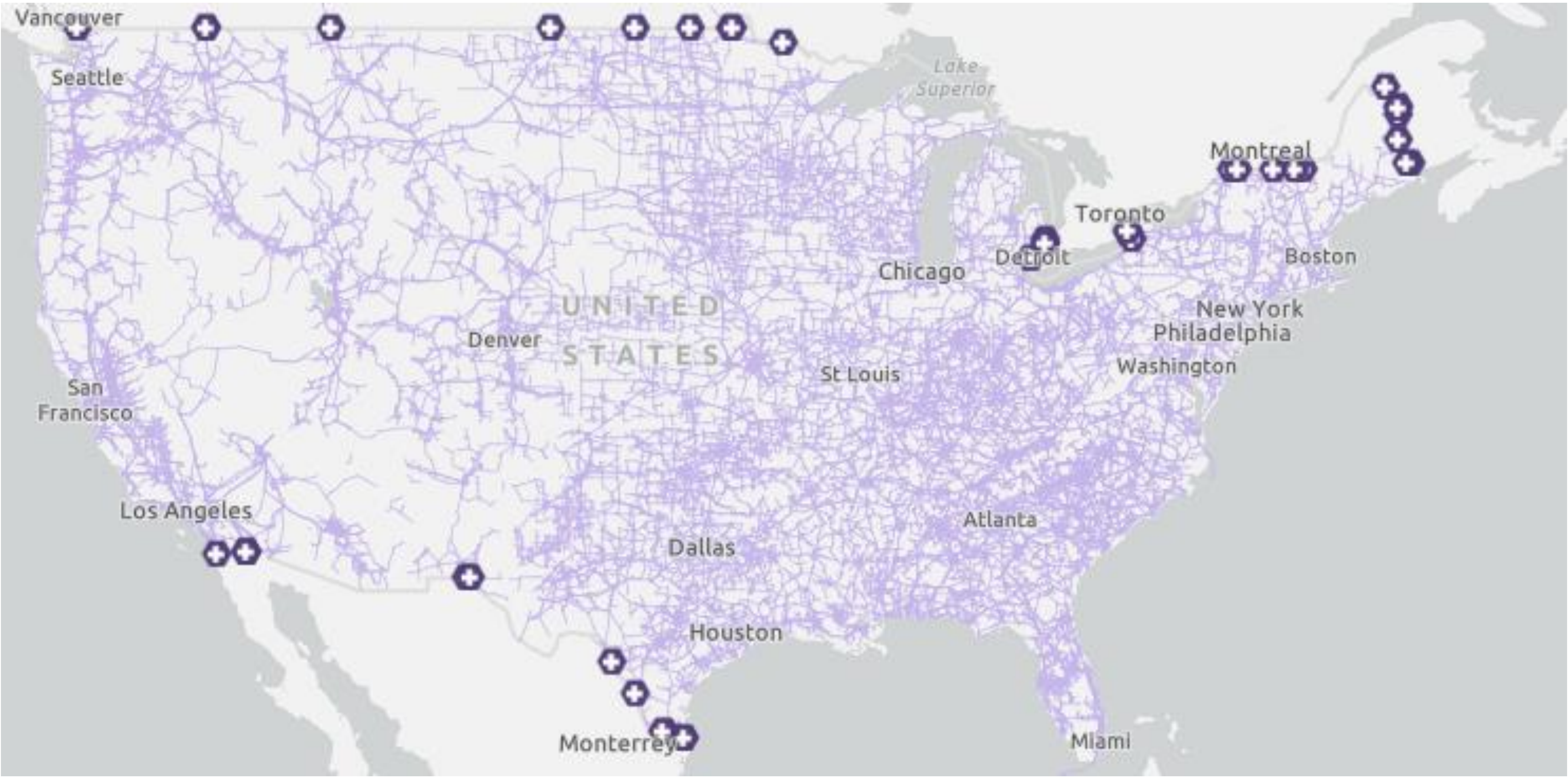
A top network of >=345,000 volt long haul lines…



>= 345,000 volts

https://atlas.eia.gov/apps/electricity/explore

…feeds a grid of regional transmission lines



<= 287,000 volts

https://atlas.eia.gov/apps/electricity/explore

And finally delivers power to a local distribution network

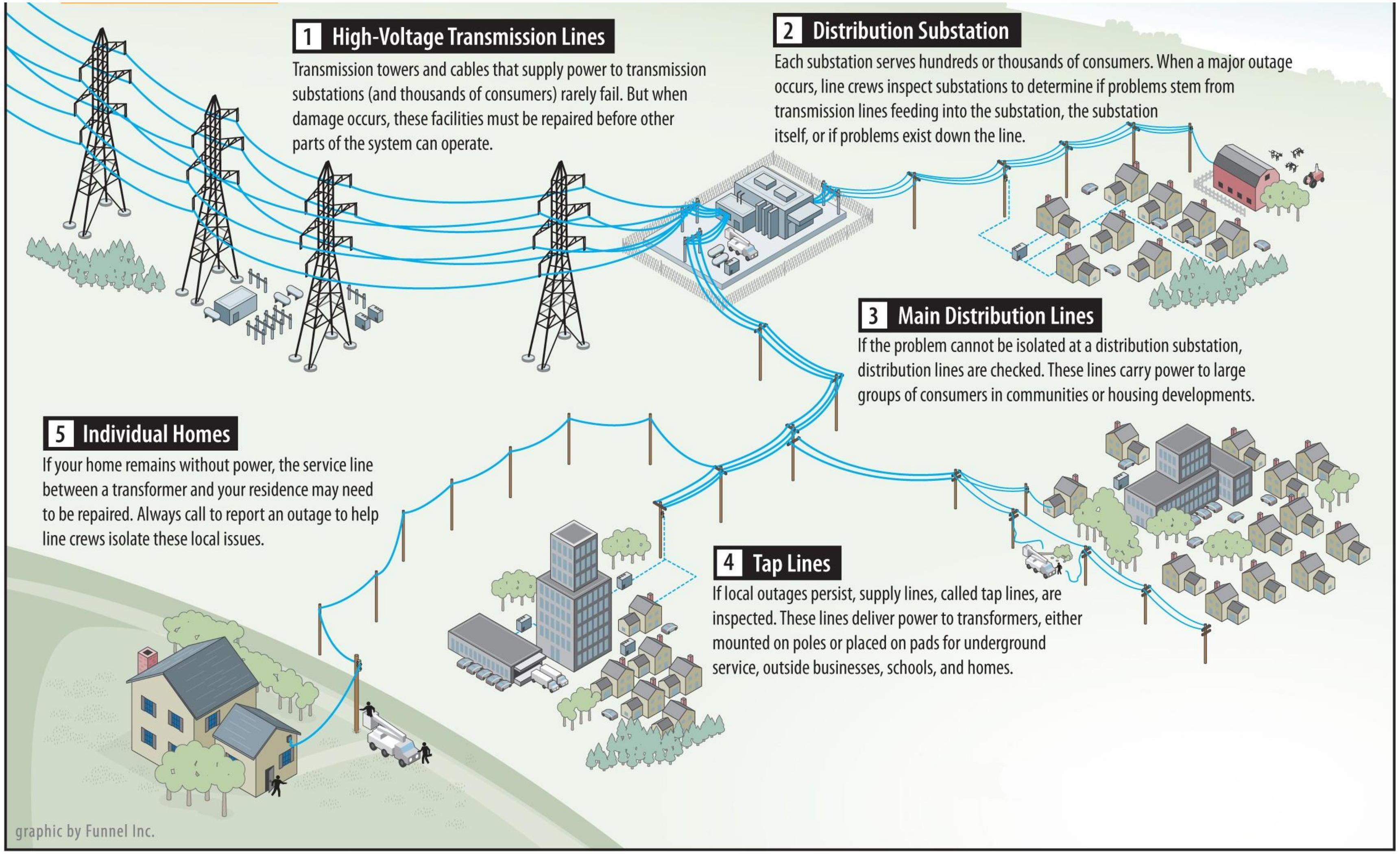
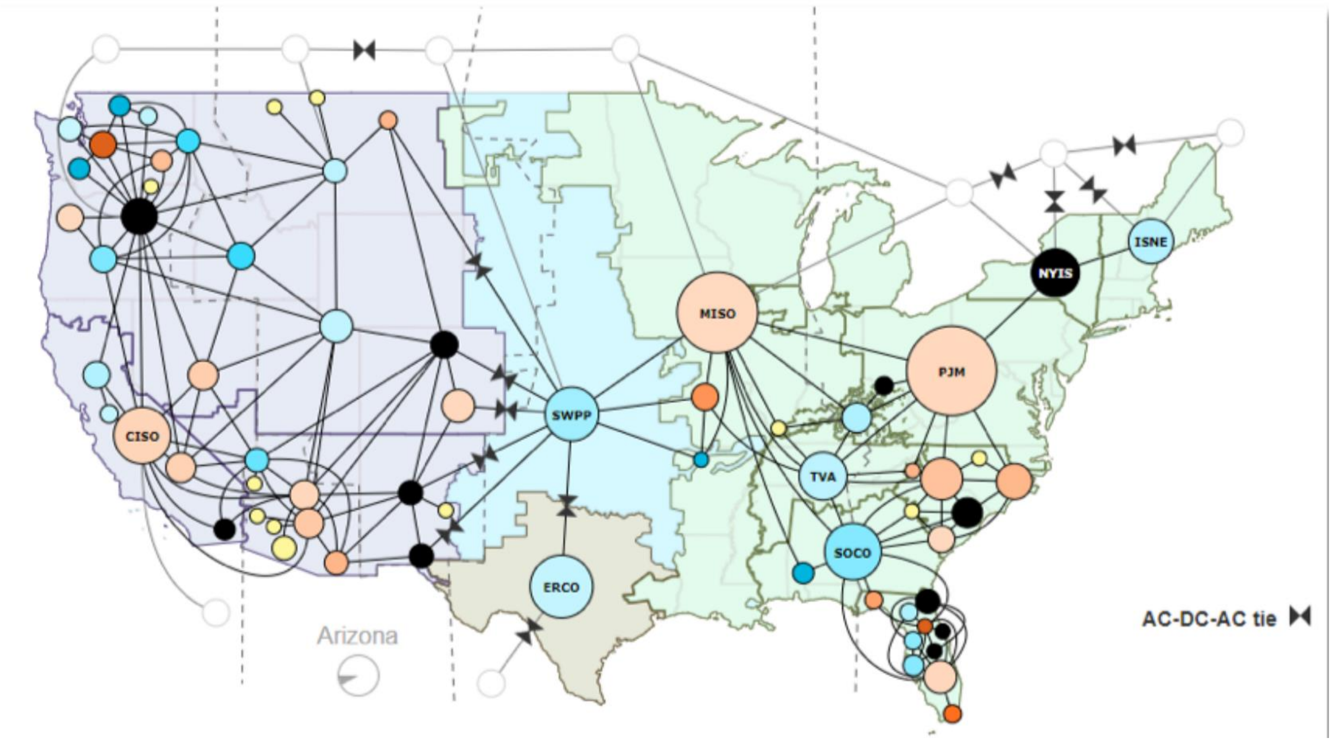


