

CE 4240: Infrastructure Systems Engineering

Module 4: Intro to Power Systems and Climate Change

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Module outline



1. Part I: Traditional energy/power systems
2. Part II: Smart grids and the duck curve
3. Part III: Climate change
4. Part IV: Research at Vandy



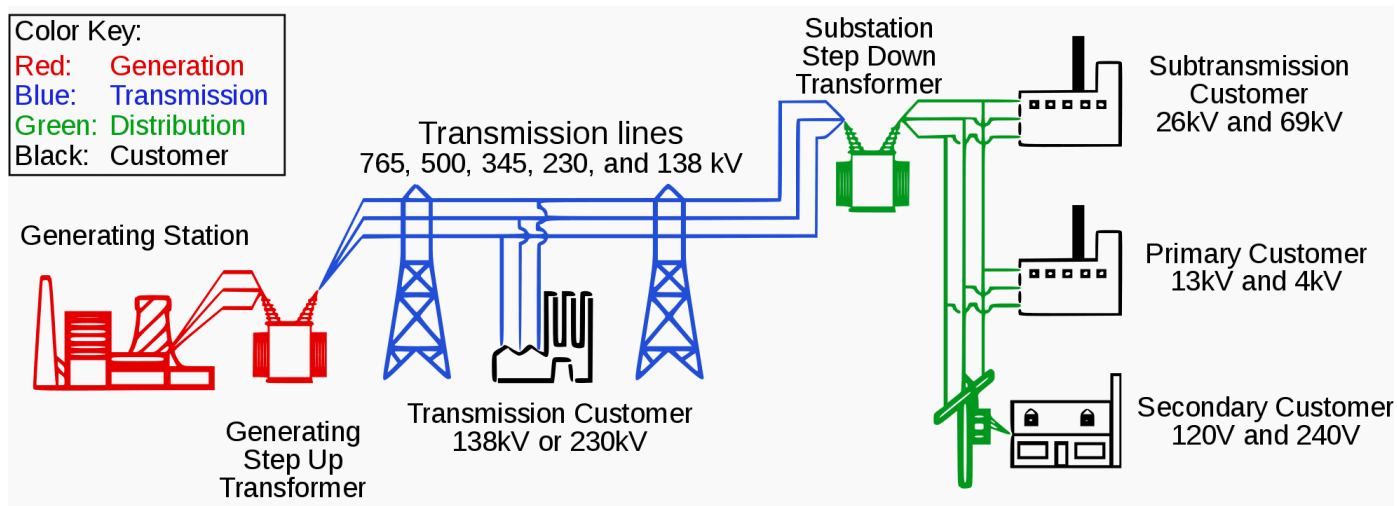
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Part I:

Traditional Power/Energy Systems: Fossil Fuel Dependence

What are power systems?

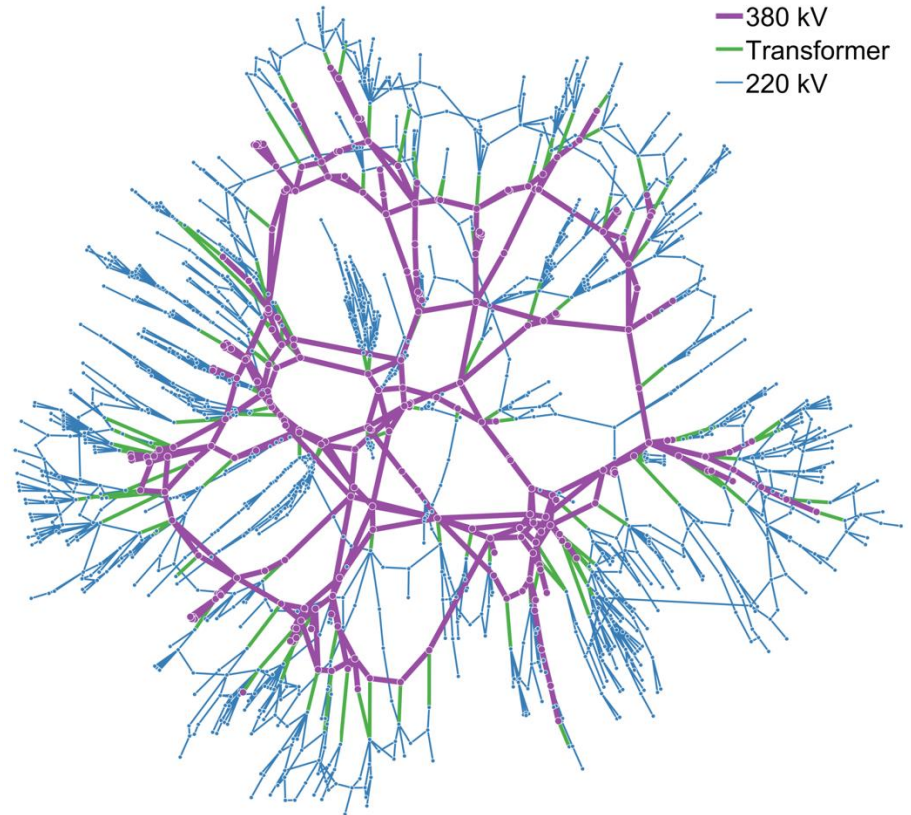
- Power/energy/electricity systems are giant infrastructure comprised of
 - generation, transmission and distribution of:
 - electric power (generation) → various loads (consumers)
 - think real-time chocolate delivery but electricity ;p
- Only commodity (+ water) that provides real-time service
- Electrical grid: most significant engineering achievement of 20th century



Energy systems form networks



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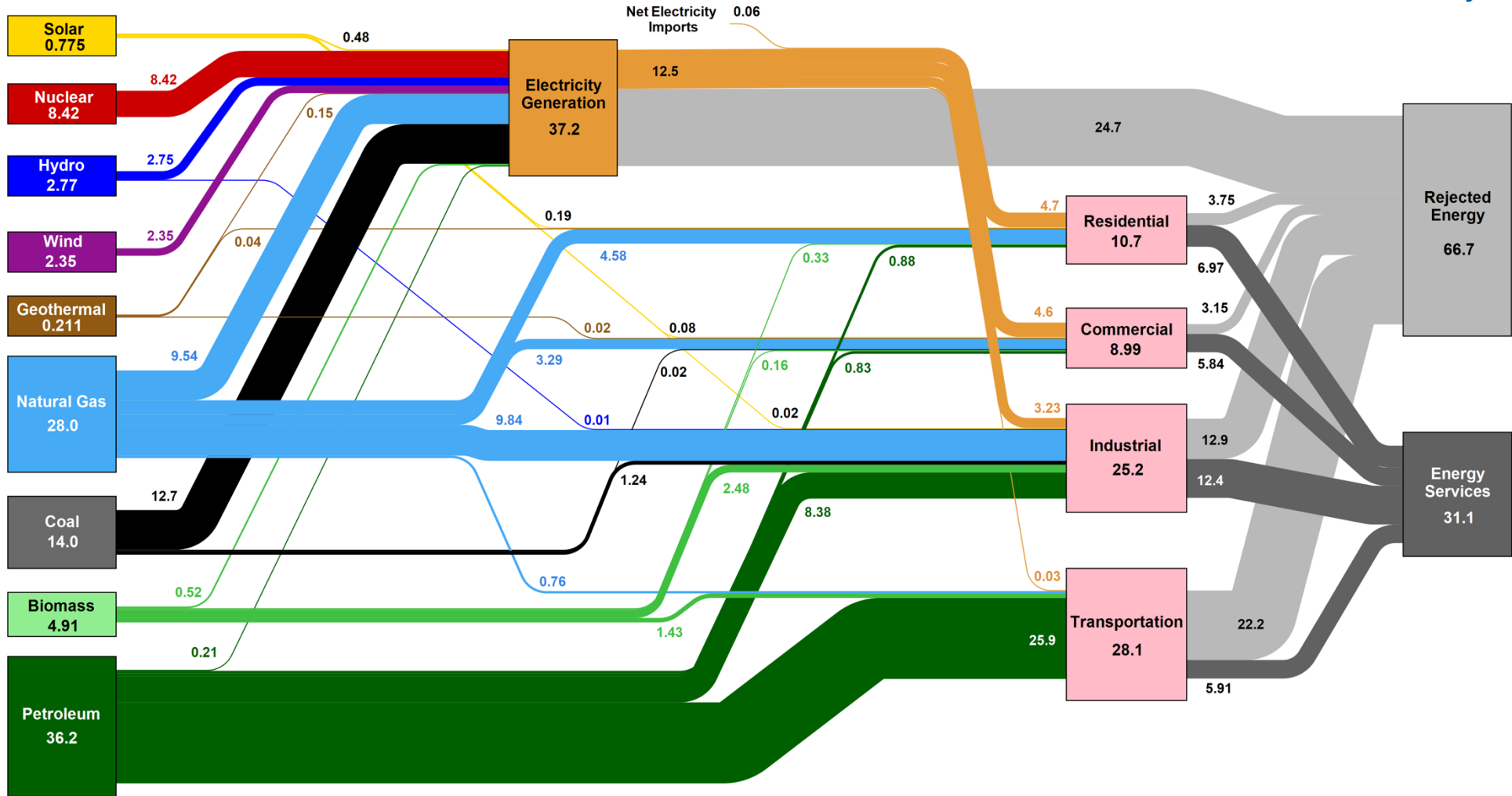


Energy 101: units and whatever



- Power: instantaneous measure of energy speed (Watt, kW, MW)
- Energy: how much you're actually consuming:
 - **Energy (kWh) = Power (kW) x Time (hour or h)**
 - *Energy unit: Joules (J), kWh, British Thermal Units (BTU)*
 - The energy content of fossil fuel is measured in BTUs
 - 1 BTU = 0.00029 kWh; 1 kWh = 3,412 Btu; 1 kWh = 3.6×10^6 J
- Electricity bill comes in kWh not kW (devices are rated with kW)
- How much energy does your iPhone charger consume per year?
 - **P = 20 W ; charging time = 6 hours x 365 days →**
 - **E = P x time = 20 x 6 x 365 = 43800 Wh = 43.8 kWh (per year)**
 - Price per kWh = 10cents → yearly cost = \$0.1 x 43.8 kWh = **\$4.38/year**
- **Exercise:** how much \$\$ do you spend on your AC?

Estimated U.S. Energy Consumption in 2017: 97.7 Quads



1 Quad is 1 Quadrillion (10^{15}) Btu

Sources of electricity



Sources of electricity are divided into two categories

- **Nonrenewable:** Cannot be easily replenished

1. Coal

2. Natural Gas

3. Petroleum (oil)

4. Nuclear (uranium)

Fossil fuels: Formed over millions of years, used in *thermal* plants

- **Renewable:** Can be easily replenished

1. Wind

2. Solar

3. Hydropower

4. Biomass

5. Geothermal

Thermal plants

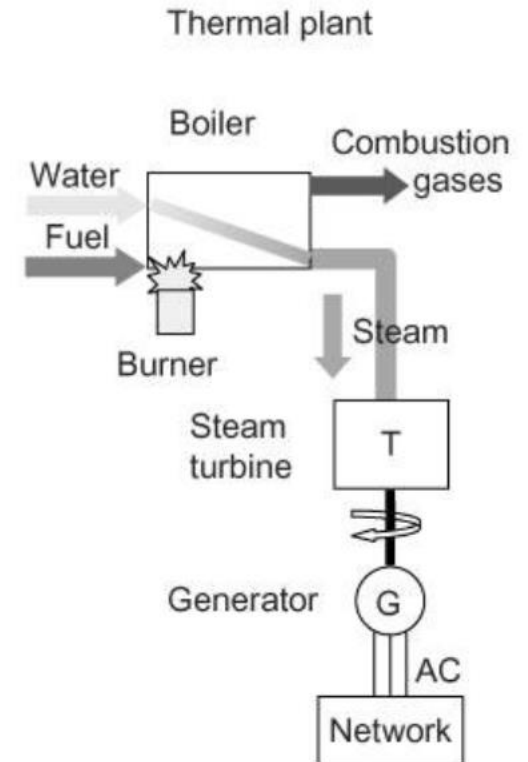


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- **Coal, natural gas, and oil** are used in thermal plants following pretty much the same

operating principle:

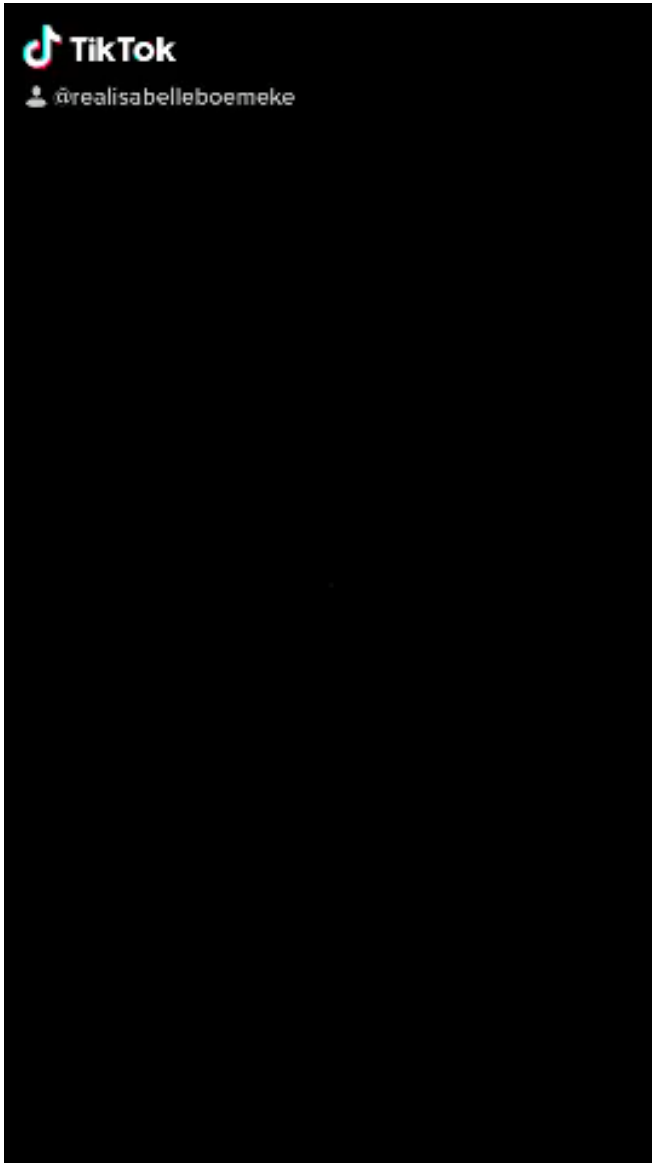
1. Fuel is burned → produces high-pressure steam
 2. Steam rotates a turbine
 3. Mechanical energy of turbine is converted to electric energy (fancy electromagnetics)
- All are bad for you and our planet



