International Council on Systems Engineering
A better world through a systems approach

A State of the System Analysis of the world's energy transformation towards net zero

Thomas Manley, ESEP

INCOSE International Symposium 2025 | Ottawa, Canada

“Systems thinking is a way of understanding complex problems by looking at how different parts interact within a larger system.”

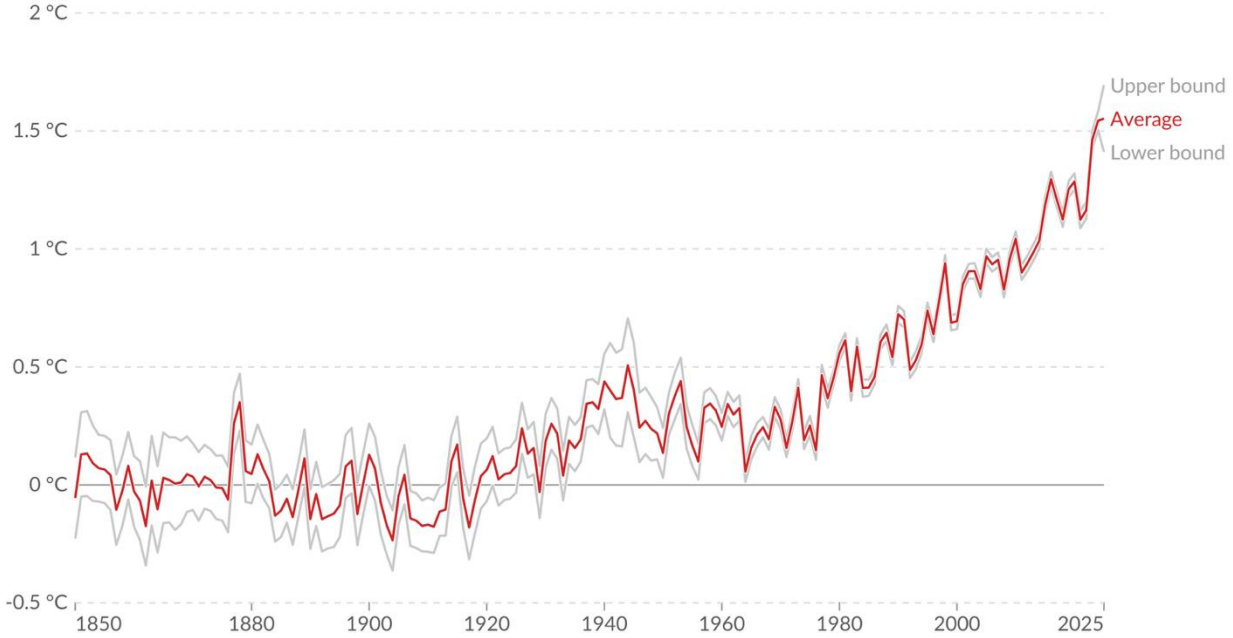
Tami Katz’ presentation “The Art of Systems Thinking” presented Monday 28th July 2025, IS25

Problem State

Annual temperature anomalies relative to the pre-industrial period, World

Our World in Data

The difference in average land-sea surface temperature compared to the 1861-1890 mean, in degrees Celsius.



Data source: Met Office Hadley Centre - HadCRUT5 (2025)

OurWorldinData.org/co2-and-greenhouse-gas-emissions | CC BY

Note: The period 1861–1890 is used as the baseline to measure temperature changes relative to pre-industrial times, as recommended by the source.

https://ourworldindata.org/grapher/temperature-anomaly

Global carbon dioxide emissions and atmospheric carbon dioxide (1751-2024)

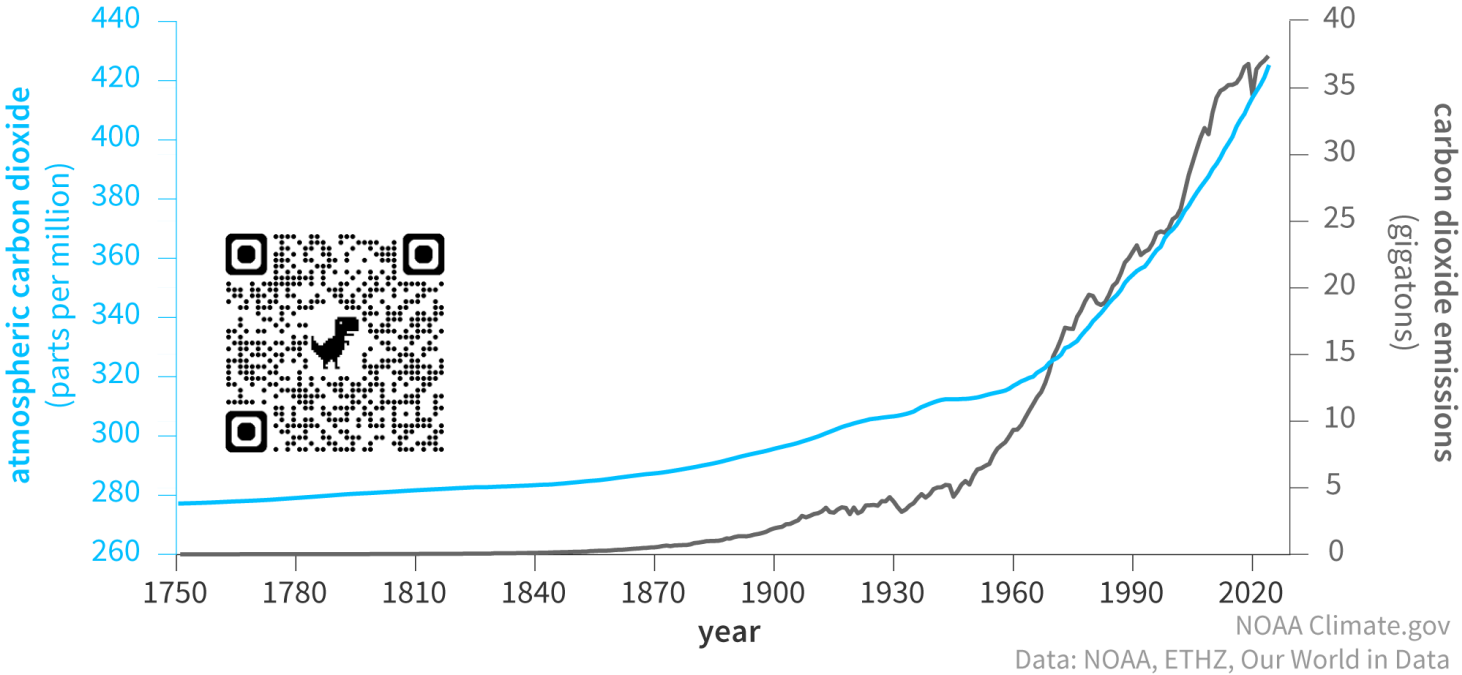
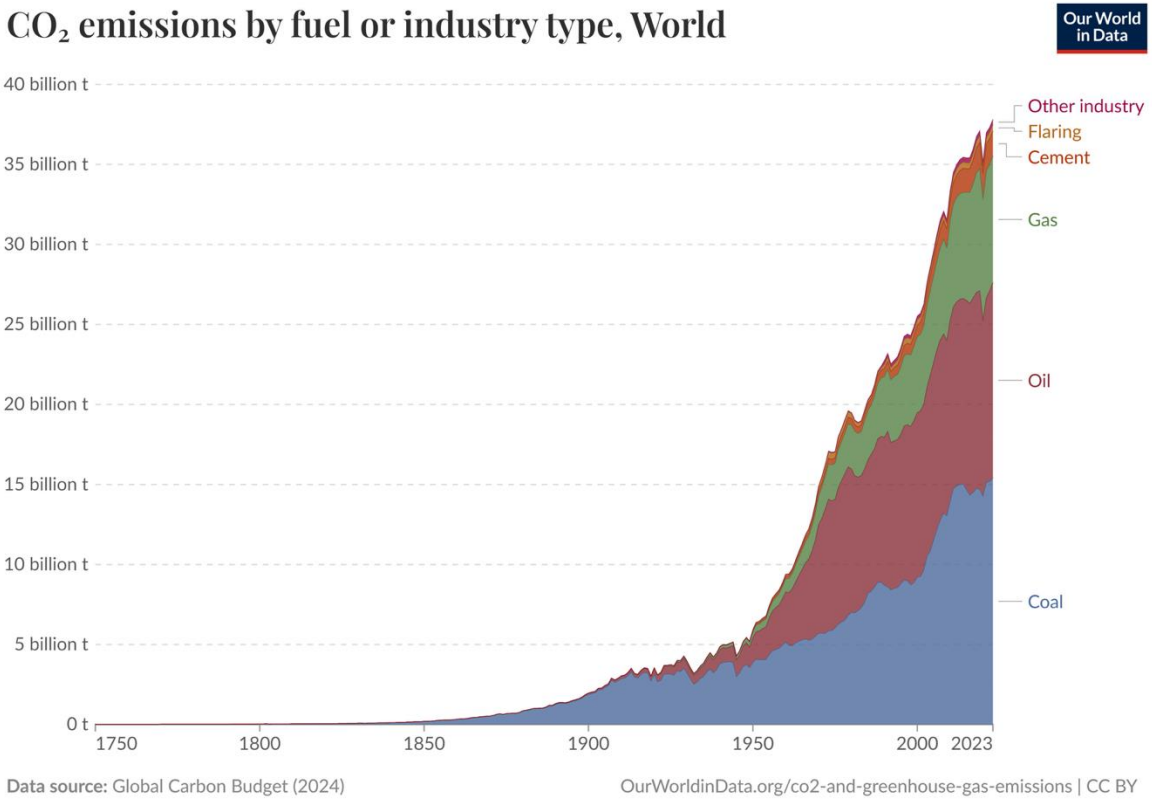


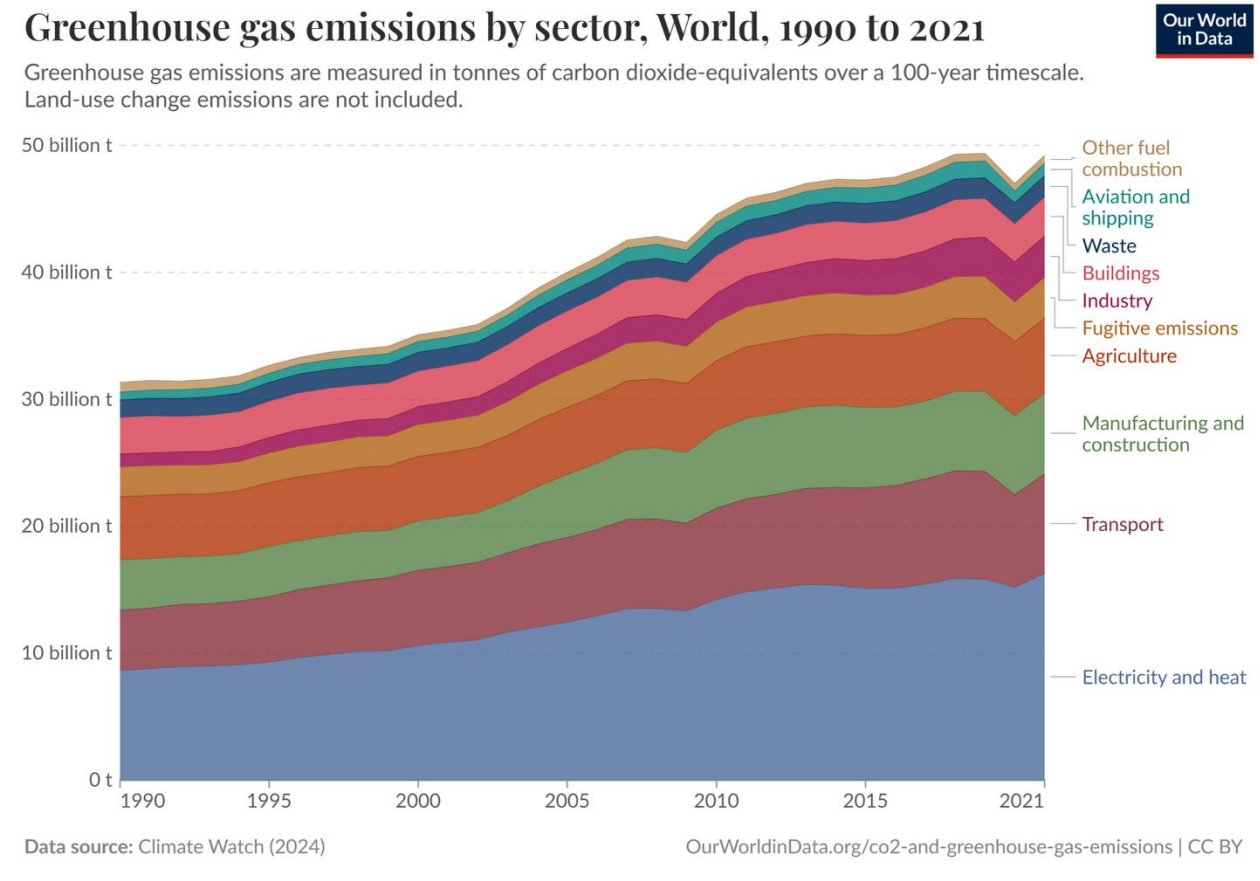
Image caption

The amount of carbon dioxide in the atmosphere (blue line) has increased along with human emissions (gray line) since the start of the Industrial Revolution in 1750. Emissions rose slowly to about 5 gigatons (1 *gigaton* is 1 billion metric tons per year) in the mid-20th century before rapidly increasing to more than 35 billion tons per year by the end of the century. NOAA Climate.gov graph, adapted from original by Dr. Howard Diamond (NOAA ARL). Atmospheric carbon dioxide data from NOAA and ETHZ. Carbon dioxide emissions data from Our World in Data and the Global Carbon Project.

https://www.climate.gov/media/12990

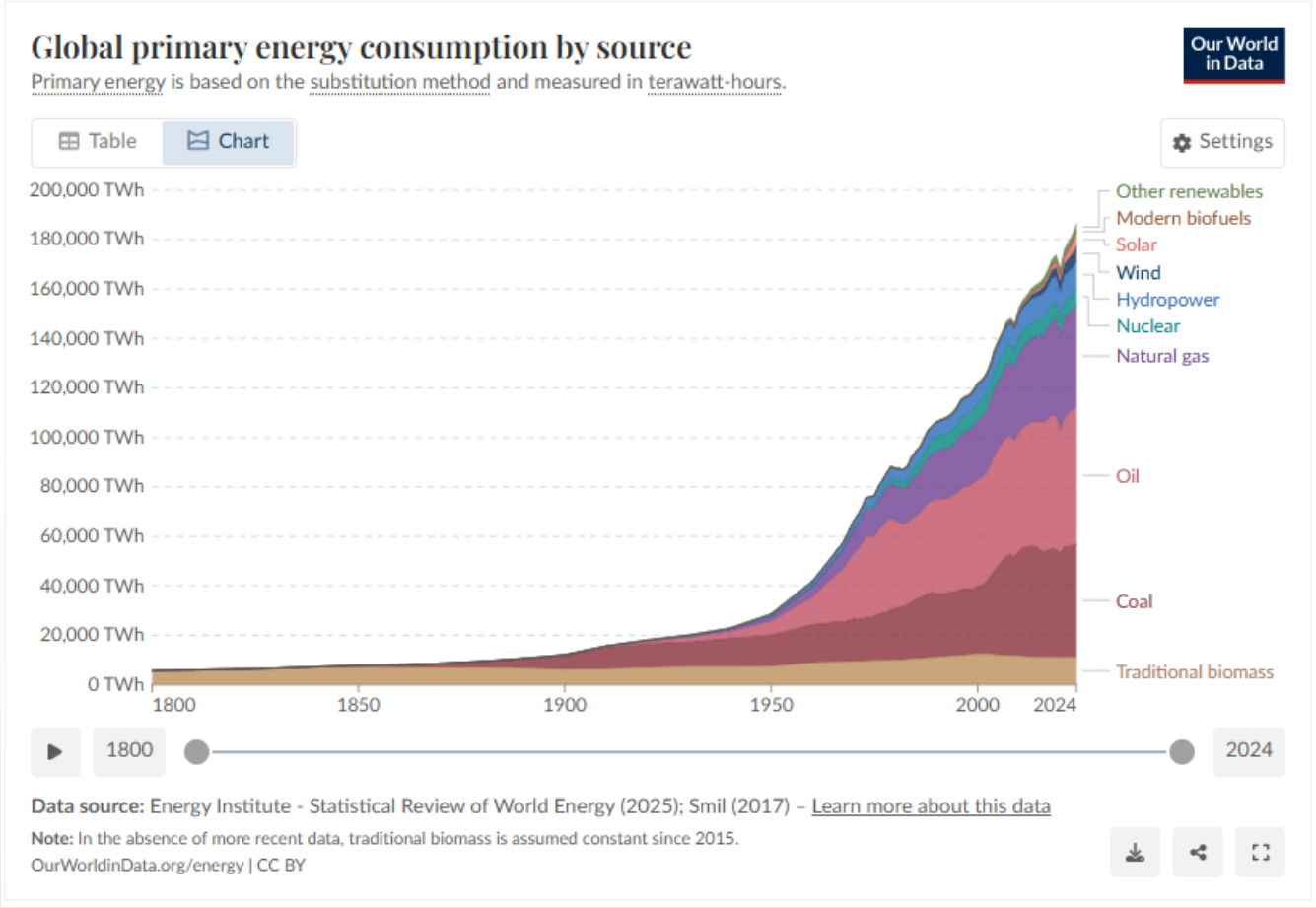


https://www.climate.gov/media/12990



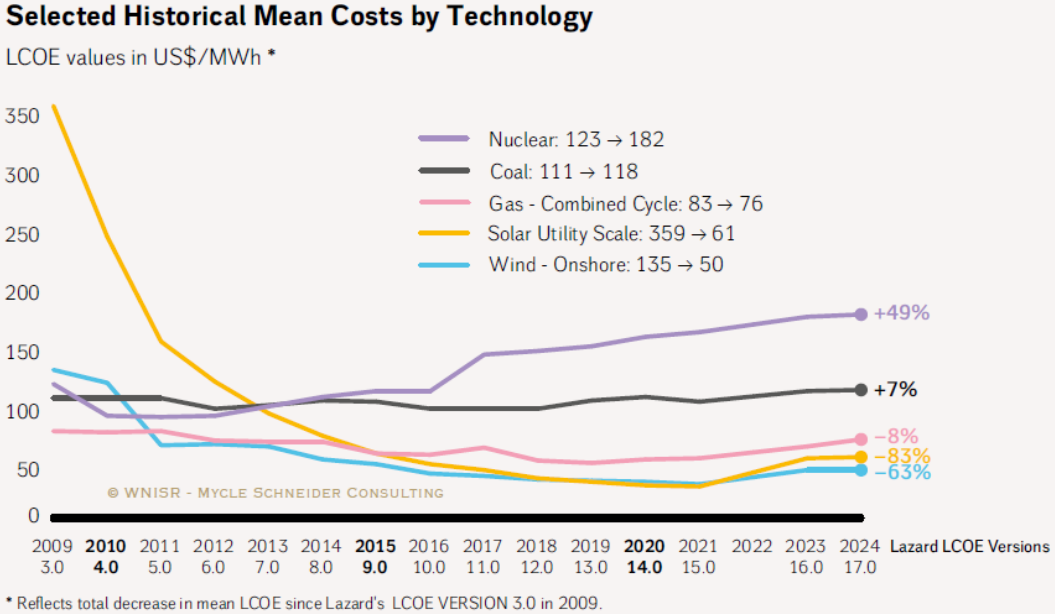
https://ourworldindata.org/emissions-by-sector

Global Analysis



https://ourworldindata.org/energy-production-consumption

Figure 58 • The Declining Costs of Renewables vs. Traditional Power Sources



Source: Lazard Estimates, 2024

Notes: **LCOE**: Levelized Cost of Energy

*This graph reflects the average unsubsidized LCOE values for a given version of LCOE study. It primarily relates to the North American energy landscape but reflects broader/global cost developments. See also Figure 69.

https://www.worldnuclearreport.org

Figure 3-1 provides capital costs for selected technologies since the project's inception in 2018. All costs are expressed in real 2024-25 Australian dollars, represent overnight costs and do not include any available subsidies.

