

HÛPERCAST · TOOL SHOWCASE

How the world makes electricity

From four equations to 31,772 terawatt-hours a year. Every picture on this page was built by a different tool from the HÛpercast catalogue, from open data.

31.8k TWh

world electricity, 2025

43%

low-carbon share

8.7%

from solar

33%

still from coal

Maxwell: what electricity is

In 1865 James Clerk Maxwell wrote four equations. They explain every motor, generator and power line, and they predict light. This chapter uses 16 pieces and 20 tools.

Background: AI-generated (FLUX)

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}$$

Charge makes electric field (Gauss)

$$\nabla \cdot \mathbf{B} = 0$$

No magnetic charges: field lines always loop

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

A changing magnetic field makes an electric field (Faraday)

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Current and a changing electric field make a magnetic field (Ampère–Maxwell)

Show accessible version

The accessible version

Same equations via MathJax: numbered, with hidden MathML for screen readers, and an explorer you can step through with the arrow keys.

• MathJax

MathJax 3, assistive MathML and the a11y explorer.

Four equations, all of electricity

KaTeX draws them instantly. An AC wave  is just these equations at work (three-phase, drawn inline by function-plot).

• KaTeX

• function-plot

Equations: Maxwell (1865), modern vector form.

Maxwell's equations

Maxwell, built term by term

Each equation arrives with what it means. Then empty space is assumed, and the wave equation and the speed of light fall out.

► Manim CE

Manim Community, rendered on CPU.

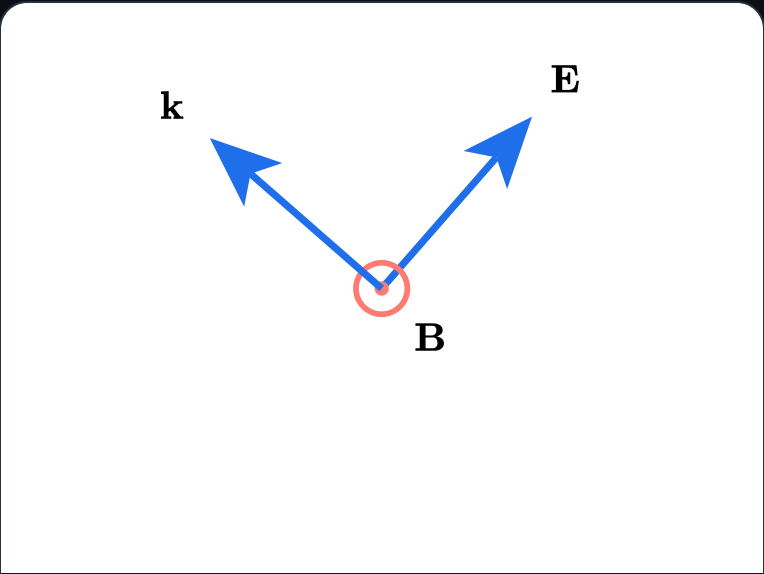
SymPy	curl(curl E) identity holds: yes · $c = \frac{1}{\sqrt{\mu_0\sqrt{\epsilon_0}}} = 299,792,458.000 \text{ m/s}$
SageMath	$\text{sqrt}(1/(\text{eps0}*\mu_0)) = 299,792,458.000 \text{ m/s}$
Maxima	$1/(\sqrt{\epsilon_0}\cdot\sqrt{\mu_0}) = 299,792,458.000 \text{ m/s}$
Defined	$c = 299,792,458 \text{ m/s}$ exactly (SI). Constants: CODATA 2018.

Three maths engines, one answer

SymPy derives the wave equation from Maxwell. SageMath and Maxima re-derive the speed separately. All three agree.

► SymPy ► SageMath ► Maxima

Computed here; scripts kept with the page.



E, B and the direction of travel

Penrose lays the diagram out from the maths: it is told $E \perp k$ and B points out of the page, and solves for a layout that obeys.

► Penrose

Penrose: Domain, Substance and Style programs.

Couldn't load mathbox

Cannot read properties of undefined (reading 'renderer')



Move the magnet, light the bulb

PhET's tested simulation, embedded as is.

• PhET

PhET Interactive Simulations, University of Colorado Boulder, CC BY 4.0.

Light, seen as E and B

A travelling wave in 3D. The electric field (amber) and magnetic field (blue) stay at right angles. Drag to orbit.

• Mathbox

Mathbox 2 on three.js.

t = 2.03 ns light travelled 0.61 m



```
for n in range(steps):
    Hx[:, :] -= dt / (mu0 * dx) * (Ez[:, 1:] - Ez[:, :-1])
    Hy[:, :] += dt / (mu0 * dx) * (Ez[1:, :] - Ez[:-1, :])
    Ez[1:-1, 1:-1] += dt / (eps0 * dx) * ((Hy[1:, 1:-1] - Hy[:-1, 1:-1])
    - (Hx[1:-1, 1:] - Hx[1:-1, :-1]))
    Ez[cx, cy] += np.sin(2 * np.pi * f0 * n * dt) * (1 - np.exp(-(n /
60) ** 2))
    Ez *= damp
    if n % 3 == 0:
```

The loop that does it

The whole simulation is these seven lines: update H from E, then E from H.

▶ Shiki

Highlighted at build time.

NumPy FDTD · Yee scheme · 1 GHz dipole · λ = 30 cm

A wave leaving an antenna

Maxwell's curl equations stepped on a 360 × 360 grid (the Yee scheme). Rings spread at the speed of light, 30 cm apart at 1 GHz.

