The Cleantech Revolution

It’s exponential, disruptive, and now

Presentation

SENATE presidents’ FORUM

Daan Walter

September 2024

Topics

Two visions for the energy future

The cleantech story so far

The drivers of continued change

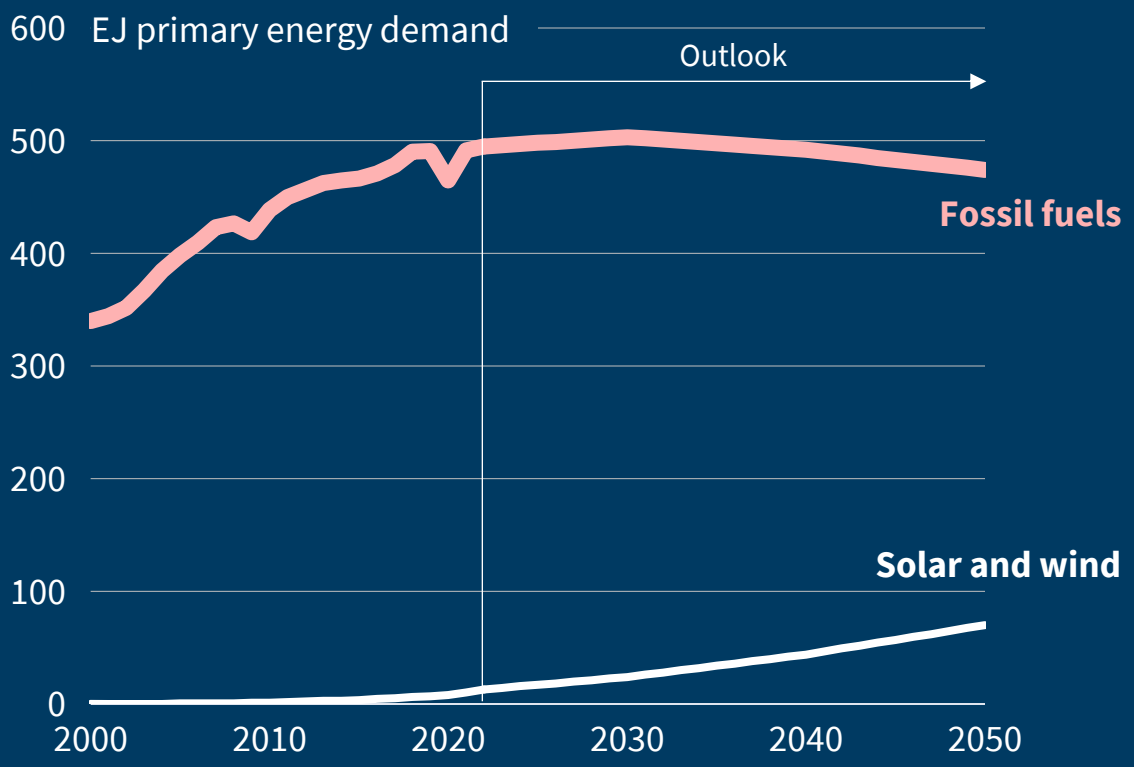
The shape of things to come

Implications

The two visions of the energy future

The **old commodities** narrative of business-as-usual: reducing fossil fuel demand will be slow, expensive, and painful

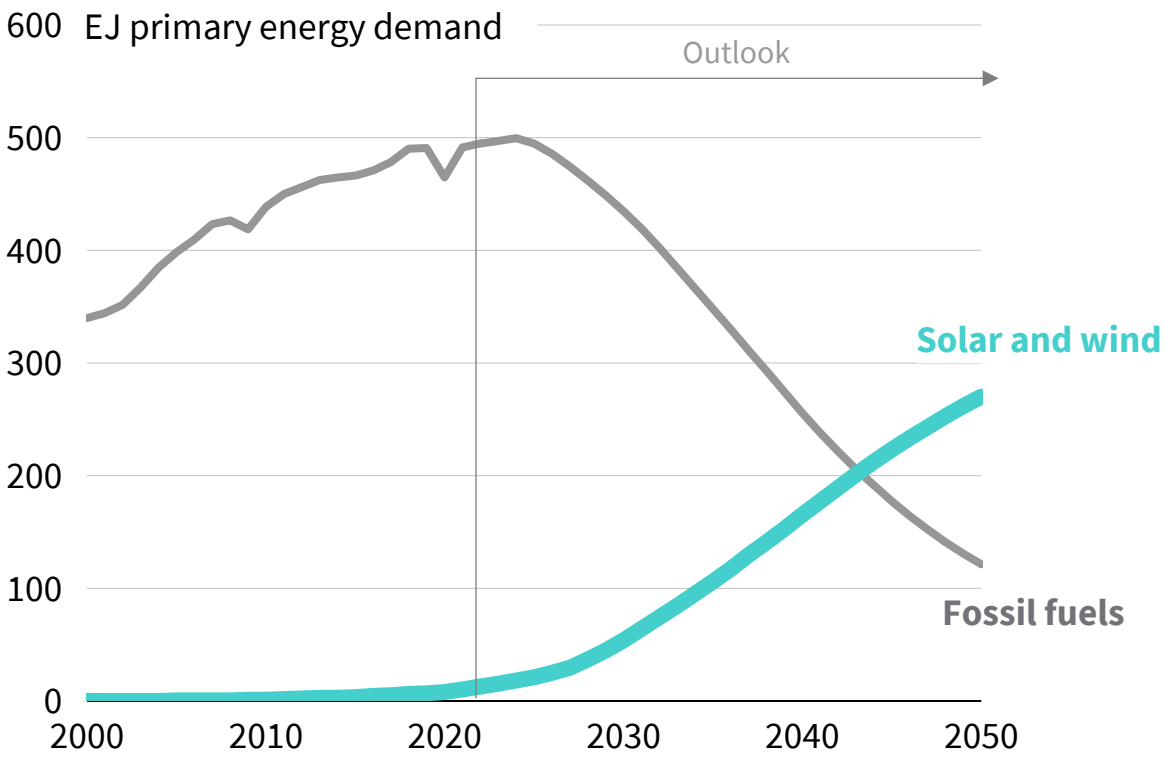
The old guard's energy outlook



Source: Exxon Mobil Global Outlook 2023.

The **new technology** narrative of exponential and beneficial change: a shift to a cheaper, faster, and distributed energy system

The new technology insurgent's energy outlook

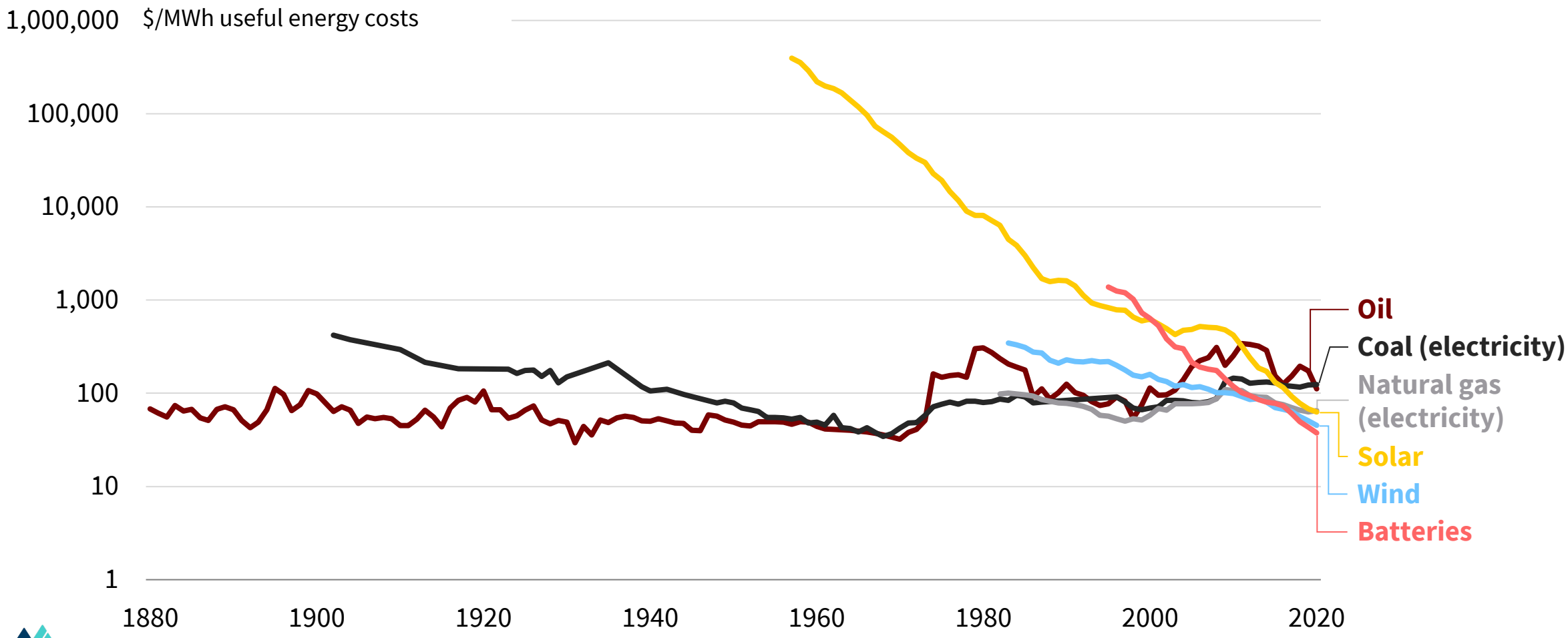


Source: Rystad Energy 1.6°C Scenario.

Technologies beat commodities on costs

Manufactured technologies (e.g., solar and wind) enjoy cost learning curves; (fossil) commodities don't

Historical costs of energy sources

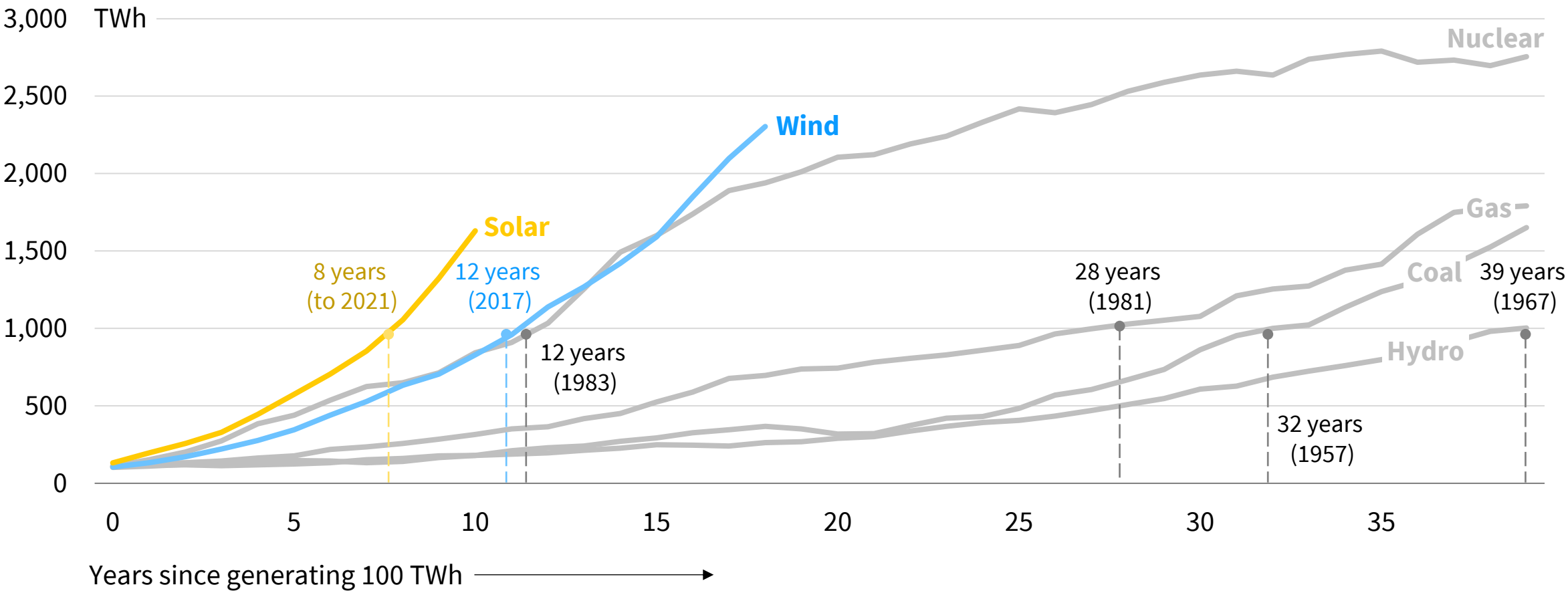


Source: Way et al. 2022. Individual fossil fuel technologies of course do have learning curves; but because of depletion and cartels, fossil fuel prices have not shown structural decline over time.

Technologies beat commodities on speed

Manufactured technologies grow fast; commodities grow slowly

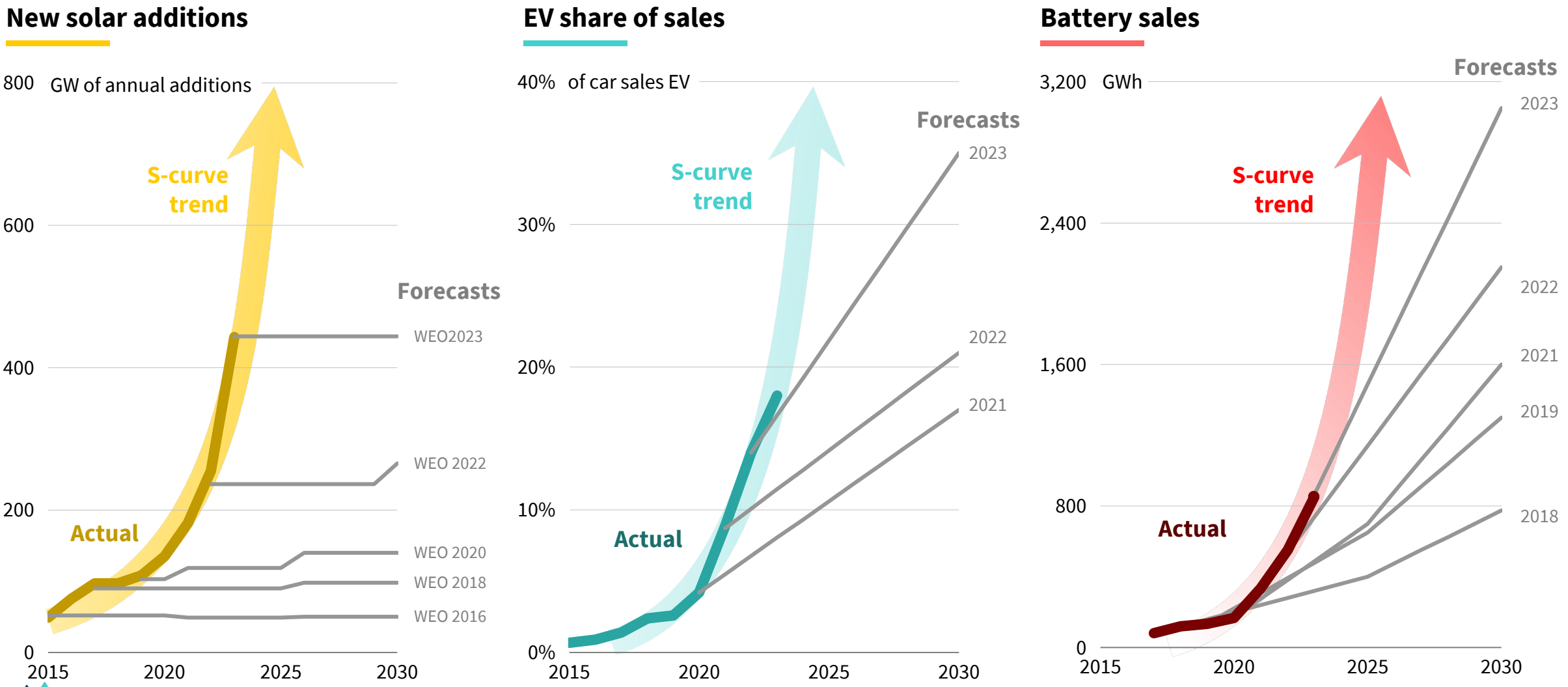
Electricity generation after reaching 100 TWh



Source: Ember 2023 Global electricity review; Wind and solar generation data from Ember annual electricity data, nuclear, gas, coal and hydro generation data from Pinto et al. (2023). This graphic is based on a chart by Nat Bullard. Nuclear technologies in 2024 have a 10–15 year lead time.

Incumbents have underestimated the speed of change

Even neutral actors modeled in **linear** terms. But change has been exponential

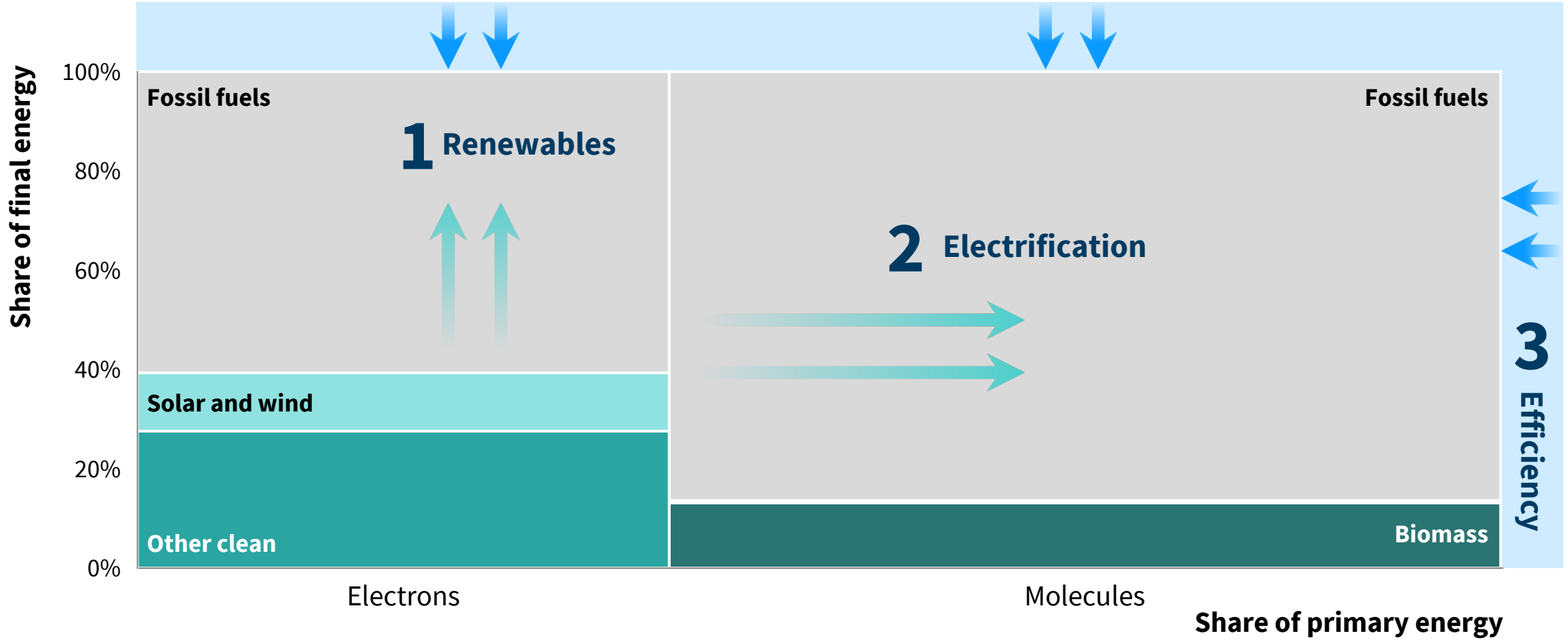


Source: BNEF (solar and battery actuals), IEA STEPS for WEO forecasts , RMI annotation.

There are three big levers of change

Renewables, electrification, and efficiency are rapidly transforming the energy system

Global energy demand in 2022



Source: IEA WEO 2023. The primary energy split is the amount of primary energy going to electricity (electrons) or other (molecules).

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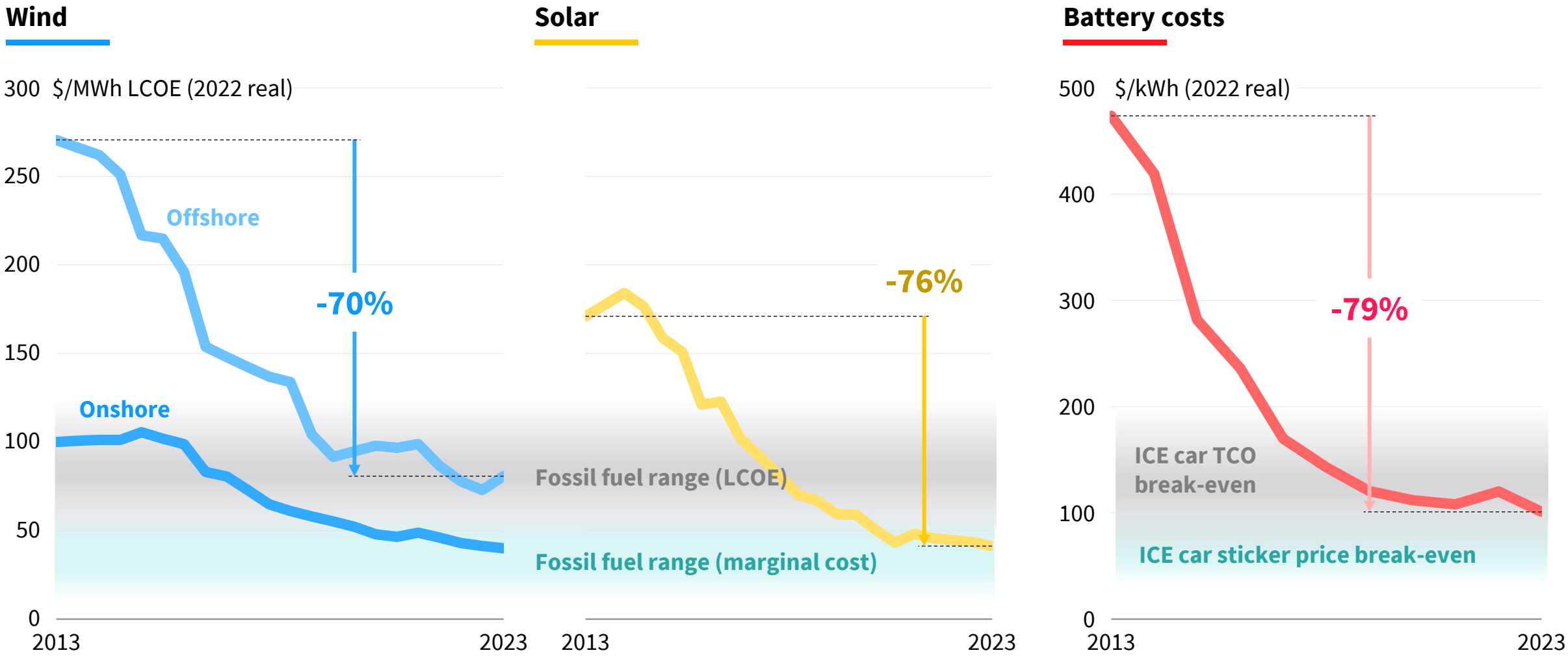
Cleantech costs have fallen rapidly

Clean technology costs fall by around 20% for every doubling of deployment — Wright's Law

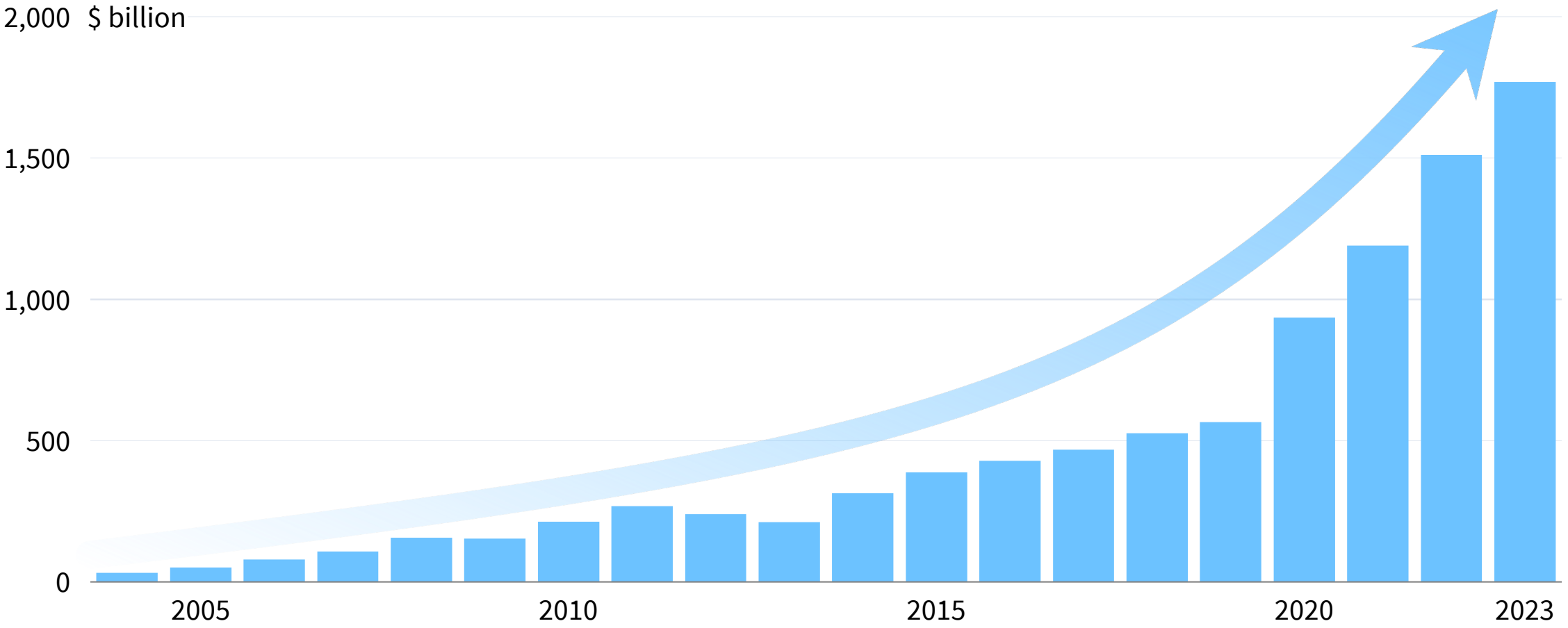


Source: BNEF, RMI ranges.

