Lecture 04
Energy supply, renewables, and the grid

CIVIL-239: Engineering a sustainable built environment

01 October 2024

Andrew Sonta

Scan to add to class Spotify paylist

Housekeeping

- Assignment 2 due next week
- Office hours: please send me an email in advance

Outline

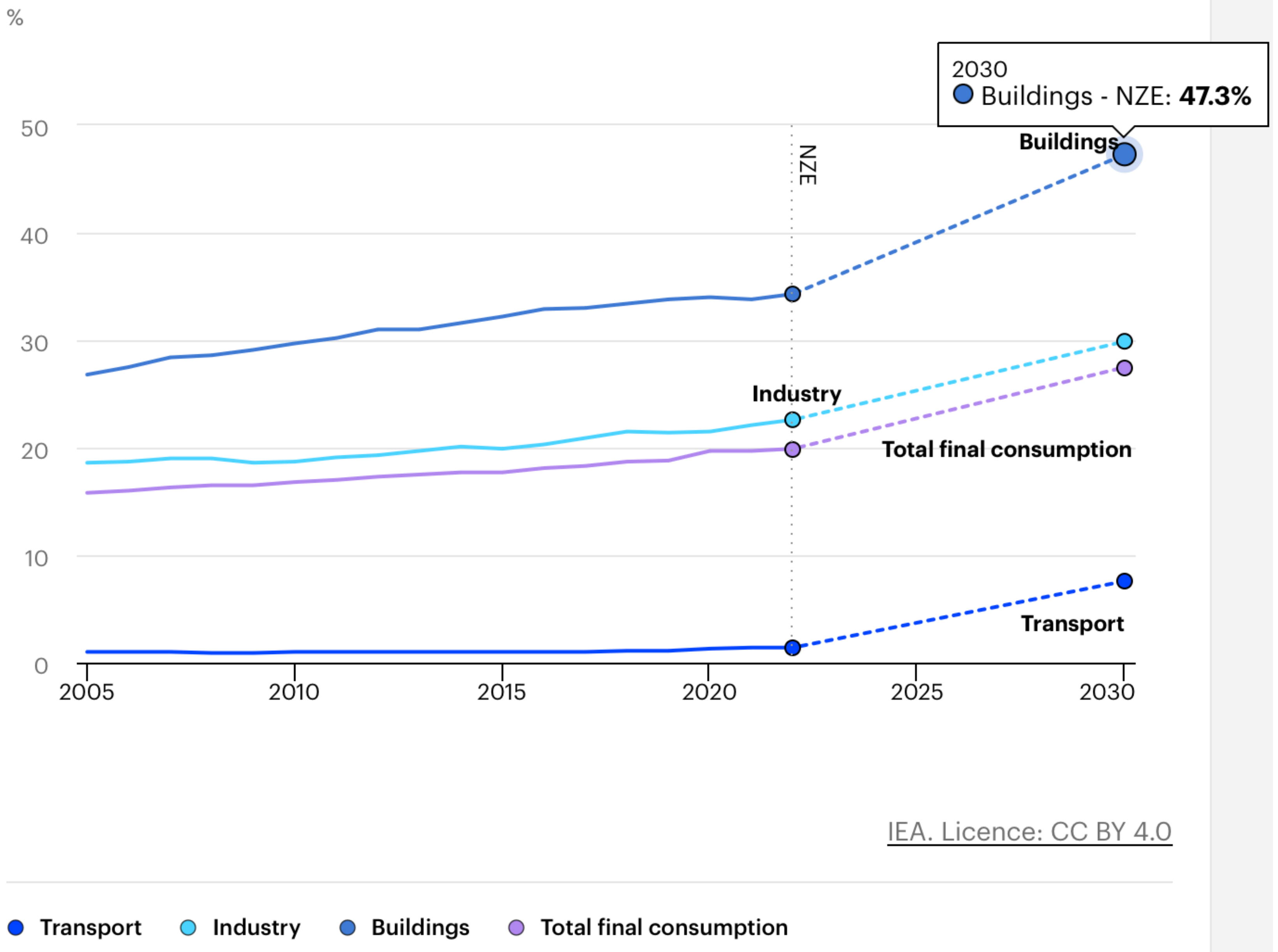
- Energy flows and current supply mix
- Renewables
  - Definitions
  - Most important types for achieving decarbonization
- Levelized Cost of Energy
- The challenge of integrating renewables into the grid
  - The duck curve
  - Energy storage
  - Flexibility

Elimination of Annual Operational GHG Emission

Source: Stanford BDLA

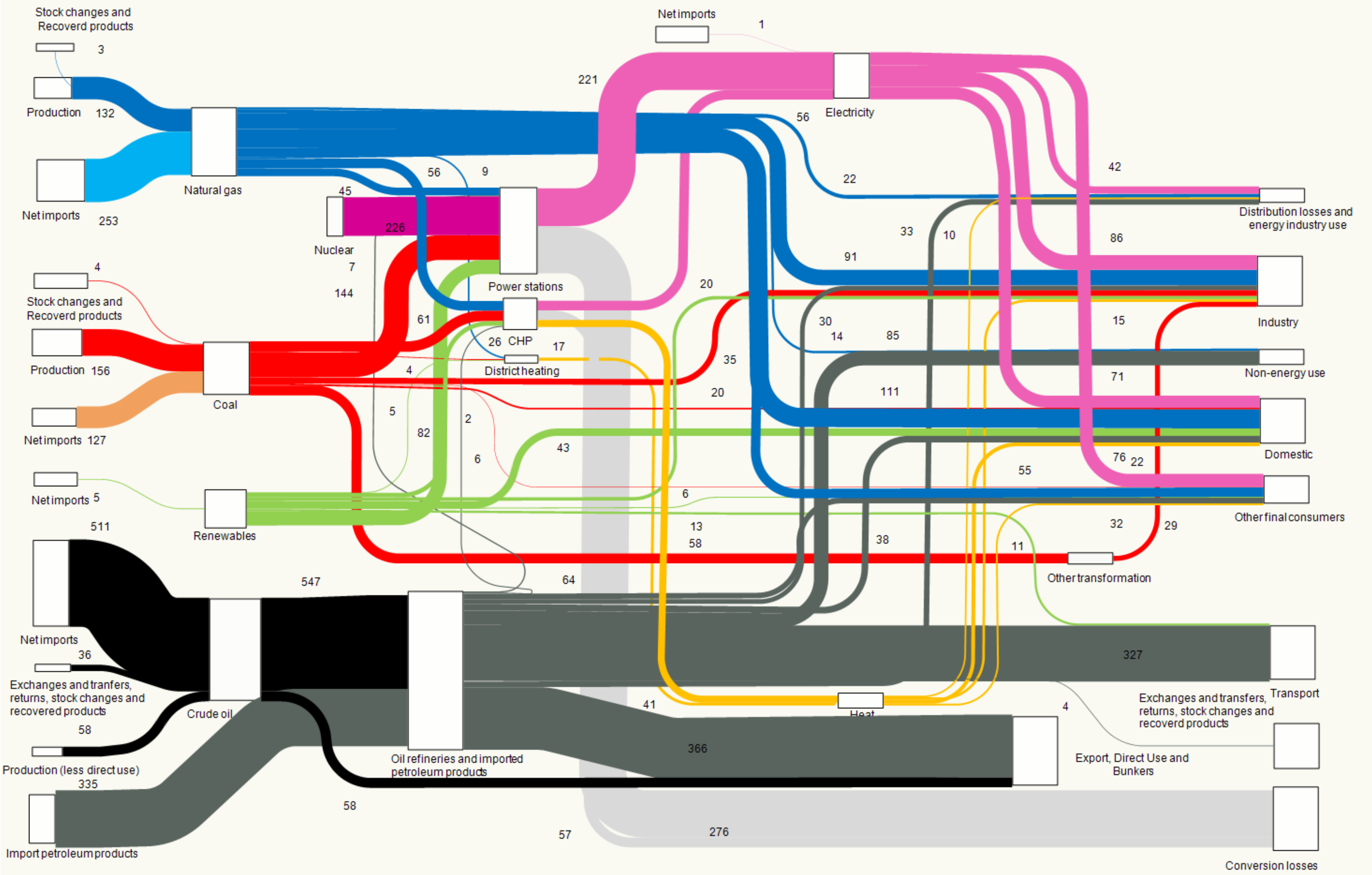
Electrification

- To reach net-zero energy, we need to electrify our buildings
- Electricity demand will rise across all sectors
  - Building electrification
  - Electric vehicles
  - etc…



Overview of the EU28 energy system in million tons oil equivalent (MTOE)

Supply

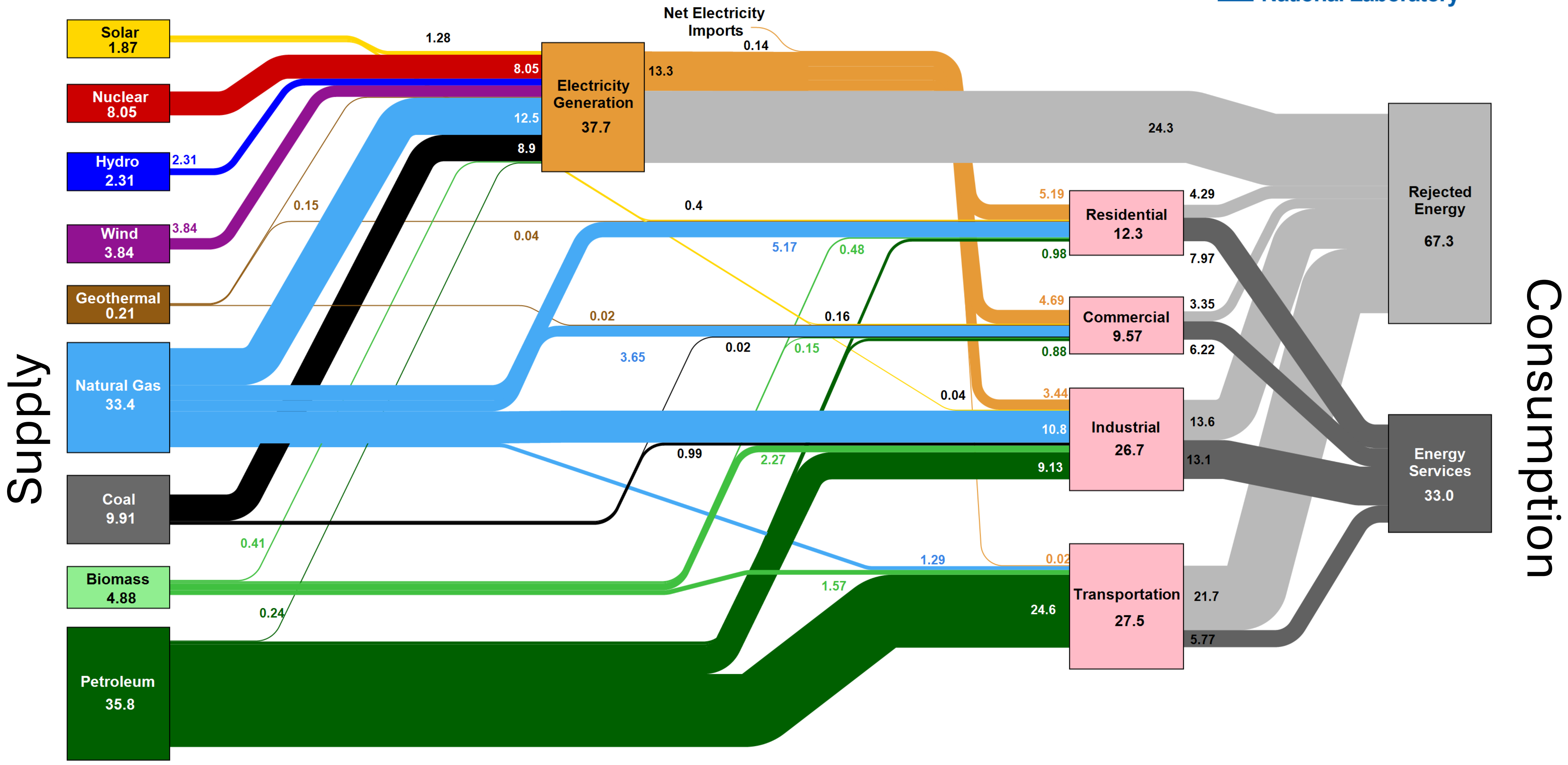


Consumption

Source: European Environment Agency

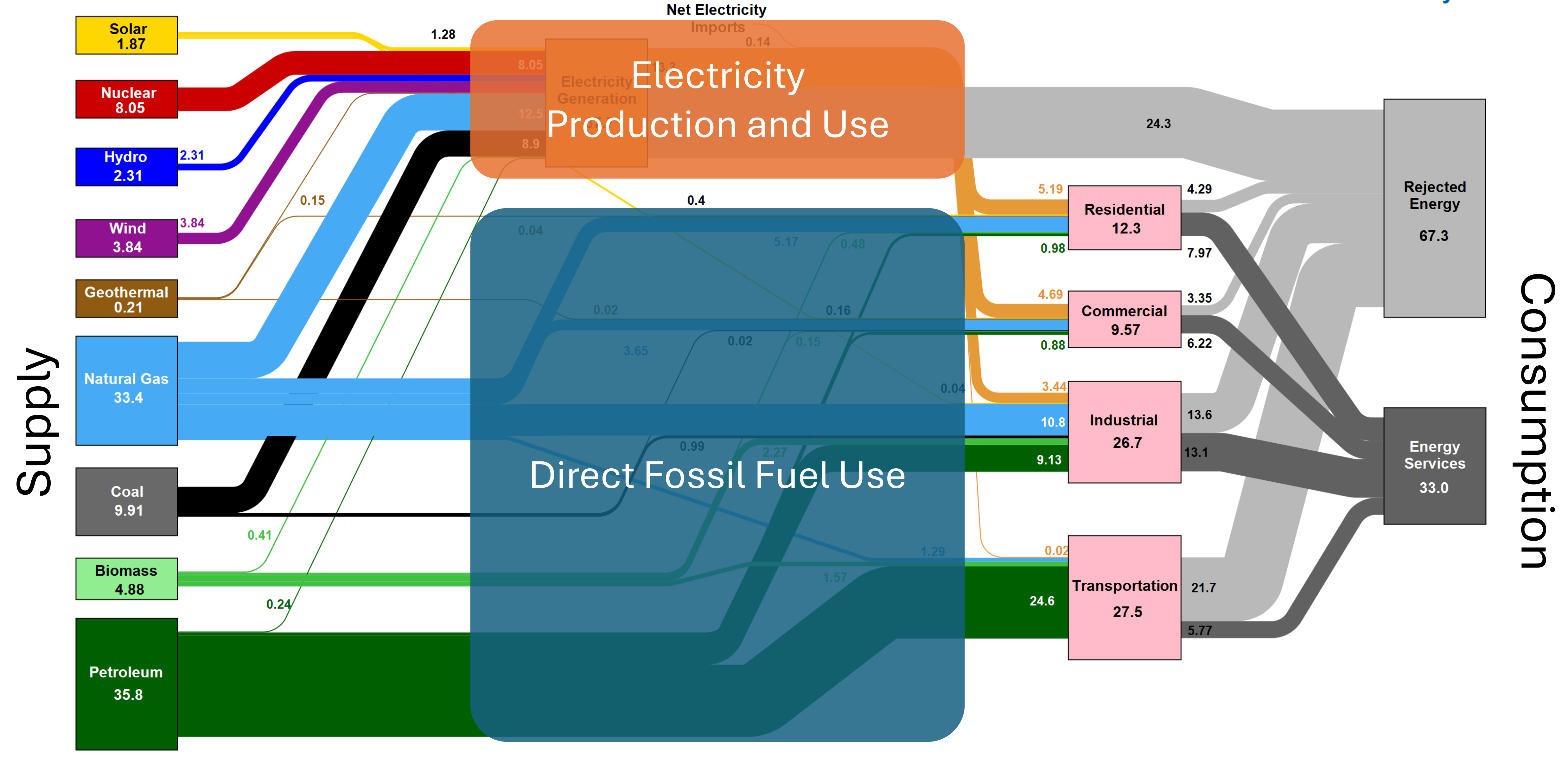
Estimated U.S. Energy Consumption in 2022: 100.3 Quads

Lawrence Livermore National Laboratory



Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Estimated U.S. Energy Consumption in 2022: 100.3 Quads

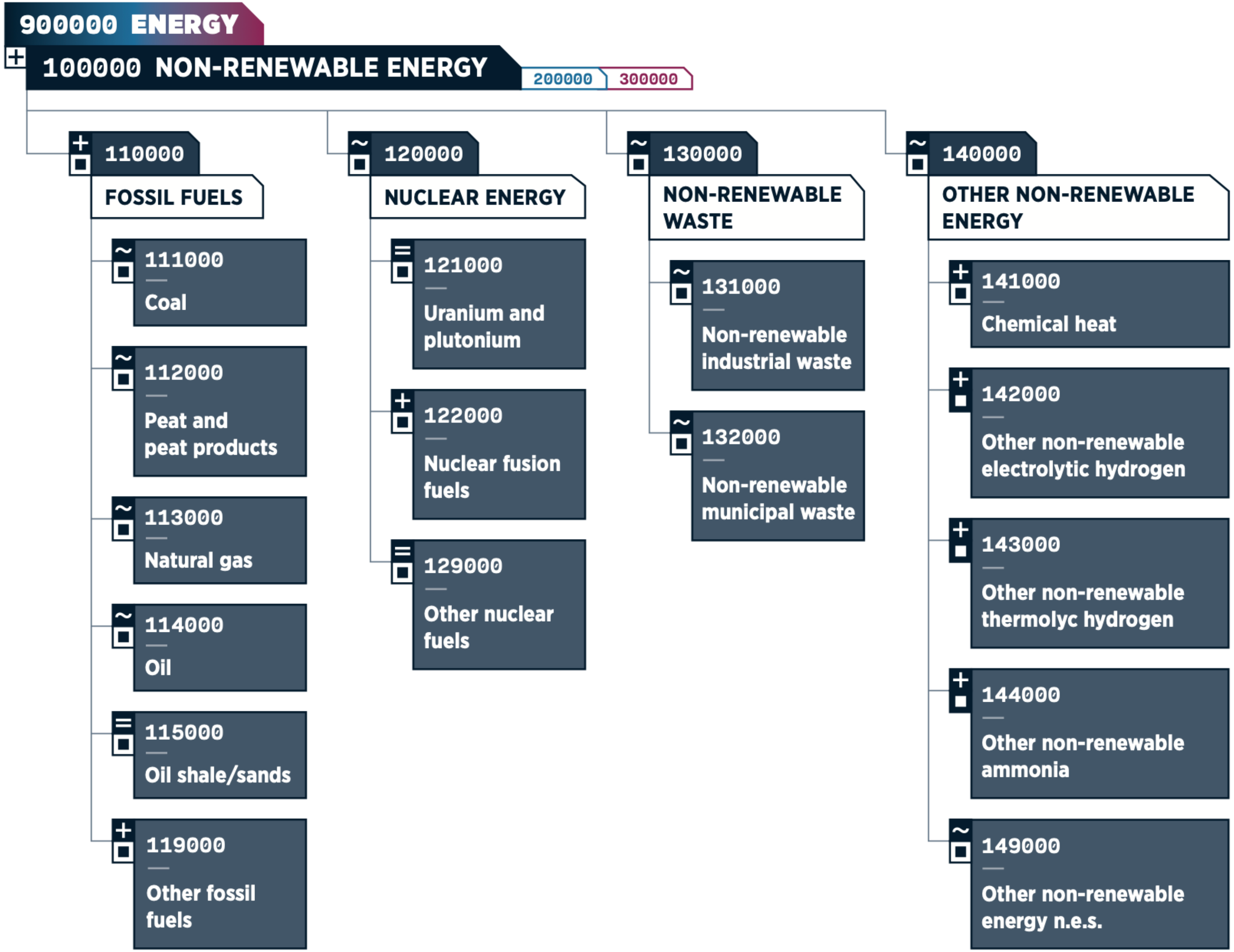


Source: LLNL July, 2023. Data is based on DOE/EIA SEDS (2021). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 0.65% for the residential sector, 0.65% for the commercial sector, 0.49% for the industrial sector, and 0.21% for the transportation sector. Totals may not equal sum of components due to independent Rounding. LLNL-MI-410527

Different definitions of energy production

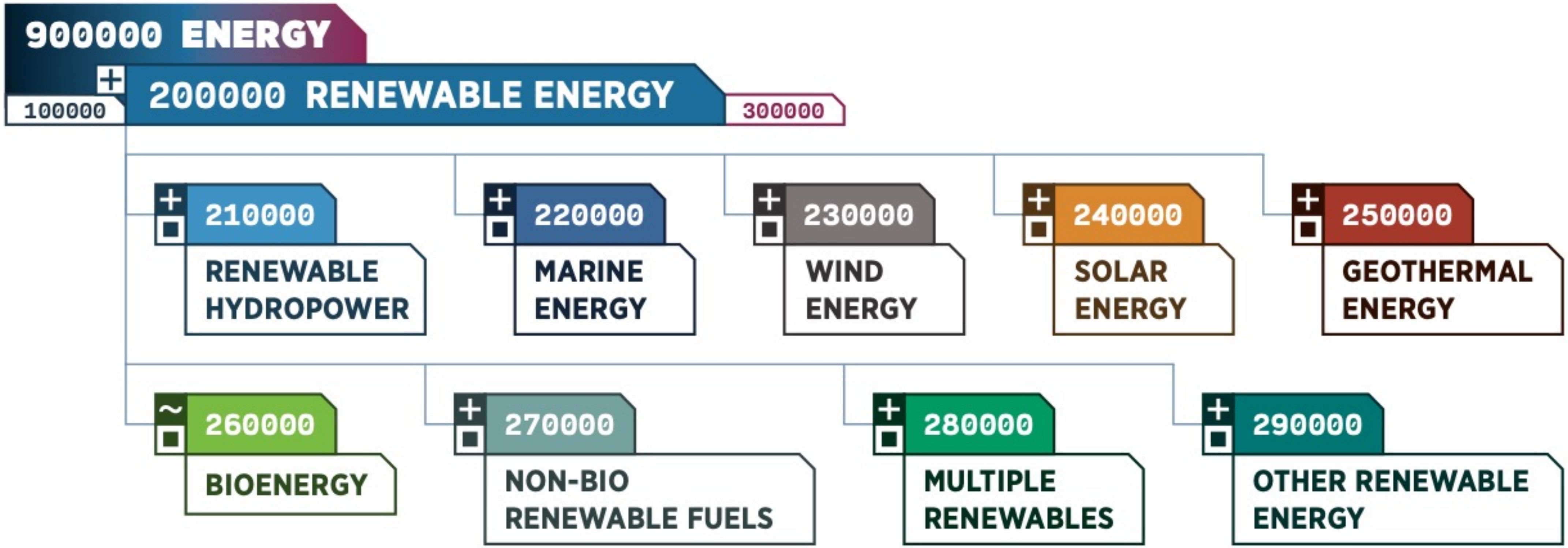
- **Renewable energy,** IEA definition: "energy derived from natural processes that are replenished at a faster rate than they are consumed"
- **Clean energy**: Energy low in emissions
- **Sustainable energy**: Energy that limits permanent negative impact on future generations
- What's an example of a clean energy that's not renewable?
- What's an example of a renewable energy that's not necessarily clean?