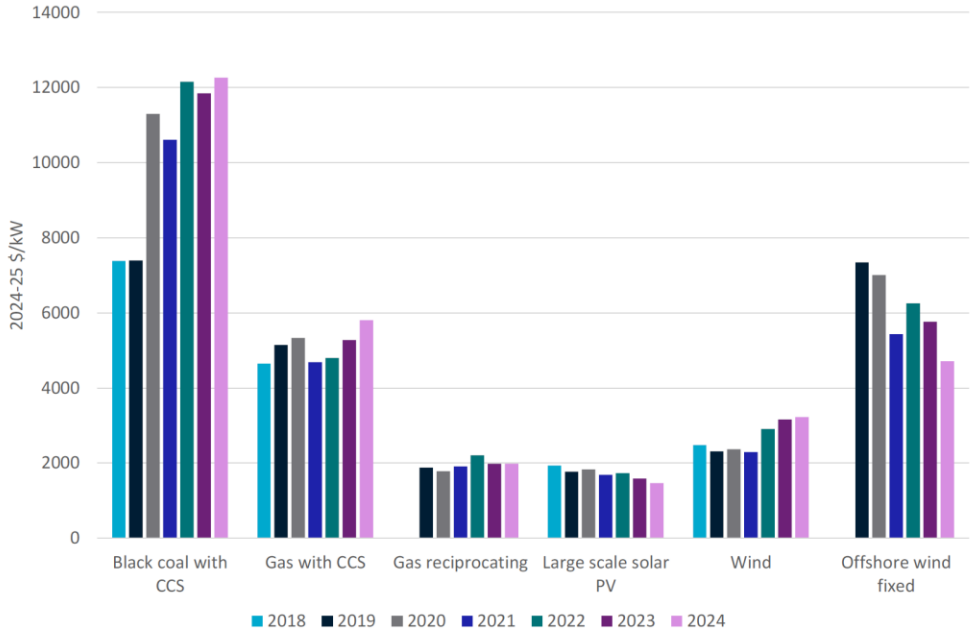
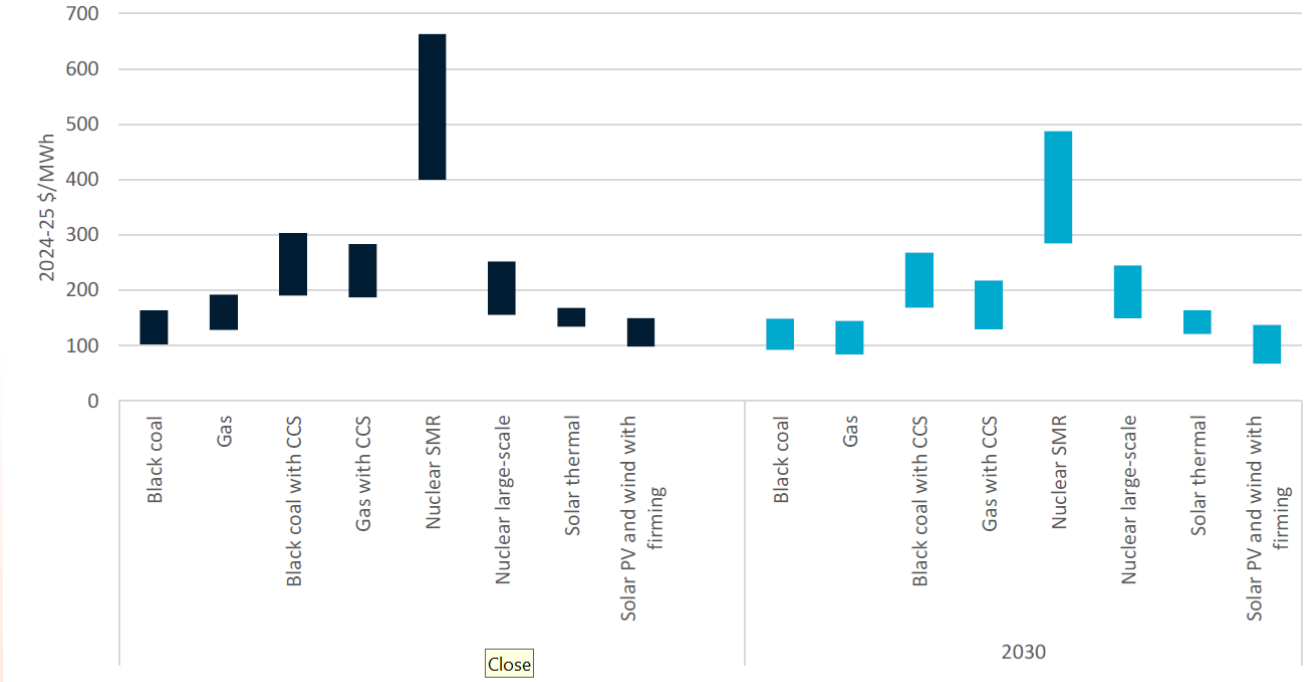


Figure 3-1 Comparison of current capital cost estimates with previous reports (FYB)

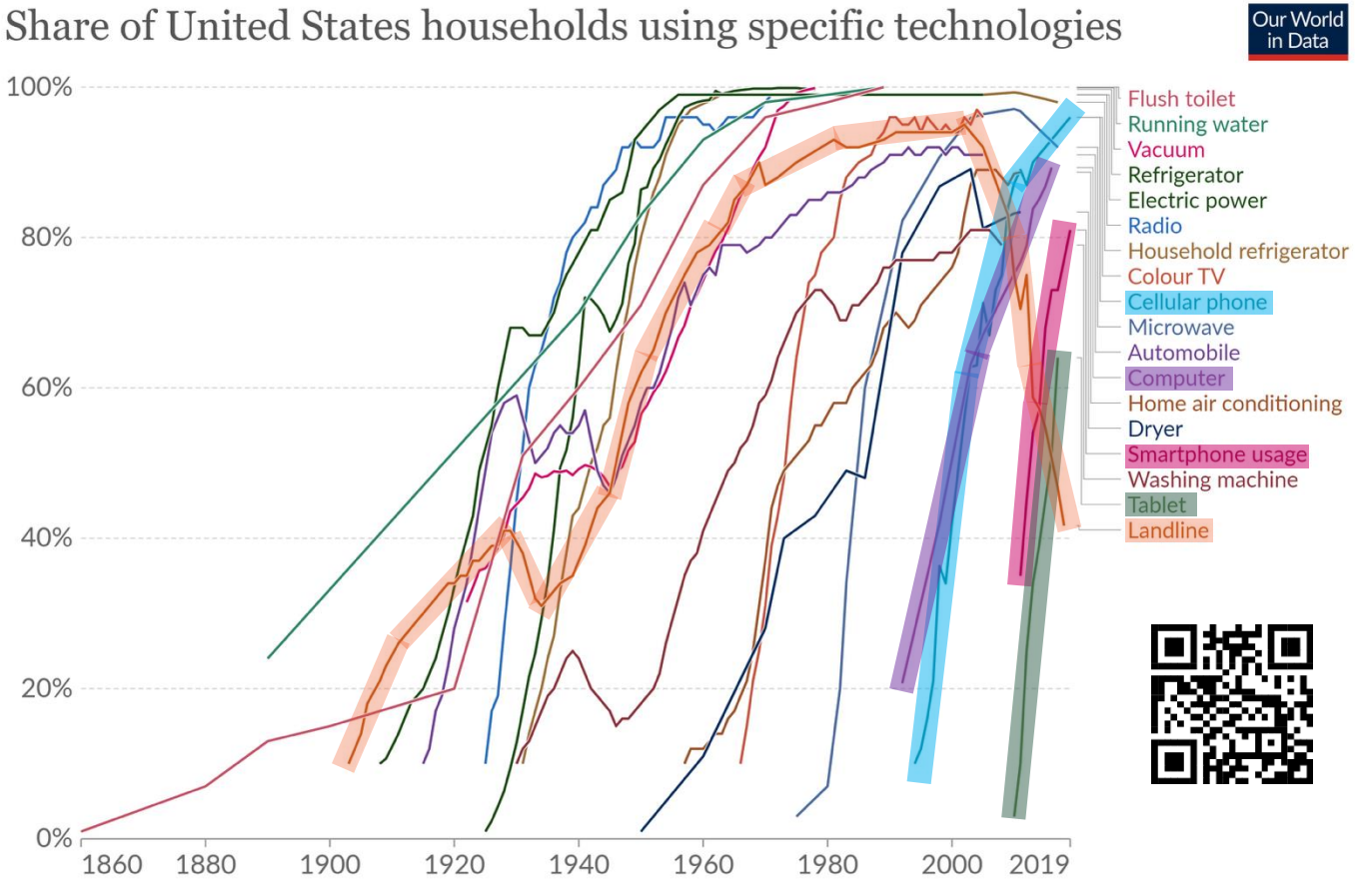
CSIRO's GenCost 2024-25 Final Report



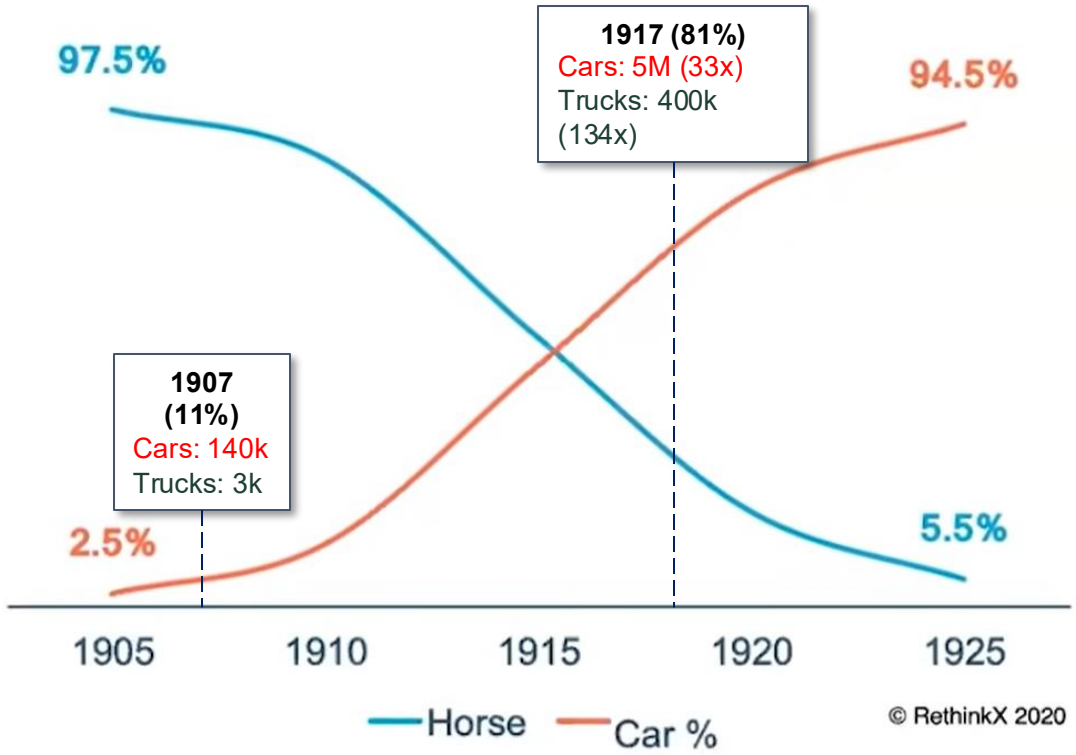
ES Figure 0-2 Calculated LCOE by technology and category for 2024 and 2030

Levelized Cost Of Electricity (LCOE), CSIRO's GenCost 2024-25 Final Report

Market Adoption (S-Curves)


Share of United States households using specific technologies
Our World in Data
100%
80%
60%
40%
20%
0%
1860
1880
1900
1920
1940
1960
1980
2000
2019
Flush toilet
Running water
Vacuum
Refrigerator
Electric power
Radio
Household refrigerator
Colour TV
Cellular phone
Microwave
Automobile
Computer
Home air conditioning
Dryer
Smartphone usage
Washing machine
Tablet
Landline
Source: Horace Dediu; Comin and Hobijn (2004); other sources collated by Our World in Data
OurWorldInData.org/technological-change • CC BY

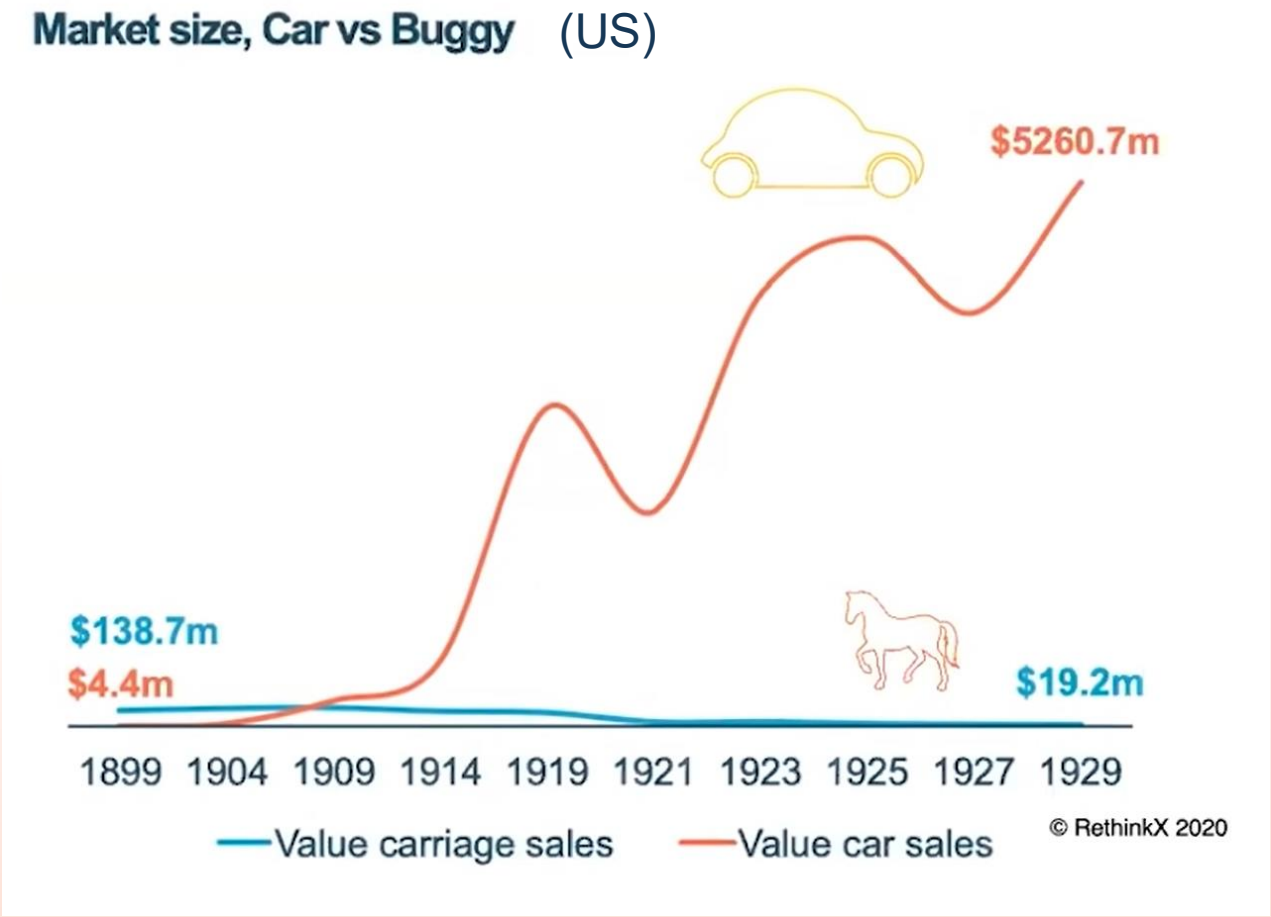
Market Share, Car vs Horse (US)