Capital has poured into cleantech

The first cleantech trillion took decades; the second trillion will happen in four years

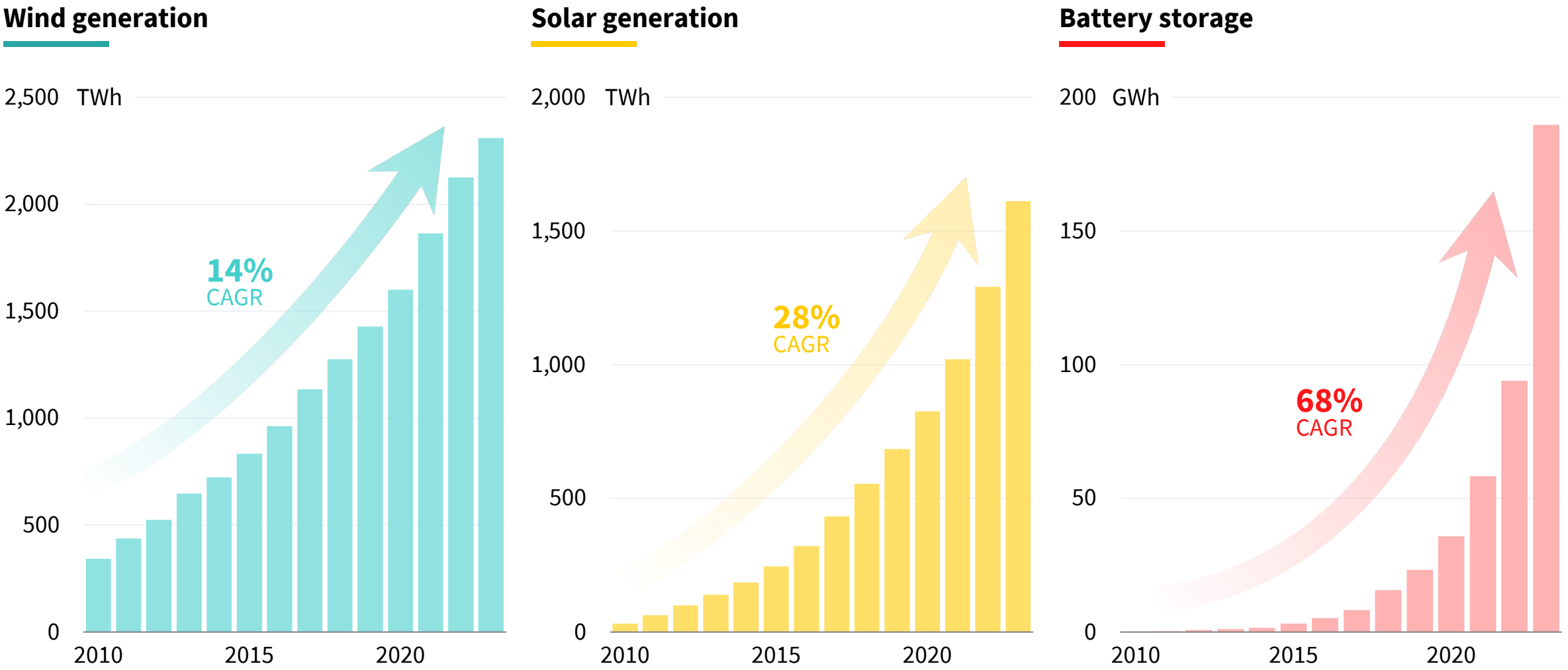
Cleantech investment



RMI *Source: BNEF.*

Leading to exponential growth in renewables

Global solar generation has been doubling every 2–3 years, and battery storage capacity every year

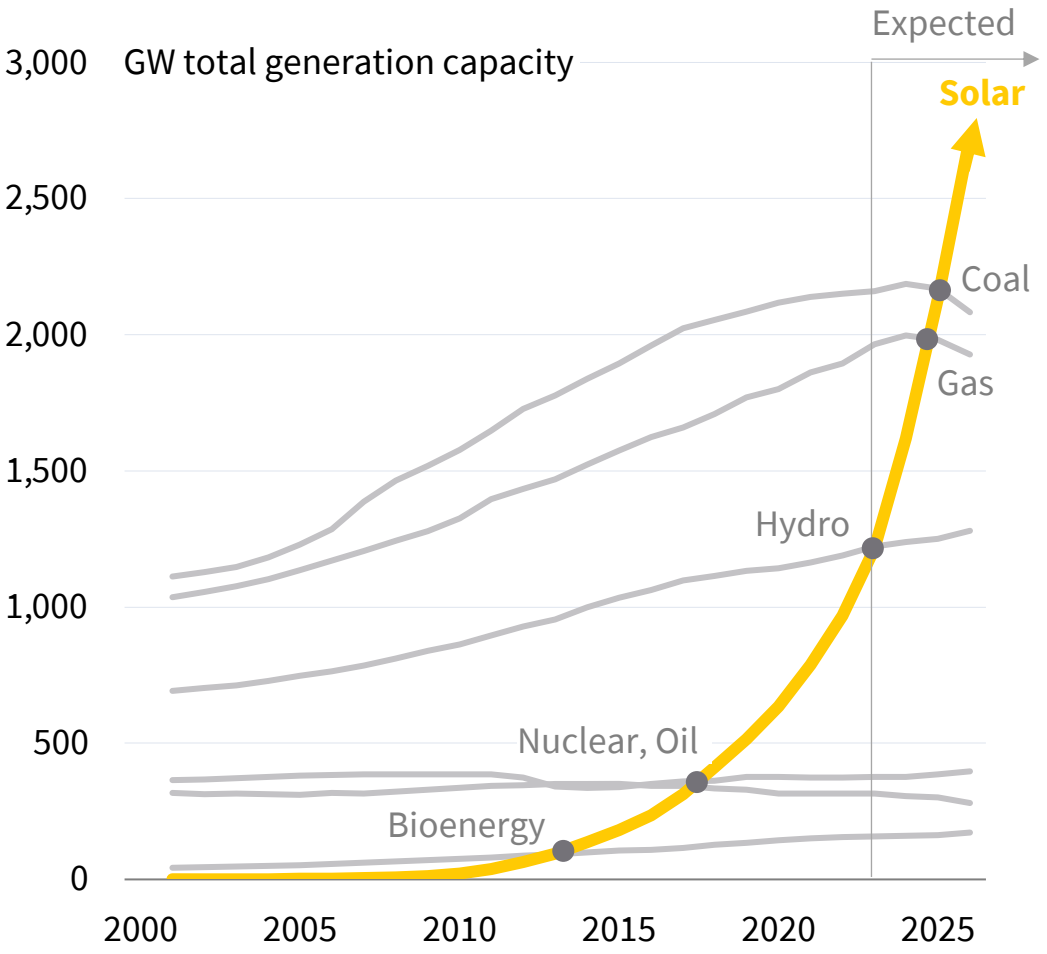


Source: IEA, BNEF; Note: CAGR is the compound annual growth rate between 2013 and 2023.

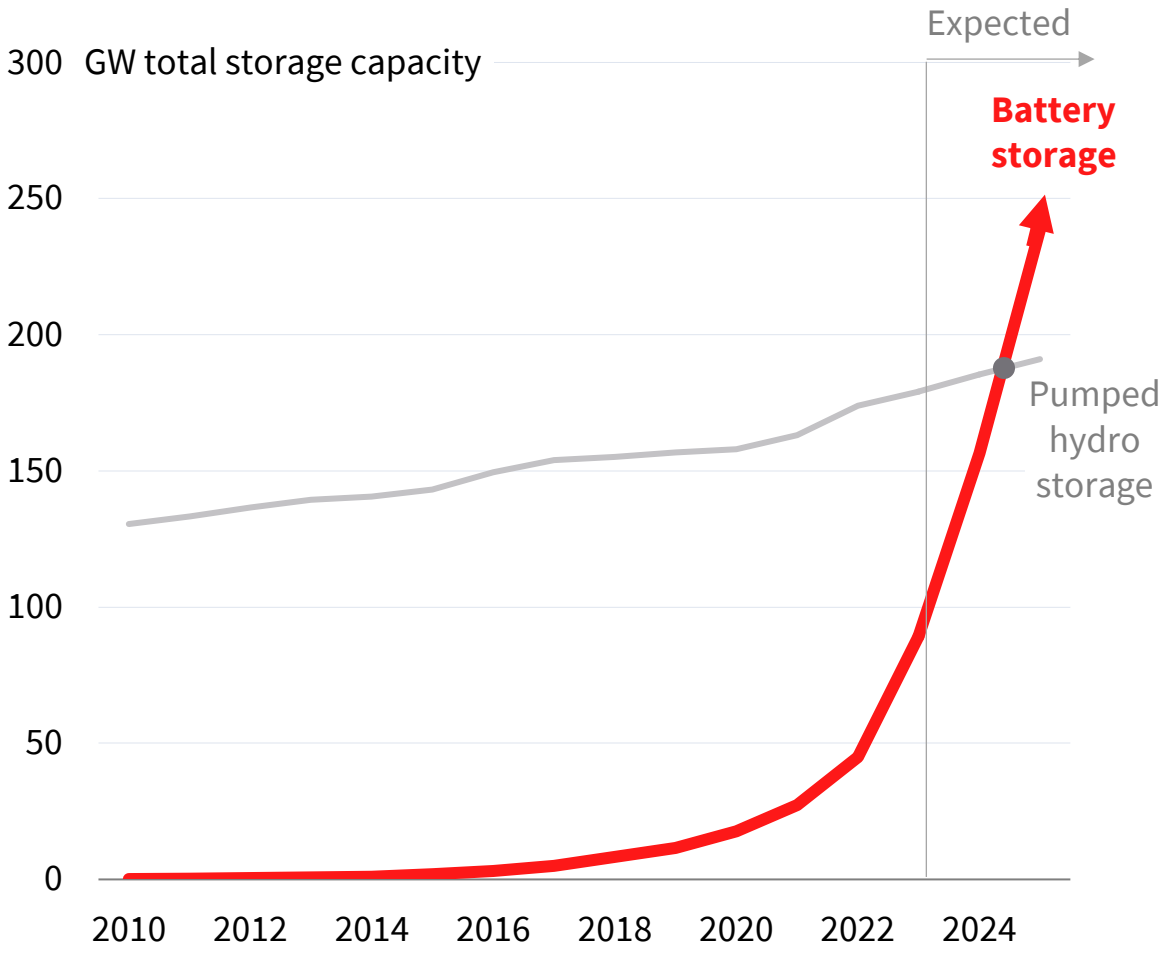
Solar and batteries are taking over

Solar will shortly overtake every other type of capacity, and battery storage will leapfrog pumped hydro

Solar



Batteries

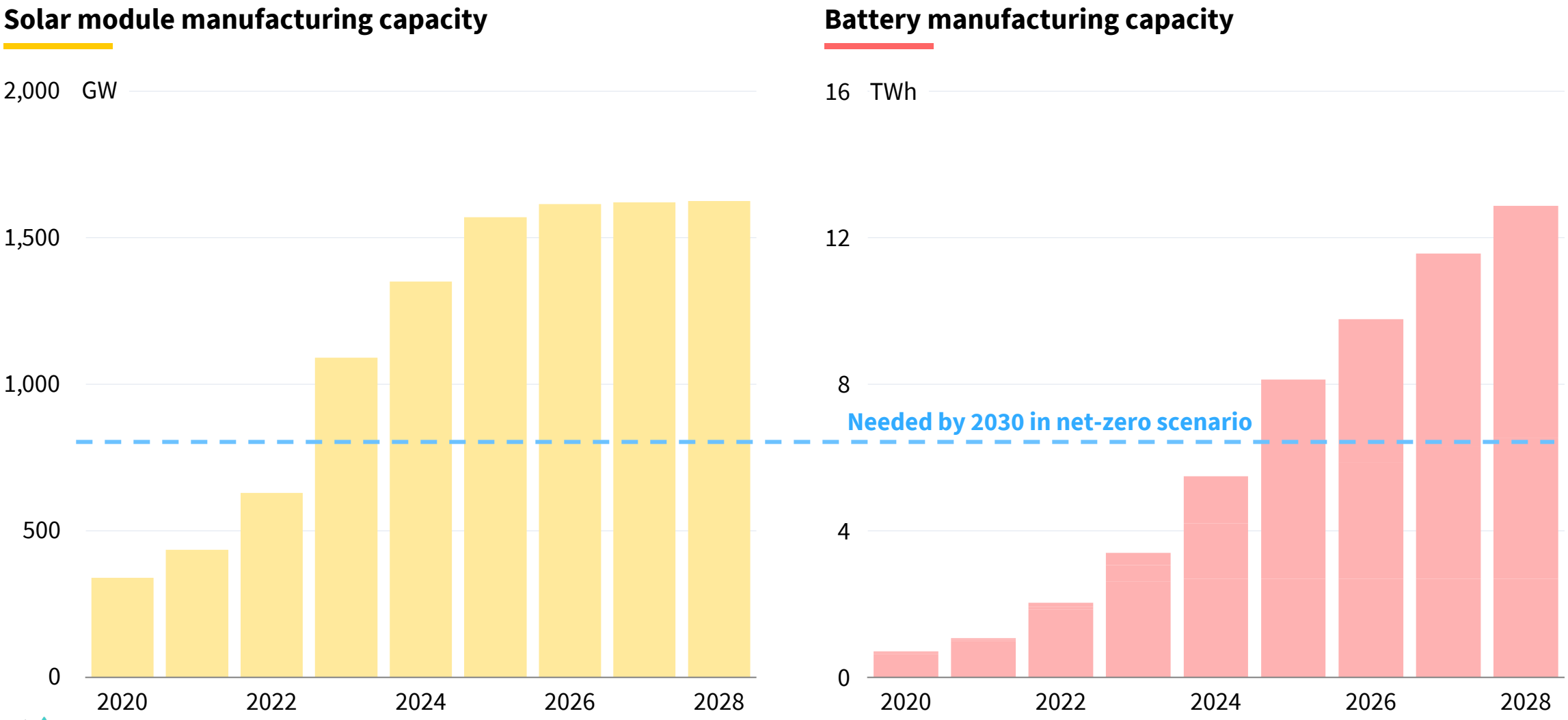


RMI

Source: BNEF, IEA.

The supply chain is in place

Companies already plan to construct more solar and battery capacity by 2030 than is needed to reach net zero

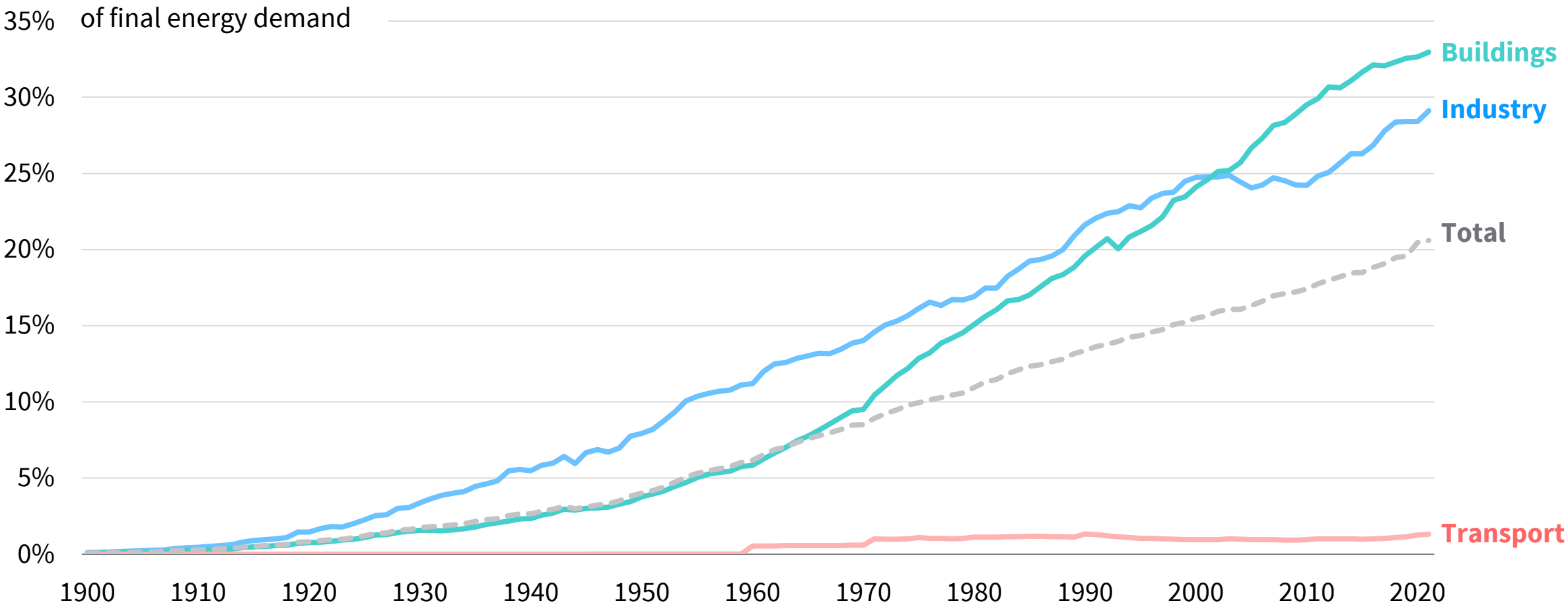


Source: IEA, BNEF.

A century of electrification

Buildings and industry have been electrifying for 120 years; now transport joins the party

Electricity share of final energy demand by sector

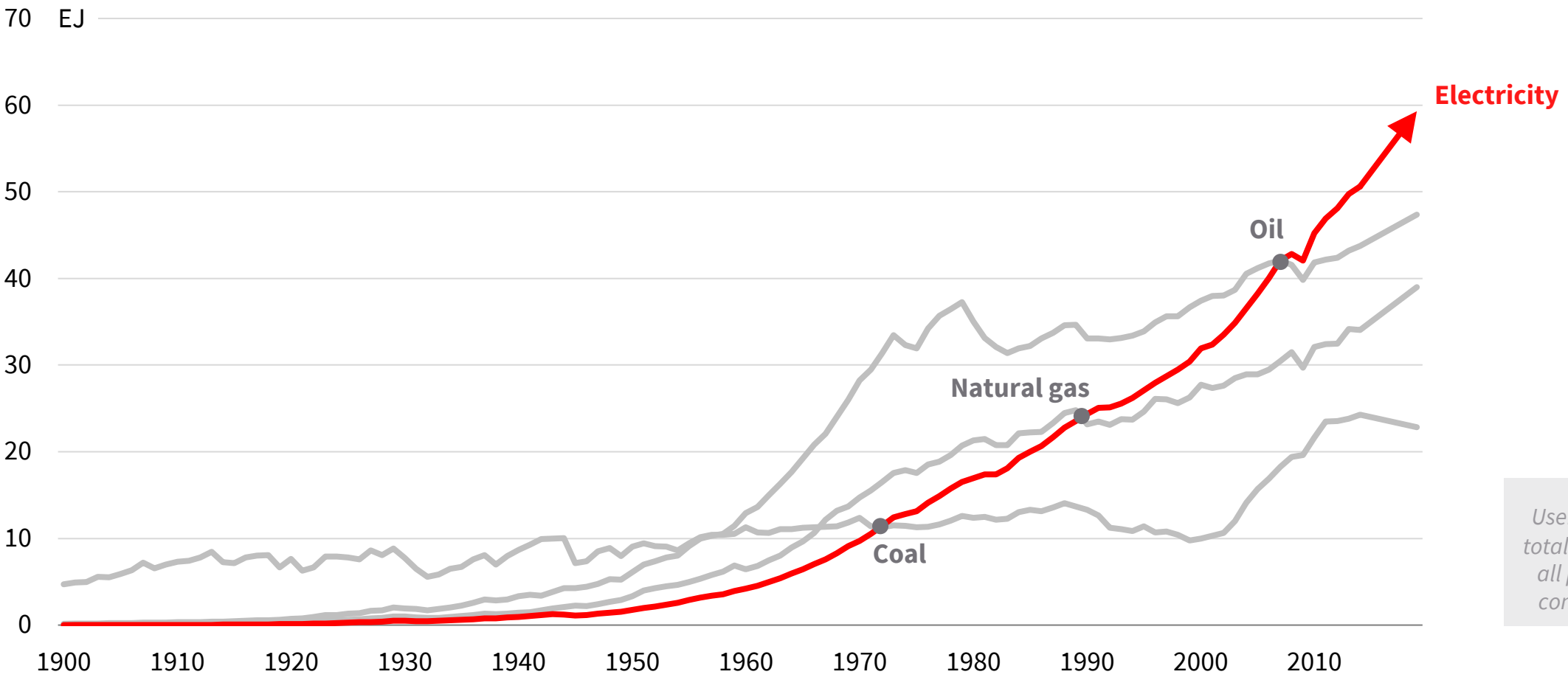


Source: IIASA, IEA WEB.

Electricity is the new king of energy

Electricity is the largest supplier of useful energy

Useful energy supply



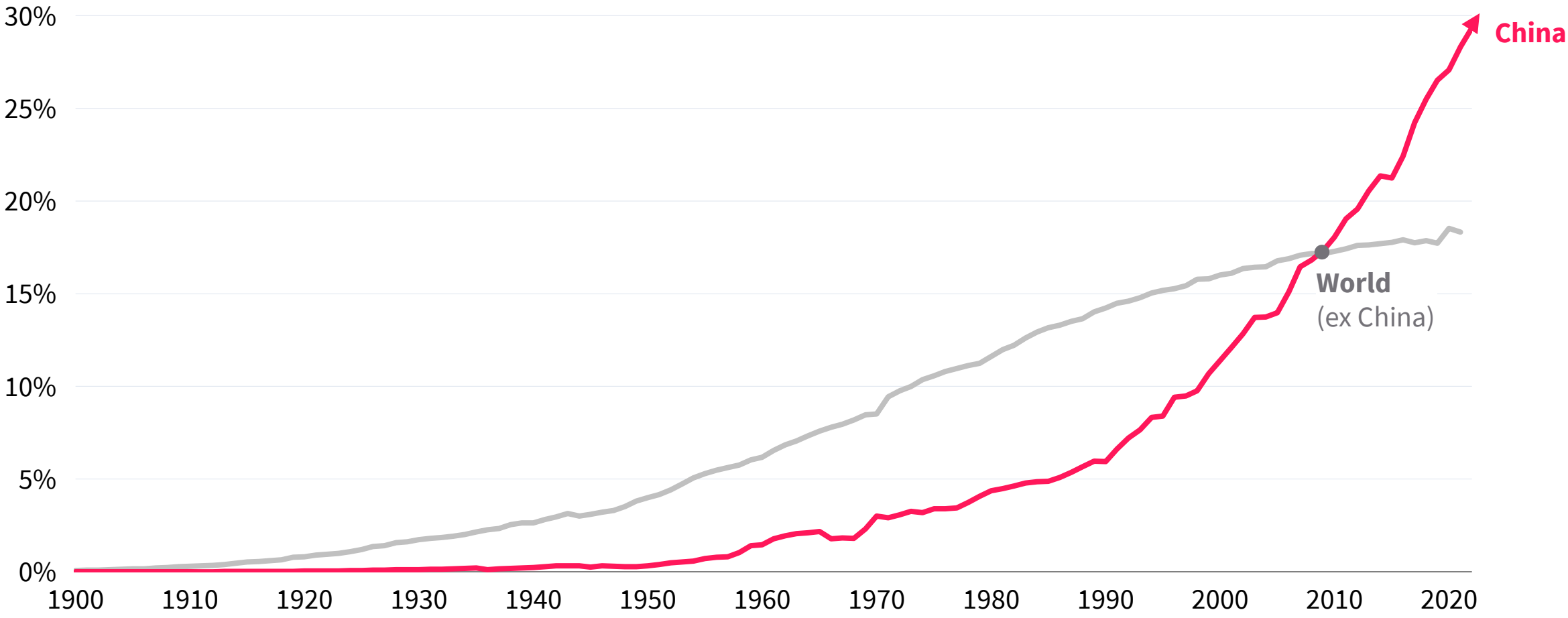
Useful energy is the total energy left after all processing and conversion losses.

Note: All sectors excluding non-energy uses. Estimates for useful energy differ, and here we have taken data from IIASA, which has prepared the most detailed data we have seen.
Source: IIASA.

And China is the king of electricity

China has been electrifying at 10 percentage points per decade, nine times faster than the rest of the world

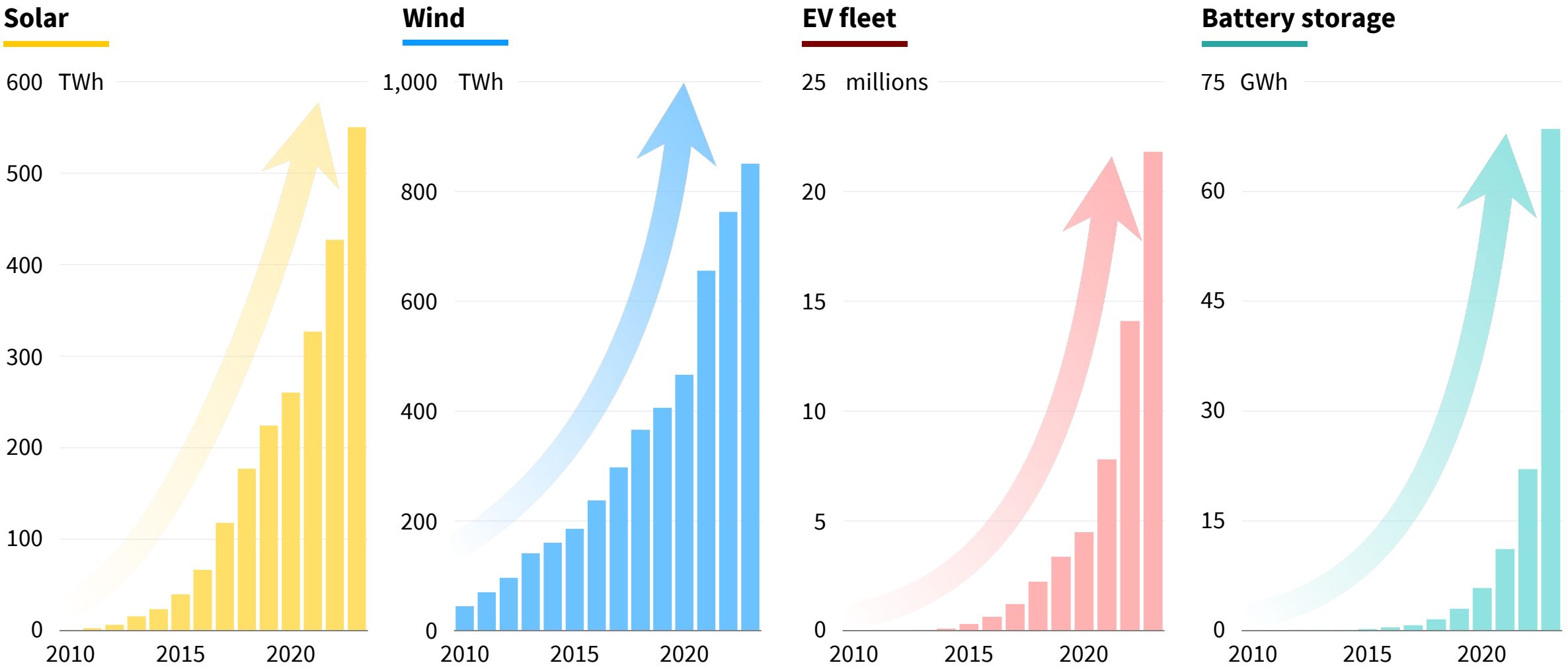
Electricity share of final energy



Notes: IIASA data to 1971, IEA onward.
Source: IIASA, IEA WEB. WEB defines final energy slightly differently than WEO.