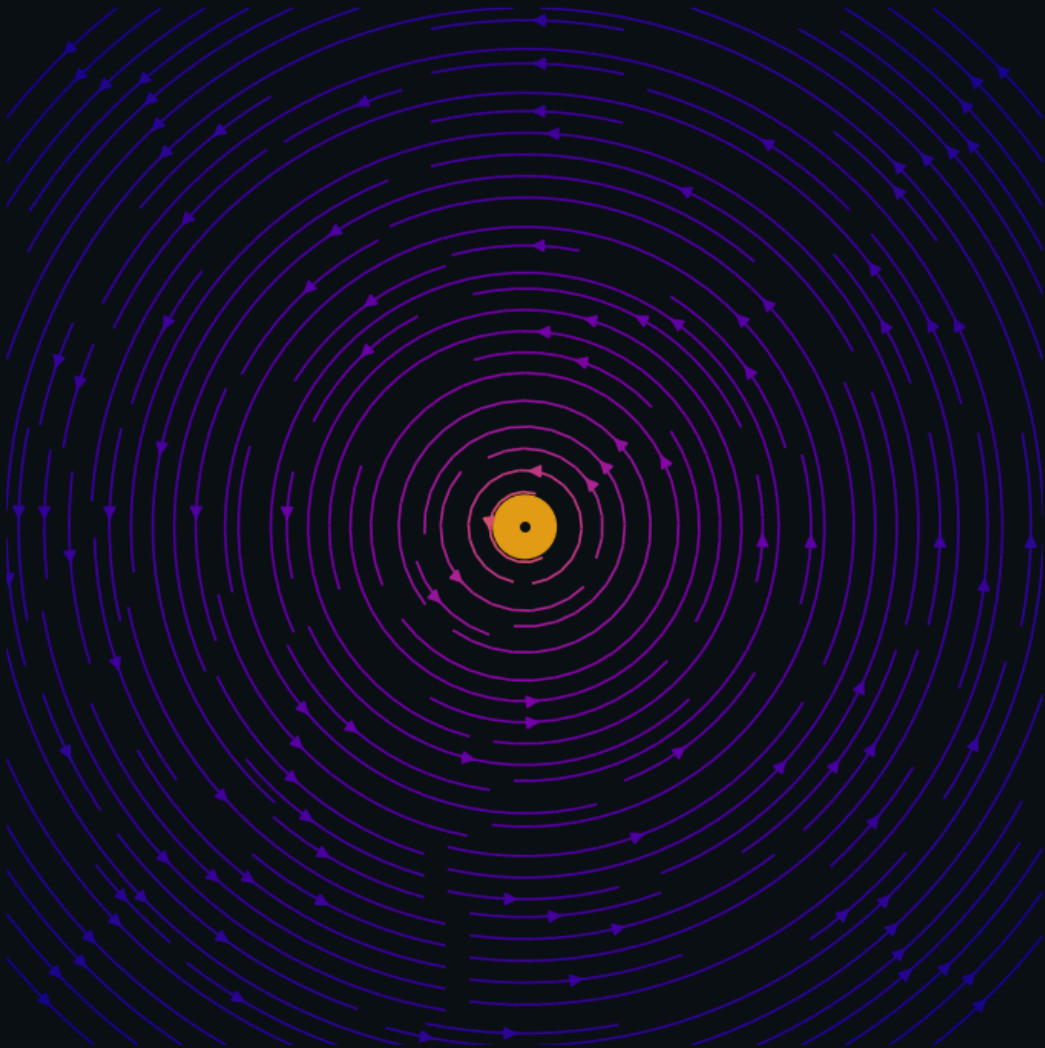
▶ NumPy

▶ SciPy

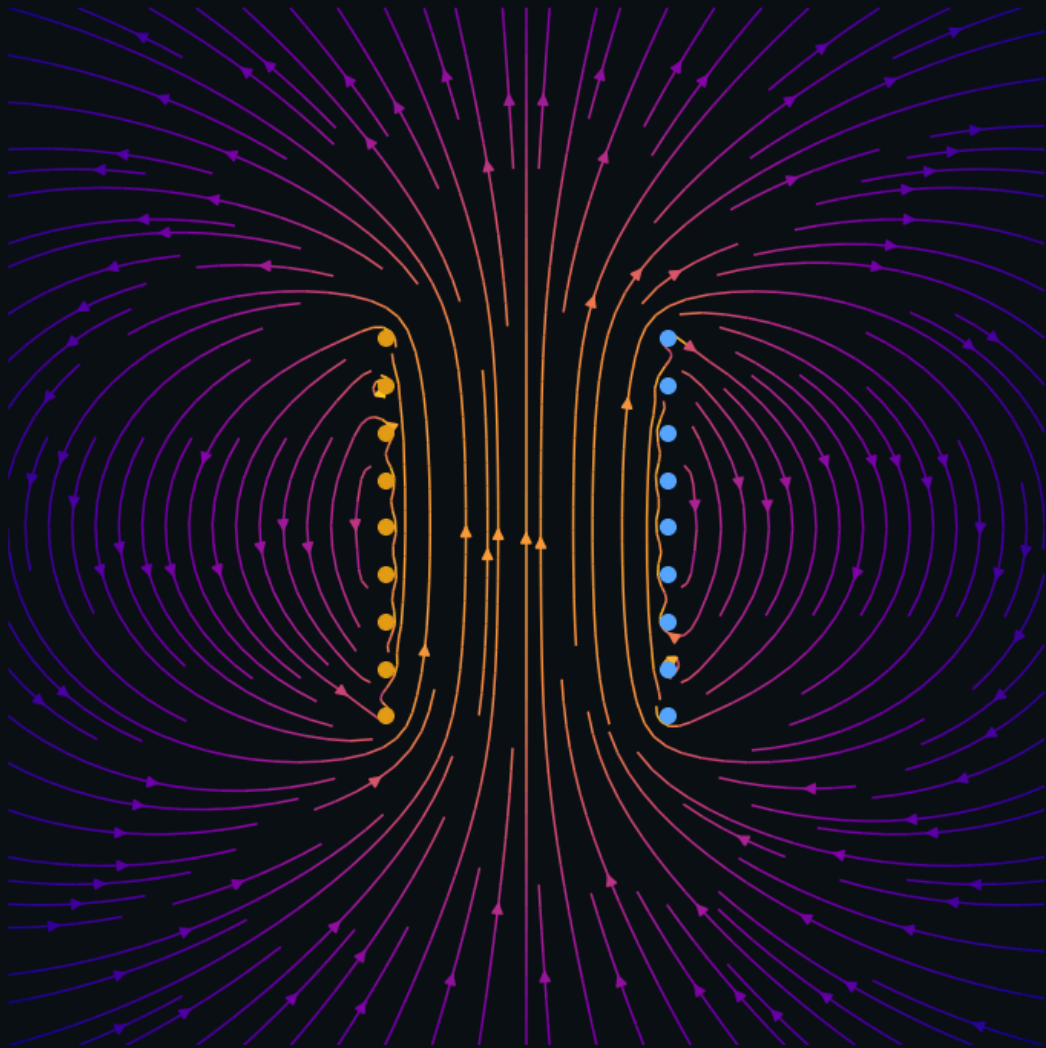
▶ matplotlib

Computed here, 900 time steps.

Straight wire, current out of the page



Coil (solenoid), side view: field runs straight through the middle



matplotlib streamplot · Biot–Savart computed with NumPy

Field lines round a wire and a coil

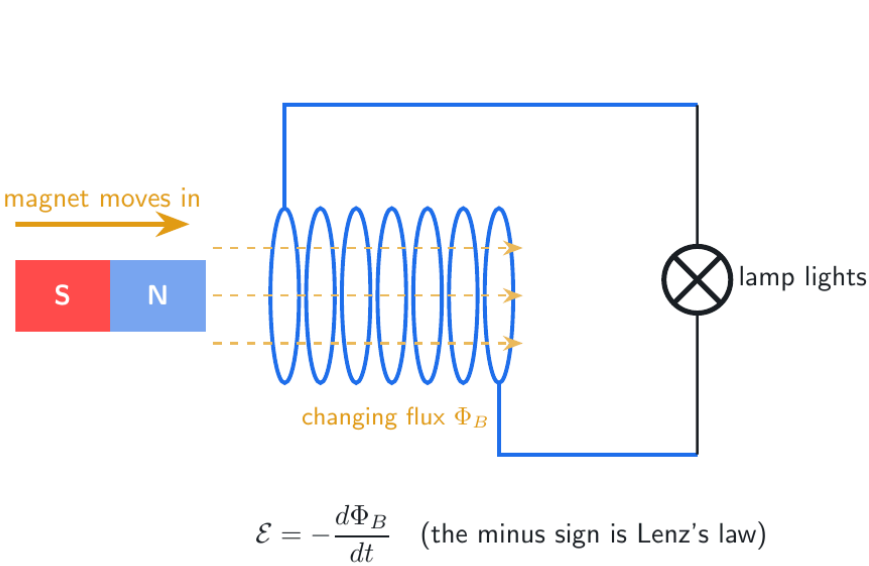
Biot–Savart summed over every bit of wire, then traced with streamplot. A coil straightens the field into a beam through its middle.

▶ matplotlib

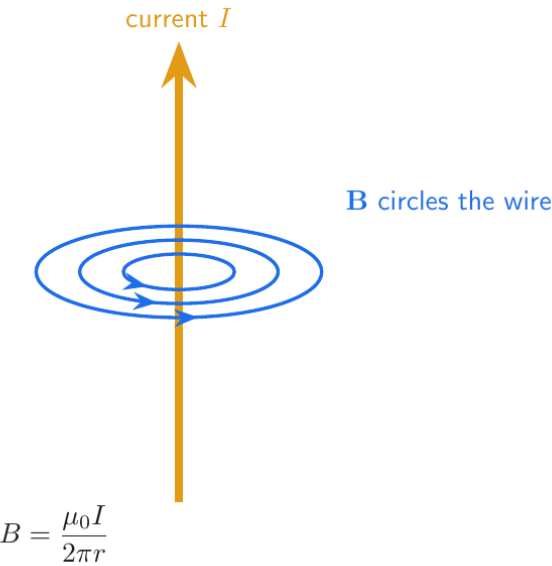
▶ NumPy

Computed here.

Faraday’s law of induction



Right-hand grip rule



Couldn't load glow

Can't create canvas: WebGL not supported

An electron in a magnetic field

The Lorentz force $F = q \mathbf{v} \times \mathbf{B}$ bends it into a helix. Stepped live in the browser.

• GlowScript / VPython

GlowScript 3.2.

Faraday and the right hand

Print-grade figures for the handout: a moving magnet drives current through a lamp, and the grip rule for a wire.

[▶ TikZ](#) [▶ circuitikz](#)

LaTeX, vector output.

Couldn't load desmos

Desmos script blocked or key refused

Couldn't load geogebra

GeoGebra script blocked

Play with power

Drag the sliders. Real power is $V \cdot I \cdot \cos \varphi$: shift the current out of phase and the dashed power curve dips below zero.

• [Desmos](#)

Desmos API (trial key).

The field round a wire, in 3D

Rings of arrows circle the current, weaker further out ($B \propto 1/r$). Rotate it.

• [GeoGebra 3D](#)

GeoGebra, non-commercial use.

Rendering on the Mac

ManimGL scene written; runs on the Mac node.

Coming next

Qucs-S download is blocked here; will render via GitHub Actions.

The light wave, lit in 3D

Shaded 3D surfaces and a flying camera need OpenGL.

[ManimGL](#)

Scene: maxwell_gl.py

Where Maxwell meets a circuit

Matching an antenna to its feed line on a Smith chart.

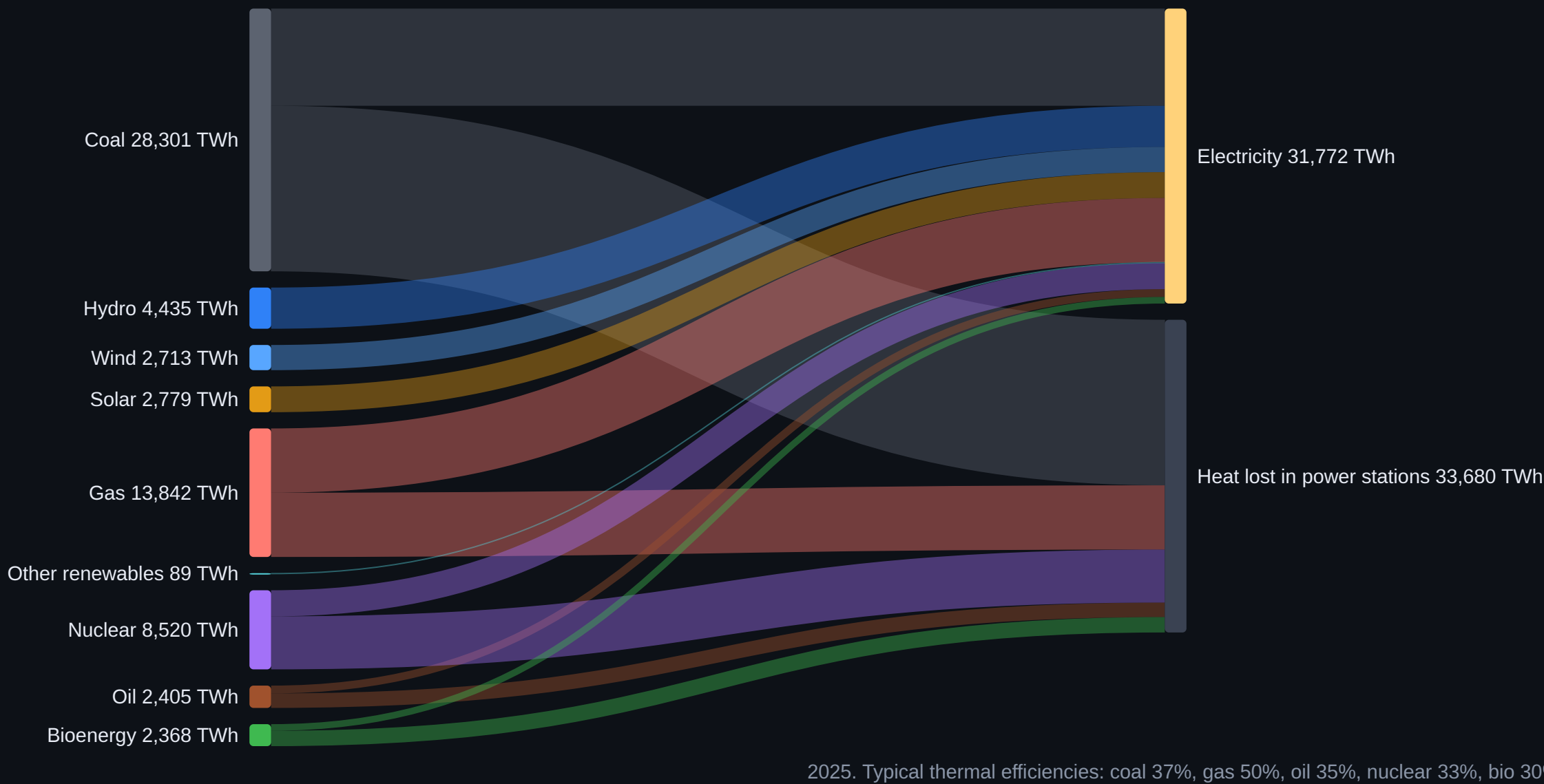
[▶ Qucs-S](#)

CHAPTER 2

Make: turning motion into current

Almost every power station spins a magnet inside coils of wire, just as Faraday found.
Water, wind, steam and sunlight are just different ways to get there.