Nuclear power plants



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- **Nuclear power plants:**
Heat from nuclear fission is used to generate steam, which similarly to thermal plants
- Lots of controversy regarding nuclear and waste and whether it's actually *clean*

Solar power/energy farms



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- ☀ power: awesome sustainable energy
- Solar energy:
 - conversion of energy from sunlight into electricity via:
 - photovoltaics (PV): fancy physics/electrochemistry thingy
 - concentrated power: use mirrors to focus a large area of sunlight into a beam
 - combination of both
- West Tennessee solar farm:



Wind power farms (they do not cause cancer)



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- Wind power/energy: use wind to provide mechanical power
 - → wind turbines turning → electric generators for electrical power
- Wind power: sustainable, renewable energy source
- Little enviro impact compared to fossil fuels
- Wind farms: many wind turbines, connected to power grid
- Buffalo Mountain, Tennessee:



Hydropower (the OG batteries)



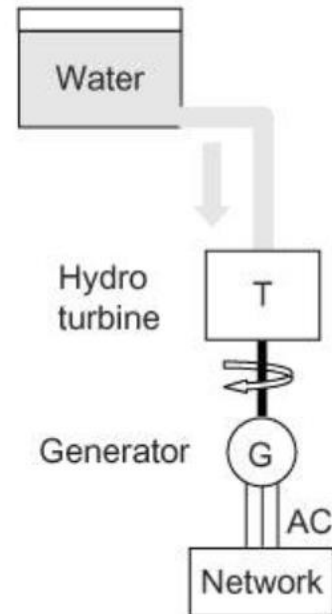
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- Hydropower *aka water-power*
 - use of falling or fast-running water to produce electricity
 - converting gravitational potential or kinetic energy of a water source to produce power
 - ancient renewable energy for irrigation
- Great Falls Dam, Tennessee, TN:



Hydro plant

Reservoir

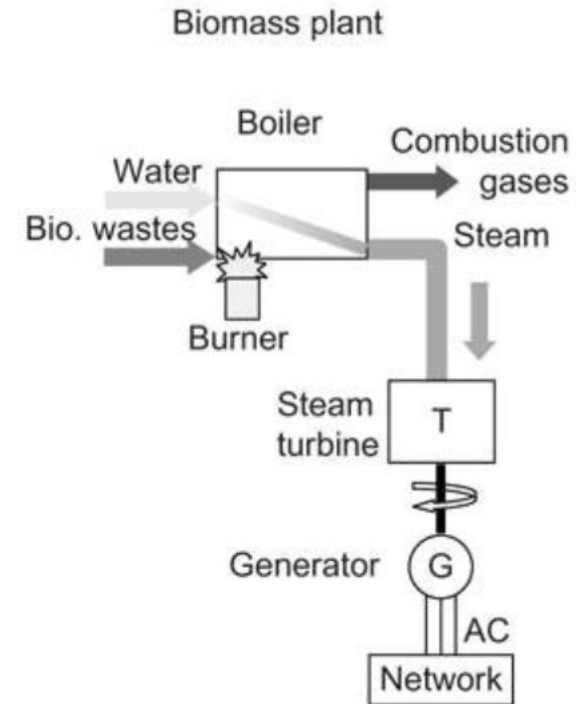


Biomass (burning your crap to fuel society)



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- Biomass: wood remains, plants, plant-based materials, animal matter
- Biomass: burned to produce steam, which is used for electricity generation as in thermal plants
- Other technologies available
- Conventional thermal plants can be retrofitted to burn a mixture of fossil fuel and biomass



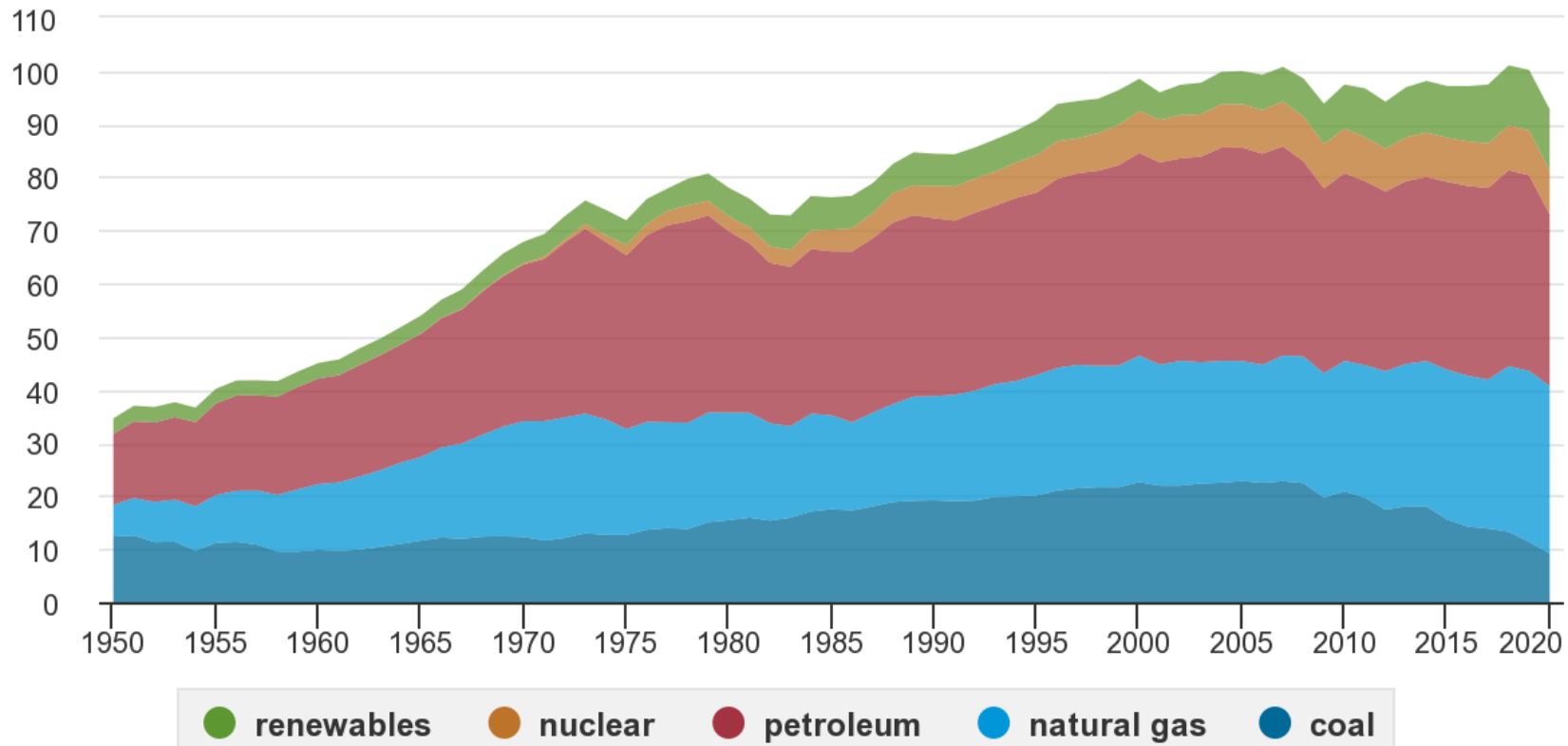
US primary energy consumption



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U.S. primary energy consumption by major sources, 1950-2020

quadrillion British thermal units



Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 1.3, April 2021, preliminary data for 2020

Note: Petroleum is petroleum products excluding biofuels, which are included in renewables.



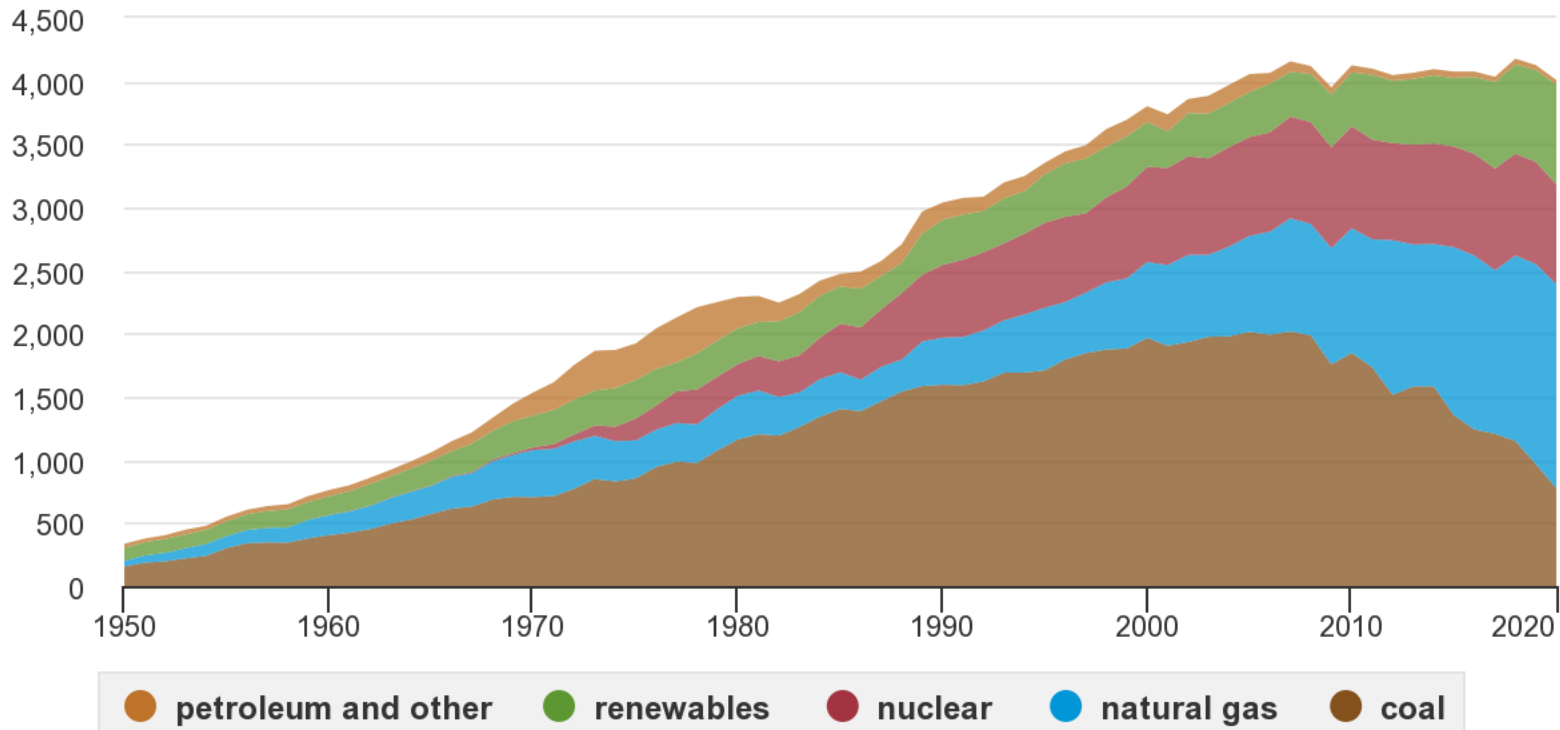
US primary electricity consumption



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U.S. electricity generation by major energy source, 1950-2020

billion kilowatthours



Note: Electricity generation from utility-scale facilities.

Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, January 2021 and *Electric Power Monthly*, February 2021, preliminary data for 2020



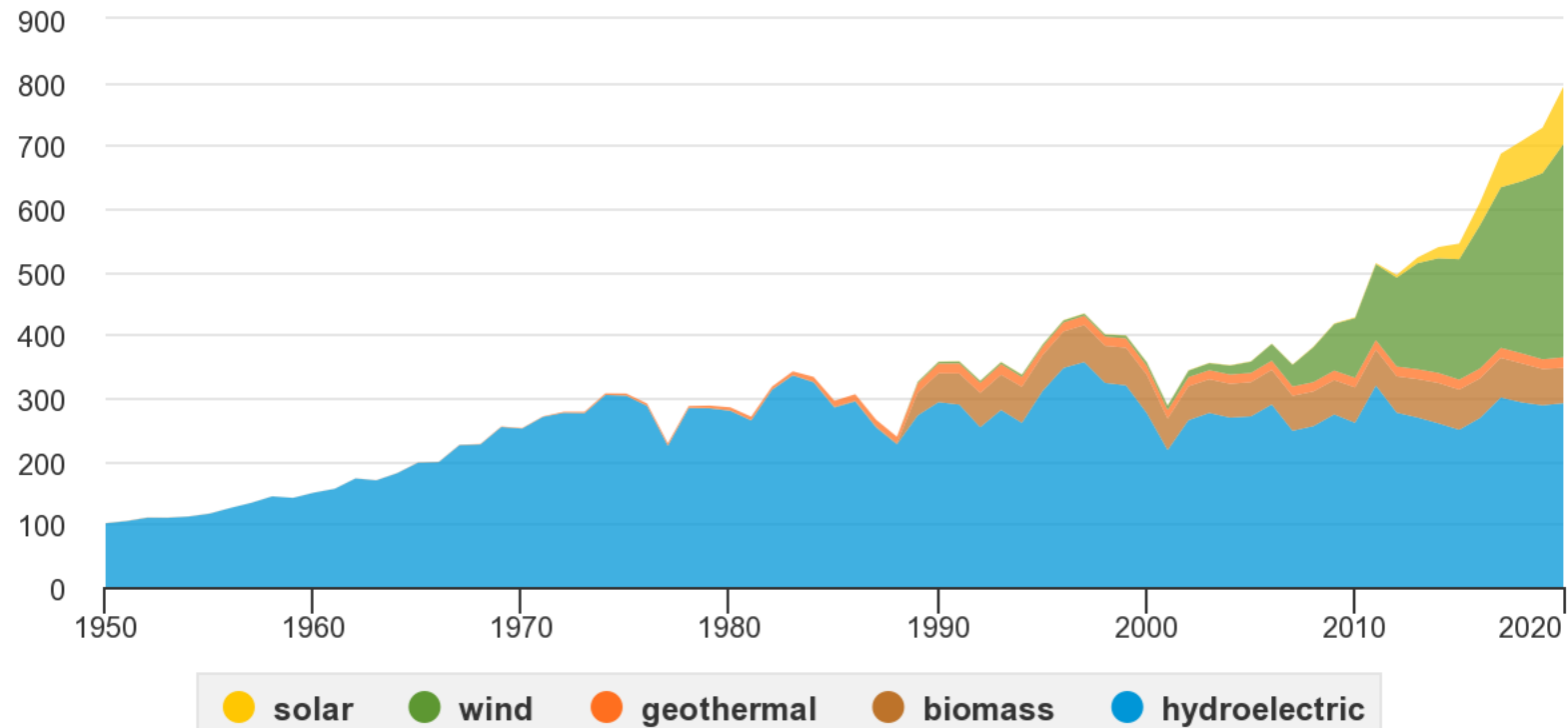
US electricity generation from renewables



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U.S. electricity generation from renewable energy sources, 1950-2020

billion kilowatthours



Note: Electricity generation from utility-scale facilities. Hydroelectric is conventional hydropower.