Non-renewable energy



Source: International Renewable Energy Agency

Renewable energy

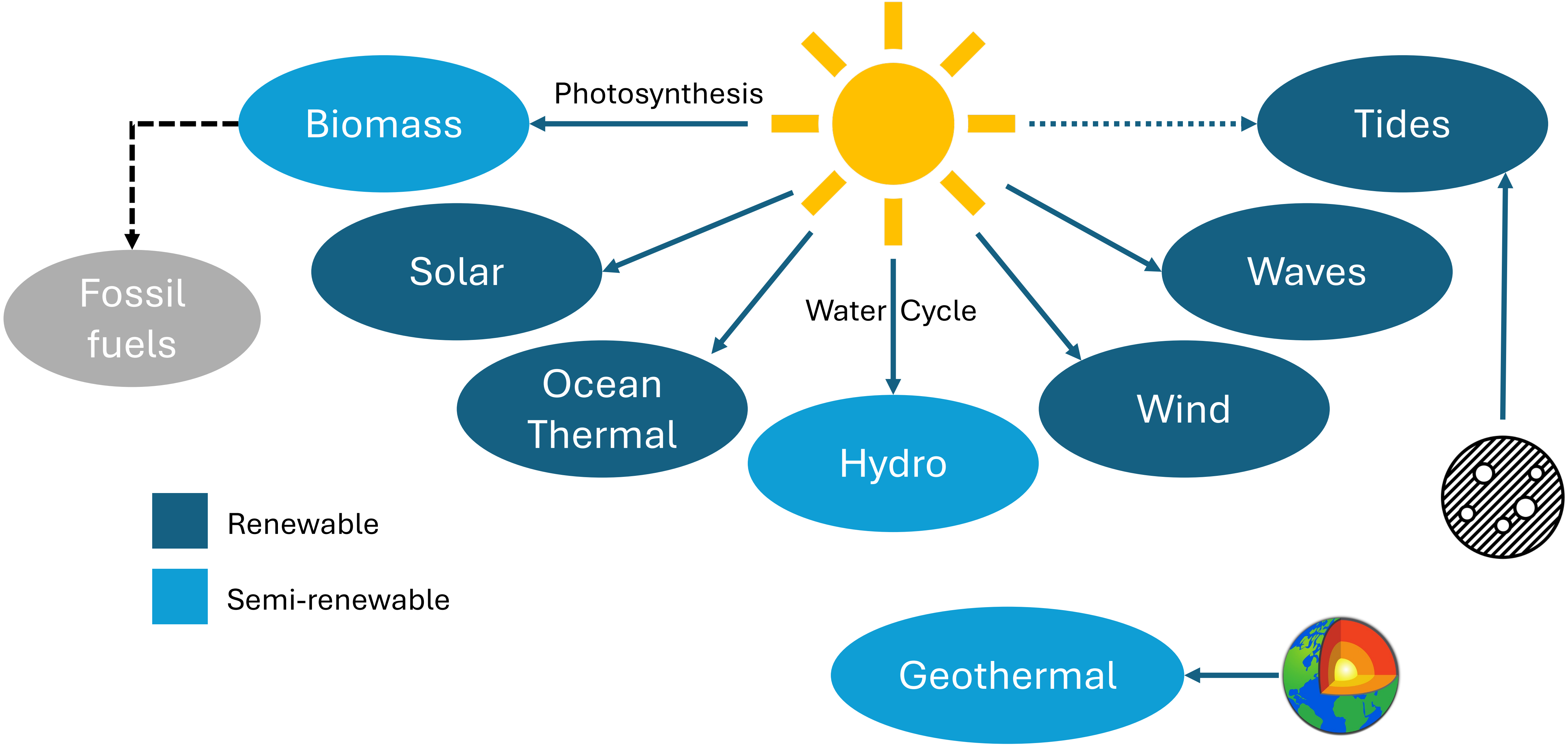


Source: International Renewable Energy Agency

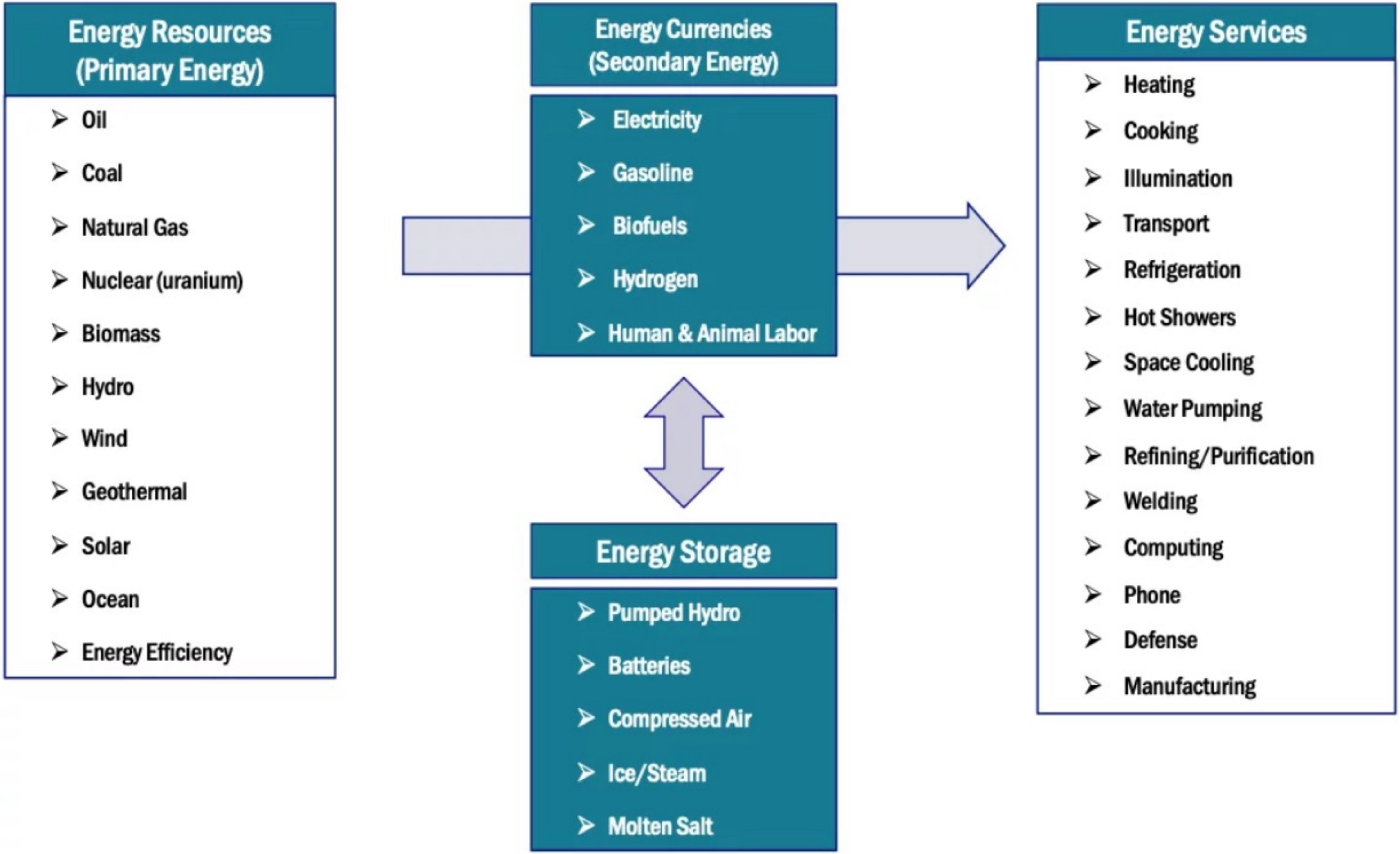
Category	Technology	Primary Application	Small Scale	Large Scale
Biomass	Traditional (gather and burn)	Heating and cooking	X	
	Commercial (refined and traded)	Electricity and heat	X	X
	Biofuels	Transportation	X	X
Hydropower	Dam turbines	Electricity	X	X
	Run of river turbines	Electricity	X	
Wind	Turbines	Electricity	X	X
Solar	Thermal / direct use	Space and water heating	X	
	Thermal electric	Electricity		X
	Photovoltaic (PV)	Electricity	X	X
Geothermal	Steam cycle power plant	Electricity		X
	Direct use	Space and water heating	X	
	Ground source heat pump	Space heating and cooling	X	
Ocean/Marine	Tidal	Electricity		X
	Wave	Electricity	X	X
	Thermal	Electricity		X

Source: Stanford University

Renewables overview – where the energy comes from



Source: Stanford University


Energy Resources (Primary Energy)
Oil
Coal
Natural Gas
Nuclear (uranium)
Biomass
Hydro
Wind
Geothermal
Solar
Ocean
Energy Efficiency
Energy Currencies (Secondary Energy)
Electricity
Gasoline
Biofuels
Hydrogen
Human & Animal Labor
Energy Storage
Pumped Hydro
Batteries
Compressed Air
Ice/Steam
Molten Salt
Energy Services
Heating
Cooking
Illumination
Transport
Refrigeration
Hot Showers
Space Cooling
Water Pumping
Refining/Purification
Welding
Computing
Phone
Defense
Manufacturing

Refining our definition of “renewable”

- **Renewable**: Inexhaustible and naturally-replenishing. Using the resource does not affect future availability of the resource
  - Wind
  - Solar
  - Ocean
- **Semi-renewable**: Use of the resource can be renewable if carefully managed so that use does not result in depletion
  - Hydro
  - Geothermal
  - Biomass

Source: Stanford University

How do we compare the cost of energy and electricity?

- Standard industry method: **Levelized Cost of Electricity** (LCOE)
- LCOE: the cost of producing electricity **over the lifetime** of the power-producing system divided by the total amount of energy it produces

$$\text{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total electricity produced}}$$

- Tells you the amount of revenue a system would need to earn to break even
- **One problem**: is the power produced next year worth the same to me now as the power produced today?

Net present value

- Fundamental idea in valuing future costs and benefits: money is worth more today than it is in the future
  - Money you have today can be invested and grow
- Assign a **discount rate** to discount (reduce) the value of future costs and benefits
- This gives you the **net present value**

$$NPV = \boxed{\text{discount}} \otimes \boxed{\text{value}}$$

$$NPV = \frac{1}{(1 + \underbrace{r}_{\text{discount rate}})} \cdot value$$

LCOE: Definition

$$\mathrm{LCOE} = \frac{\text{Total life cycle cost}}{\text{Total electricity produced}}$$

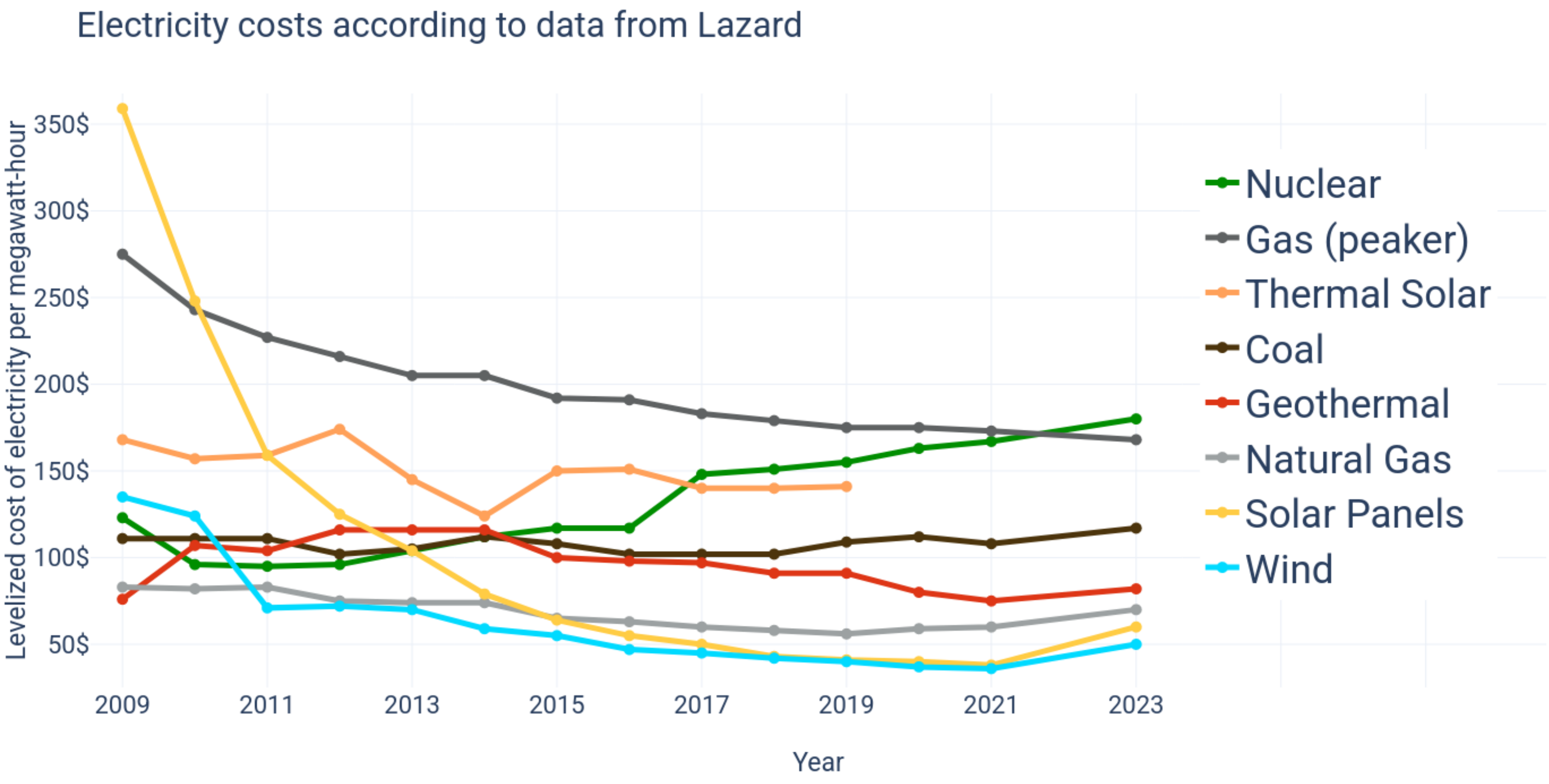
- Total life cycle cost:
  - (I=investment, M=maintenance, F=fuel expenditures)

$$Cost = \sum_{t=0}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}$$

- Sum of electricity produced:

$$Production = \sum_{t=0}^{n} \frac{E_t}{(1+r)^t}$$

LCOE of major electricity technologies



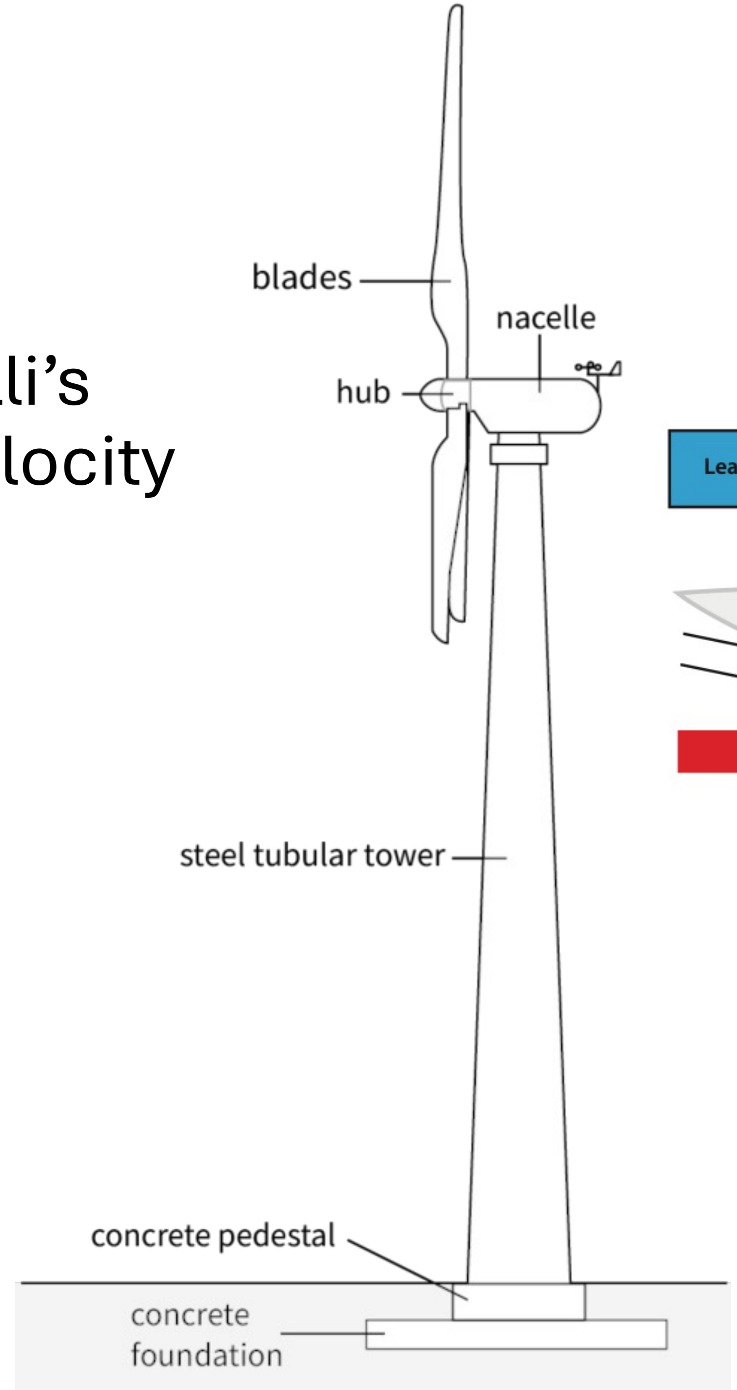
Source: Wikimedia Commons

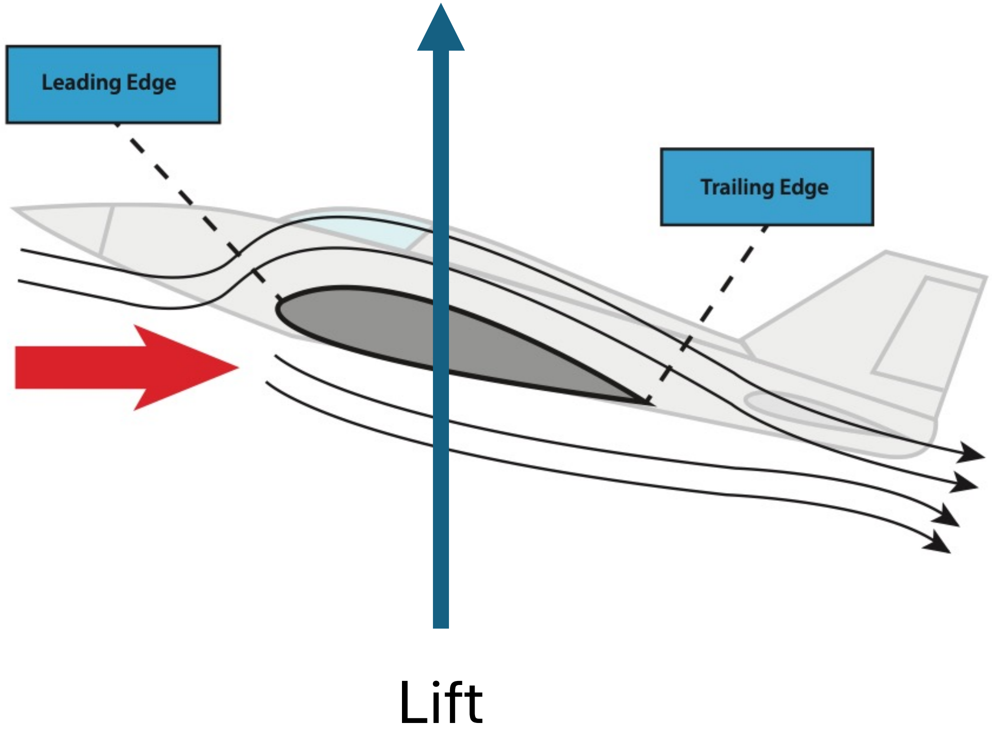
Exercises

- An investment company is interested in developing a wind farm. The upfront cost of installing the system is **€3 million**. The wind farm is expected to produce **35,000 MWh** of energy each year. The operation and maintenance costs are estimated to be **€5/MWh** of produced electricity. The wind farm is expected to last **10 years** (reduction for the purpose of simplifying the exercise). The investment firm uses a discount rate of **5%** for valuing projects like this. What is the LCOE?
- For future thinking: what financial risks are present for fossil fuel power plants (e.g., natural gas) that are not present for renewable power plants?