Background: AI-generated (FLUX)



Where the energy goes

Fuel burned on the left; electricity made and heat lost on the right. A third to a half of a thermal plant's fuel leaves as waste heat.

[D3](#) [d3-sankey](#)

Our World in Data energy dataset (CC BY 4.0). Efficiencies: typical values, labelled.

WebGL is not supported by your browser - visit <https://get.webgl.org> for more info

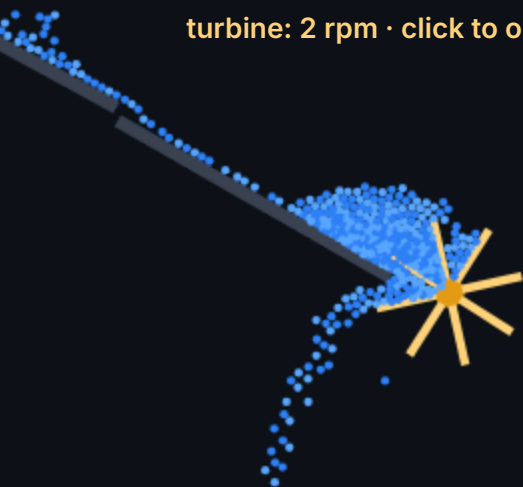
Every technology on three axes

How often it runs, what it costs and what it emits. Rotate the cube.

[Plotly](#)

Lifecycle CO₂: IPCC AR5 WGIII Annex III medians. Capacity factor and cost: rough typical values.

turbine: 2 rpm · click to open the gate



Water through a turbine

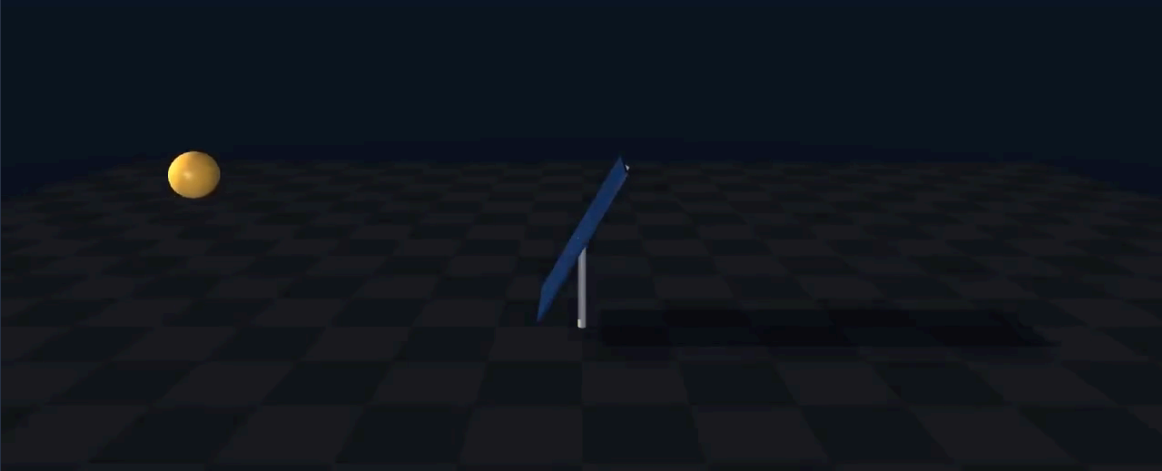
2D physics: falling water pushes the blades round. Click to open the gate wider.

[matter.js](#)

Couldn't load rapier

07:28 panel tilt -60°

THREE.WebGLRenderer: Error creating WebGL context.



A rotor in the wind

3D physics: gusts push three blades on a hinged hub while the generator holds it back.

• [Rapier](#) • [three.js](#)

Illustrative torque model.

A panel that follows the sun

A motor turns a solar panel to face the sun from 6 am to 6 pm, simulated with joints and control.

▶ [MuJoCo](#)

Simulated here.

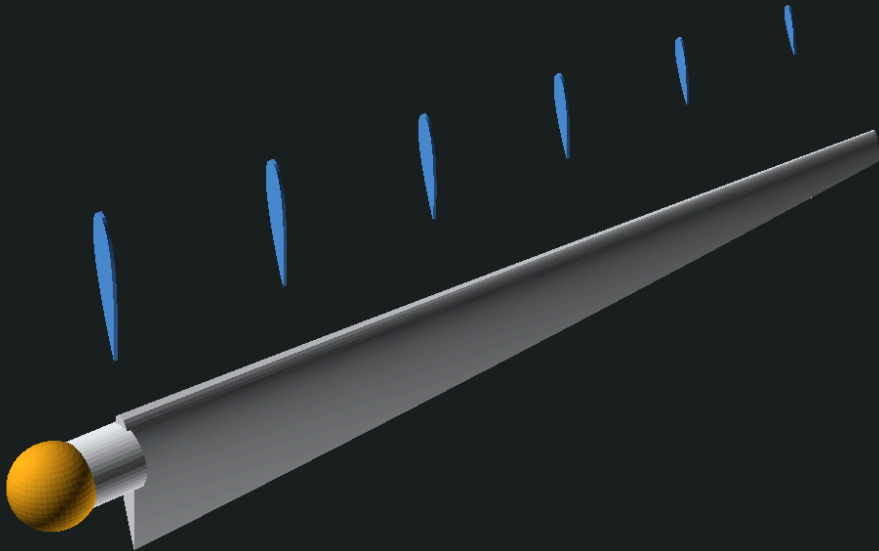
Blender render of a wind farm at dusk

A wind farm at dusk

Photoreal rendering, built entirely from code: terrain, sky and 36 turbines.

▶ [Blender](#)

Cycles, CPU.



Couldn't load mol3d

error creating viewer: TypeError: Cannot read properties of null (reading 'clearDepth')

The silicon in a solar cell

The diamond-lattice crystal every panel is made of, built atom by atom.

• [3Dmol.js](#)

Lattice constant 5.431 Å.

A blade, as a parametric part

Airfoil sections (blue) show how the blade tapers and twists from root to tip. Change one number; the part rebuilds.

▶ OpenSCAD



WebGL does not seem to be available.

This can be caused by an outdated browser, graphics card driver issue, or bad weather. Sometimes, just restarting the browser helps. Also, make sure hardware acceleration is enabled in your browser.

For a list of supported browsers, refer to <http://caniuse.com/#feat=webgl>.

Nature's solar cell

Photosystem II, the protein plants use to turn sunlight into electrical charge, loaded live from the Protein Data Bank.

● Mol*

PDB 3WU2 (Umena et al. 2011), RCSB PDB.

Waiting for a photo API key

Pexels/Unsplash API is blocked here.

Rendering next

rembg's model download is blocked here.

The real thing

A real photograph where it matters.

● Pexels / Unsplash

Lifting the turbine out

An AI cutout turns a flat picture into layers for parallax.

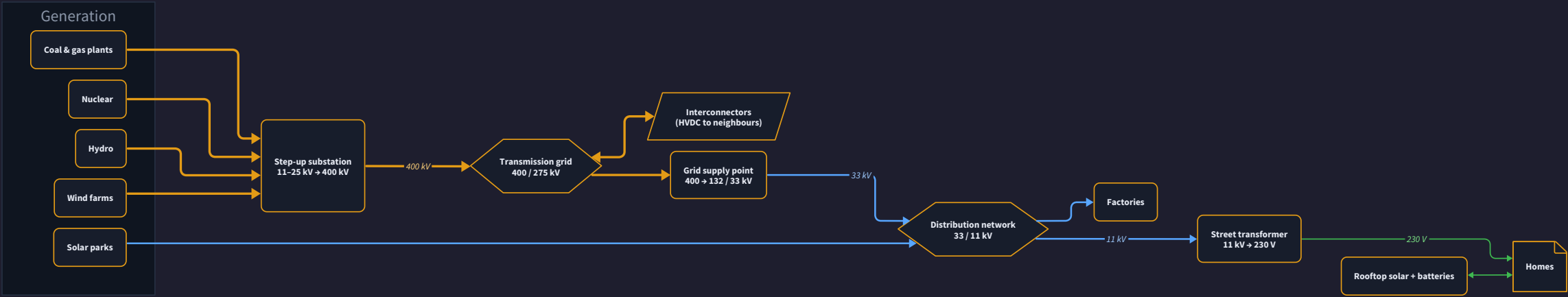
▶ rembg

CHAPTER 3

Move: wires, transformers and switches

Electricity is made far away and used at 230 V. Transformers, rectifiers and inverters bridge the gap, and the grid keeps everything at 50 Hz.

Background: AI-generated (FLUX)



From power station to plug

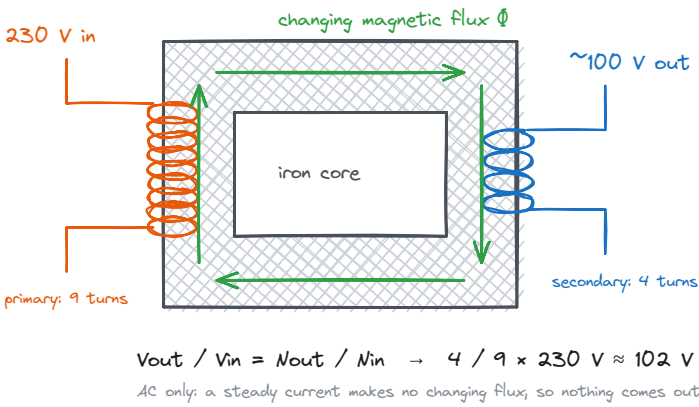
The grid as an architecture diagram. The power lines draw themselves in order: generation, transmission, distribution, home.

▶ D2 anime.js

Voltages: typical European values.

Couldn't load transformer

THREE.WebGLRenderer: Error creating WebGL context.



How a transformer works

The same idea as a whiteboard sketch: turns ratio sets the voltage, and only AC passes.

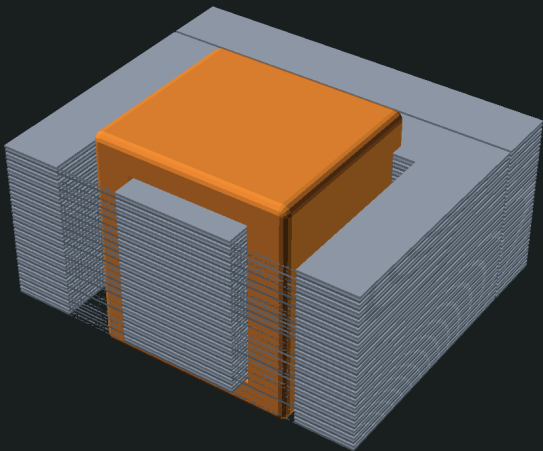
▶ Excalidraw

A transformer, built in 3D

Magnetic flux (green) runs round the iron core and reverses with the AC, slowed 100×. The camera follows a keyframed path; grab it to orbit.

three.js Theatre.js

Built in code; no model files.



