Energy, electricity, and DERs

Purdue ME 597, Distributed Energy Resources

Kevin J. Kircher

Outline

Units of energy and power

Energy in the United States

Electricity in the United States

Why DERs?

Metric units of energy and power

- the basic metric unit of energy is the Joule: $1 \text{ J} = 1 \text{ Nm}$
- the basic metric unit of power is the Watt: $1 \text{ W} = 1 \text{ J/s}$
- 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:

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

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

Units of energy and power

Energy in the United States

Electricity in the United States

Why DERs?

Why study energy?

- fossil fuels supply $\sim$80% of global primary energy[1]
- fossil-fuel air pollution kills $\sim$5 to 10 million people per year[2][3]
- fossil fuels cause $\sim$75% of climate pollution[4]
- humanity spends/earns $\sim$\$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

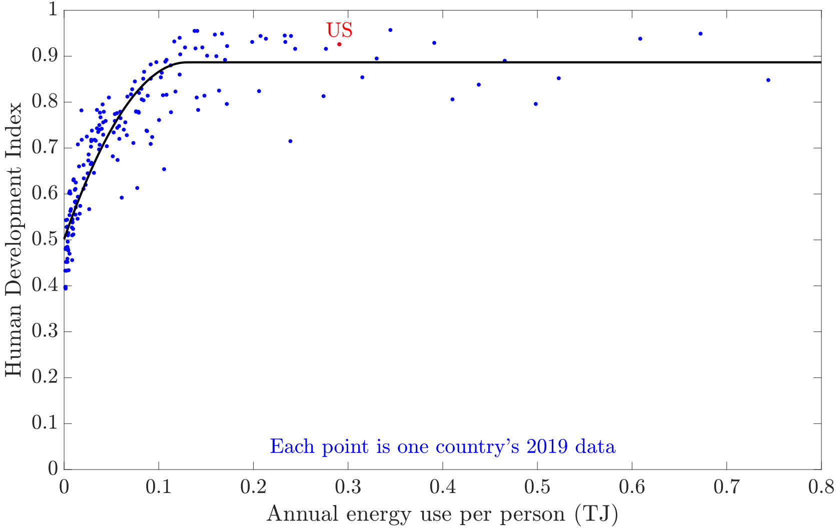
[2] Karn Vorha et al. (2021): Global mortality from outdoor fine particle pollution generated by fossil fuel combustion: Results from GEOS-Chem

[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?