https://www.youtube.com/watch?v=Kj96nxtHdTU&t=599s

https://www.scientificamerican.com/article/the-motor-vehicle-1917-slide-show/

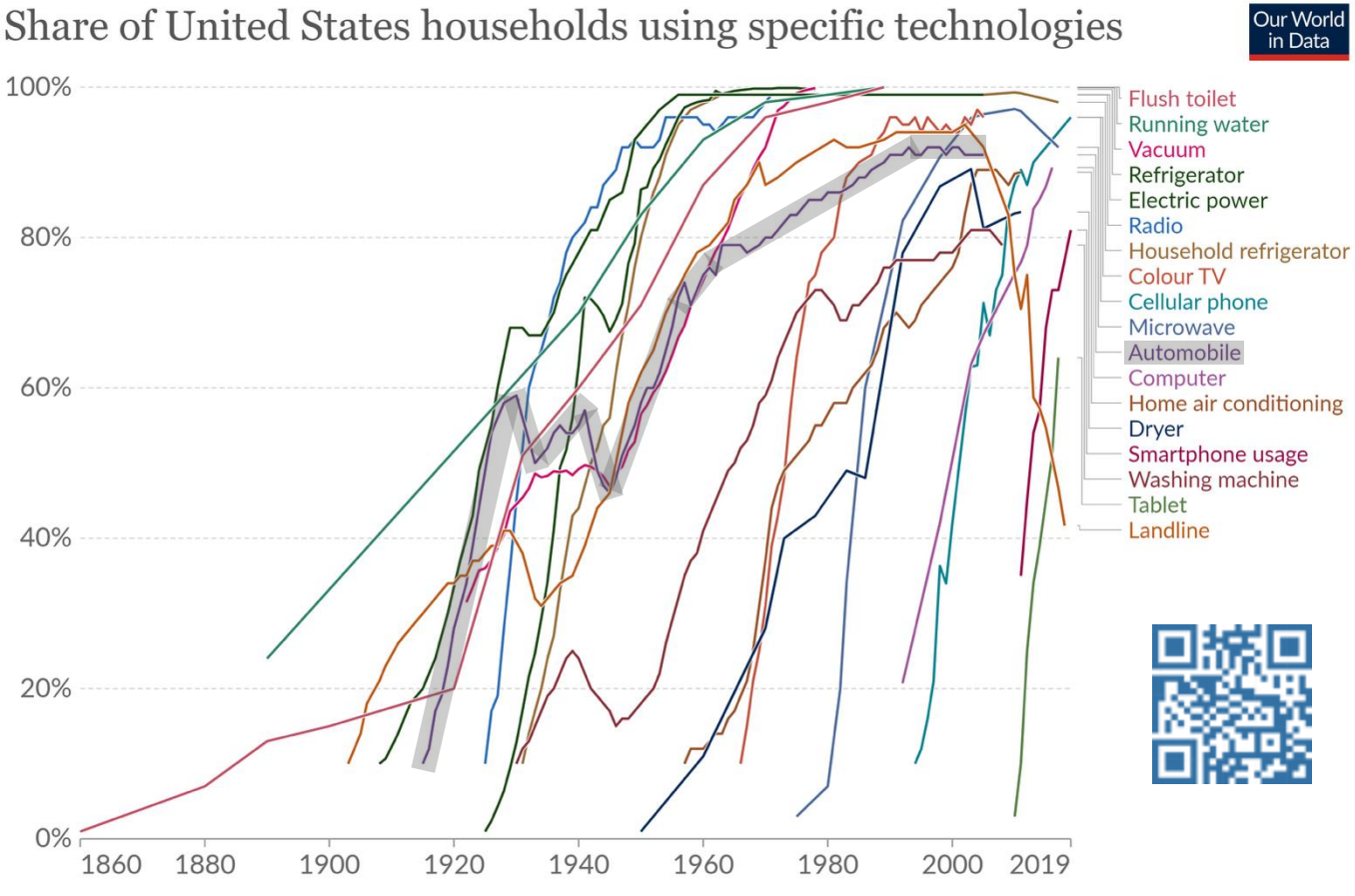
Source: Tony Seba and Asymco, BlackRock



https://www.scientificamerican.com/article/the-motor-vehicle-1917-slide-show/

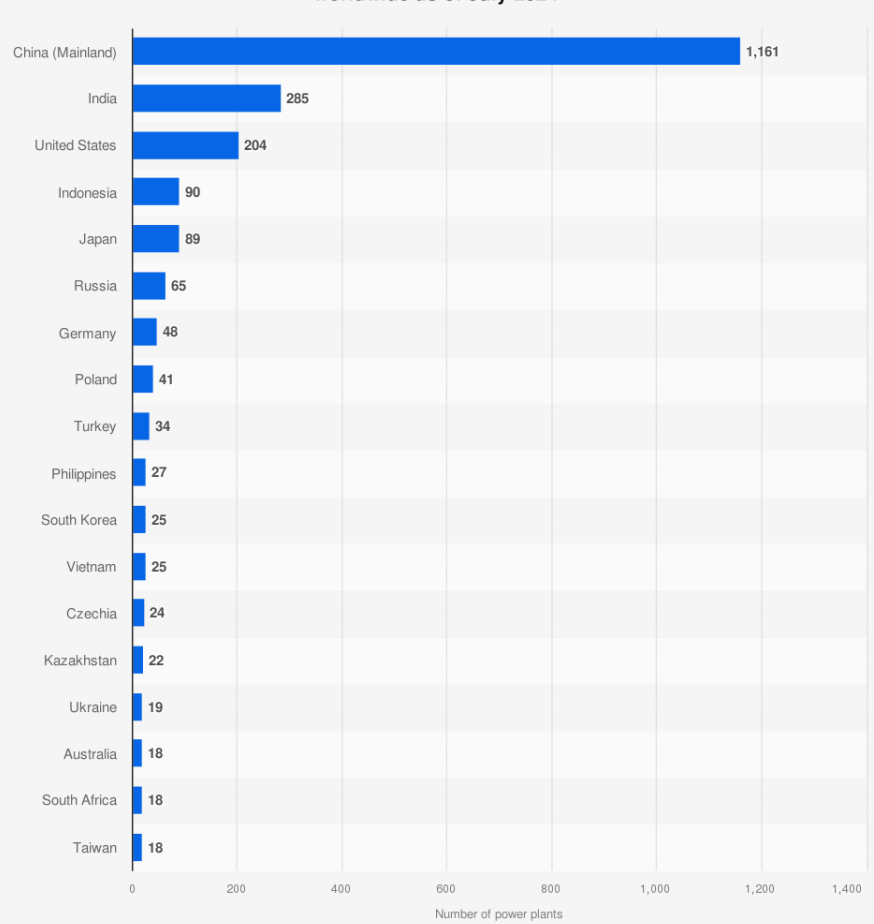
Source: Tony Seba and Asymco, BlackRock

Share of United States households using specific technologies



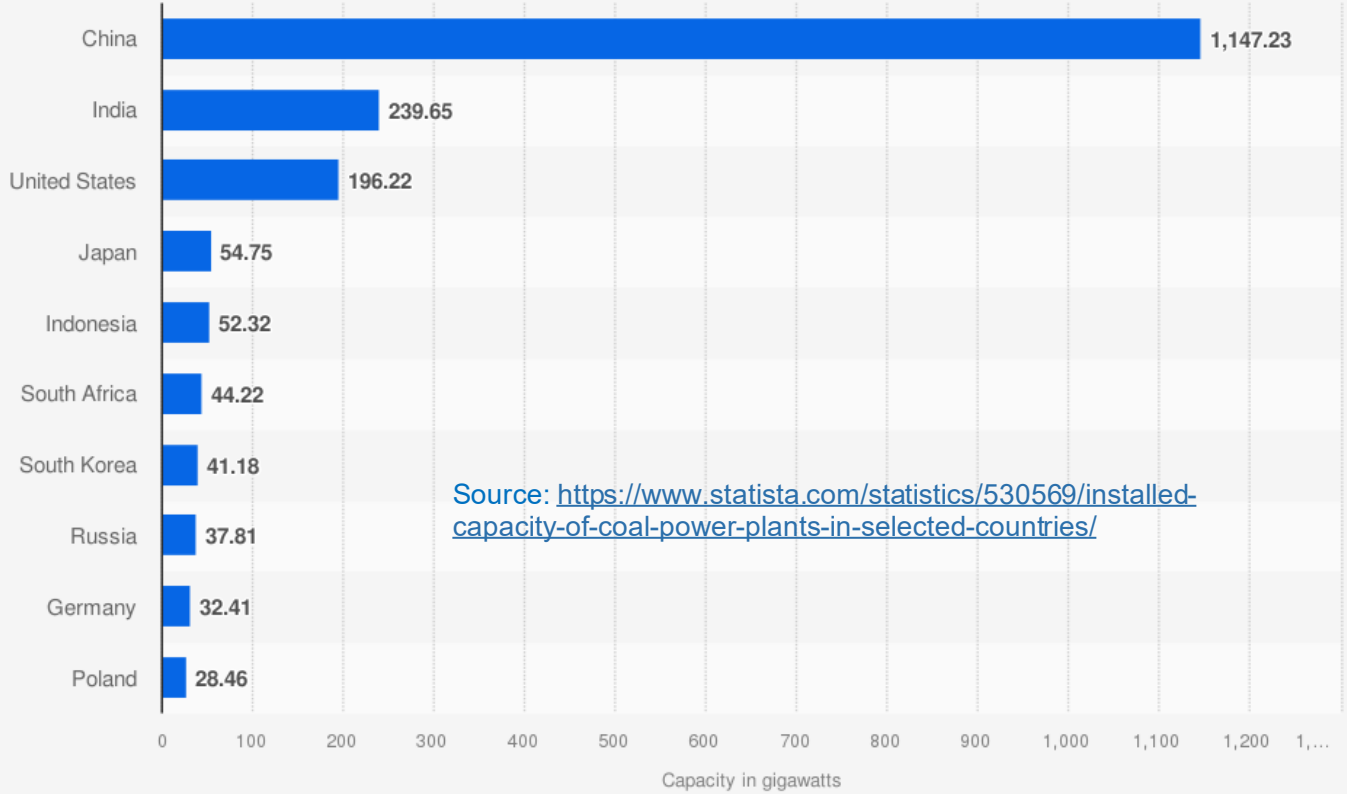
Source: Horace Dediu; Comin and Hobijn (2004); other sources collated by Our World in Data OurWorldInData.org/technological-change • CC BY

Coal



Source: https://www.statista.com/statistics/859266/number-of-coal-power-plants-by-country/#:~:text=China%20has%20the%20greatest%20number,or%20territory%20in%20the%20world

Countries with largest installed capacity of coal power plants worldwide as of July 2024 (in gigawatts)



Source: https://www.statista.com/statistics/530569/installed-capacity-of-coal-power-plants-in-selected-countries/

Source
Global Energy Monitor
© Statista 2024

Additional Information:
Worldwide; July 2024

statista

Coal Capacity (Australia)

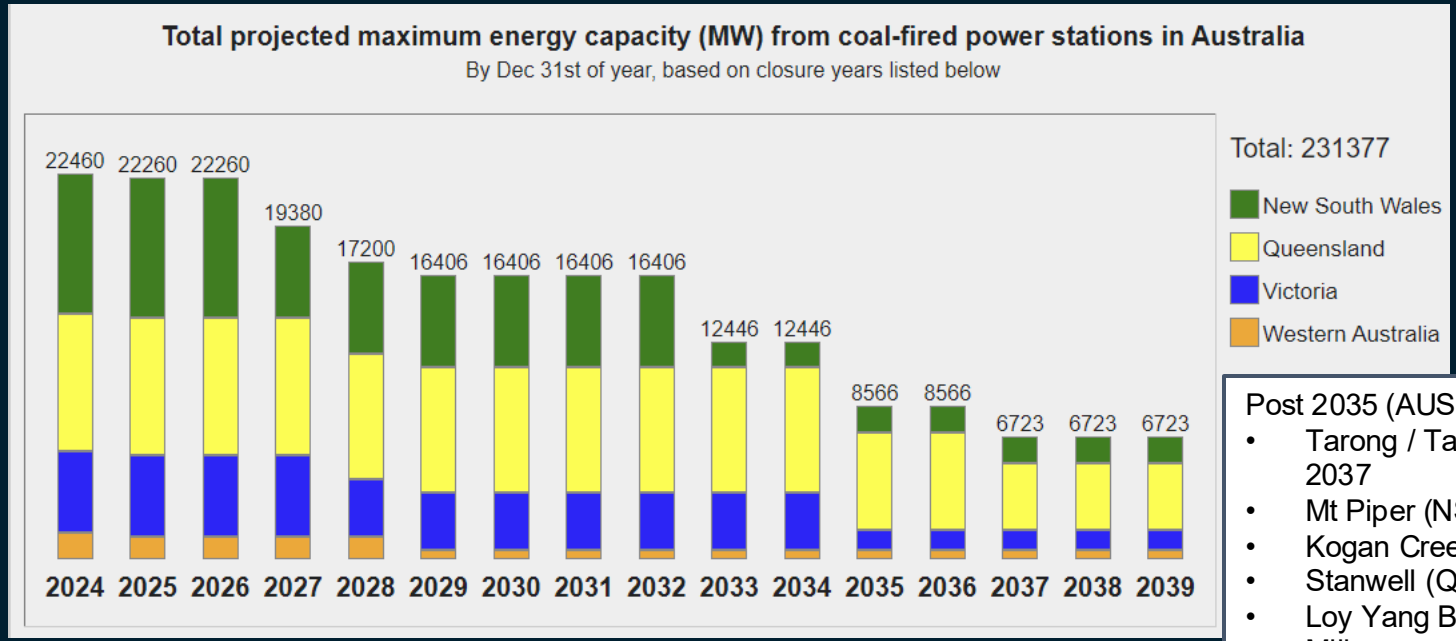
Top 10 Coal Power Stations (AUS) = **18GW (all 18x = 22.5GW)**:

- Eraring (NSW) 2880MW, 2027
- Bayswater (NSW) 2640MW, 2033
- Loy Yang A (VIC) 2200MW, 2035
- Tarong + Tarong North (QLD) 1843MW, 2037
- Gladstone (QLD) 1680MW, 2035
- Yallourn (VIC) 1480MW, 2028
- Stanwell (QLD) 1445MW, 2046
- Mt Piper (NSW) 1400MW, 2040
- Vales Point B (NSW) 1320MW, 2033
- Loy Yang B (VIC) 1050MW, 2047

Sources:

1: https://en.wikipedia.org/wiki/List_of_coal-fired_power_stations_in_Australia

Coal Capacity (Australia) – Projected



Post 2035 (AUS) = **8.5GW (8x)**:

- Tarong / Tarong Nth (QLD) 1843MW, 2037
- Mt Piper (NSW) 1400MW, 2040
- Kogan Creek (QLD) 750MW, 2042
- Stanwell (QLD) 1445MW, 2046
- Loy Yang B (VIC) 1050MW, 2047
- Millmerran (QLD) 852MW, 2051
- Callide C (QLD) 810MW, TBD
- Bluewaters (WA) 416MW, TBD

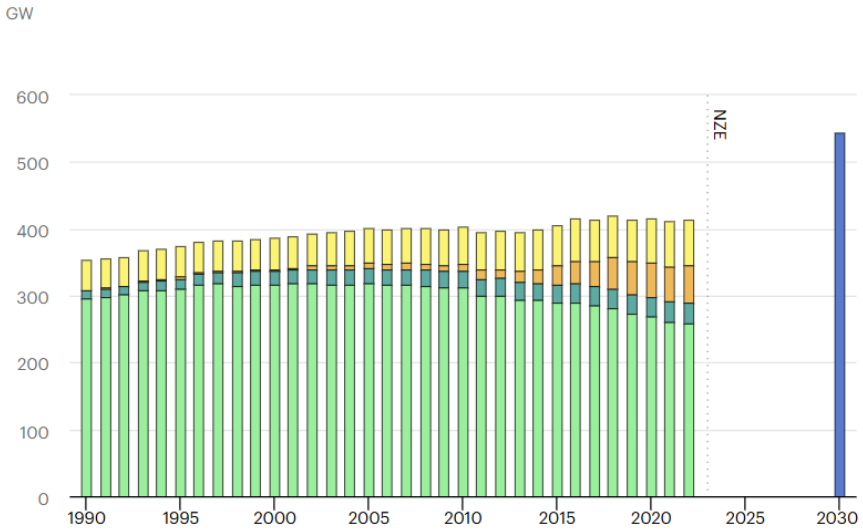
Sources:

1: https://en.wikipedia.org/wiki/List_of_coal-fired_power_stations_in_Australia

Nuclear

Nuclear power capacity by country or region in the Net Zero Scenario, 1990-2030

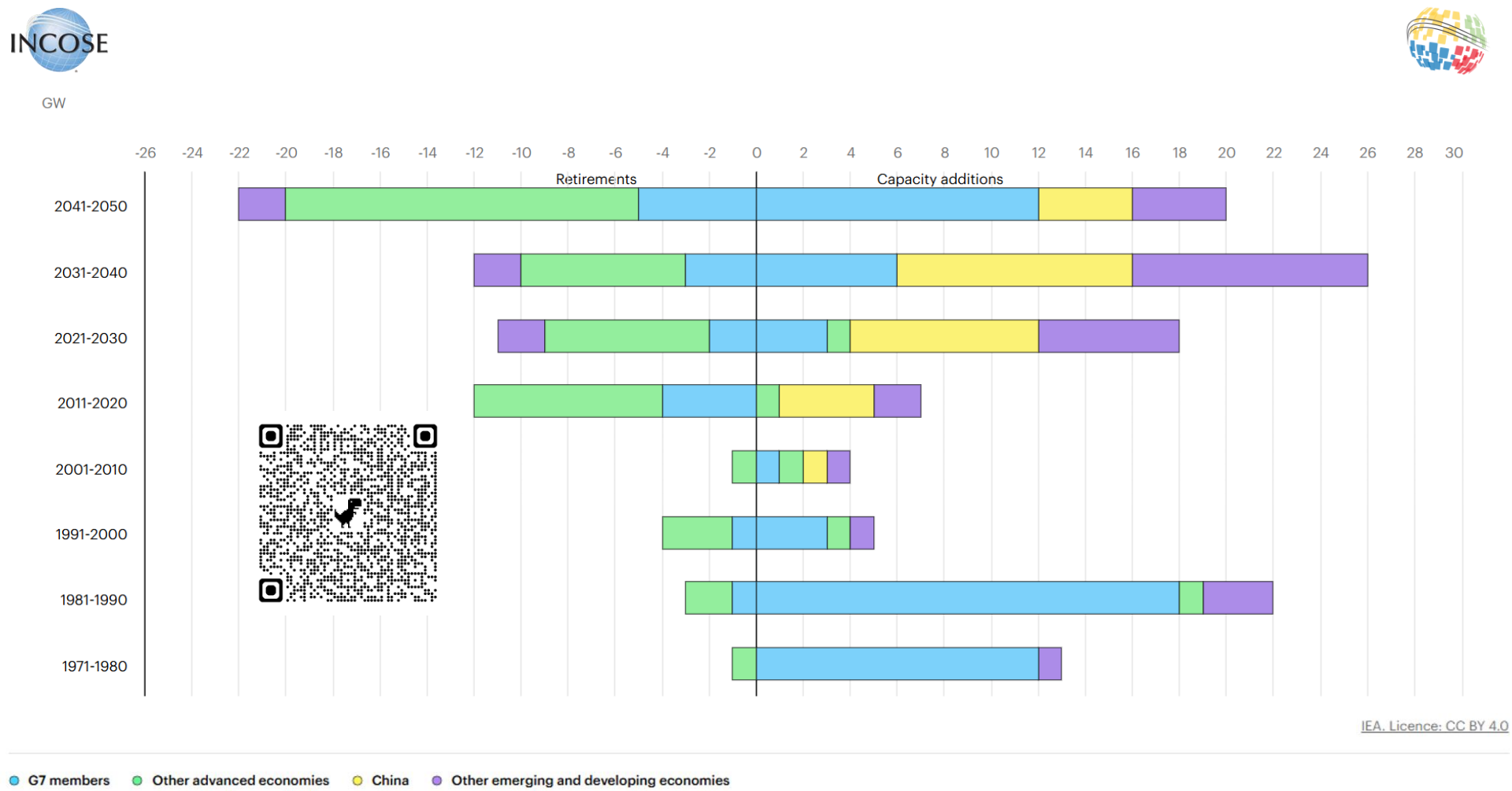
Open



IEA. Licence: CC BY 4.0

G7 members | Other advanced economies | China | Other EMDEs | NZE

EMDE = Emerging market and developing economies
https://www.iea.org/energy-system/electricity/nuclear-power