The core, as a real part



Poke a live circuit

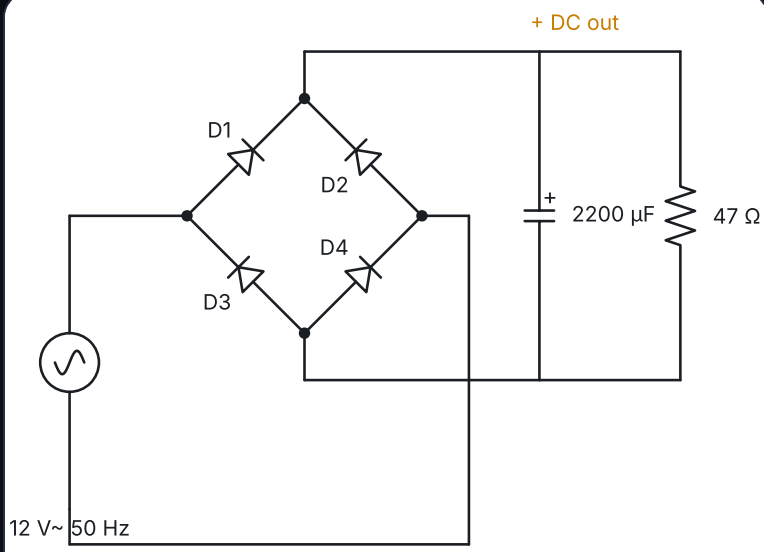
A parametric E-I core: 40 laminations and a copper winding. Change one number in the code and the part rebuilds.

► [OpenSCAD](#)

Falstad's simulator: current dots flow through a transformer. Click switches, drag values.

● [CircuitJS](#)

CircuitJS by Paul Falstad (GPL).



AC in, DC out

The bridge rectifier in every charger, drawn from code.

► [schemdraw](#)



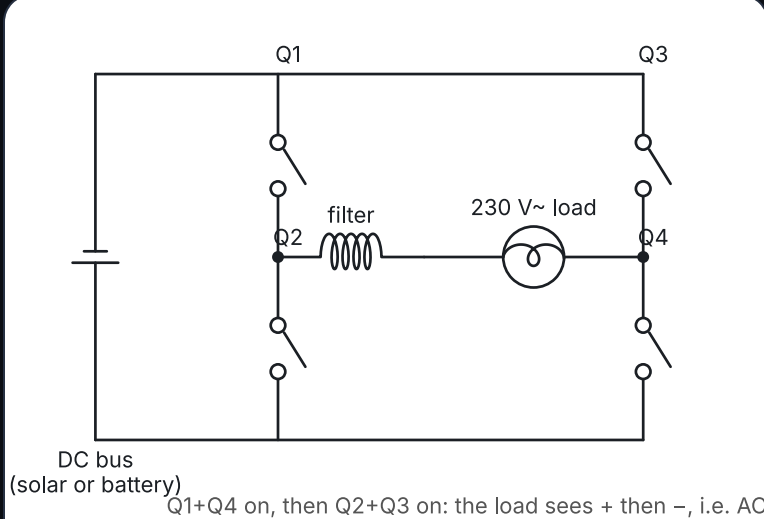
...and simulated

ngspice runs the same circuit. The capacitor holds the voltage up between peaks; the mains current comes in short gulps.

► [ngspice](#)

► [matplotlib](#)

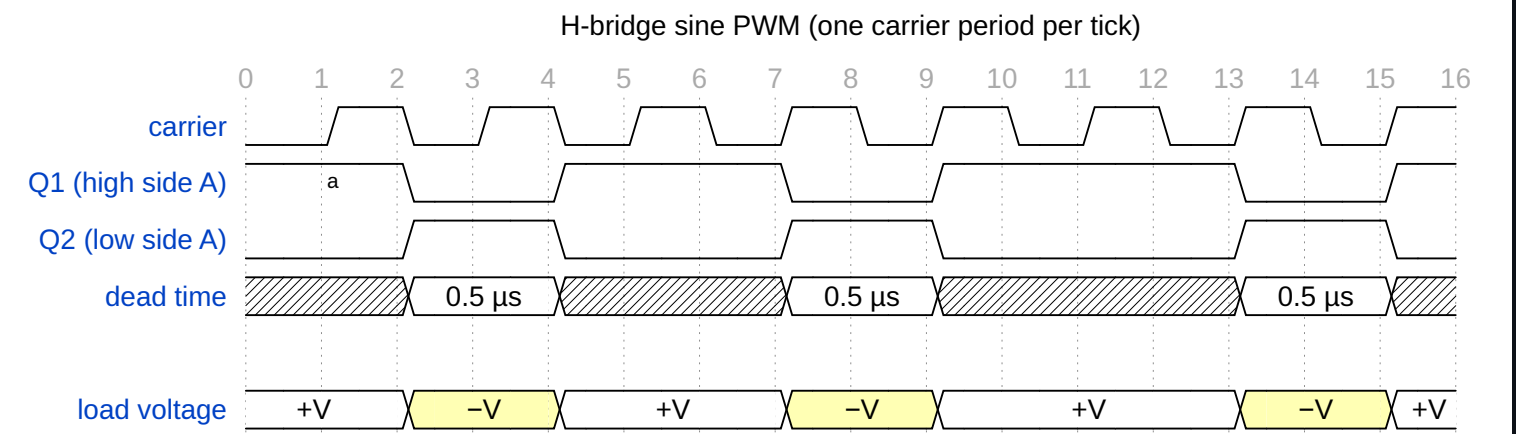
SPICE model 1N4007; 12 V rms, 2200 µF, 47 Ω.



DC back to AC: the inverter

Every solar panel and battery needs one. Four switches flip the load's polarity many times a cycle.

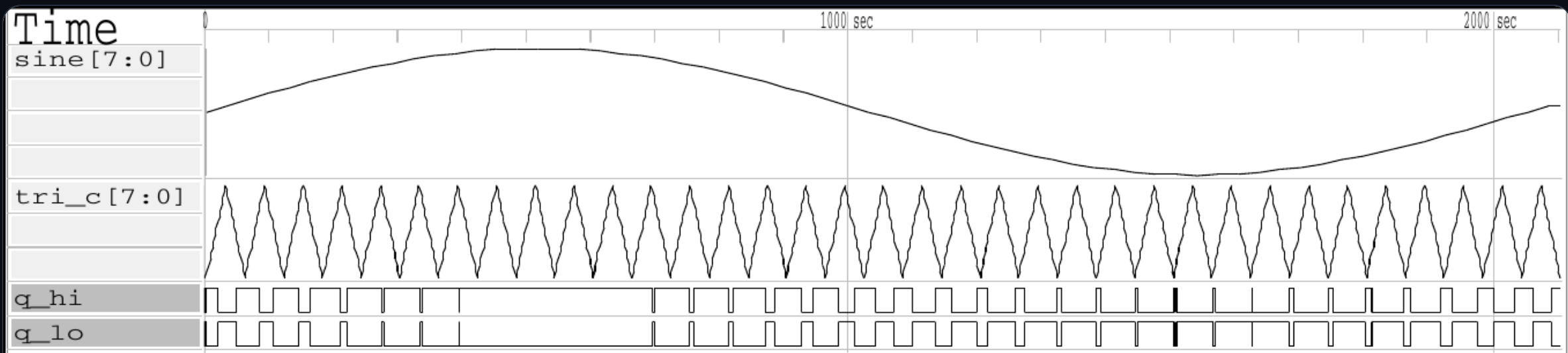
► [schemdraw](#)



The switching pattern, drawn

A timing diagram of the H-bridge's gate signals and the voltage the load sees.

● [WaveDrom](#)



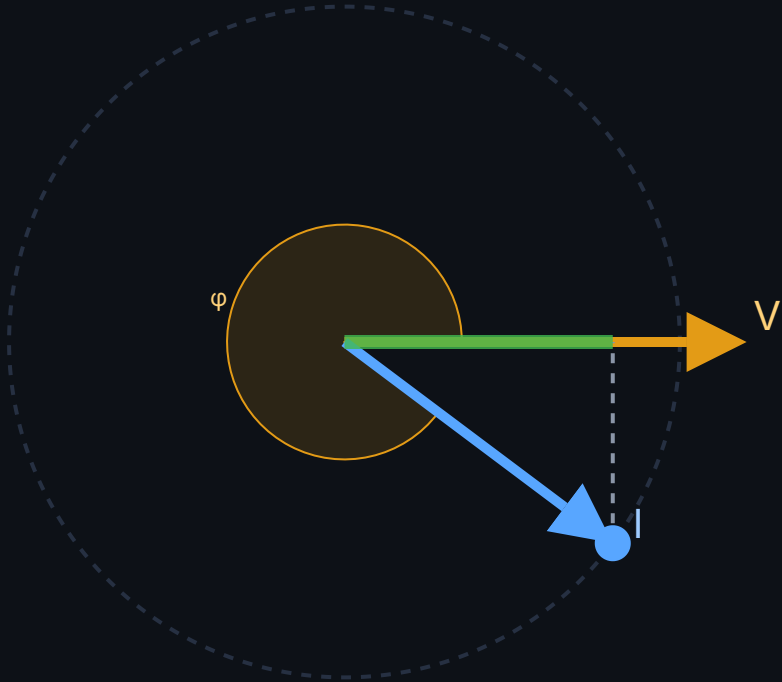
The switching pattern, simulated

The PWM generator written as real Verilog and simulated cycle by cycle. A sine is compared with a fast triangle; the gate signals widen and narrow with the sine.

► [Icarus Verilog](#)

► [GTKWave](#)

$\varphi = 37^\circ \cdot$ power factor = **0.80** · lagging (motors)



green bar = the part of the current that does real work

Power factor, by hand

Drag the current arrow. The angle to the voltage sets how much of the current does real work.