Diagram also shows outage restoration, one of the responsibilities of the local distribution operator.

https://may1728.sd.ece.iastate.edu/

The entire grid is too complex to be managed all at once

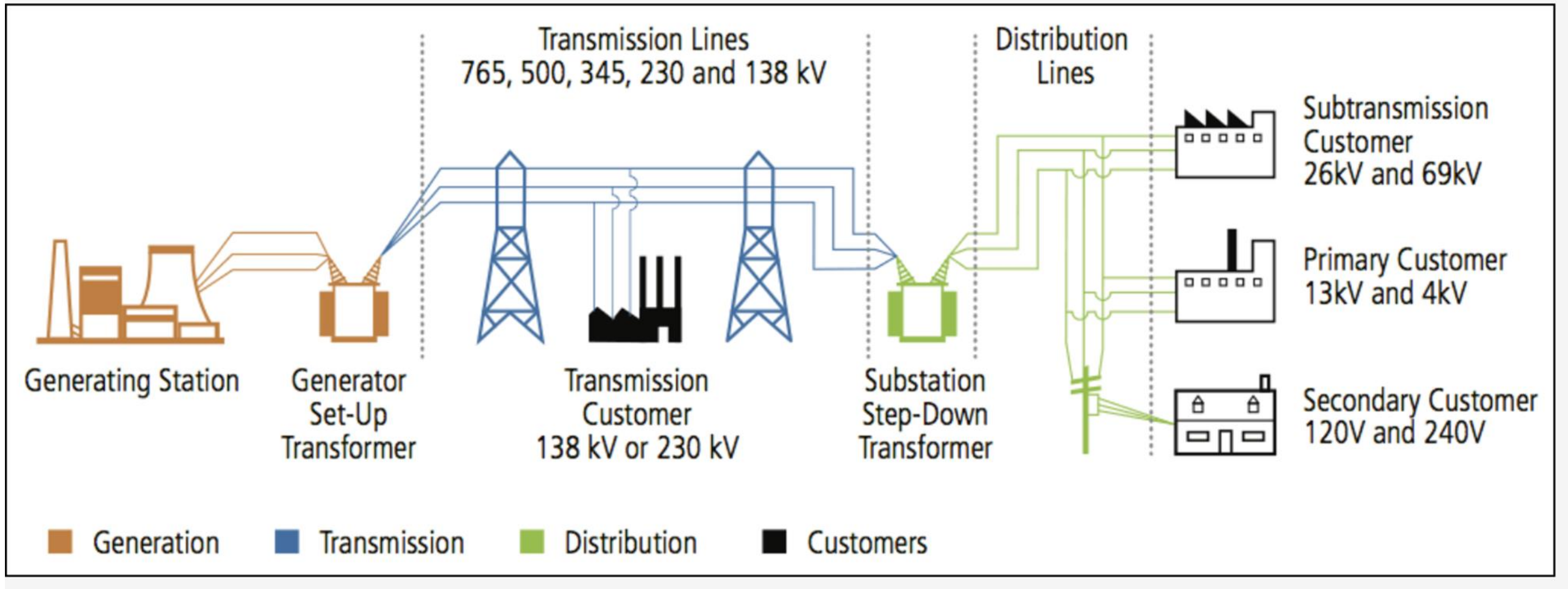


The country is divided into several independent control regions, with a central operating entity in each region.

The regions are interconnected so power can be transferred from one to another for economic or stability reasons

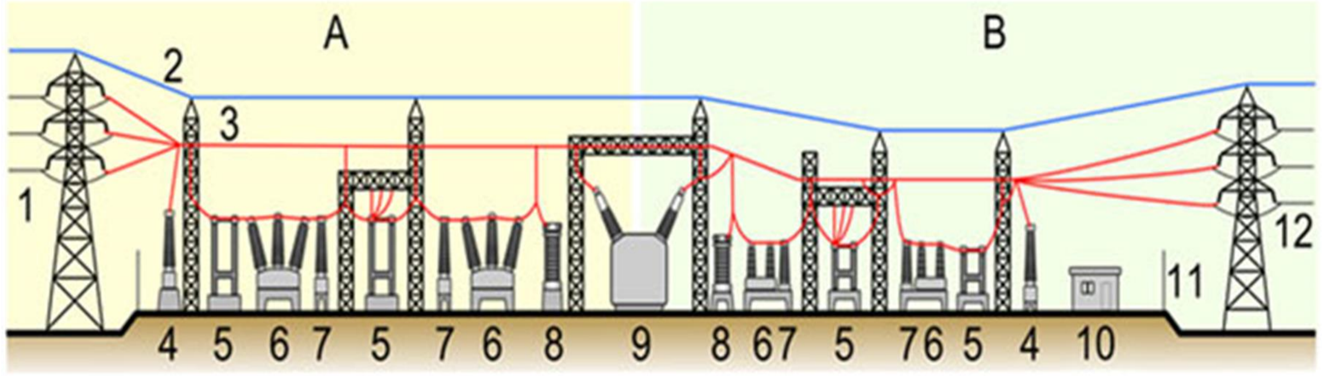
The map shows the regions and the major interties

Although complex, the grid has a few generic major parts



The substation provides functions beyond raising or lowering voltage

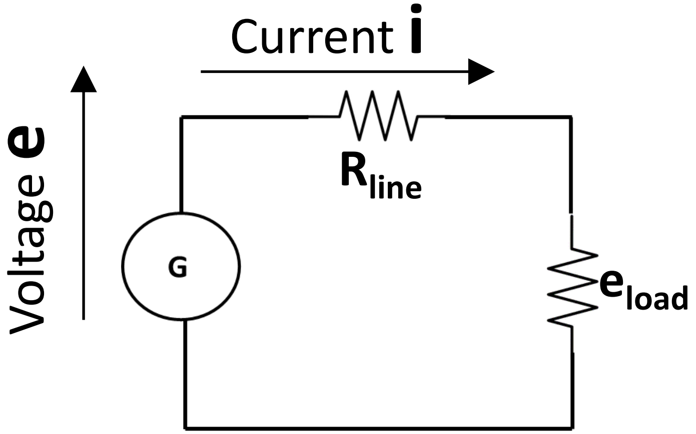
- Measures voltage, current and frequency; reports values to central control
- Switches power to several distributing circuits as required
- Provides breaker protection in case of short circuits, overloads or other anomalies