Super-fast growth in China drives change

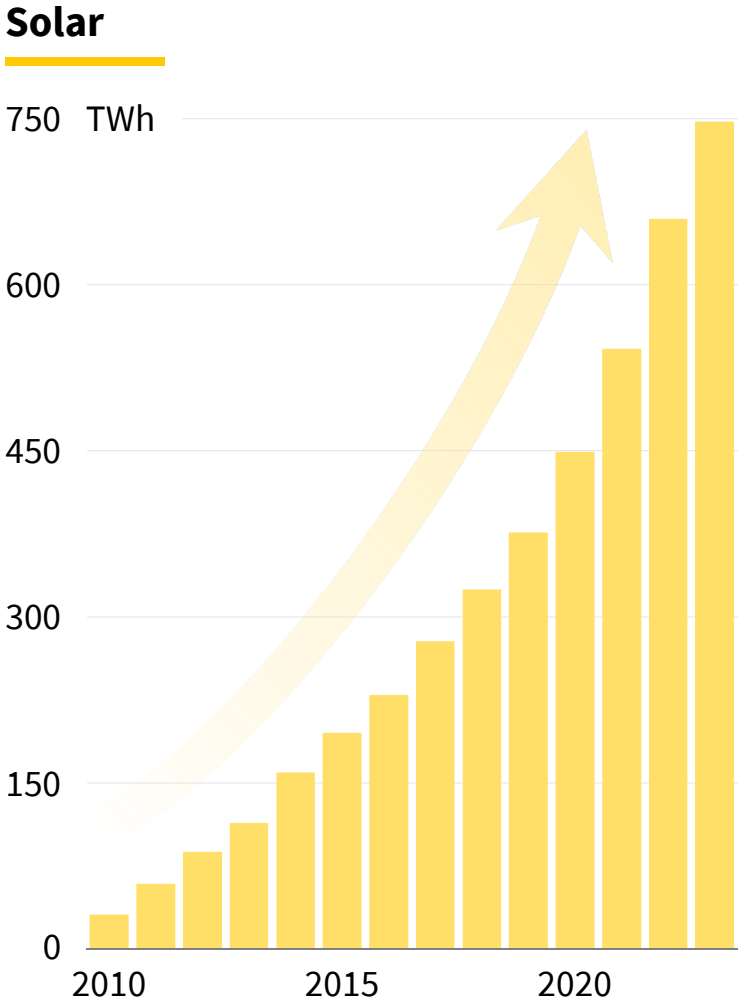
In a decade, solar generation increased by 35 times, wind 9 times; EVs and batteries scaled even faster

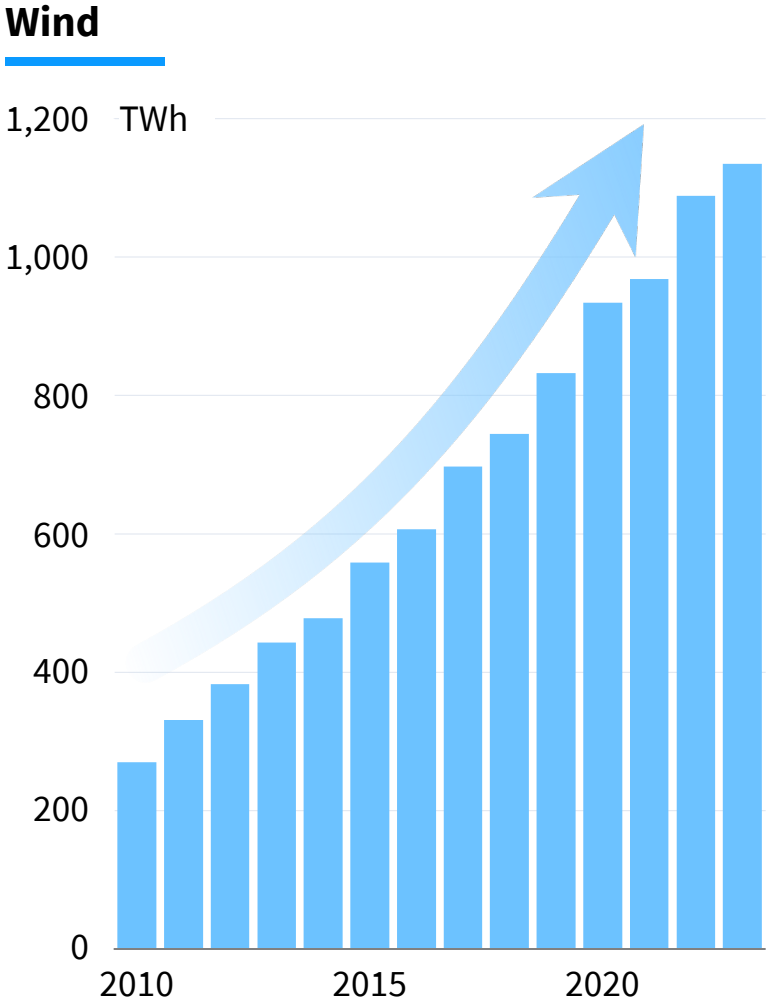


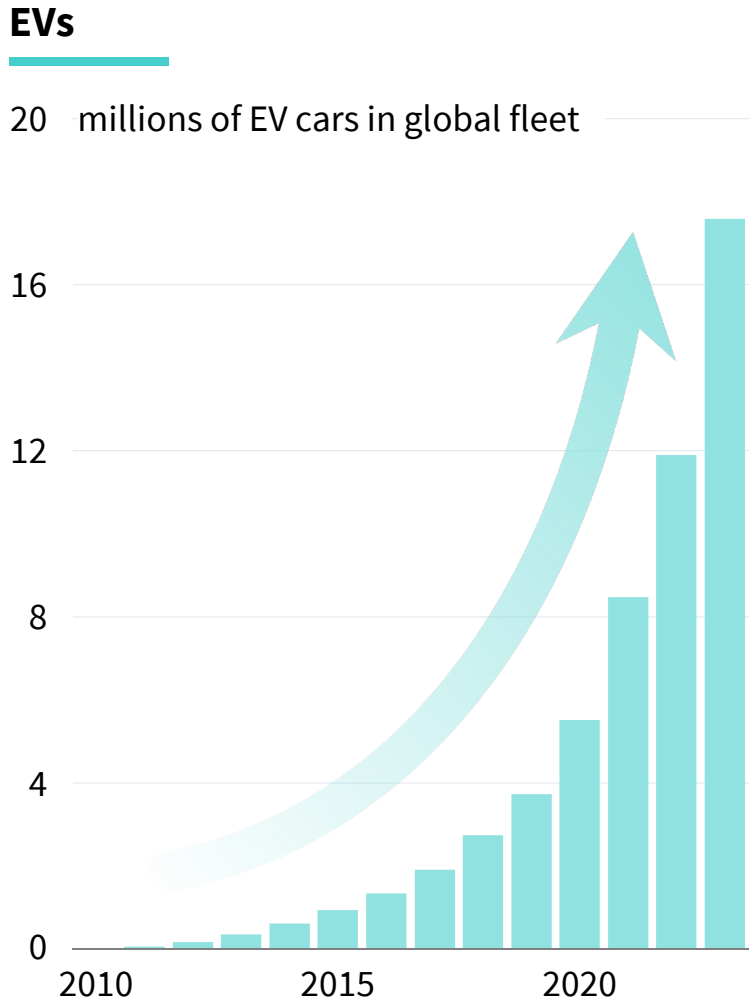
RMI *Source: IEA, BNEF.*

Exponential growth is also happening in the OECD

Over the past decade, solar generation went up 7 times, wind 3 times, and EVs sales up over 50 times



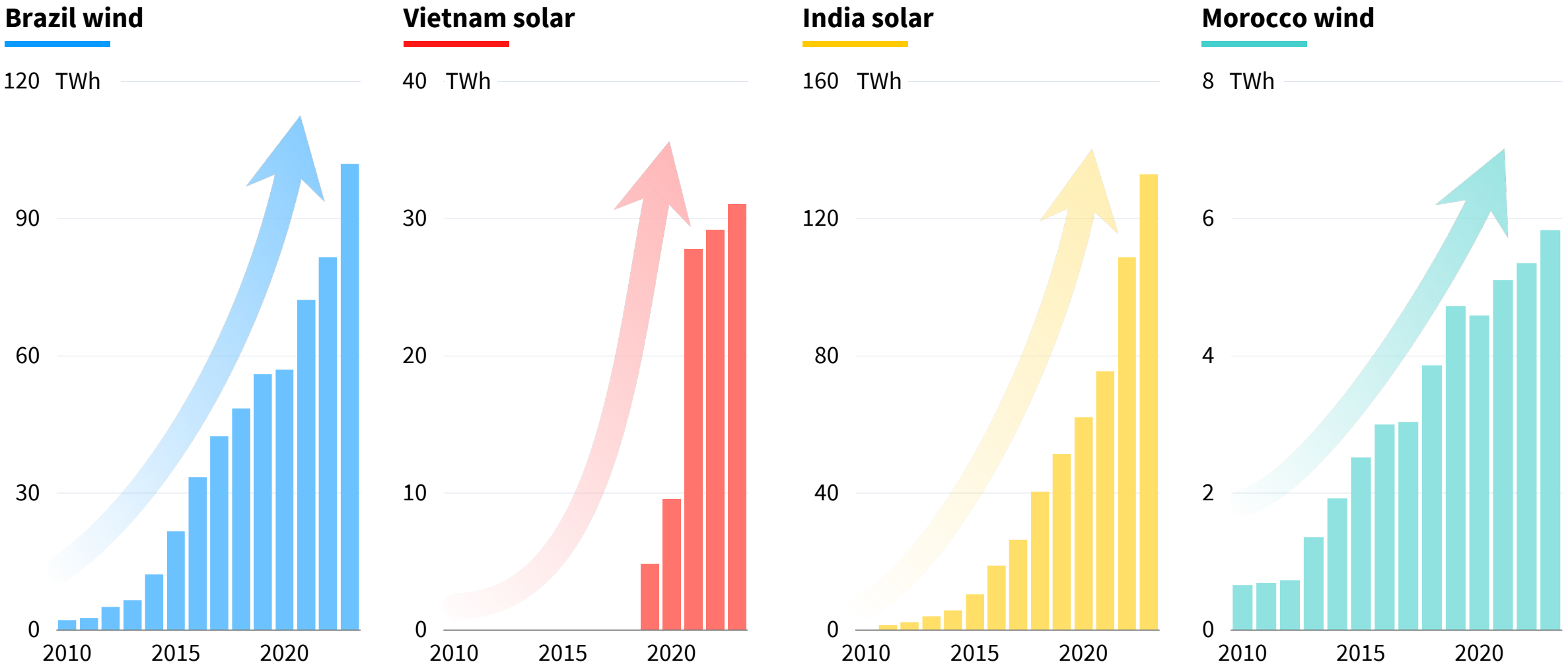




RMI *Source: Ember, IEA.*

Exponential growth in emerging economies

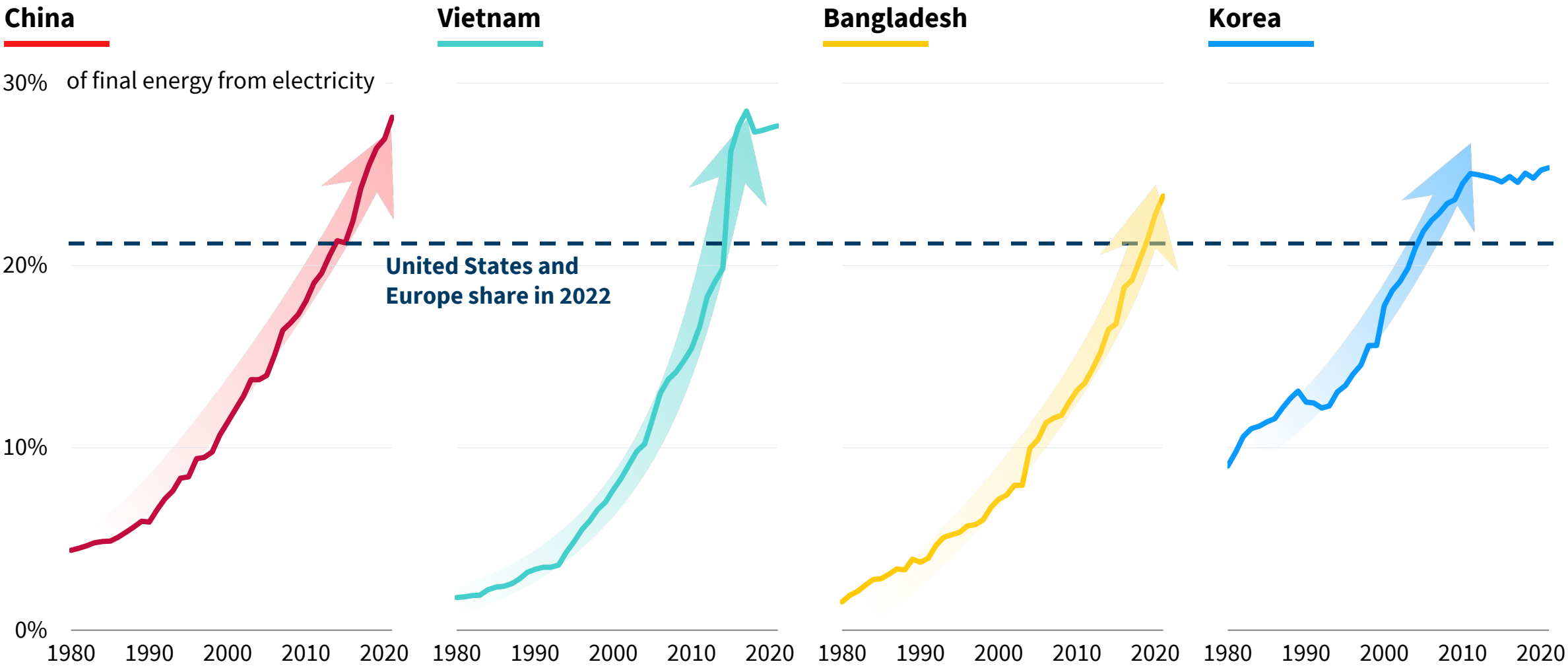
The adoption of superior technology is not confined to the Global North



Source: IEA.

Electric Asia

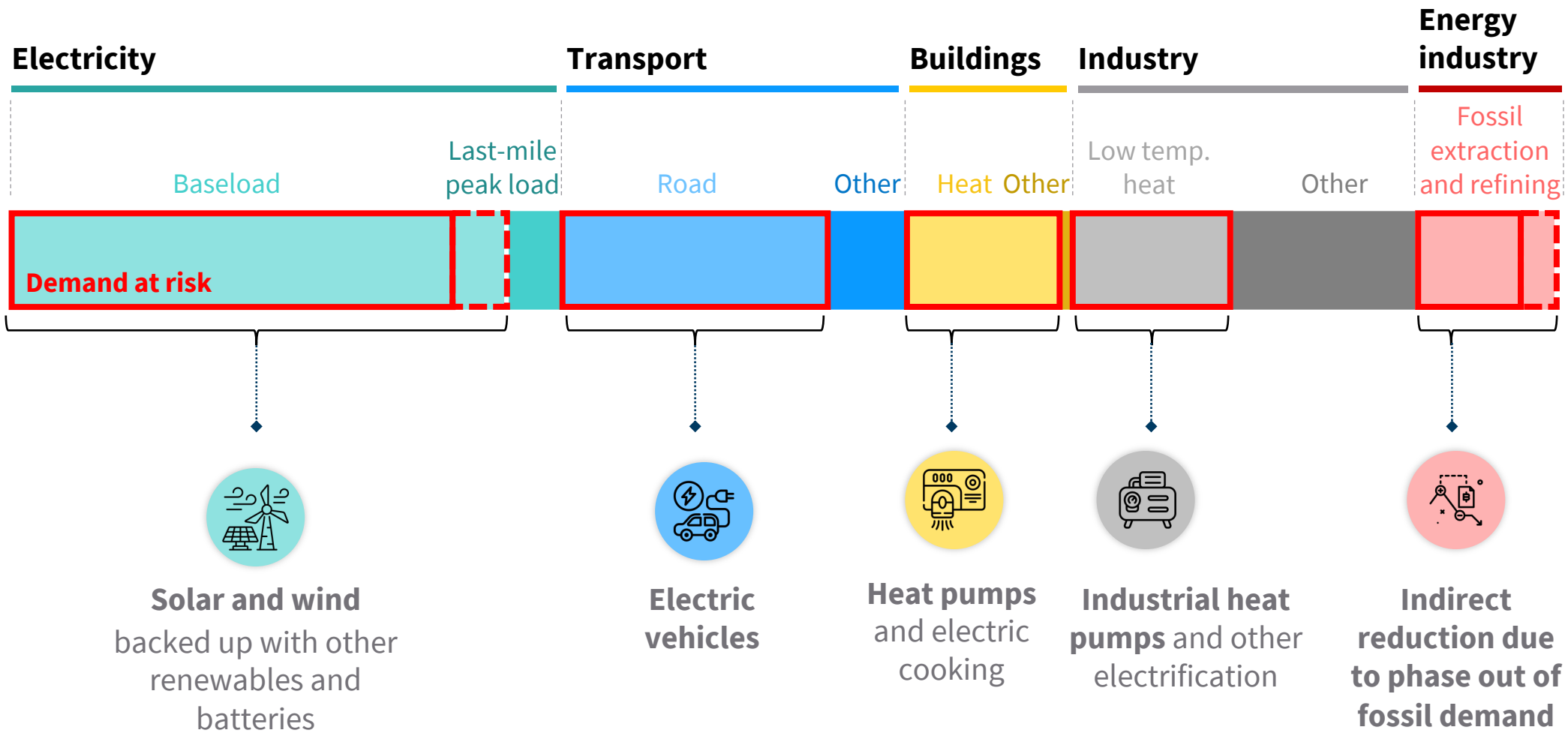
Asia is leading the charge to electrify everything



Source: IEA WEB.

The vast majority of fossil demand is at immediate risk

Over 75% of fossil demand today is under direct threat by exponentially growing cleantech

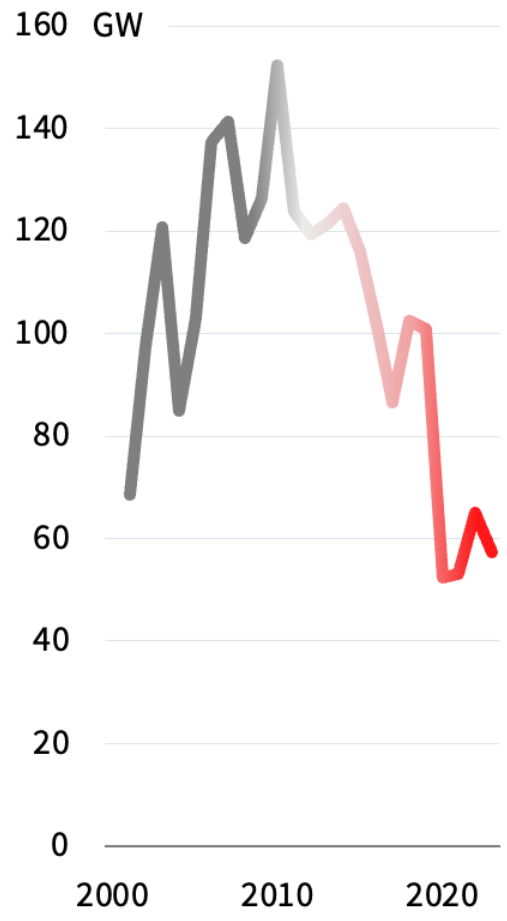


Source: IEA, IIASA, RMI.

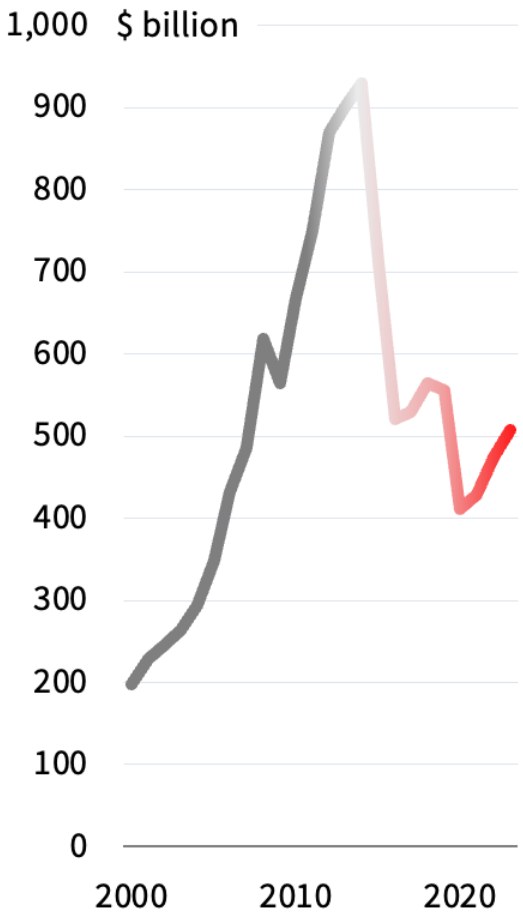
Flashing red lights all over the fossil fuel system

As growth turns to decline

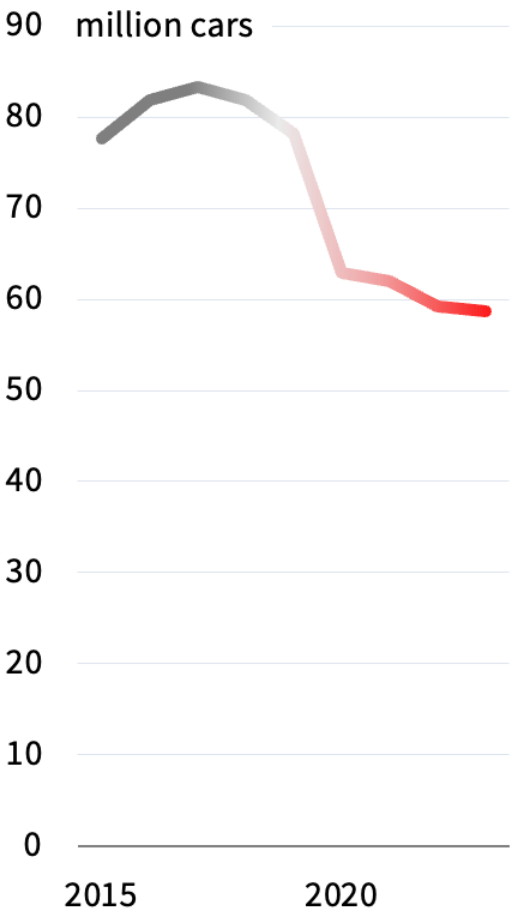
Fossil fuel capacity additions



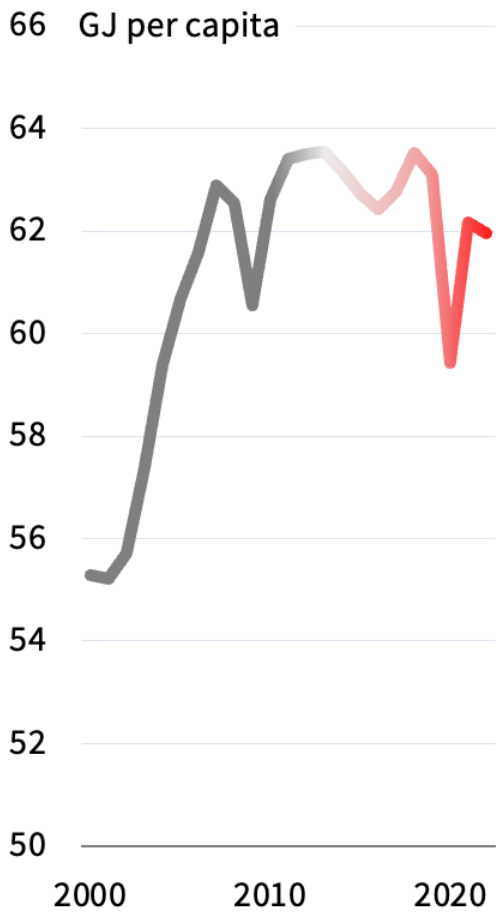
Oil and gas capex



ICE sales



Fossil fuel demand

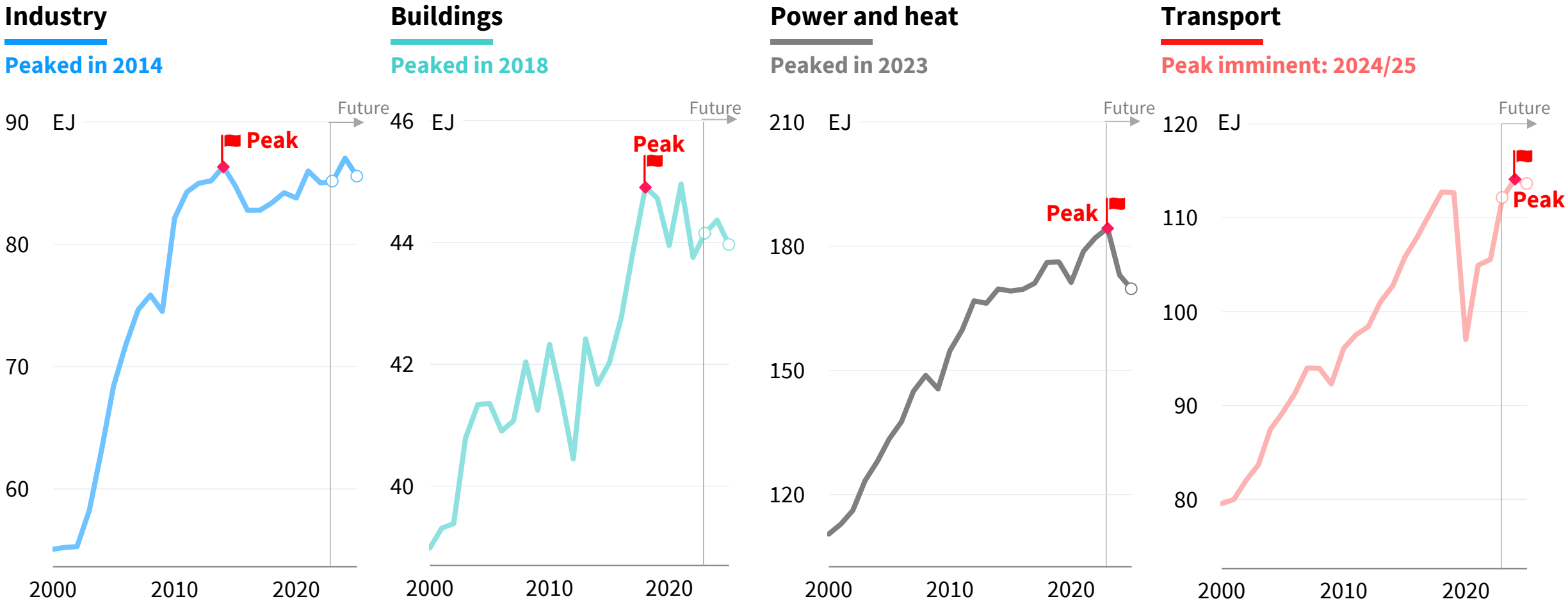


Source: Ember (new fossil fuel electricity generation capacity), IEA WEI (oil and gas upstream capex), BNEF (ICE sales), Energy Institute (global fossil fuel demand pp).
Note fossil fuel capacity additions are a net figure.

The era of peaking fossils is here

Building and industry peak fossil fuels are behind us; electricity and transport are peaking now

Fossil fuel demand by sector



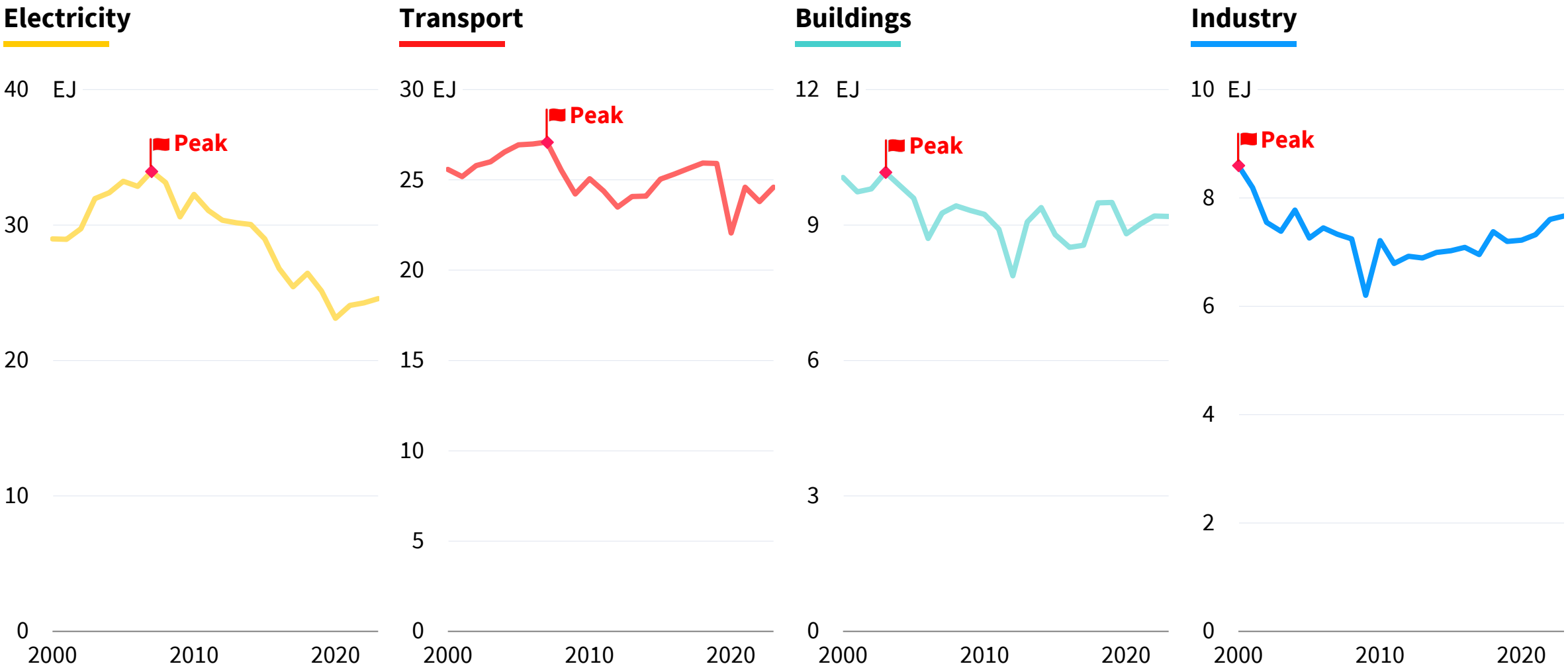
RMI

Source: BNEF NEO 2024 NZS.

Power & transport peak last, but have the fastest growing challengers

United States — every major sector is past peak fossil demand

Fossil fuel demand across sectors peaked more than 15 years ago



Source: BNEF NEO 2024.