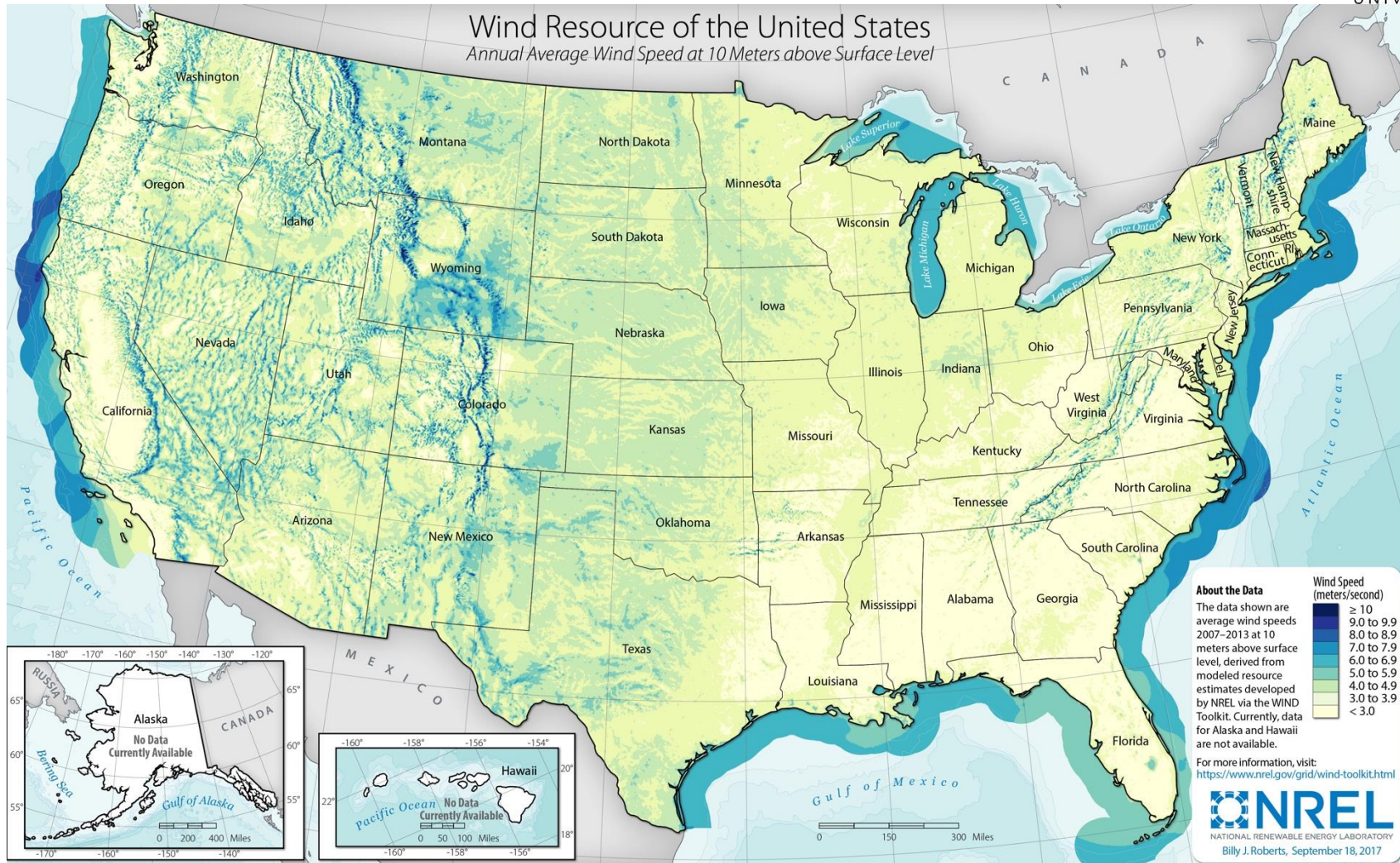
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 7.2a, January 2021 and *Electric Power Monthly*, February 2021, preliminary data for 2020



US average wind speed



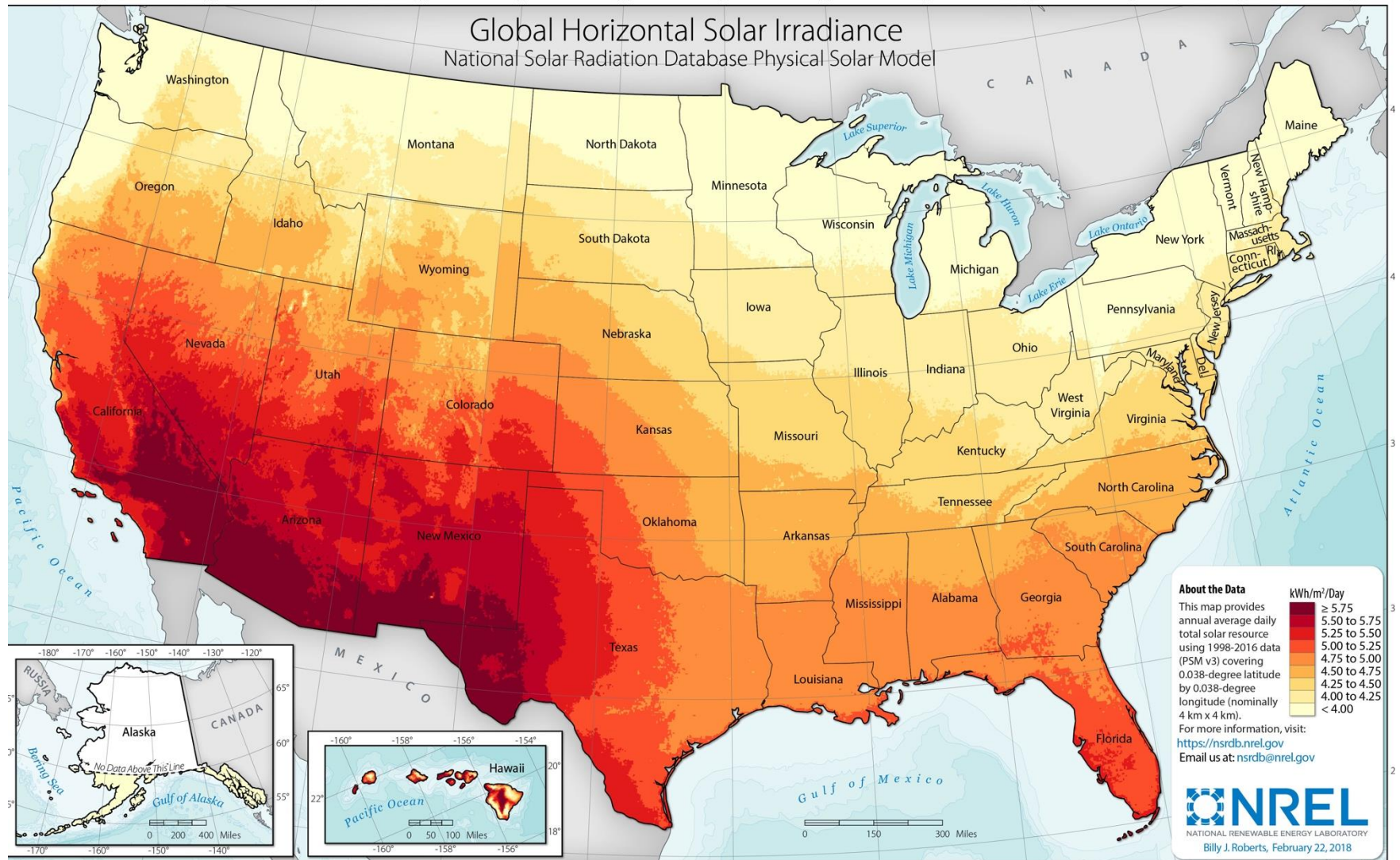
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US solar radiation map



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Problems with renewables?



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Part II:

*Smart Grids and
The Duck Curve*

What is a “smart grid”?

- More communication / sensors
- More distributed energy resources (DERs)
- Cleaner energy
- More modular systems
- Responds to climate disasters
- Are there dumb grids?



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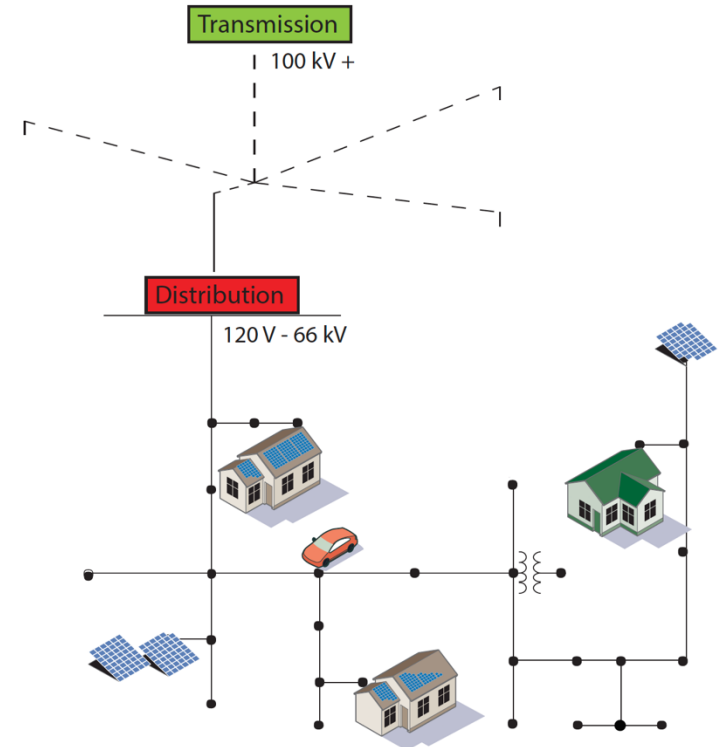
Billing & Payment Start, Stop, Transfer Programs & Rebates Outage & Emergencies

Electric Outage Map

Report an Electric Outage

Legend

- < 50 Impacted
- 51 - 499 Impacted
- 500 - 2,500 Impacted
- > 2,500 Impacted
- Multiple Outages
- Crew in the Area



Many grid threats



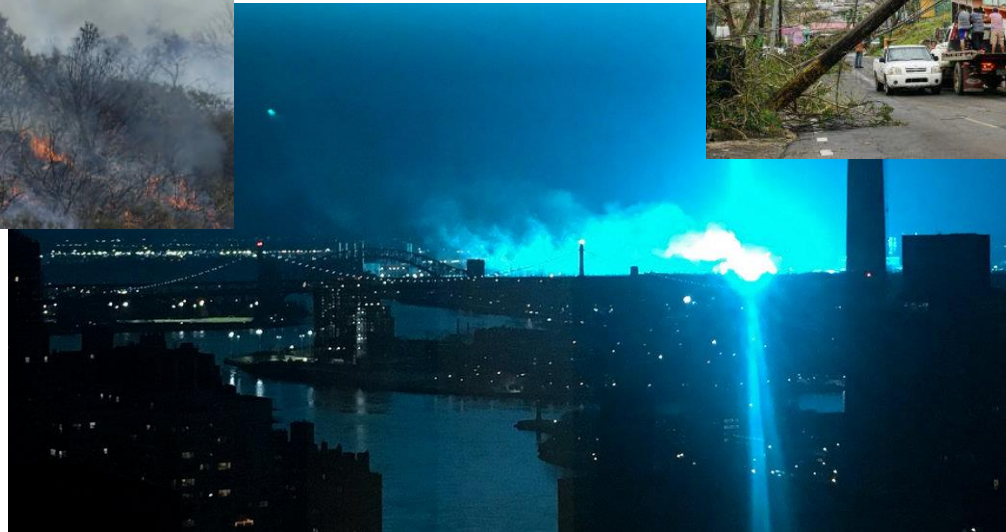
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Wildfires, CA 2018-2020