JSXGraph

Circuit

$R = 2\ \Omega$, $L = 1\text{ mH}$, $C = 100\ \mu\text{F}$, step input V_o

Maxima

$$v_C(t) = V_0 \left[1 - e^{-1000t} \left(\cos 3000t + \frac{1}{3} \sin 3000t \right) \right]$$

Check

$$\omega_o = 1/\sqrt{LC} = 3162\text{ rad/s}; \alpha = R/2L = 1000\text{ s}^{-1};$$
$$\omega_d = \sqrt{(\omega_o)^2 - \alpha^2} = \text{3000 rad/s} \checkmark$$

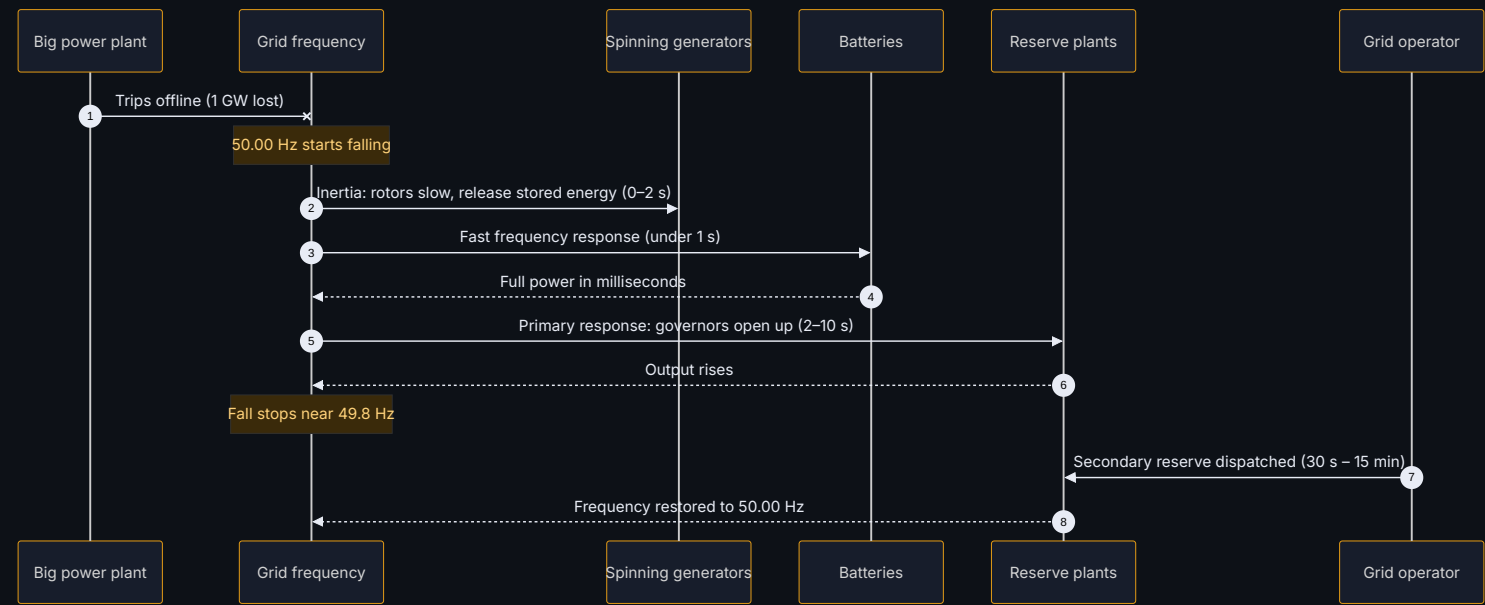
Switching on a grid filter

Maxima solves the series RLC filter exactly with a Laplace transform: the voltage rings at 3 kHz and settles in about 5 ms.

Maxima

KaTeX

Computed here (maxima_check.mac).



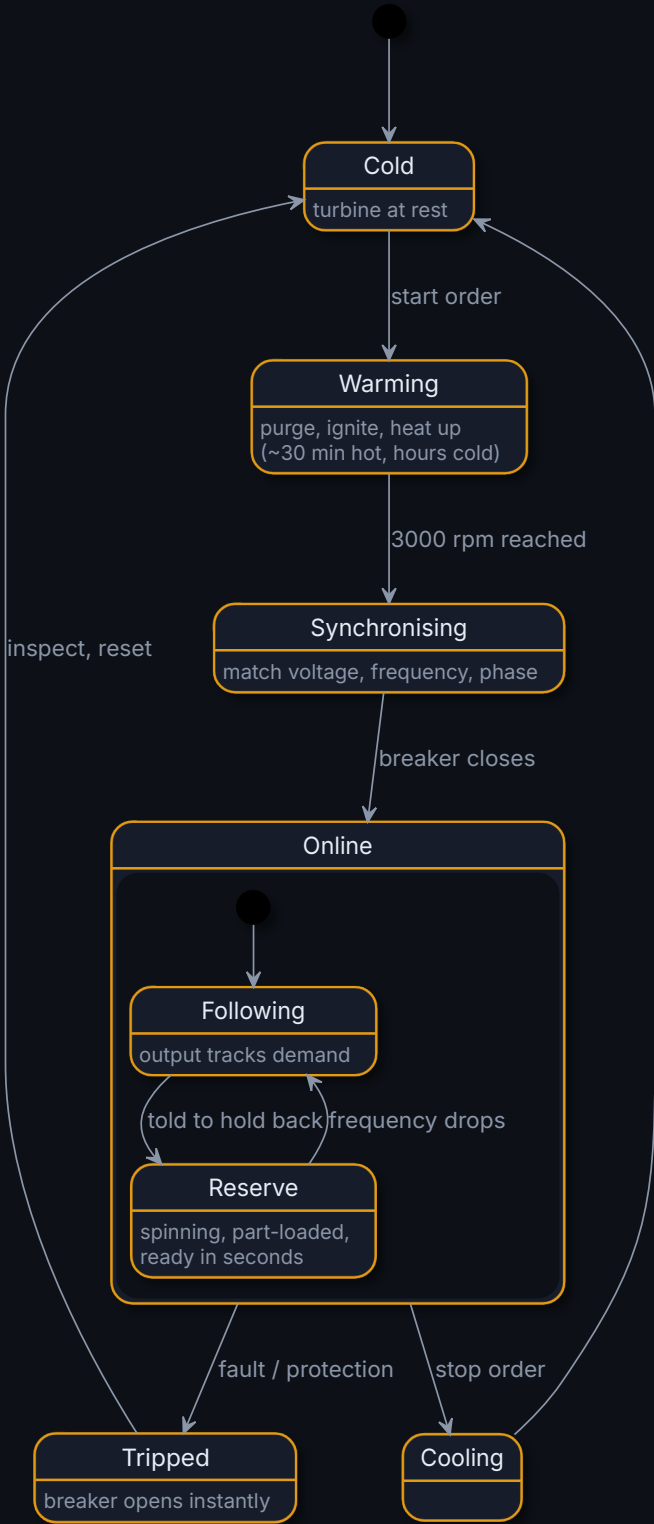
The 5 seconds after a plant trips

Who reacts, in what order, to hold the grid at 50 Hz.

Mermaid

Typical timescales (GB/EU grid codes).

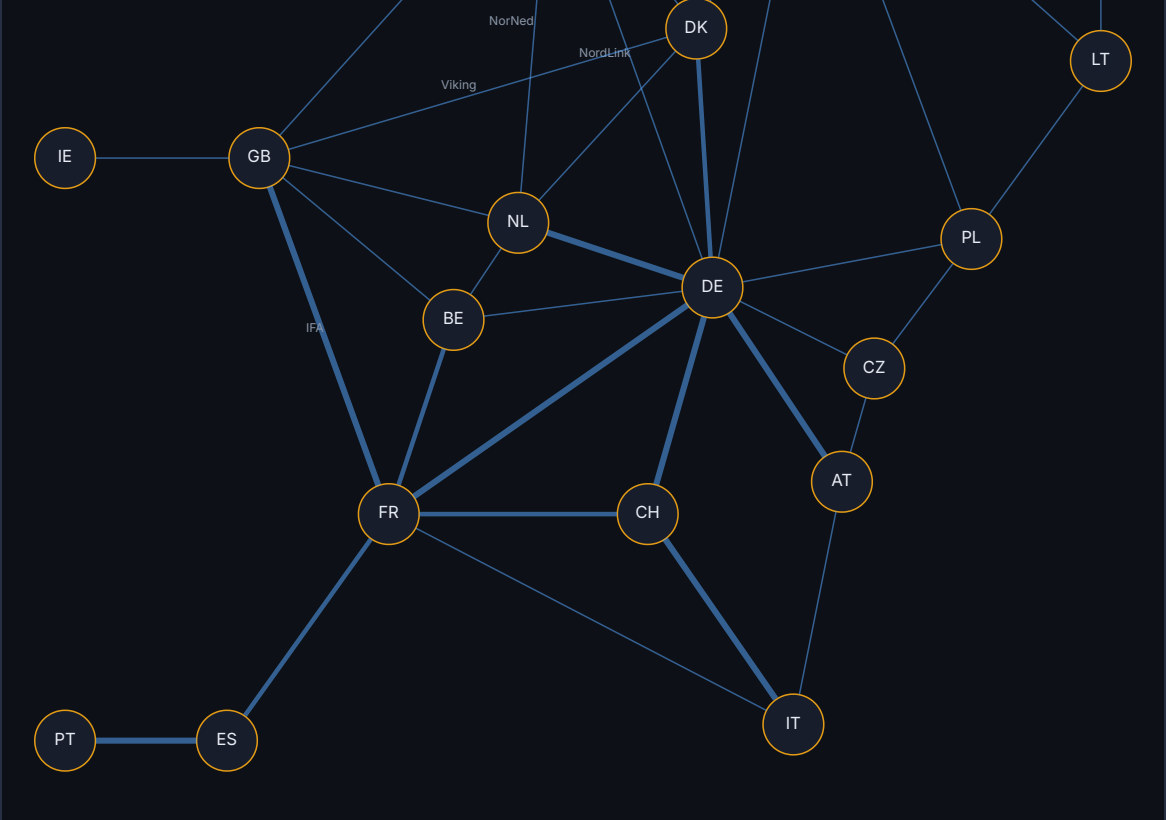
A gas power plant's day (PlantUML state machine)



A gas plant's day

The states a power plant moves through, as a UML state machine.

PlantUML



Europe, wired together

Main cross-border links, laid out automatically. Thicker lines are bigger links.