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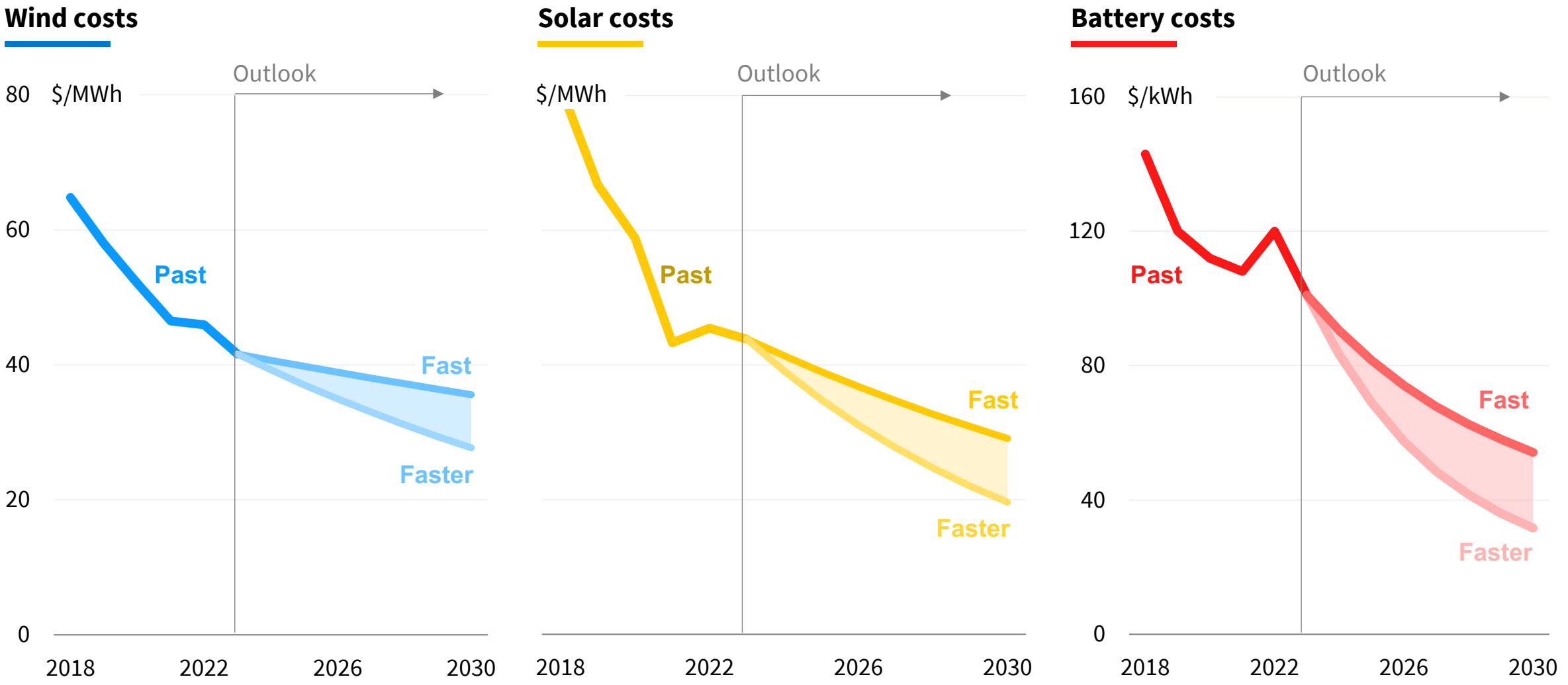
Cleantech costs will continue to fall

Solar, the cheapest energy source in history, will halve in price by the end of the decade

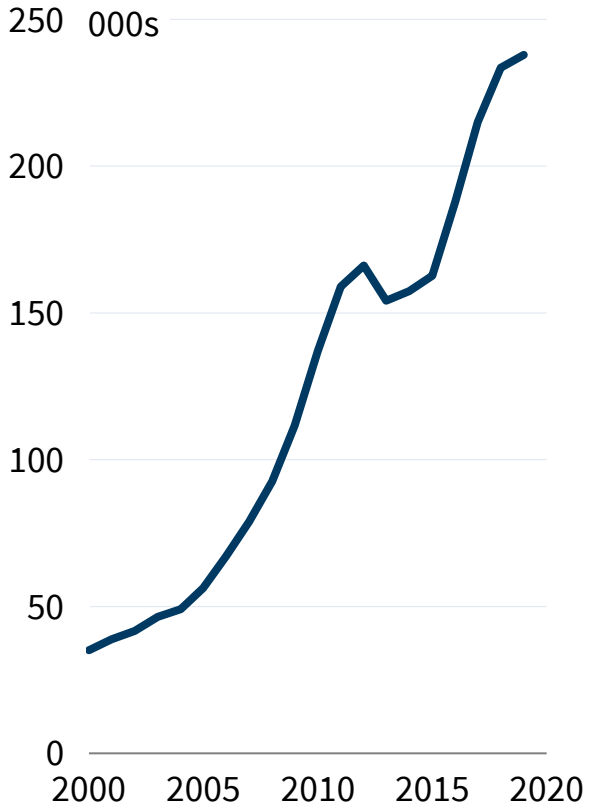


Source: BNEF, RMI analyses.

Cleantech keeps getting better

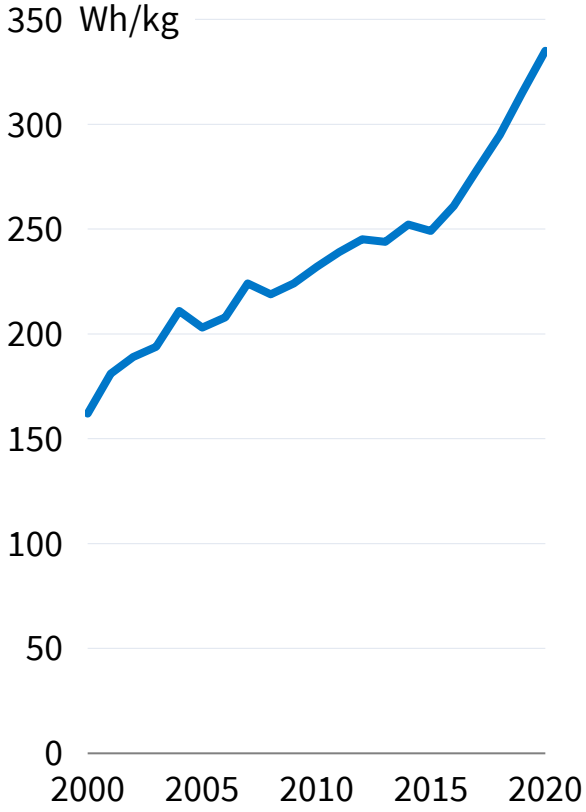
More patents, higher battery density, more solar and wind generation per unit, economies of scale, new ideas, …

Cleantech patents per year



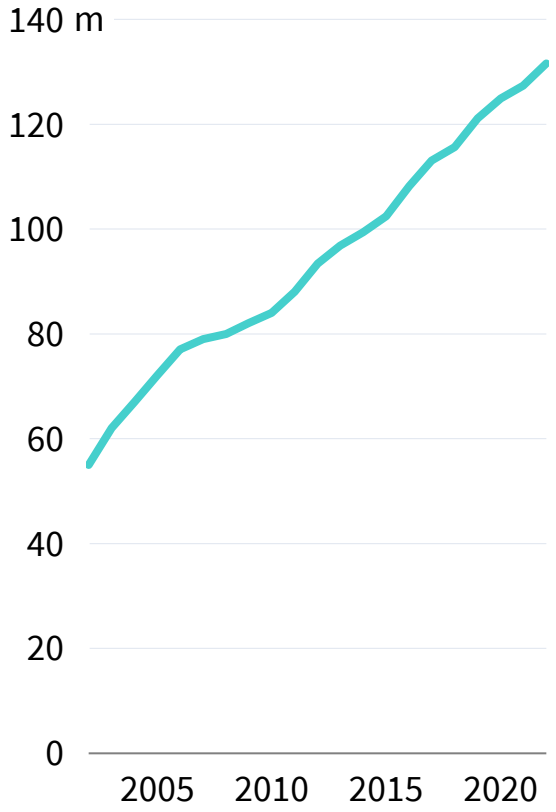
More innovation

Top-tier battery cell density



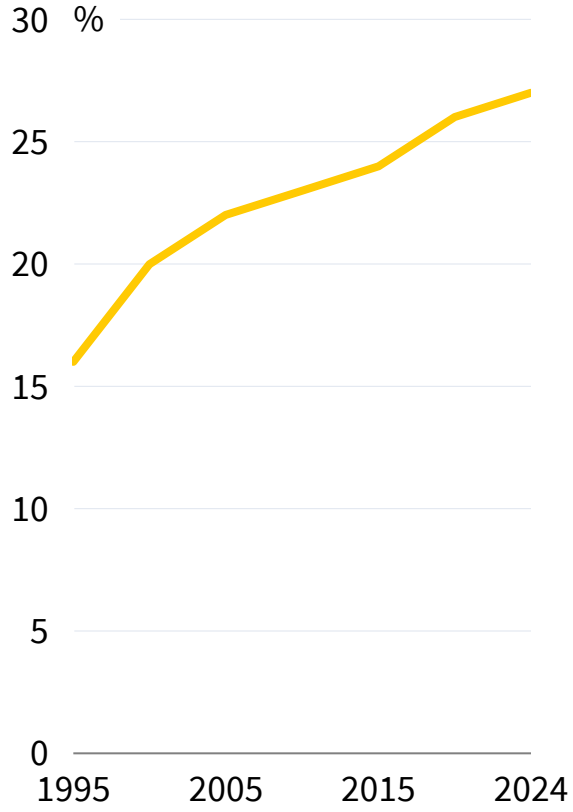
Denser batteries open up new sectors for batteries to play in

Wind rotor diameter



Bigger rotors reduce cost per MWh

Solar cell efficiency



More efficient solar panels reduce cost per MWh

Sources: IRENA Patent database, RMI X-Change Batteries, US DOE, US NREL representative.

Cleantech is 3 times more efficient

Cleantech is around 3x more efficient than fossil technologies across applications

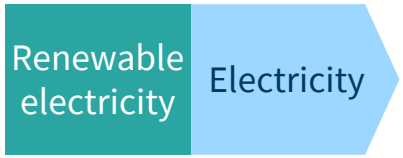
Energy production

Electricity

Fossil thermal

30%–40% efficiency

Wind and solar



100% efficiency

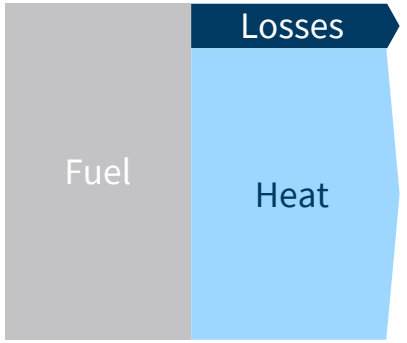
2–3x

as efficient

Energy use

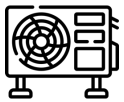
Heating

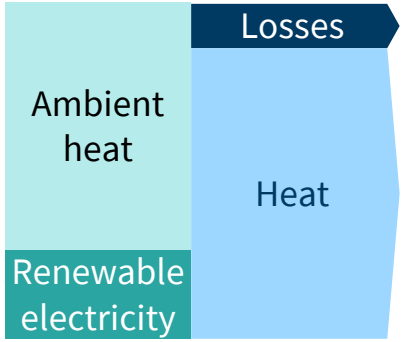
Gas boiler



85% efficiency

Heat pump





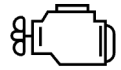
300%–400% efficiency

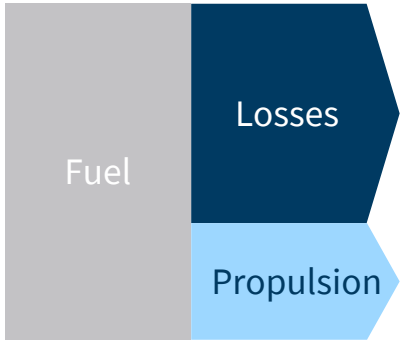
3–4x

as efficient

Transport

Internal com-bustion engine





25%–40% efficiency

Electric vehicle

80%–90% efficiency

2–4x

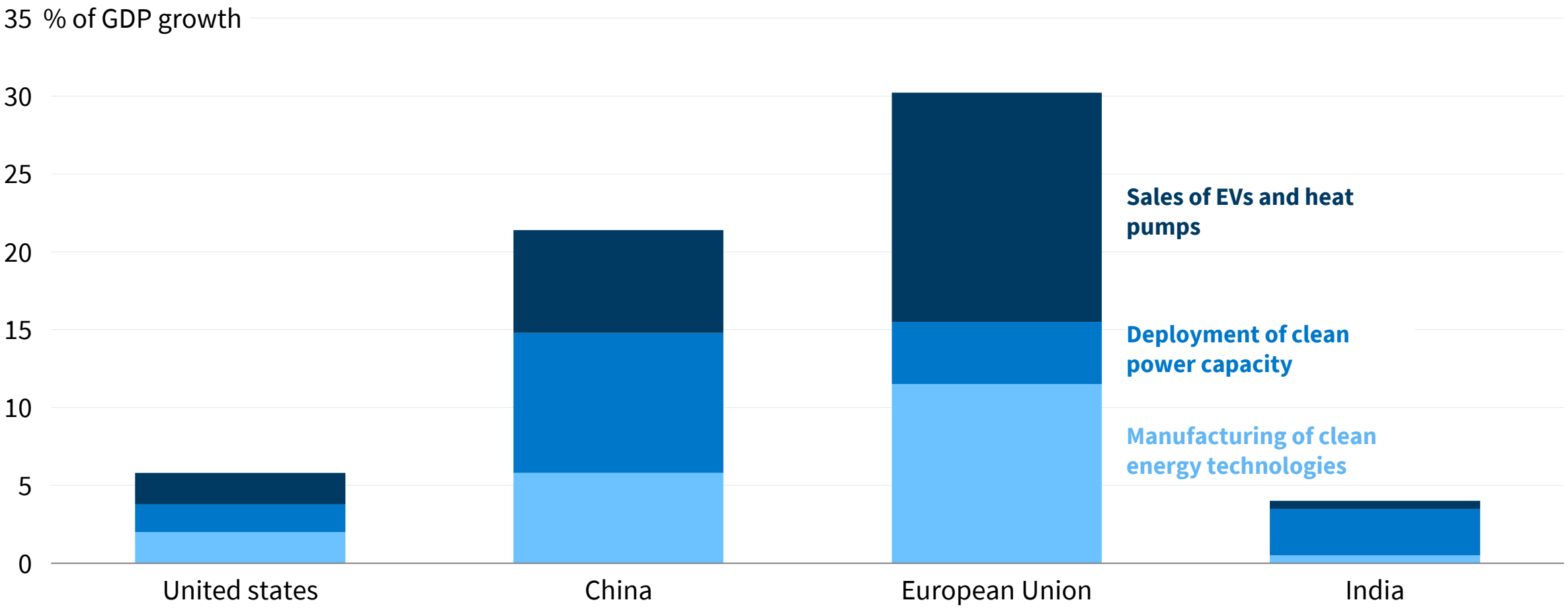
as efficient

Source: IEA, IIASA, RMI analysis, Adapted from Prof. Tomas Kåberger. Note: Solar and wind's 100% efficiency represents the fact that there are no conversion losses from primary to secondary energy.

Everyone wants a piece of the action

Cleantech is now a key driver of GDP growth all over the world

Contribution of cleantech to GDP growth, 2023

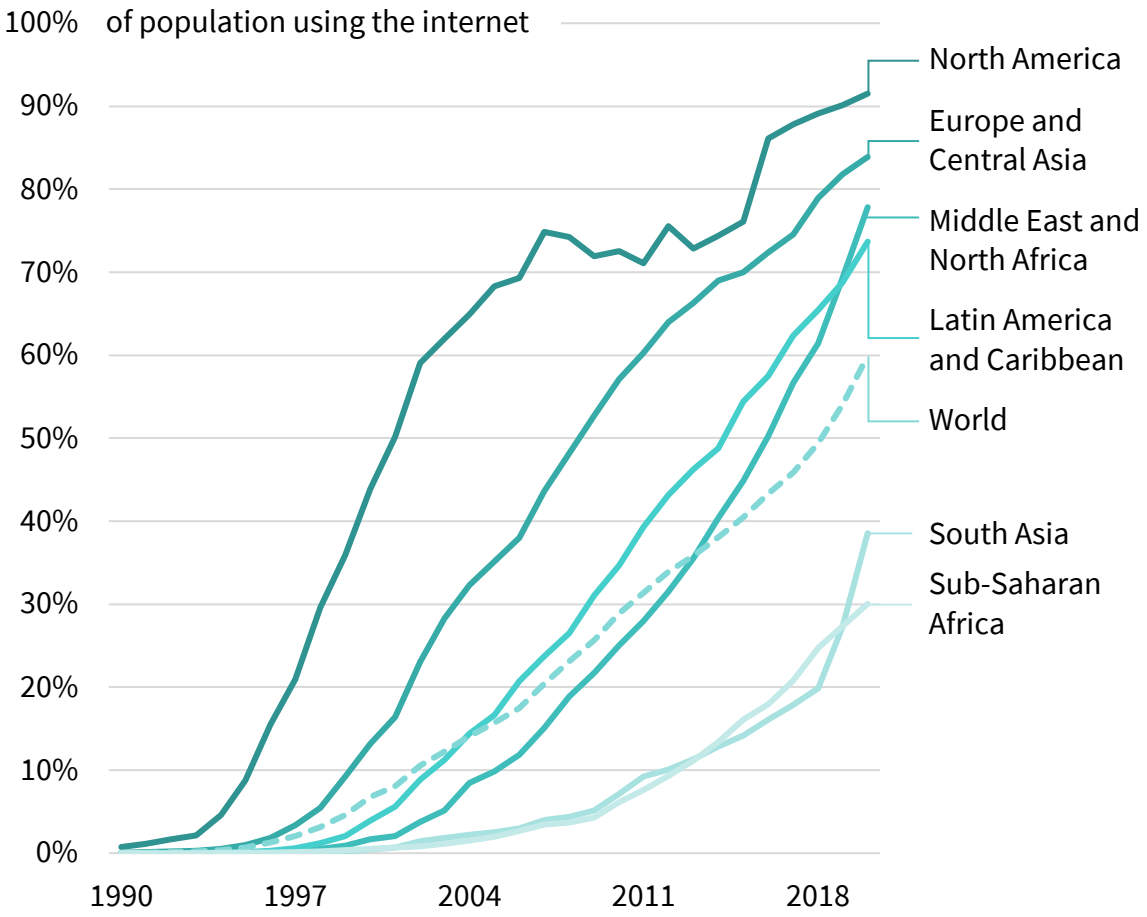


RMI *Source: IEA.*

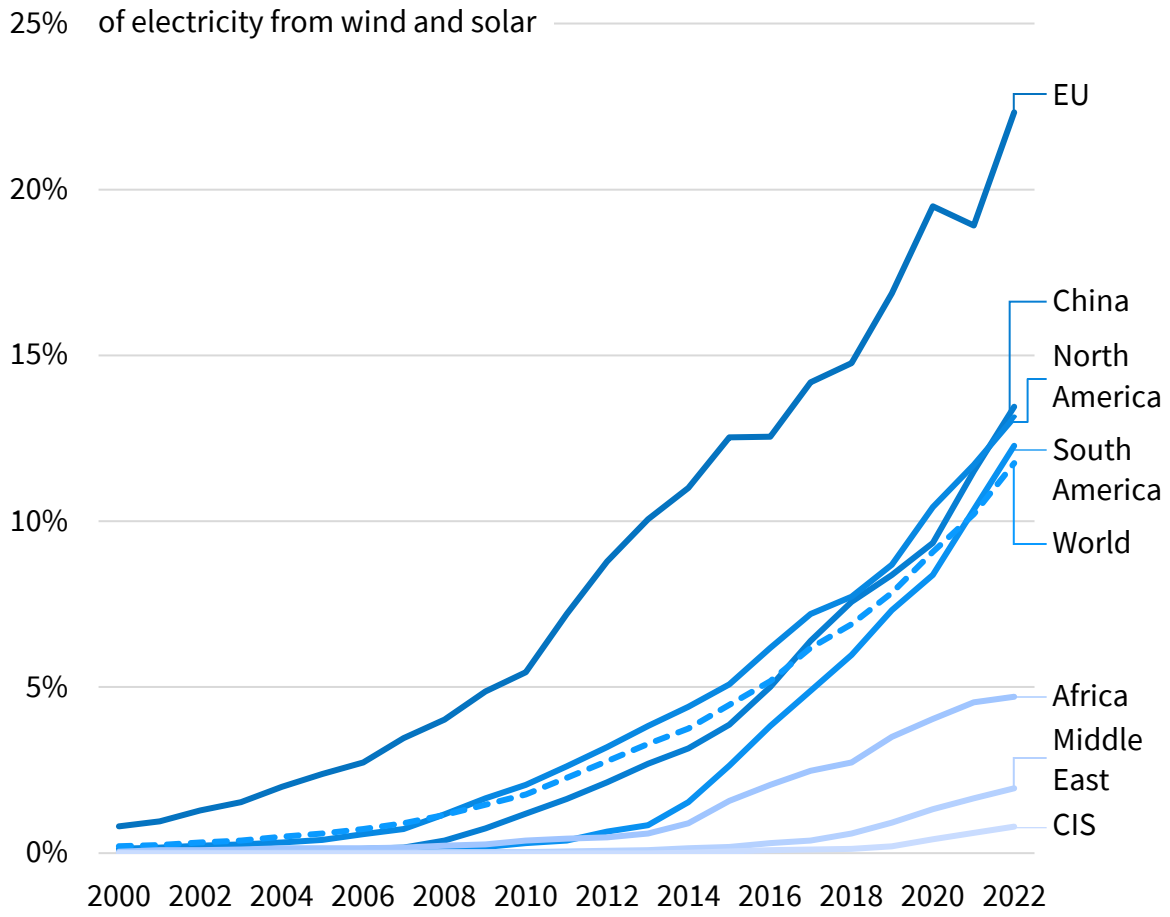
Cleantech adoption resembles that of the internet

Adoption moves from early adopters to laggards up a series of S-curves. This time anyone can be a leader

Share of population using the Internet



Solar and wind as a share of generation



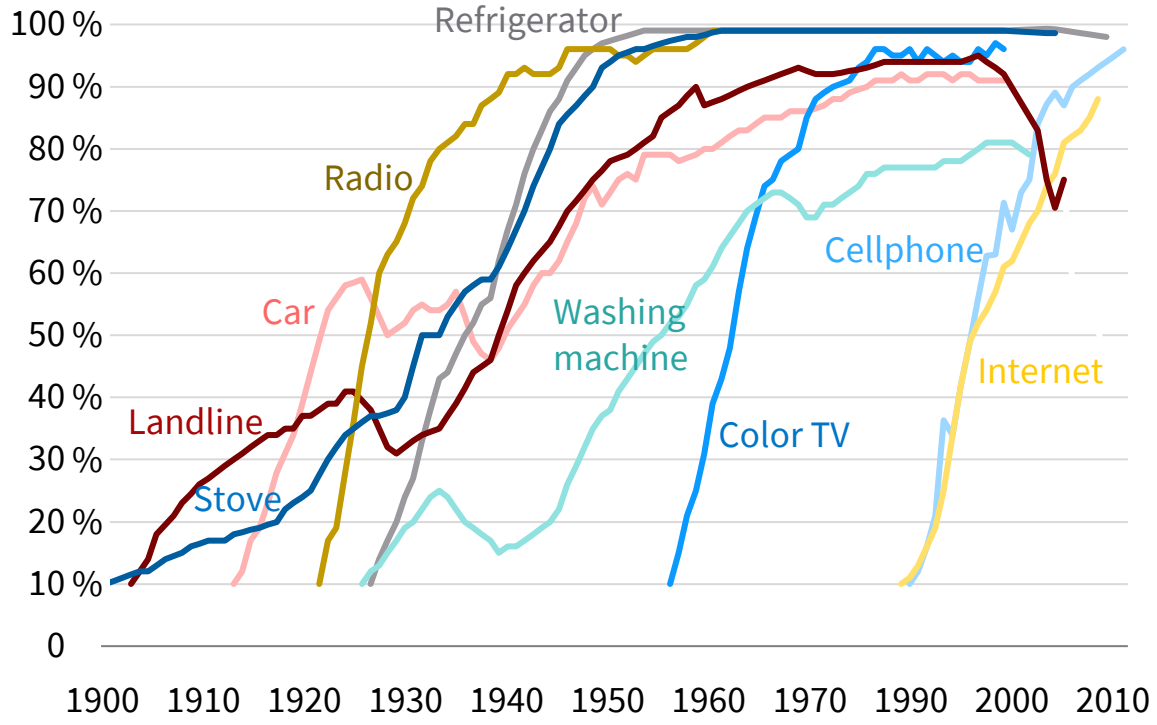
RMI *Source: OWID, Energy Institute.*

S-curves as usual, not business as usual

We've seen this movie before. We know how technology shifts work

Individual products

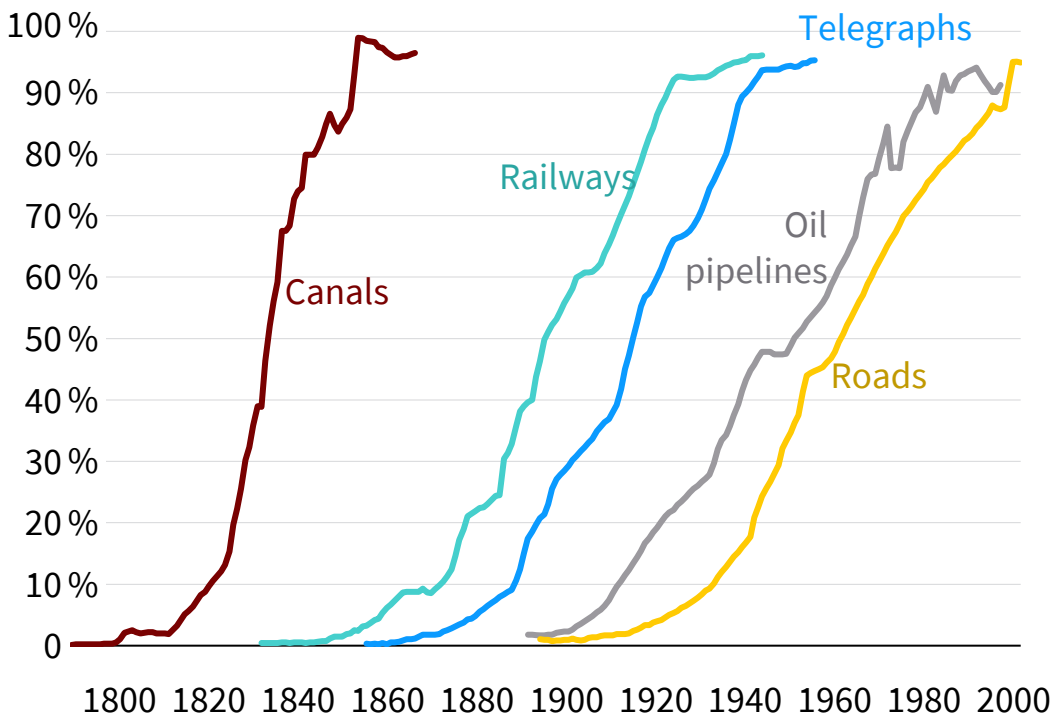
Technological adoption by household in the United States



Rapid exponential growth along S-curves is a standard characteristic of successful new technologies.

Infrastructure systems

Share of maximum size in the United States



S-curve-type growth even applies to infrastructure.

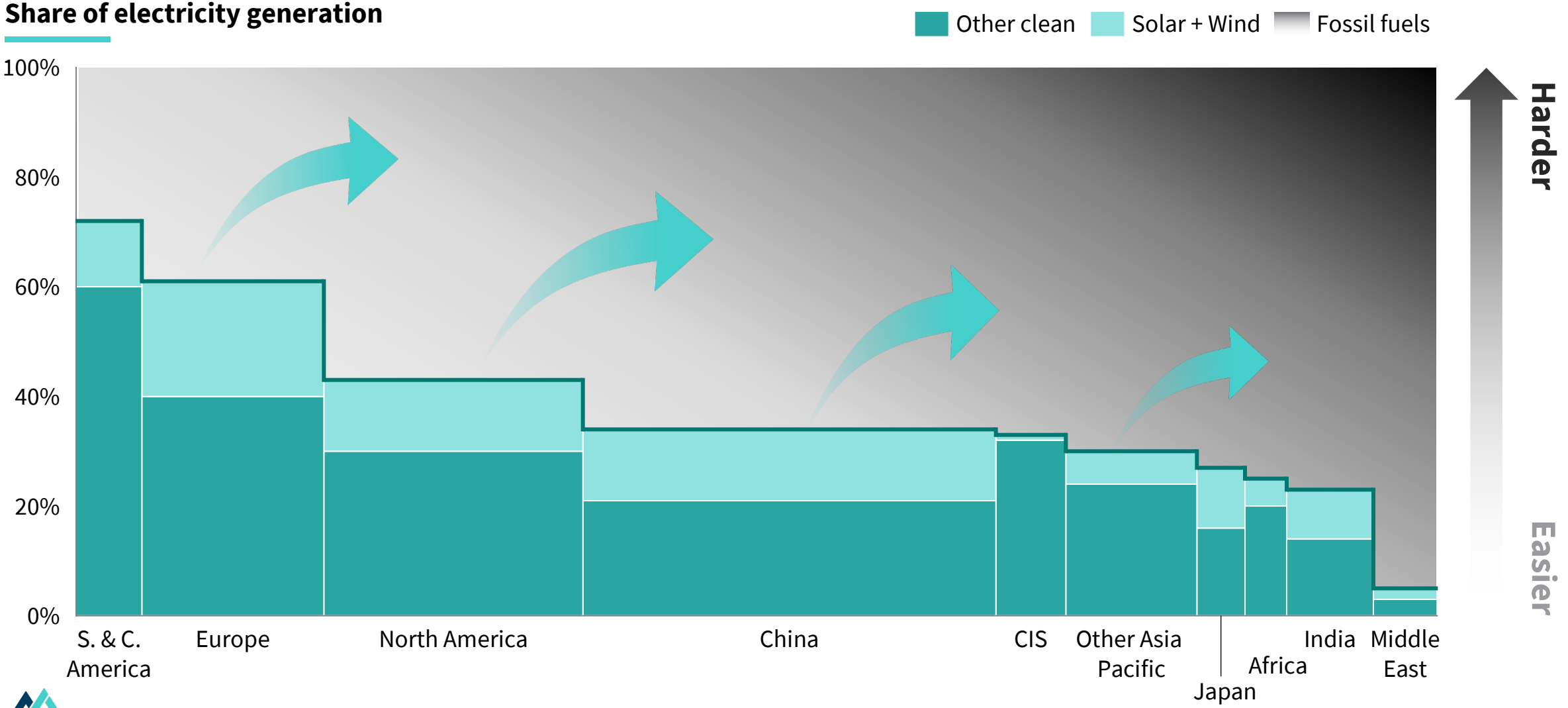
RMI

Source: Comin & Hobijn via OWID (L); Grubler (R).