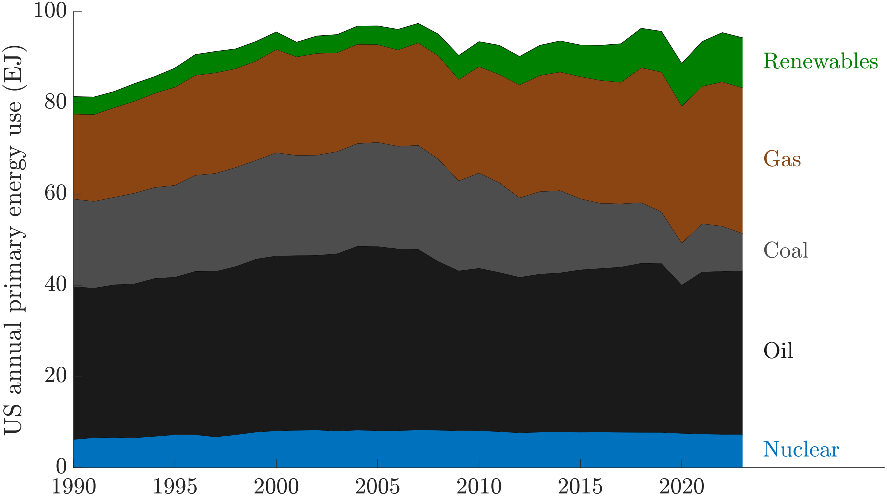
[5] EnerData: World Energy Expenditures

Energy use and human development



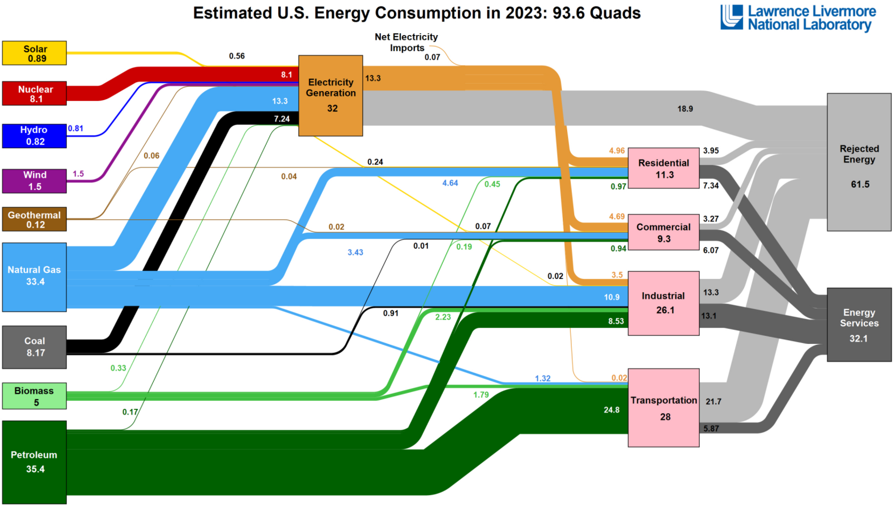
Data from BU Institute for Global Sustainability: Visualizing Energy

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 ≈ 1 EJ)



Lawrence Livermore National Laboratory: Energy Flow Charts

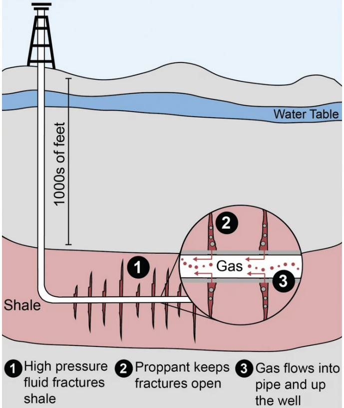
Primary energy and waste heat

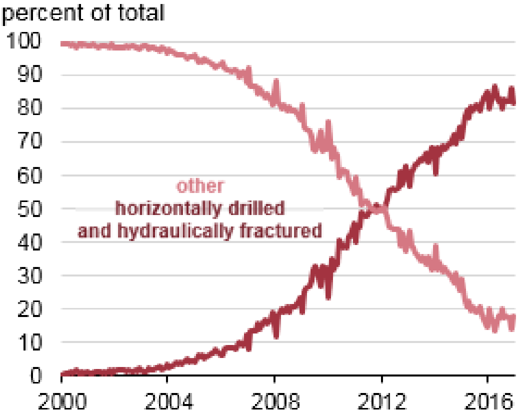
why does the US waste ∼66% (∼62 EJ) of primary energy (∼94 EJ)?

- 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

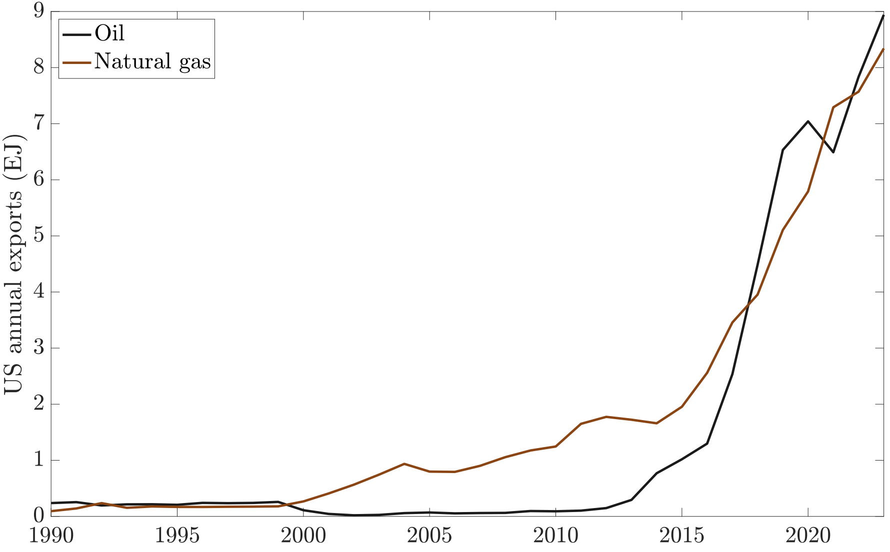
- historically, oil and gas came from 'loose' (porous/permeable) rock
- around 2005, companies began extracting from 'tight' rock