Wind turbines

- Enabled by Bernoulli's principle: Higher velocity flow yields lower pressure



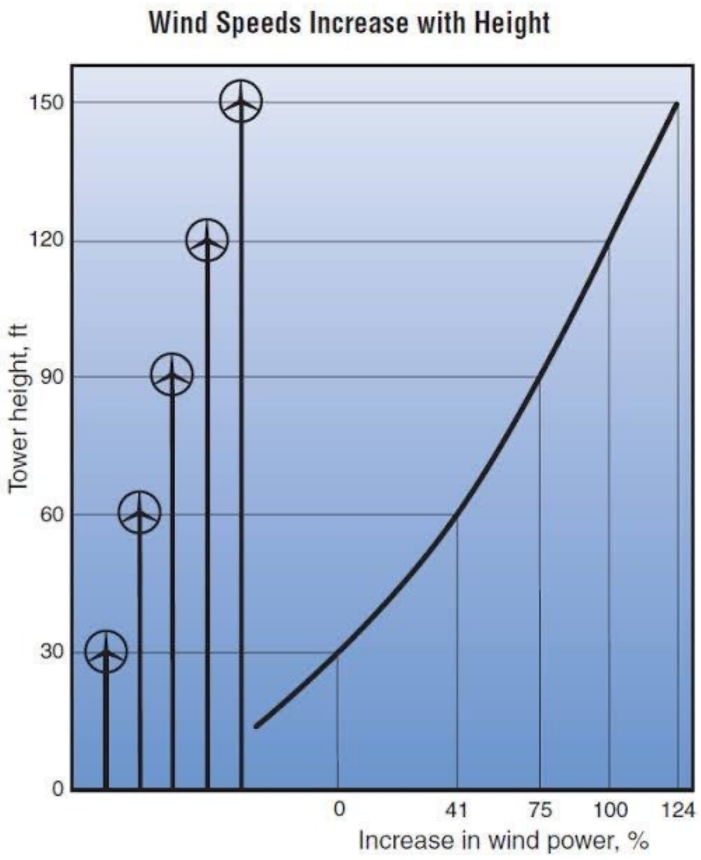


Source: NASA

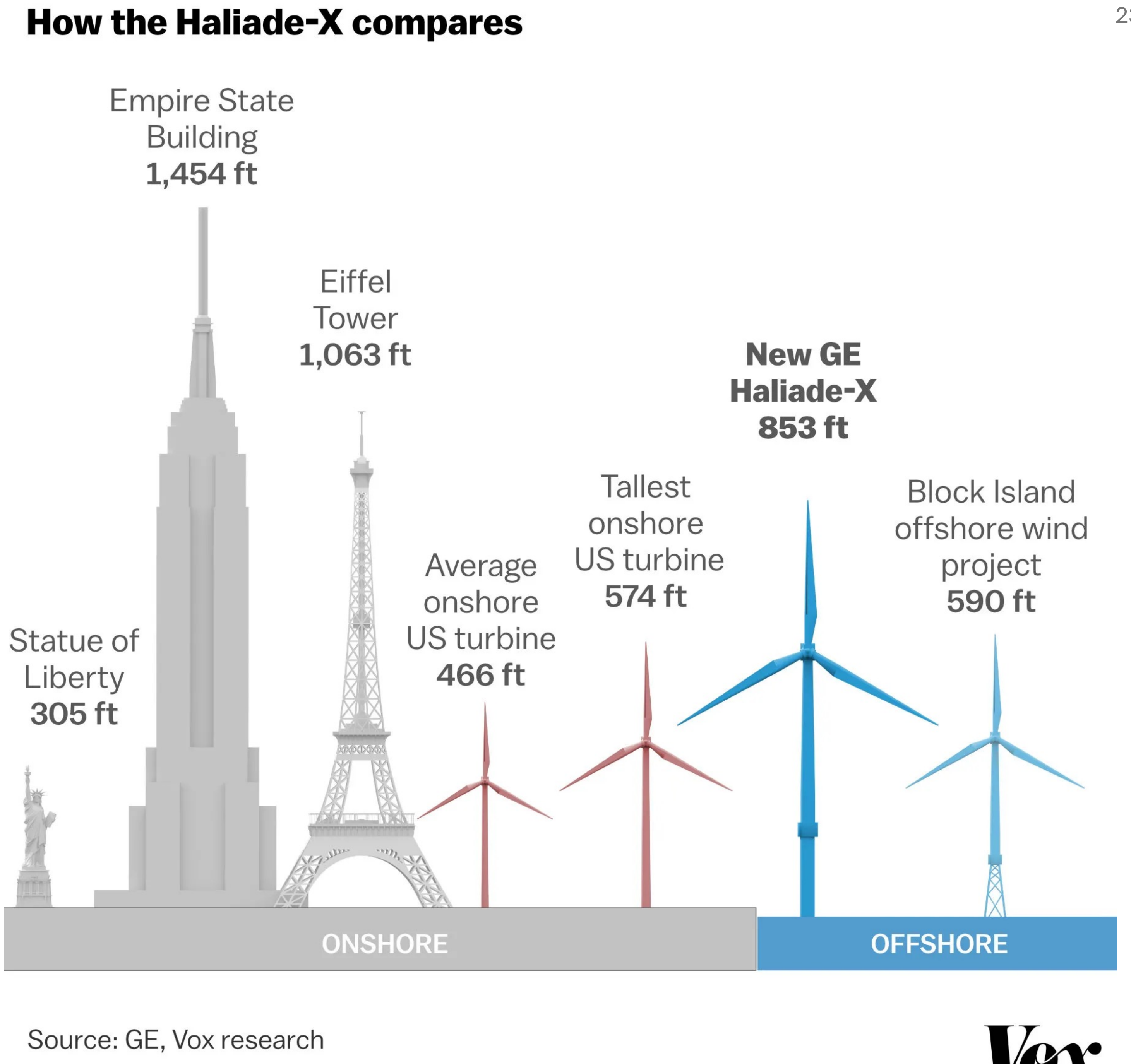
Wind turbine physics

- Energy is extracted from the total kinetic energy of the moving air
- Kinetic energy: $\frac{1}{2}mv^2$
- Rate of kinetic energy arriving at turbine (power units): $\frac{1}{2}\dot{m}v^2$
- Rate of mass of air arriving at turbine: $\dot{m} = \frac{m}{t} = A(\mathrm{m}^2) \cdot \rho(\frac{kg}{\mathrm{m}^3}) \cdot v(\frac{\mathrm{m}}{s})$
- Total power in arriving air: $\frac{1}{2}A\rho v^3$
- Maximum power that can be extracted: $\frac{8}{27}A\rho v^3$ (Betz’s Law)

Wind turbine size and power



S W Wasiati *et al* 2020 *J. Phys.: Conf. Ser.* **1517** 012064



ONSHORE & OFFSHORE WIND RESOURCE MAP

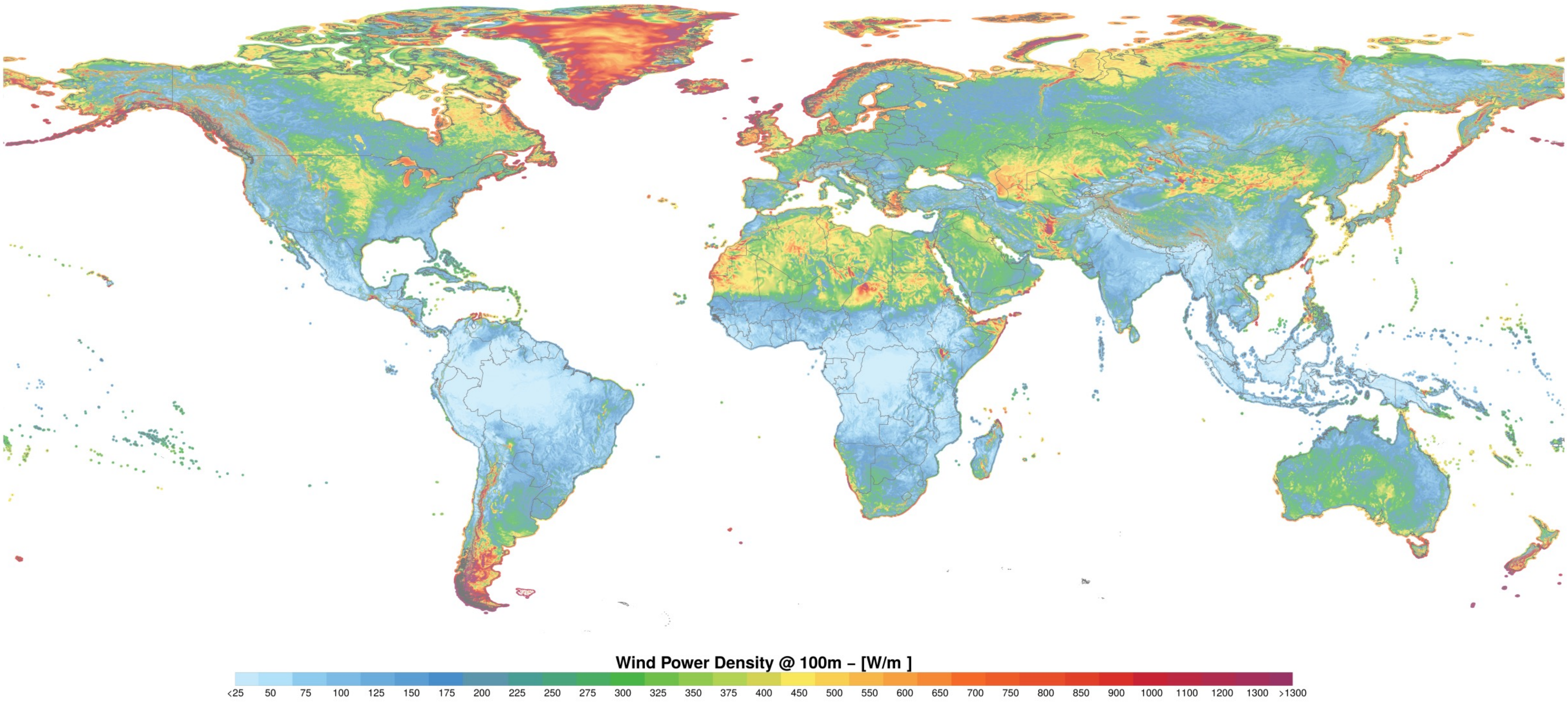
WIND POWER DENSITY POTENTIAL

WORLD BANK GROUP

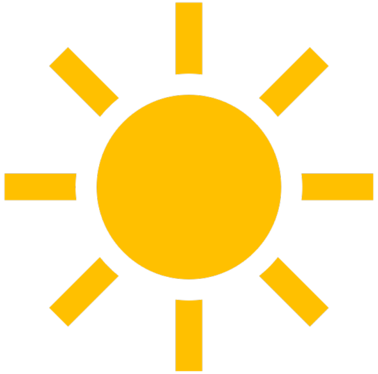
DTU Wind Energy
Department of Wind Energy

ESMAP
Energy Sector Management Assistance Program

VORTEX

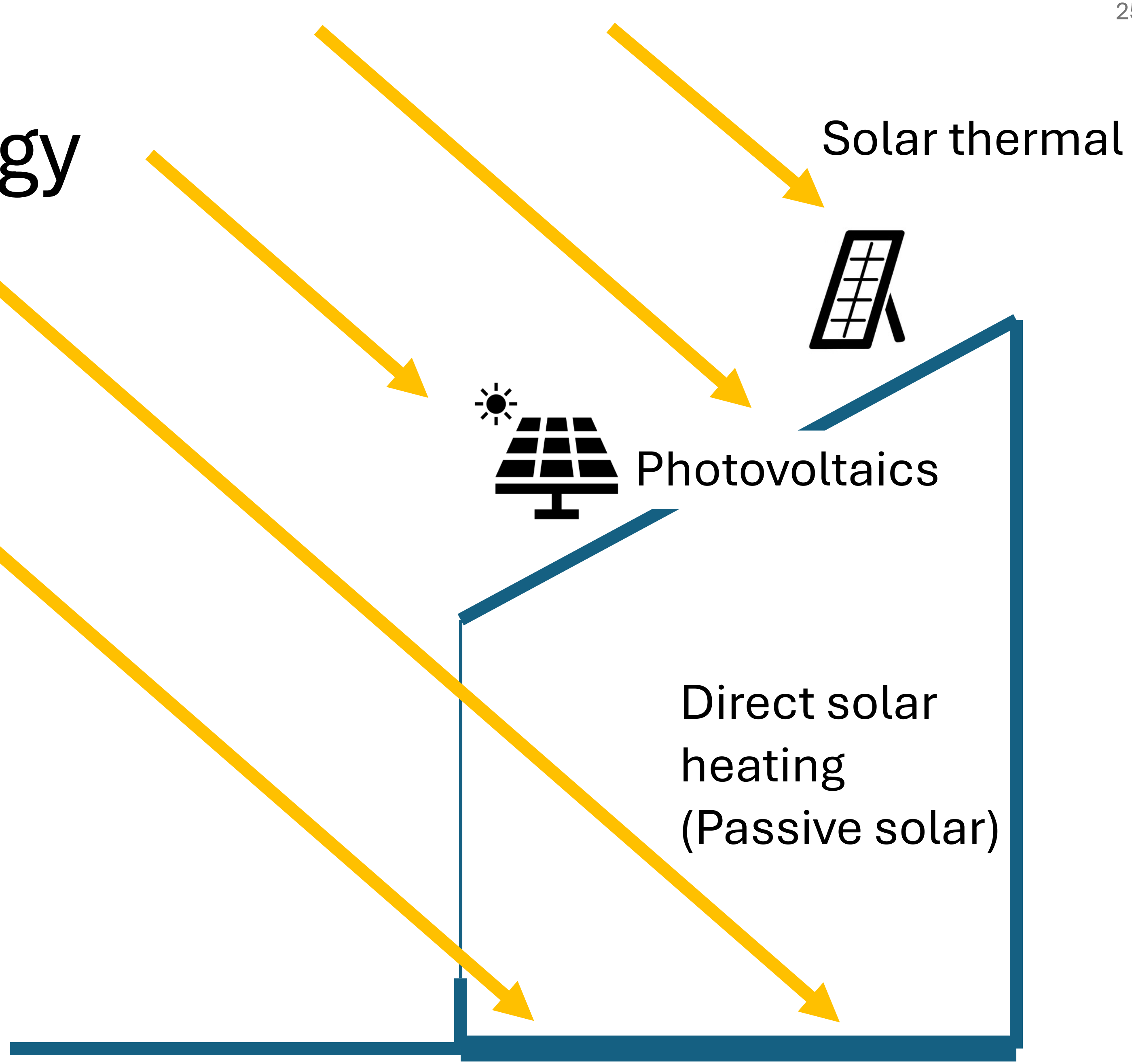


This map is published by the World Bank Group, funded by ESMAP, and prepared by DTU and Vortex. For more information and terms of use, please visit http://globalwindatlas.info

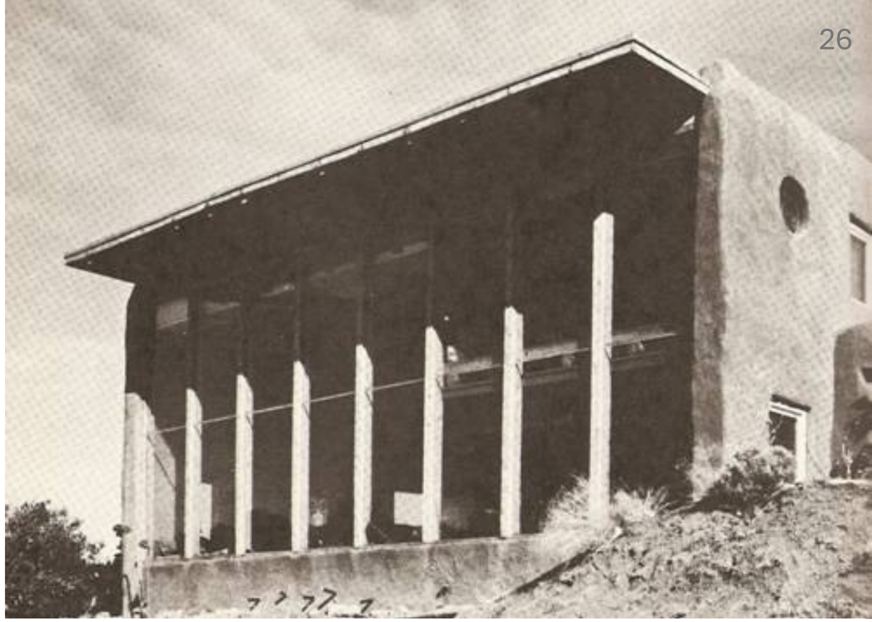


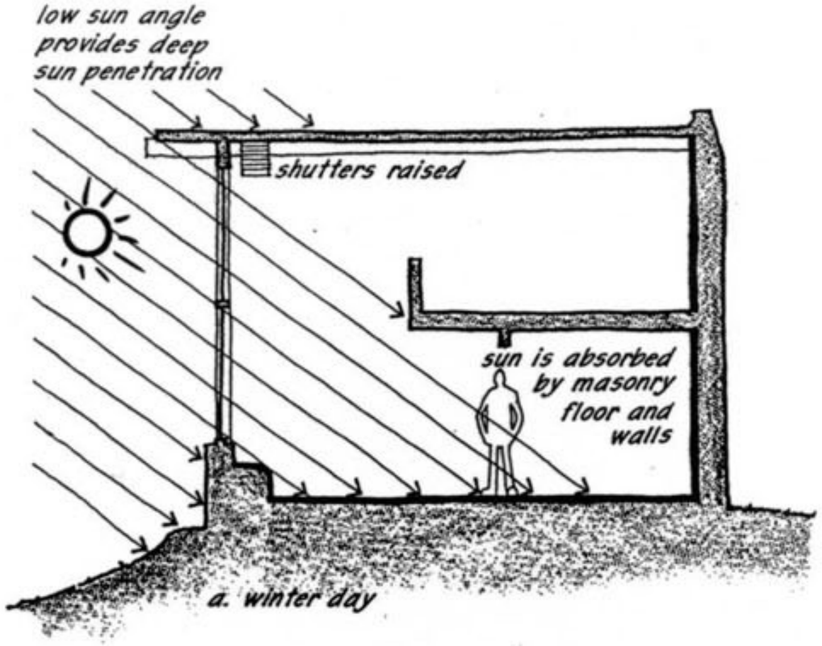
Solar energy

- Energy from the sun arrives as light (electromagnetic) energy and can be converted into electricity or heat through a variety of mechanisms