A:Primary power lines' side B:Secondary power lines' side
1.Primary power lines 2.Ground wire 3.Overhead lines 4.Transformer for measurement of electric voltage 5.Disconnect switch 6.Circuit breaker 7.Current transformer 8.Lightning arrester 9.Main transformer 10.Control building 11.Security fence 12.Secondary power lines

How we got the present grid: Edison was wrong

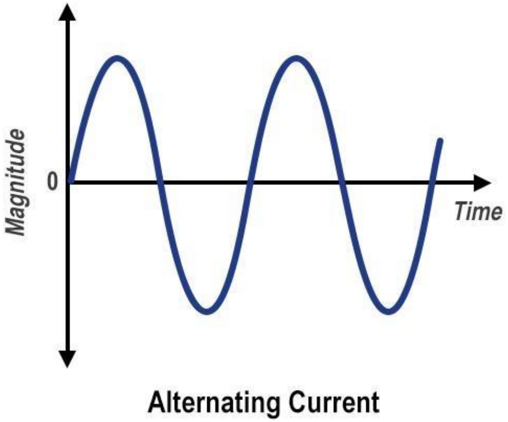
- Thomas Edison's Pearl Street Station was the first commercial central power plant in the United States.
- It was powered by reciprocating steam engines driven by coal-fired boilers.
- The station's sole purpose was supplying power for electric lighting
- Use of direct current required *that generation and transmission voltage had to be close to that of the end use site.*
- $I^2 \times R$ line losses limited generator-customer distances
- Direct current generation technology was eventually abandoned and replaced with AC



Power $_{load}$ **=** $i \times e_{load}$

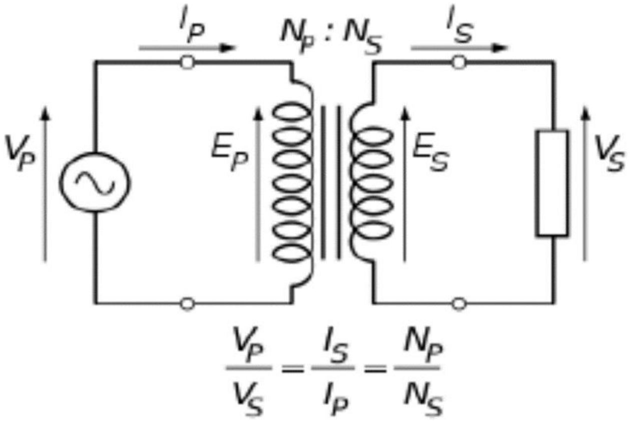
Line Loss = $i^2 \times R_{line}$

Solution: alternating current



A conceptually simple device called a transformer can raise or lower circuit voltage to minimize the I^2xR losses for long distance transmission lines while lowering the voltage to the safe levels for end users.

AC became the foundation of today's grid operation.



High voltage power transformer

Local distribution transformer

But not all technological change is simple

This perfectly sensible technical change did not go smoothly.

The transition from DC to AC needed a technical, financial and public relations war, with Thomas Edison pitted against George Westinghouse and Nikola Tesla. It involved financial manipulation by J. P. Morgan.

Thomas Edison's first power stations produced direct current and he wanted the eventual grid to run on DC. He pulled some nasty PR stunts, mostly trying to prove that AC was much more dangerous than DC. These stunts, including a (live?) demonstration of the electric chair were intended to provoke public fear of alternating current.

Economics and clear technical thinking eventually won out, but it was an ugly fight.

A lesson to be learned from this story is: Don't let fears, agendas and manipulation influence and delay or derail important decisions.

For an overview of the story, see https://en.wikipedia.org/wiki/War_of_the_currents

Other written sources and film documentaries are available as well

A synchronous AC grid allows generators to self-regulate

A property of AC machines is that they operate synchronously, i.e. they all try to run at the frequency of the network they are connected to. This provides a level of inherent stability to the grid

- In a synchronous grid all the generators naturally lock together electrically and run at the same frequency, and stay very nearly in phase with each other.
- For rotating generators, a local governor regulates the driving torque, and helps maintain more or less constant speed as loading changes.
- “Droop” speed control ensures that multiple generators share load changes in proportion to their rating, without outside intervention
- Energy is stored in the immediate short term by the rotational kinetic energy of the generators. This helps the system ride through short term power excursions.

This is why frequency control is emphasized in grid operations: it holds the network together.

Functions of a grid operator

Daily

Forecast system load

Prioritize and commit generation and transmission resources

- Economics, including contracts
- Emissions
- Reliability
- Commit transmission resources (maintenance, other conditions)

Constantly match supply to demand

- Track system load vs. forecast, adjusting dispatch according to conditions
- Maintain constant frequency control
- Monitor power flow, switching lines and substations in response to anomalies
- Control voltage and current flow at all points in the network
- Run frequent network stability models (“what if” studies) to spot upcoming problems