Technologies cascade across geographies

We should focus on the opportunities before our very eyes, not on potential end-game barriers

Share of electricity generation



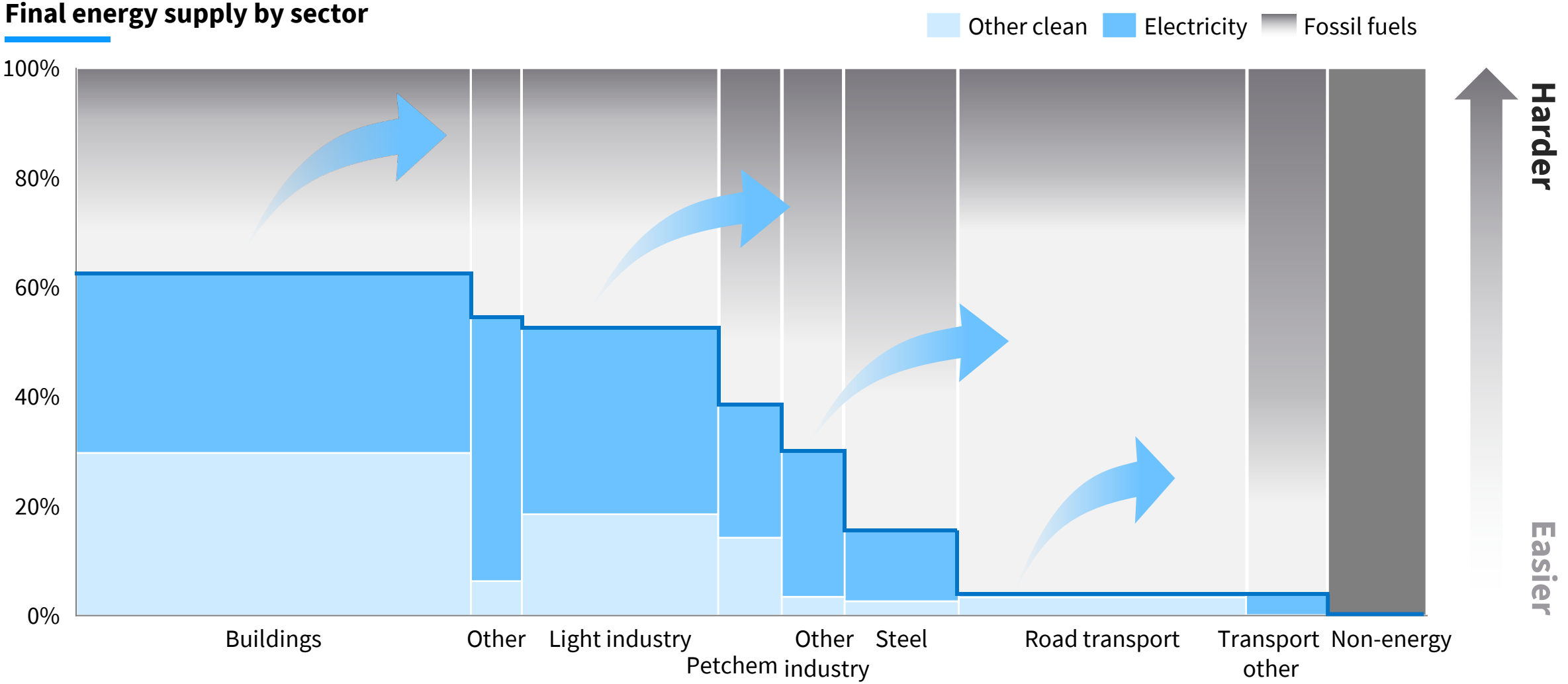
RMI

Source: Energy Institute, RMI. For more see X-Change: Electricity.

Technologies cascade across sectors

Every sector has low-hanging fruit at the frontier

Final energy supply by sector



Source: BNEF for final energy supply 2022, RMI.

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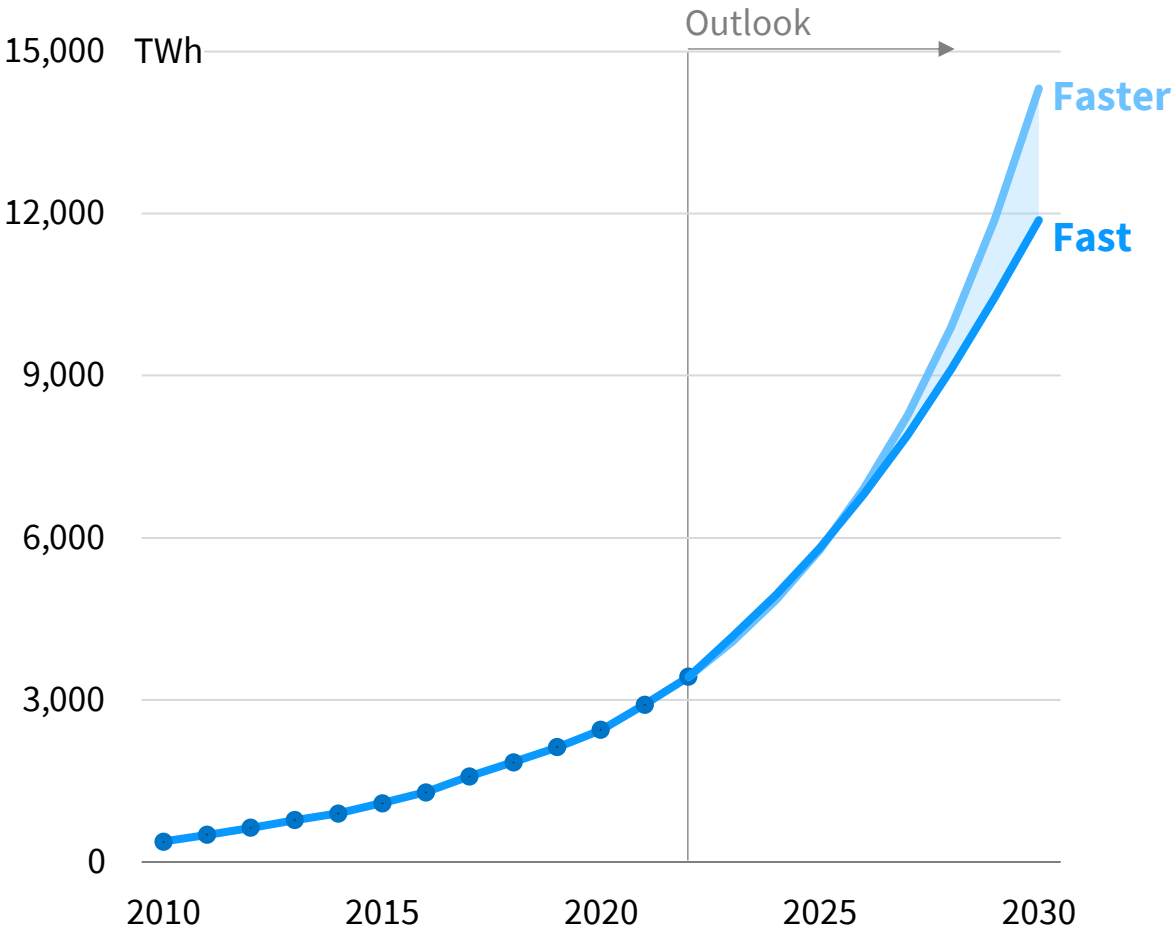
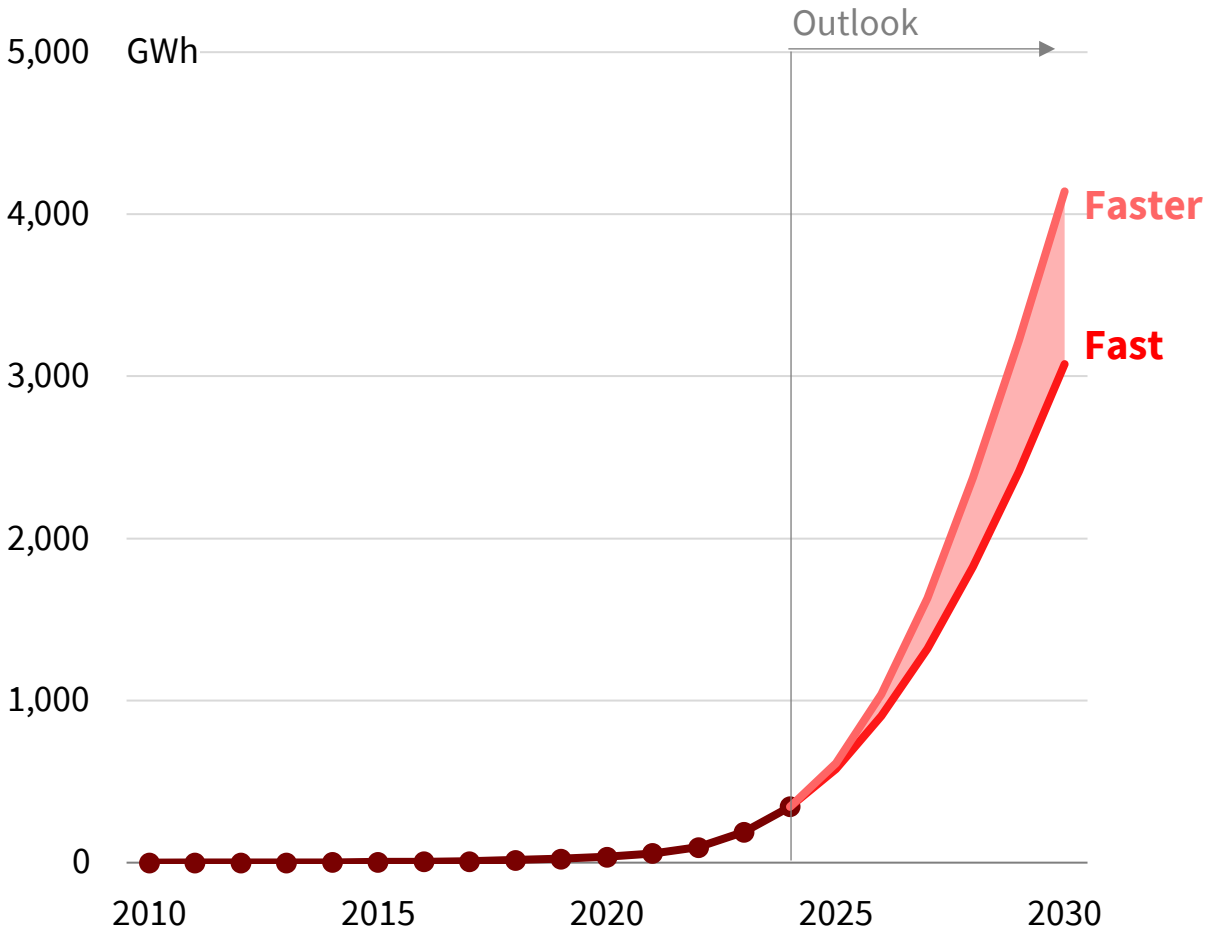
Renewables will keep rising up their S-curves

As the renewable revolution will continue to solve barriers to change

Solar and wind generation



Battery stationary storage



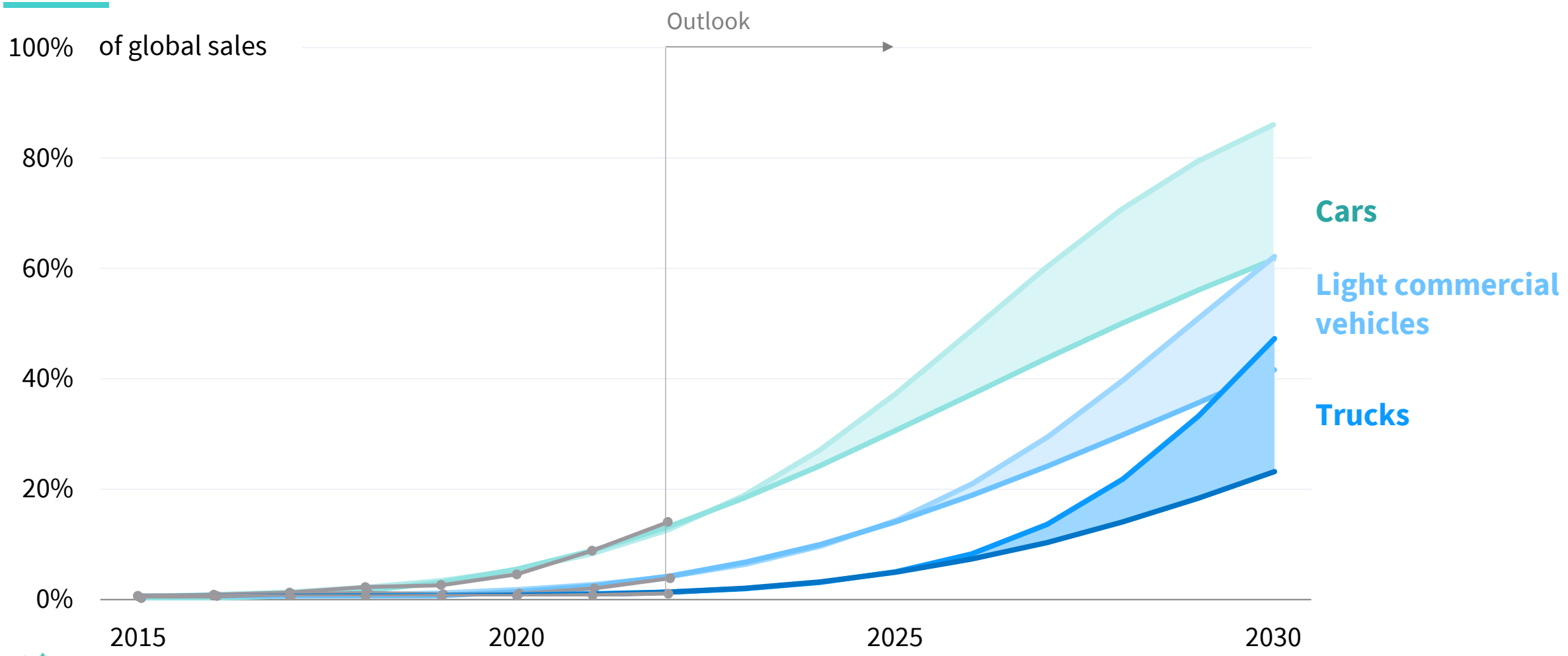
RMI

Source: Energy Institute, BNEF, RMI S-curves. For more see X-Change: Electricity.

The electric vehicle domino effect will continue

Where cars go, vans and trucks follow

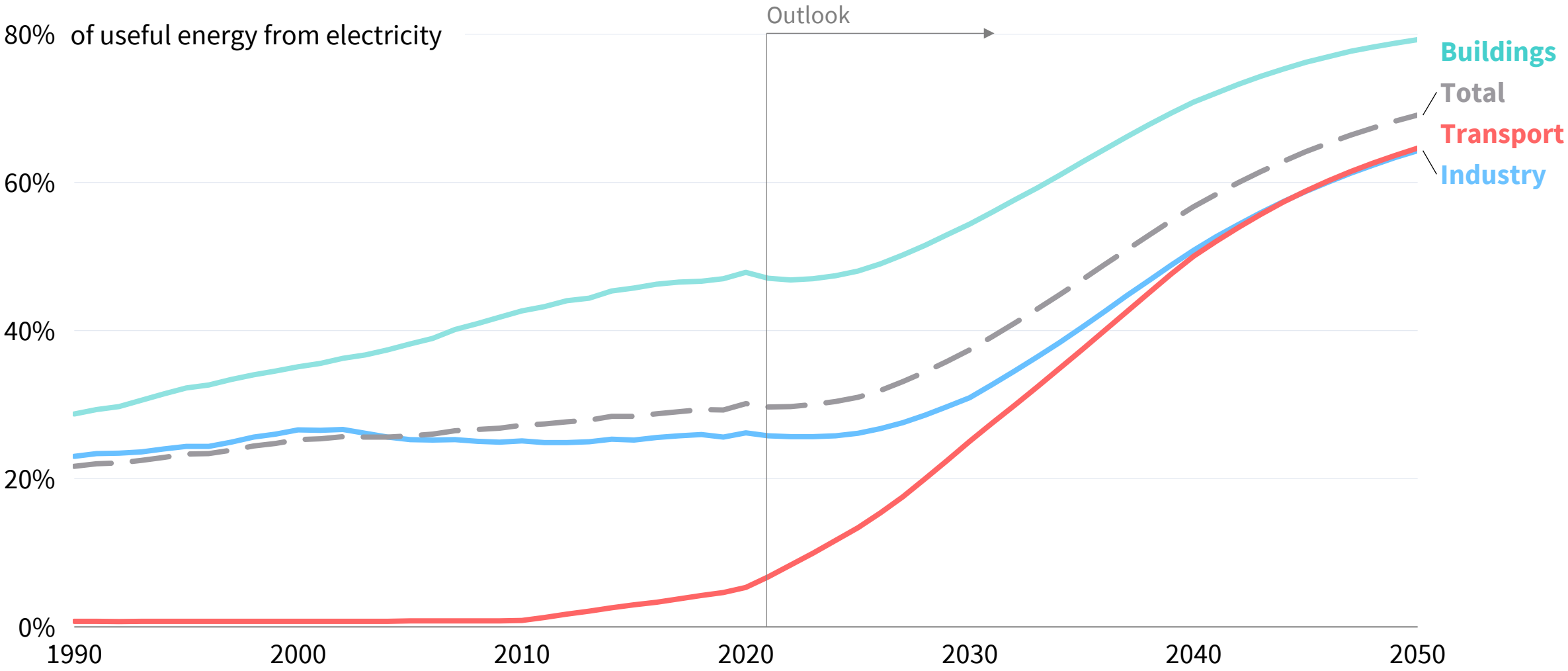
The electric vehicle domino



Source: BNEF, RMI S-curves. For more see X-Change: Batteries.

Electrification will pick up speed

Transport is joining the party just as electrification picks up in other sectors



RMI

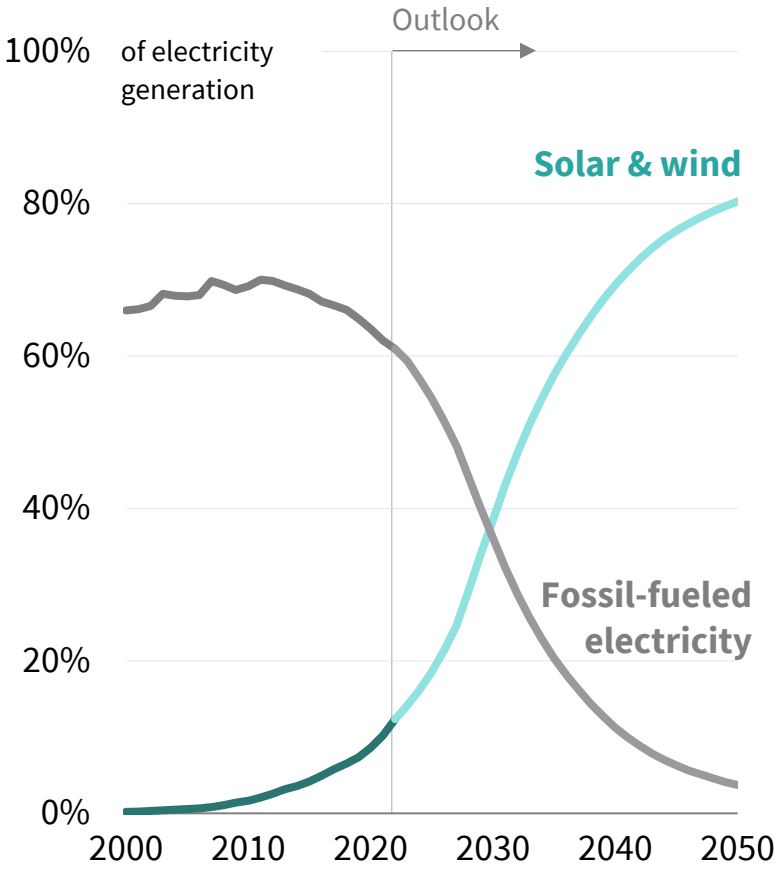
Source: Rystad Energy 1.6°C.

In with the new, out with the old

Renewables push out fossil electricity, electrons push out molecules, and efficiency reduces waste

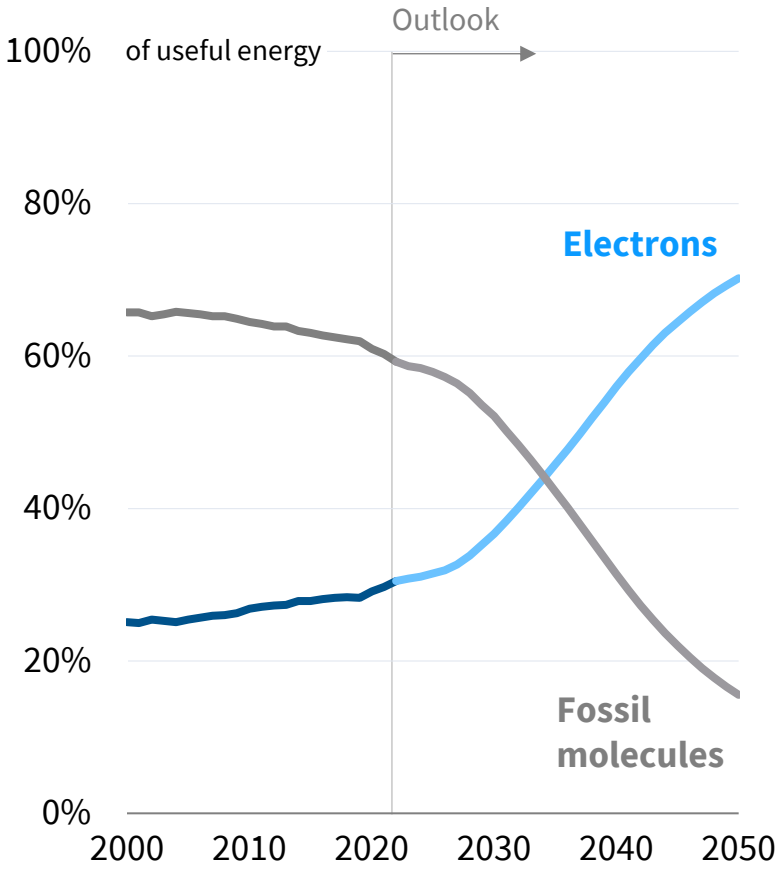
Renewables

Renewables beat fossil-fueled electricity



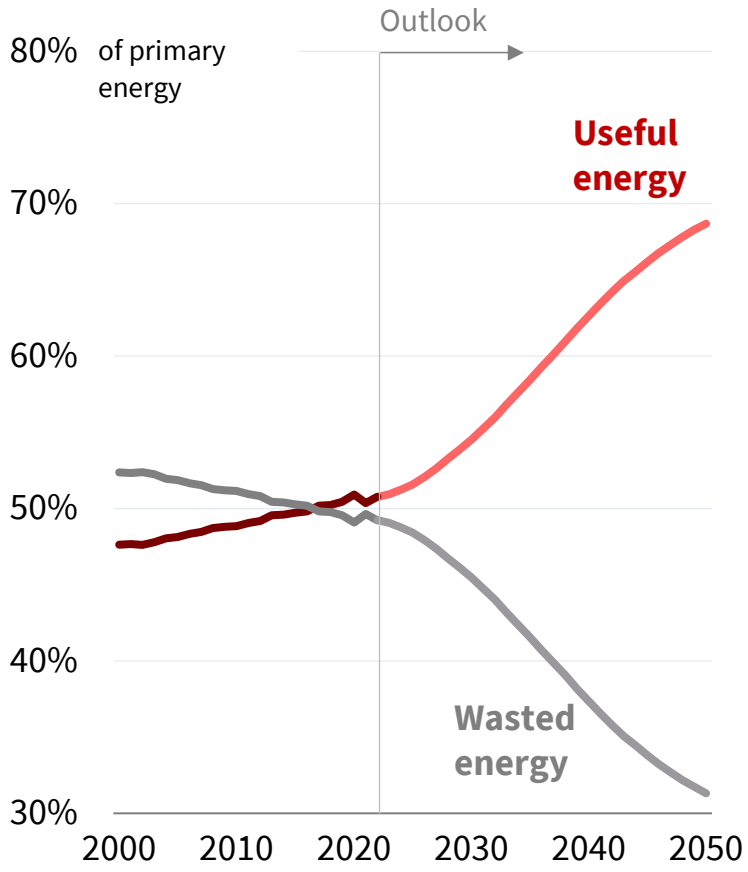
Electrification

Obedient electrons beat fiery molecules



Efficiency

Efficiency beats waste



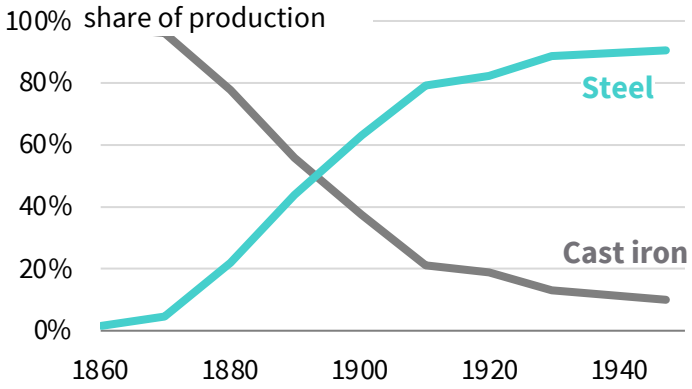
RMI

Source: Rystad Energy 1.6°C scenario.

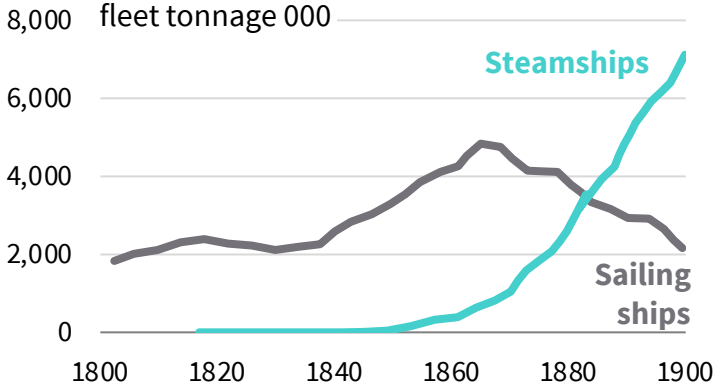
We have seen this X shaped pattern before

An X shaped technology transition is standard so we should not be surprised

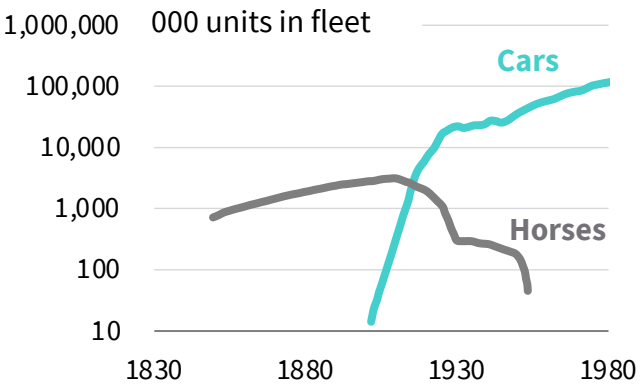
Industry: Cast iron to steel



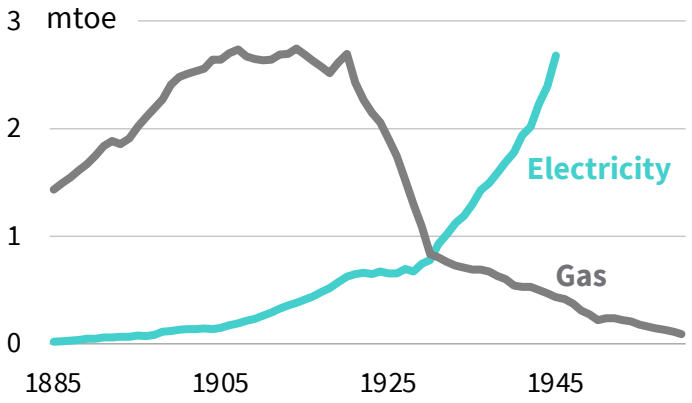
Ships: Sailing ships to steamships



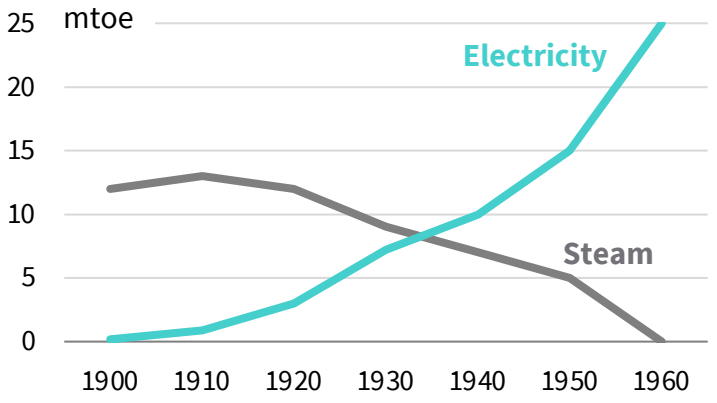
Land transport: Horses to cars



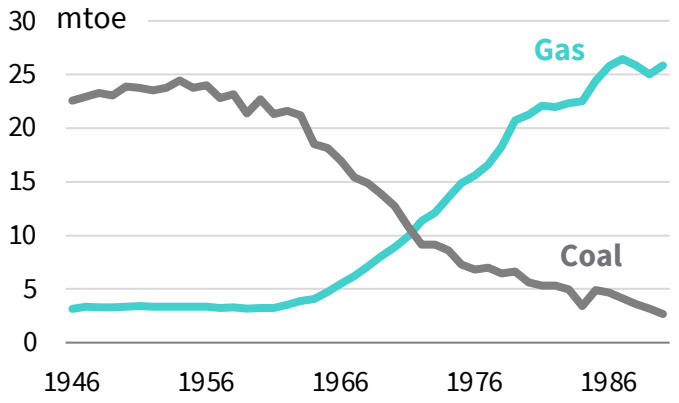
Lighting: Gas to electricity



Power: Steam to electricity



Heat: Coal to gas



Source: Perez, Fouquet, Nakicenovic, Mitchell; Note: all UK charts except horses to cars (US).