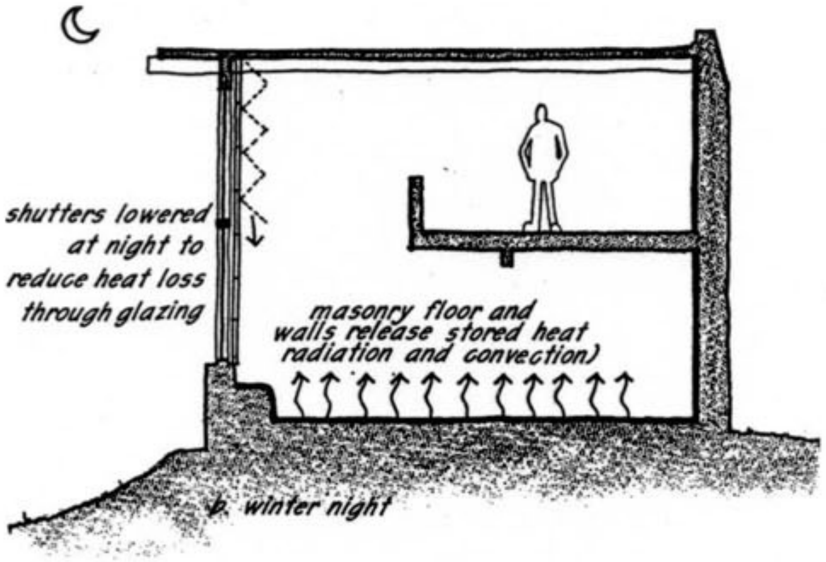


Passive solar heating

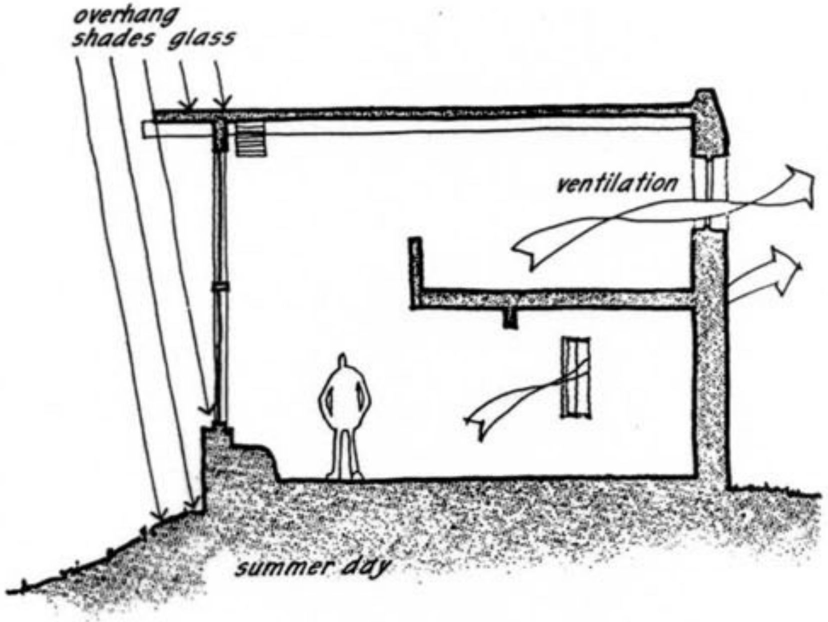




Winter day



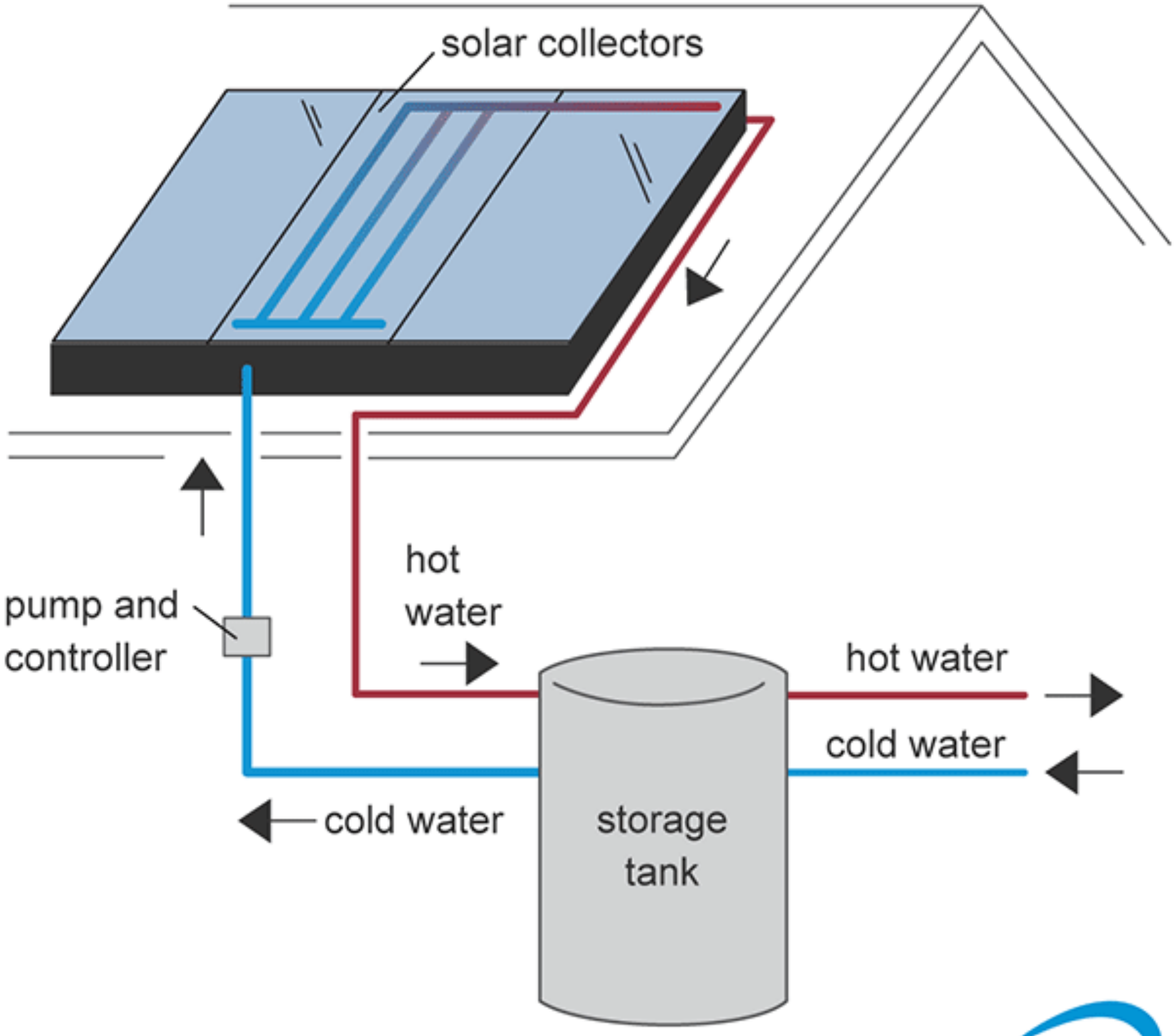
Winter night



Summer day

Solar thermal

- The sun's energy is good at heating things up
- Aside from directly heating buildings, it can be used to heat water for use in buildings and other uses



Source: U.S. Energy Information Administration
Note: This is a simplified diagram of a drainback-type solar water heating system.

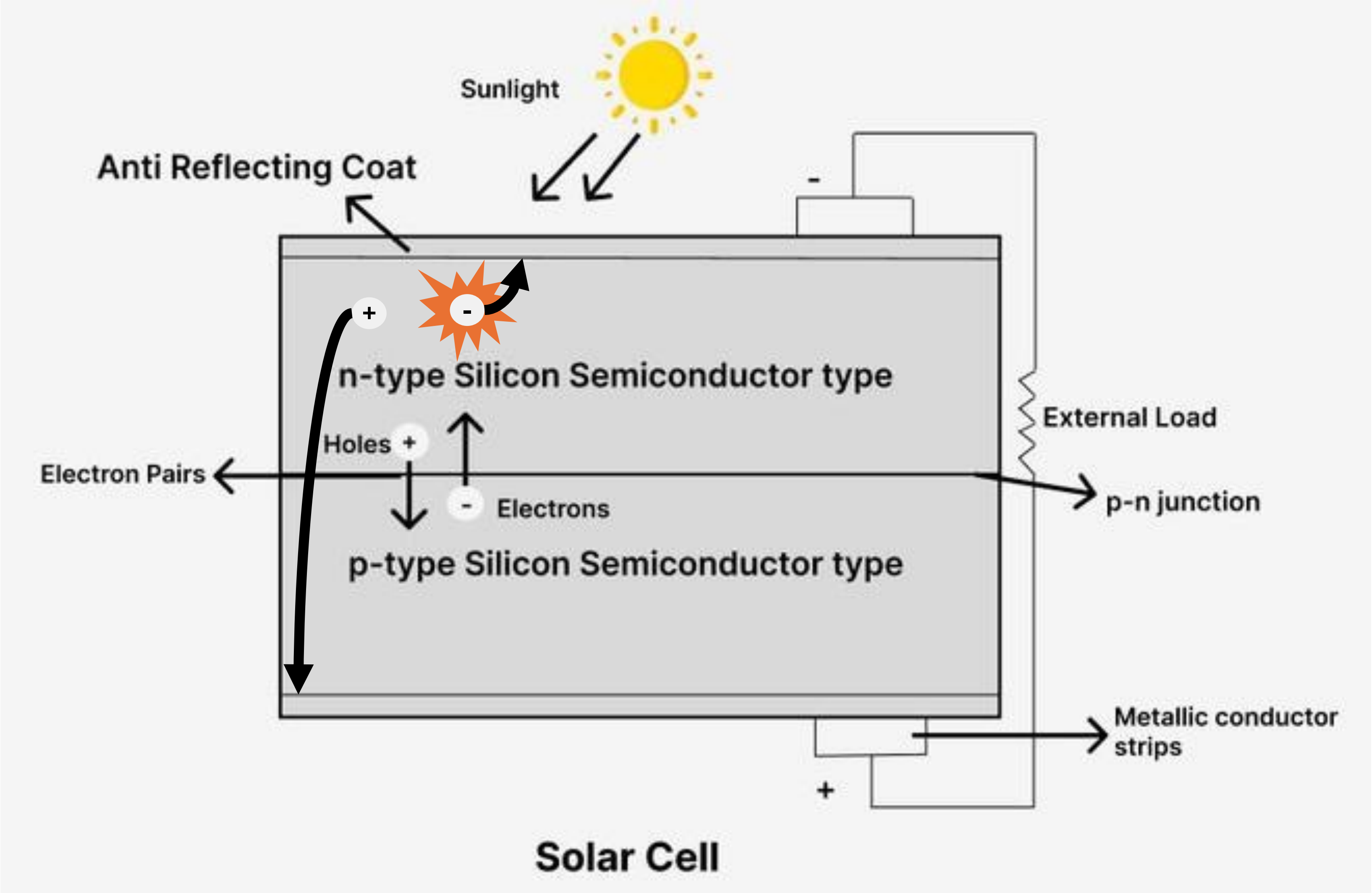
Solar photovoltaics

Sunlight energy causes some electrons in N-type layer to break free from silicon lattice, these flow

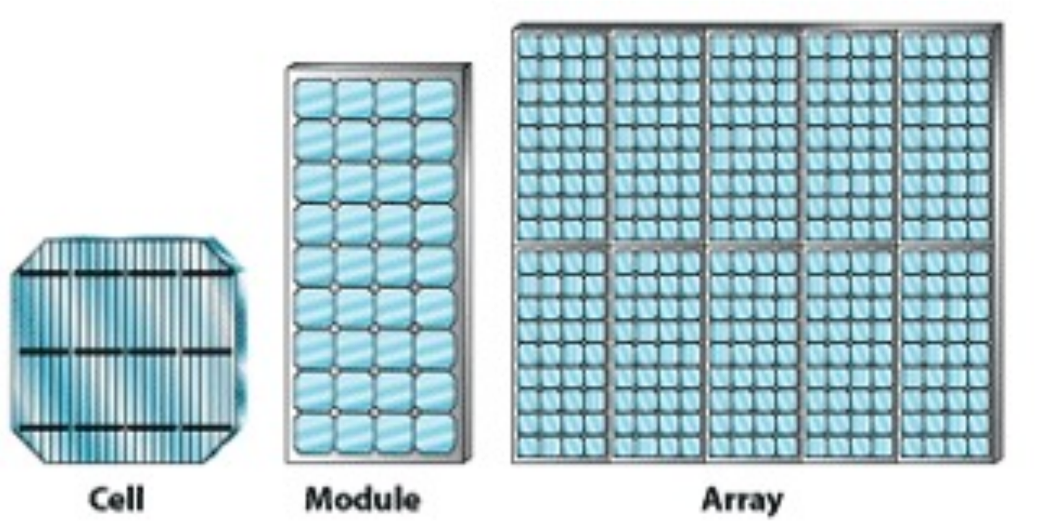
N-type silicon: extra electrons, negative charge

P-type silicon: electron deficit (holes), positive charge

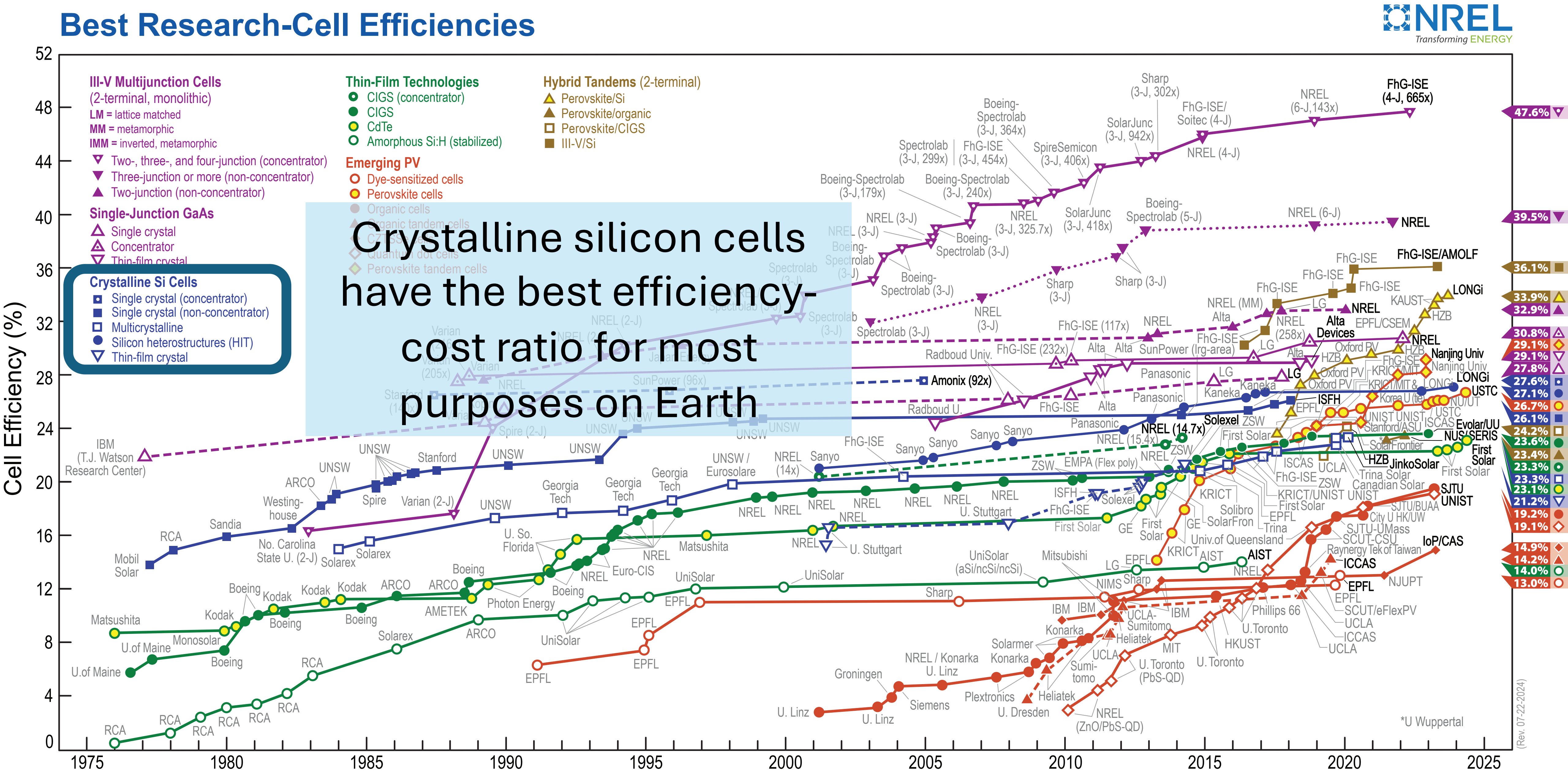
No emissions or moving parts



Solar cells, modules, and arrays



Best Research-Cell Efficiencies



Crystalline silicon cells have the best efficiency-cost ratio for most purposes on Earth

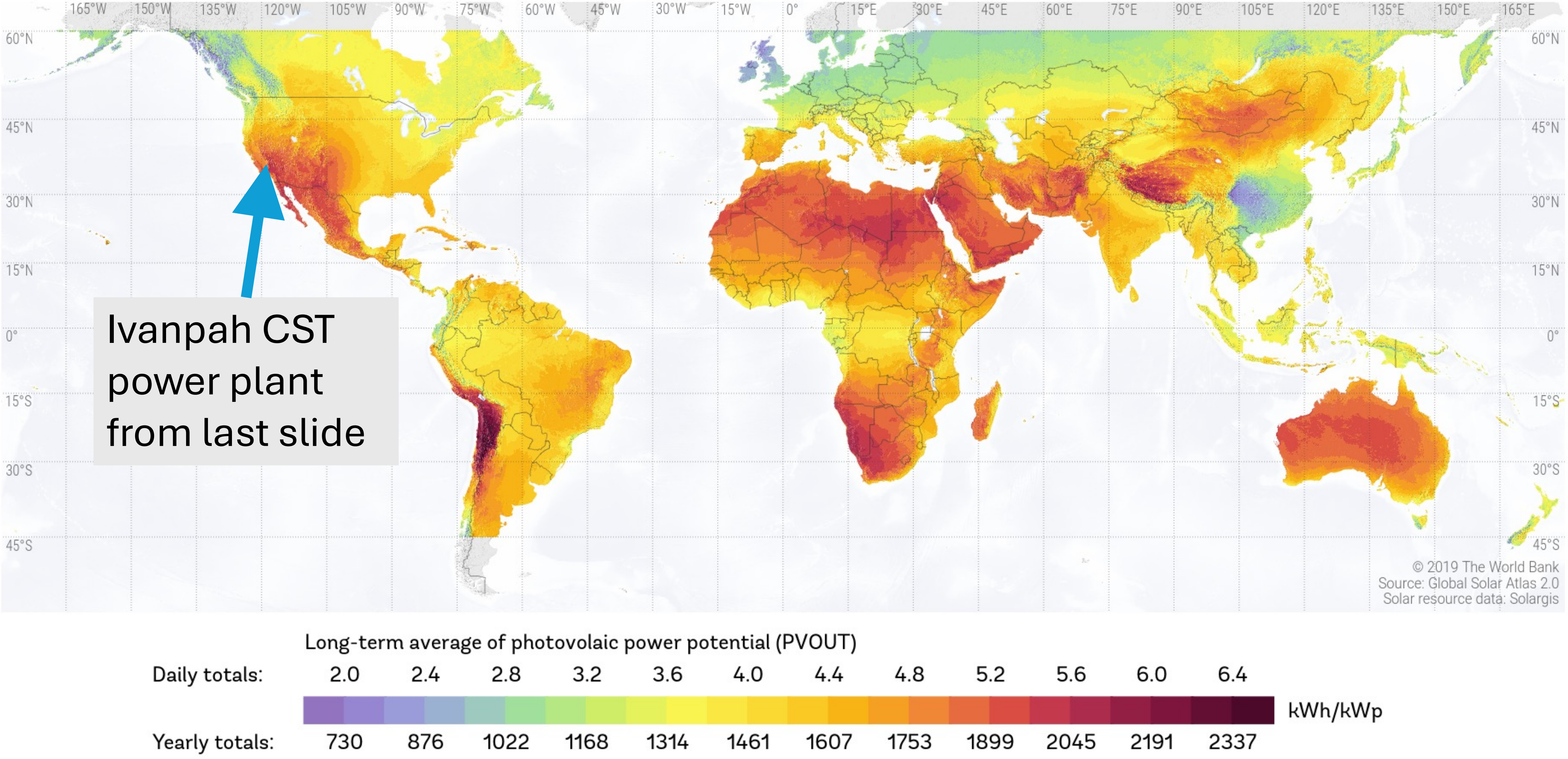
Concentrated solar thermal for electricity