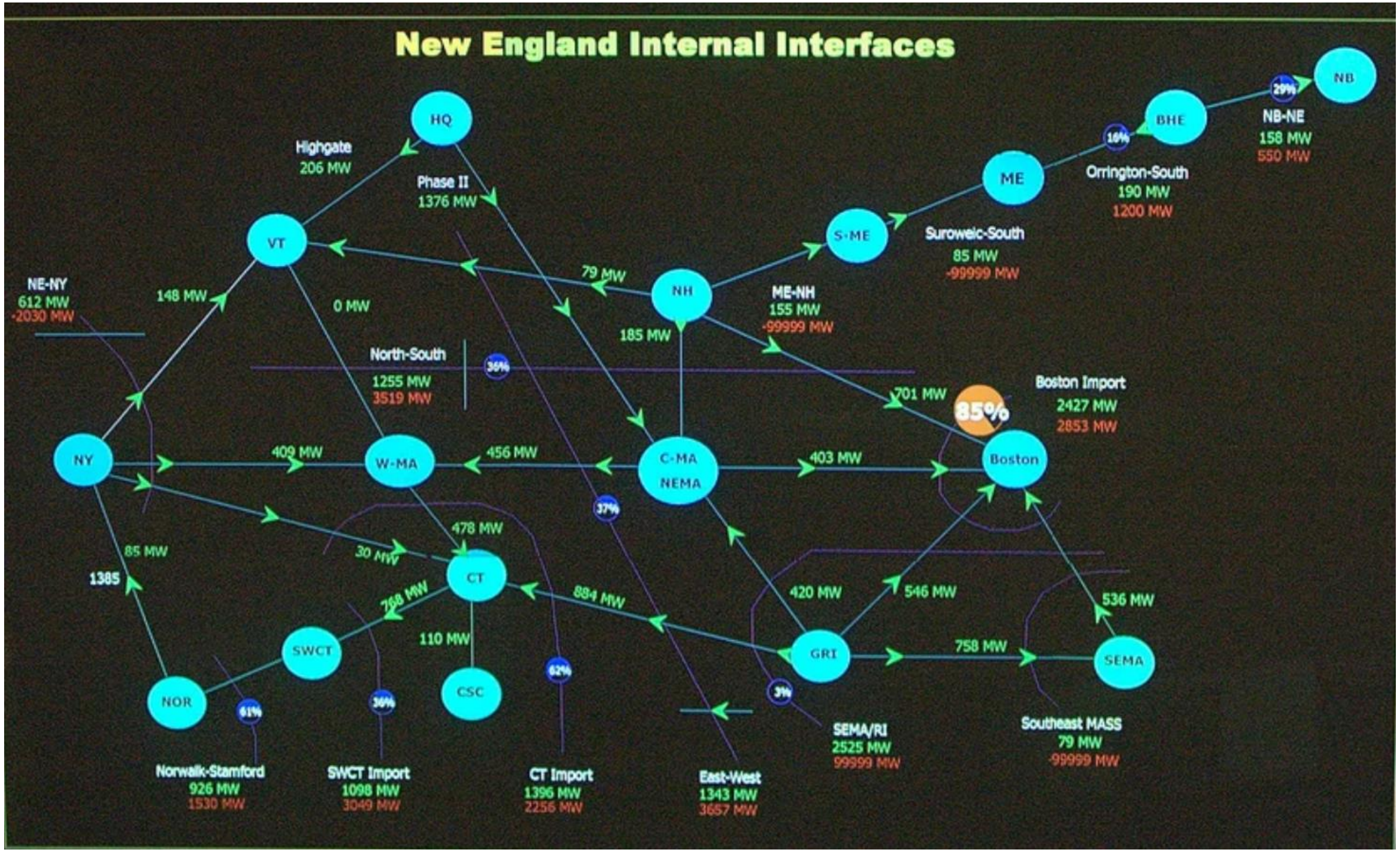
Additionally

Administer the area wholesale energy market

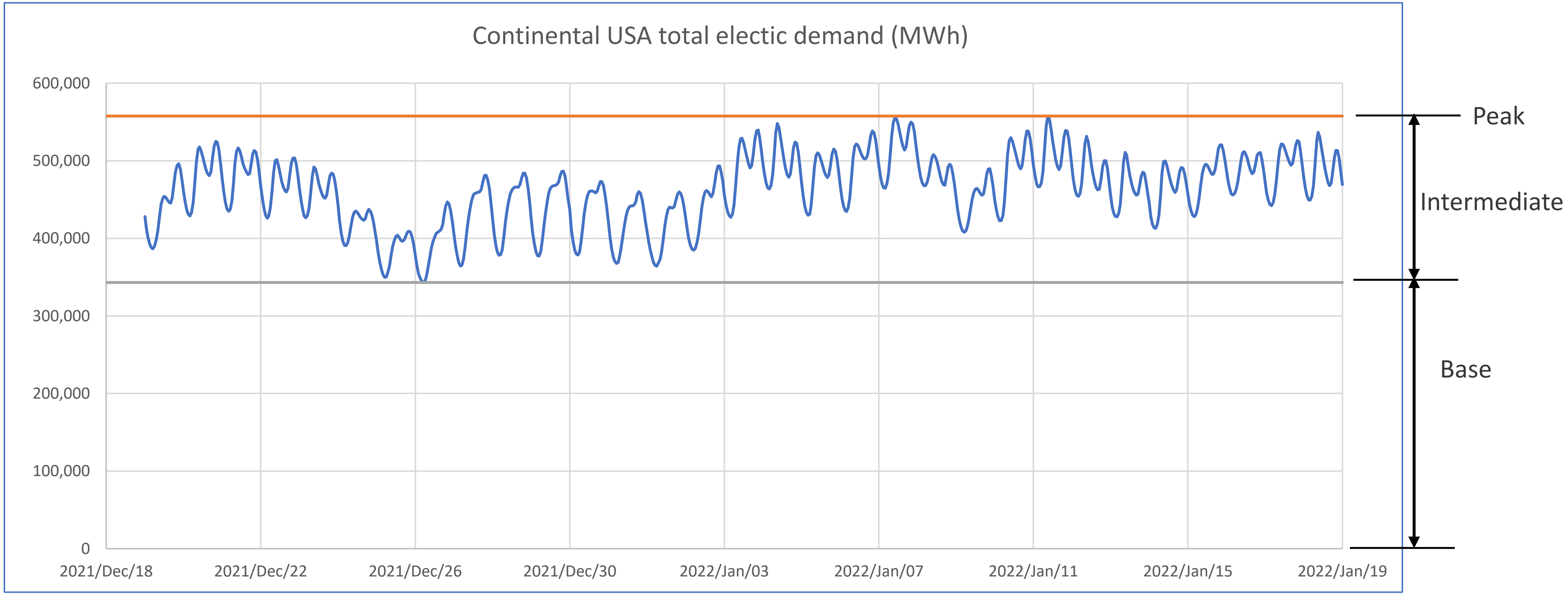
Produce long-range plans for generation and transmission resources

Grid management: New England ISO control center

Grid management: major NE internal transmission lines



Grid operators balance demand and generation



The overall purpose of the grid operator is to match supply and demand on a millisecond time scale.
Demand is essentially not controllable, so generation has to be adjusted to meet it.
A future "smart grid" could help shape the demand curve by controlling end uses, but not yet.

Most future electricity will come from these sources

Shepherds Ridge wind farm, Oregon

Solar PV farm, France

Chief Joseph dam, Washington

Watts Bar nuclear station, Tennessee

Combined Cycle Gas Turbine station, Florida

Schkopau Lignite-fired Plant, Germany

Each source has its own characteristics that grid operators must account for

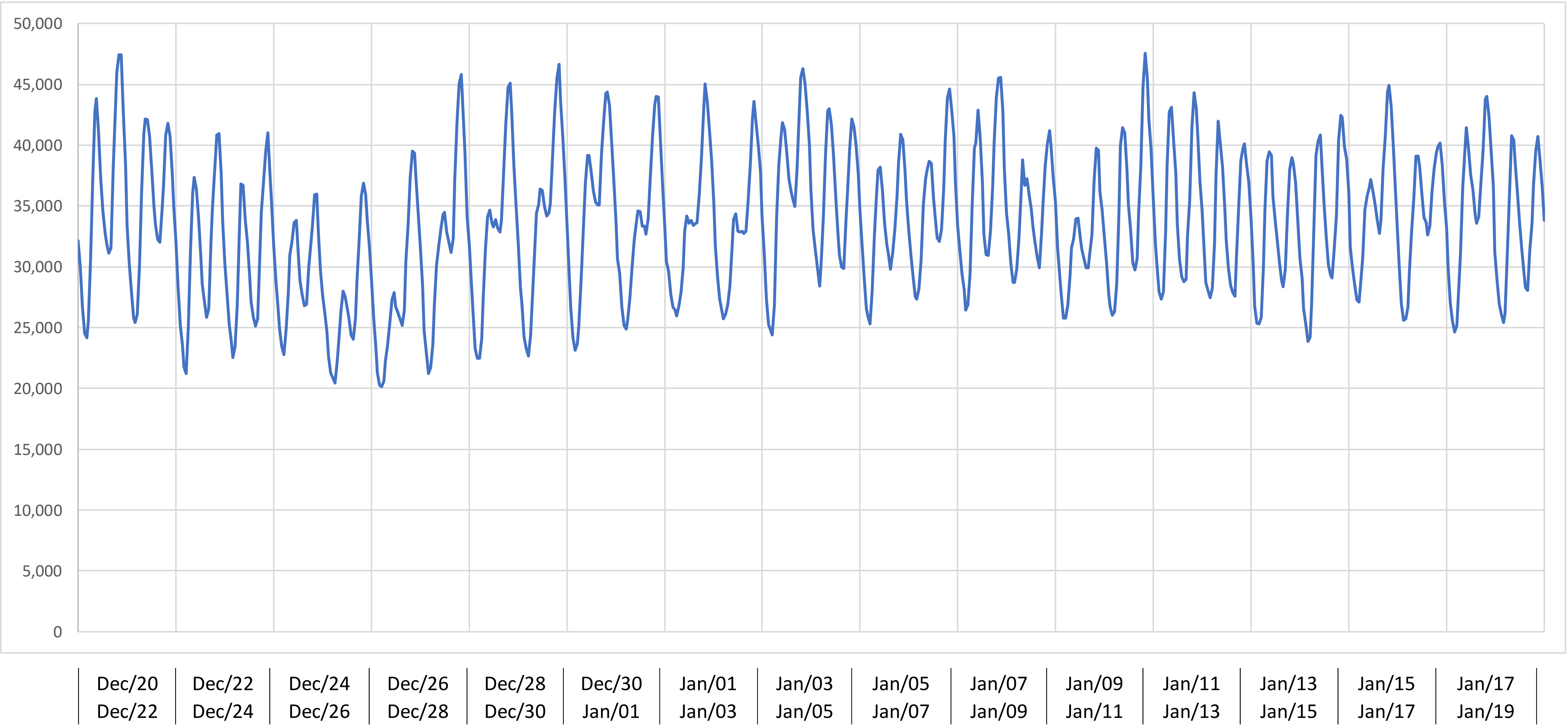
Each generation type has its own characteristics

- Dispatchable generation means: sources of electricity that can be dispatched on demand at the request of power grid operators.
- Dispatchable generators can adjust their power output according to an order.
- Non-dispatchable renewable energy sources such as wind and solar power cannot be controlled by operators.