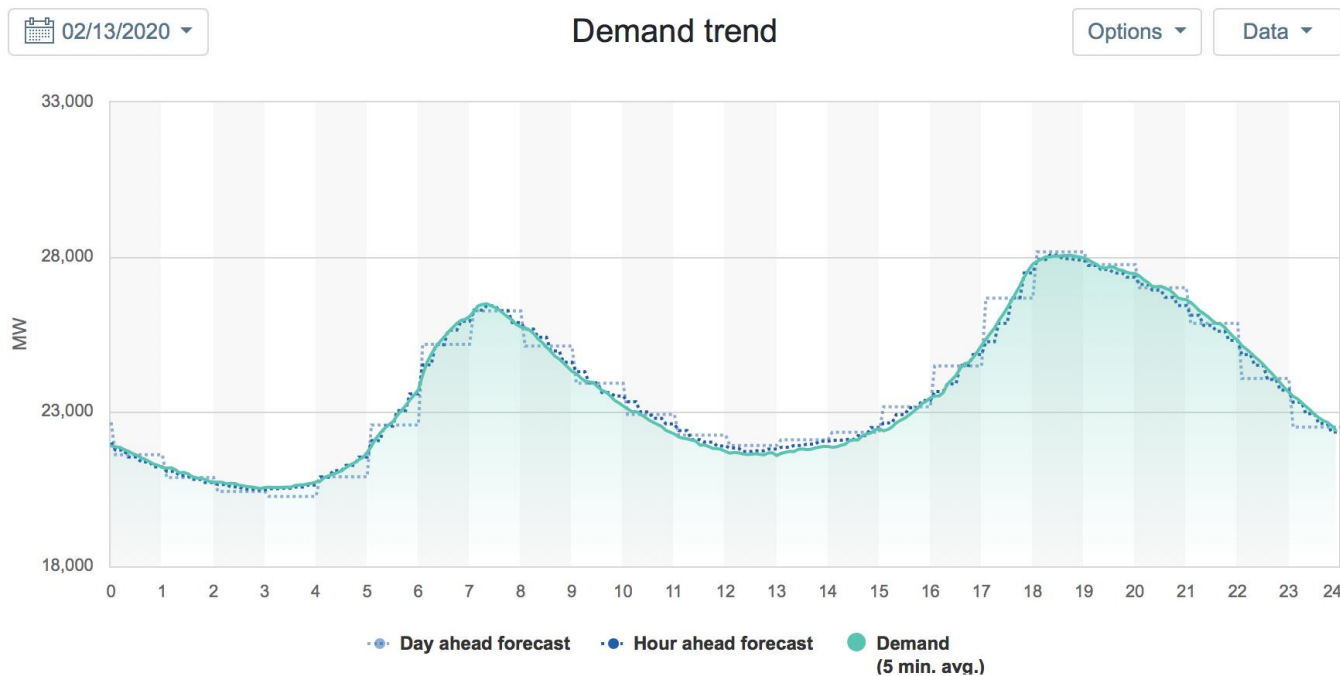
Hurricane Maria,
Puerto Rico
2017



NY substation arc fault 2018

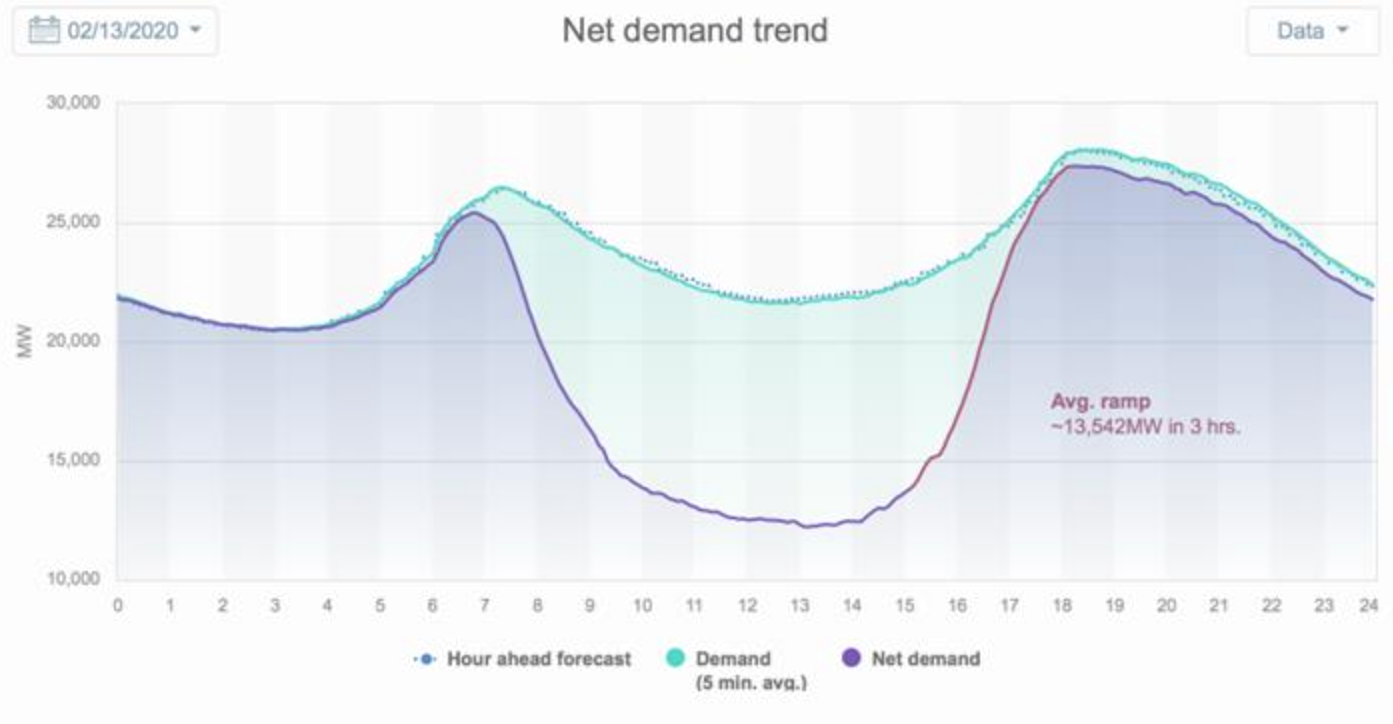


Typical Renewable Problems: Duck Curve



Source: California Independent System Operator (CAISO)

Subtract Solar and Wind = “Net Demand”

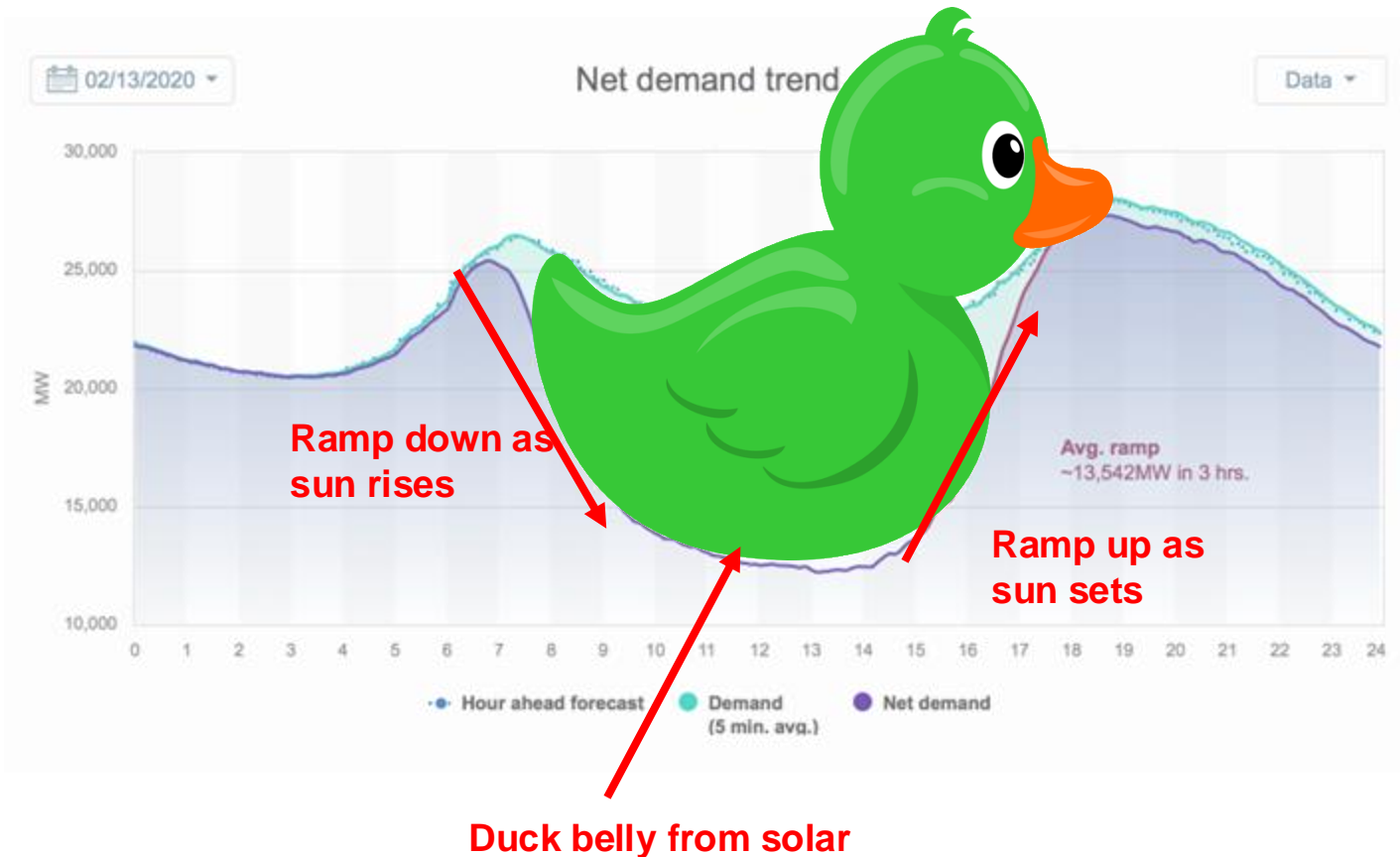


Source: California Independent System Operator (CAISO)

Duck curve: Sharp ramps



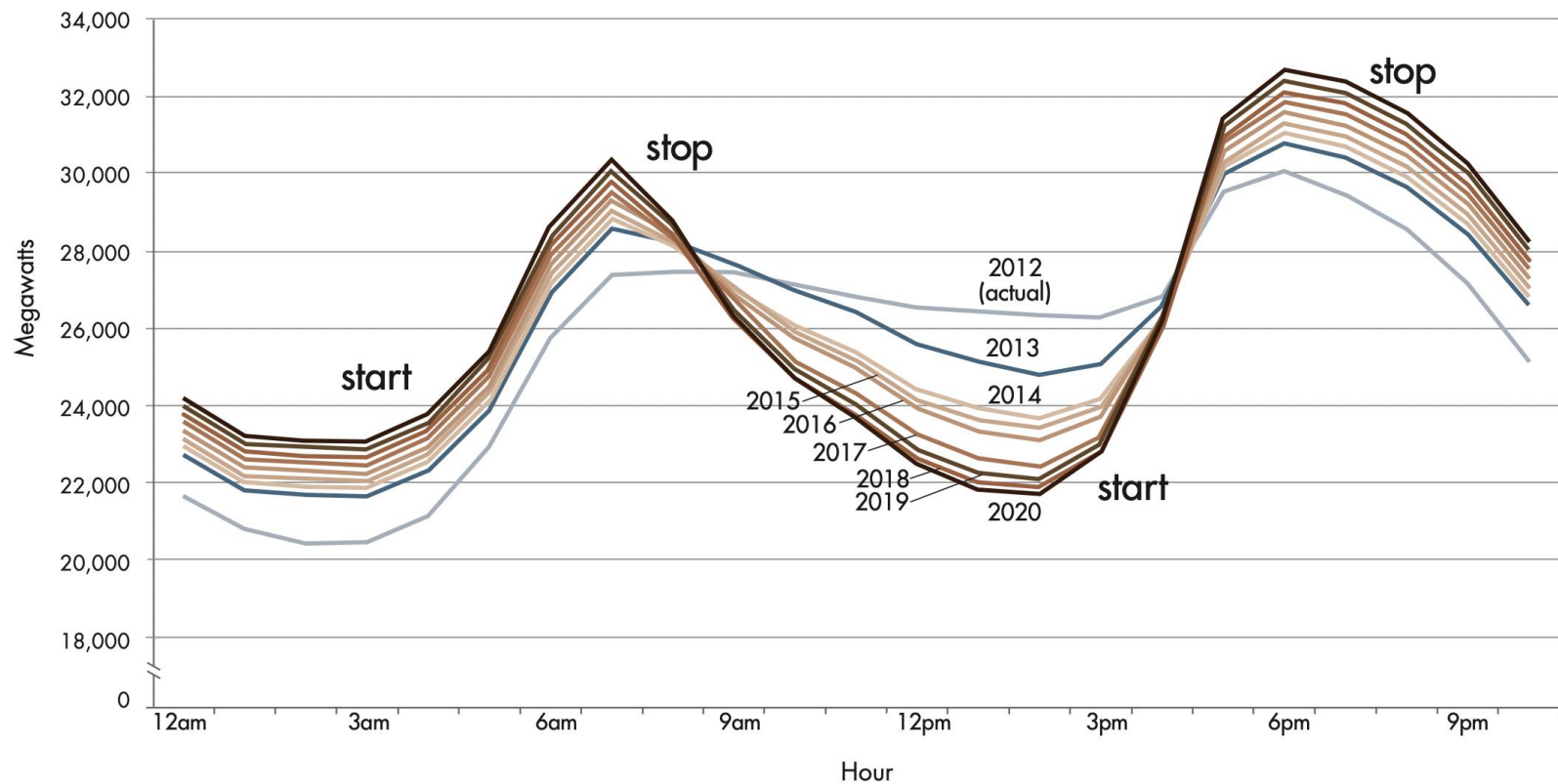
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Cali duck curve over the years

Figure 1

Net load - January 11

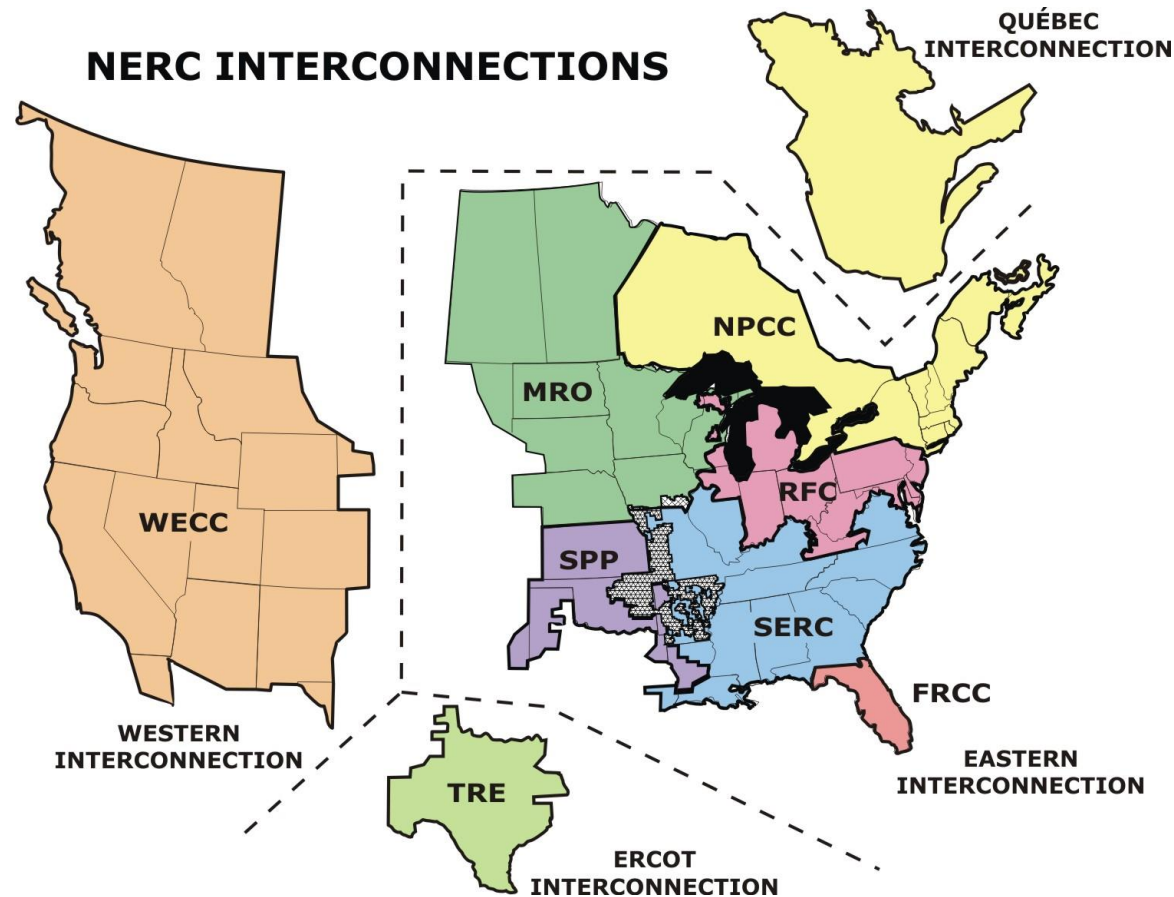


Who's in charge of power systems?