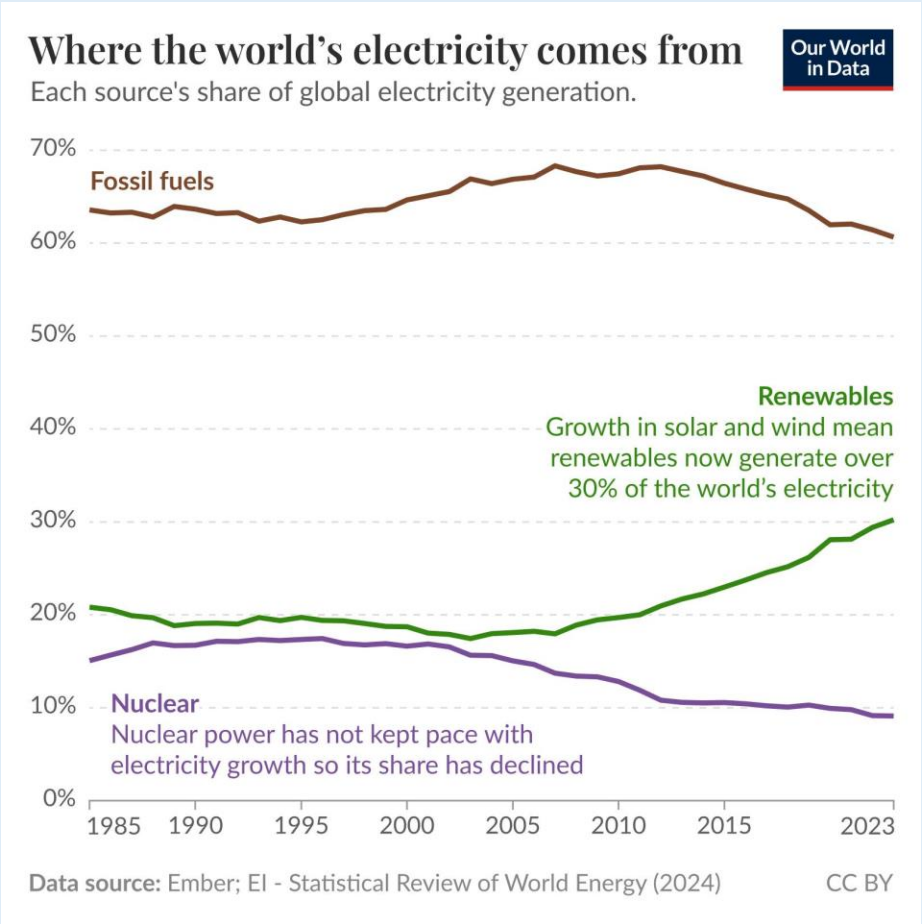
https://www.iea.org/reports/nuclear-power-and-secure-energy-transitions/executive-summary

Operable nuclear power plants

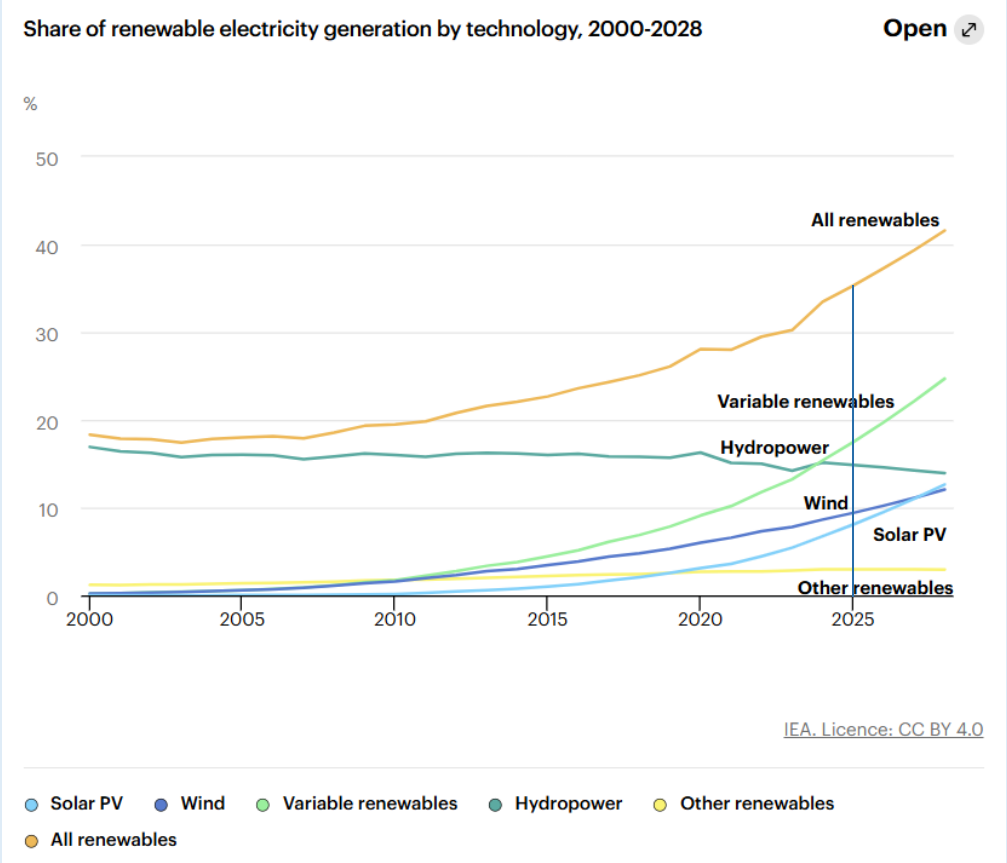
Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurized water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	311	298.1	enriched UO2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	60	60.9	enriched UO2	water	water
Pressurized heavy water reactor (PHWR)	Canada, India	47	24.5	natural UO2	heavy water	heavy water
Light water graphite reactor (LWGR)	Russia	10	6.5	enriched UO2	water	graphite
Advanced gas-cooled reactor (AGR)	UK	8	4.7	natural U (metal), enriched UO2	CO2	graphite
Fast neutron reactor (FNR)	Russia	2	1.4	PuO2 and UO2	liquid sodium	none
High temperature gas-cooled reactor (HTGR)	China	1	0.2	enriched UO2	helium	graphite

https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors

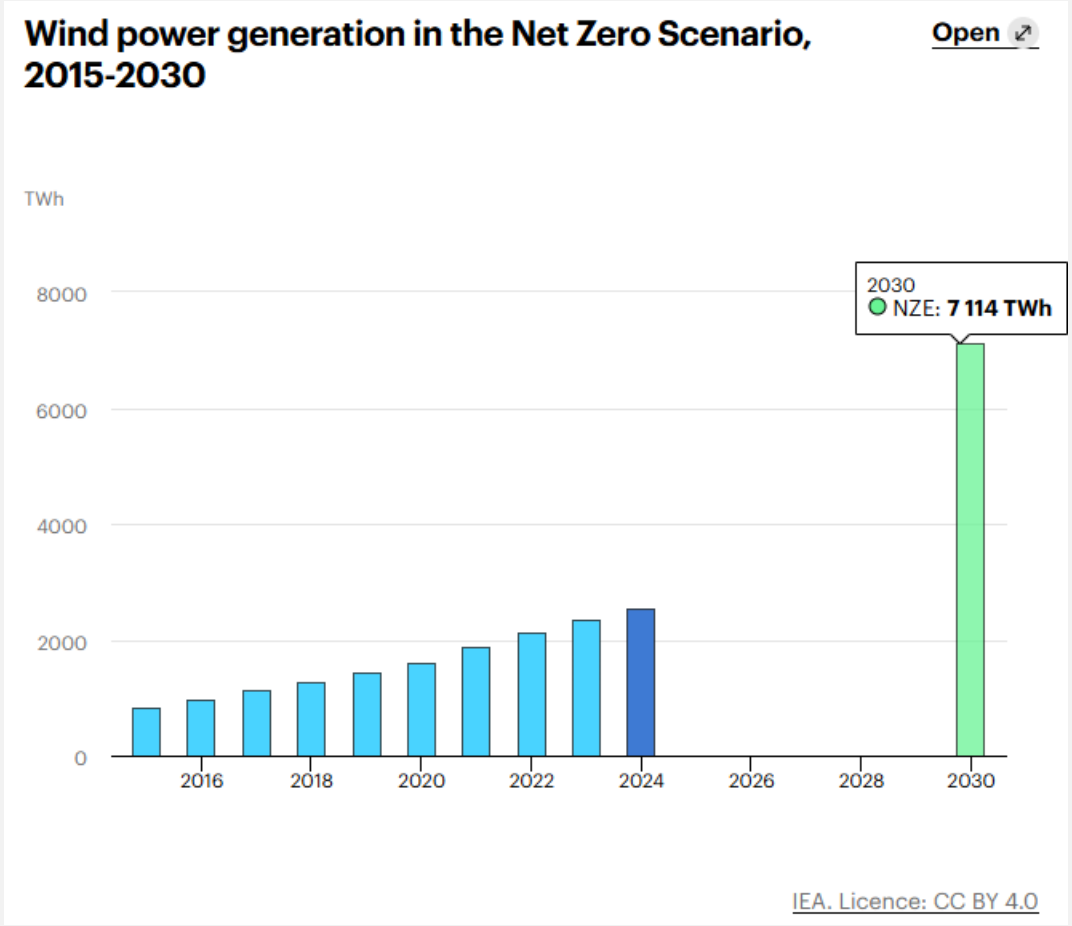
Renewables



https://www.iea.org/energy-system/renewables



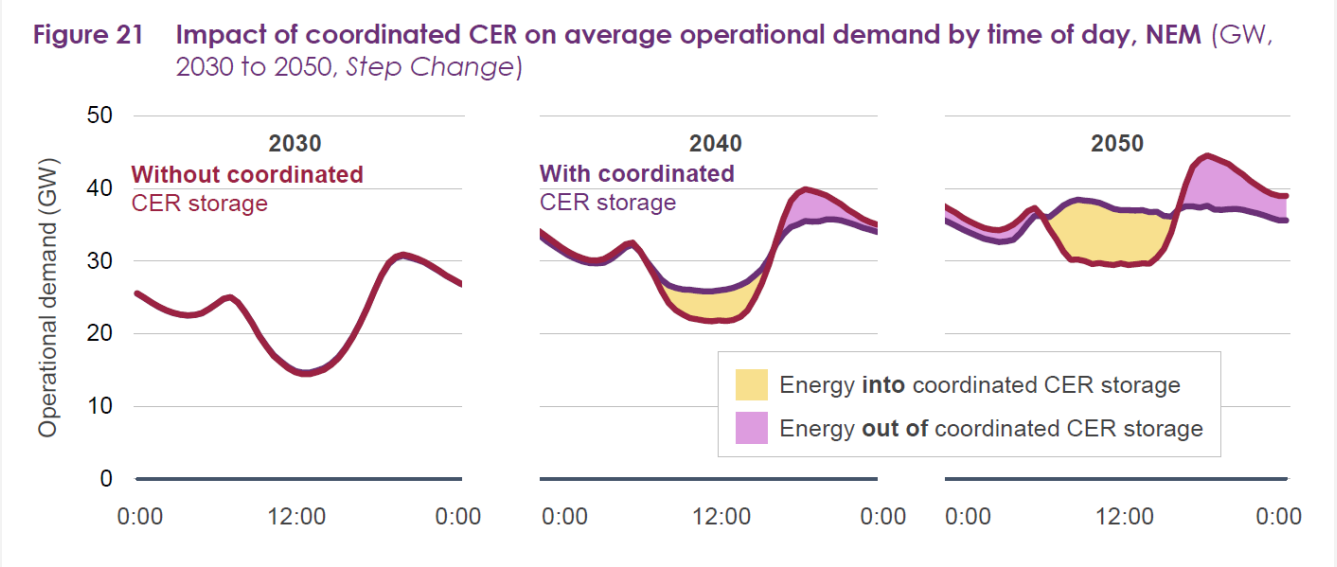
https://www.iea.org/energy-system/renewables



https://www.iea.org/energy-system/renewables/wind

Firmed Renewables

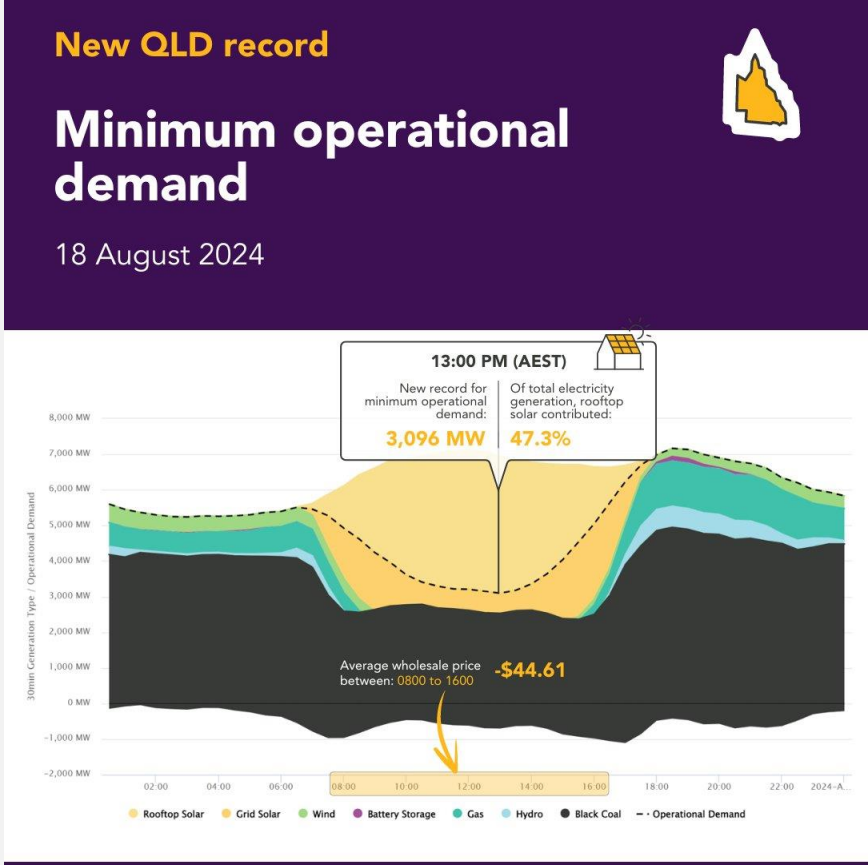
Consumer Energy Resources (CER)

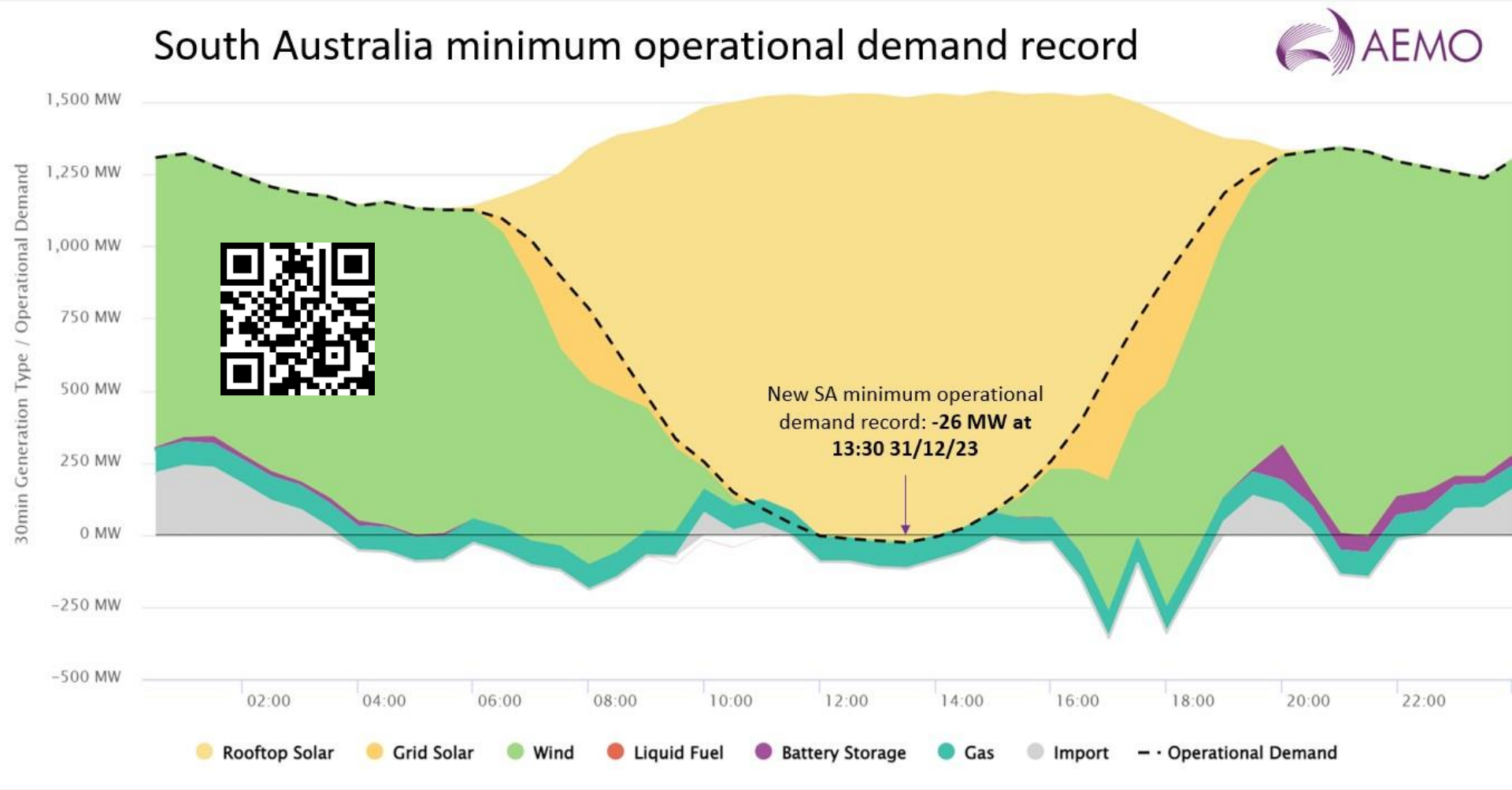


Source: Australian Energy Market Operator (AEMO) 2024 Integrated System Plan (ISP)