Topics

Two visions for the energy future

The cleantech story so far

The drivers of continued change

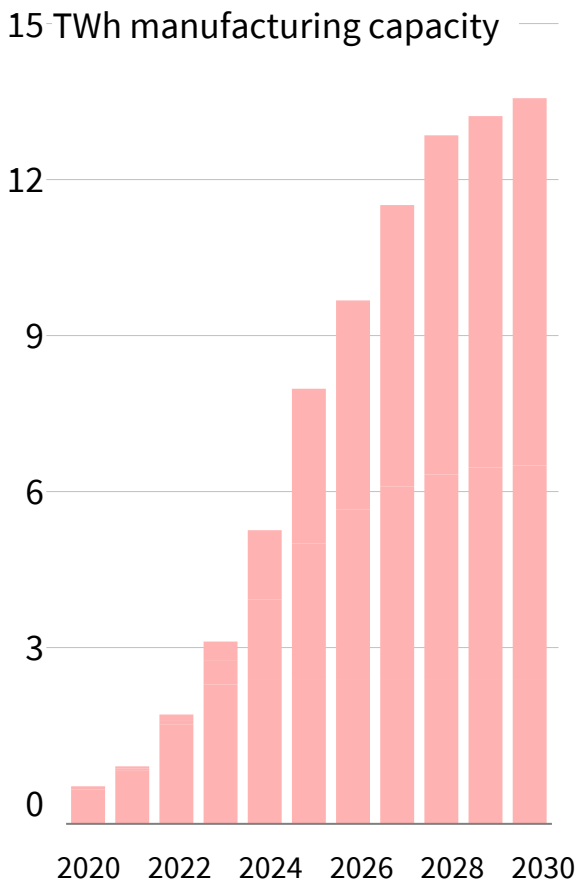
The shape of things to come

Implications

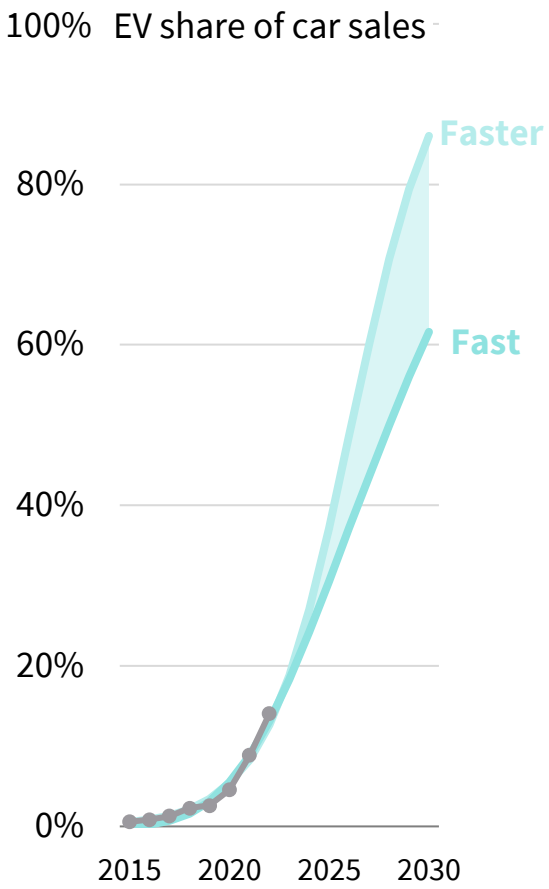
The 2020s are the pivotal decade

You snooze, you lose

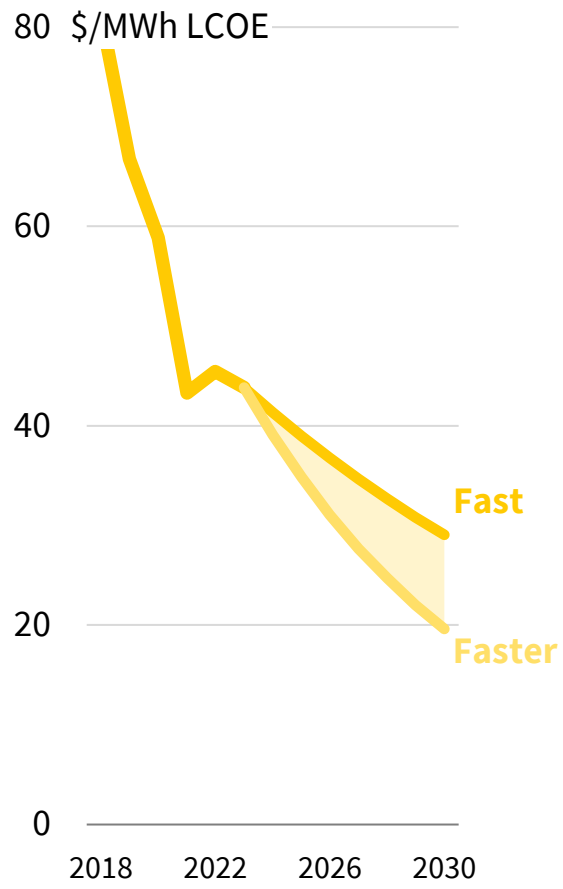
Manufacturing capacity is built: Batteries



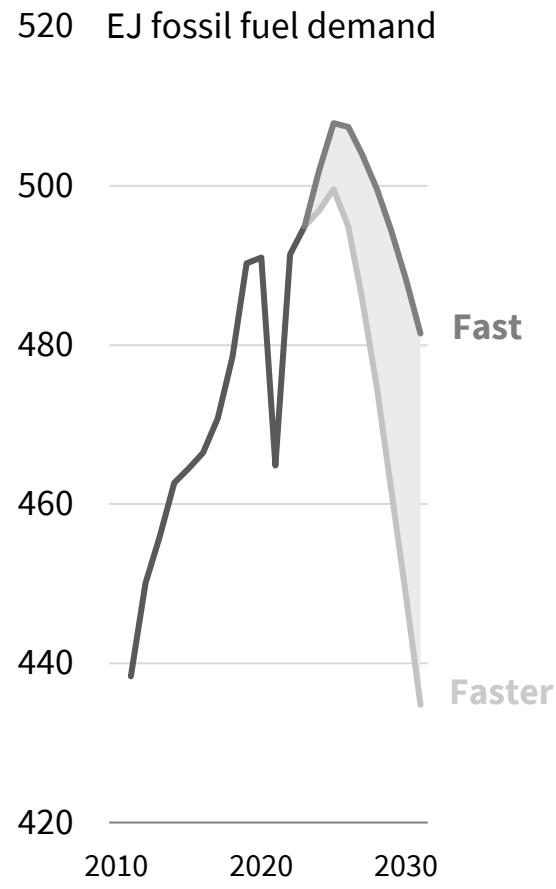
Cleantech goes up the steep part of the S-curve: EV



Renewables get too cheap to resist: Solar



Fossil fuel demand enters terminal decline

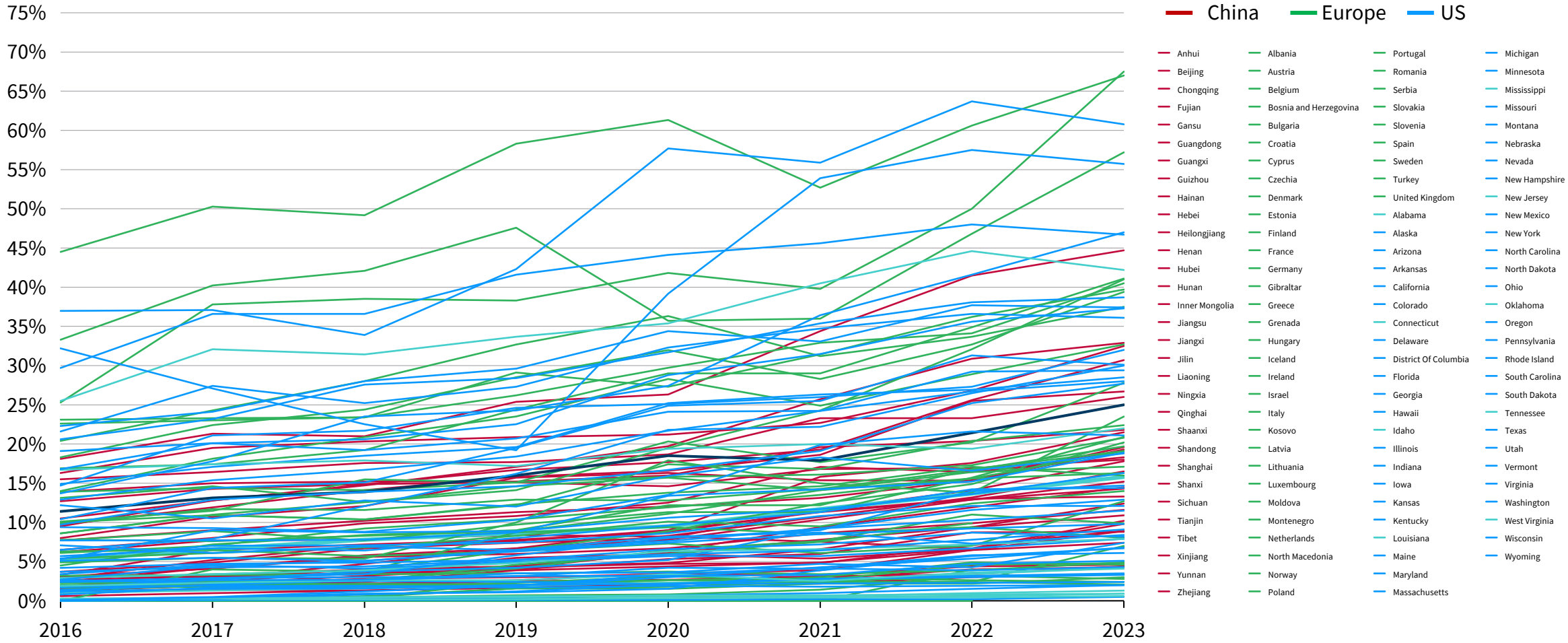


Sources: BNEF, RMI, Rystad Energy.

Find the signal in the noise

And ride the renewable wave

Share of generation from renewables[1], %GWh



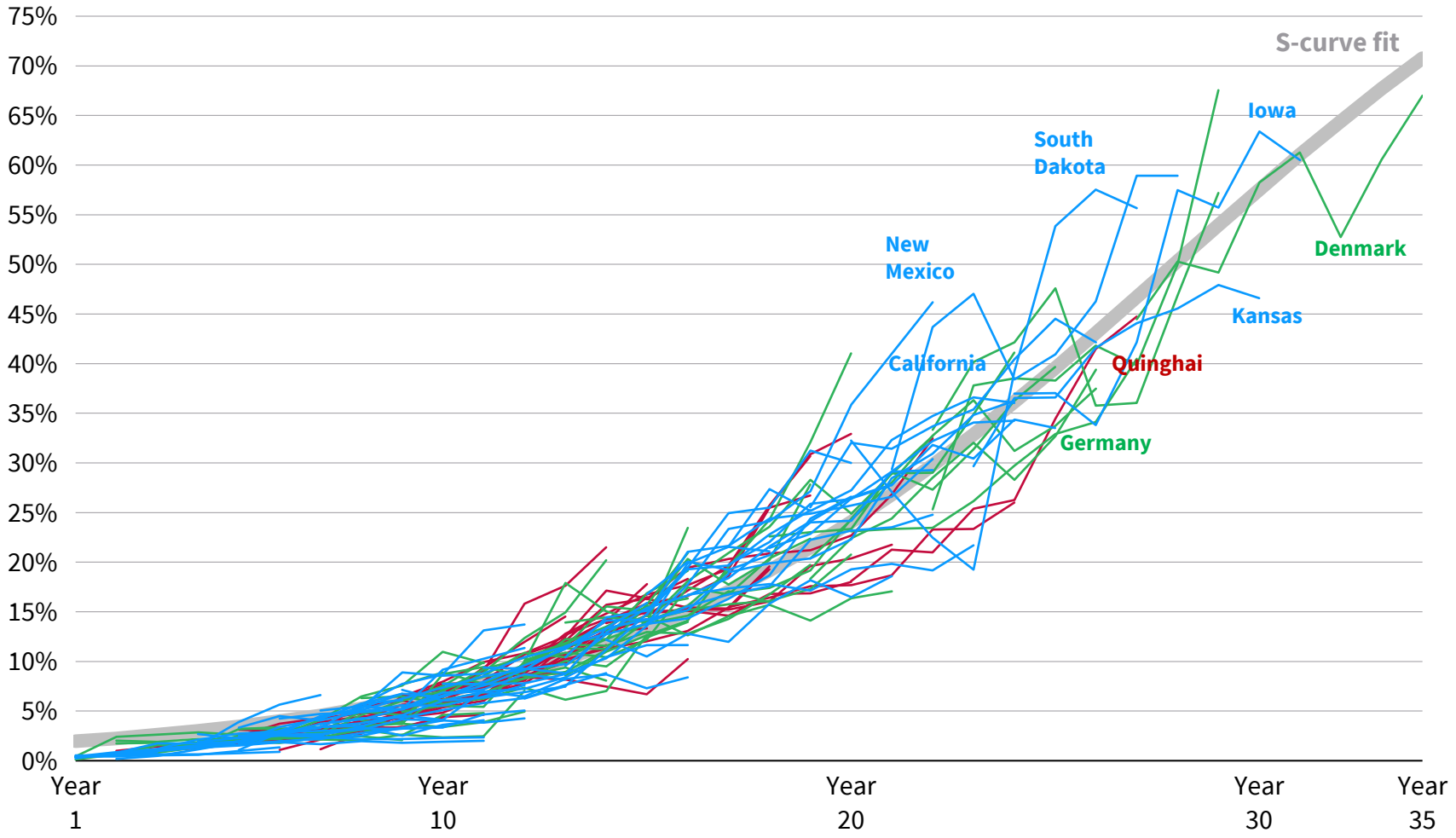
1. Offset by number of years to maximize overlap; Y1 means a different year for each region.

Source: 2013-2023 National Electricity Industry Statistics Bulletn; China electricity council; ENSTO-E; EIA

Find the signal in the noise

And ride the renewable wave

Share of generation from renewables[1], %GWh



China Europe US

Anhui	Albania	Portugal	Michigan
Beijing	Austria	Romania	Minnesota
Chongqing	Belgium	Serbia	Mississippi
Fujian	Bosnia and Herzegovina	Slovakia	Missouri
Gansu	Bulgaria	Slovenia	Montana
Guangdong	Croatia	Spain	Nebraska
Guangxi	Cyprus	Sweden	Nevada
Guizhou	Czechia	Turkey	New Hampshire
Hainan	Denmark	United Kingdom	New Jersey
Hebei	Estonia	Alabama	New Mexico
Heilongjiang	Finland	Alaska	New York
Henan	France	Arizona	North Carolina
Hubei	Germany	Arkansas	North Dakota
Hunan	Gibraltar	California	Ohio
Inner Mongolia	Greece	Colorado	Oklahoma
Jiangsu	Grenada	Connecticut	Oregon
Jiangxi	Hungary	Delaware	Pennsylvania
Jilin	Iceland	District Of Columbia	Rhode Island
Liaoning	Ireland	Florida	South Carolina
Ningxia	Israel	Georgia	South Dakota
Qinghai	Italy	Hawaii	Tennessee
Shaanxi	Kosovo	Idaho	Texas
Shandong	Latvia	Illinois	Utah
Shanghai	Lithuania	Indiana	Vermont
Shanxi	Luxembourg	Iowa	Virginia
Sichuan	Moldova	Kansas	Washington
Tianjin	Montenegro	Kentucky	West Virginia
Tibet	Netherlands	Louisiana	Wisconsin
Xinjiang	North Macedonia	Maine	Wyoming
Yunnan	Norway	Maryland	
Zhejiang	Poland	Massachusetts	

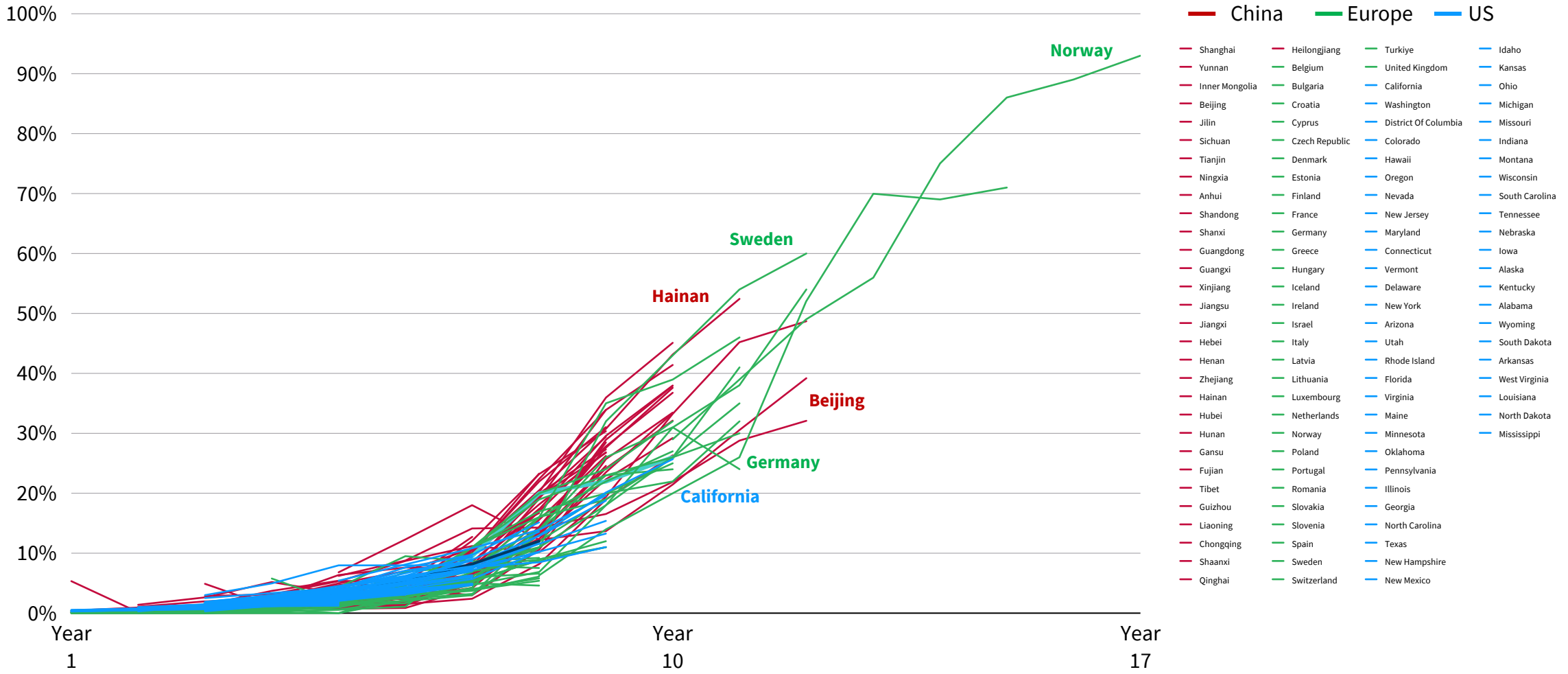
1. Offset by number of years to maximize overlap; "year 1" means a different year for each region.

Source: 2013-2023 National Electricity Industry Statistics Bulletn; China electricity council; ENSTO-E; EIA

EV growth also follows an S-curve

Offset region uptake data shows a clear S-curve trend across China, Europe and the US

Share of sales from EV [1], %GWh

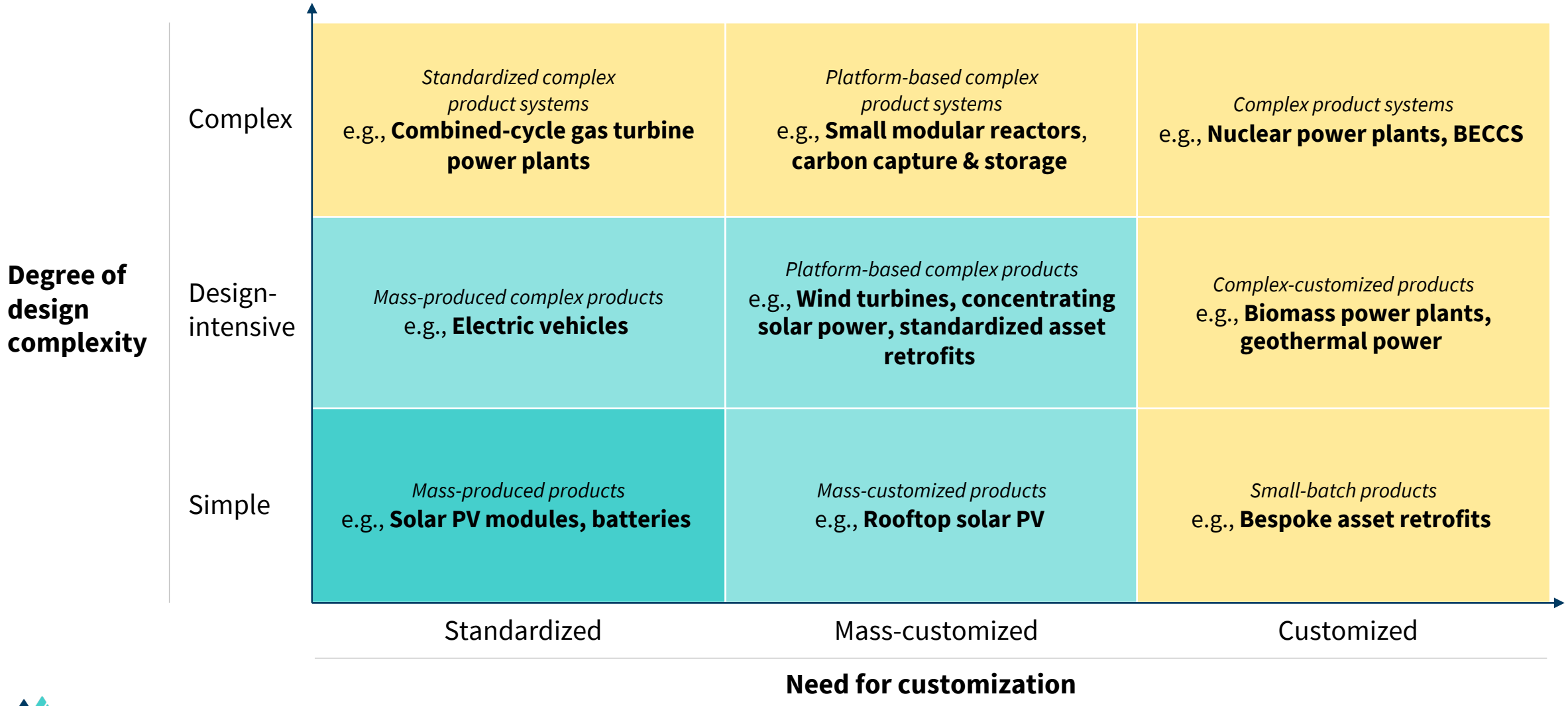


1. Offset by number of years to maximize overlap; Y1 means a different year for each region.

Source: 2013-2023 National Electricity Industry Statistics Bulletn; China electricity council; ENSTO-E; EIA

Pay close attention to the small, modular technologies

Focus on modular technologies with steep learning curves; avoid expensive and hard-to-deploy technologies

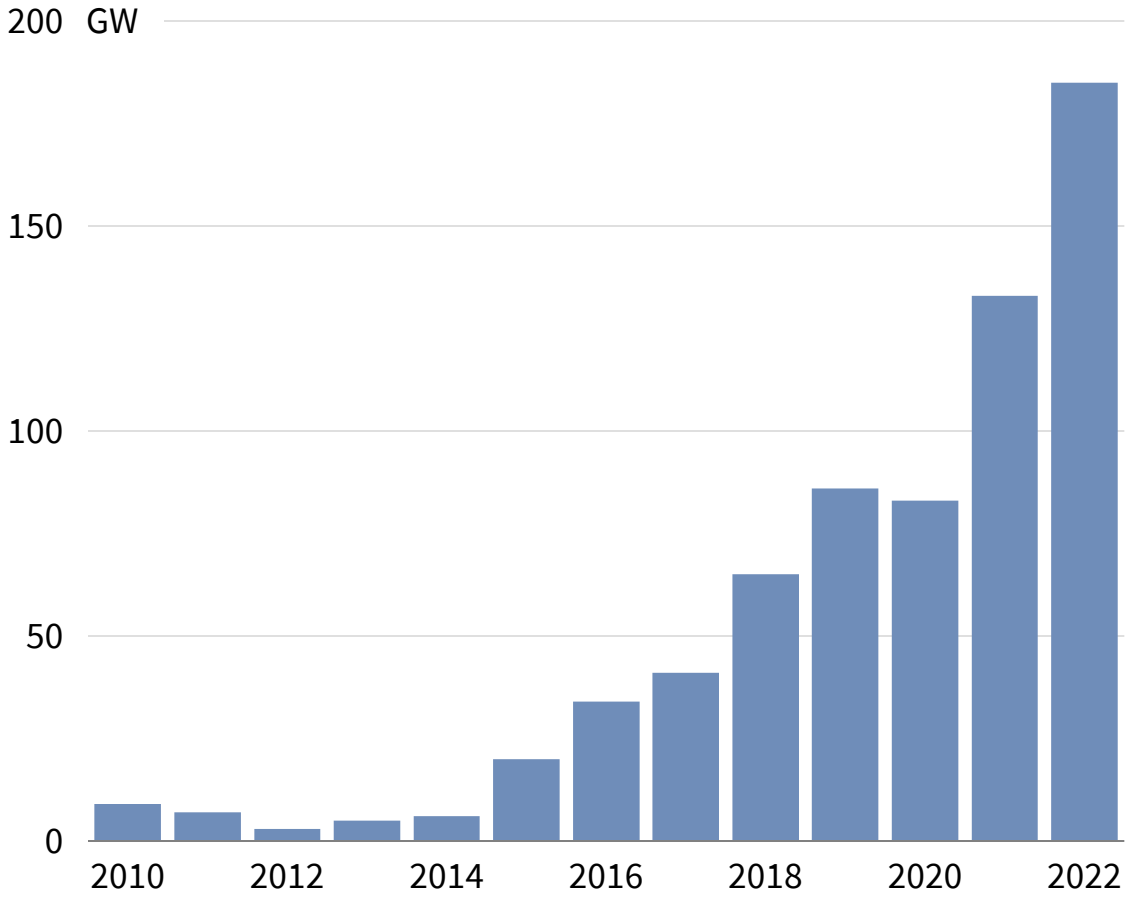


Source: Adapted from Malhotra and Schmidt, "Accelerating Low-Carbon Innovation."