- Power system management is extremely complex
- 4-5 different operators
 - GENCOs
 - TRANSCO
 - DISCOs
 - ISOs
 - Utilities
- Market structure
- High-level objective: ensuring everyone gets electricity all the time
- Prices vary in real-time

North America's interconnected grids and ISOs



Source: NERC

NERC: North American Electric Reliability Corporation

Substations you see everywhere



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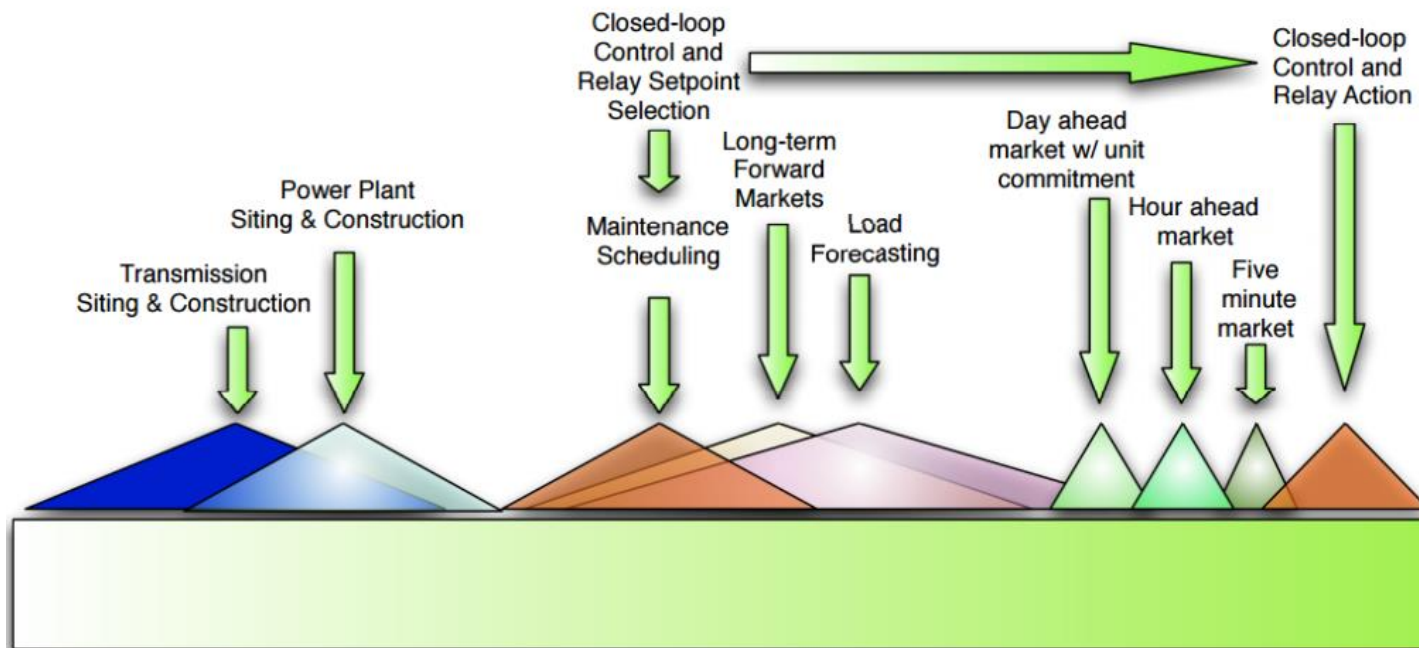


How are grids basically managed?



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- There are three basic levels or time-scales of grid management
 1. Time-Scale 1: Long-term planning (years and decades in planning)
 2. Time-Scale 2: Short-term operation (day- or hour- or minute-ahead operation)
 3. Time-Scale 3: Real-time control (second-to-second control)



Time-Scale 1: The Long-Term Planning Scale



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- This long-term time-scale is very broad
- General idea: optimize long-term impact of investments
- Figure out where to build solar power plants or wind
- Find out where to install high voltage transmission lines to transmit excess solar from Cali to PNW or to the Midwest
- These involve a lot of market economics, investment banks, some grid physics/constraints
- Problems that are solved often are labeled *capacity expansion models*
- Almost always, this involves formulating nonconvex, mixed-integer programs

Time-Scale 2: Short-Term Operation



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- This time-scale entails day-to-day, hour-to-hour management of grid assets
- By assets we mainly mean generators, dispatchable generators (fossil fuels, nuclear, hydro, batteries)
- In general, this time-scale has two different layers
 - First layer is a day-ahead or week-ahead planning optimization
 - This is referred to as the unit commitment problem (UCP)
 - Second layer is a minute-to-minute or sometimes hour-to-hour operation
 - This is referred to as the economic dispatch or optimal power flow (OPF) problem
- These two problems are solved in every market by the ISO
- Both require predictions of loads (demands) and renewables
- ISOs publish real-time data
- <http://www.caiso.com/Pages/default.aspx>

Unit Commitment Problem (UCP)



- This is an example on what UCP is
- Problem is solved for a week-worth of time-scale to account for various demands
- Formulation results in what generators should be on or off
- Problem is mixed integer non-cvx
- Taken from: *Unit commitment problem: A new formulation and solution method*

$$\begin{aligned}
 & \min_{\mathbf{y}^i, \mathbf{y}^{i'}, \bar{\mathbf{p}}^i, \mathbf{u}^i, \mathbf{u}^{i'}} \sum_{i \in \mathcal{I}_s} \sum_{t=1}^T SC^i(x_{t-1}^{i, \text{off}}) (1 - u_{t-1}^i) u_t^i \\
 & + \sum_{i \in \mathcal{I}_s} \sum_{t=1}^T \left[\mathcal{F}C^i \cdot u_t^i + \mathcal{V}C^i(y_t^i) \right] \\
 & + \sum_{i' \in \mathcal{I}_f} \sum_{t=1}^T \left[\left(SC^{i'}(0) + \mathcal{F}C^{i'} \right) u_t^{i'} + \mathcal{V}C^{i'}(y_t^{i'}) \right]
 \end{aligned}$$

subject to following constraints:

$$\sum_{i' \in \mathcal{I}_f} (y_t^{i'} + P_{\min}^{i'} u_t^{i'}) + \sum_{i \in \mathcal{I}_s} (y_t^i + P_{\min}^i u_t^i) = d_t \quad \forall t$$

$$\sum_{i \in \mathcal{I}_s} (\bar{p}_t^i - (y_t^i + P_{\min}^i u_t^i)) \geq \alpha d_t \quad \forall t$$

$$0 \leq y_t^{i'} \leq (P_{\max}^{i'} - P_{\min}^{i'}) u_t^{i'} \quad \forall i' \in \mathcal{I}_f, \forall t$$

$$0 \leq y_t^i \leq \bar{p}_t^i - P_{\min}^i u_t^i \quad \forall i \in \mathcal{I}_s, \forall t$$

$$0 \leq \bar{p}_t^i \leq P_{\max}^i u_t^i \quad \forall i \in \mathcal{I}_s, \forall t$$

$$\bar{p}_t^i - y_{t-1}^i \leq P_{\min}^i u_{t-1}^i + \bar{R}^i u_{t-1}^i + \bar{S}^i (u_t^i - u_{t-1}^i) + P_{\max}^i (1 - u_t^i) \quad i \in \mathcal{I}_s, \forall t$$

$$\bar{p}_t^i \leq \underline{S}^i (u_t^i - u_{t+1}^i) + P_{\max}^i u_{t+1}^i \quad i \in \mathcal{I}_s, \forall t \neq T$$

$$y_{t-1}^i - y_t^i \leq P_{\min}^i (u_t^i - u_{t-1}^i) + \underline{R}^i u_t^i + \underline{S}^i (u_{t-1}^i - u_t^i) + P_{\max}^i (1 - u_{t-1}^i) \quad i \in \mathcal{I}_s, \forall t$$

$$(x_{t-1}^{i, \text{on}} - T^{i, \text{on}}) (u_{t-1}^i - u_t^i) \geq 0 \quad i \in \mathcal{I}_s, \forall t$$

$$(x_{t-1}^{i, \text{off}} - T^{i, \text{off}}) (u_t^i - u_{t-1}^i) \geq 0 \quad i \in \mathcal{I}_s, \forall t$$

$$u_t^i \in \{0, 1\} \quad i \in \mathcal{I}_s, \forall t$$

$$u_t^{i'} \in \{0, 1\} \quad i' \in \mathcal{I}_f, \forall t$$

Optimal Power Flow (OPF)



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- Once the operator knows which generators will be on/off for the next day or week, operation problem is solved every 1 hour or sometimes 5-10 minutes
- This determines varying setpoints of generators
- OPF can be written in many ways; here's one of them:

$$\min \sum_{i \in \mathcal{G}} C_i(p_i^g) \quad (1a)$$

$$\text{s.t. } p_i^g - p_i^d = G_{ii}(e_i^2 + f_i^2) + \sum_{j \in \delta(i)} [G_{ij}(e_i e_j + f_i f_j) - B_{ij}(e_i f_j - e_j f_i)] \quad i \in \mathcal{B} \quad (1b)$$

$$q_i^g - q_i^d = -B_{ii}(e_i^2 + f_i^2) + \sum_{j \in \delta(i)} [-B_{ij}(e_i e_j + f_i f_j) - G_{ij}(e_i f_j - e_j f_i)] \quad i \in \mathcal{B} \quad (1c)$$

$$\underline{V}_i^2 \leq e_i^2 + f_i^2 \leq \bar{V}_i^2 \quad i \in \mathcal{B} \quad (1d)$$

$$p_i^{\min} \leq p_i^g \leq p_i^{\max} \quad i \in \mathcal{G} \quad (1e)$$

$$q_i^{\min} \leq q_i^g \leq q_i^{\max} \quad i \in \mathcal{G}. \quad (1f)$$

- This problem is non-cvx...source of non-convexity?
- Variables are voltages, powers
- Literally 1000s+ papers on how to solve this problem, convexify it
- Lagrange multipliers
- Taken from *Strong SOCP Relaxations for the Optimal Power Flow Problem*

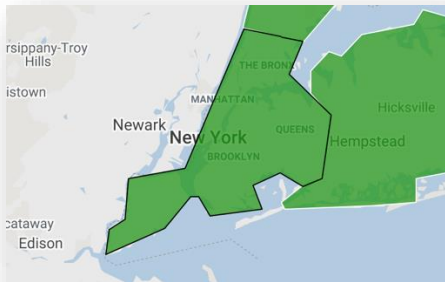
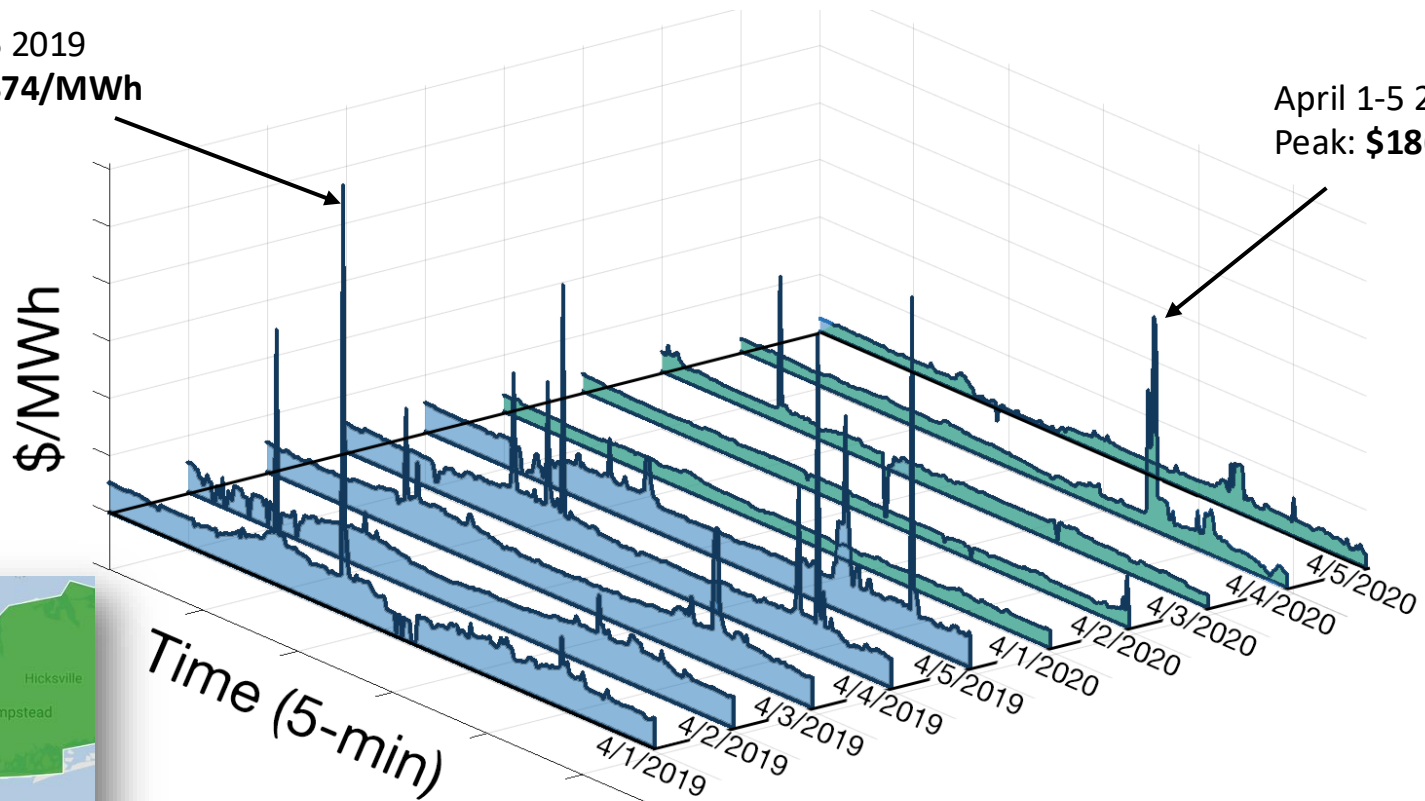
NYC Locational Marginal Price: April 2019 vs 2020