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

Units of energy and power

Energy in the United States

Electricity in the United States

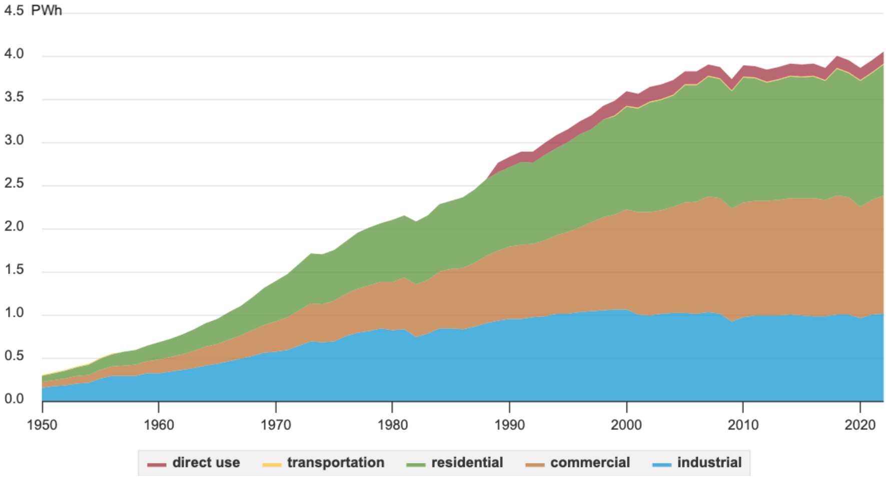
Why DERs?

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

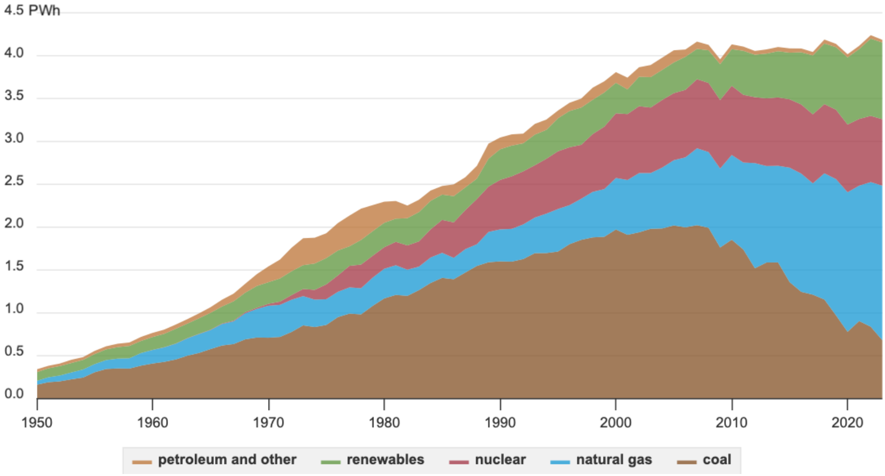
Nissan: Gas Powered Everything

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



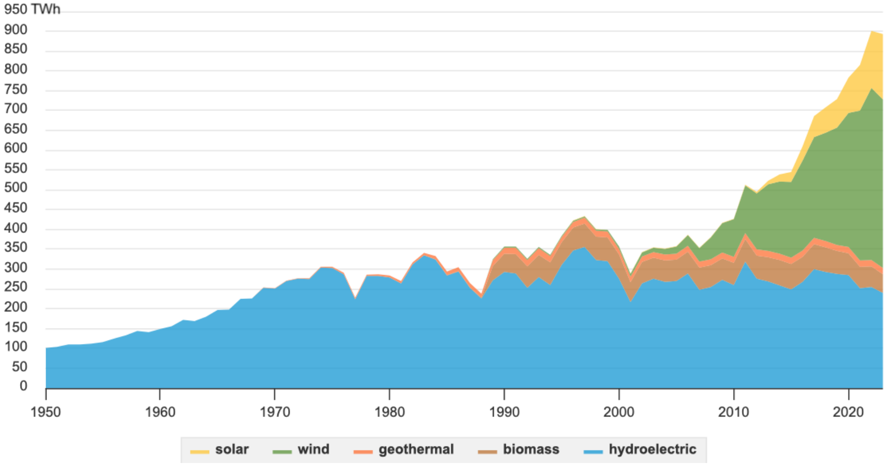
Energy Information Administration: Use of electricity