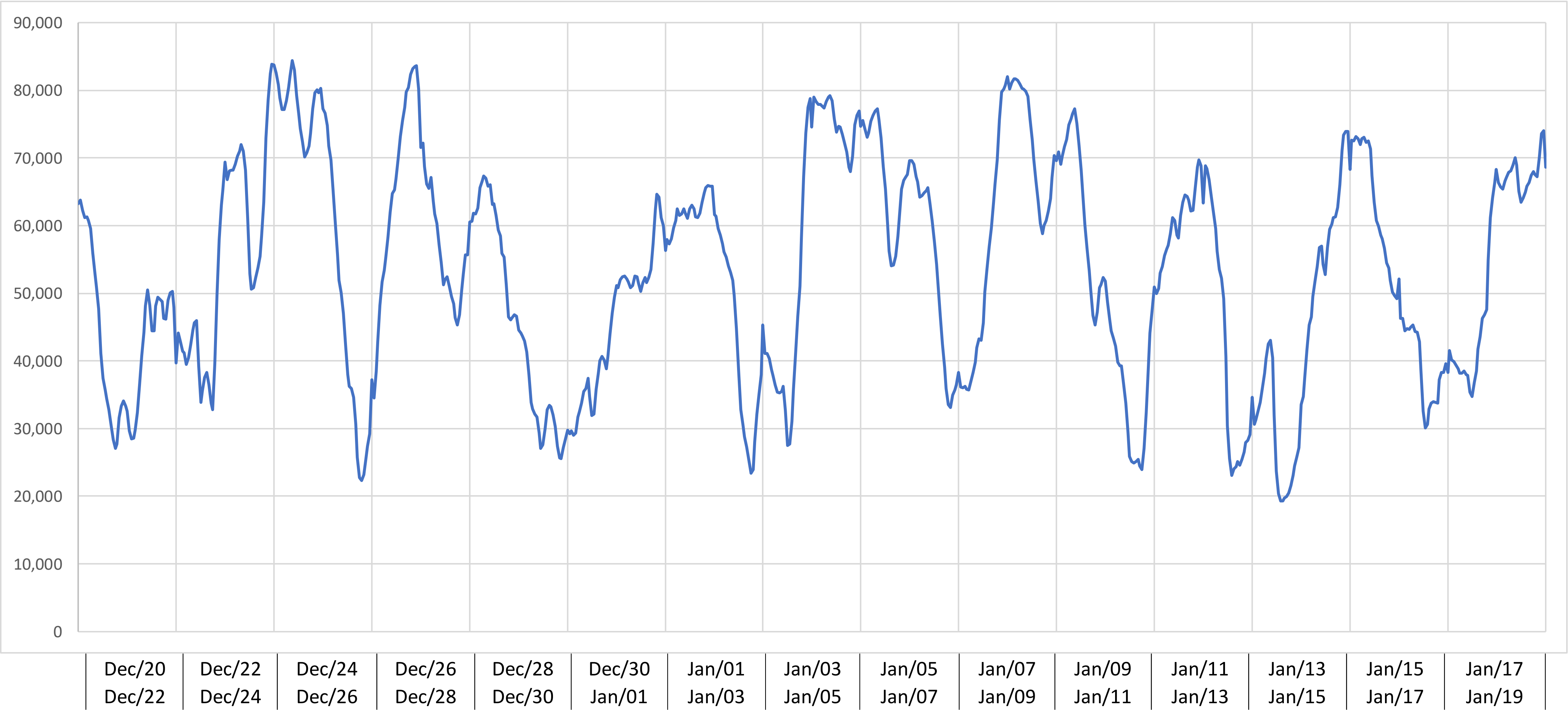
The intermittency of renewable generation is an issue for grid operation

Type	Predictable	Dispatchable	CO_2	
Wind	No	No	None	
Solar	Partially	No	None	
Hydro	Yes	Yes	None	
Nuclear	Yes	Yes	None	
Coal	Yes	Yes	Highest	Carbon producing generation
Simple Cycle Gas Turbine	Yes	Yes	Medium	
Combined Cycle Gas Turbine	Yes	Yes	Lowest	

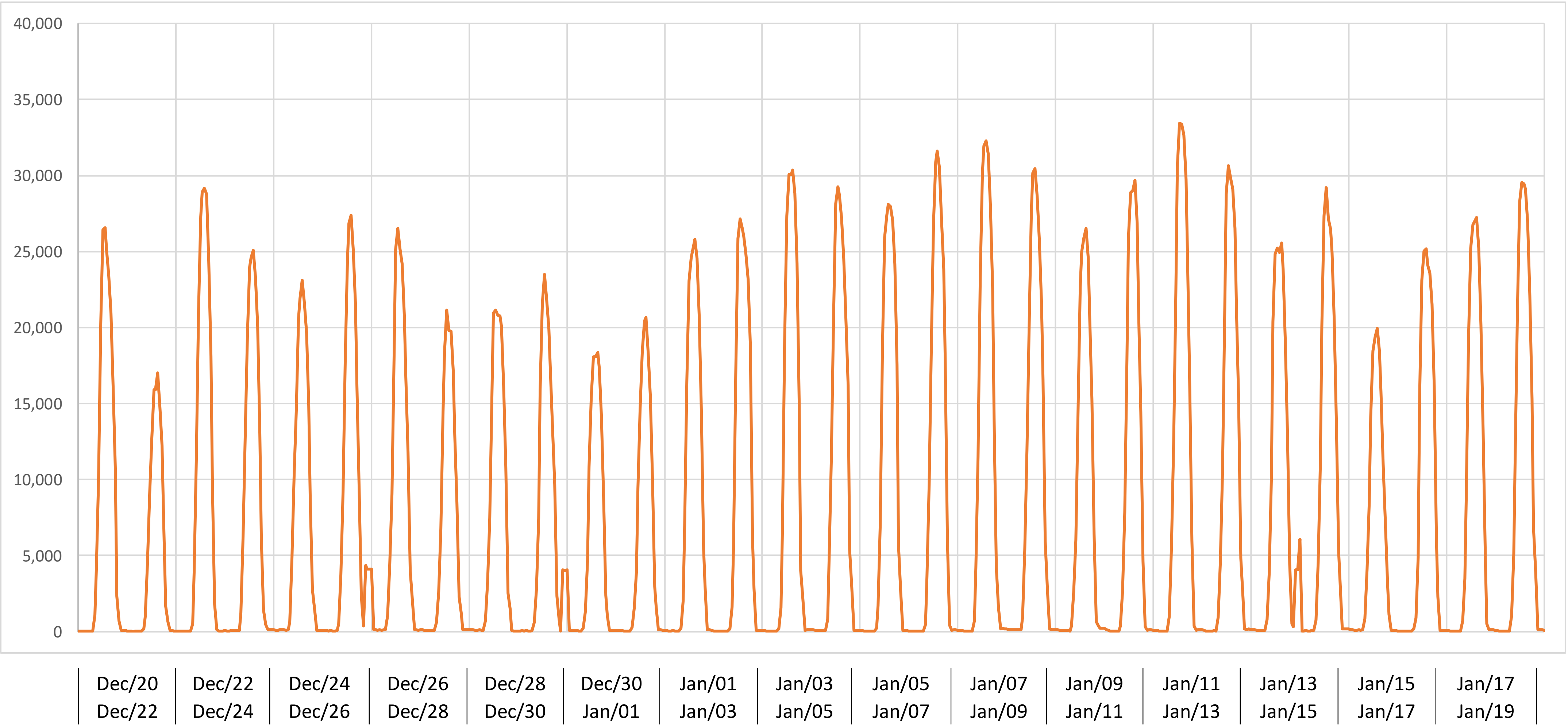
Hydroelectric power is predictable and controllable



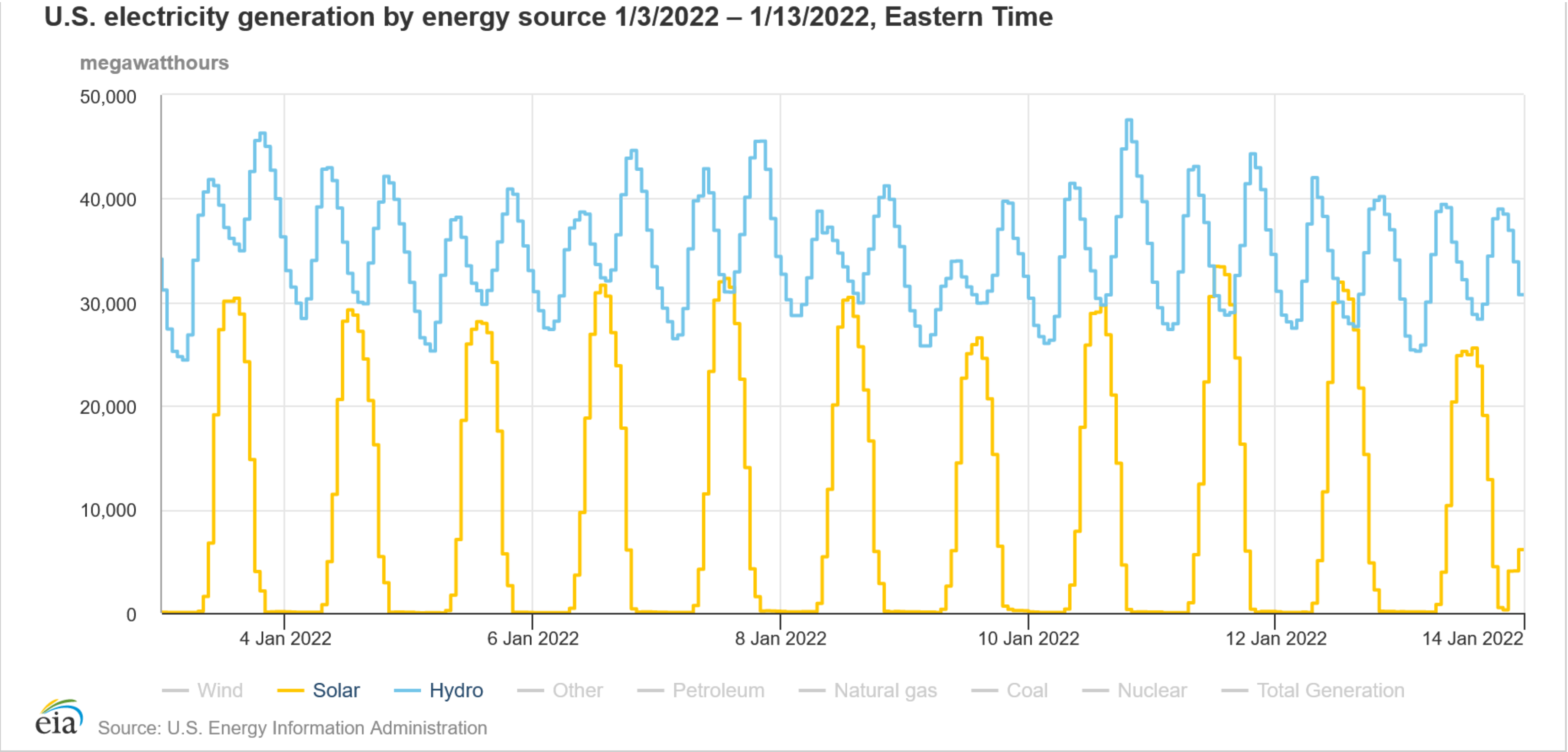
Wind is unpredictable and uncontrollable



