Energy, electricity, and DERs

Purdue ME 597, Distributed Energy Resources

Kevin J. Kircher

Outline

Metric units of energy and power

- the basic metric unit of energy is the Joule: 1 J = 1 Nm
- the basic metric unit of power is the Watt: 1 W = 1 J/s
- to convert units, multiply by a ratio equal to one:

$$1\text{ h} = 3600\text{ s} \iff \frac{3600\text{ s}}{1\text{ h}} = 1$$
$$1\text{ W} = 1\text{ J/s} \iff \frac{1\text{ J}}{1\text{ Ws}} = 1$$

- for example, another metric unit of energy is the Watt-hour:

$$1\text{ W}\cancel{\text{h}}\underbrace{\left(\frac{3600\text{ s}}{1\text{ }\cancel{\text{h}}}\right)}_{=1} = 3600\text{ }\cancel{\text{Ws}}\underbrace{\left(\frac{1\text{ J}}{1\text{ }\cancel{\text{Ws}}}\right)}_{=1} = 3600\text{ J}$$

Metric prefixes

prefix	symbol	meaning
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}

Power scales

- solar power incident on earth's upper atmosphere: ∼170 PW
- humanity's time-average use of all forms of energy: ∼20 TW
- global electricity generation capacity: ∼9 TW
- US electricity generation capacity: ∼1.2 TW
- Indiana peak electricity demand: ∼20 GW
- nuclear power plant capacity: ∼1 GW
- Greater Lafayette peak electricity demand: ∼350 MW
- electric vehicle power use when 'flooring it': ∼400 kW
- central air conditioner peak power use: ∼5 kW
- LED light bulb: ∼10 W

Non-metric units of energy

- a non-metric unit of energy is the British thermal unit:

$$1 \text{ Btu} = 1055 \text{ J} \left(\frac{1 \text{ Wh}}{3600 \text{ J}} \right) = 0.293 \text{ Wh}$$

- others:
  - ◇ 1 foot-pound-force (ft·lbf) $= 1.28 \times 10^{-3}$ Btu
  - ◇ 1 calorie $= 3.97 \times 10^{-3}$ Btu
  - ◇ 1 kilocalorie (kcal) or 'large calorie' (used for food) $= 3.97$ Btu
  - ◇ 1 MBtu $= 10^3$ Btu
  - ◇ 1 therm $= 10^5$ Btu
  - ◇ 1 MMBtu $= 10^6$ Btu
  - ◇ 1 tonne of TNT $= 3.97 \times 10^6$ Btu
  - ◇ 1 barrel of oil equivalent (boe) $= 5.4 \times 10^6$ Btu
  - ◇ 1 ton of oil equivalent (toe) $= 7.33$ boe $= 3.97 \times 10^7$ Btu
  - ◇ 1 quad $= 10^{15}$ Btu

Non-metric units of power

- a non-metric unit of power is the Btu per hour:

$$1\ \frac{\text{Btu}}{\text{h}}\left(\frac{0.293\ \text{Wh}}{1\ \text{Btu}}\right) = 0.293\ \text{W}$$

- others:
  - ◇ 1 foot-pound-force per second (ft·lbf/s) = 4.63 Btu/h
  - ◇ 1 horsepower (hp) = 2544 Btu/h
  - ◇ 1 ton of cooling = 12000 Btu/h

Outline

Why study energy?

- fossil fuels supply ~80% of global primary energy[1]
- fossil-fuel air pollution kills ~5 to 10 million people per year[2][3]
- fossil fuels cause ~75% of climate pollution[4]
- humanity spends/earns ~$6.5 trillion per year on energy[5]
- energy influences domestic and international politics
- energy use correlates with human development, to a point