US electricity generation by source

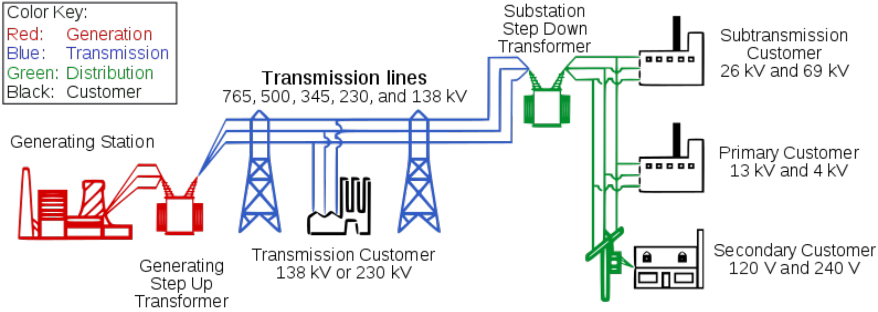


Energy Information Administration: Electricity in the United States

US renewable electricity generation by source



Energy Information Administration: Electricity in the United States



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

$\Longrightarrow$ 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 $\Longrightarrow$ 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 ($\sim$30% of US suppliers)
  - ◇ good service, public $\Longrightarrow$ 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

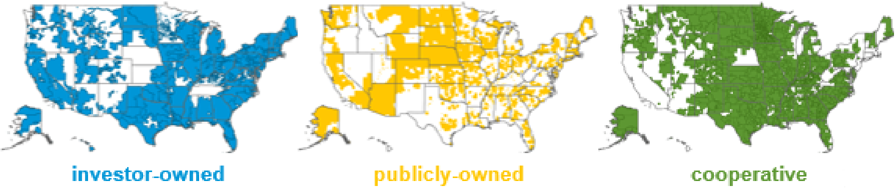
Regulatory capture

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



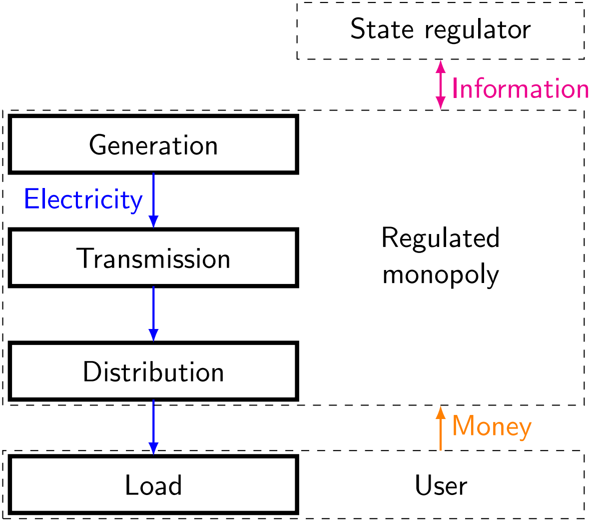
- regulated monopoly utilities serve ∼250 million people
- some towns and cities run their own power grids
  - ◇ municipal nonprofits serving ∼35 million people[6]
- in 1933, FDR created the Tennessee Valley Authority
  - ◇ federal nonprofit serving ∼10 million people
- FDR's 1936 Rural Electrification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

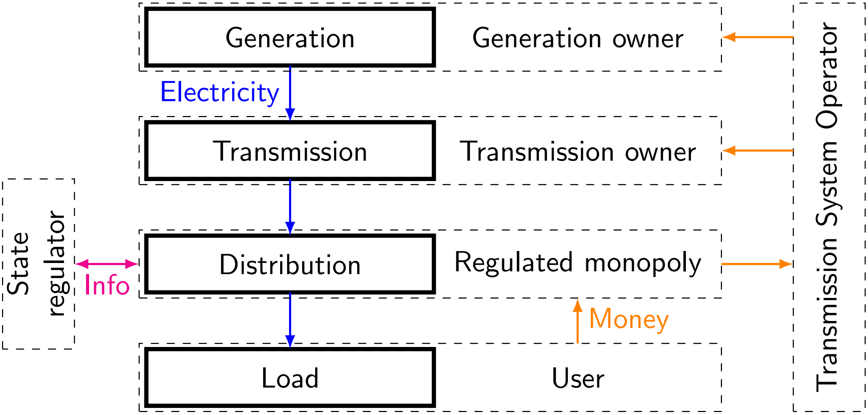
Restructuring of generation/transmission/distribution