Solar generation is partly predictable, not controllable

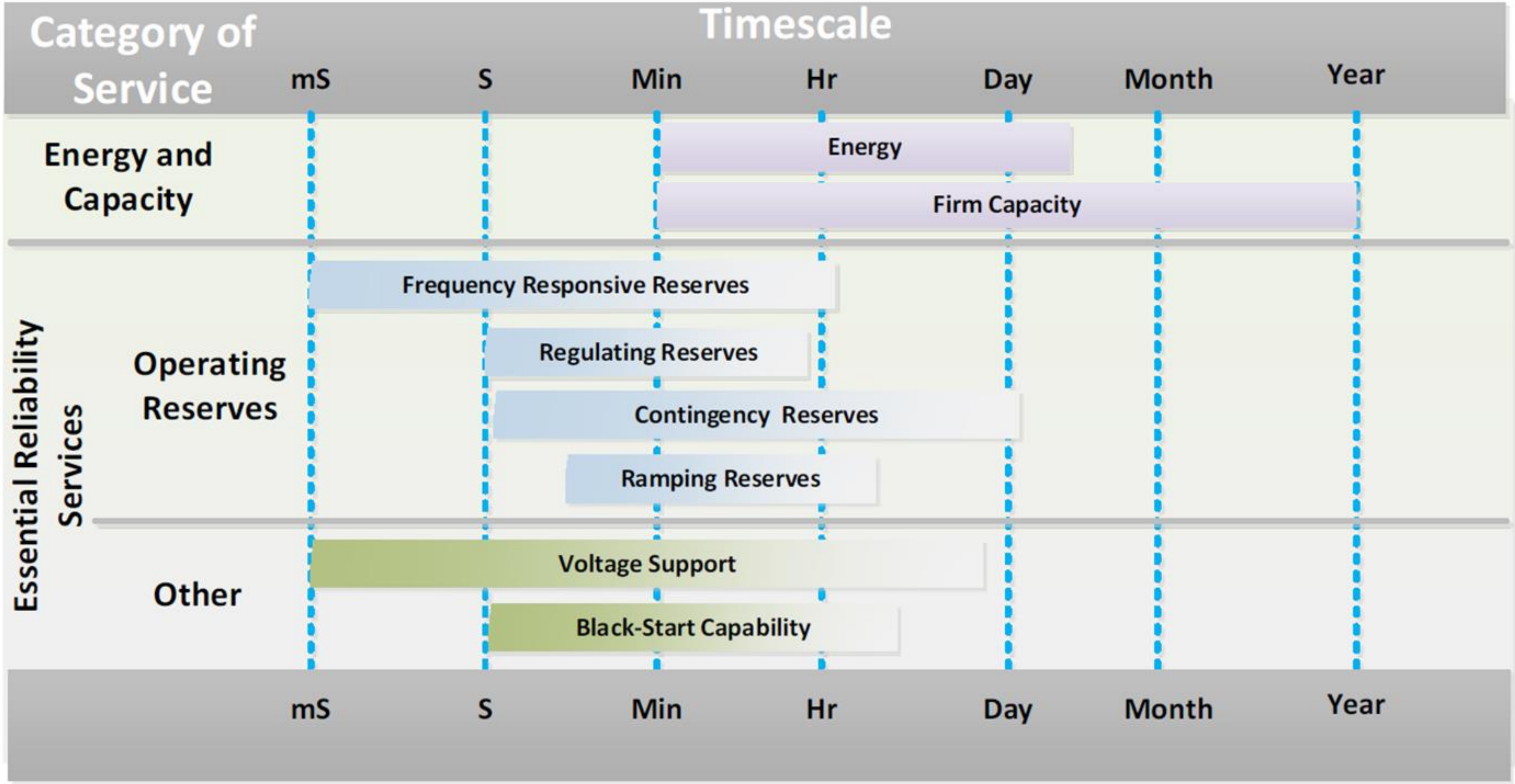


Some renewables can be jointly dispatched



Hydro generation is dispatched to drop off at night when demand is low, drop off midday when solar generation is high and follow load at other times

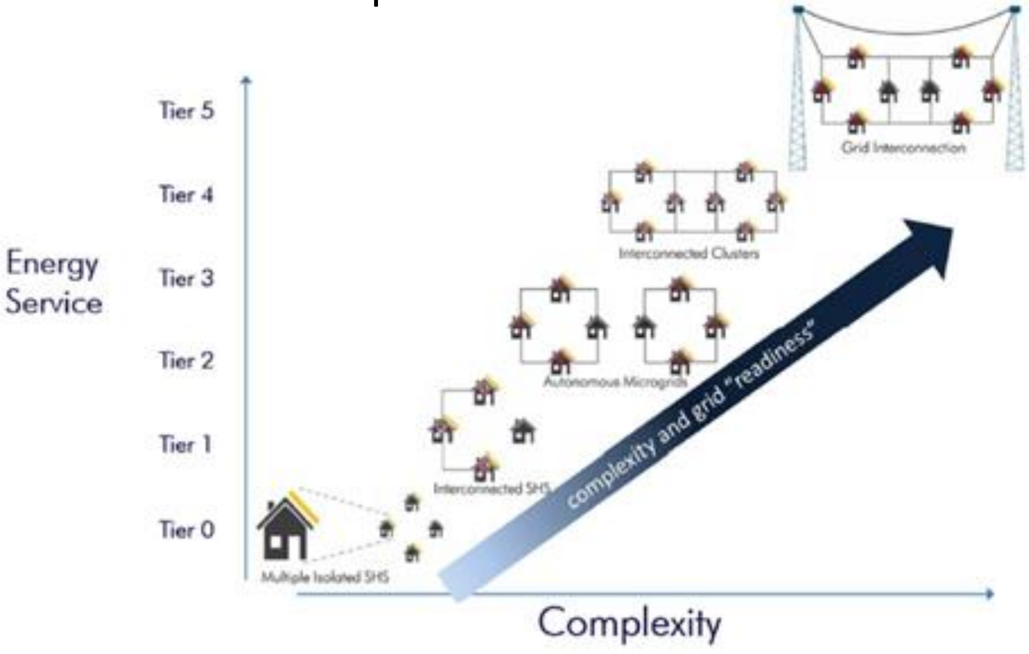
Services other than energy delivery promote stability