► Graphviz

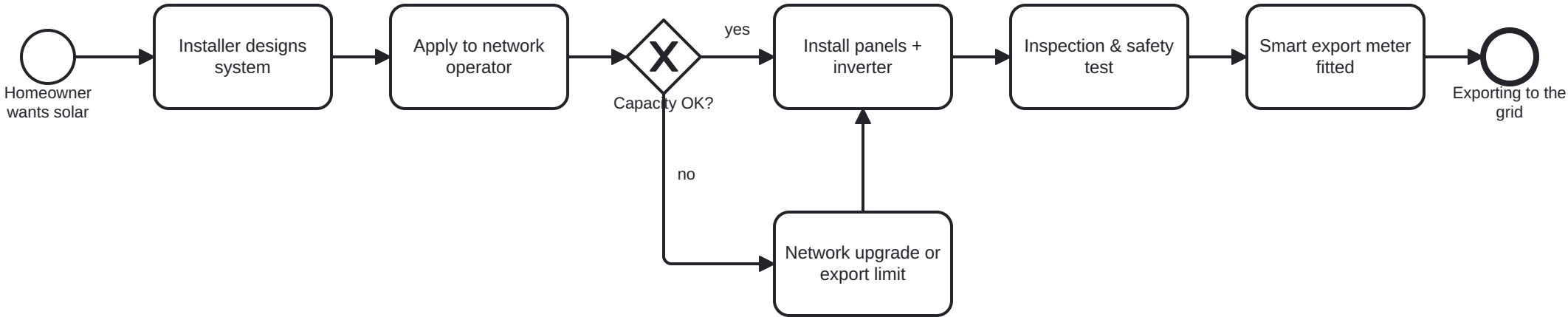
Selected links; widths indicative.



Why blackouts happen

Causes grouped as a fishbone diagram.

► AntV GPT-Vis



BPMN.io

Getting rooftop solar connected

The steps as a formal business process (BPMN 2.0), with the branch when the local network is full. Scroll to zoom.

• bpmn.io

Typical process; varies by country.

Couldn't load babylon

WebGL not supported

Walk through a substation

Game-engine rendering. The camera glides until you click; then use WASD or the arrow keys.

• [Babylon.js](#)

Built in code.

Waiting for the Wokwi project link

I'll send the code; you paste it into Wokwi and share.

Rendering next

Logisim needs a screen; automating with a virtual display.

A smart meter, counting

A microcontroller counting meter pulses, simulated in the browser.

• [Wokwi](#)

The meter's counter, gate by gate

The same pulse counter as logic gates.

▶ [Logisim-evolution](#)

Rendering via GitHub Actions

Xyce builds there.

Rendering via GitHub Actions

FreeCAD's download is blocked here.

A whole grid after a fault

Hundreds of nodes in one transient run.

▶ [Xyce](#)

A tower under wind load

Stress colours on a transmission tower.

▶ [FreeCAD](#)

Rendering next

Structurizr via its CLI.

Rendering next

draw.io export.

The grid at three zoom levels

One model, shown at country, region and street level.

The substation's single-line diagram

With proper IEC electrical symbols.

▶ **Structurizr**

Building next

tldraw component.

Sketch your own grid

An open canvas for visitors.

• **tldraw**

▶ **draw.io**

Rendering next

PyBullet.

An inspection drone on a power line

Robot physics: a drone flying a line.

▶ **PyBullet**

CHAPTER 4

Mix: what the world burns

31,772 TWh in 2025. Coal is still the biggest single source; solar is the fastest-growing.
Same data, 9 ways.

Background: AI-generated (FLUX)

Where the world's electricity comes from

10,041 TWh a year

36% low-carbon

1986

Coal

Gas

Oil

Nuclear

Hydro

Source: Our World in Data energy dataset (CC BY 4.0) · Motion Canvas (Revideo)

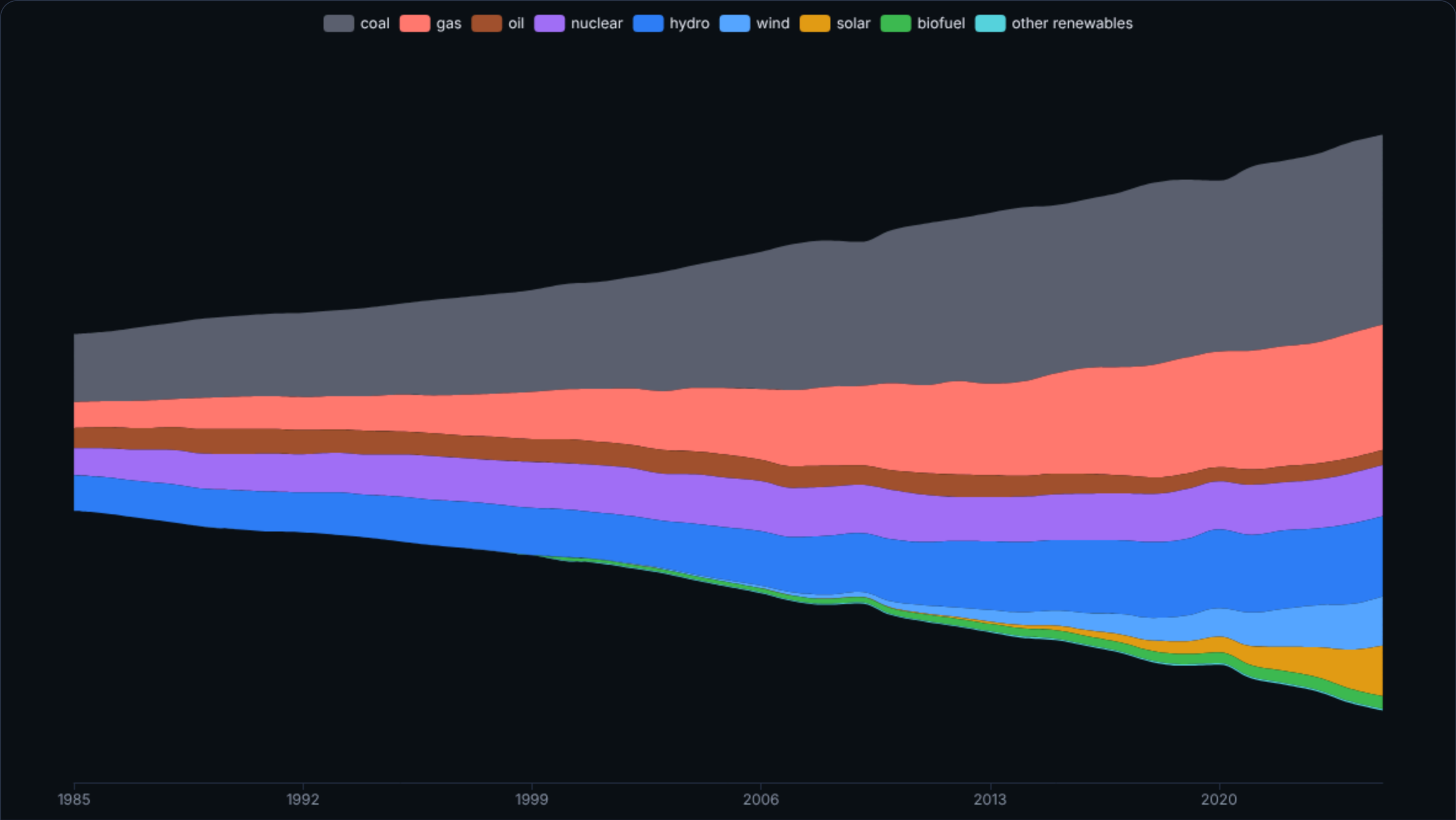
Forty years in one bar

The world's mix re-divides itself year by year while the total climbs. At the end, solar lifts out of the bar.

► Motion Canvas

► Revideo

Our World in Data energy dataset (CC BY 4.0).

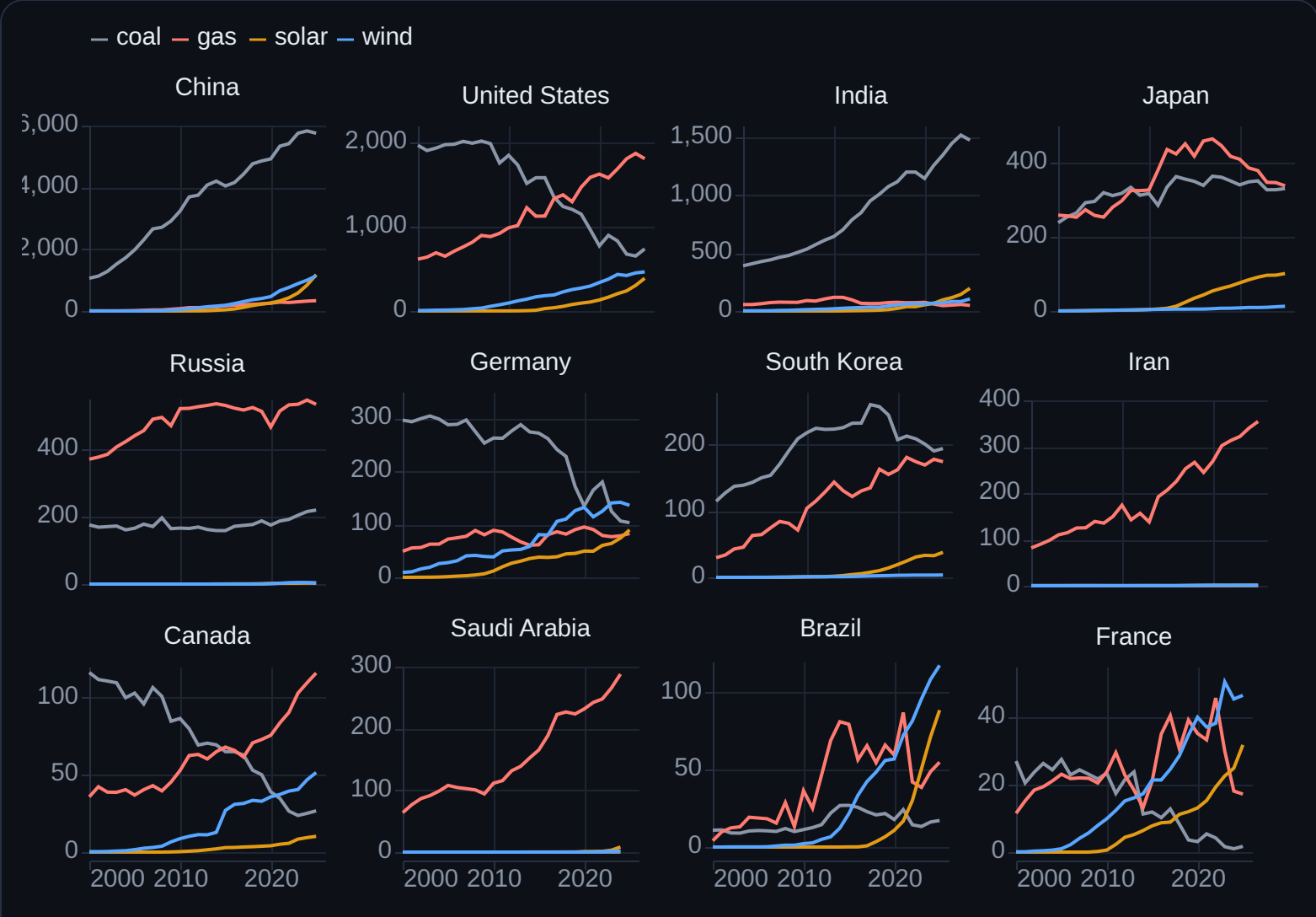


The world's electricity as a river

Each band is a fuel; its width is terawatt-hours that year. Hover anywhere for the numbers.