- 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

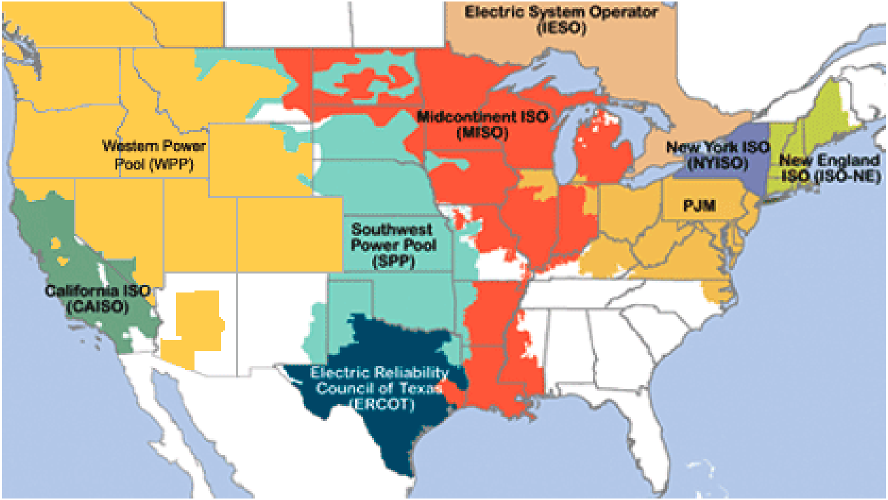
Vertical integration



Wholesale competition

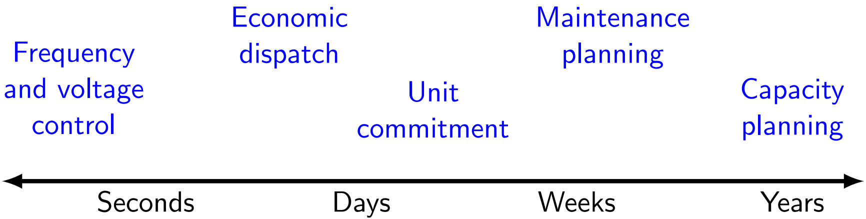


US Transmission System Operators

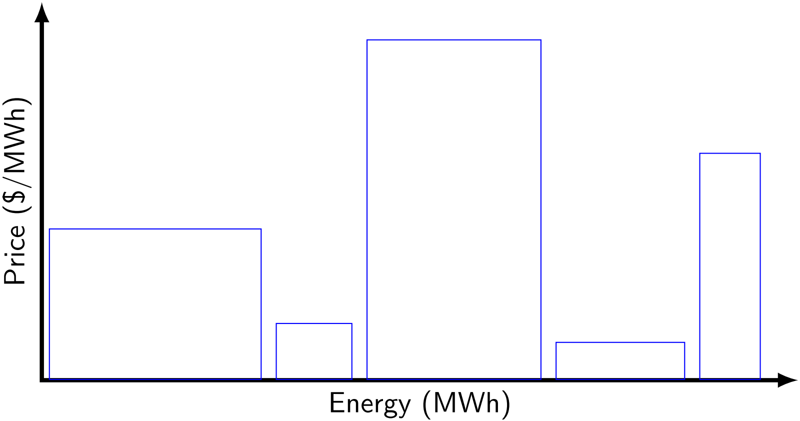


Wikipedia: Regional transmission organization (North America)