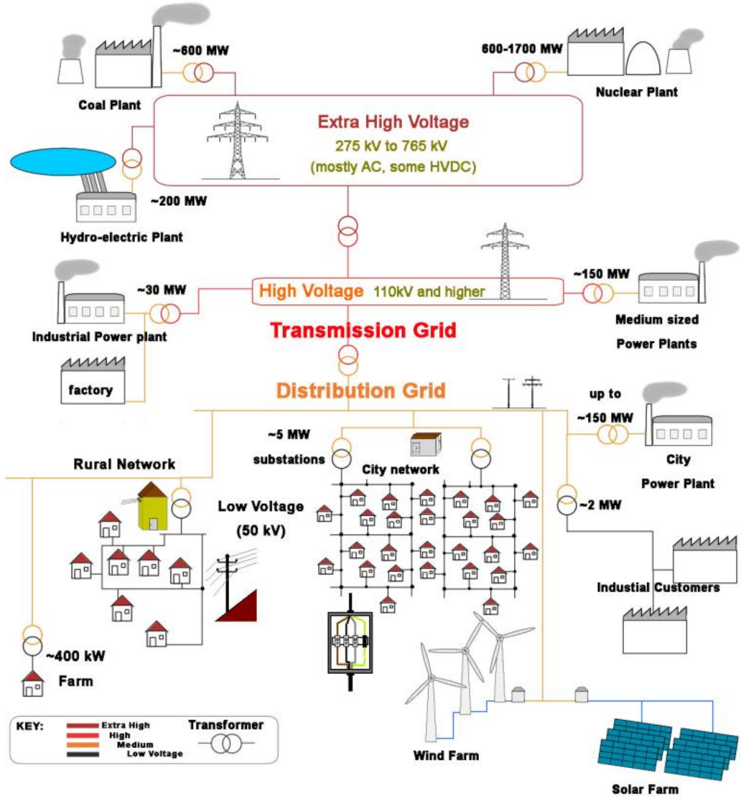
These services are like insurance: operators pay for them whether or not they are used

Traditional grids and microgrids

Microgrids will probably evolve to become a component of the national grids, just like Edison’s “microgrid” grew to the present form. They could offer a path for electrification of underserved parts of the world.



https://commons.wikimedia.org/wiki/Category:Microgrids



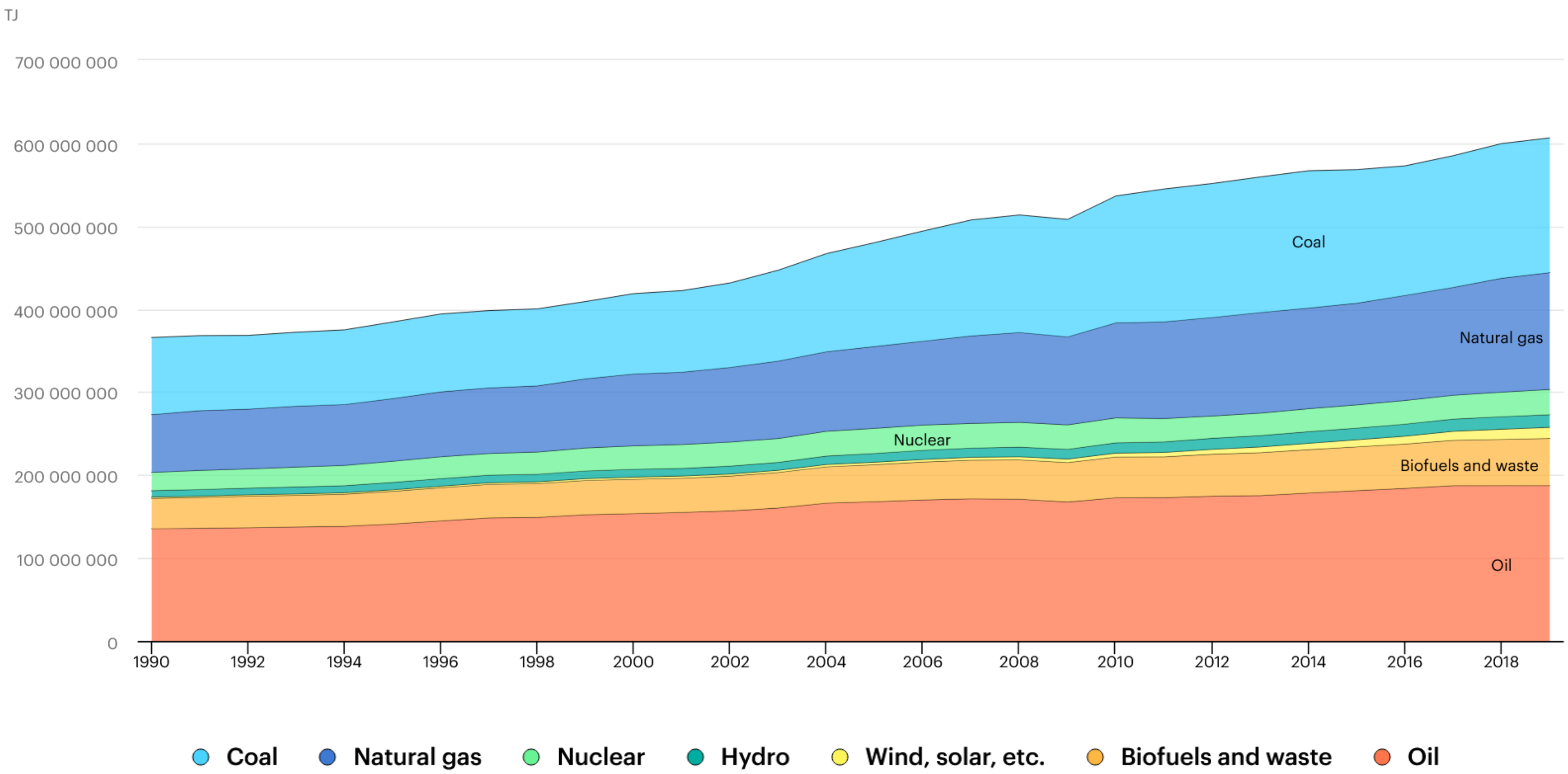
https://commons.wikimedia.org/wiki/Category:Power_grids

Considerations for world-wide decarbonization

- 940 million people (13% of the world) do not have access to electricity.
- 3 billion people (40% of the world) do not have access to clean fuels for cooking.
  This comes at a high health cost for indoor air pollution.
- Per capita *electricity* consumption varies more than 100-fold across the world.
- Per capita *energy* consumption varies more than 10-fold across the world.
- Energy access is strongly related to income: households without access are poor

"Access to energy does not guarantee prosperity, but lack of access to energy guarantees poverty"