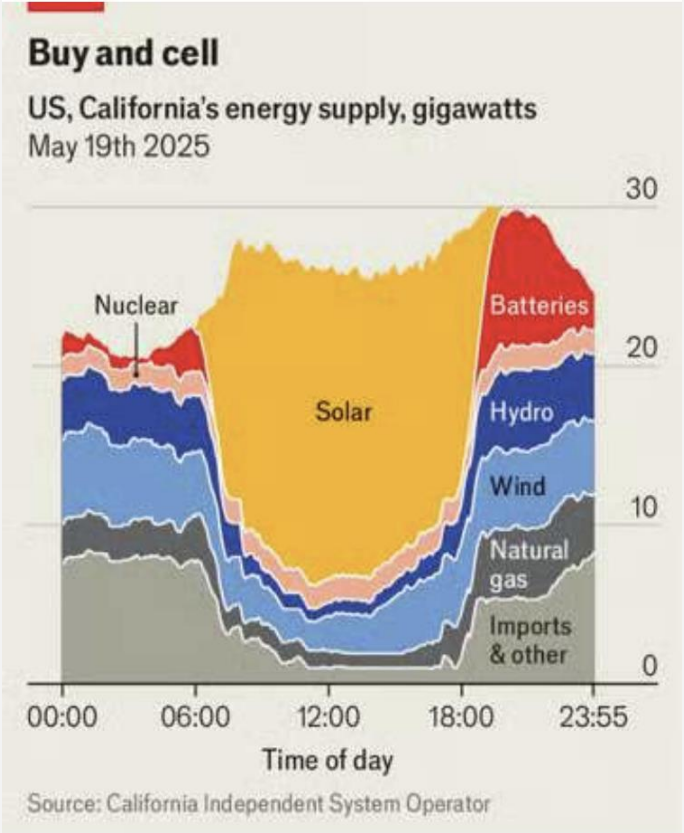
Rooftop Solar

- Not currently part of the AEMO NEM dashboard
- Source of variability/instability in contrast to traditional ‘baseload’ power
- Sizeable capacity (36GW installed in AUS)
- 47.3% instantaneous share of QLD underlying demand (18th Aug)
- Peaked at 4,151MW in QLD (30 Nov 2023)
- NEM hit 48.3% in Oct 2023
- https://pv-map.apvi.org.au/analyses





Source: AEMO X Post



2018: 500MW

↓

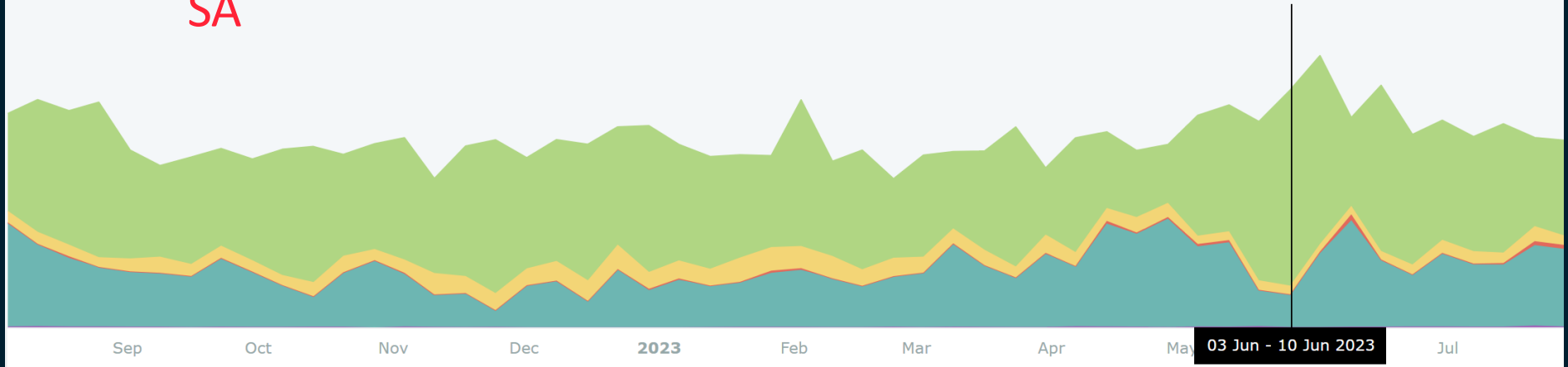
2025: 16GW

30%

The Economist, *California has got really good at building giant batteries*, 2025-05-22

Mix By Time

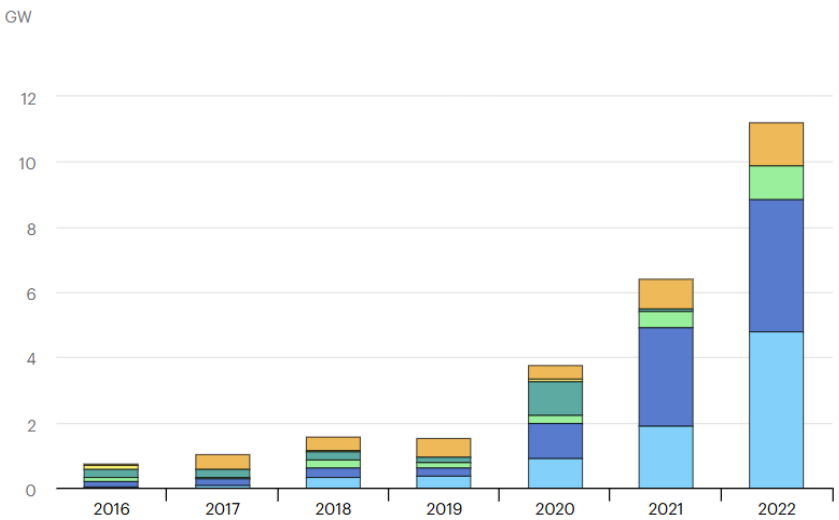
SA



Battery	**1,165** MWh	**0%**
Gas	**35.1** GWh	**14%**
Liquid Fuel	**229** MWh	**0%**
Solar	**9,413** MWh	**4%**
Wind	**211.0** GWh	**82%**

Annual grid-scale battery storage additions, 2017-2022

Open

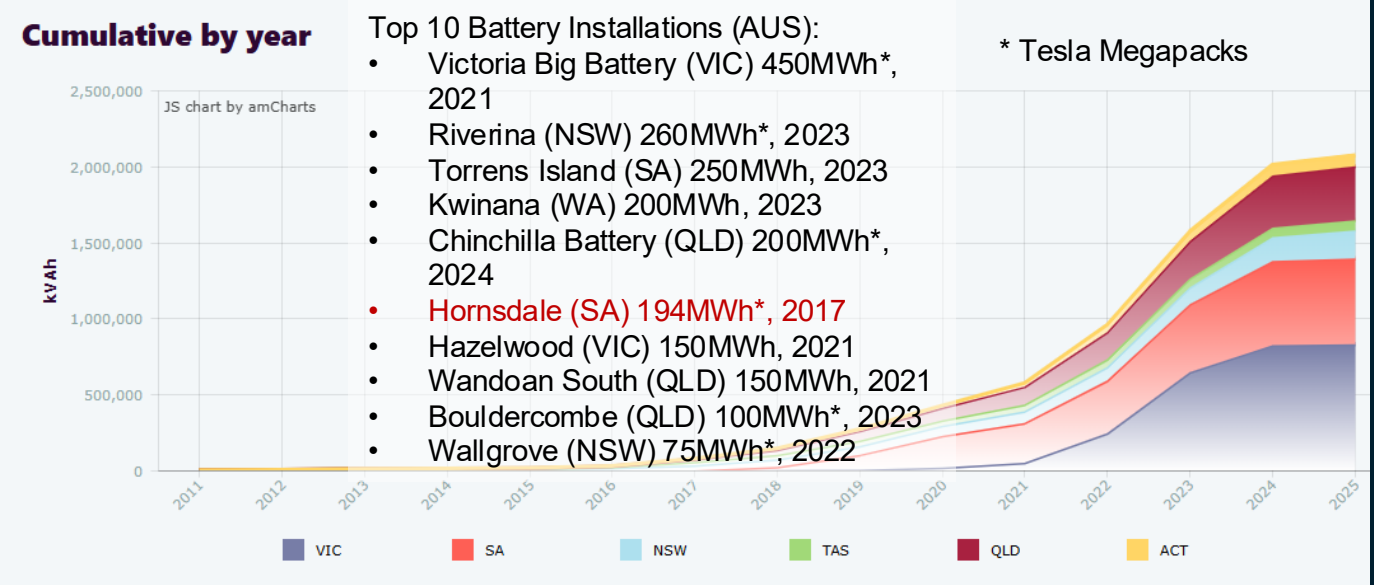


China · United States · European Union · Korea · Japan · Rest of the world

https://www.iea.org/energy-system/electricity/grid-scale-storage

Battery Storage Capacity (Australia)

20x operational
39x construction
39x announced
43x proposed



Top 10 Battery Installations (AUS):

- Victoria Big Battery (VIC) 450MWh*, 2021
- Riverina (NSW) 260MWh*, 2023
- Torrens Island (SA) 250MWh, 2023
- Kwinana (WA) 200MWh, 2023
- Chinchilla Battery (QLD) 200MWh*, 2024
- Hornsdale (SA) 194MWh*, 2017
- Hazelwood (VIC) 150MWh, 2021
- Wandoan South (QLD) 150MWh, 2021
- Bouldercombe (QLD) 100MWh*, 2023
- Wallgrove (NSW) 75MWh*, 2022

* Tesla Megapacks

Sources:
1: https://aemo.com.au/energy-systems/electricity/der-register/data-der/data-dashboard
2: https://reneweconomy.com.au/big-battery-storage-map-of-australia/

Battery Storage Capacity (Australia)

20x operational
39x construction
39x announced
43x proposed

Top 10 Battery Installations under Construction (AUS) = 16GWh:

- Eraring (NSW) 2800MWh, 2025
- Collie (WA) 2240MWh, 2024
- Smithfield (NSW) 2200MWh, 2026
- Collie Bess (WA) 2000MWh, 2025
- Waratah Super Battery (NSW) 1680MWh, 2025
- Melbourne Renewable Energy Hub (VIC) 1600MWh 2025
- Orana (NSW) 1660MWh, 2025
- Liddell (NSW) 1000MWh, 2025
- Mortlake (VIC) 650MWh, 2026
- Wagerup (NSW) 600MWh, TBD

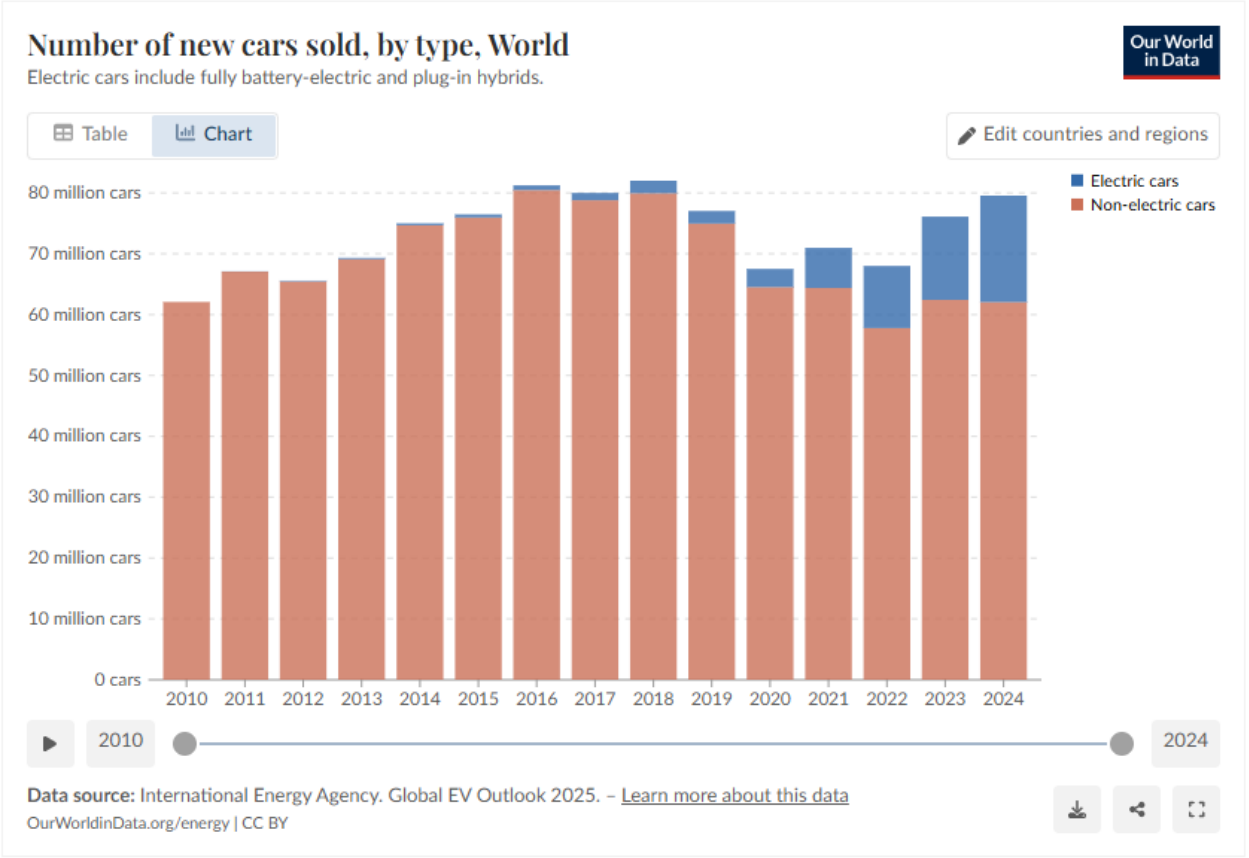
Top 10 Battery Installations Proposed (AUS):

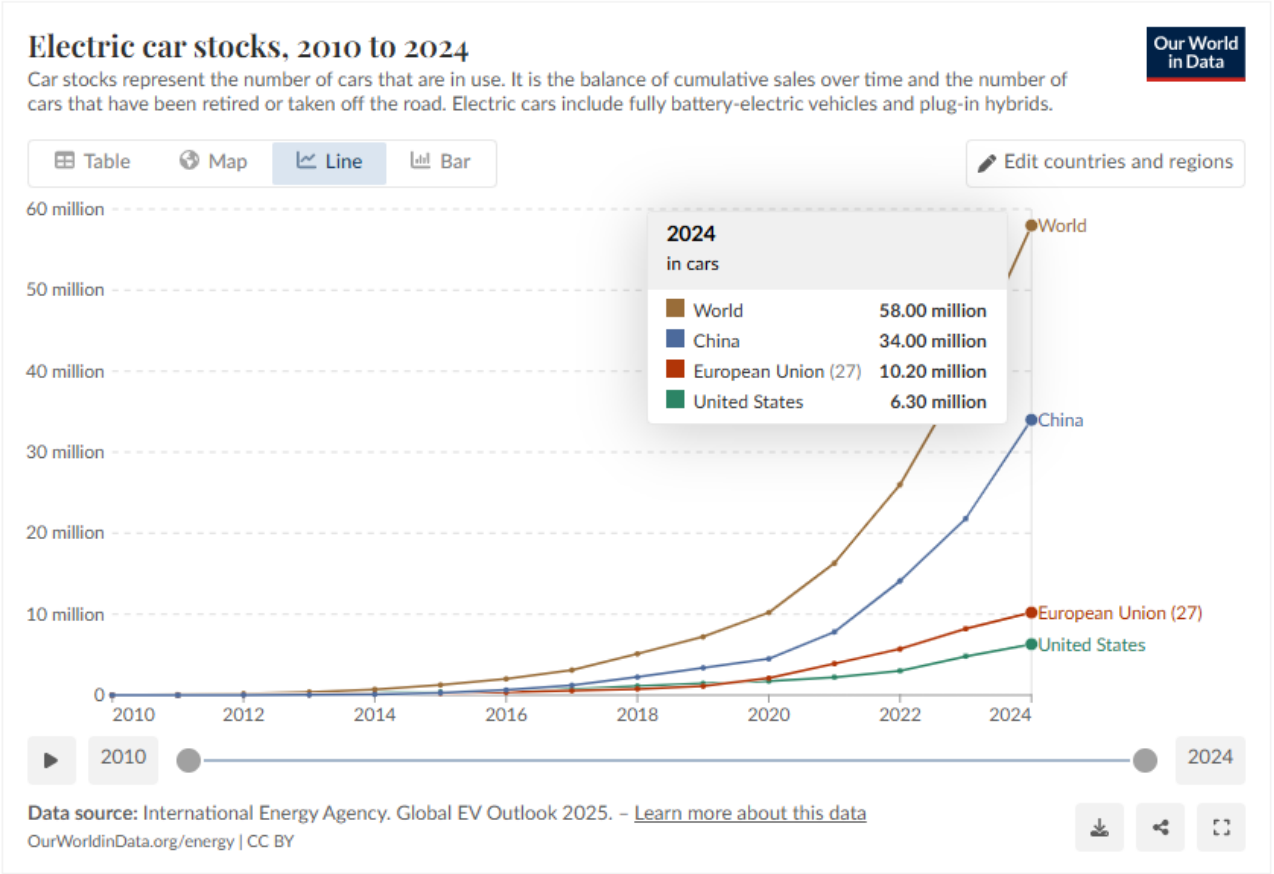
- Sun Cable (NT) 22-30GWh (to power Singapore)
- Uaroo Renewable Energy Hub (WA) 9.1GWh, 2030
- Tomago (NSW) 2GWh, 2025 (aluminium smelter)
- Goyder South (SA) 1.8GWh
- Tungkillo (SA) 1.48GWh 2025
- Brinkworth (SA) 1.2GWh (200MWh solar farm)
- Powercor (VIC) 1.1GWh (20 big batteries across VIC)
- Great Western (NSW) 1GWh
- Yanco Delta (NSW) 800MWh, 2027 (1.5GW wind farm)
- 800MWh in WA, 2x SA and VIC

Sources:

1: https://reneweconomy.com.au/big-battery-storage-map-of-australia/

EVs

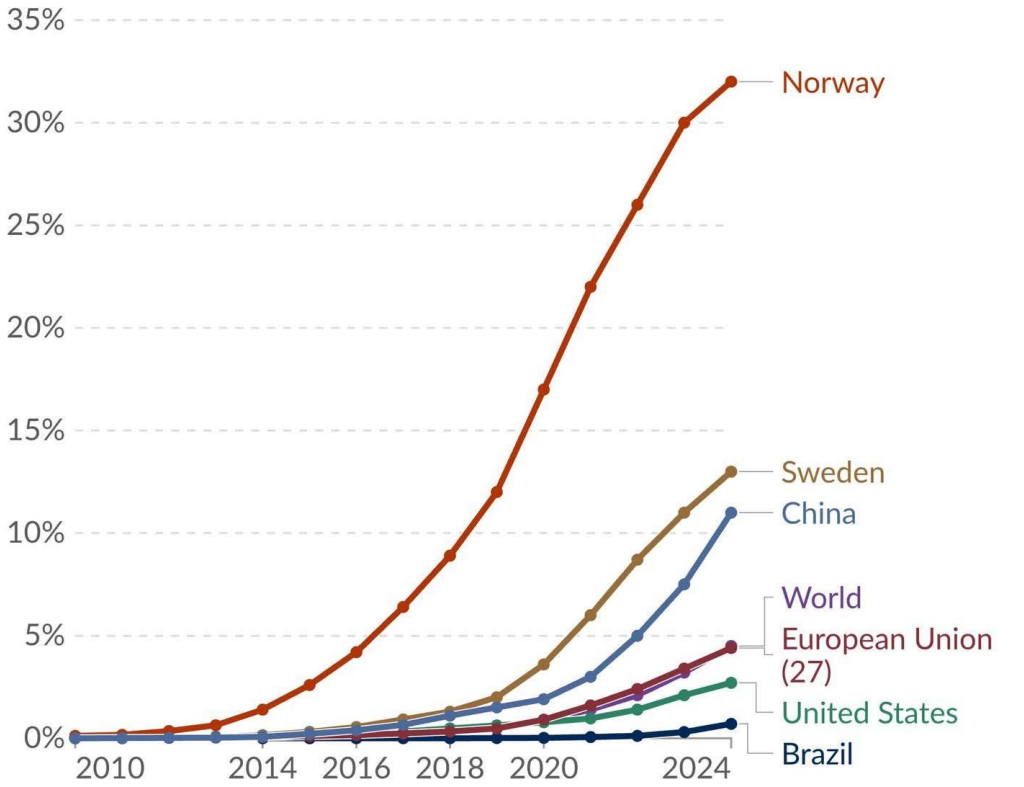

Number of new cars sold, by type, World
Electric cars include fully battery-electric and plug-in hybrids.
Our World in Data
Table
Chart
Edit countries and regions
Electric cars
Non-electric cars
80 million cars
70 million cars
60 million cars
50 million cars
40 million cars
30 million cars
20 million cars
10 million cars
0 cars
2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024
2010
2024
Data source: International Energy Agency. Global EV Outlook 2025. – Learn more about this data
OurWorldinData.org/energy | CC BY


Electric car stocks, 2010 to 2024
Car stocks represent the number of cars that are in use. It is the balance of cumulative sales over time and the number of cars that have been retired or taken off the road. Electric cars include fully battery-electric vehicles and plug-in hybrids.
Our World in Data
Table
Map
Line
Bar
Edit countries and regions
60 million
50 million
40 million
30 million
20 million
10 million
0
2024
in cars
World 58.00 million
China 34.00 million
European Union (27) 10.20 million
United States 6.30 million
World
China
European Union (27)
United States
2010
2012
2014
2016
2018
2020
2022
2024
2010
2024
Data source: International Energy Agency. Global EV Outlook 2025. – Learn more about this data
OurWorldinData.org/energy | CC BY

Share of cars currently in use that are electric

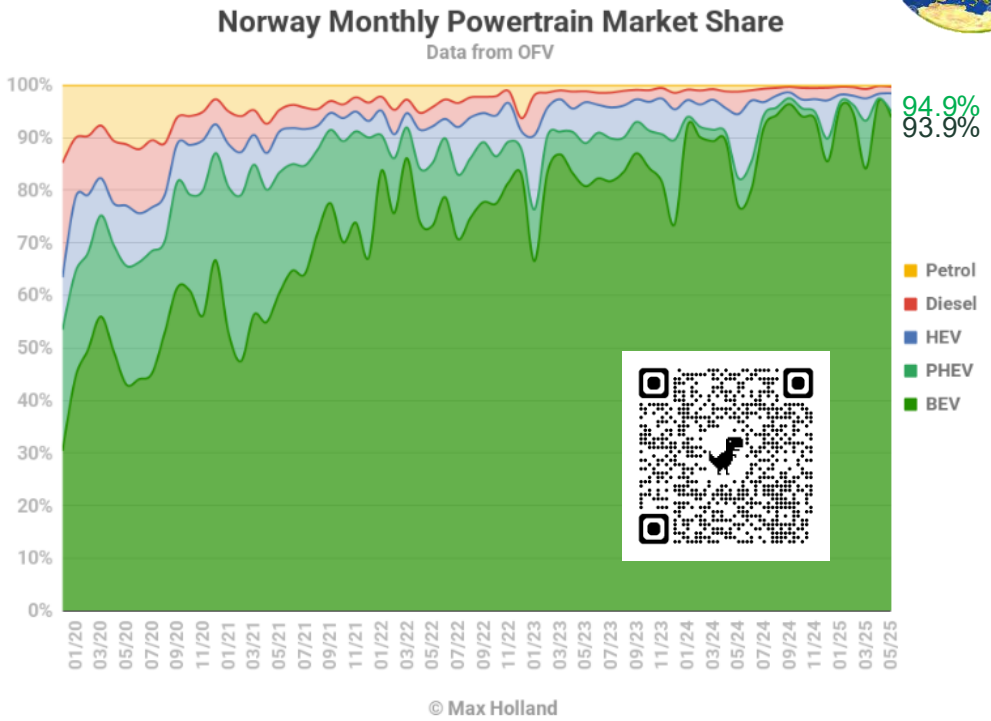
Our World in Data

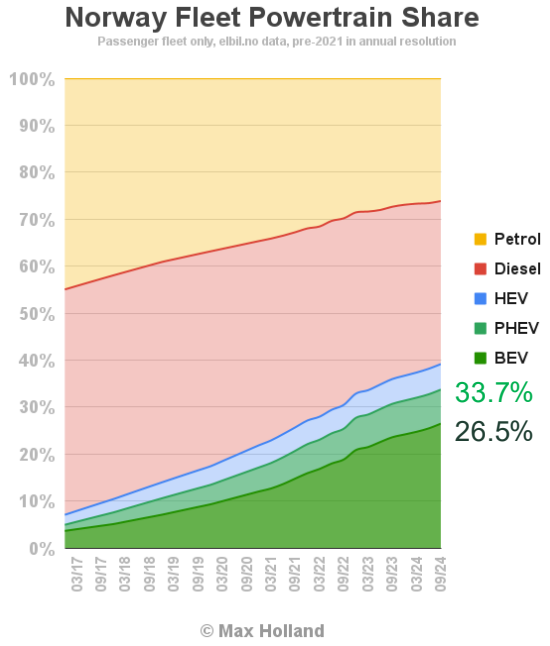
Electric cars include fully battery-electric and plug-in hybrids.



Data source: International Energy Agency. Global EV Outlook 2025.

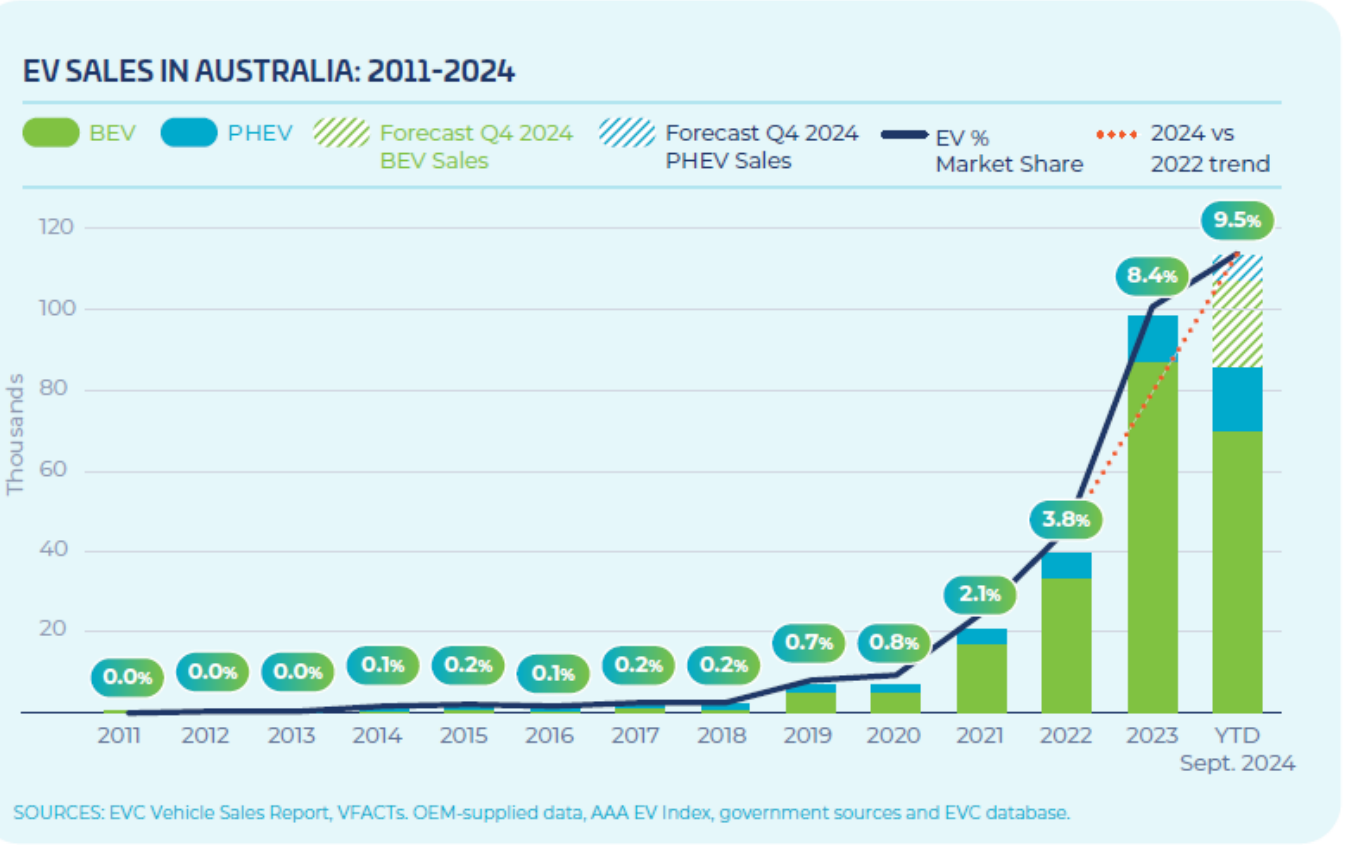
CC BY

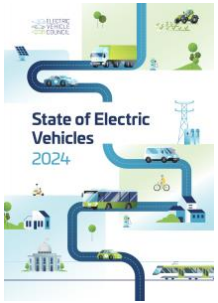




Source: Clean Technica

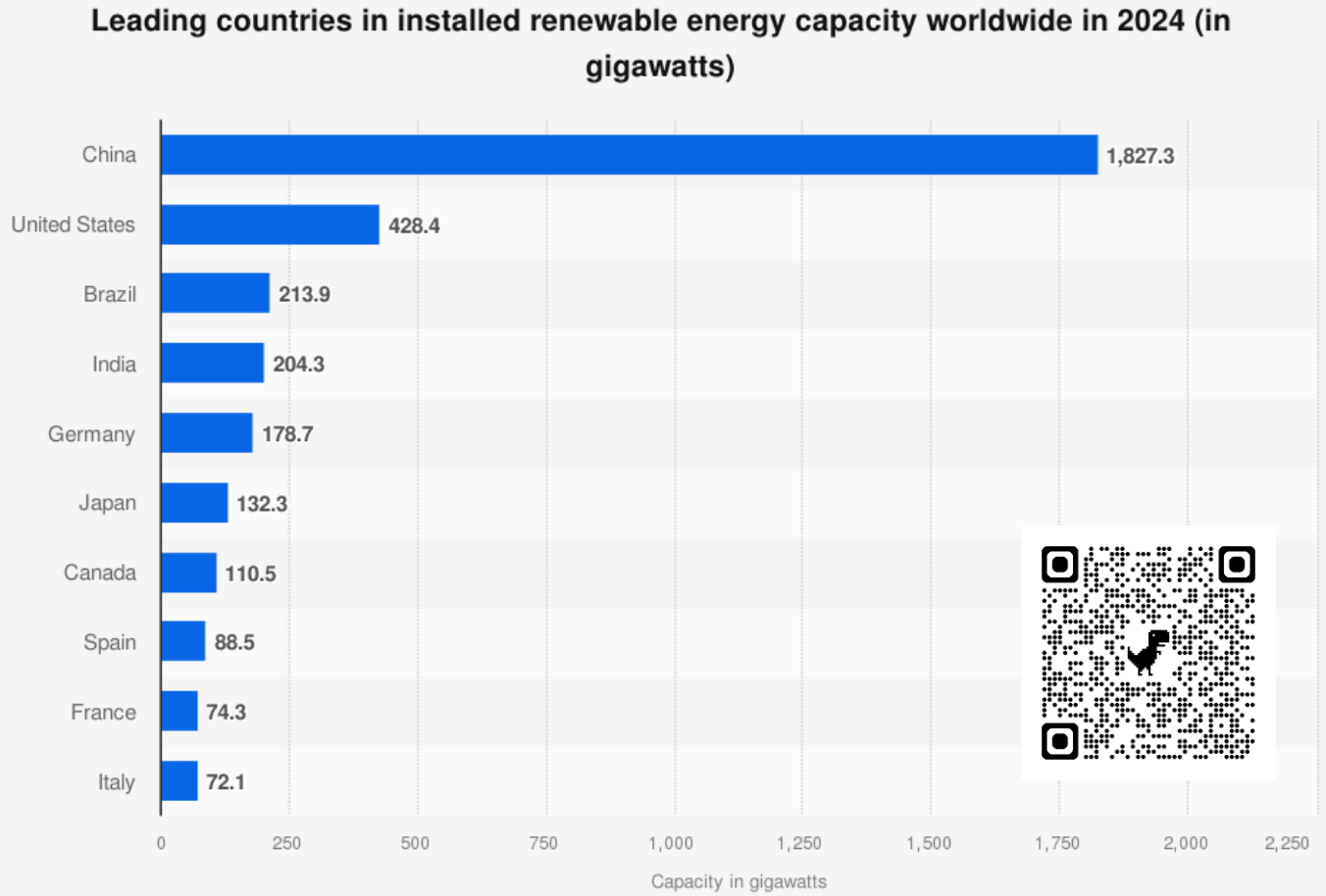
14.5 publicly accessible charging points per 1000 passenger vehicles in 2021, over seven times the EU market average





https://electricvehiclecouncil.com.au/reports/state-of-evs-2024/

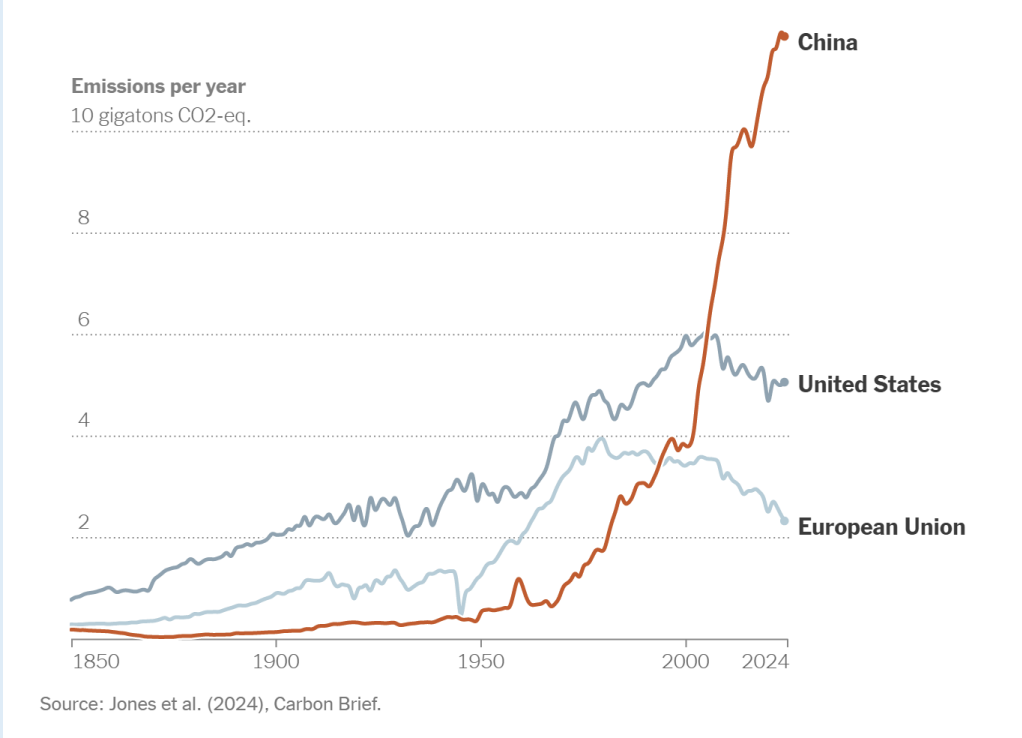
China



China:

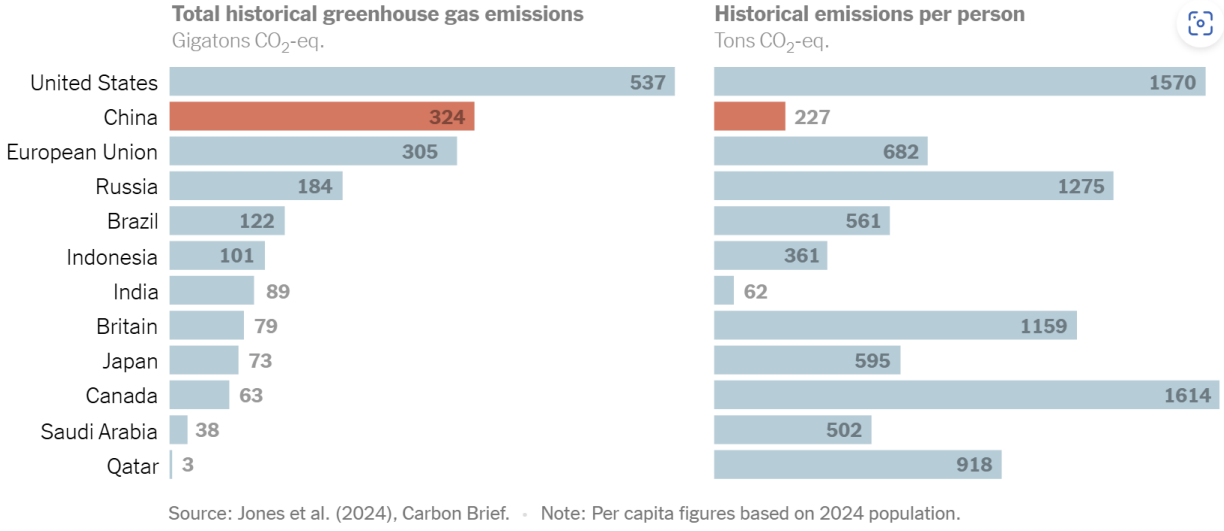
- Renewables now 51% of installed capacity
- Renewables 26% of electricity generation in 2022