● ECharts

Our World in Data energy dataset (CC BY 4.0).

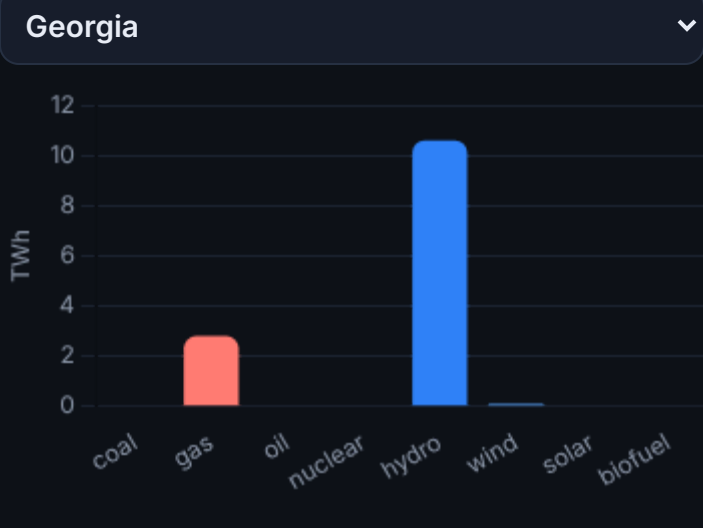


The 12 biggest producers, side by side

Coal, gas, solar and wind since 2000. Each panel has its own scale, so small countries are readable too.

● Vega-Lite

Our World in Data energy dataset (CC BY 4.0).

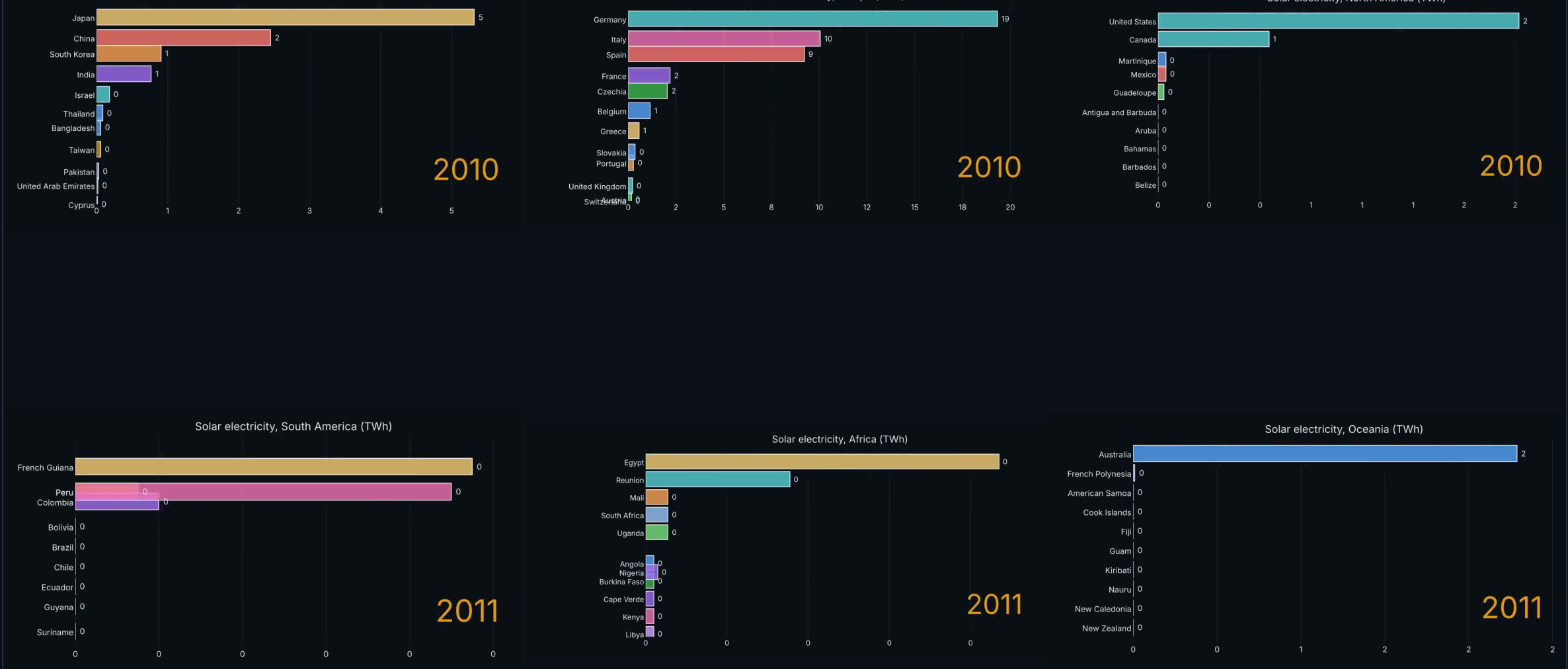


Any country, at a glance

Pick a country. A light canvas chart shows its mix for the latest year.

● Chart.js

Our World in Data energy dataset (CC BY 4.0).



A solar race for every continent

Six races made in bulk from one table, one line of code each.

- ▶ [bar_chart_race](#)
- ▶ [pandas](#)

Our World in Data energy dataset (CC BY 4.0).

```
$ ls -lh energy.csv gppd.csv
-rw-r--r-- 1 root root 8.9M Oct 29 17:09 energy.csv
-rw-r--r-- 1 root root 12M Oct 29 17:09 gppd.csv
$ head -c 160 energy.csv
country,year,iso_code,population,gdp,biofuel_cons_change_pct,biofuel_cons_change_twh,biofuel_cons_per_capita,biofuel_consumption,biofuel_elec_per_capita,biofuel
$ grep -c '^World,' energy.csv # years of world data
126
$ sha256sum energy.csv | cut -c1-16
266f2e2baad79753
$ python3 prep.py
latest 2025 world TWh 31772 solar 2778.6 coal 10471.5 countries 213 plants 34936 top12 ['CHN', 'USA', 'IND', 'RUS', 'JPN', 'BRA', 'CAN', 'KOR', 'FRA', 'DEU', 'SAU', 'IRN']
```

The data step, as it really ran

A recorded terminal session. Pause it and copy any command: it's text, not video.

- [asciinema](#)

Recorded in this build.

Rendering via GitHub Actions

VHS needs Go modules this workspace can't reach.

The same step, as a video

A scripted terminal clip for the showreel.

- ▶ [VHS](#)

Waiting for your Flourish story

I'll send the CSV and the two clicks.

Waiting for a Datawrapper API token

Then I create and publish it by API.

A story version

Flourish's hosted scrollytelling template, fed the same data.

- [Flourish](#)

The press-kit chart

Datawrapper's newsroom-style, fully responsive chart.

- [Datawrapper](#)

Map: where the power is made

Where electricity is clean, and where every one of about 35,000 power plants stands.

Background: AI-generated (FLUX)

Couldn't load maplibre

WebGL2 is required to display this map. We are sorry, but it seems that your browser does not support WebGL2, a technology for rendering 3D graphics on the web.

Where electricity is clean

Low-carbon share of each country's electricity (nuclear plus renewables). Hover a country; the map tours the continents by itself until you touch it.

MapLibre GL

Our World in Data energy dataset (CC BY 4.0).

Couldn't load deck

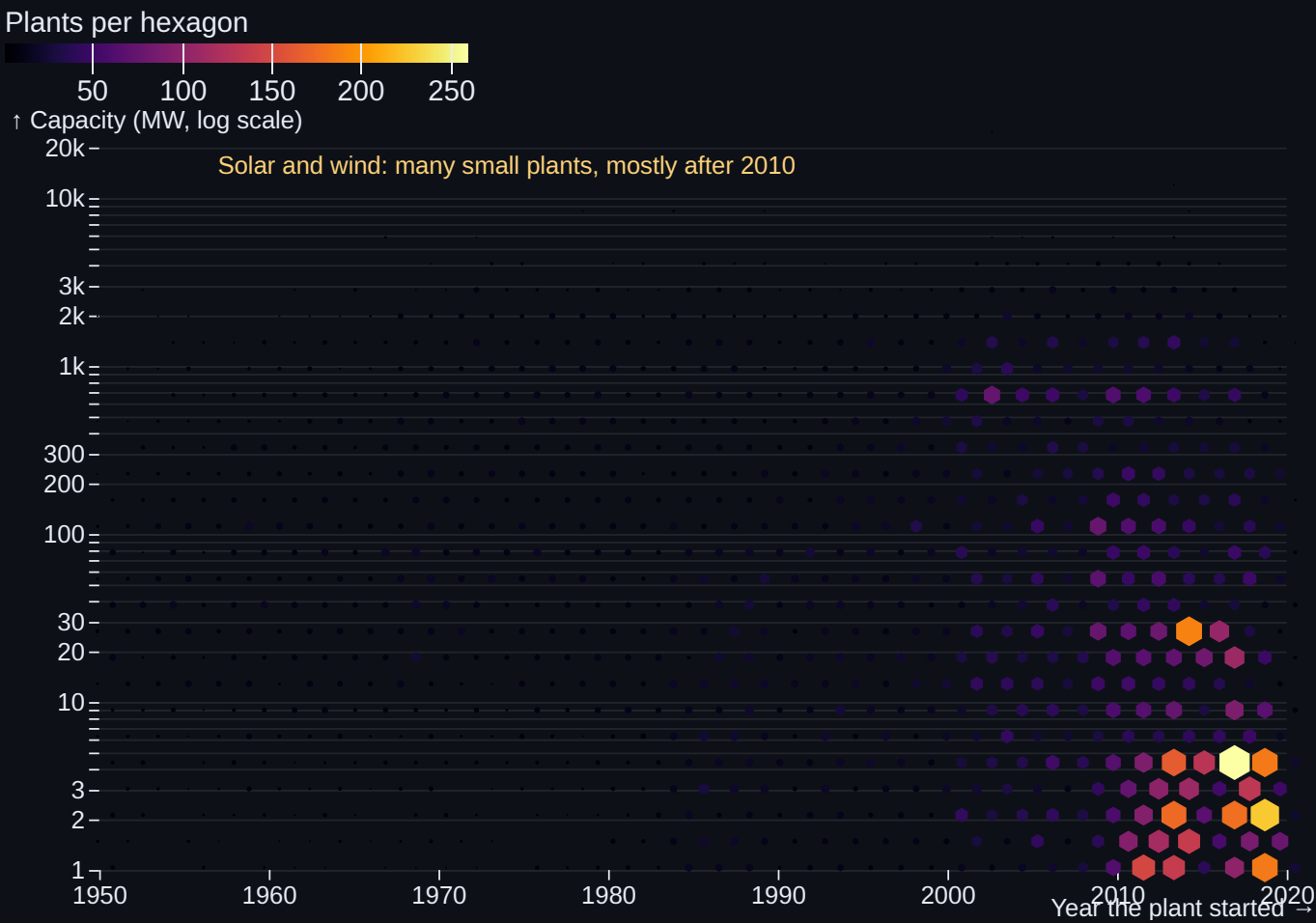
WebGL2 is required to display this map. We are sorry, but it seems that your browser does not support WebGL2, a technology for rendering 3D graphics on the web.