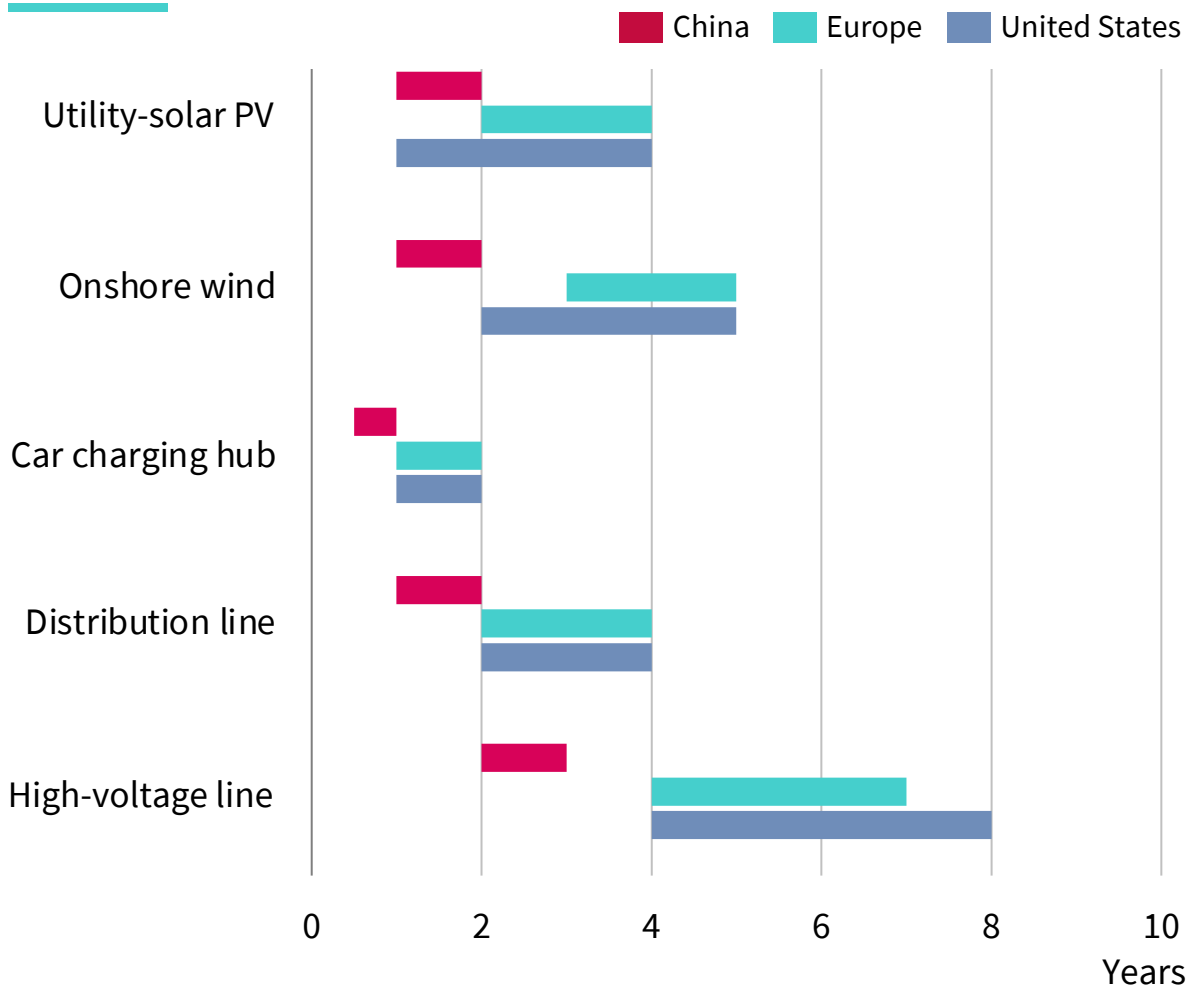
Build, baby, build…

If you want to stay in the game, you need to deploy renewables and electrify end-use demand, and fast

Connection queue growth in United States



Typical deployment time

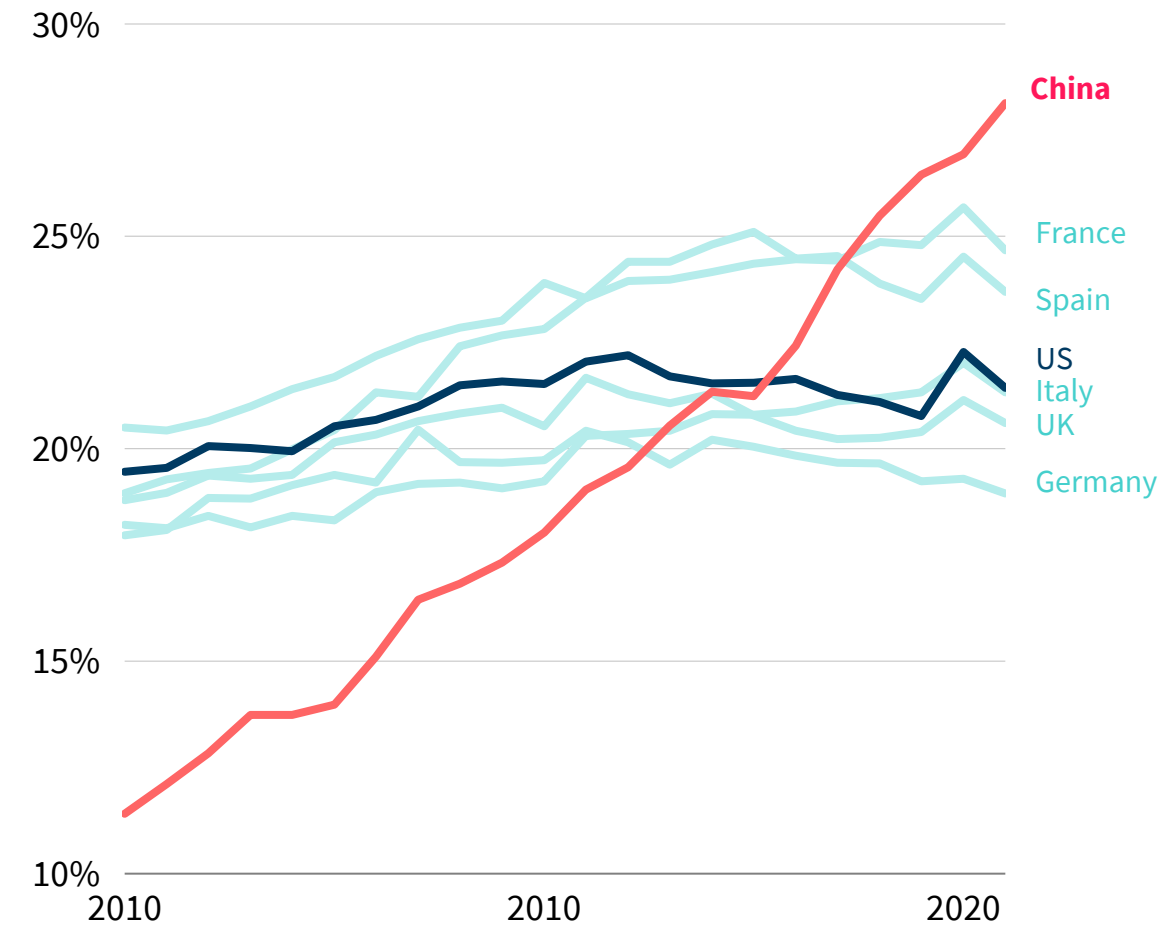


RMI *Source: IEA.*

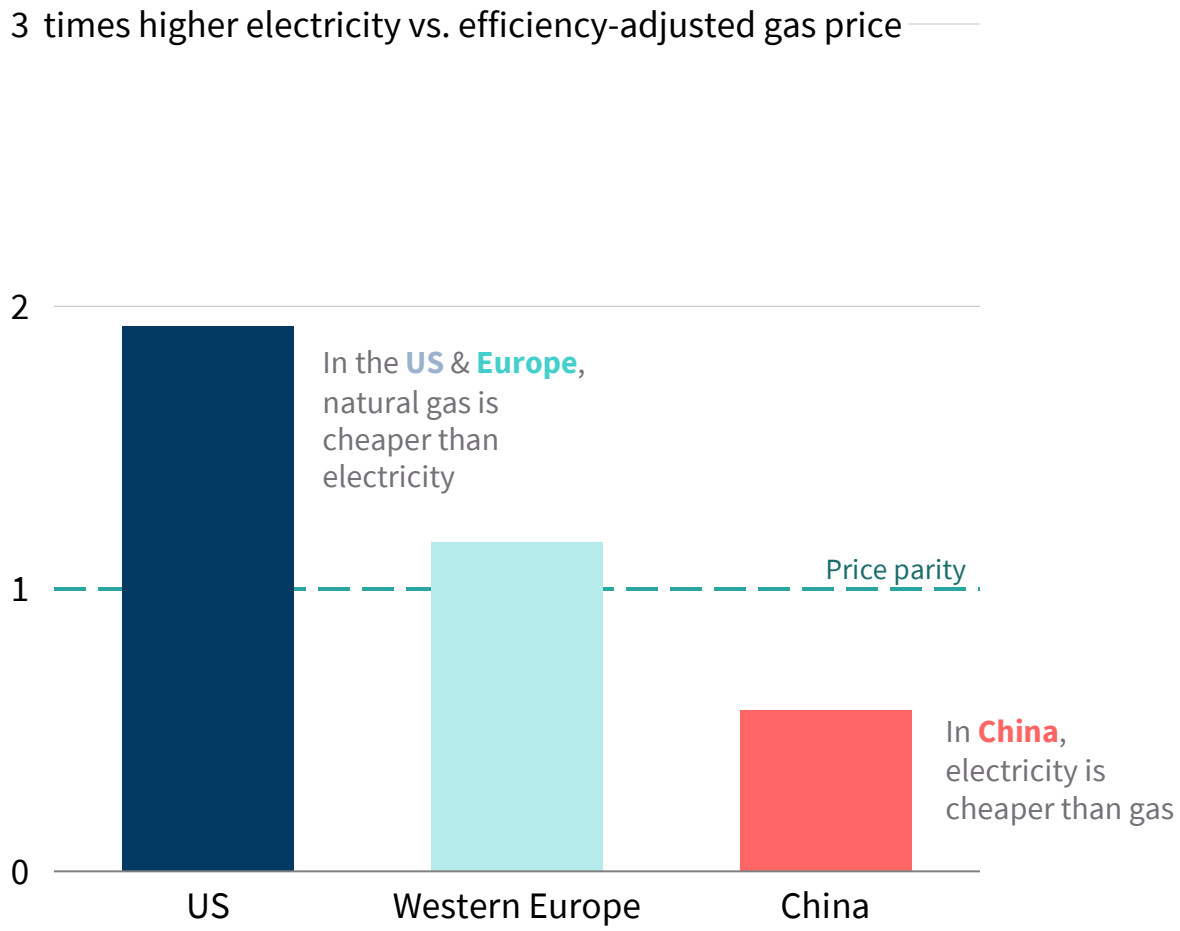
Speed up electrification

Redesign electricity markets to pass the low cost of renewables onto industry and households

Electricity share of final energy



Electricity multiple of natural gas prices in 2023

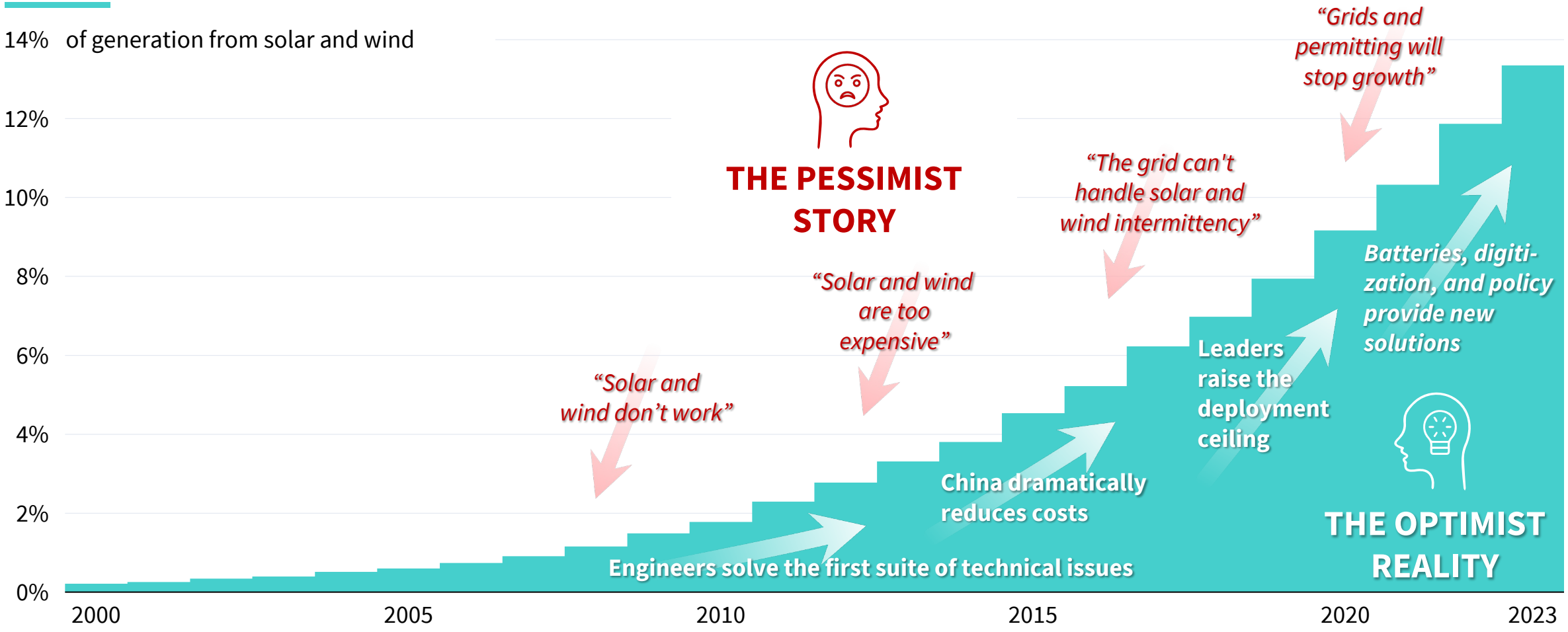


Source: IEA WEB, IEA, RMI. Note: assuming a 40% efficiency of natural gas for a fairer comparison between the two energy carriers.

Pessimists sound clever; optimists make money

Innovation beats bottlenecks, time and again

Pessimist's and optimist's take on solar and wind uptake



Source: Ember.

About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and NGOs to identify and scale energy system interventions that will cut climate pollution at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; Abuja, Nigeria; and Beijing.

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Acknowledgments

With thanks to: Amory Lovins, Hannah Ritchie, Joseph Zacune, Will Atkinson, Chiara Gulli, Laurens Speelman, Ita Kettleborough, and Harry Benham.

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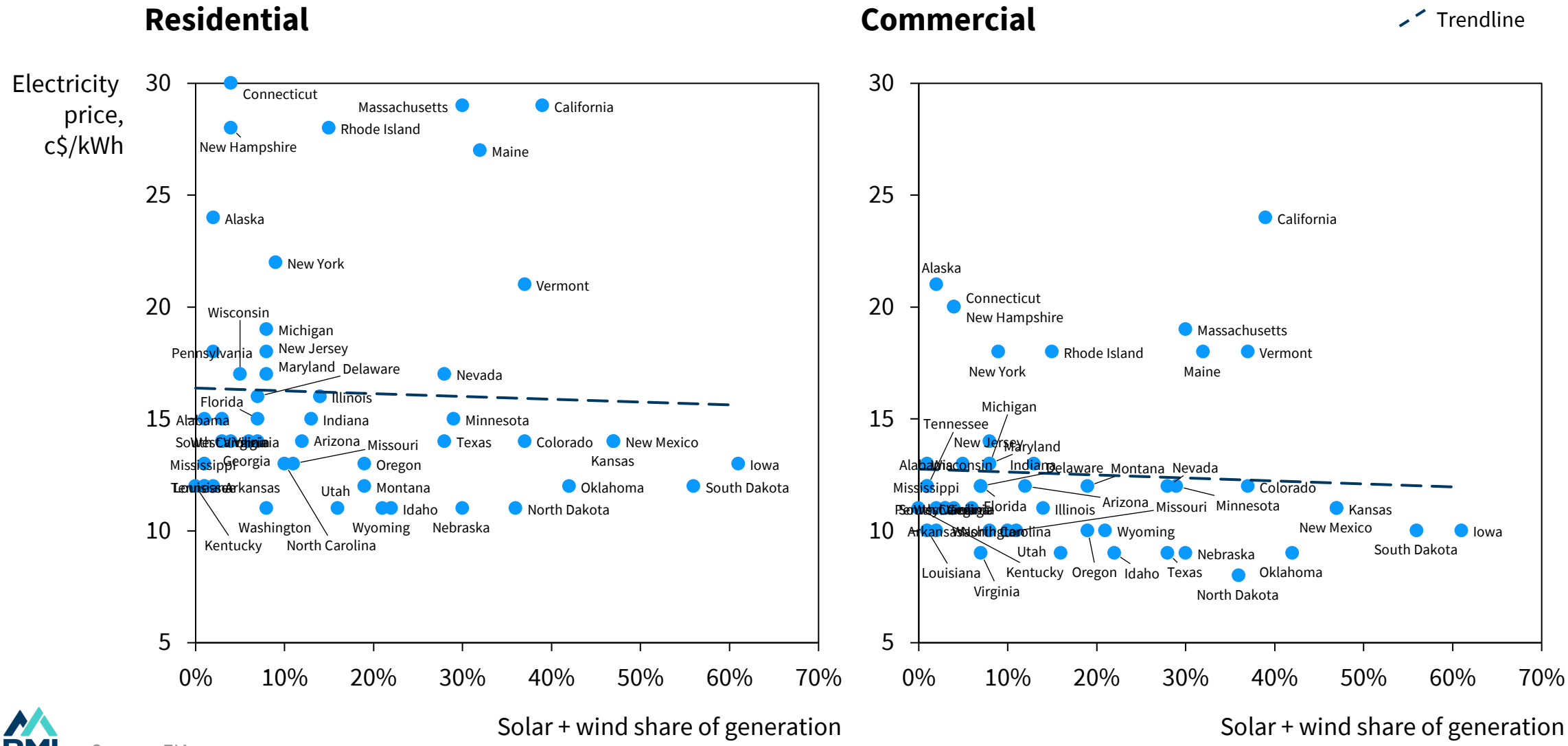
BACKUP

More renewables does not mean higher prices

Across US states, wind and solar uptake does now correlate with higher electricity prices

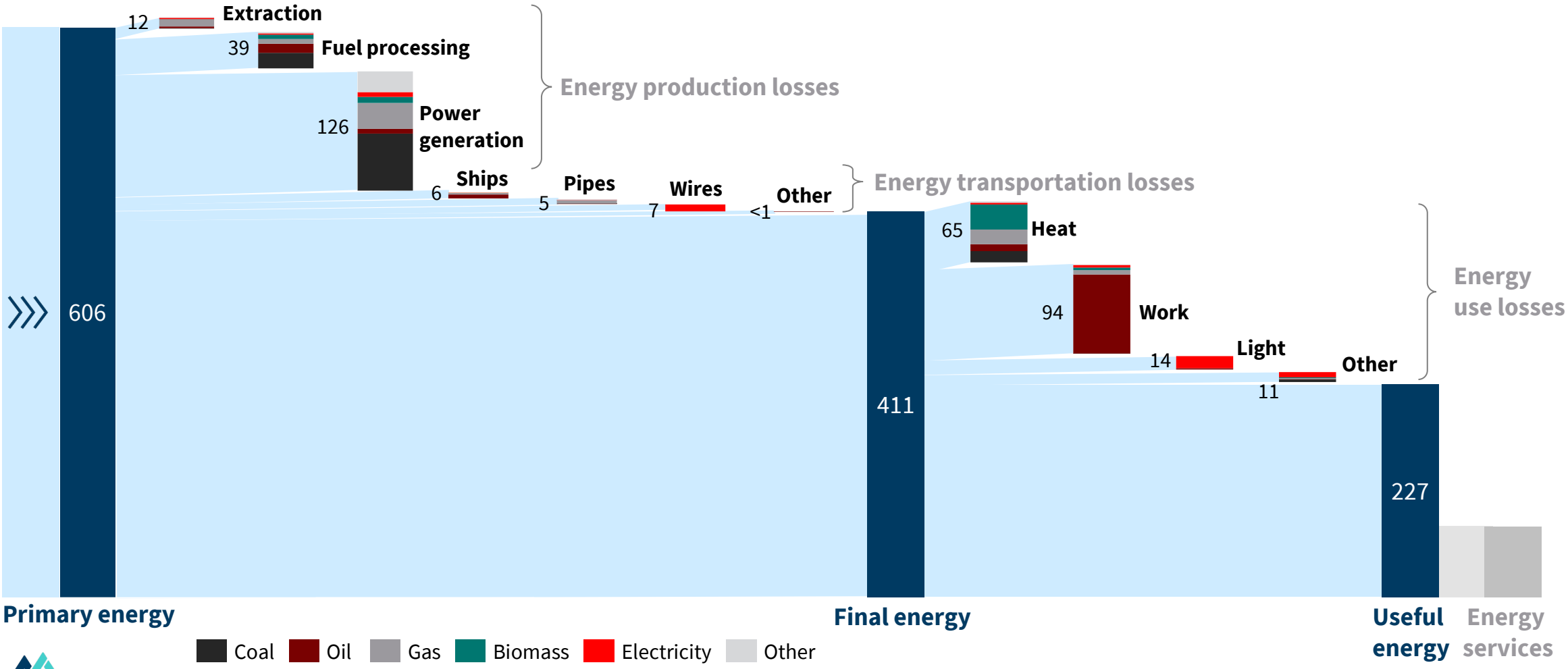


Source: EIA

Fossil fuels are extremely inefficient

Two thirds of all fossil fuel primary energy is wasted in thermodynamic and system losses

Energy system flows, EJ, 2019

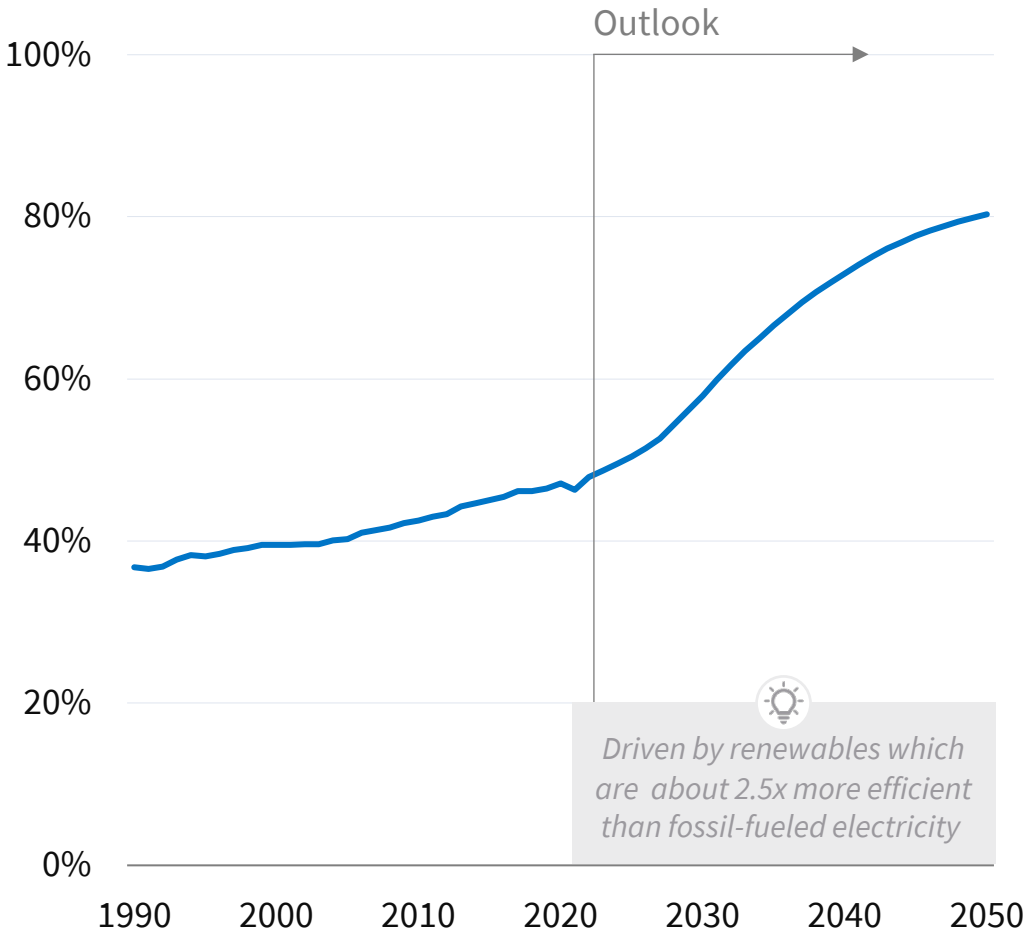


Sources: IEA, IIASA, RMI. For more see The Incredible Ineffciency of the Fossil Fuel System.

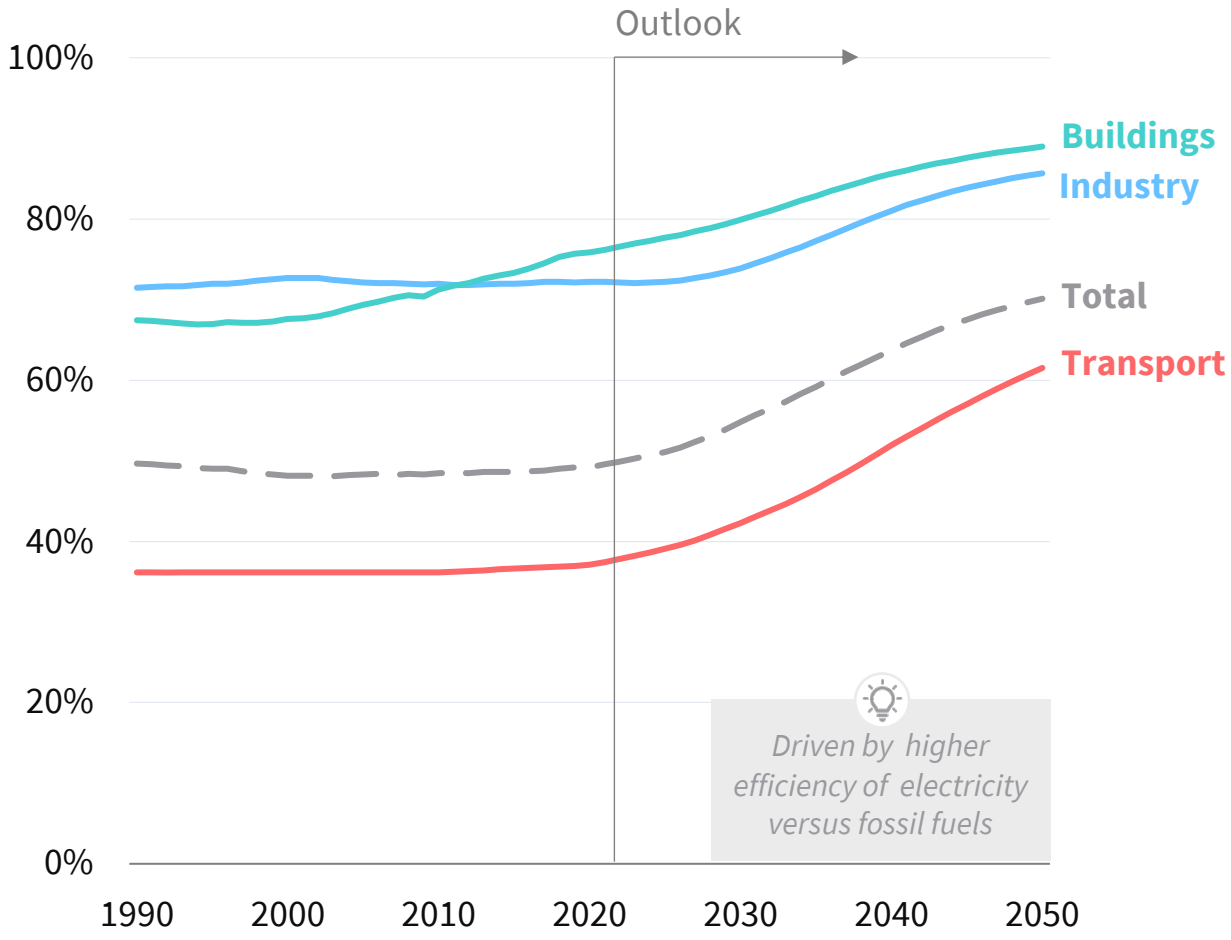
Efficiency will be pulled up the S-curve

Faster cleantech deployment will speed up efficiency improvements

Electricity generation efficiency



End-sector efficiency

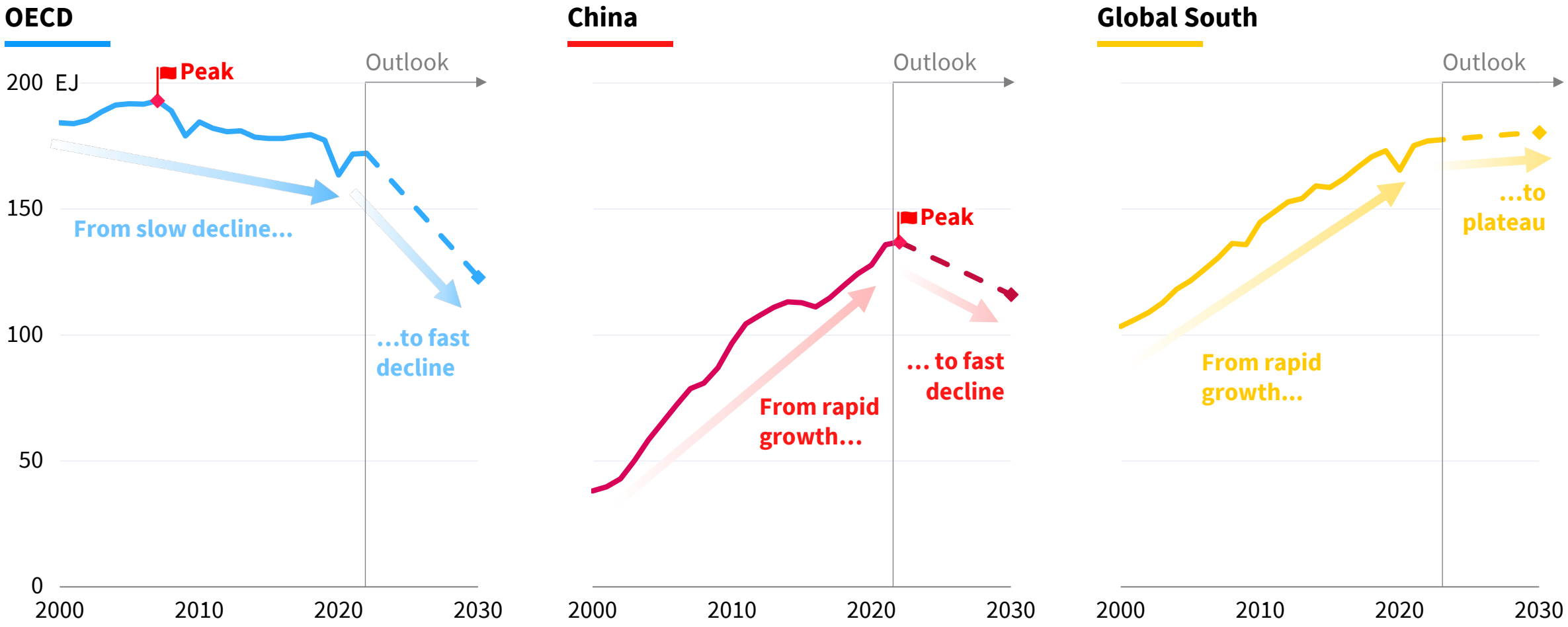


Source: Rystad Energy 1.6 °C. Electricity efficiency is final as a share of primary. Sector efficiency is useful as a share of secondary.