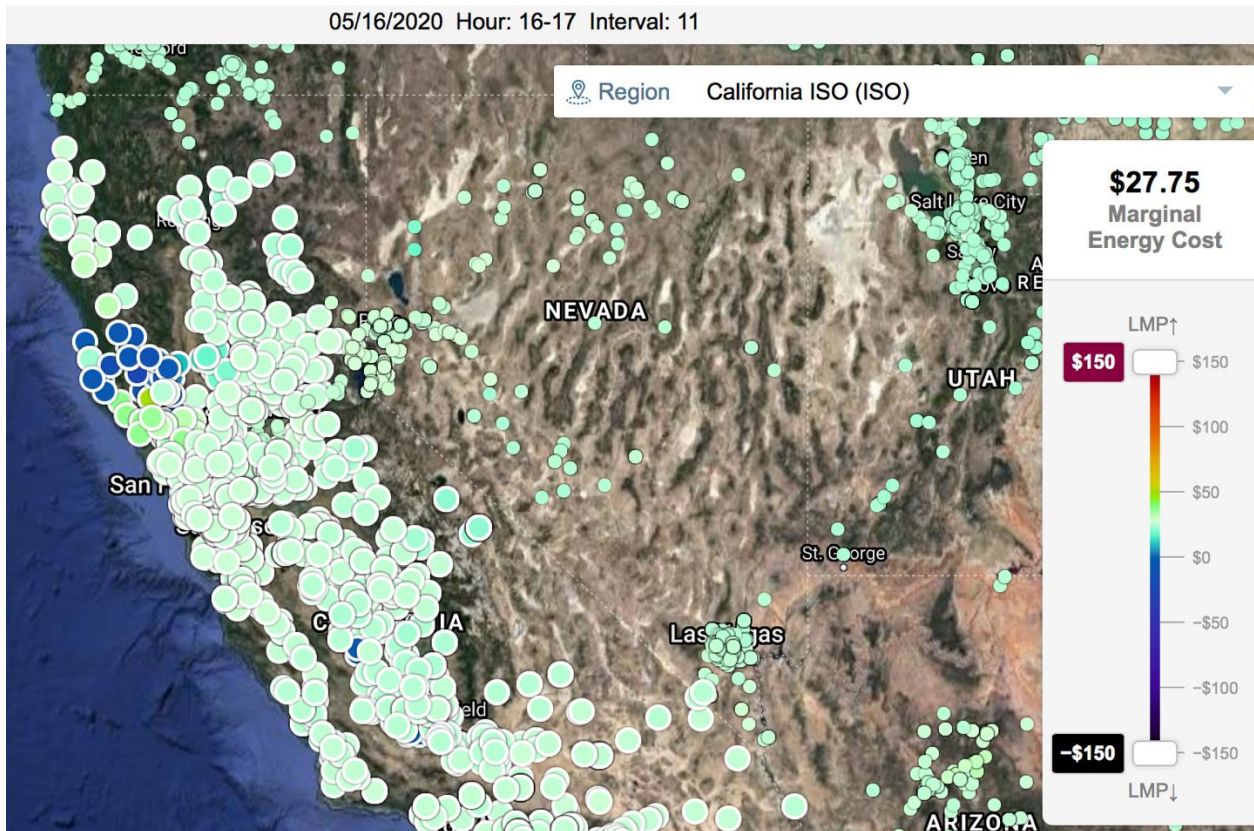
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April 1-5 2019
Peak: \$374/MWh

April 1-5 2020
Peak: \$186/MWh



Electricity prices are going negative in many areas



Supply is exceeding demand

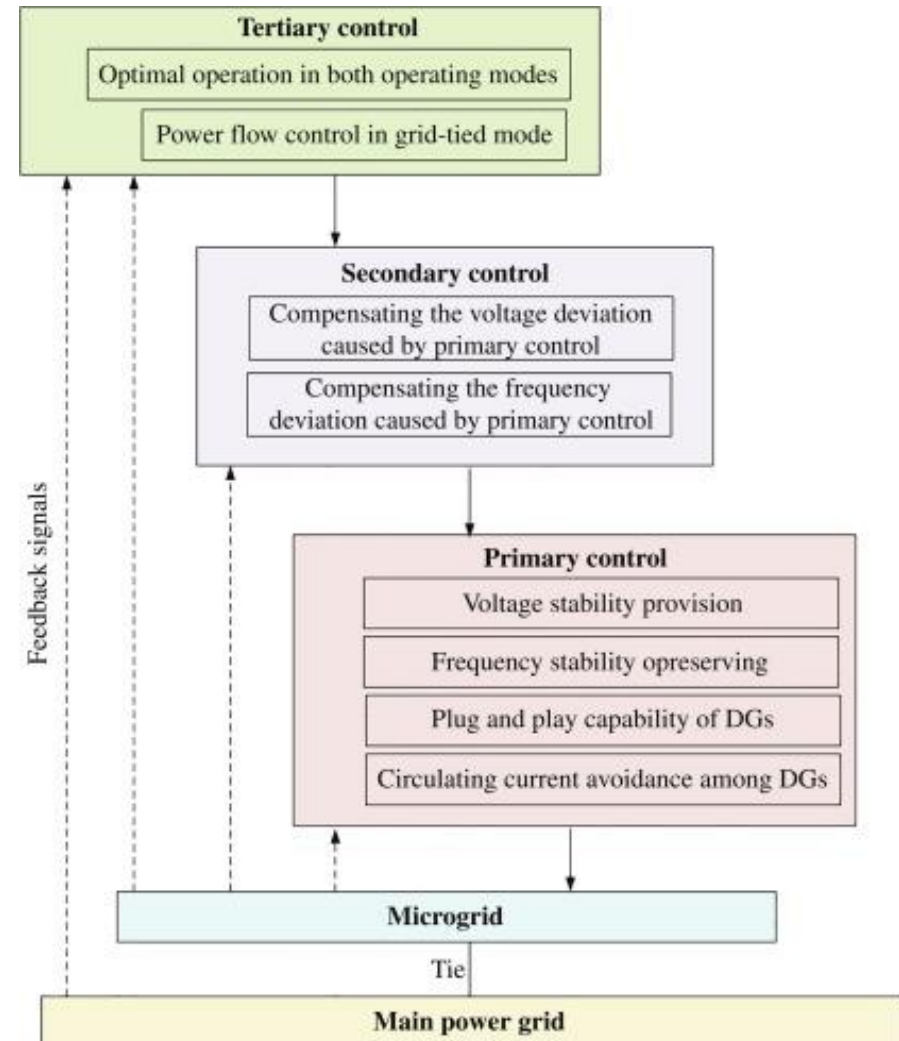
Might be more expensive to curtail renewables or shut off power plants than to pay people to use more power

Time-Scale 3: Real-Time Control



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- So now we know how to operate the grid every few minutes, and dispatch generators economically, we need to deal with second-to-second changes in loads
- There are three kind of *real-time control algorithms*
 1. Primary Control
 2. Secondary Control
 3. Tertiary Control (kinda OPF)





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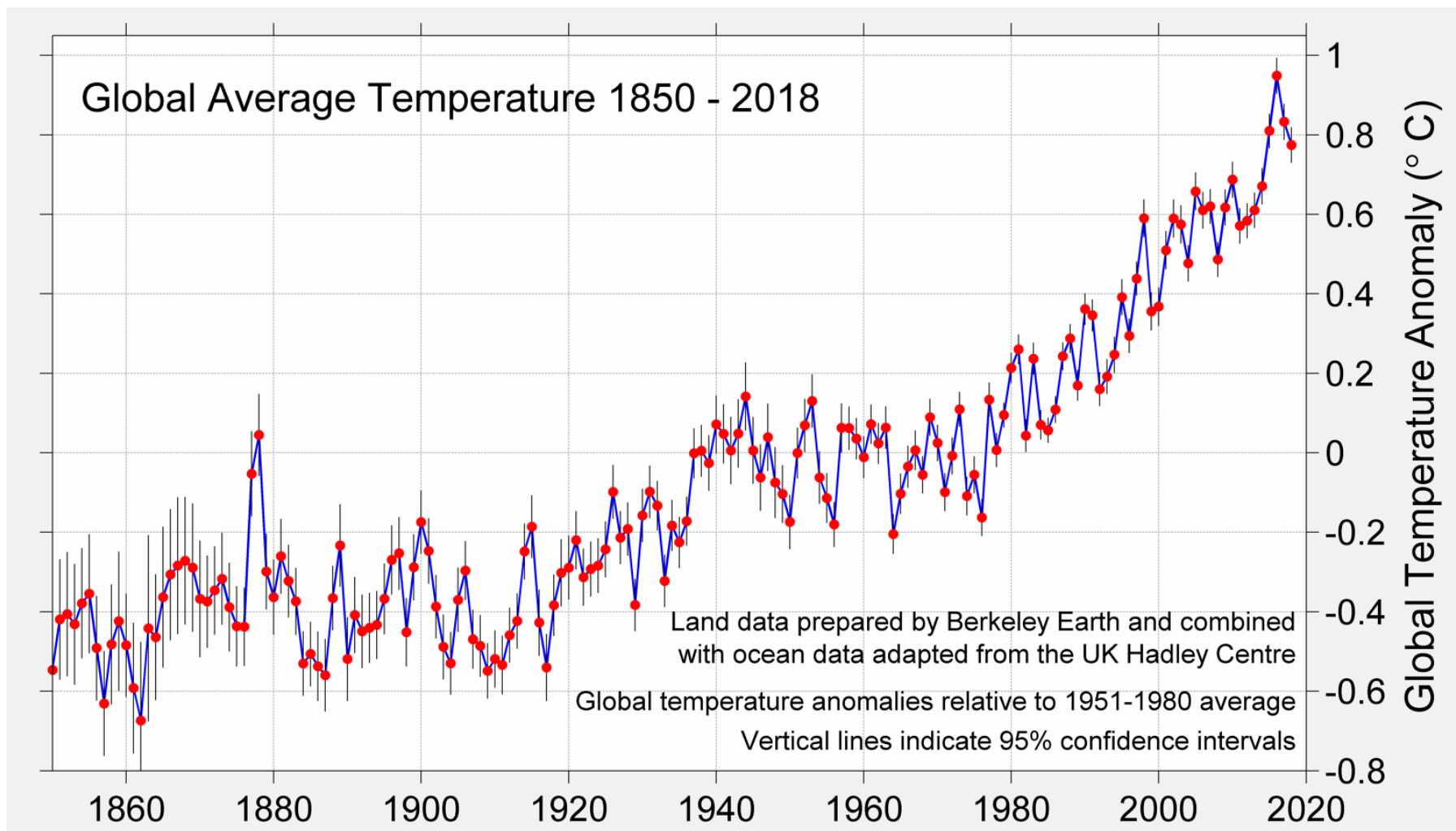


Part III:

Climate Change



Climate change: mean annual global temperatures



Climate Change Terminology



- Infrared Radiation
 - Radiation that has a wavelength that is longer than that of visible light, but shorter than that of radio waves
- Greenhouse Gases
 - Gas that absorbs infrared radiation
 - Ex: Carbon dioxide, methane, nitrous oxide, chlorofluorocarbons and tropospheric ozone
- Positive Feedback
 - Change in some condition triggers a response that intensifies the changed condition
- Greenhouse Effect
 - Increase of heat in a system where energy enters (often as light), is absorbed as heat, and released sometime later
- Simple experiment to link CO₂ increase with increase in temperatures
 - When there's more CO₂ in the atmosphere, it makes the atmosphere warmer by trapping heat
 - Observation made many decades ago

Meanwhile, wtf is this?



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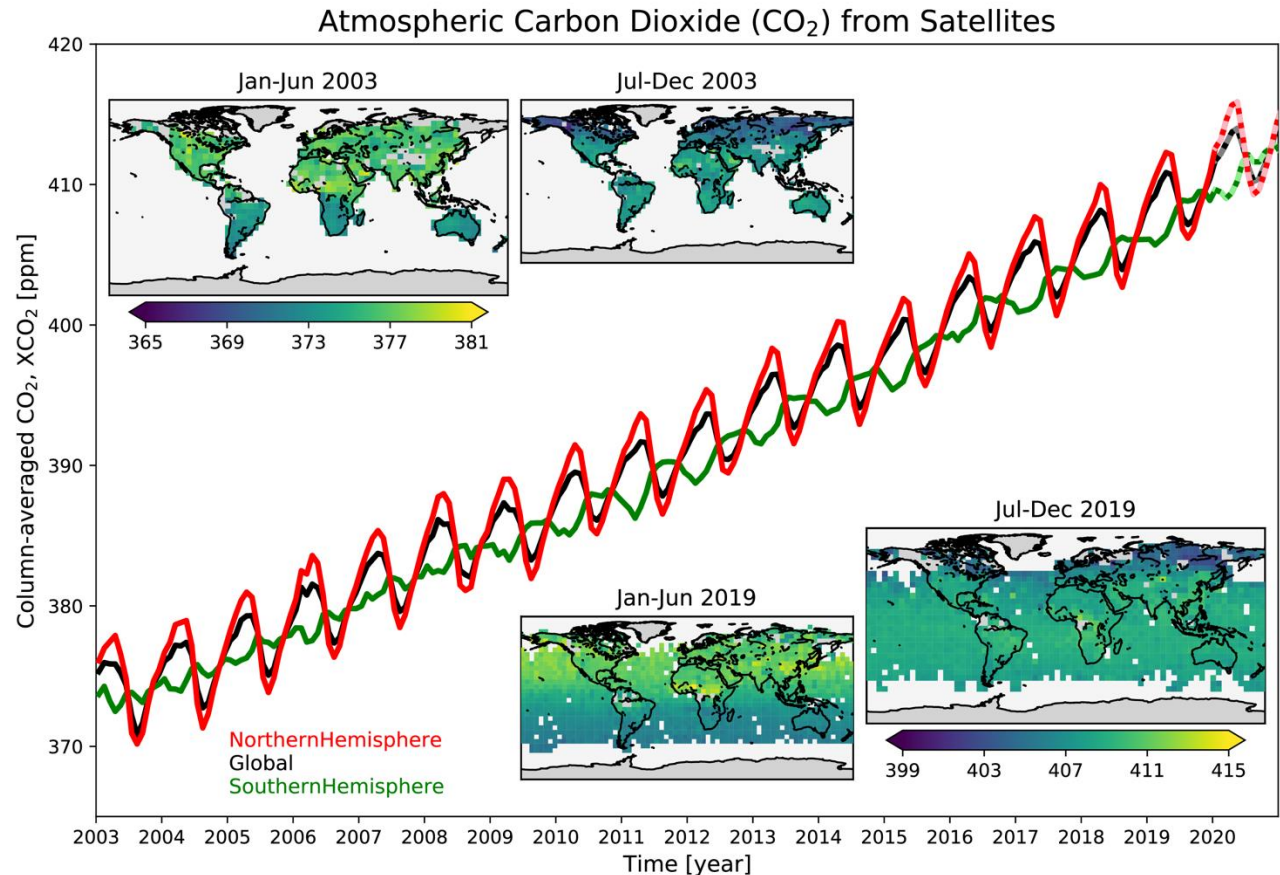


Causes



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- Greenhouse gas concentrations increasing



Data:2003-2019:XCO2_OBS4MIPS(v4.2);2020:CAMS(NRT) - Satellites:SCIAMACHY/ENVISAT+GOSAT+OCO-2 - Credit:C3S/CCI/CAMS/Univ.Bremen/SRON