Yale

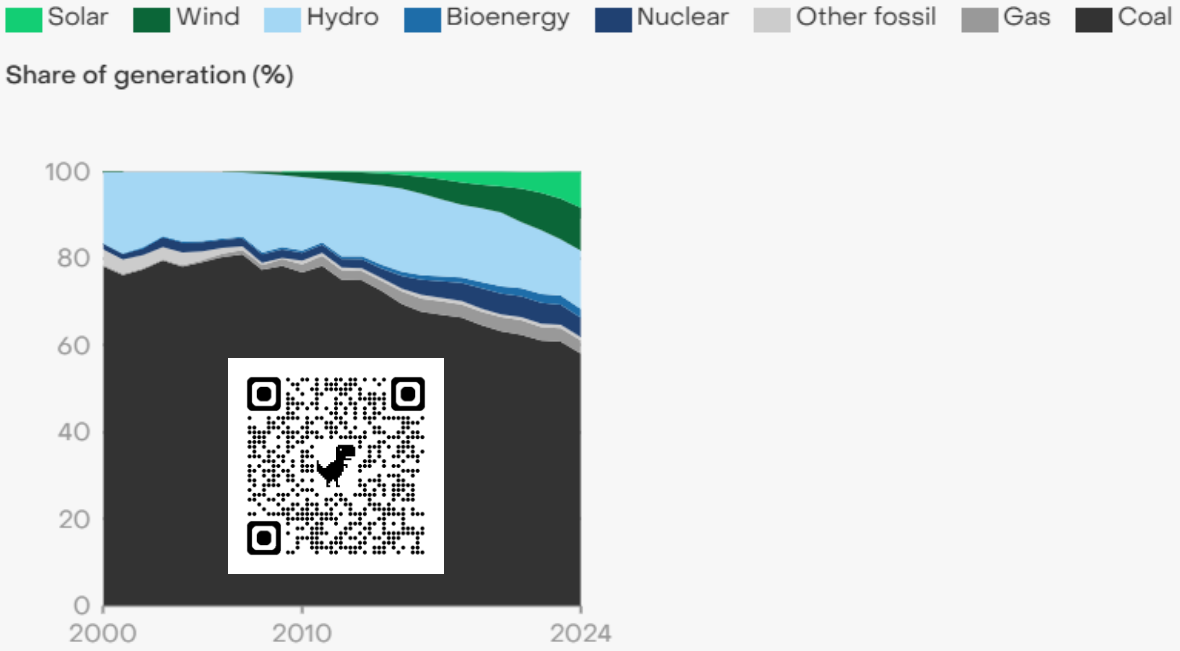


[How China's Rising Emissions Could Change Global Climate Politics - The New York Times]

How China's Rising Emissions Could Change Global Climate Politics - The New York Times



China: Power sector overview

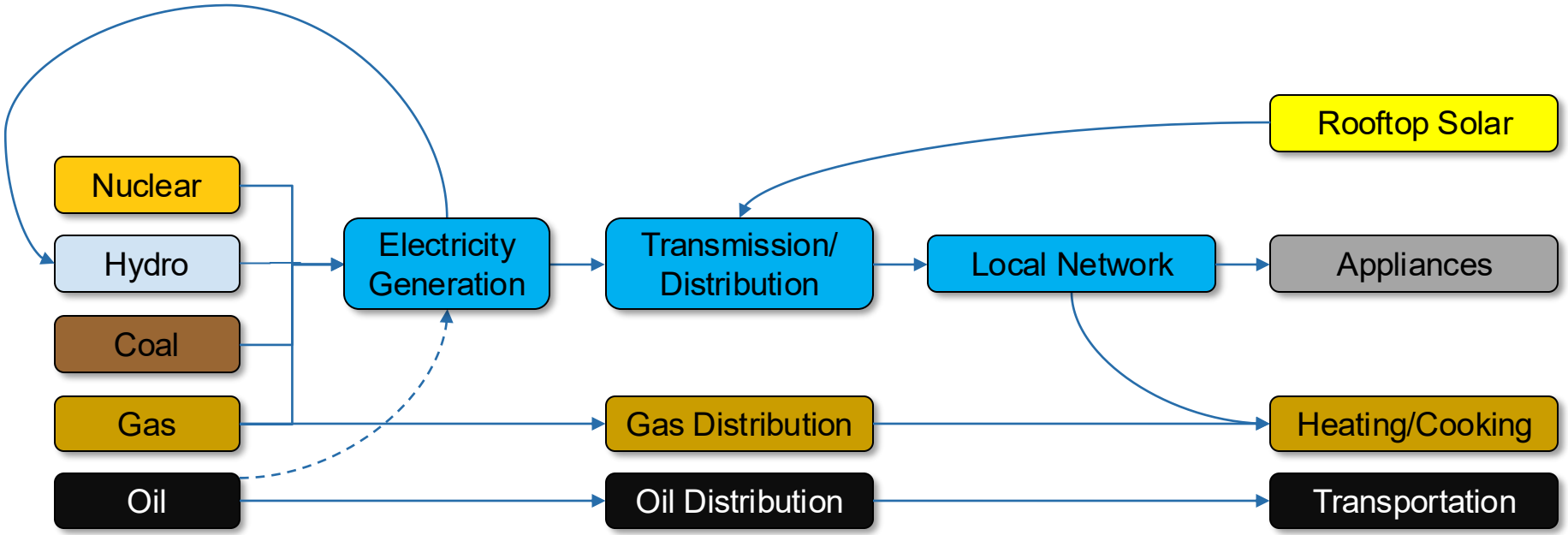


Source: Yearly electricity data, Ember

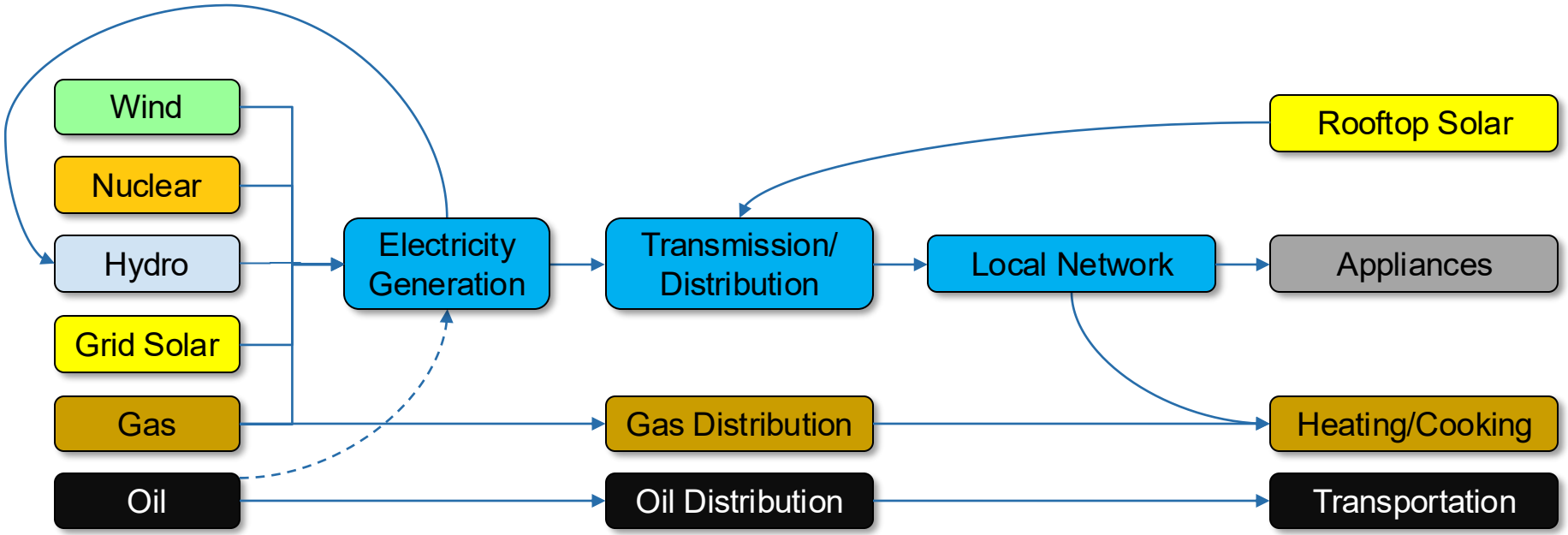
EMBER

https://ember-energy.org/countries-and-regions/china/

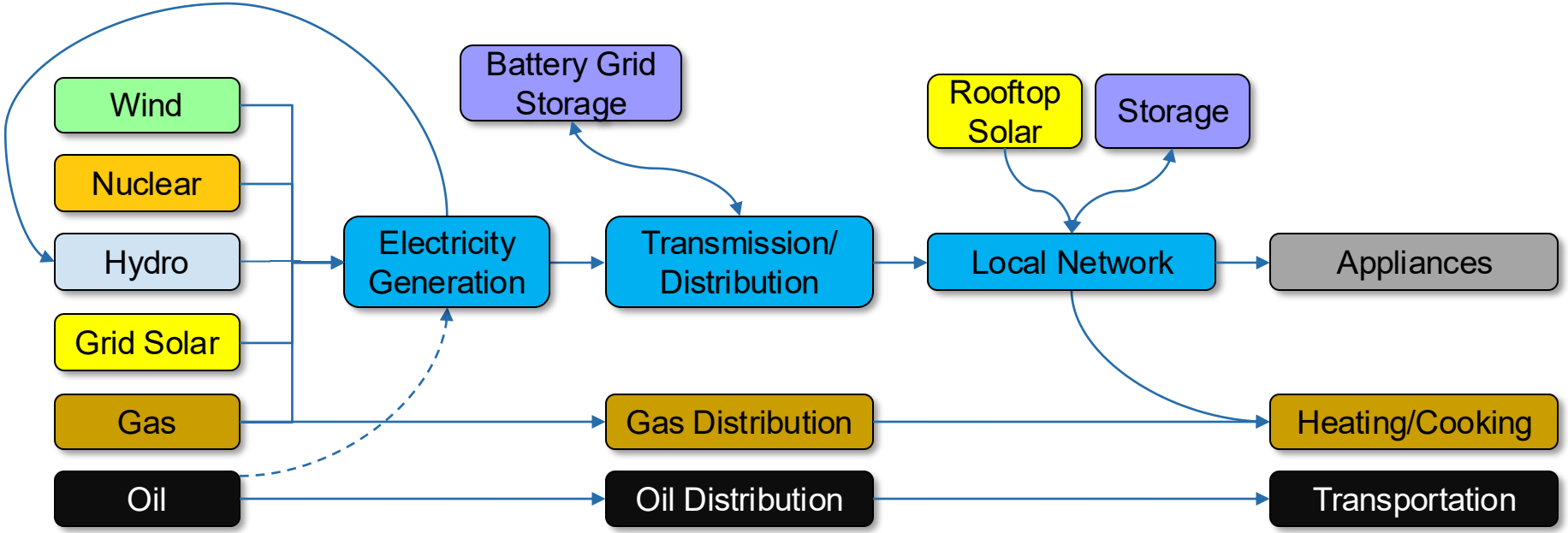
Simplified Plan for Energy Transformation



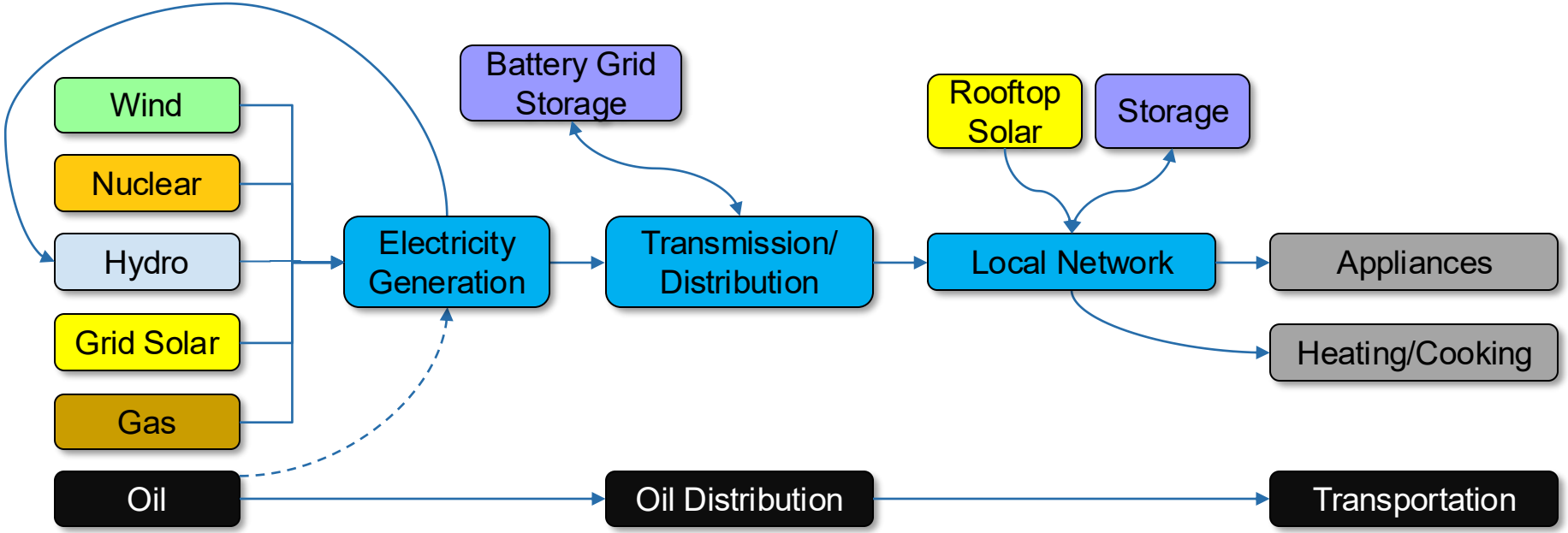
Legacy Energy Systems (Historical)



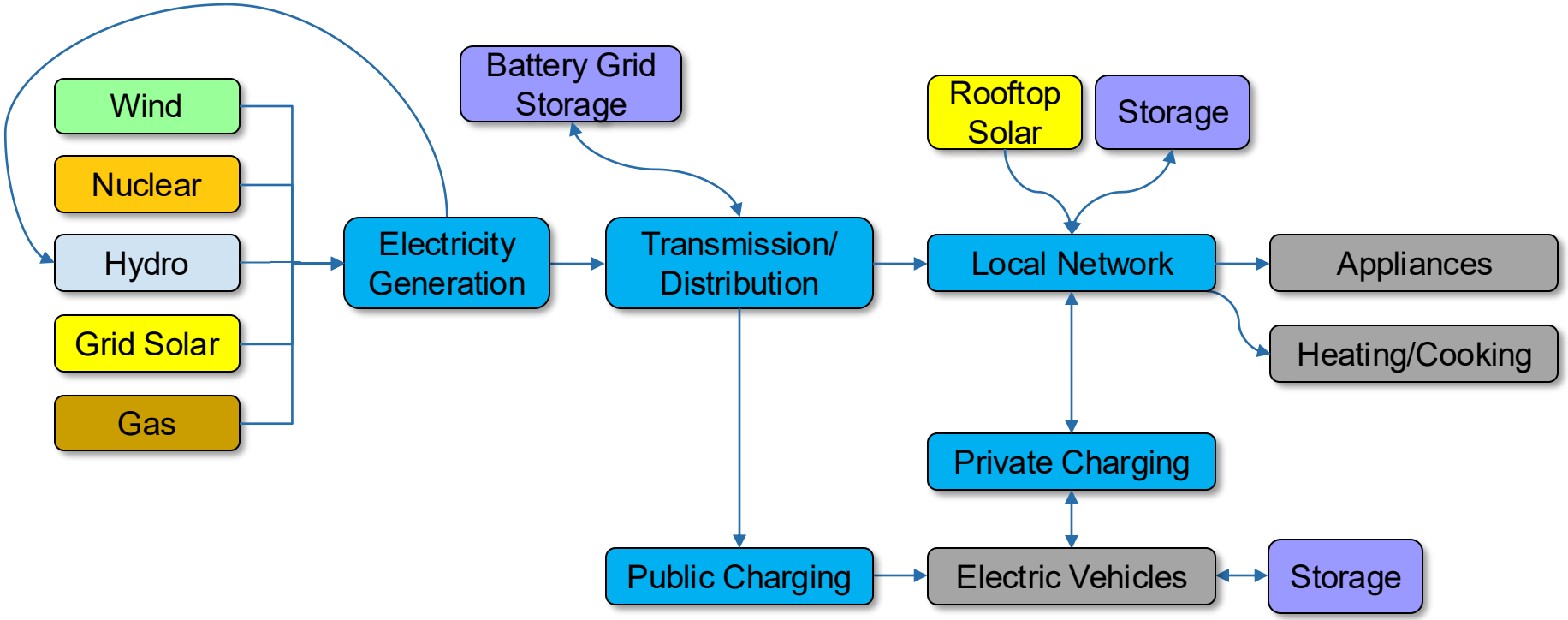
Decommission Coal, Build Wind and Solar



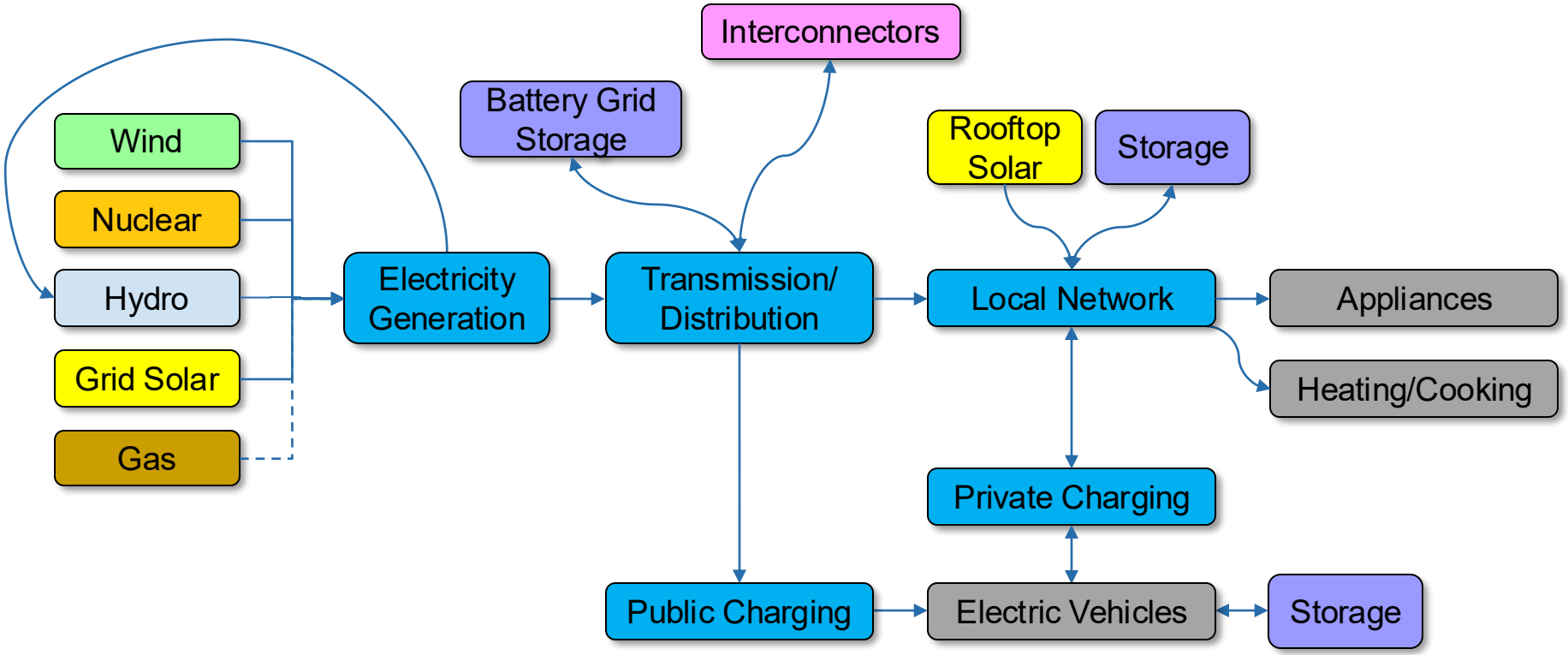
Add Storage (Grid and Consumer)