Every power plant on Earth

About 35,000 plants as columns: height is capacity, colour is fuel. Right-drag to tilt and spin; hover a column for its name.

- deck.gl
- MapLibre GL

WRI Global Power Plant Database v1.3 (CC BY 4.0).



When each kind of plant was built

Every plant by start year and size. Big coal and hydro cluster in the past; a swarm of small solar and wind fills the last decade.

- Observable Plot

WRI Global Power Plant Database v1.3 (CC BY 4.0).

Recording next

Captured with rrweb while a scripted visitor explores the map.

Someone exploring the map

A recorded visit, replayed as live page content rather than video, so it stays sharp at any zoom.

- rrweb

Rendering next

Remotion renders the map's frames exactly.

The flyover, as a video

The same live map rendered frame by frame into a smooth video for the showreel.

- ▶ Remotion

Store: holding electricity for later

Sun and wind don't follow demand, so storage matters more each year. Here is what is inside a battery, down to the atoms.

Background: AI-generated (FLUX)

Couldn't load mol3d

error creating viewer: TypeError: Cannot read properties of null (reading 'clearDepth')

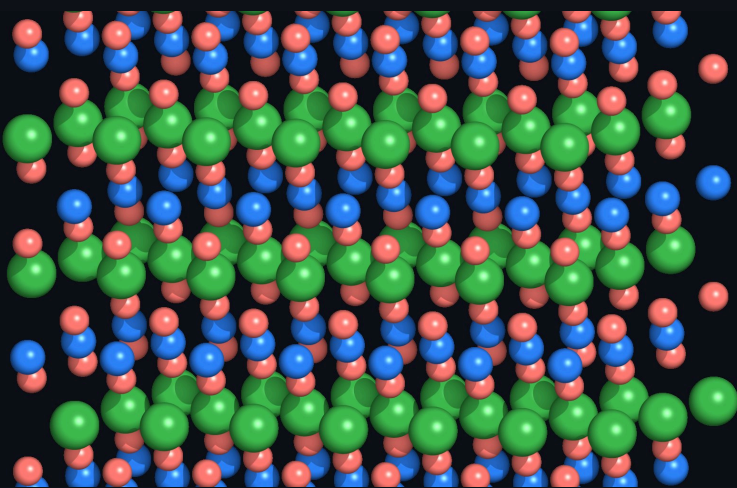
- 1 · Maxwell
- 2 · Make
- 3 · Move
- 4 · Mix
- 5 · Map
- 6 · Store
- 7 · Story

Inside a battery's cathode

Lithium cobalt oxide: lithium (green) sits between layers of cobalt (blue) and oxygen (red). Charging pulls the lithium out. Drag to rotate.

3Dmol.js

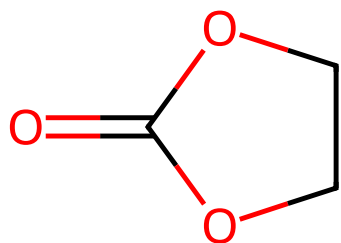
R-3m, a = 2.816 Å, c = 14.05 Å; built here.



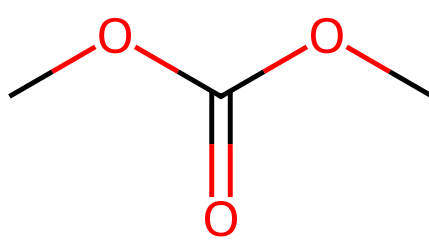
The same crystal, ray-traced

A cover-quality still of the layered structure.

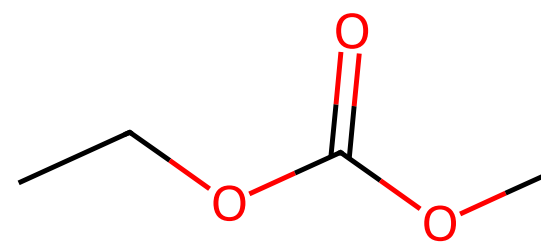
PyMOL



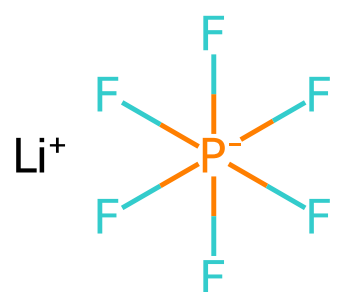
Ethylene carbonate 88.1 g/mol



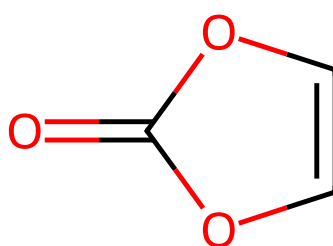
Dimethyl carbonate 90.1 g/mol



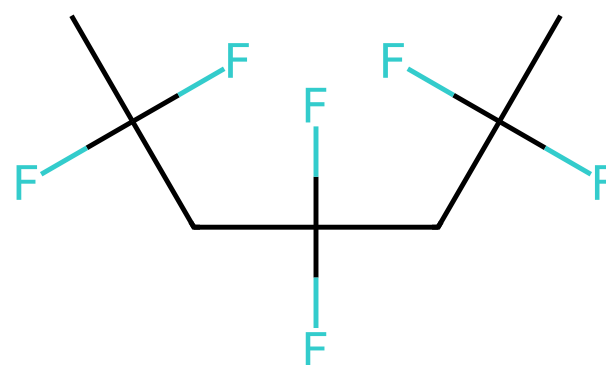
Ethyl methyl carbonate	104.1 g/mol
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LiPF ₆ (salt)	151.9 g/mol
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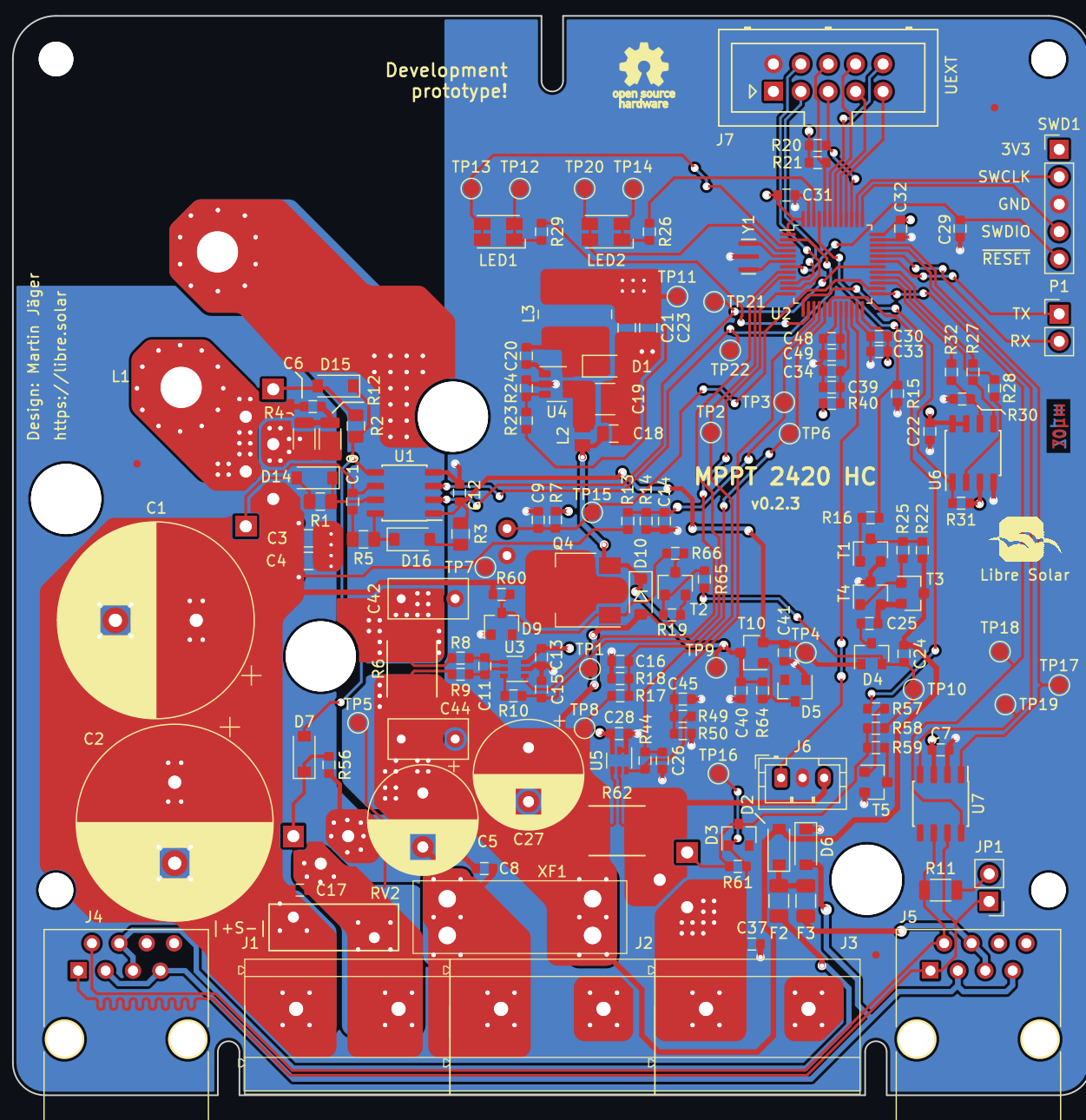
Vinylene carbonate (additive)	86.0 g/mol
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PVDF binder (3 units)	208.1 g/mol
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What the liquid is made of

Molar masses computed by RDKit.



A real solar charge controller

The open-hardware LibreSolar MPPT 2420 HC board, exported straight from its KiCad design files.

▶ KiCad

LibreSolar MPPT 2420 HC v0.2.3 (open hardware, see repo licence).