[1] Our World in Data: Energy Mix

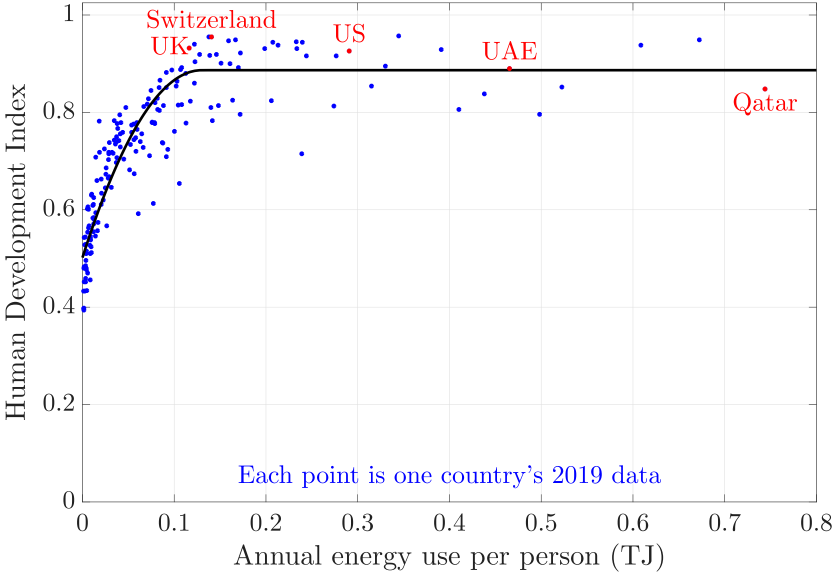
[2] Karn Vorha et al. (2021): Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem

[3] Lelieveld et al. (2023): Air pollution deaths attributable to fossil fuels: Observational and modelling study

[4] World Resources Institute: Where Do Emissions Come From?

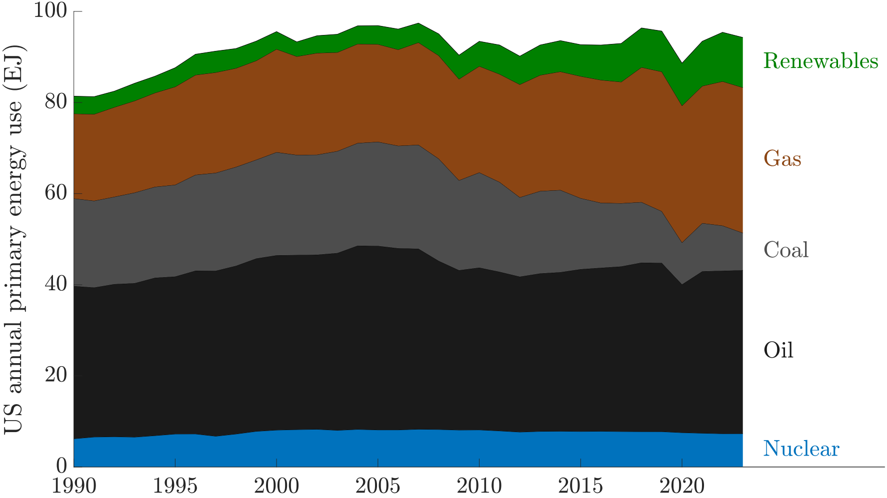
[5] EnerData: World Energy Expenditures

Energy use and human development



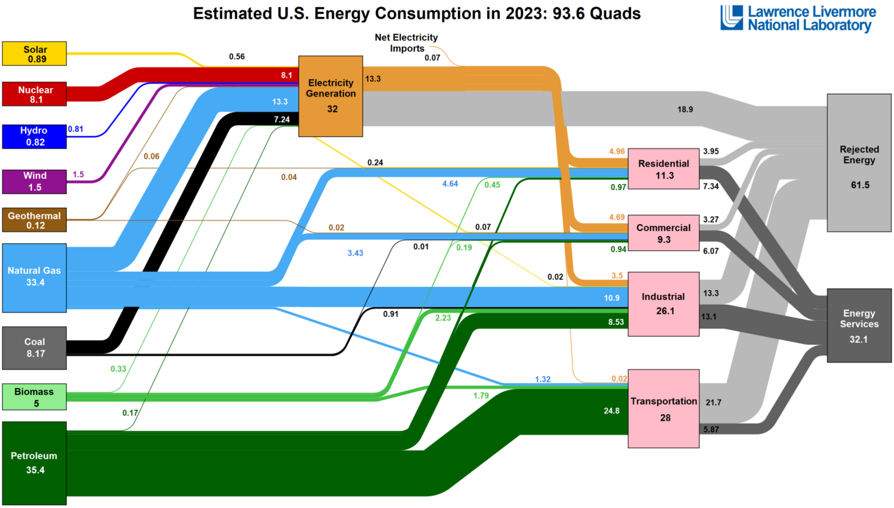
Data from BU Institute for Global Sustainability: Visualizing Energy