Electrify Heating/Cooking



Electrify Vehicle Fleet (with Charging Infrastructure)



Interconnect Grids and Use Gas for Resiliency

Transformational Changes

- Centralised Generation → Decentralised Generation
- Baseload Power → Variable Supply (Intermittent Wind and Solar)
- Increasing relevance of Consumer Energy Resources (CER) e.g. rooftop solar, behind-the-meter batteries and EVs
- Electrification (EVs, Heating, Cooking) is greatly increasing electricity demand
- Large scale expansion of solar (incl rooftop) and wind (offshore?)
- Large scale retirement of coal
- New concept: **Storage** (offsets variability of renewable energy supply)
- Storage includes Pumped Hydro, Utility Batteries, CER, EVs
- New concept: **Interconnectors** (for reliability/resilience)
- Disruption will occur
- Systems Thinking is a new requirement for the future management of energy systems

Systems View

AEMO

2024

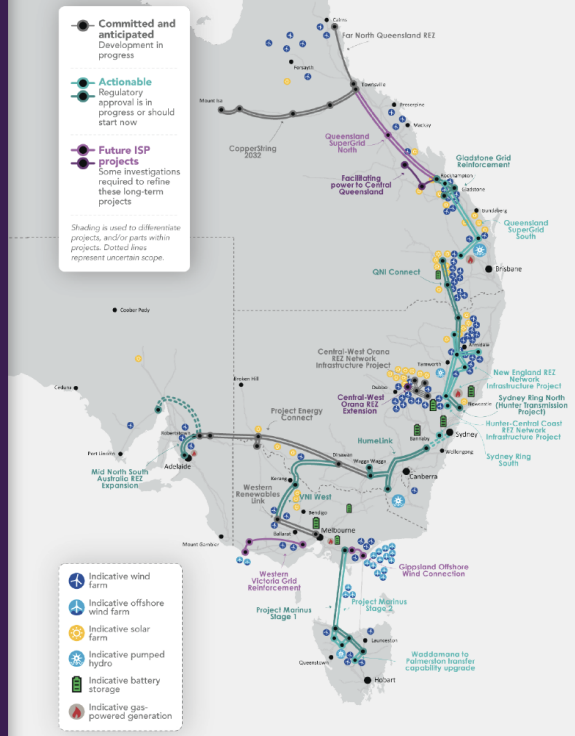
Integrated System Plan (ISP)

AEMO has published the 2024 ISP, a roadmap for the transition of the National Electricity Market (NEM) to meet future energy needs and enable a net zero economy by 2050.

At a high level, the ISP presents the 'optimal development path' (ODP), which is the lowest-cost path to the NEM's energy future of net zero by 2050. The ODP sets out new grid-scale generation, firming, storage and transmission needed in the NEM, and has an annualised capital cost of $122 billion to 2050.

Western Australia and the Northern Territory are not part of the NEM, and have their own independent power systems.

Network projects in the optimal development path



Consultation

AEMO's 2024 ISP takes into account feedback from a wide range of different groups and sources, including workshops, webinars, public forums, other engagements and submissions.

- **2,100** stakeholders engaged
- **12** webinars hosted
- **85** presentations and reports
- **220** written submissions

Inputs to the ISP include:

- Government policies on renewable energy and storage
- Emissions reduction policies and targets
- Requirements of the National Electricity Objective and Rules
- Demand forecasts
- Technology capabilities and costs
- Reliability and security needs
- Relevant sector forecasts (gas, hydrogen)
- Consumer energy resources

Net benefits

The ODP is the lowest-cost path through the NEM's transition to a net zero future.

It calls for around 10,000 km of new transmission projects by 2050 to connect new generation across the power system. These transmission projects would reduce costs for consumers by delivering benefits that would recoup their $16 billion investment costs, save consumers a further $18.5 billion in avoided costs, and deliver emissions reductions valued at $3.3 billion.

Actionable projects

Seven transmission projects have been progressed since the 2022 ISP to 'actionable' status, allowing more coordinated and effective community consultation to commence earlier.

Work for both new and previously actionable projects should progress to deliver these projects to schedule.

- Hunter-Central Coast Renewable Energy Zone (REZ) Network Infrastructure project
- Sydney Ring South
- Gladstone Grid Reinforcement
- Mid North South Australia REZ Expansion
- Waddamana to Palmerston Transfer Capability Upgrade
- Queensland SuperGrid South
- Queensland-New South Wales Interconnector Connect (QNI Connect).

Key facts and figures ('Step Change' scenario)

Storage capacity to increase significantly
Batteries, virtual power plants, pumped hydro
NOW 3 GW → 2030 22 GW → 2050 49 GW

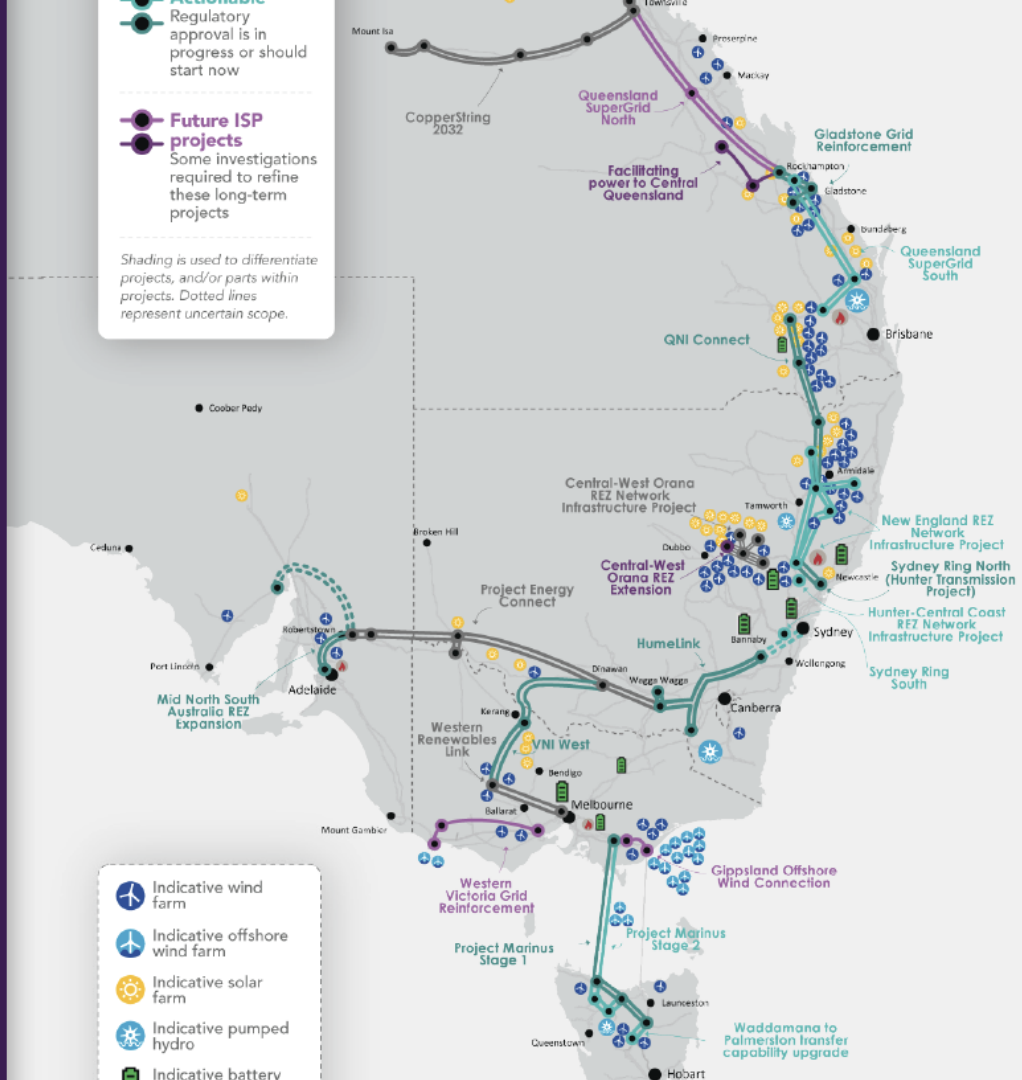
Grid-scale wind and solar to increase 6-fold
NOW 21 GW → 2030 55 GW → 2050 127 GW

Distributed solar PV to increase 4-fold
Rooftop solar, other distributed solar
NOW 21 GW → 2030 36 GW → 2050 86 GW

Electricity consumption from the grid to nearly double
NOW 174 TWh → 2030 202 TWh → 2050 313 TWh

Gas-powered generation to increase
While current mid-merit plants will all retire within that period
NOW 11.5 GW → 2050 15 GW

Coal generation to be withdrawn
Capacity to be retired by:
2030 46% → 2038 100%



2,100 stakeholders engaged

12 webinars hosted

85 presentations and reports

Inputs to the ISP include:

- Government policies on renewable energy and storage
- Emissions reduction policies and targets
- Requirements of the National Electricity Objective and Rules
- Demand forecasts
- Technology capabilities and costs
- Reliability and security needs
- Relevant sector forecasts (gas, hydrogen)
- Consumer energy resources

Net benef

The ODP is the lo path through the to a net zero futu

It calls for around transmission proje connect new gene power system. The projects would rec consumers by deli would recoup thei investment costs, further $18.5 billio and deliver emissi valued at $3.3 billi

Actionable projects

Seven transmission projects have been progressed since the 2022 ISP to 'actionable' status, allowing more coordinated and effective community consultation to commence earlier.

Work for both new and previously

- Hunter-Central Coast Energy Zone (REZ) Ne Infrastructure project
- Sydney Ring South
- Gladstone Grid Reinfo
- Mid North South Austr
- Waddamana to Palme Capability Upgrade
- Queensland SuperGri

storage

Indicative gas-powered generation

actionable projects should progre
deliver these projects to schedule

Key facts and figures ('Step Change' scenario)

Storage capacity

to increase significantly

Batteries, virtual power plants, pumped hydro

NOW	2030	2050
3 GW	22 GW	49 GW

Grid-scale wind and solar

to increase 6-fold

NOW	2030	2050
21 GW	55 GW	127 GW

Distributed solar PV

to increase 4-fold

Rooftop solar, other distributed solar

NOW	2030	2050
21 GW	36 GW	86 GW

Electricity consumption from the grid

to nearly double

NOW	2030	2050
174 TWh	202 TWh	313 TWh

actionable projects should progress to deliver these projects to schedule.

- Queensland-New South Wales Interconnector Connect (QNI Connect).

rio)

Distributed solar PV

to increase 4-fold

Rooftop solar, other distributed solar

NOW 21 GW ▶ 2030 36 GW ▶ 2050 86 GW

Electricity consumption from the grid

to nearly double

NOW 174 TWh ▶ 2030 202 TWh ▶ 2050 313 TWh

Gas-powered generation

to increase

While current mid-merit plants will all retire within that period

NOW 11.5 GW ▶ 2050 15 GW

Coal generation

to be withdrawn

Capacity to be retired by:

2030 46% ▶ 2038 100%

INCOSE

National Energy Analysis Centre (NEAC) Australia

- Enduring national research infrastructure, physical and digital
- Supports energy transition: decarbonisation, resilience, equity
- Backed by Commonwealth Science and Industry Research Organisation (CSIRO), supported by the sector, open to all
- Combines modern systems science with social innovation

Q&A

World's largest electric ferry (China Zorilla) being built by **Incat Tasmania** in Australia for Buquebús to operate in South America:

- 130m
- 2,100 passengers and 225 vehicles
- 40MWh
- 90 min run-time
- 160km range
- 40 mins charge time

https://www.offshore-energy.biz/wartsila-to-power-worlds-largest-battery-electric-ferry/
https://www.abc.net.au/news/2025-05-02/incat-launches-worlds-largest-battery-electric-ship-hull096/105243498

Support Slides

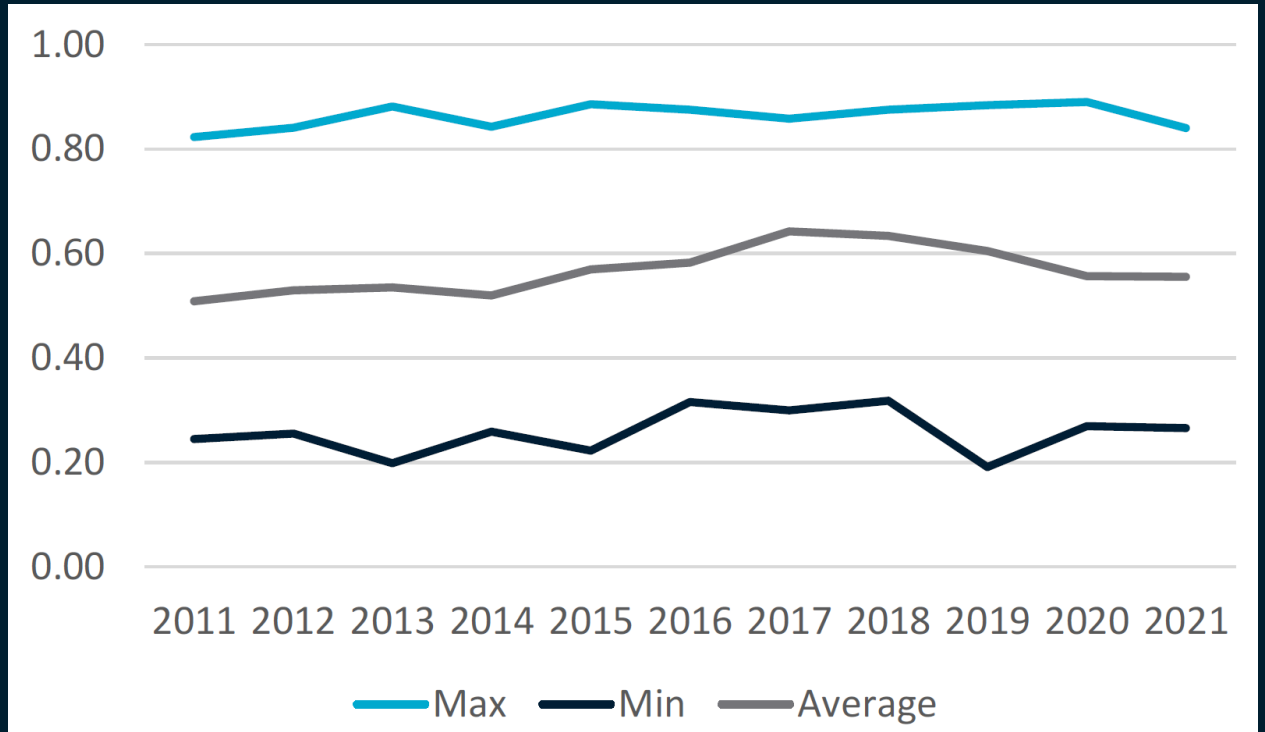
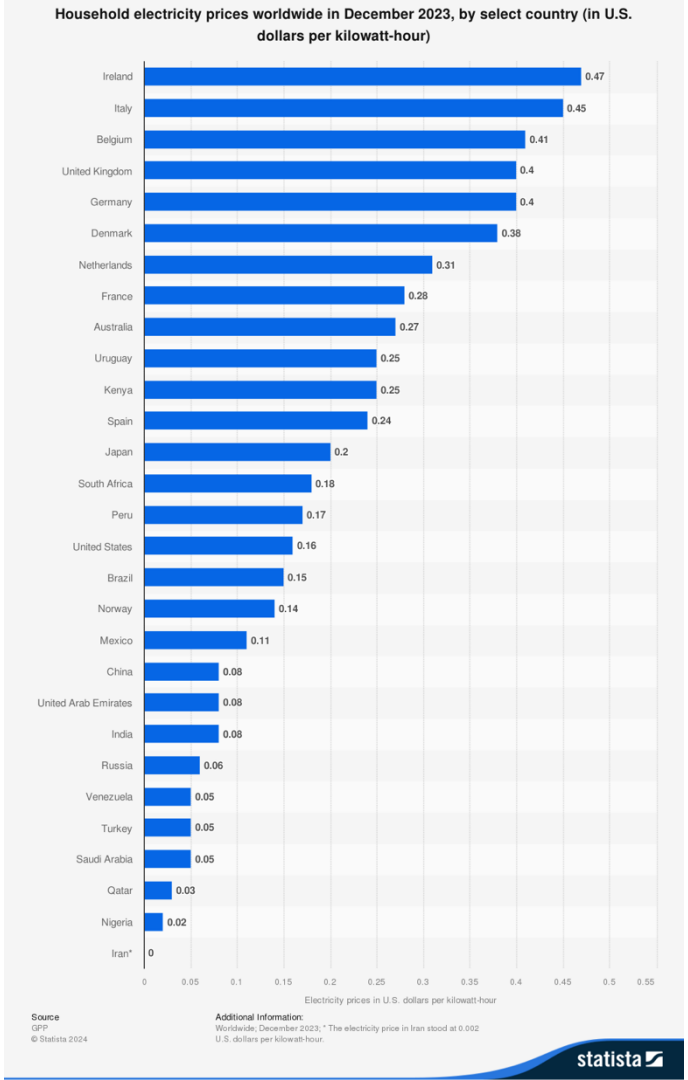


Figure 2-2 Historical capacity factors for black coal in Australian electricity generation (NEM states)

Gen Cost 2024 Report



Source: https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/