Causes

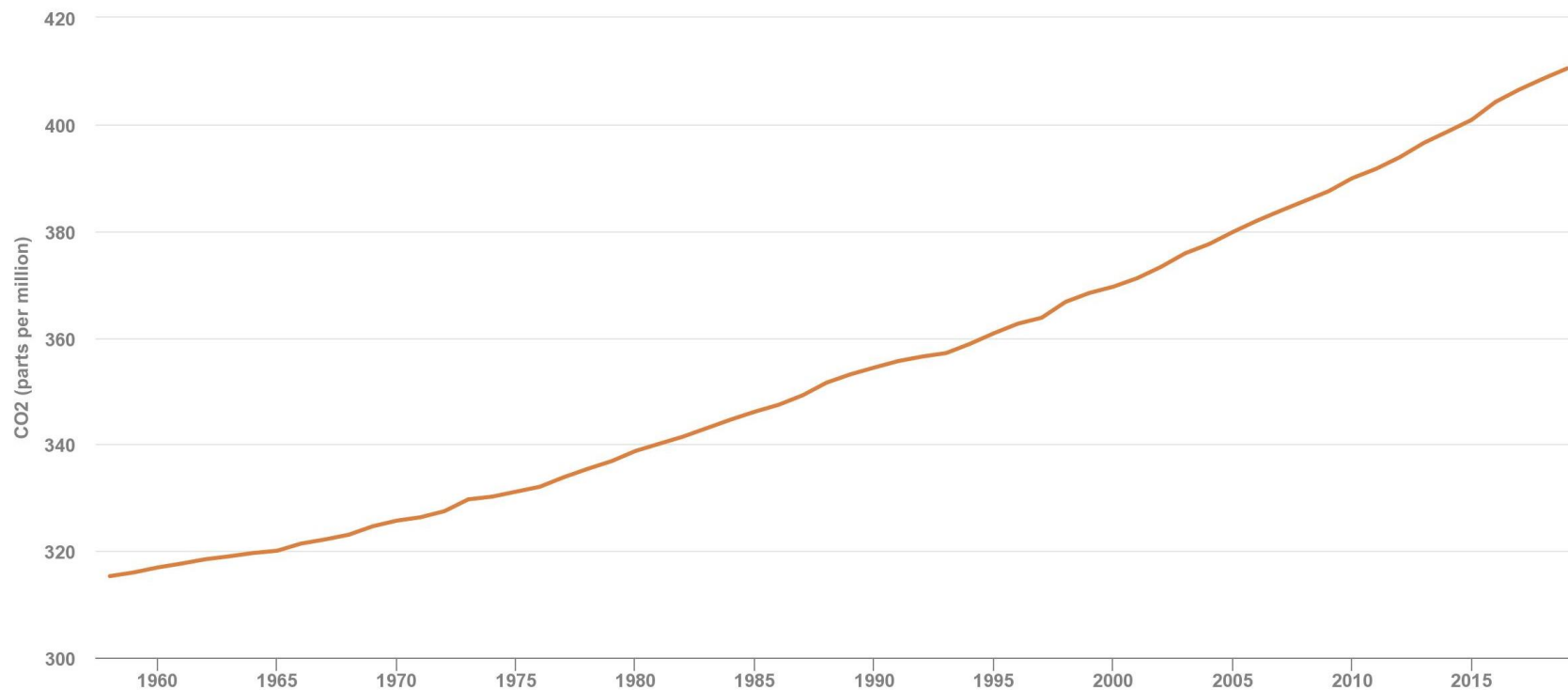


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- Increased concentration of CO₂
 - Burning fossil fuels in cars, industry and homes, deforestation, burning of forests

Global CO₂ emissions have risen steadily in recent decades. Between 2008 and 2017, fossil fuel CO₂ emissions increased at a rate of 1.5 percent per year. As of early 2019, CO₂ emissions had reached 410 parts per million (ppm).

Carbon dioxide (direct measurement)



Cows and climate change

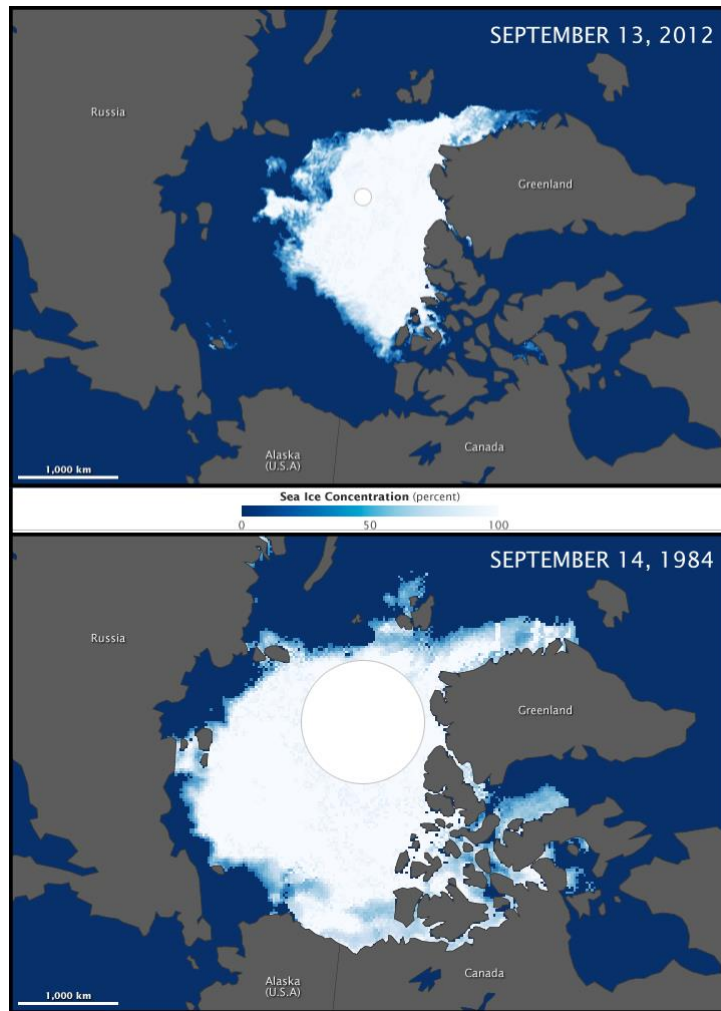


- Cows burp and fart, a lot
- Copulation (cow population, not a real word): ~1.6 billion
- Each cow releases 100kg of methane every year
- Methane impact on climate is ~23x CO₂
- Cowsies responsible for > 18% of GHGs
- But methane lasts only 10 years (compared to CO₂ which last 100s of years)
- So should we stop eating beef?
- New technologies (masking cows, feeding them seaweed, alternate meat sources)
- No one is coming after your cheeseburger but yes we need to eat less beef

Melting ice and rising sea levels



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Case-in-point impacts in fragile areas



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- Eskimo Inuit live traditional life dictated by freezing climate
- Climate change is altering their existence
 - Wildlife are smaller or displaced
 - Reduced snow cover and shorter river ice seasons





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Effects on organisms

- Decline in krill around Antarctica
 - Caused decrease in penguin populations
- Species have shifted their geographic range
- Migrating birds are returning to summer homes earlier
 - Food is not available at this time





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Effects on organisms: coral reefs

- Coral reefs can be bleached (right) due to increase in water temperature



Reduction of carbon emissions



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- Burn less fossil fuel: turn down your thermostat
- Plant Trees for shade and CO₂ uptake
- Insulate your house
- Replace old appliances
- Use compact fluorescence light bulbs
- Use renewable energy
- Buy EVs

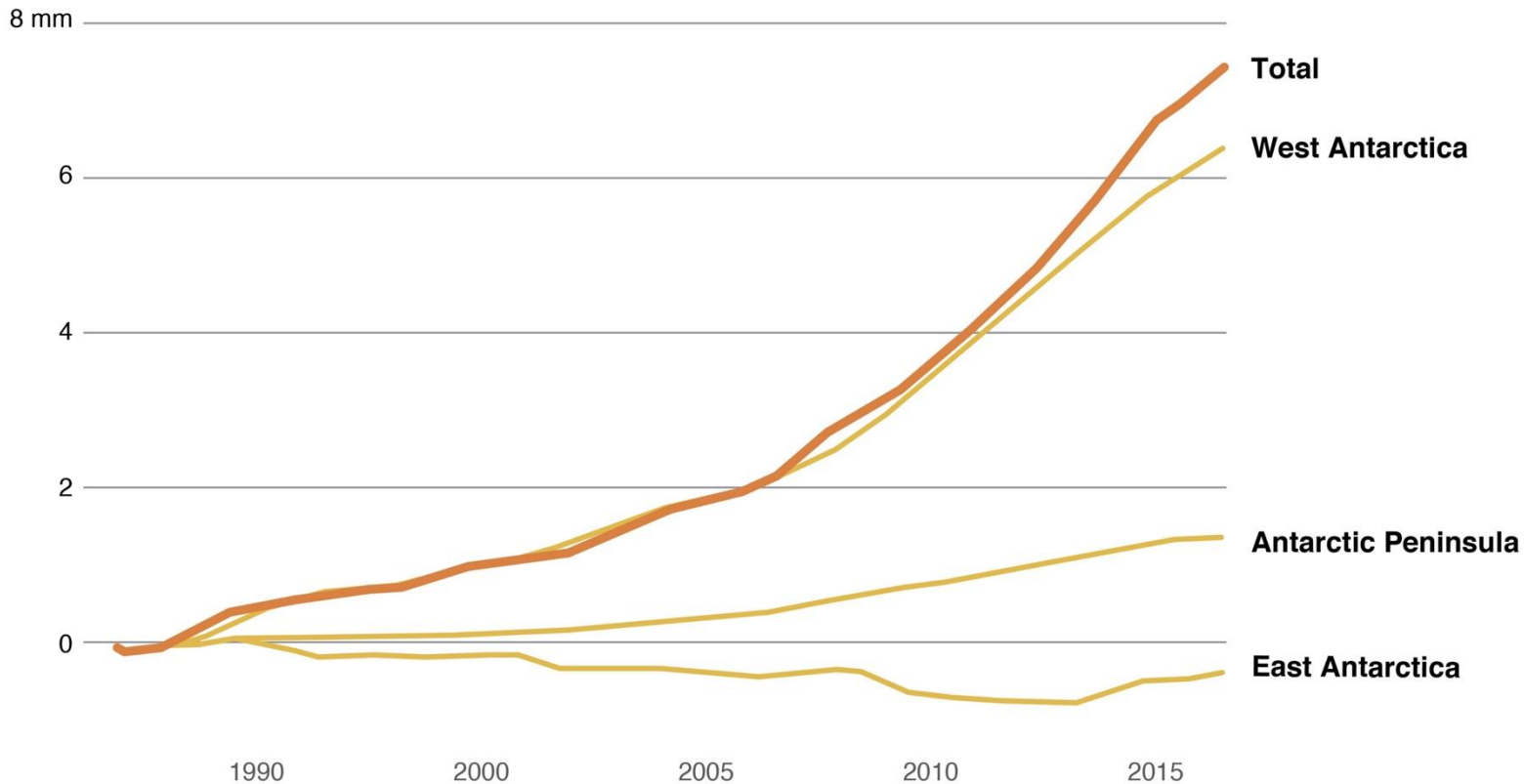
Antarctica ice loss

Since 2012, the amount of annual ice loss in Antarctica has tripled, increasing the global sea level by 3 millimeters (0.12 inch).



By 2100, global sea level could rise 65 centimeters (21 inches) if the rate of sea-level rise continues to accelerate at the observed rate; ice melt from Antarctica could account for nearly 25 percent of this rise.

Antarctic ice sheet contribution to global sea level



Current vs. other climate policies

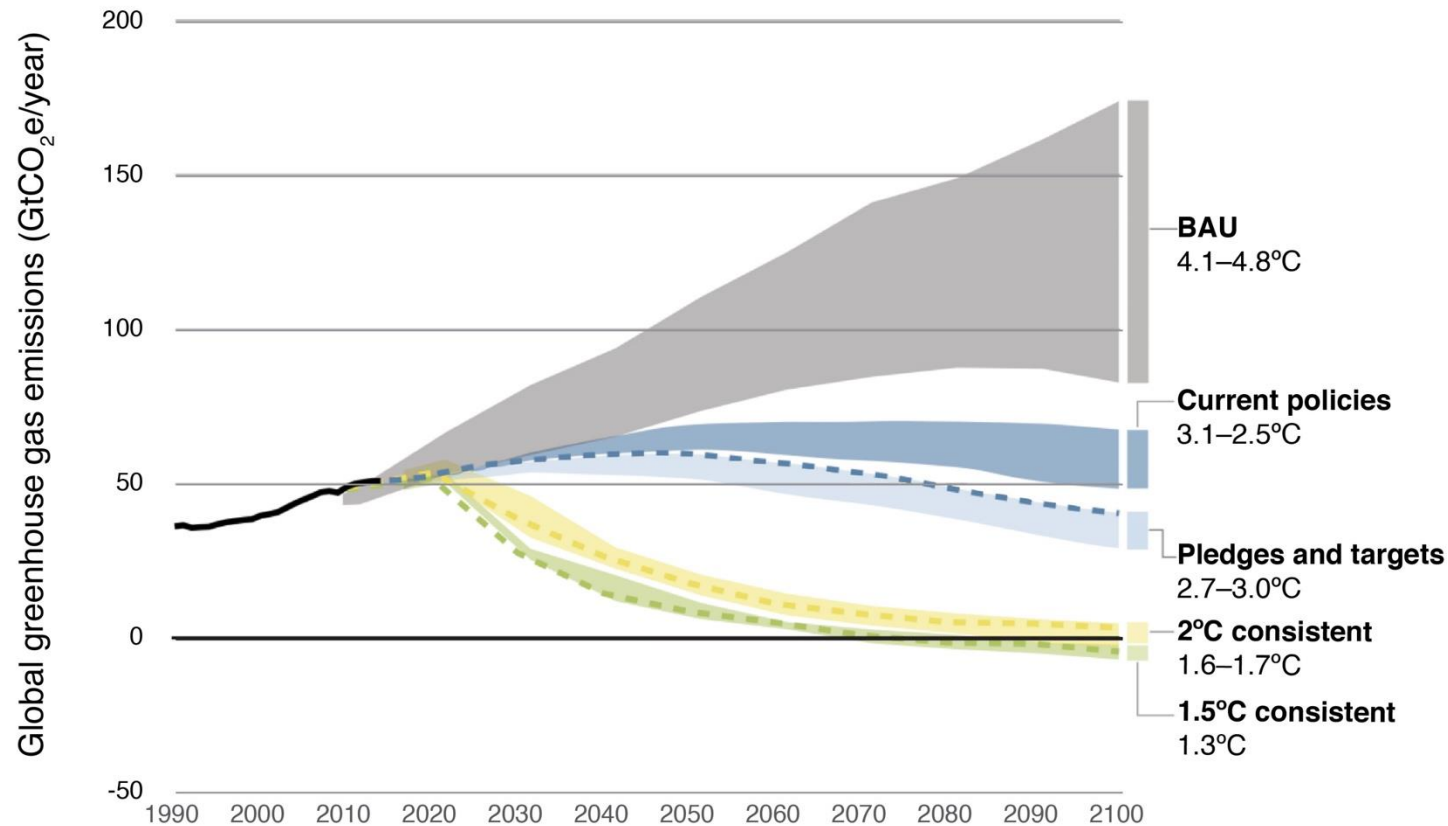


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Current policies are expected to lead to warming of 3.3 degrees Celsius by 2100; under business-as-usual, warming is projected to reach over 4 degrees Celsius by 2100.