US primary energy sources over time (1 EJ = 10^{18} J)



Data from Our World in Data: United States Energy

US energy flows in 2023 (1 quad = 10^{15} Btu $\approx$ 1 EJ)



Lawrence Livermore National Laboratory: Energy Flow Charts

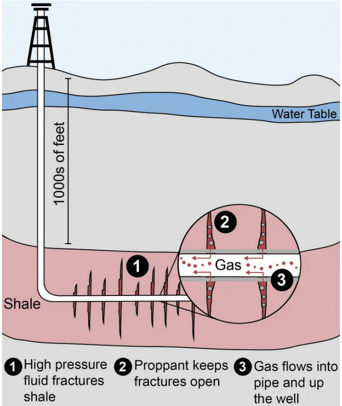
Primary energy and waste heat

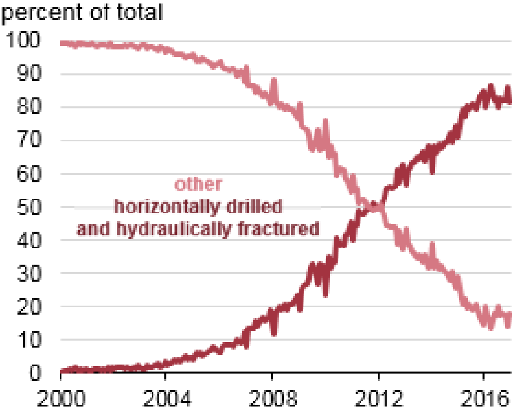
why does the US waste ∼66% (∼62 EJ) of primary energy (∼94 EJ)?

- gasoline/diesel automobile engines waste ∼75% of input energy
- coal and nuclear power plants waste ∼67%
- natural gas power plants waste ∼55%
- heating with natural gas, propane, or oil wastes ∼20%

Horizontal drilling + hydraulic fracturing = oil/gas boom

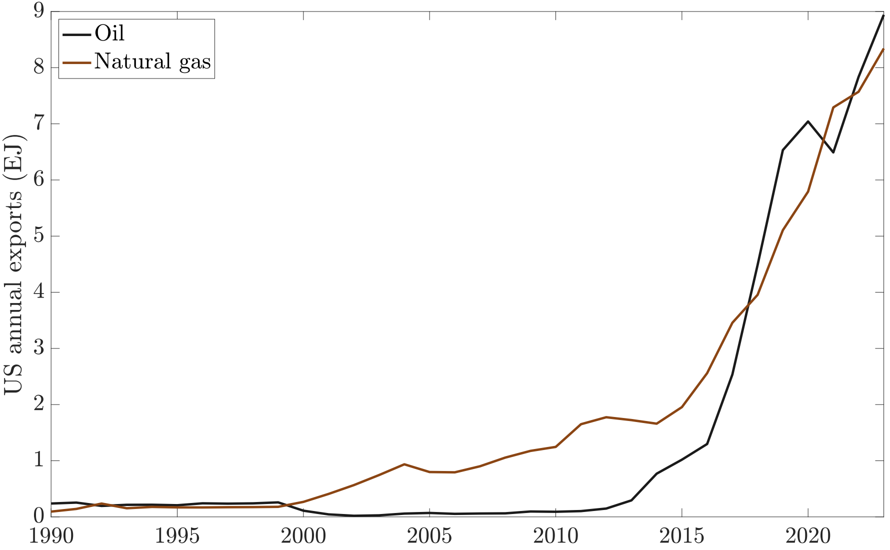
- historically, oil and gas came from 'loose' (porous/permeable) rock
- around 2005, companies began extracting from 'tight' rock





U. of Michigan Center for Sustainable Systems: Unconventional Fossil Fuels Factsheet
Energy Information Administration: Hydraulically fractured horizontal wells