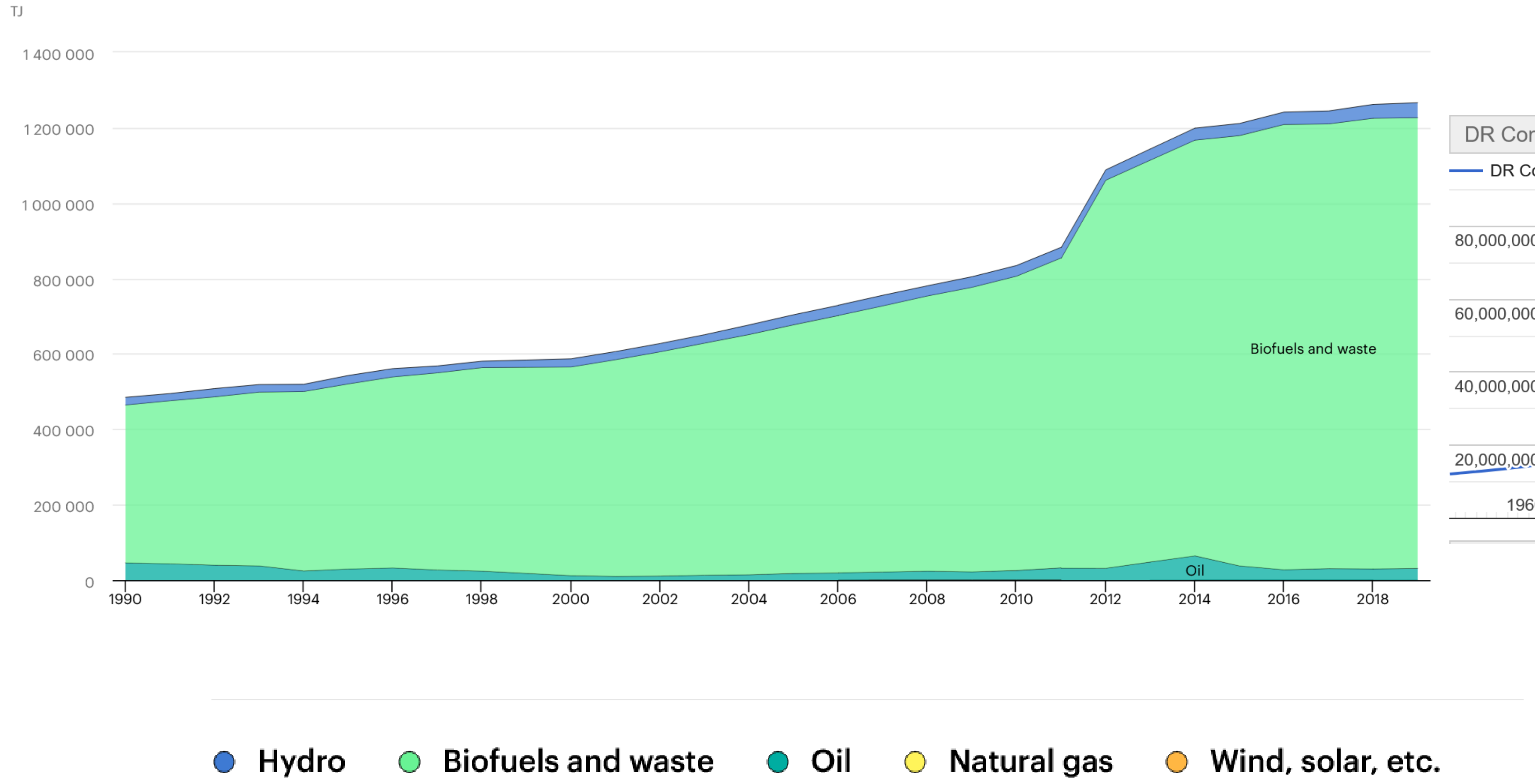
Total world energy consumption by year

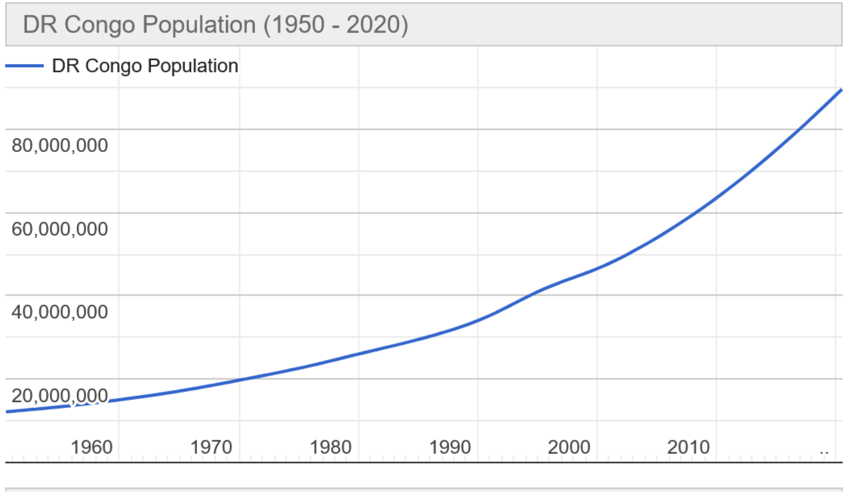


Year	%Combustion
1990	91%
1995	91%
2000	90%
2005	91%
2010	91%
2015	91%
2019	90%

https://www.iea.org/data-and-statistics/data-browser?country=WORLD&fuel=Energy%20supply&indicator=TESbySource

Data from Democratic Republic of the Congo

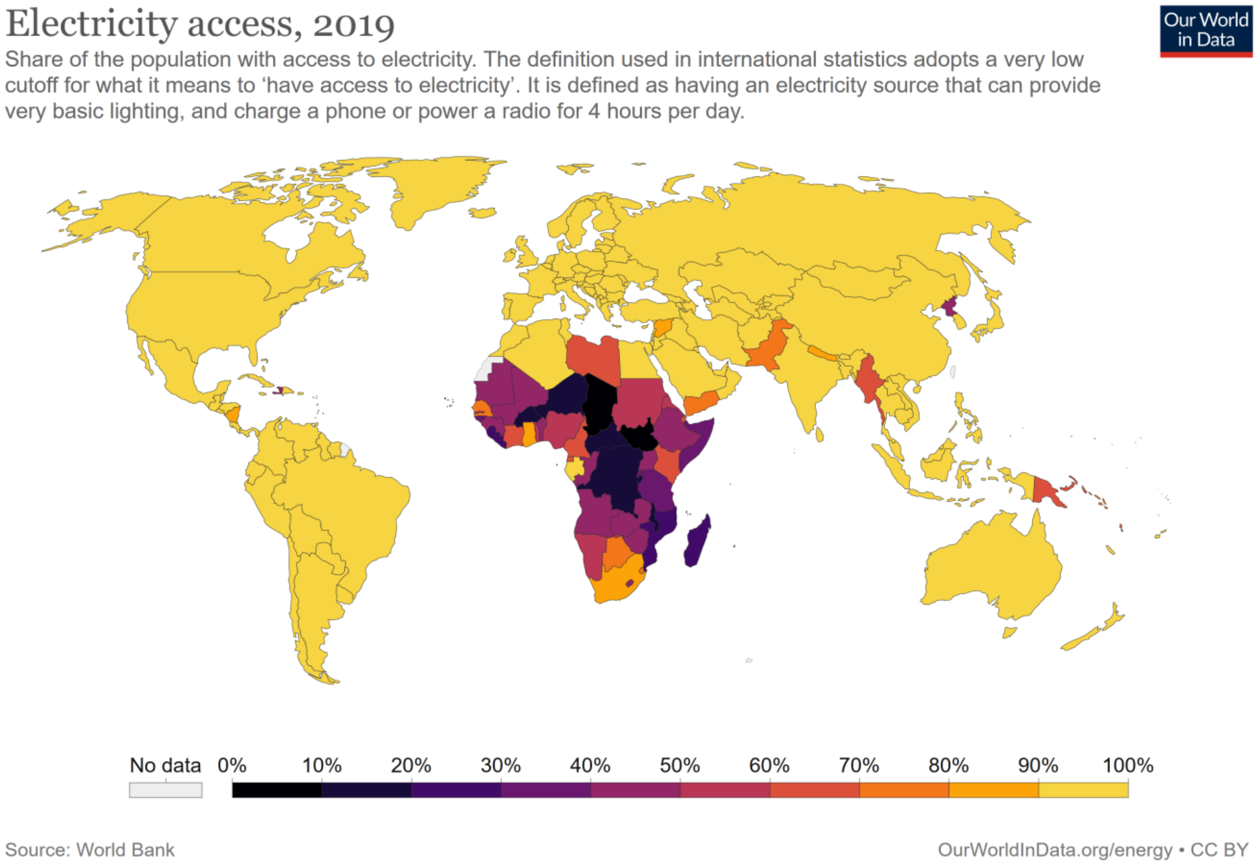


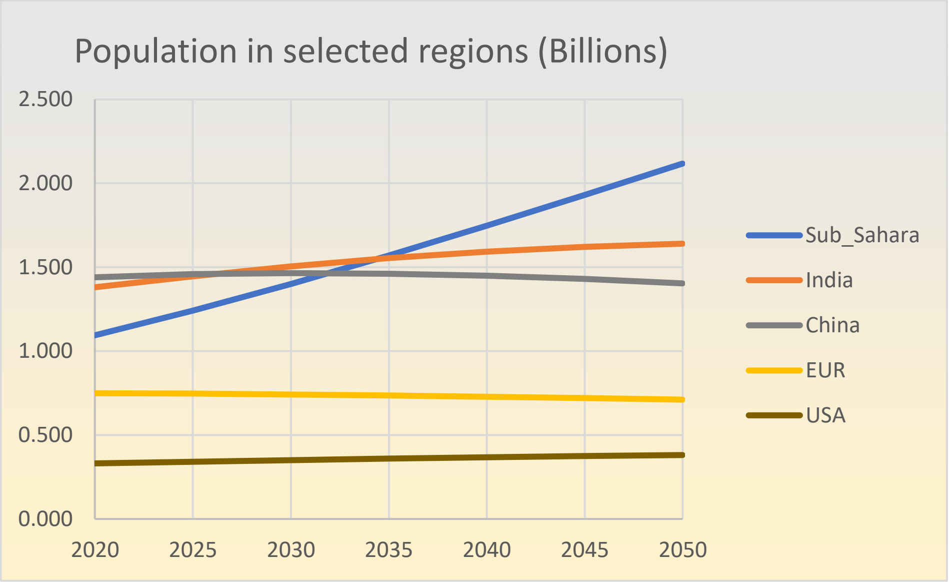


2022 population: 94,000,000
(per Worldometer)

That’s a lot of Carbon that isn’t sequestered anymore.

Population is growing fastest in the energy-poorest area





Conclusion, for the future:

- Decarbonization will require huge increases in electricity generation
- Much of this new generation will have to be installed in poor, energy deficient areas
- Population in these areas is growing much faster than in the richer parts of the world
- New economic and technical models will be needed to electrify the world’s poorest areas
- This will probably include evolving and eventually linked microgrids
- The intermittency problem of renewable generation will have to be solved