At current rates of warming, it is projected that the world will reach the 1.5-degree threshold between 2030 and 2052.

Greenhouse gas emissions: warming projected by 2100



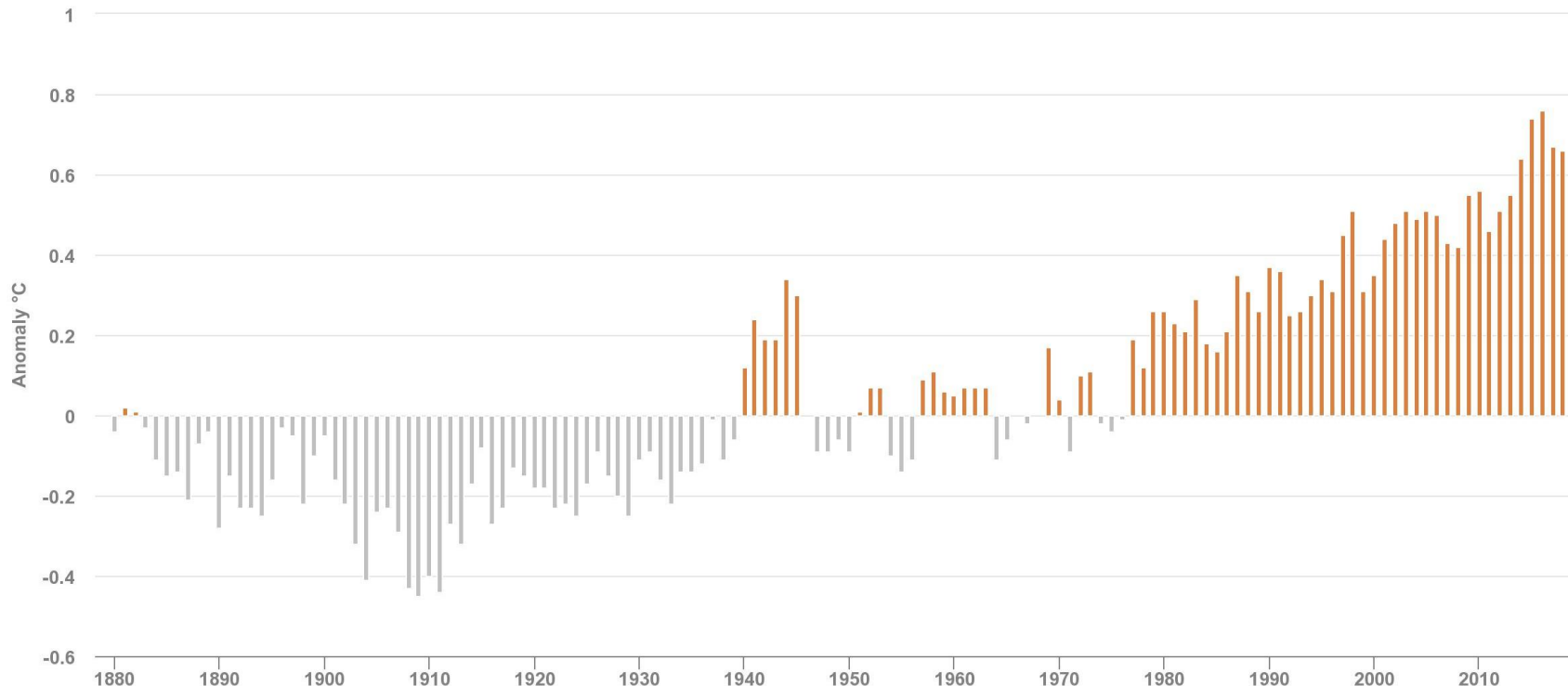
Global Ocean Temperatures



The average global sea surface temperature—the temperature from the upper few meters of the ocean—has risen about 0.12 degrees Celsius per decade over the past 50 years, with a higher rate of warming in recent years.

These higher temperatures are contributing to: mass bleaching of coral reefs, die offs of other ecosystems with low thermal sensitivity (such as kelp and intertidal communities), shifts in fisheries stocks due to temperature, a reduction in algae productivity, and more frequent and intense extreme weather events.

Global ocean temperature anomaly



Sea Level Change

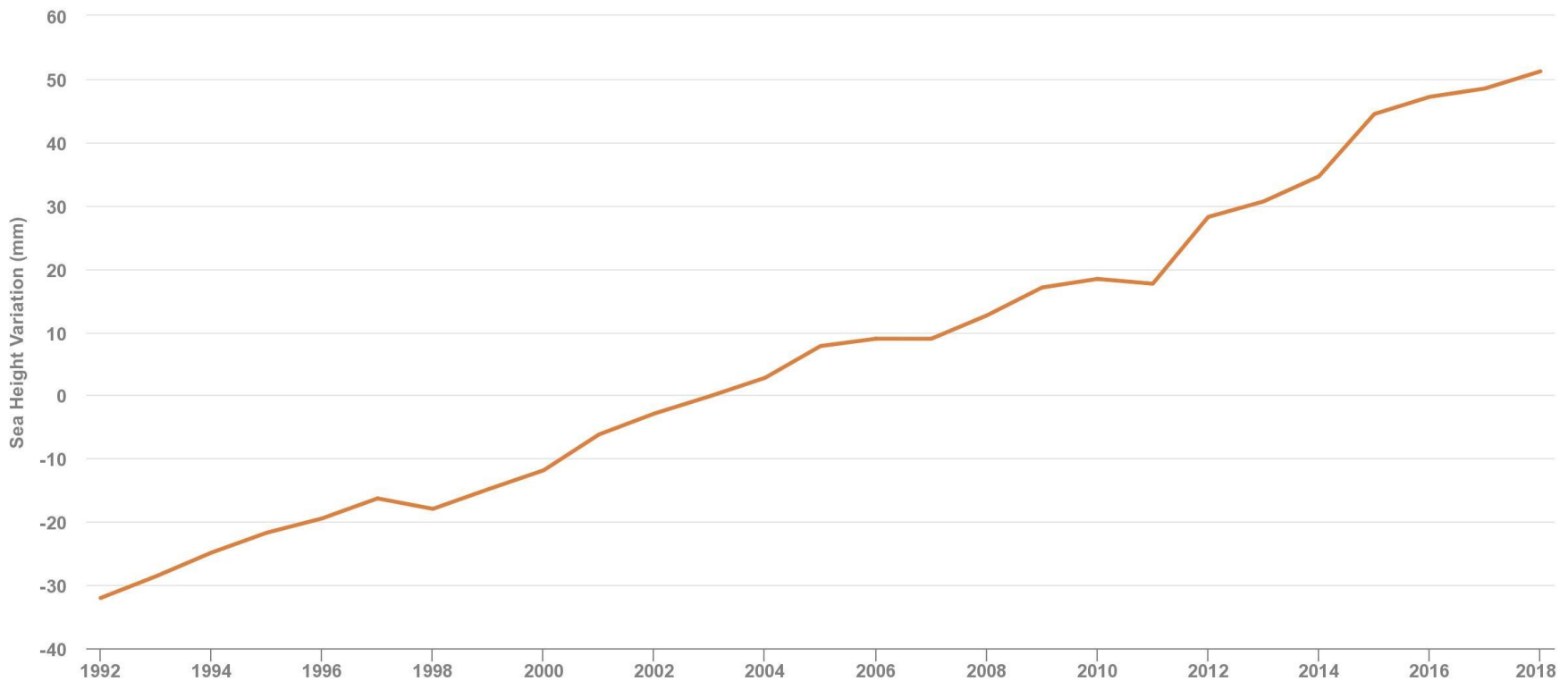


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The rate of global sea-level rise nearly doubled from 1.7 mm annually throughout most of the 20th century to 3.1 mm (0.12 inch) per year since 1993.

About one-third of the rise in global sea level has been caused by the thermal expansion of water. The increase in ocean heat in 2018 led to a 29.5 millimeter (1.2 inches) global mean sea-level rise above the 1981–2010 average. Sea-level rise is further exacerbated by melting of ice sheets in the polar regions.

Global sea level change (satellite observations)



Consequences of Climate Change



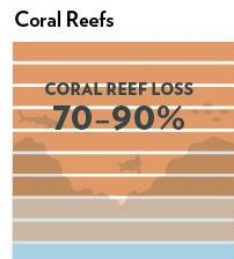
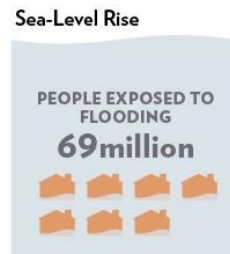
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A recent IPCC report examined the consequences of a future with warming of 1.5 or 2 degrees Celsius. While both scenarios would heavily impact the ocean, a half degree of warming will lead to vastly different futures for natural and human communities.

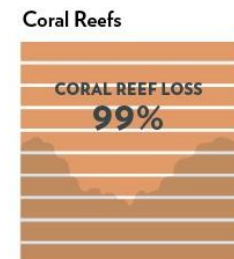
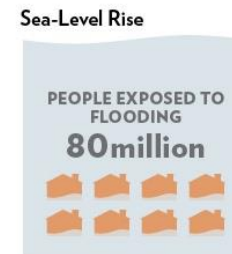
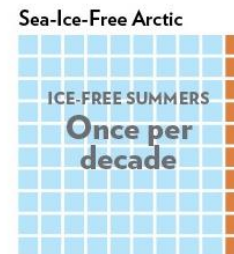
By 2100, Arctic summers could be ice-free once a decade in a world with 2 degrees of warming, or once a century under 1.5 degrees of warming. Nearly all of coral reefs could be irreversibly destroyed under 2 degrees of warming, or 10 to 30 percent may persist if warming is limited to 1.5 degrees Celsius.

Impacts associated with 1.5 and 2-degree Celsius temperature increase

1.5°C scenario



2°C scenario

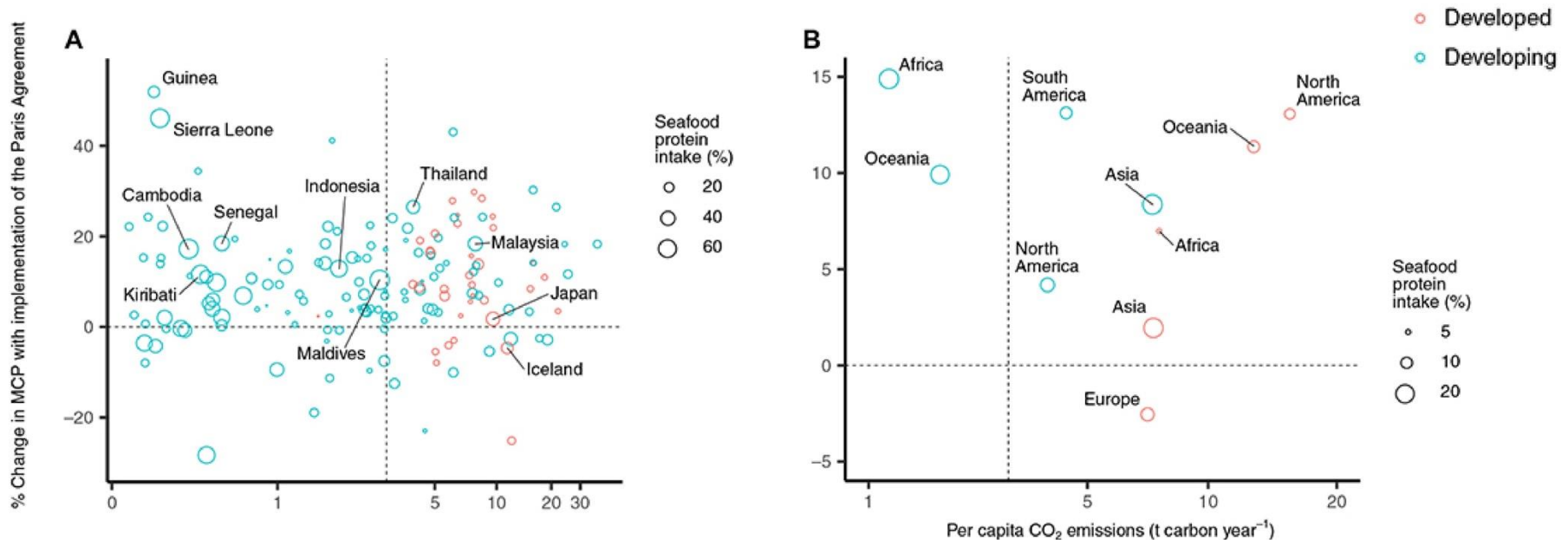


Paris Agreement

New research suggests that as compared to a high-emissions scenario of 3.5 degrees Celsius, achieving the Paris Agreement would result in significant benefits for ocean productivity, economies, and human communities.

Limiting warming to 1.5°C could increase global fishers' revenues by USD 13.1 billion annually (due to higher fish biomass and ocean productivity), raise seafood workers' income by USD 10.6 billion, and reduce household seafood expenditures by USD 18.3 billion.

Projected gains in Maximum Catch Potential under Paris Agreement targets, by country and continent



Action



- Is everything terrible? Paris Agreement (probably not enough)
- Climate justice...what is that?
- Inequity and unfairness of climate change
 - The poor gets screwed; the powerful rich run away with it
 - Developed nations should pay and be responsible
- Politics and voting
- Technology and progress
- Billionaires, doomsdays, apocalypse economy, luxury bunkers
- On going to Mars
- Free speech and censorship



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Part IV:

Research at Vandy

Research at Vandy



- Old/current energy systems are somewhat predictable
- Kinda easy to control them in real-time (second-to-second)
- Research at Vandy:
 - Better models for renewables
 - New control algorithms that ensure resilience
 - Problem is very difficult and requires new math
- My lab at Vandy:
 - Coming up with new real-time control algorithms for fossil fuel-free energy systems
 - Big impact in the next few decades when fossil fuels are phased out
- Research at Vandy is multi-disciplinary
 - Energy, power systems, machines, devices
 - Computer science, machine learning, cyber-security, resilience, climate change
 - Applied math, network science, etc..

CE 4240: Infrastructure Systems Engineering

Module 4: Intro to Power Systems and Climate Change

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