US oil and natural gas exports



Data from Energy Information Administration: Oil and gas exports

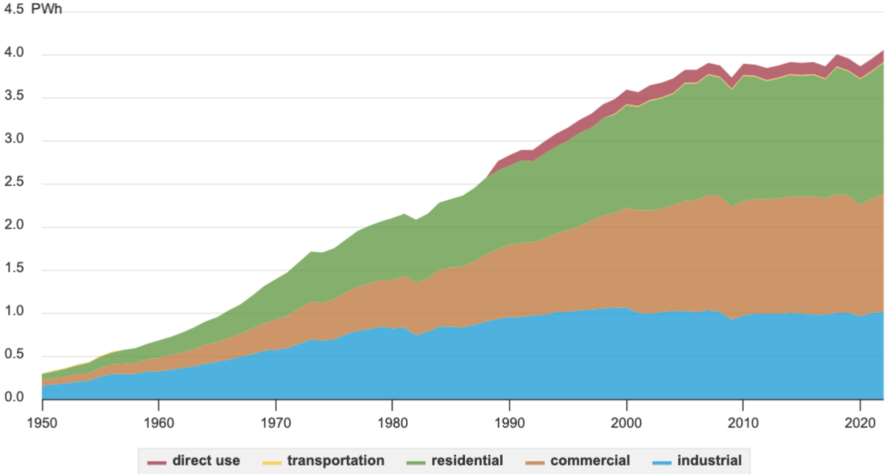
Outline

Why study electricity?

- essential or convenient for lots of stuff we need or want
- key to climate action
  - generate clean electricity
  - use it to replace fossil fuels for heating, transport, cooking, ...
- interesting intersection of disciplines
  - engineering (electrical, mechanical, industrial, civil, nuclear, CS, ...)
  - economics
  - policy

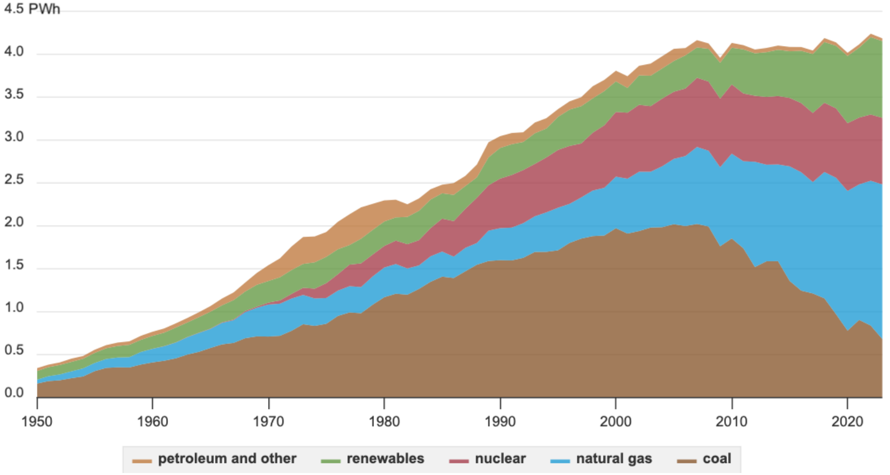
Nissan: Gas Powered Everything

US electricity use by sector (1 PWh $= 3.6 \times 10^{18}$ J)



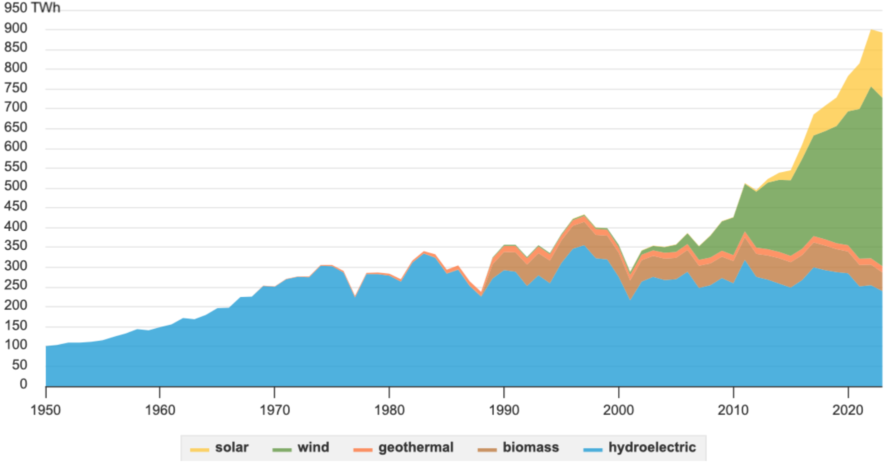
Energy Information Administration: Use of electricity