- Heat from the sun can be concentrated (through mirrors) to create steam that runs through a turbine
- Need very reliable sunlight
- Typically, much more expensive than PVs and wind

SOLAR RESOURCE MAP

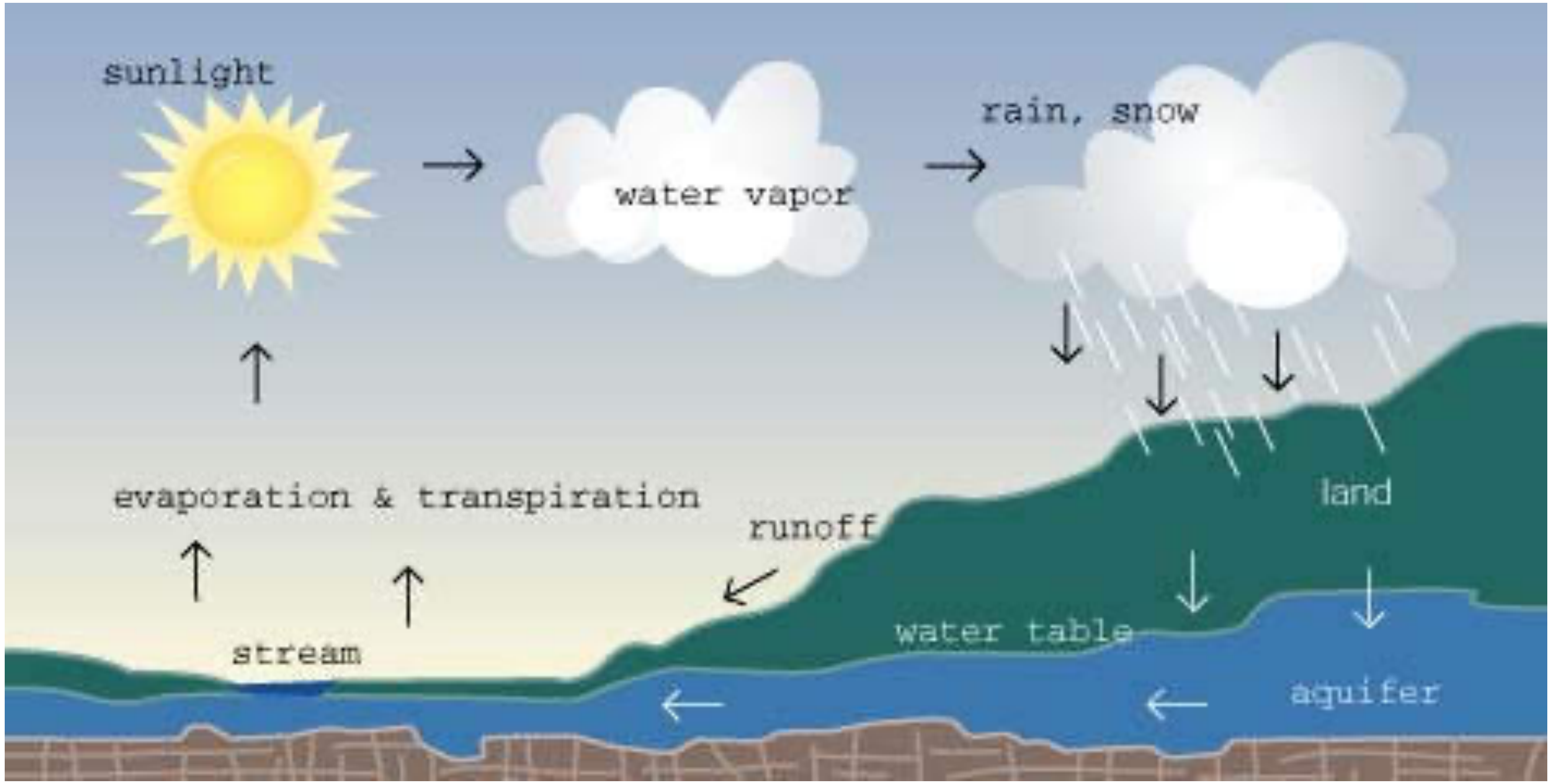
PHOTOVOLTAIC POWER POTENTIAL

WORLD BANK GROUP ESMAP SOLARGIS

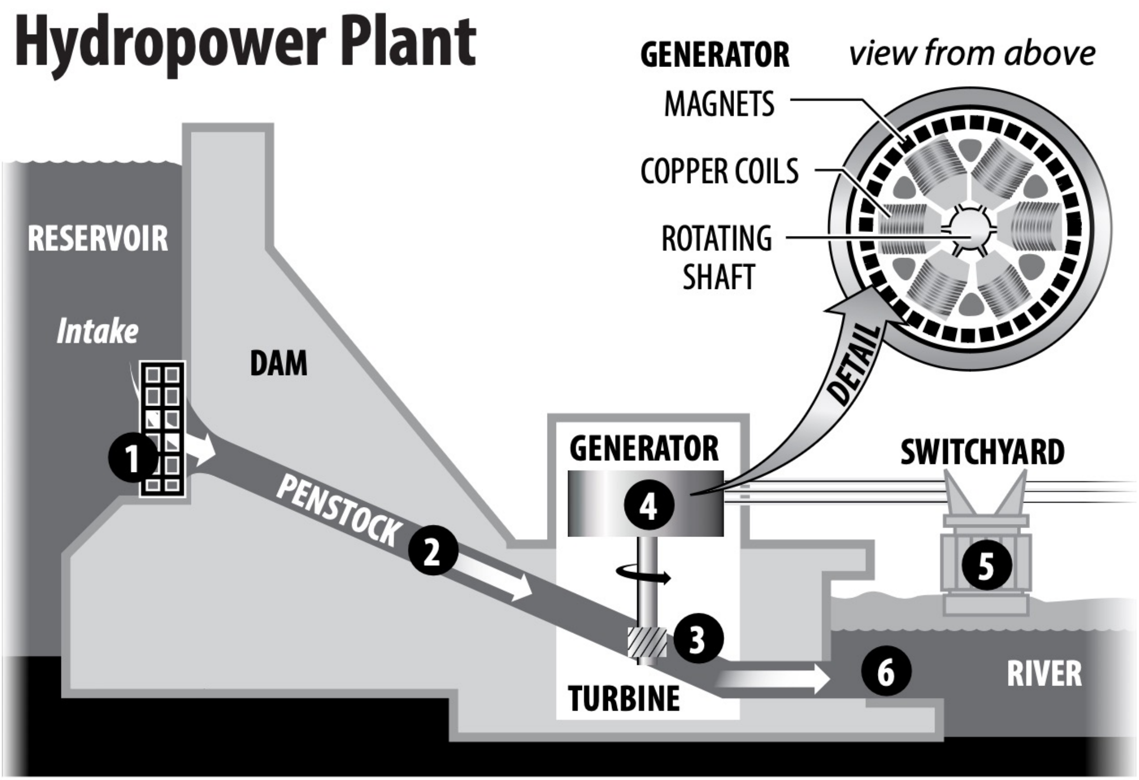


This map is published by the World Bank Group, funded by ESMAP, and prepared by Solargis. For more information and terms of use, please visit http://globalsolaratlas.info.

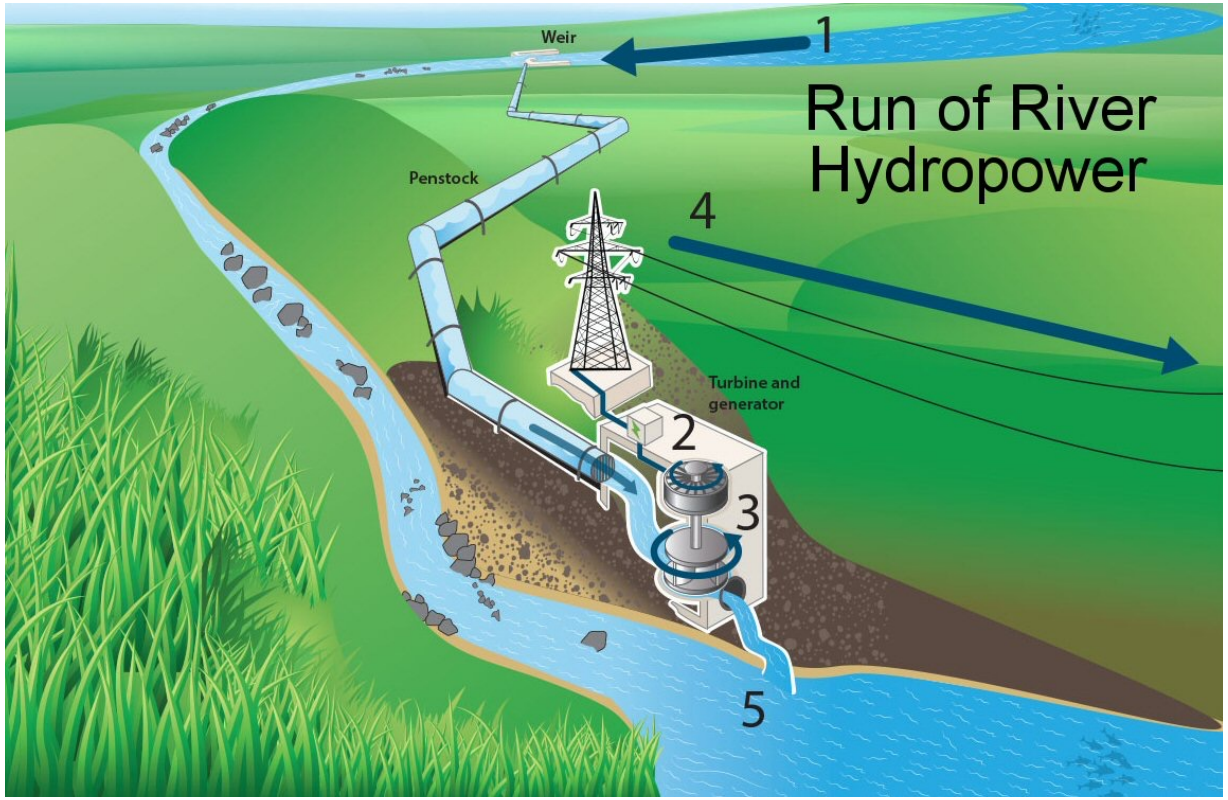
Hydropower – driven by the sun



Hydropower



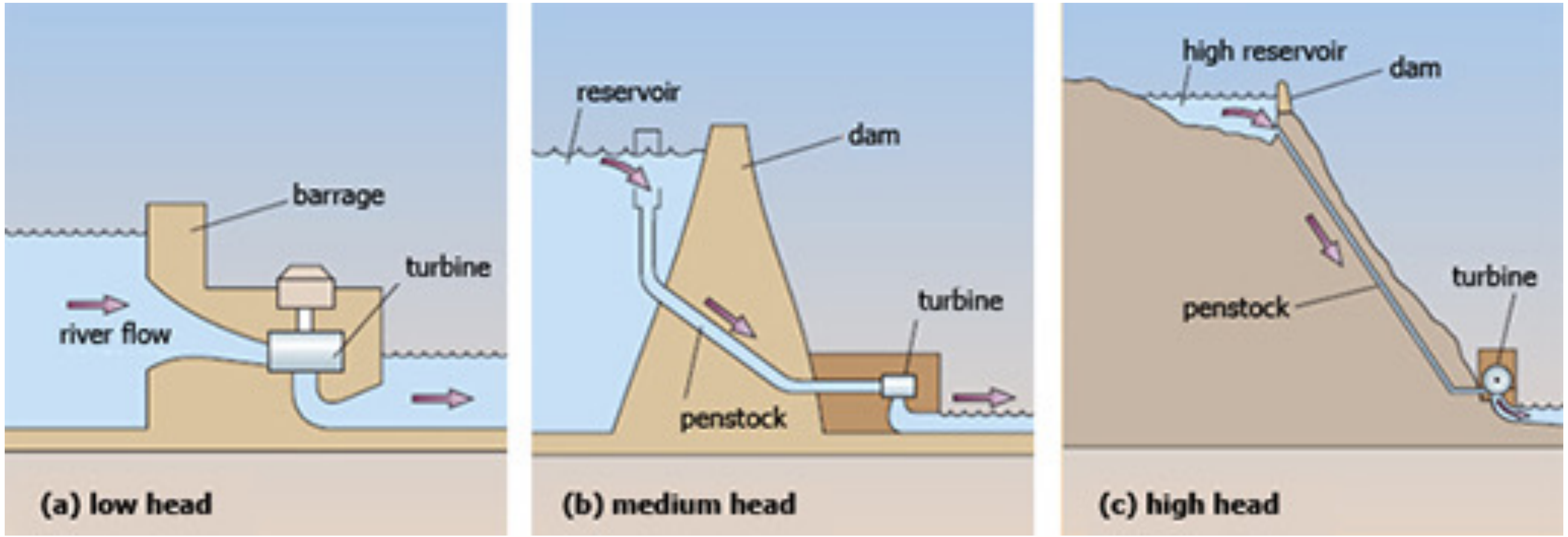
Storage hydro
(small or large scale)



Run of river hydro
(small scale)

Sources: need.org; DOI 10.1080/10286608.2021.1893310

Hydropower physics

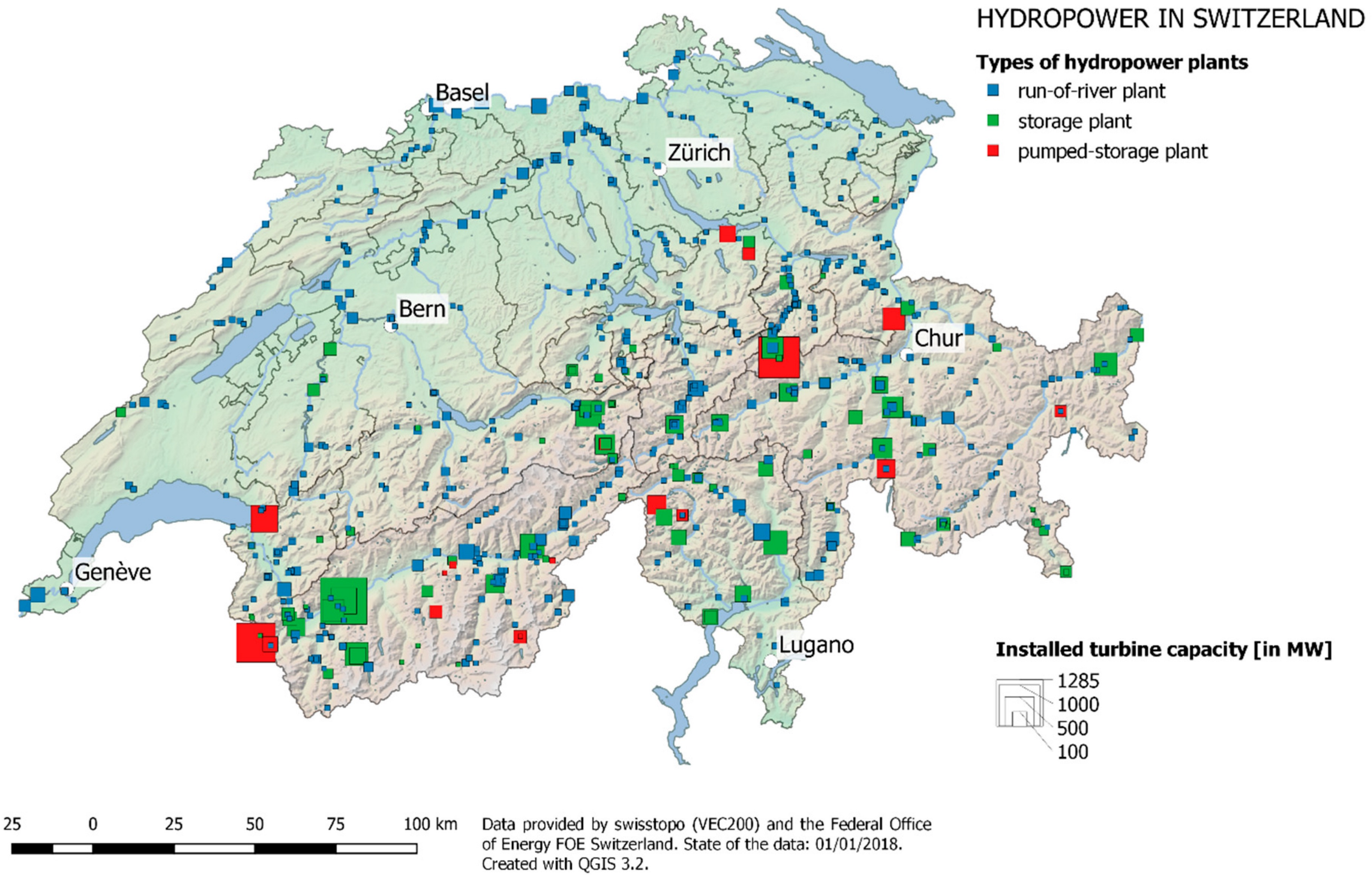


- Energy is extracted from the energy potential of flowing water
- Potential energy: mgh
- Rate of mass of water arriving at turbine: $\rho\dot{V}\ (\frac{kg}{s})$
- Turbine power: $\rho\dot{V} \cdot g \cdot \Delta h \cdot \eta$

turbine efficiency

Hydropower in Switzerland

- Hydropower is about 57% of electricity **produced** in Switzerland
- Switzerland has tapped much of its hydropower potential

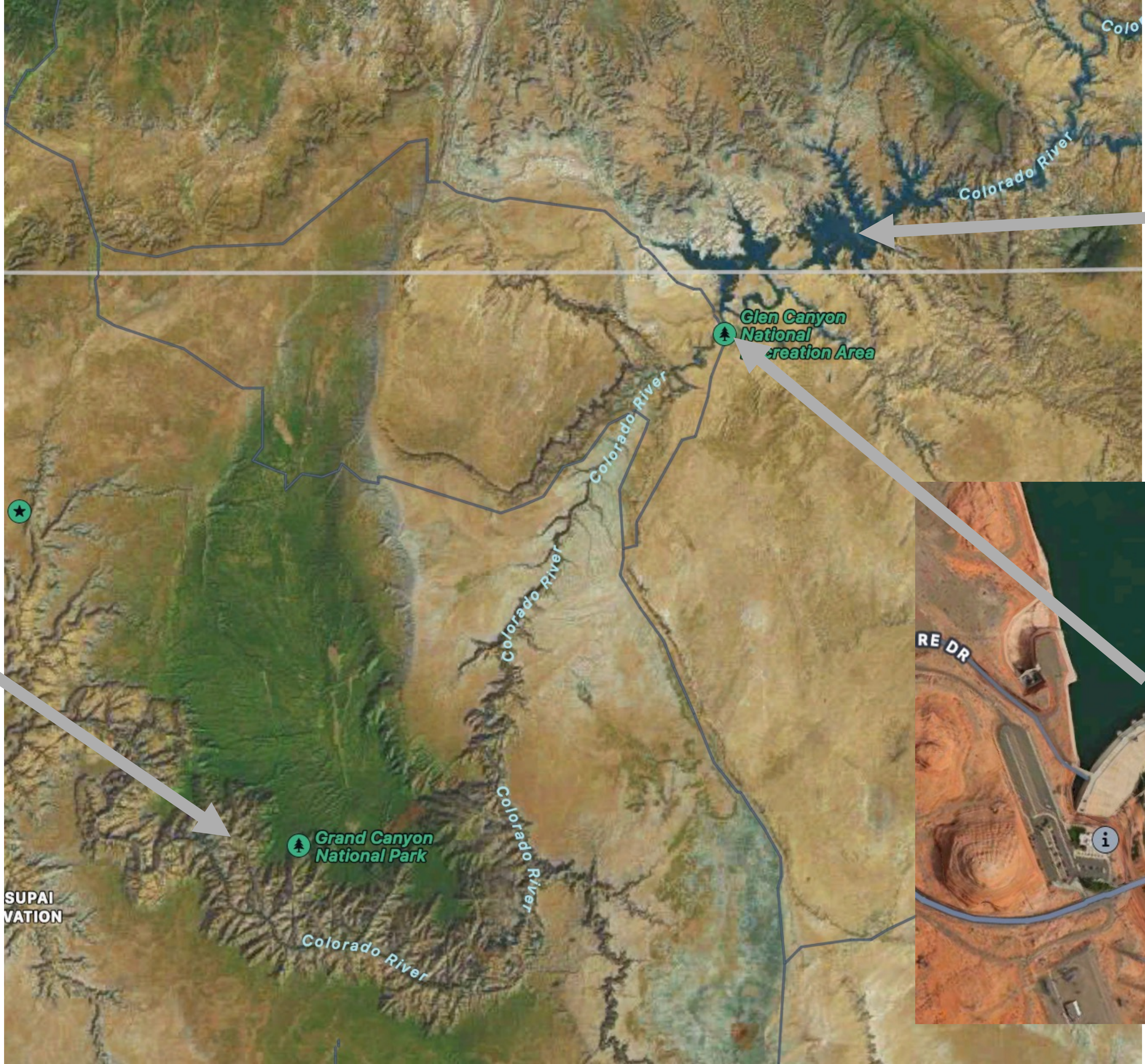


Sustainability **2018**, *10*(10), 3594; https://doi.org/10.3390/su10103594

Negative environmental impacts of hydro

- Upstream:
  - Reservoirs transform river ecosystems into lake ecosystems
  - Submerged vegetation can release CO_2 and methane
  - Inundation of land causes human displacement
  - Impedes fish passage
  - Sediment buildup reduces dam capacity over time
- Downstream:
  - Halts sediment flow and changes river morphology
  - Ecosystem alteration
  - Water quality issues

Fish ladder



Lake Powell, Reservoir from Glen Canyon Dam

Grand Canyon, Arizona, USA

THE CONTROL OF NATURE

THE LOST CANYON UNDER LAKE POWELL

Drought is shrinking one of the country's largest reservoirs, revealing a hidden Eden.