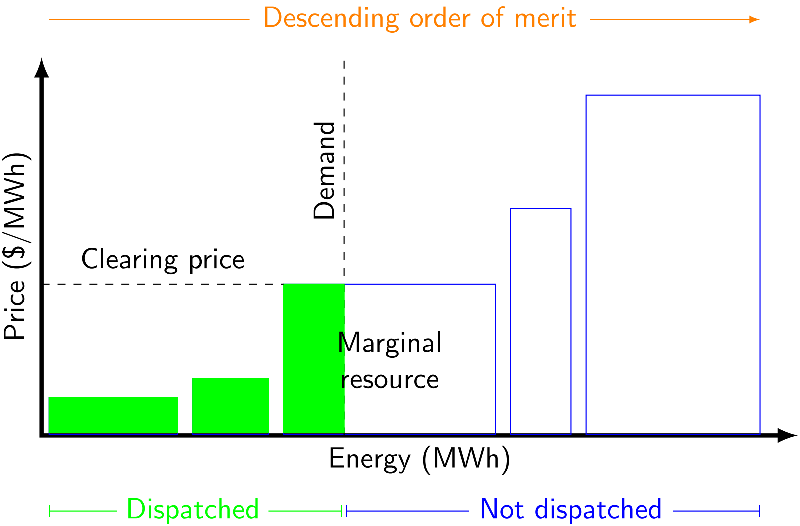
Basic TSO problem: Match supply and demand at all times



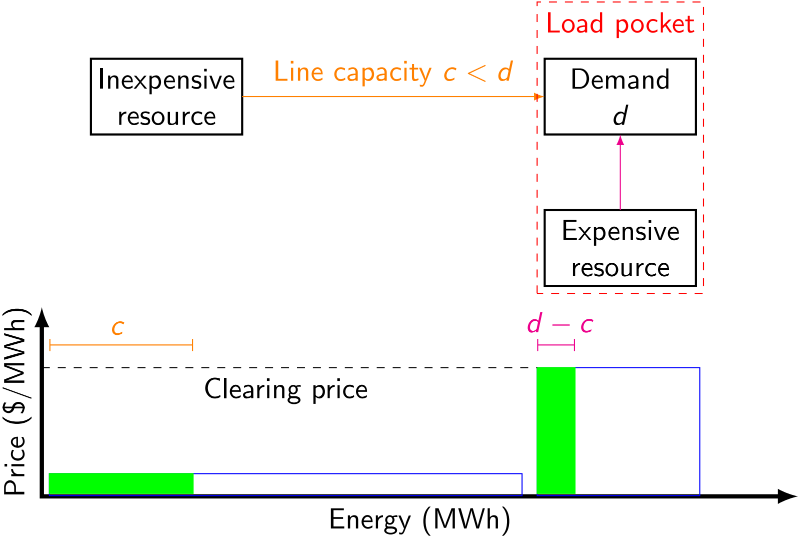
Economic dispatch, merit order, and wholesale pricing



Economic dispatch, merit order, and wholesale pricing



Transmission constraints and load pockets



Outline

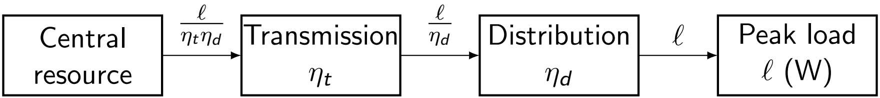
Units of energy and power

Energy in the United States

Electricity in the United States

Why DERs?

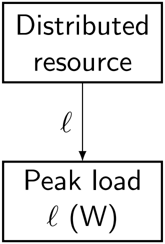
Central grid capacity cost and blackout risk



- 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

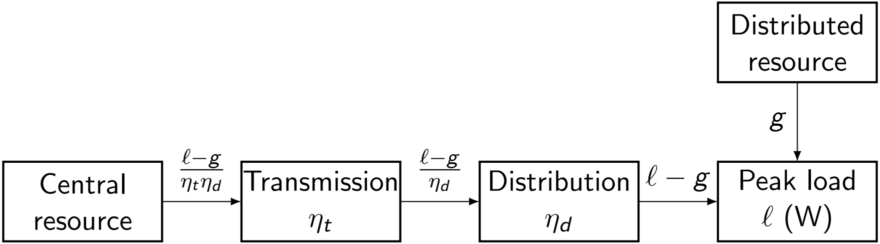


- blackout risk: DR
- capacity cost $\pi_{dr}\ell \leq$ central if

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

with (for example) $\pi_{cr} \approx \pi_t \approx \pi_d \approx 1$ \$/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