US electricity generation by source



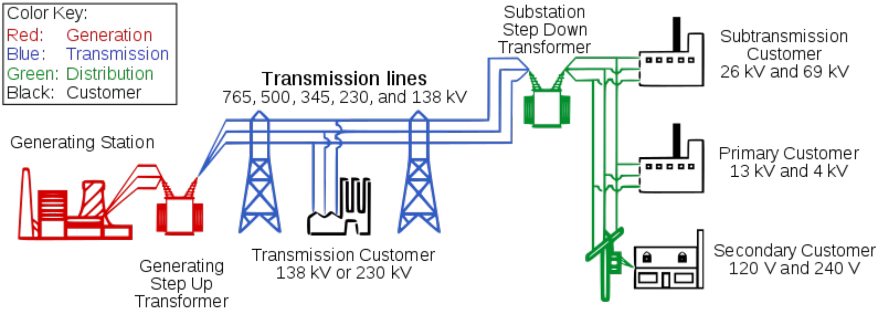
Energy Information Administration: Electricity in the United States

US renewable electricity generation by source



Energy Information Administration: Electricity in the United States

The power grid (of the 1900s)



- power transmitted by current I at voltage V: $P = IV$
- power lost over line with resistance R: $P_\ell = I^2 R$

$\implies$ to transmit a given P over a fixed R with small P_ℓ, want big V:

$$P_\ell = I^2 R = \left(\frac{P}{V}\right)^2 R \propto \frac{1}{V^2}$$

Wikipedia: Electrical grid

A brief history of US electricity hardware

- 1882: Edison builds world's first power grid in Manhattan
  - six 100 kW coal-fired steam turbine/generators, 120 V DC lines
  - low voltage $\implies$ transmission limited to $\sim$1 mile
- 1884: Parsons designs new steam turbine/generator
  - multi-stage expansion $\implies$ scalable to **MW** and above
- 1888: Tesla prototypes first AC power grid, including **transformers**
  - high voltage $\implies$ long-distance transmission with low losses
- 1896: Westinghouse runs 11 kV AC 26 miles (Niagara $\rightarrow$ Buffalo)
- 1903: Insull powers Chicago with MW-scale turbines, 9 kV AC
  - model (big turbines + high-voltage AC) replicated in many US cities

Hirsh: Power Loss, Chapter 1

A brief history of US electricity business

- late 1800s: Robber Barons take over major businesses
  - 1882: Rockefeller brings 90% of US oil under Standard Oil Trust
  - 1885-8: Morgan consolidates much of the US railroad industry
  - monopolies $\implies$ price gouging/discrimination, protests, strikes
- 1887: Interstate Commerce Act creates commission to regulate rail
- 1903-7: Insull buys 41 competitors, forms Commonwealth Edison
  - model (buy-outs and monopolization) replicated in NYC, Detroit, etc.
- 1900-7: municipalities form 1000+ grids (~30% of US suppliers)
  - good service, public $\implies$ credible threat to monopolies
- 1905: WI creates public commission to regulate monopolies
  - model (public regulation) replicated in many states

Hirsh: Power Loss, Chapter 1 – Creation of the Utility Consensus

Who got what in the grand bargain of regulation?

- people (via elected or governor-appointed commissions) got
  - ◇ control of monopoly prices
  - ◇ visibility into some monopoly practices
  - ◇ obligation to pay enough to keep monopolies profitable
- monopoly owners/shareholders got
  - ◇ state protection from competition
  - ◇ state-guaranteed returns on hardware (but not fuel) spending
  - ◇ use of eminent domain to force land sale for infrastructure
  - ◇ legitimacy in public opinion
  - ◇ obligation to serve all customers reliably at reasonable prices

Hirsh: Power Loss, Chapter 1 – Creation of the Utility Consensus

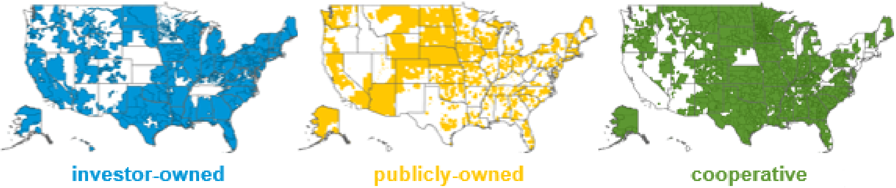
Regulatory capture

almost immediately, utility managers began to influence regulators

- public opinion (press releases, speakers, professorships, . . .)
- campaign support for commissioners or governors
- wining and dining commissioners
- hiring commissioners after their terms