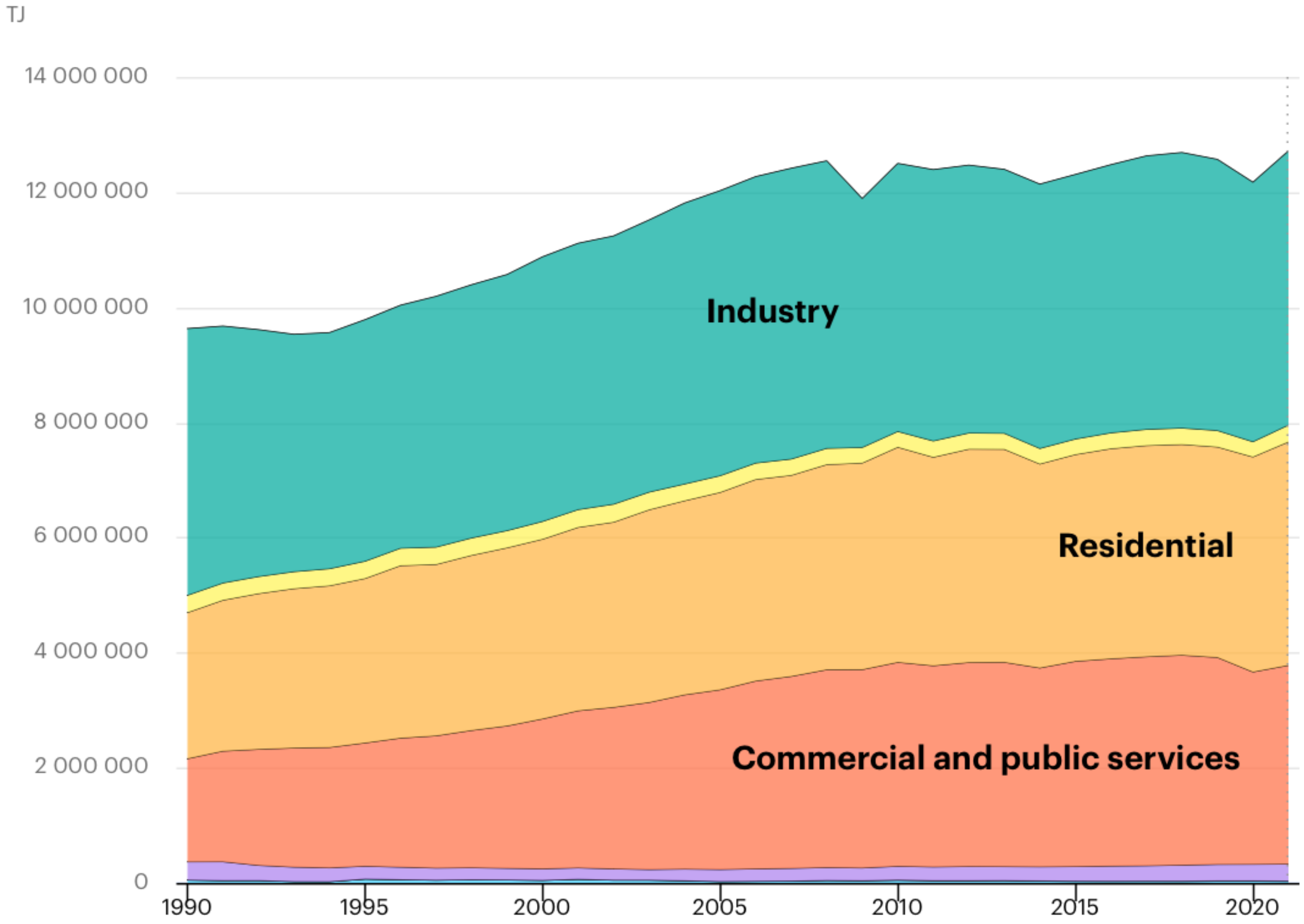
- When Glen Canyon Dam was built, there was a rush to document dwellings, petroglyphs, and pottery left behind by generations of Native Americans
- With recent droughts, the water levels in Lake Powell have dropped, and some of these sites have reemerged

Sources: The New Yorker, KNAU

Supply and demand challenges

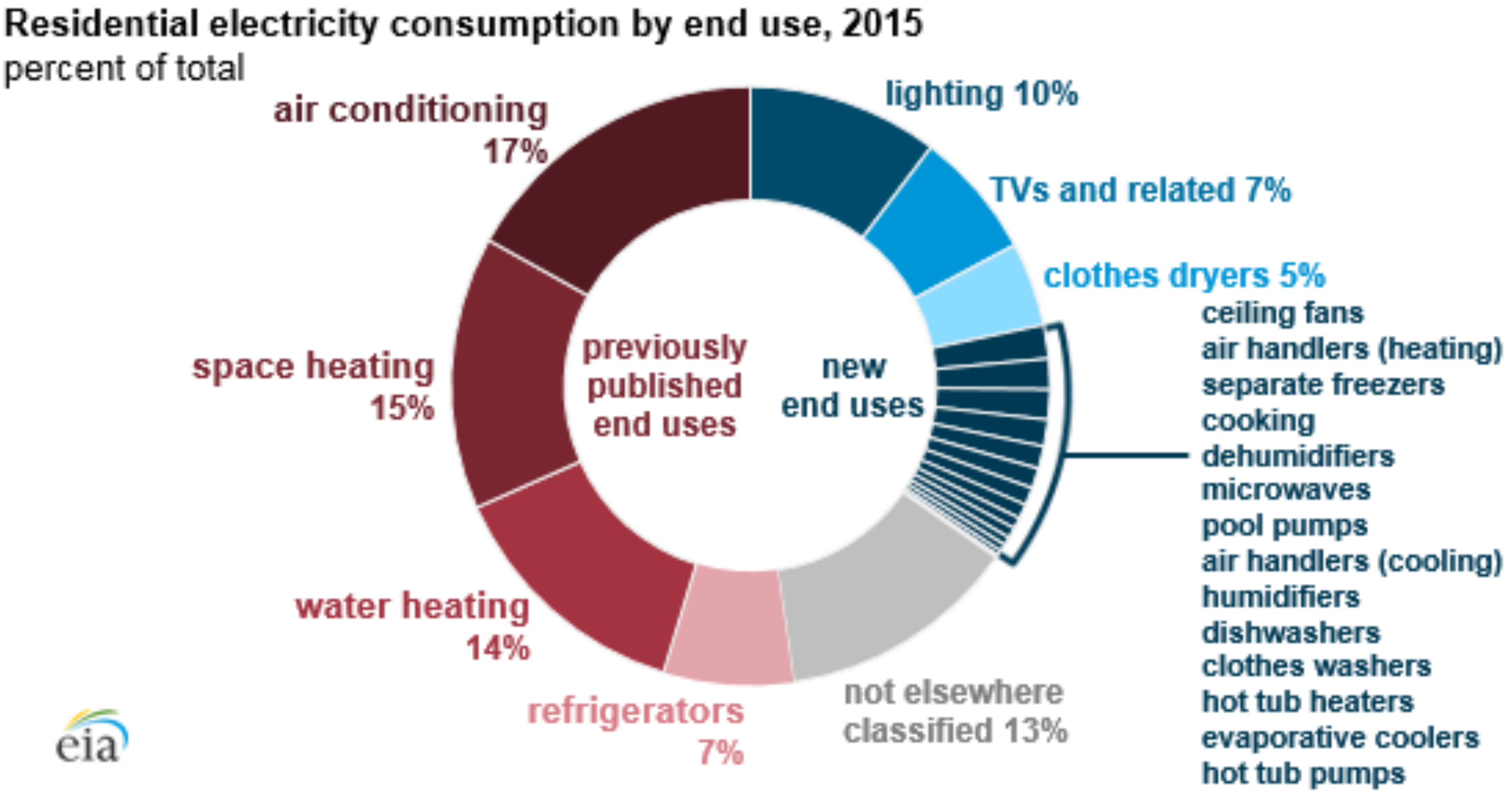
- We are electrifying (buildings and transport)
  - This adds more demand to the electricity grid
- We are replacing electricity generation
  - Removing constant producers like natural gas and coal
  - Adding intermittent producers like wind and solar
- Major challenge: balancing the grid

Electricity consumption by sector, Europe

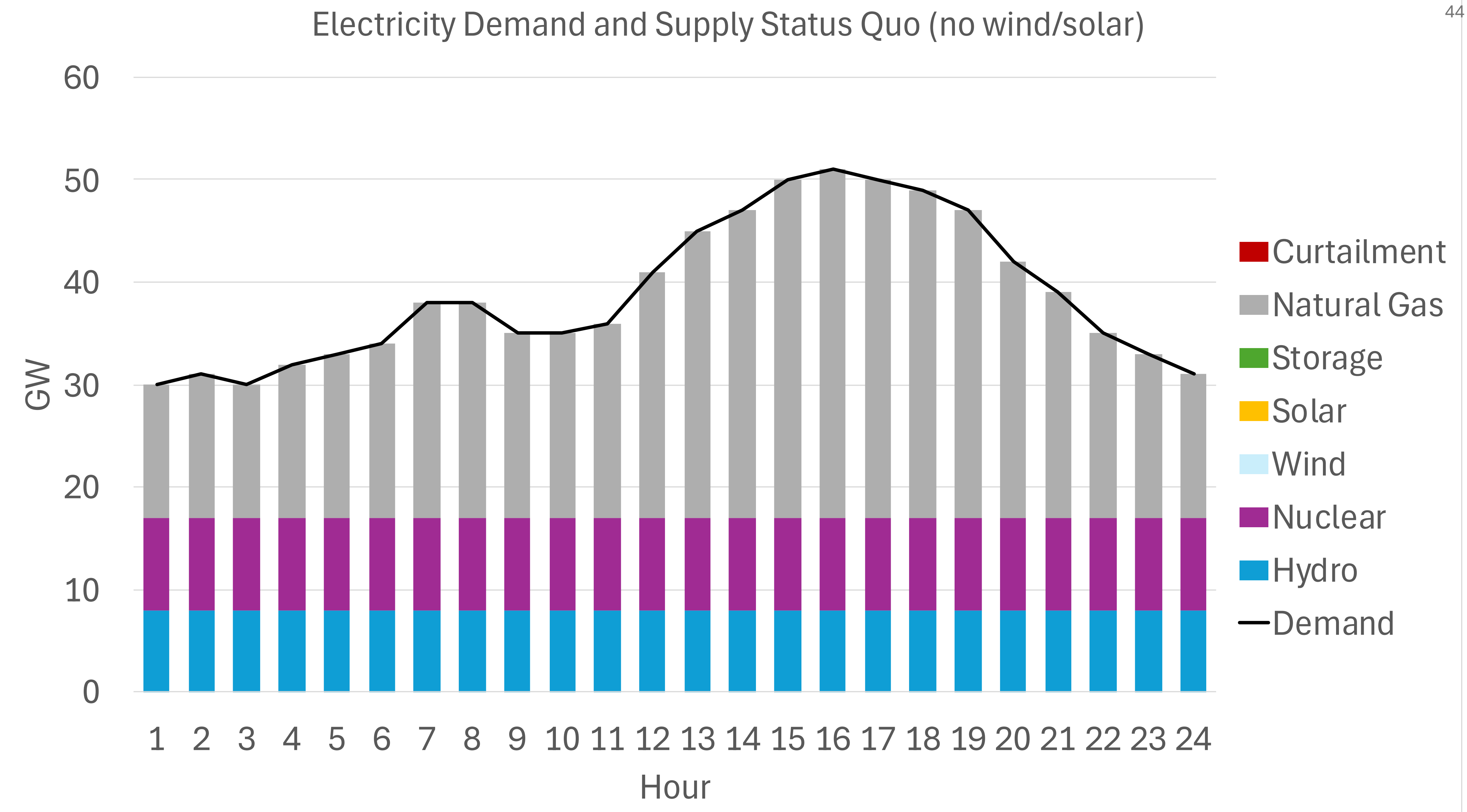


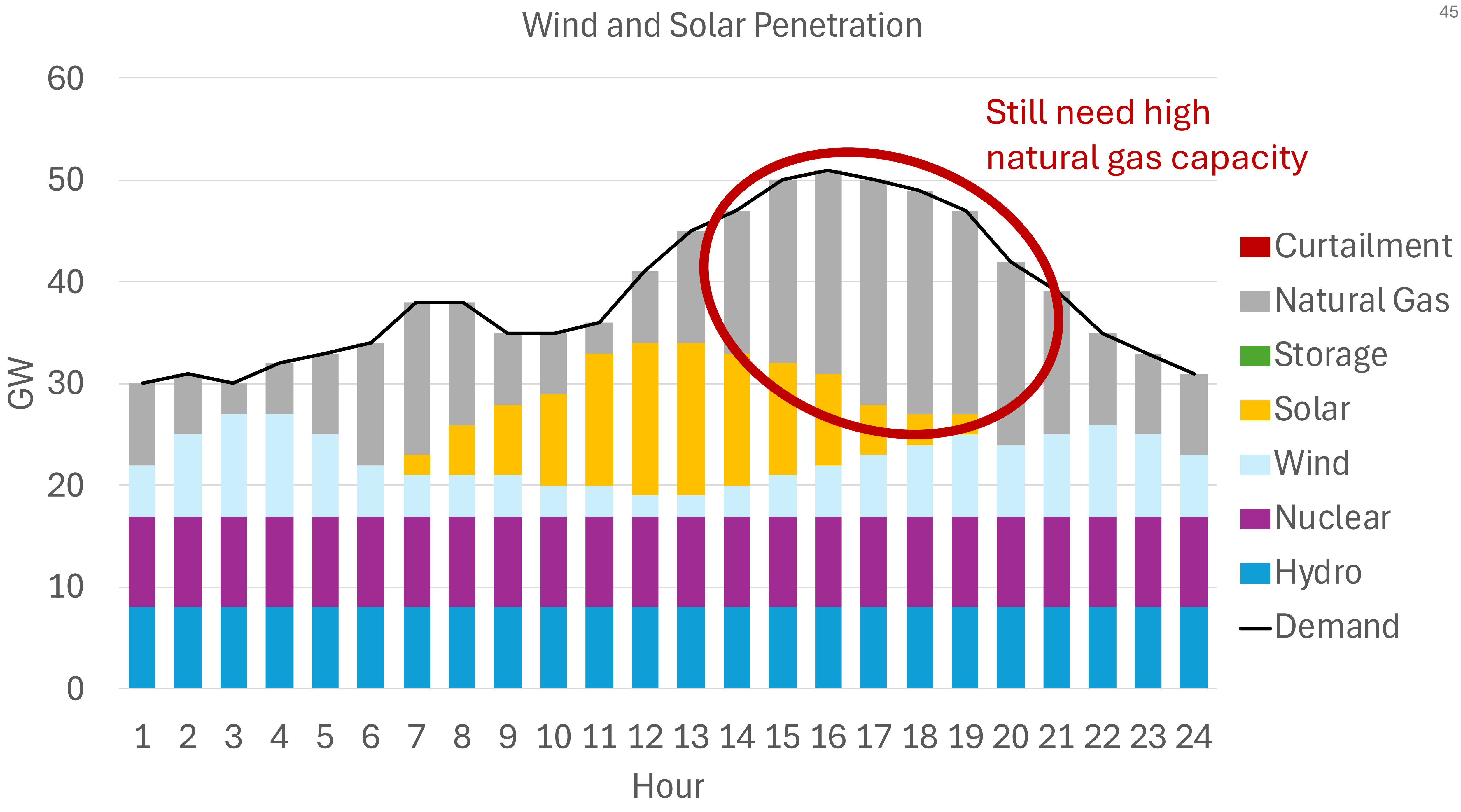
What drives energy demand variation?

- Lights, HVAC, and electrical appliances are driven by occupant behavior, especially in residential sector



Note: US Data

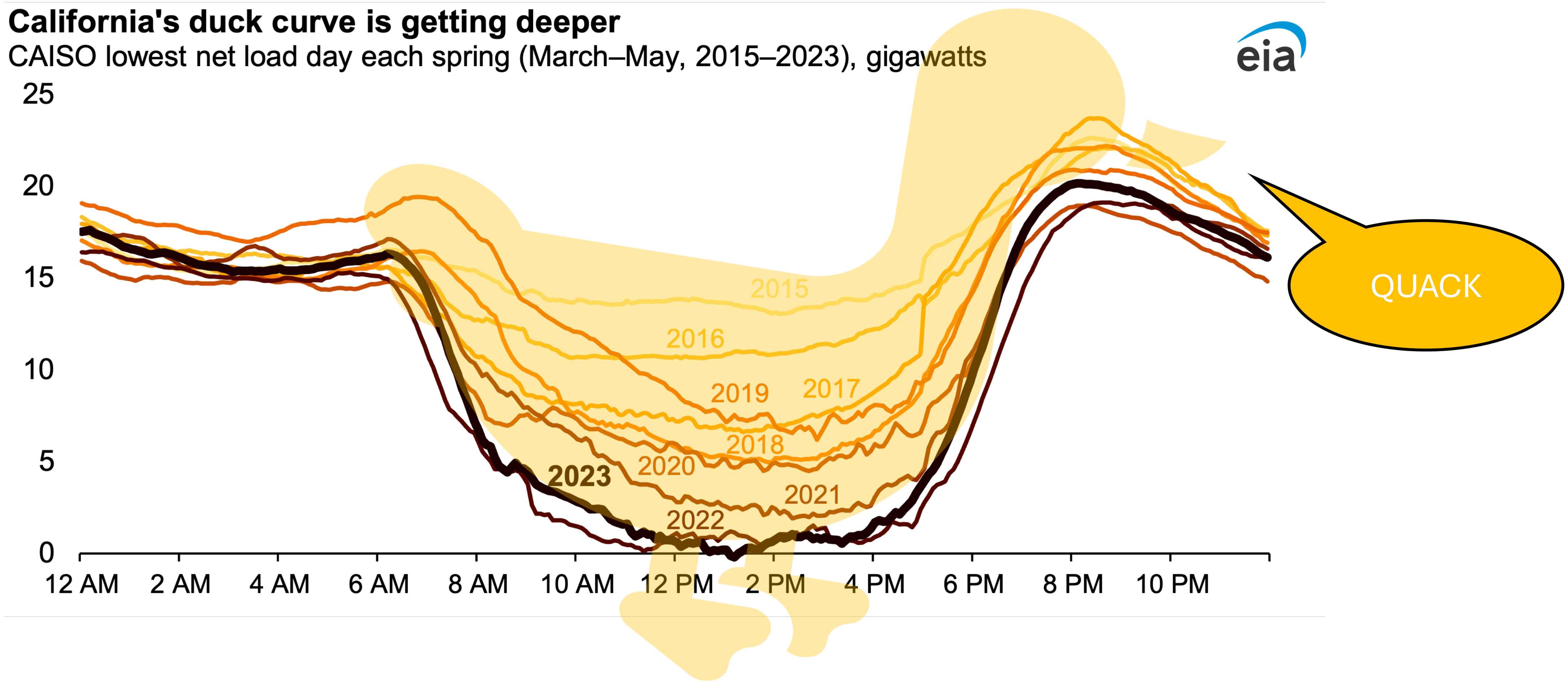

Electricity Demand and Supply Status Quo (no wind/solar)
60
50
40
30
20
10
0
GW
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Hour
Curtailment
Natural Gas
Storage
Solar
Wind
Nuclear
Hydro
Demand