Hirsh: Power Loss, Chapter 2 – Utility Managers Gain Dominance

Today's US utility mix



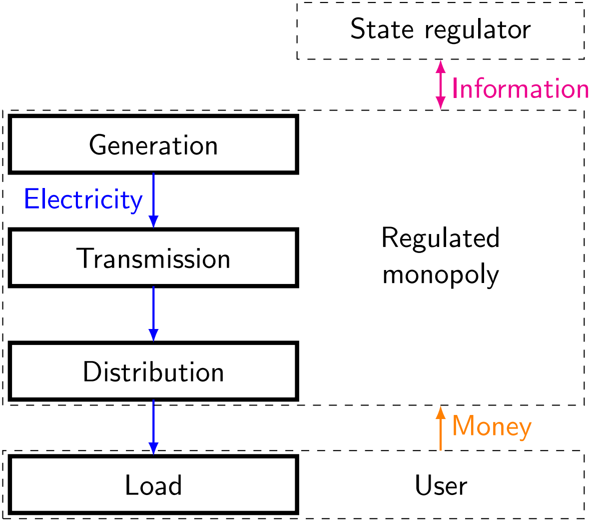
- regulated monopoly utilities serve ~250 million people
- some towns and cities run their own power grids
  - ◇ municipal nonprofits serving ~35 million people[6]
- in 1933, FDR created the Tennessee Valley Authority
  - ◇ federal nonprofit serving ~10 million people
- FDR's 1936 Rural Electrification Act created rural cooperatives
  - ◇ member-owned nonprofits serving ~40 million people[7]

[6] American Public Power Association: 100 Largest Public Power Utilities
[7] National Rural Electric Cooperative Association: Electric Co-op Facts & Figures

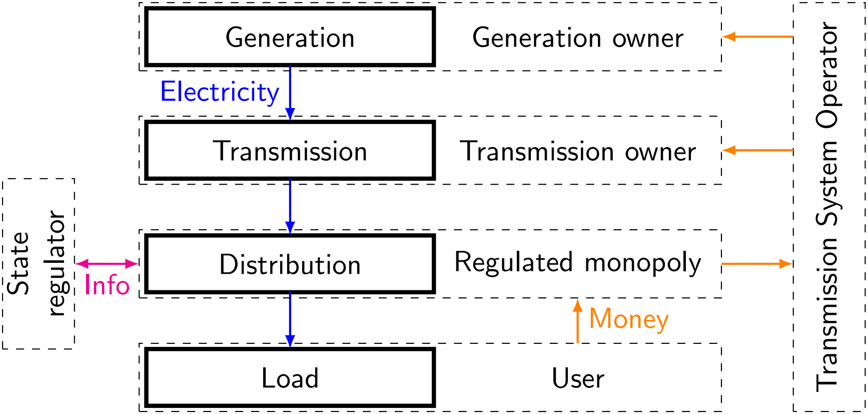
Restructuring of generation/transmission/distribution

- until ~2000, one monopoly utility typically owned G, T & D
- 1978 Public Utility Regulatory Policies Act opened generation
- 1992 Energy Policy Act opened transmission
- most transmission today: nonprofit Transmission System Operators
  - ◇ run wholesale markets, ensure grid reliability
  - ◇ one state only: Independent System Operator
  - ◇ multiple states: Regional Transmission Organization
- one utility may still own both generation and distribution
- but other power plant owners can sell electricity wholesale
- and in 13 states, other companies can buy wholesale/sell retail

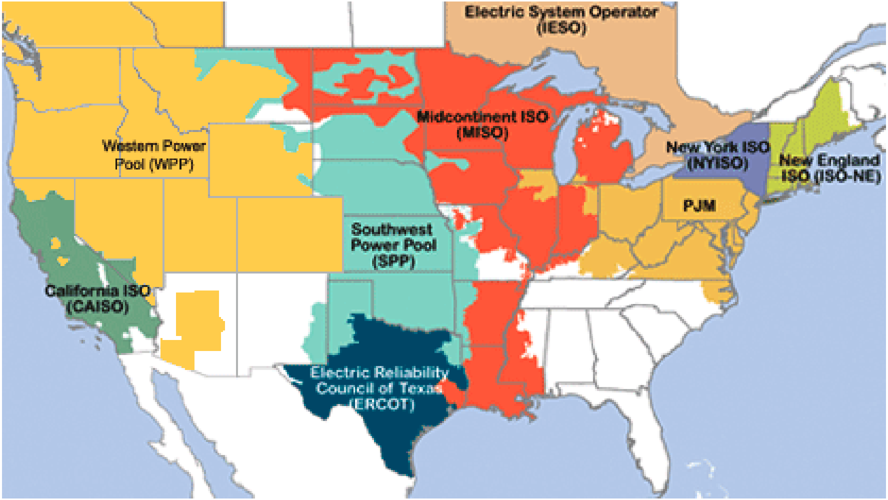
Vertical integration



Wholesale competition

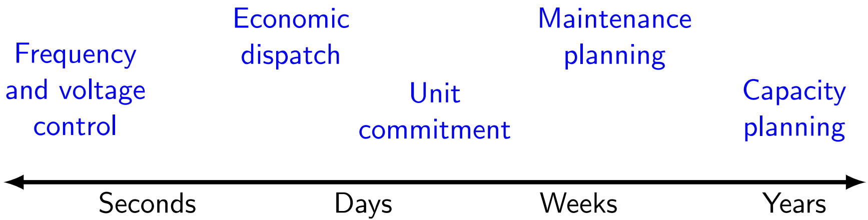


US Transmission System Operators

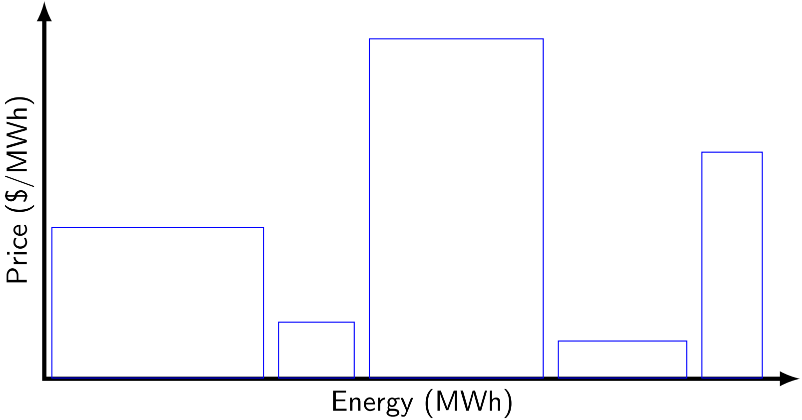


Wikipedia: Regional transmission organization (North America)

Basic TSO problem: Match supply and demand at all times



Economic dispatch, merit order, and wholesale pricing



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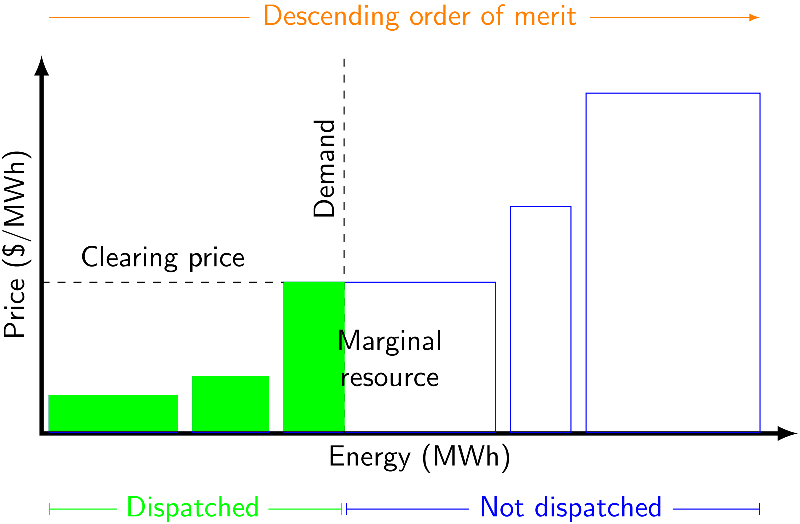
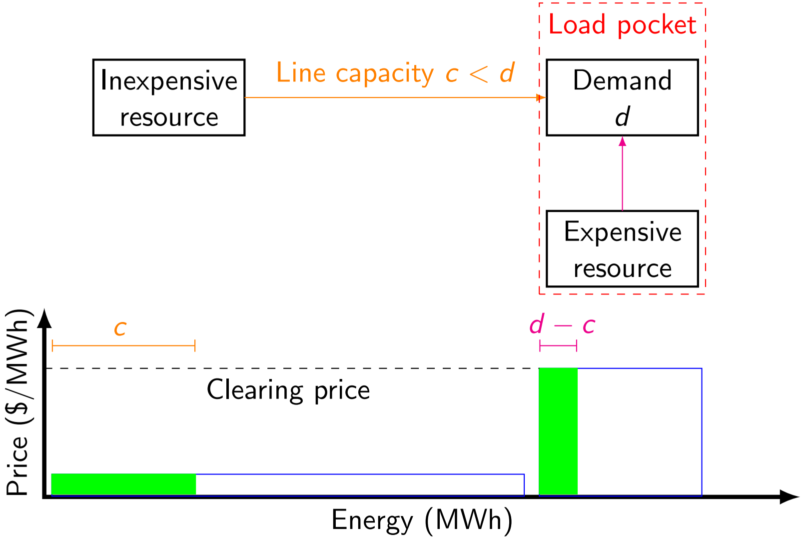
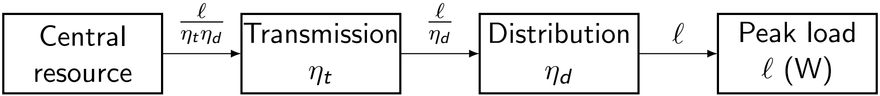