Wind and Solar Penetration
Still need high natural gas capacity
GW
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Curtailment
Natural Gas
Storage
Solar
Wind
Nuclear
Hydro
Demand

The Duck Curve

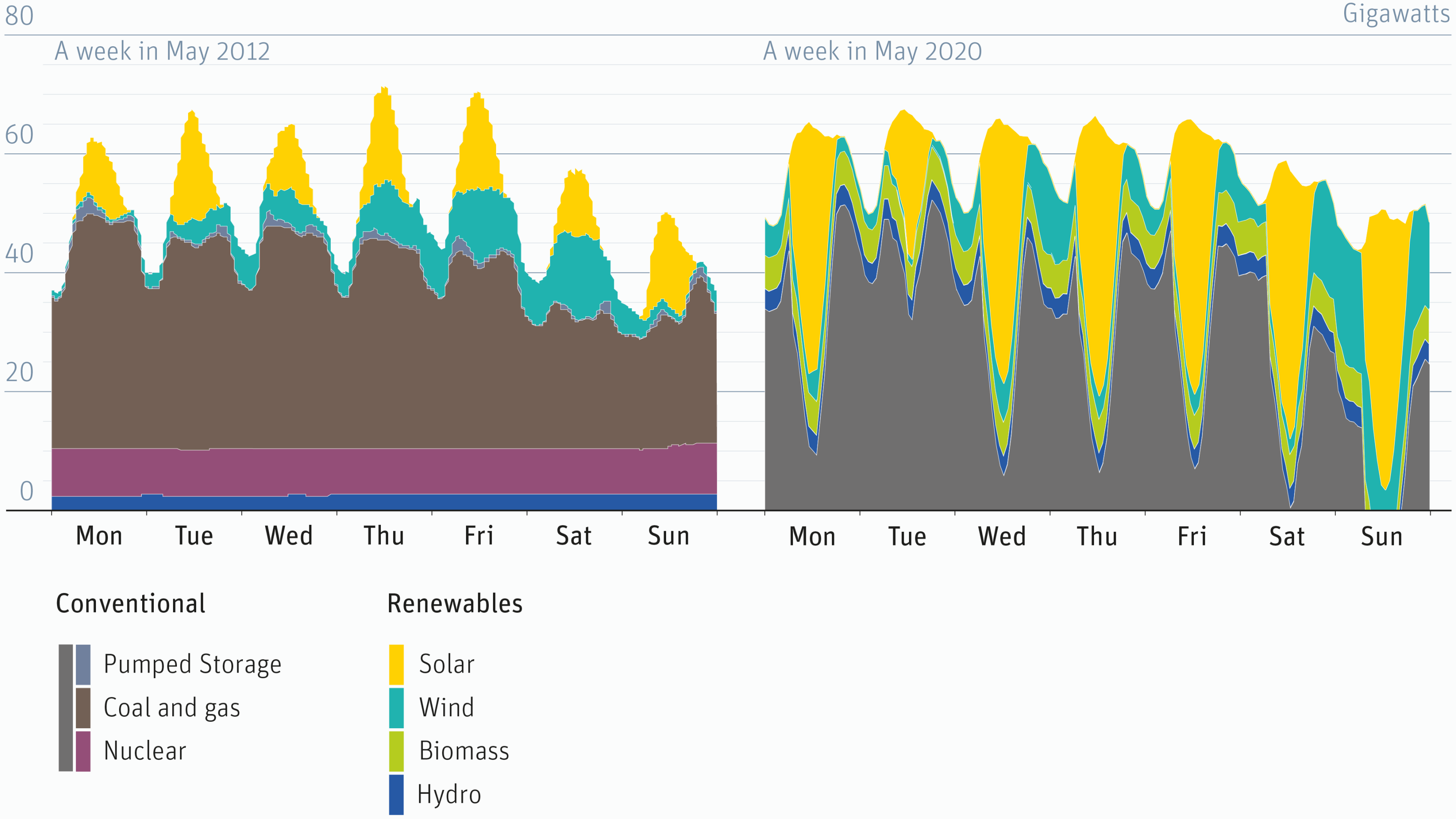
Y-axis is load on grid **after** renewable electricity production

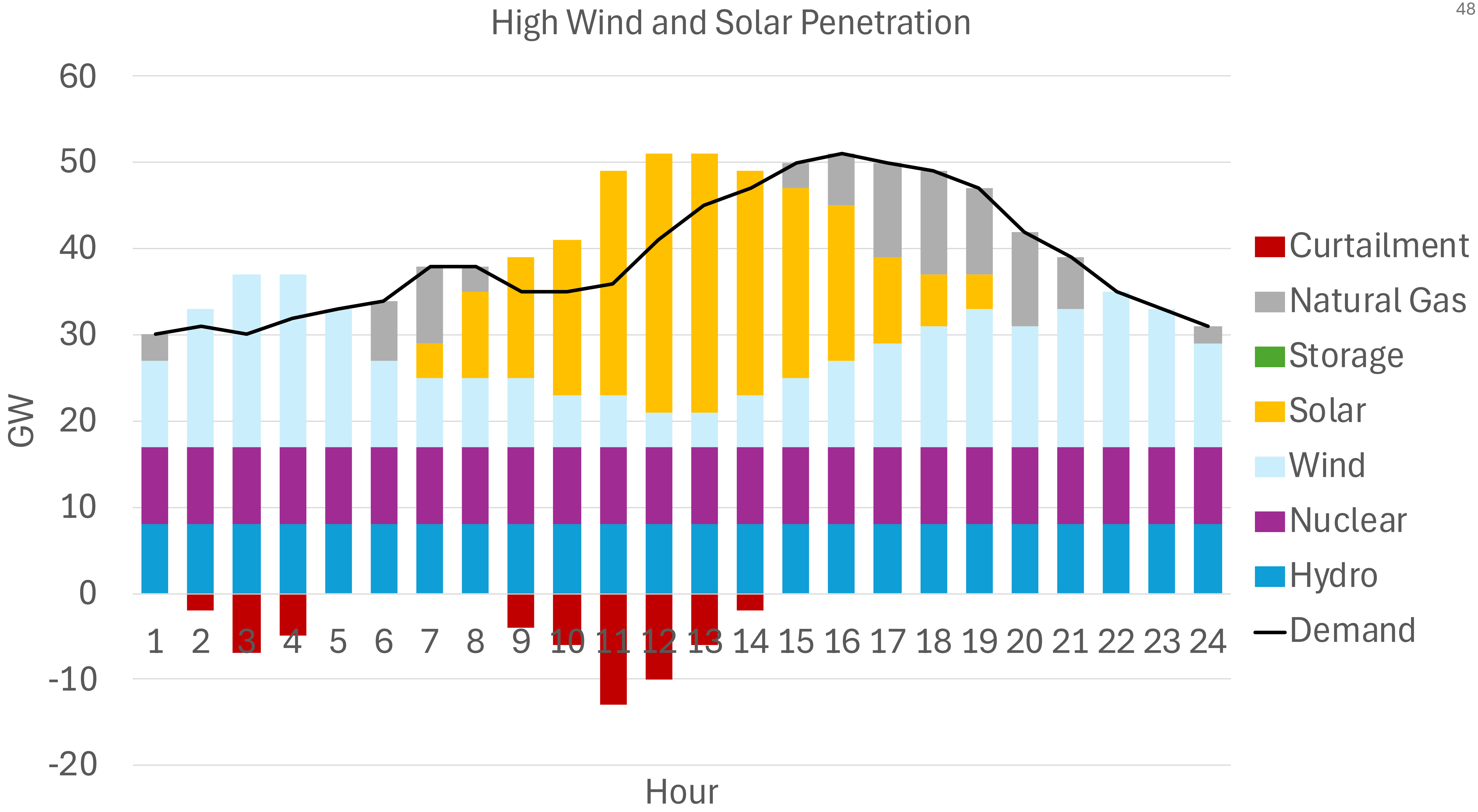


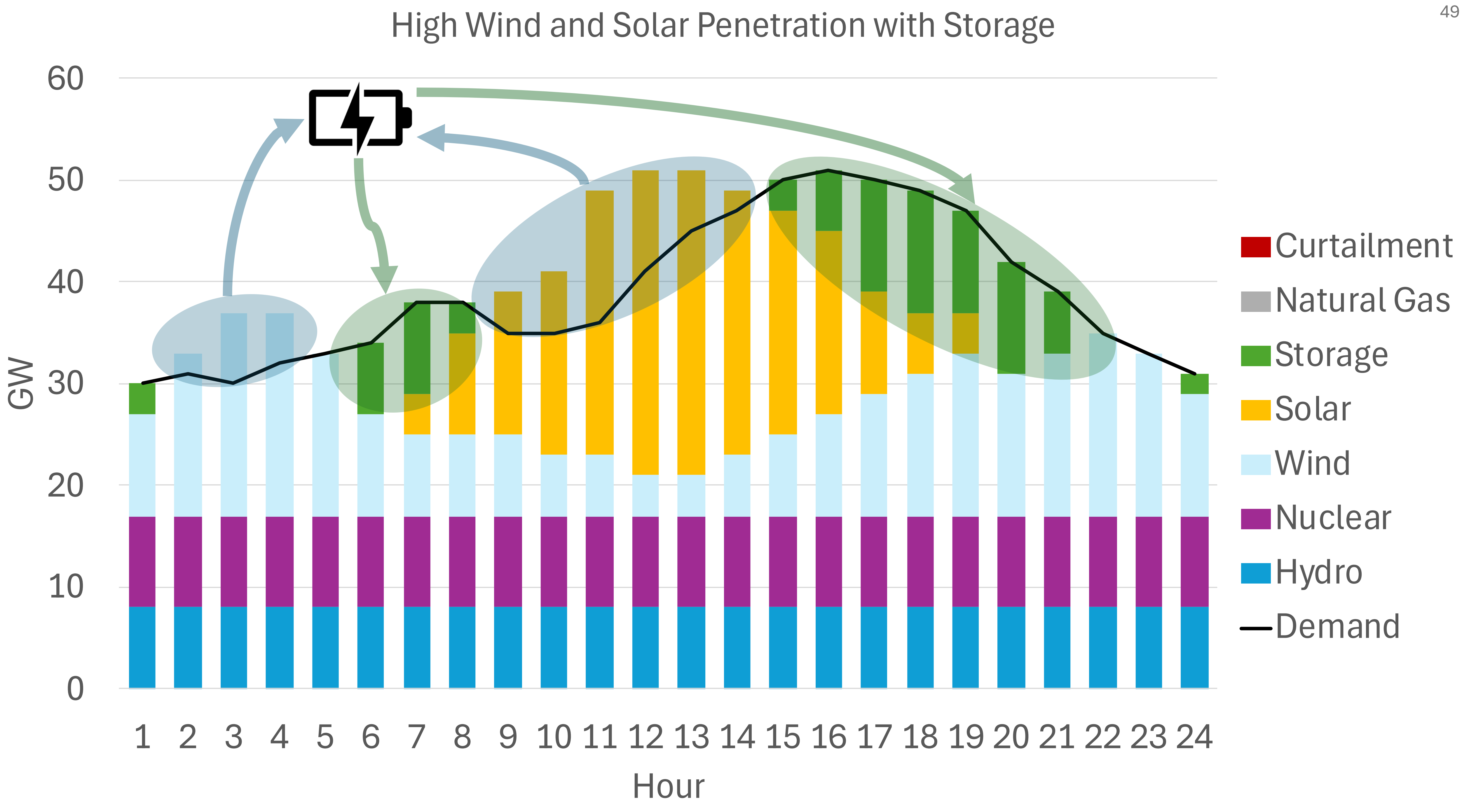
Renewables need flexible backup, not baseload

Estimated power demand over a week in 2012 and 2020, Germany

Source: Volker Quaschning, HTW Berlin

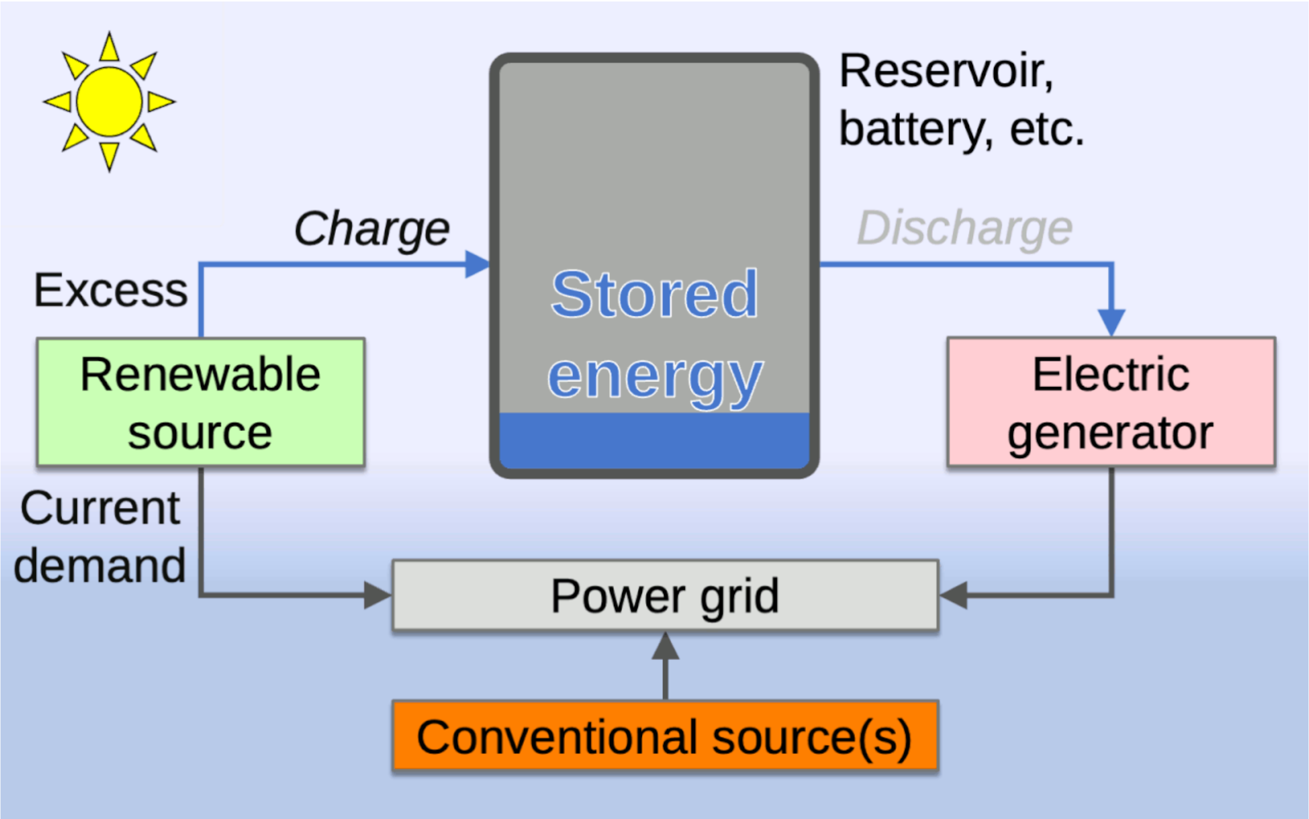



High Wind and Solar Penetration
60
50
40
30
20
10
0
-10
-20
GW
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Curtailment
Natural Gas
Storage
Solar
Wind
Nuclear
Hydro
Demand


High Wind and Solar Penetration with Storage
60
50
40
30
20
10
0
GW
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Curtailment
Natural Gas
Storage
Solar
Wind
Nuclear
Hydro
Demand

Storage

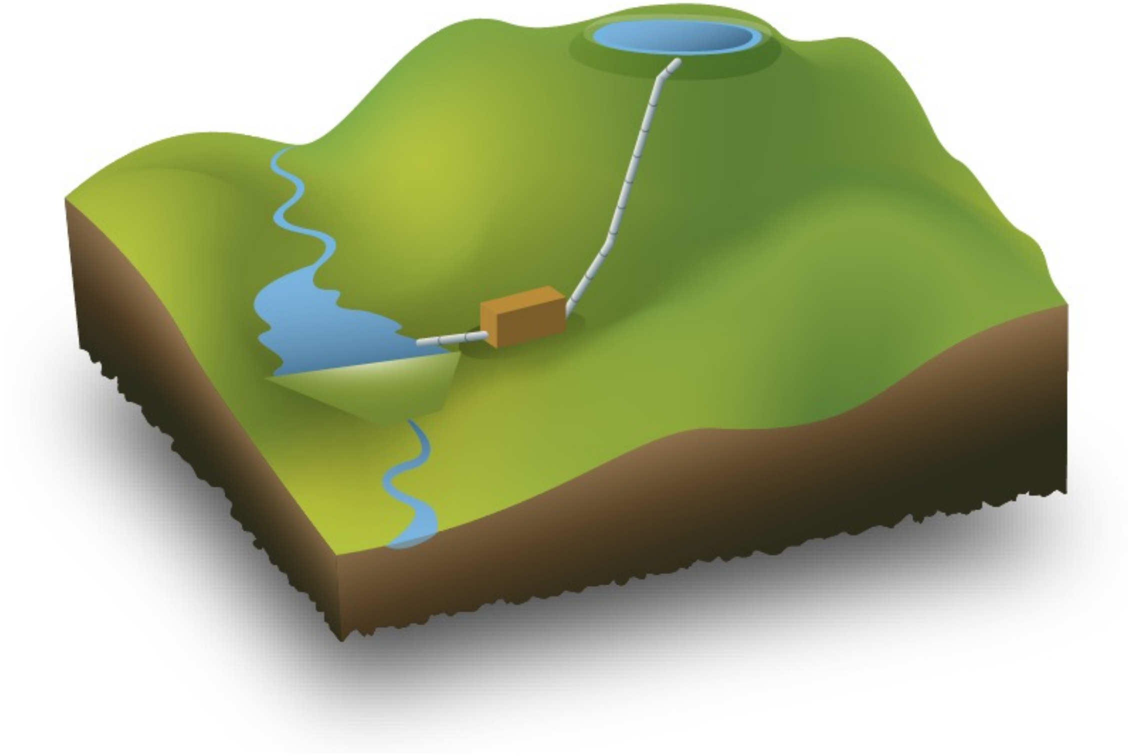
- Two primary methods for storing electricity
  - Batteries
  - Pumped hydro power