Transmission constraints and load pockets



Outline

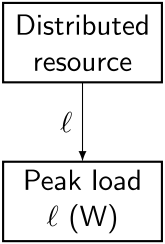
Central grid capacity cost and blackout risk



- blackout risks: CR or T or D
- with CR, T, and D prices π_{cr}, π_t, and π_d (\$/W), capacity cost is

$$\frac{\pi_{cr}\ell}{\eta_t \eta_d} + \frac{\pi_t \ell}{\eta_t \eta_d} + \frac{\pi_d \ell}{\eta_d} = \left(\frac{\pi_{cr} + \pi_t}{\eta_t} + \pi_d \right) \frac{\ell}{\eta_d}$$

Off-grid capacity cost and blackout risk

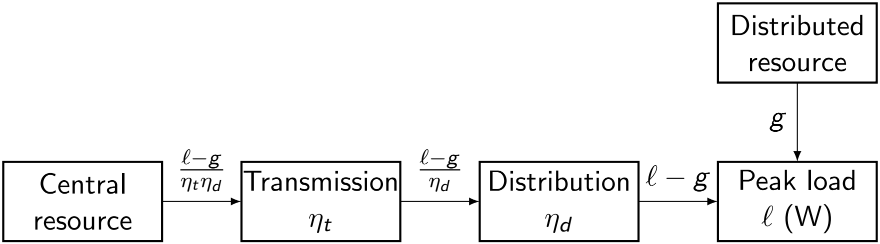


- blackout risk: DR
- capacity cost $\pi_{dr}\ell \leq$ central if

$$\pi_{dr} \leq \left(\frac{\pi_{cr} + \pi_t}{\eta_t} + \pi_d\right)\frac{1}{\eta_d} \approx 3.2\ \$/\mathrm{W}$$

with (for example) $\pi_{cr} \approx \pi_t \approx \pi_d \approx 1\ \$/\mathrm{W}$, $\eta_t \approx \eta_d \approx 0.97$

Distributed grid capacity cost and blackout risk



- blackout risk: DR and (CR or T or D)
- capacity cost $\leq$ central if

$$\left(\frac{\pi_{cr}+\pi_t}{\eta_t}+\pi_d\right)\frac{\ell-g}{\eta_d}+\pi_{dr}g \leq \left(\frac{\pi_{cr}+\pi_t}{\eta_t}+\pi_d\right)\frac{\ell}{\eta_d}$$

$$\iff \pi_{dr} \leq \left(\frac{\pi_{cr}+\pi_t}{\eta_t}+\pi_d\right)\frac{1}{\eta_d}$$

Summary

- these analyses get more complex in large networks
- but the basic idea remains:
  - ◇ DERs can reduce capacity costs and blackout risks
- DERs can also
  - ◇ deploy faster than heavy infrastructure
  - ◇ shift ownership and agency to individuals and communities