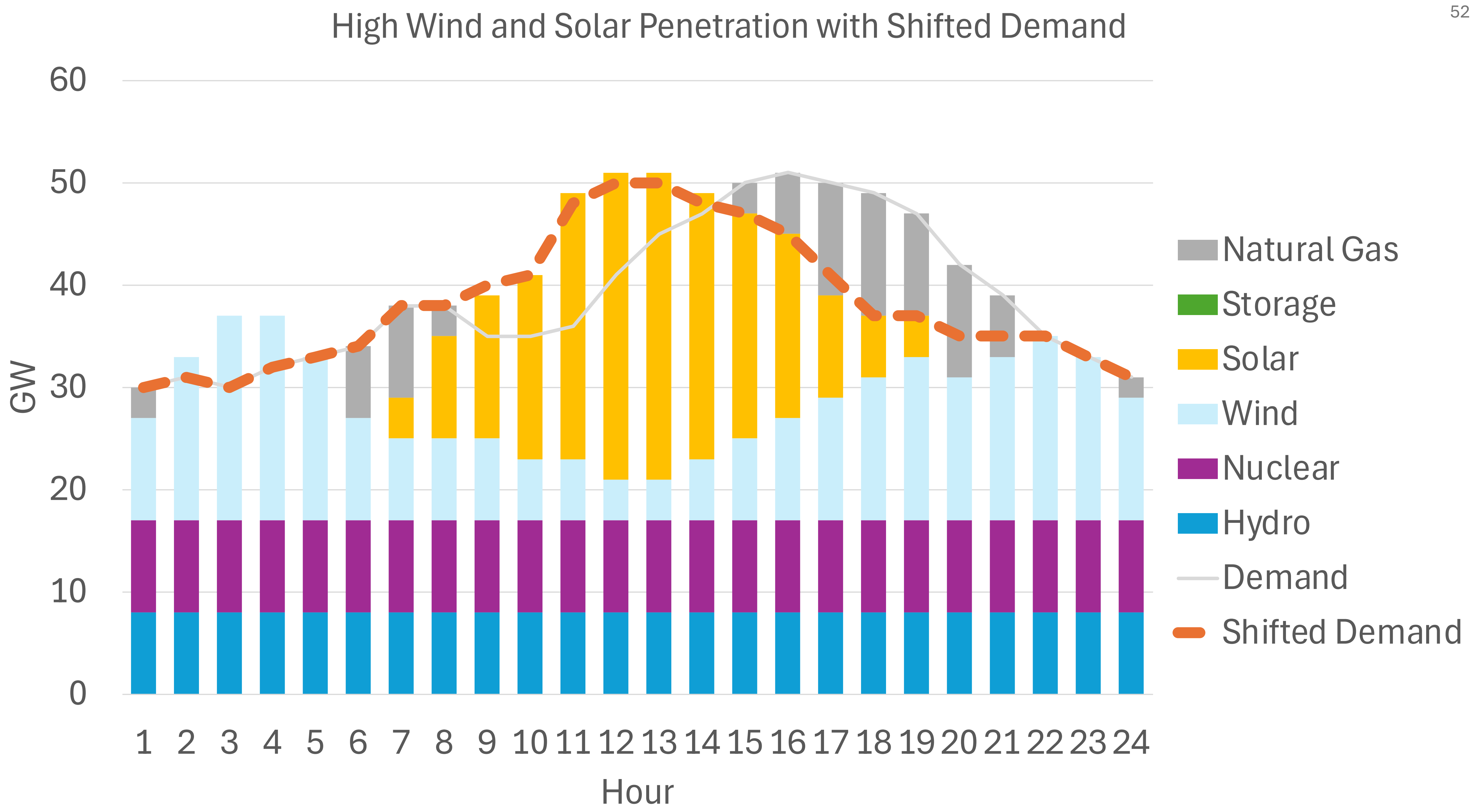


Source: Wikimedia Commons

Pumped hydro power

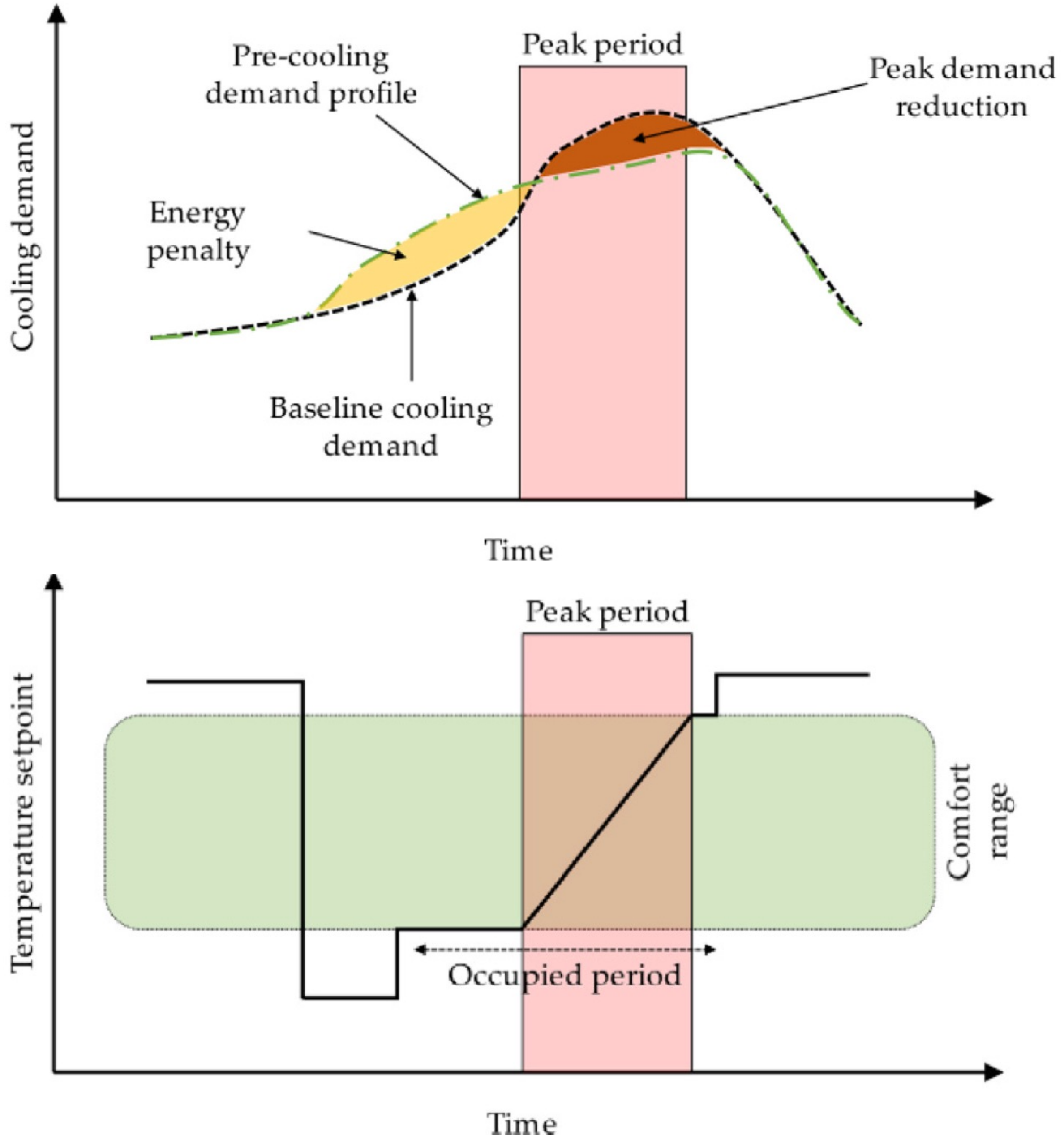
- Two reservoirs
- Pump water up to the higher reservoir (charge the battery) when electricity is clean and/or cheap
- Run water down through turbine when renewables are not producing




High Wind and Solar Penetration with Shifted Demand
GW
0
10
20
30
40
50
60
Hour
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Natural Gas
Storage
Solar
Wind
Nuclear
Hydro
Demand
Shifted Demand

Load shifting

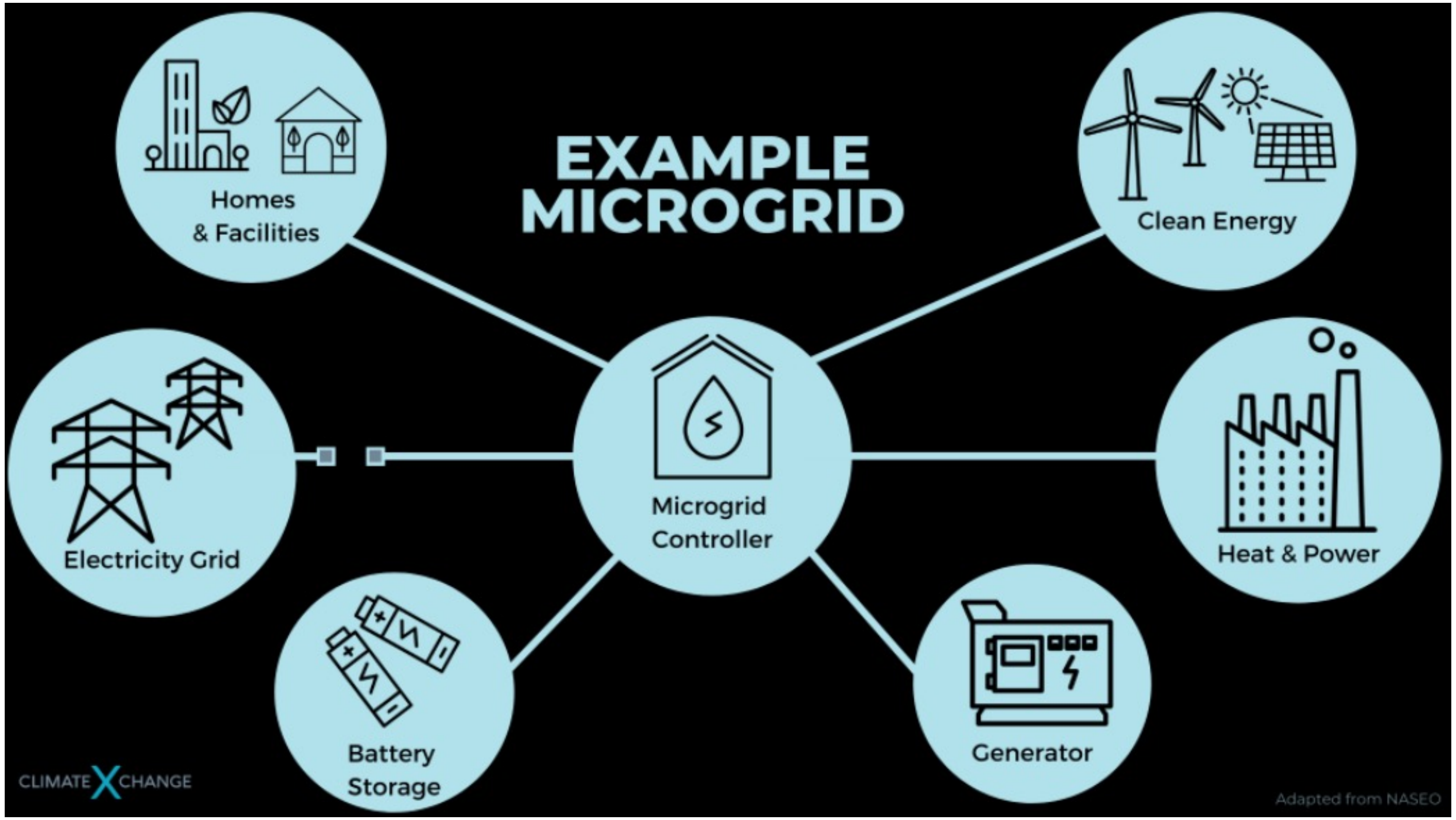
- Altering the demand side of the equation in addition to changing the supply side
- Changing time of use of certain residential appliances (e.g. dishwasher, washing machine)
- Pre-cooling or pre-heating buildings



Naderi, S., Pignatta, G., Heslop, S., MacGill, I., & Chen, D. (2022). Demand response via pre-cooling and solar pre-cooling: a review. *Energy and Buildings*, *272*, 112340.

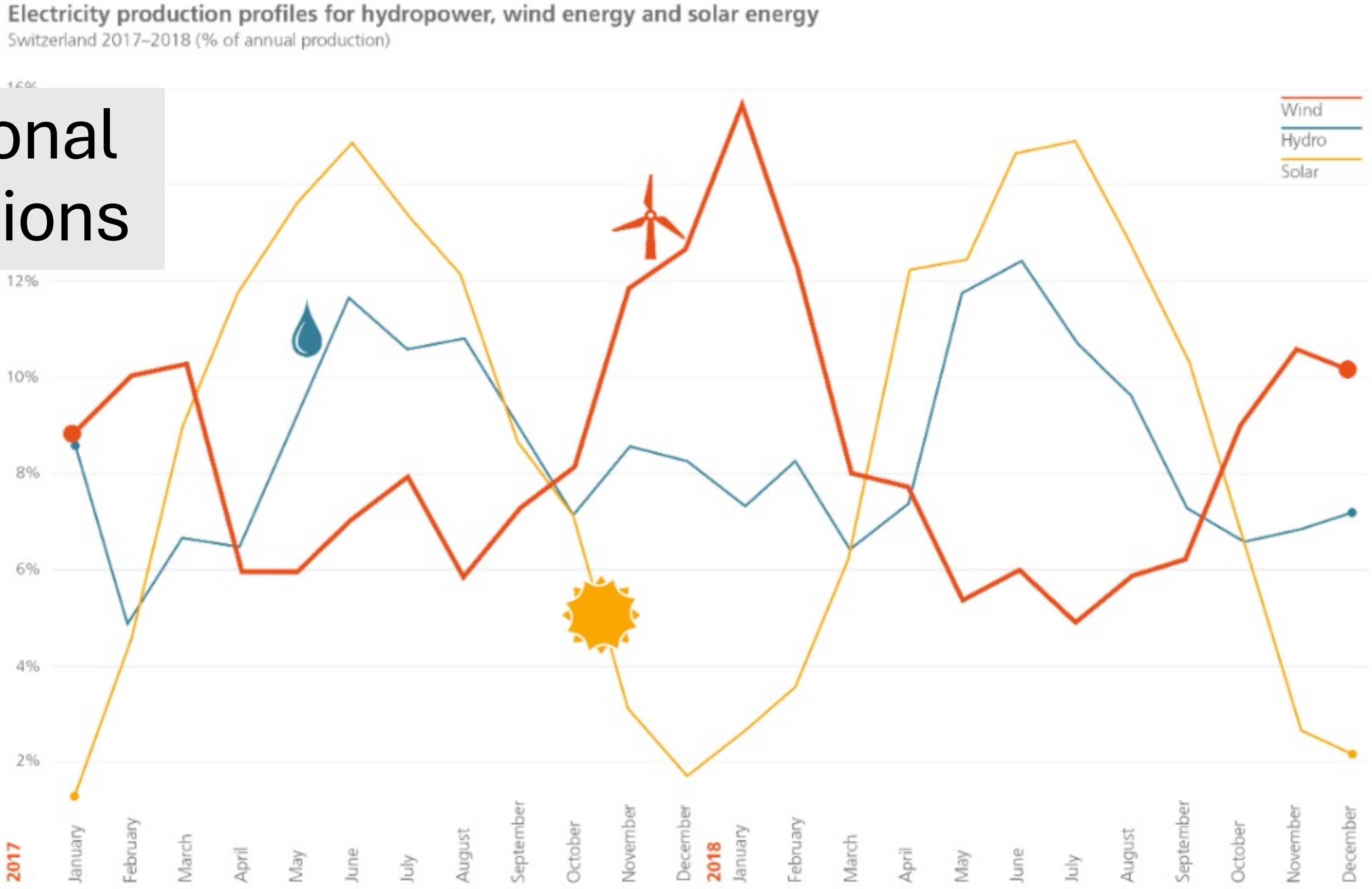
Microgrids and resiliency

- Renewables are well-situated to power microgrids, which provide power on the scale of a neighborhood or campus
- Can help with resiliency when the larger grid fails (e.g., from large storms)

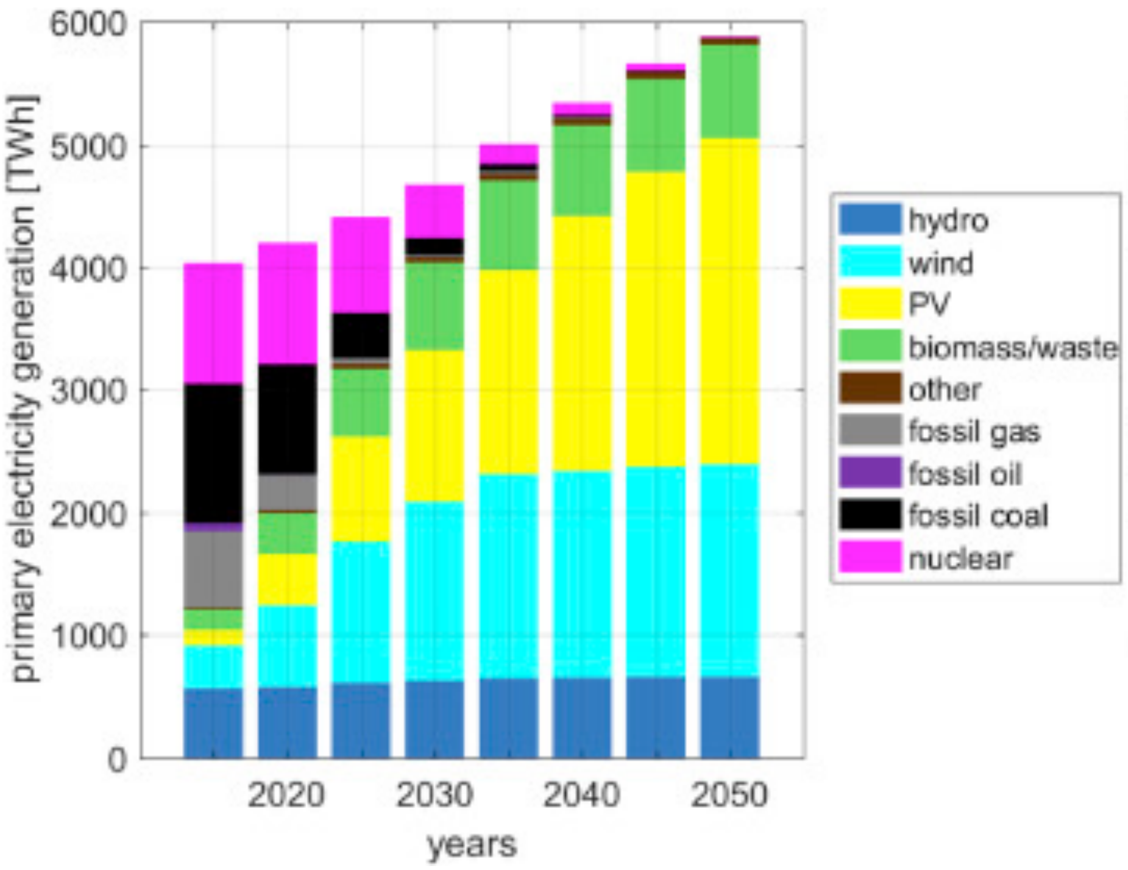


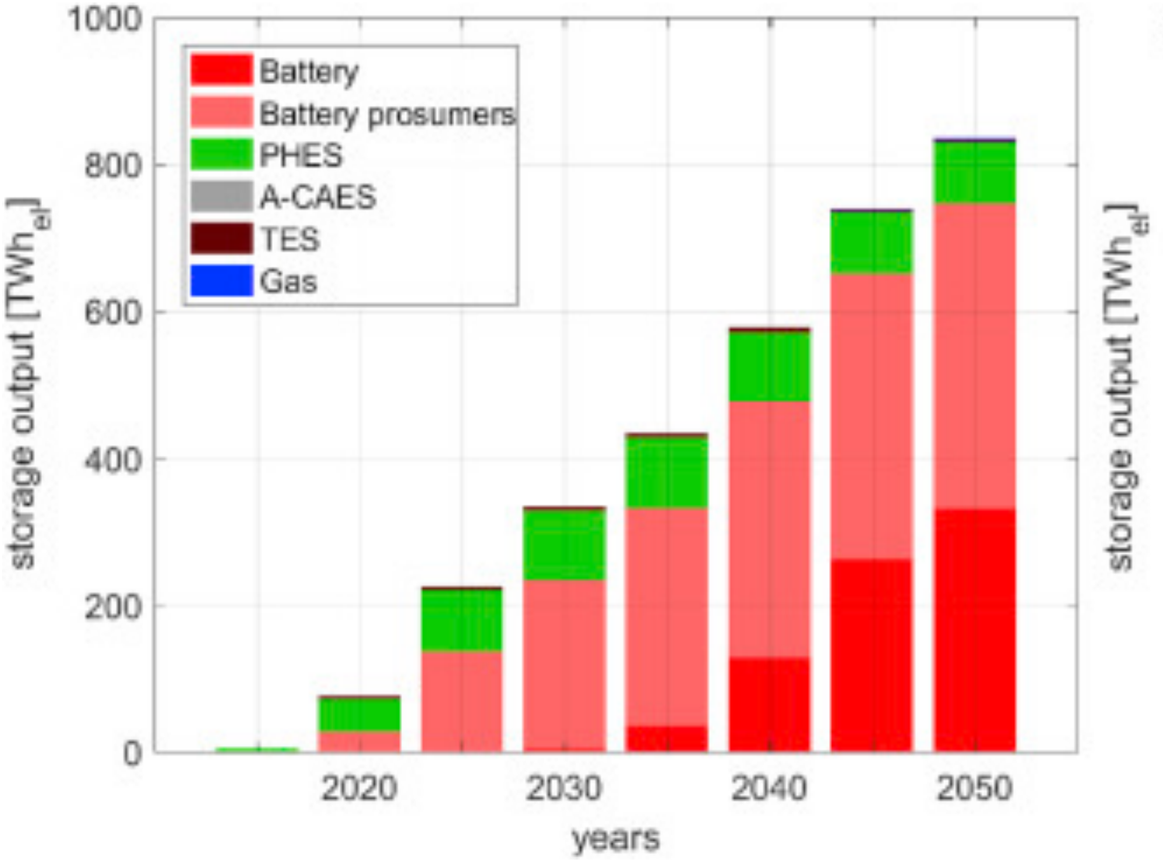
Source: Climate X Change

Seasonal variations



A 100% Renewable Europe?





Michael Child, C. Breyer, et al. Renewable Energy 139 (2019) 80-101

Resources

- Hourly “demand-driven” mix in CH: https://horocarbon.ch/mix.php