China is the global pivot nation

When China peaks, the world peaks

Primary fossil fuel demand by region

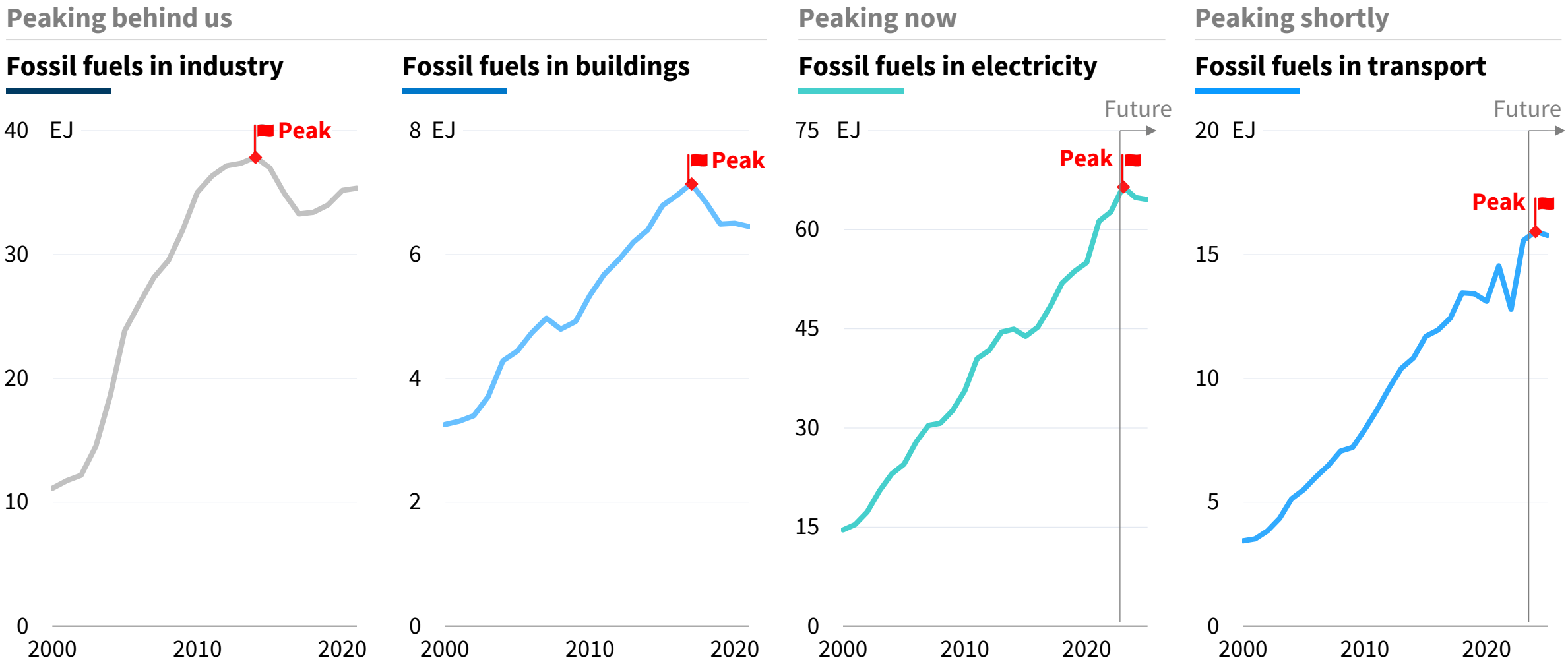


Source. IEA APS scenario.

China has driven two-thirds of fossil fuel demand growth in the past decade

Fossil fuel demand is peaking across the Chinese system

Peaks in industry and buildings are behind us, electricity peaked in 2023, and transport is coming soon

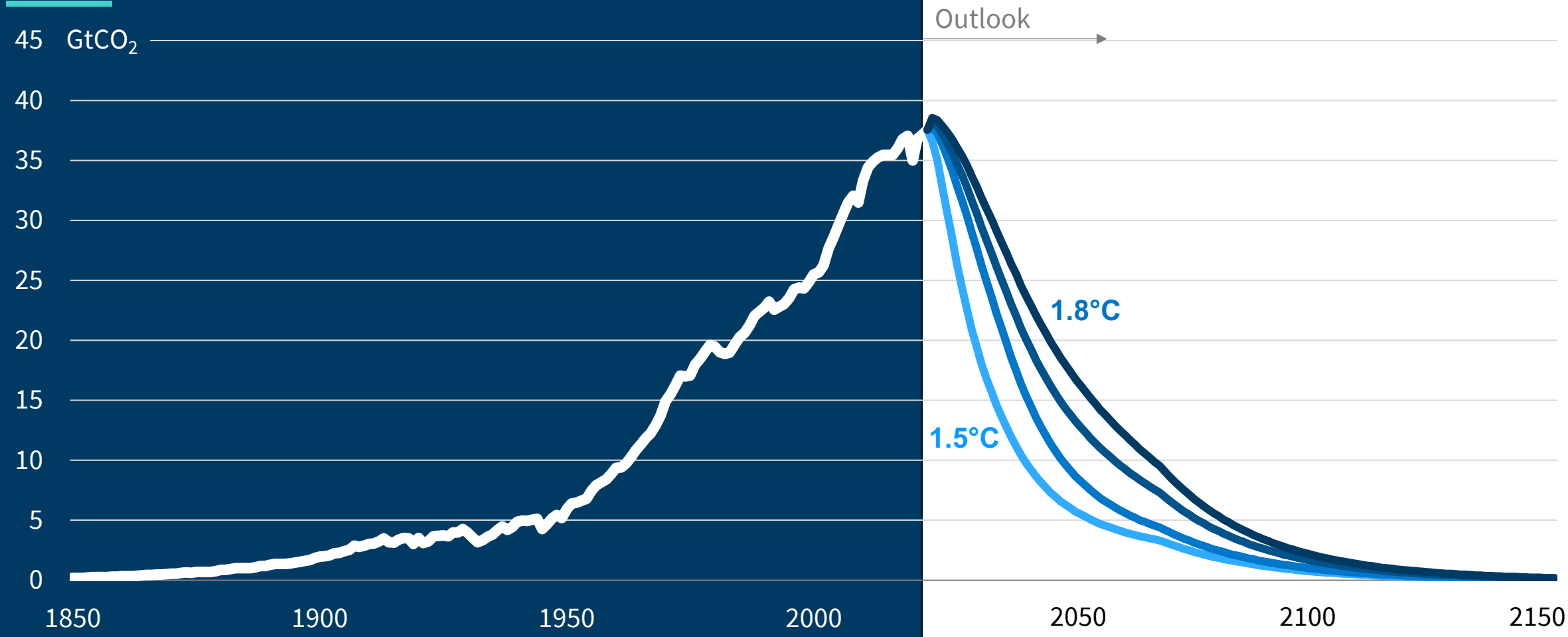


Source: IEA WEB (past), Ember, IEA Electricity 2024 (electricity generation forecast), BNEF NZS (transport forward).

Paris is feasible

This is the pivot decade from growth to decline

Global CO_2 emissions from energy

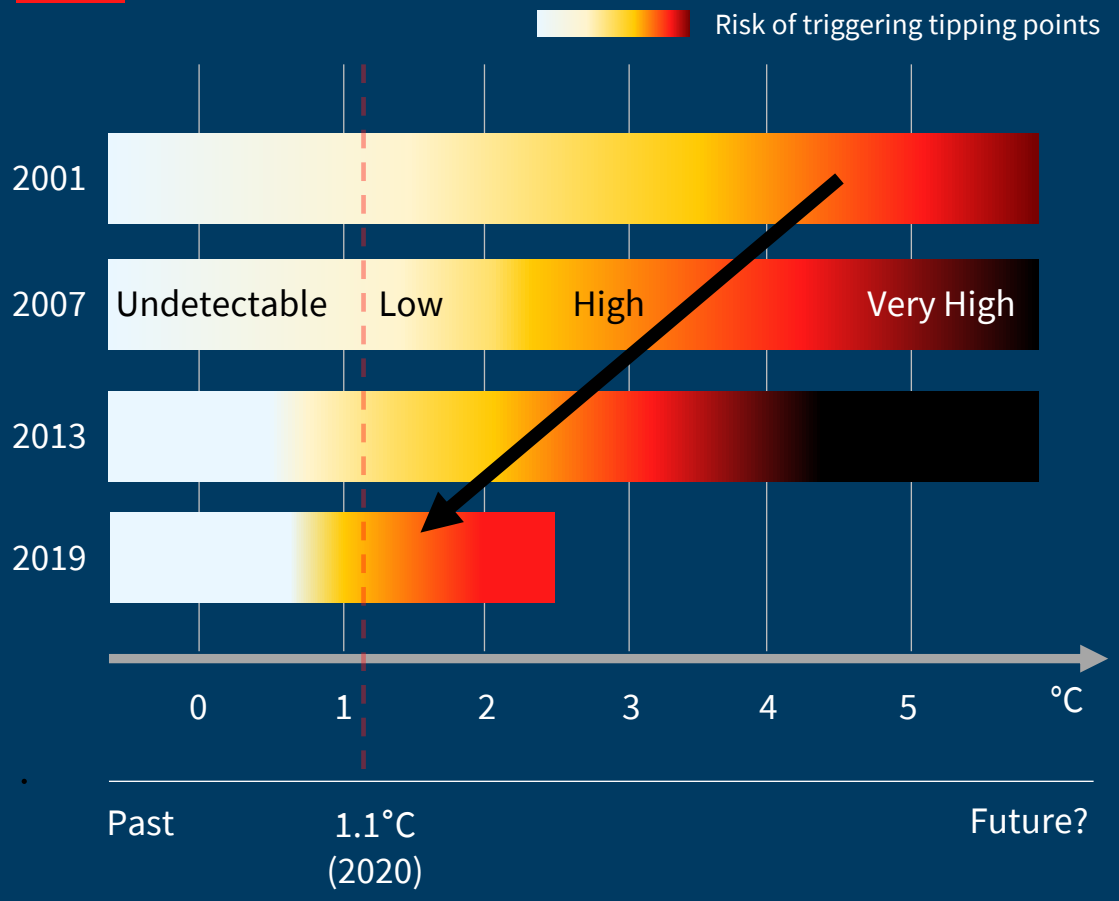


Source: Global Carbon Project, OWID (1850-2023), Rystad Energy to 2023-2070; RMI illustrative onwards. Paris here means the goal of the 2015 Paris Agreement to keep global warming well below 2°C .

We are in a race between climate and economic tipping points

On the one hand, **climate** tipping points are coming faster than expected…

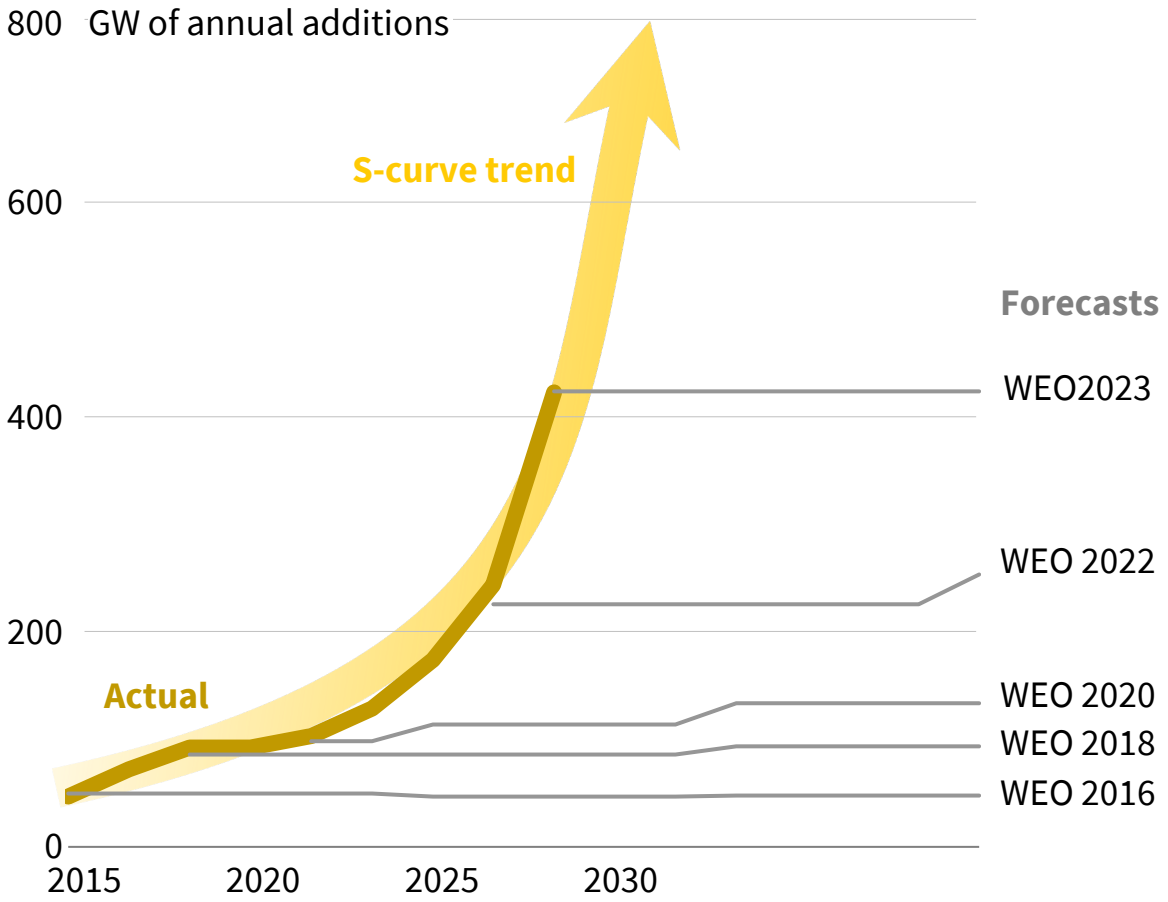
Climate tipping points



Source: Lenton et al based on IPCC reports

…on the other hand, **climate solutions are scaling faster** than most analysts thought possible.

Actual solar additions *vs.* consensus outlooks

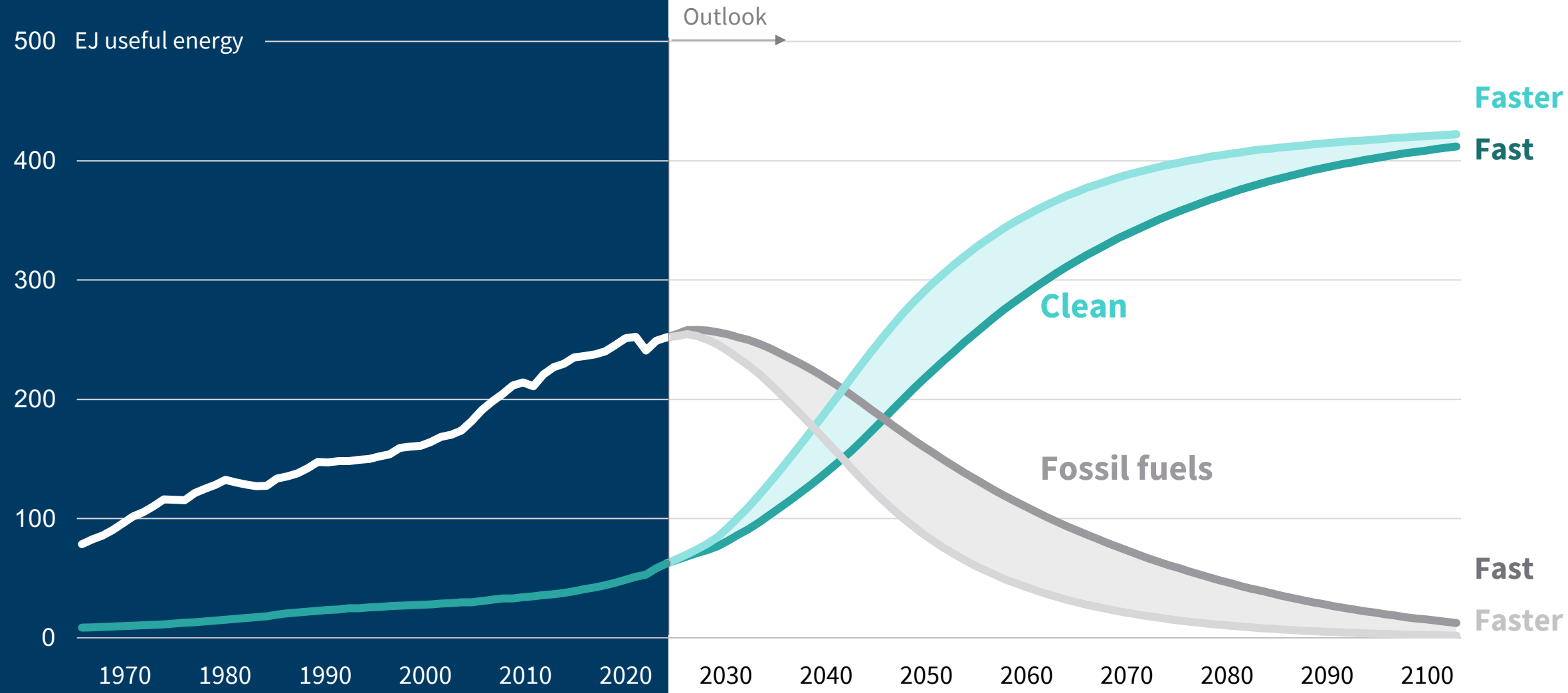


Source: IEA STEPS, BNEF actuals

Direction is inevitable, but speed is up to us

There is both inevitability and agency.

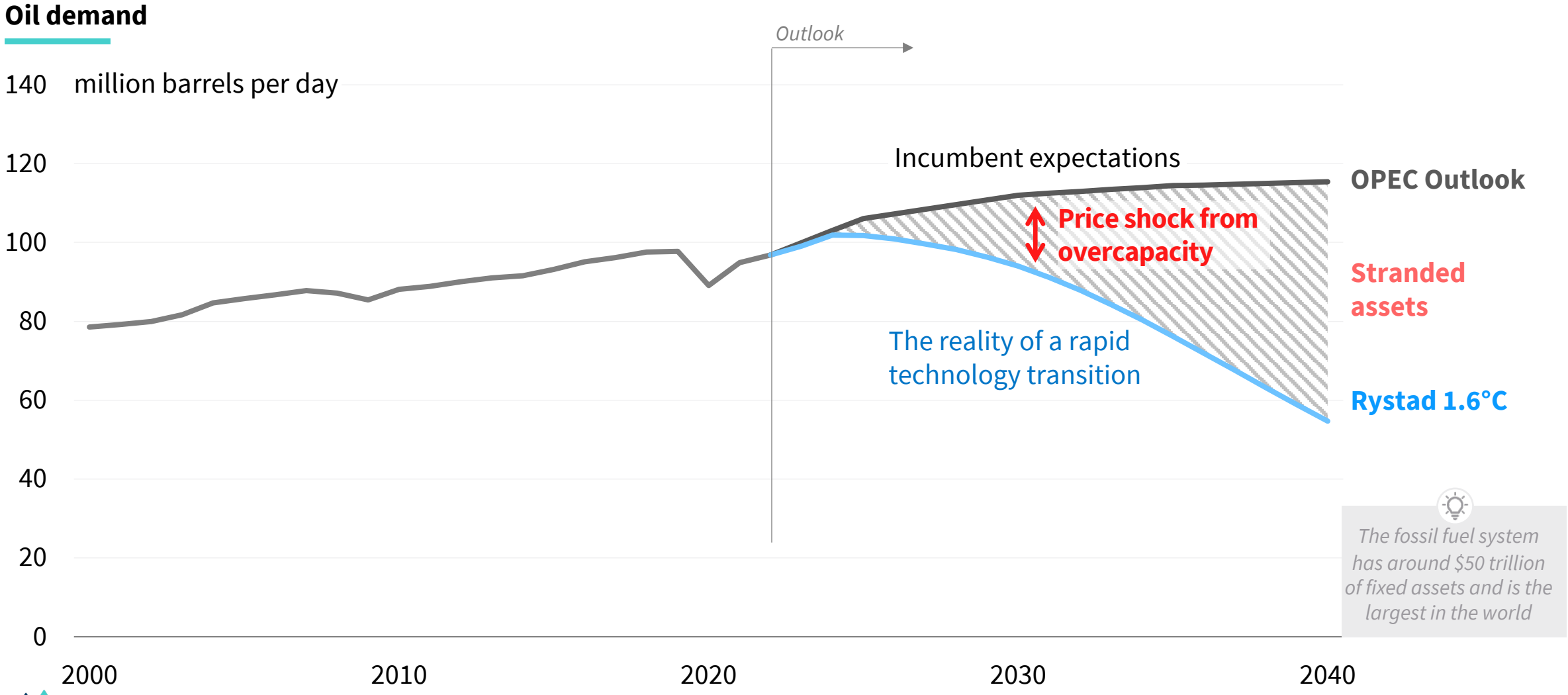
As time is short there is every reason to act.



Source: Rystad Energy scenarios (1.6°C Faster, 1.8°C Fast).

The fossil fuel system faces trillions in stranded assets

Assets get stranded at the top of the market, and disruption is driven by price changes

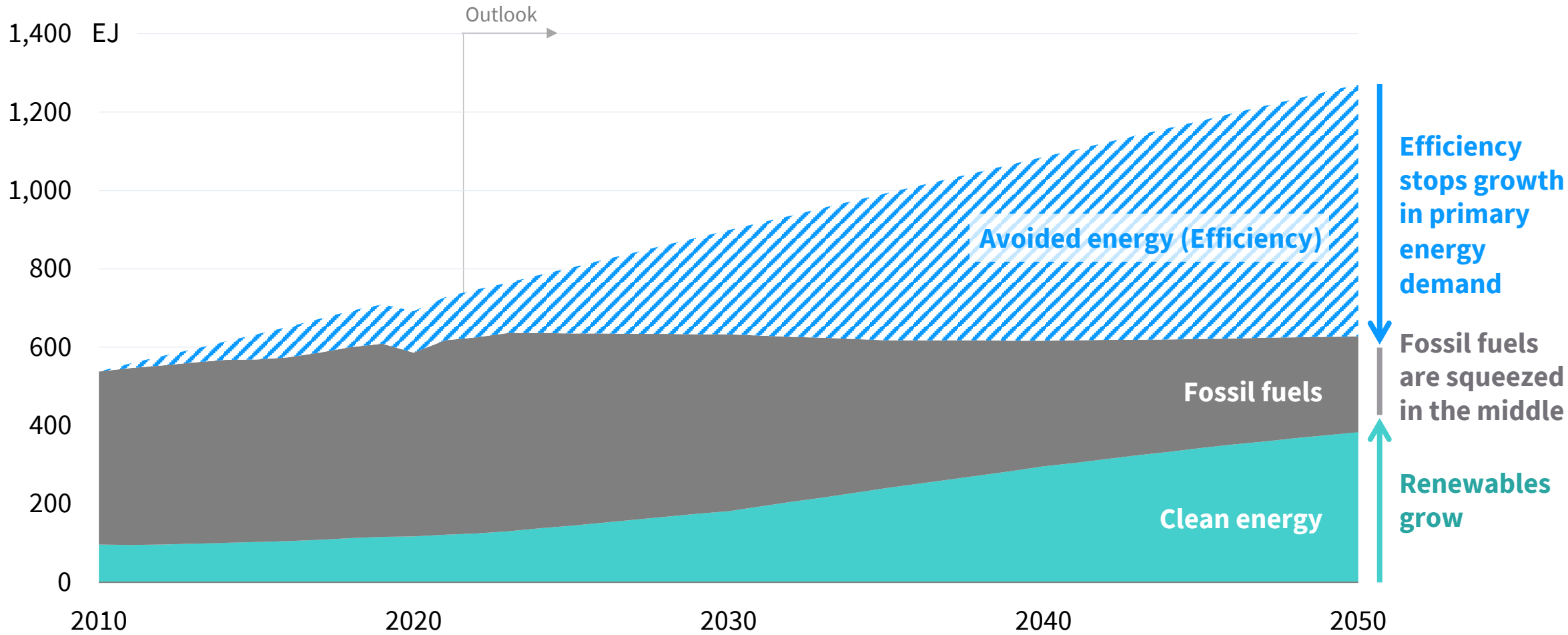


Source: Rystad Energy, OPEC, RMI.

Fossil fuel demand gets squeezed

The growth of cleantech and rising efficiency will squeeze out fossil fuel demand

Primary energy supply



RMI

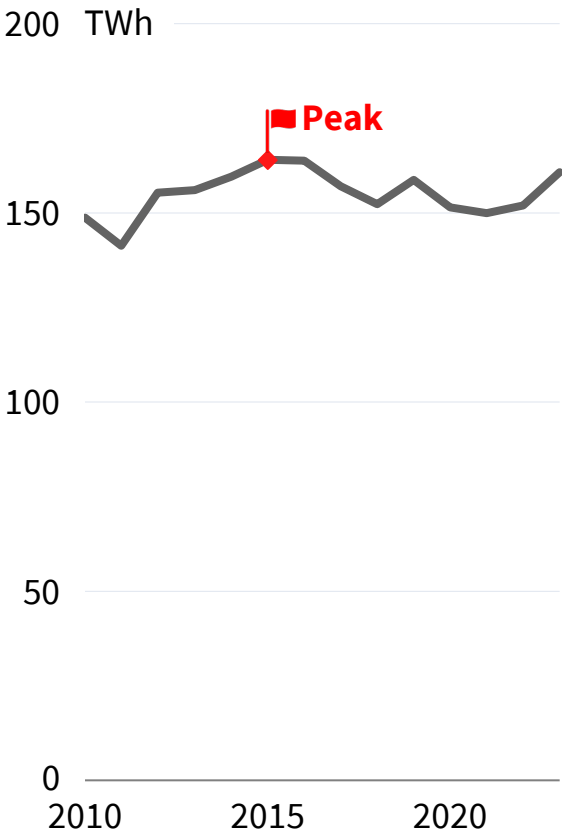
Source: IEA WEB, IEA APS scenario, RMI.

The first fossil peaks in the Global South

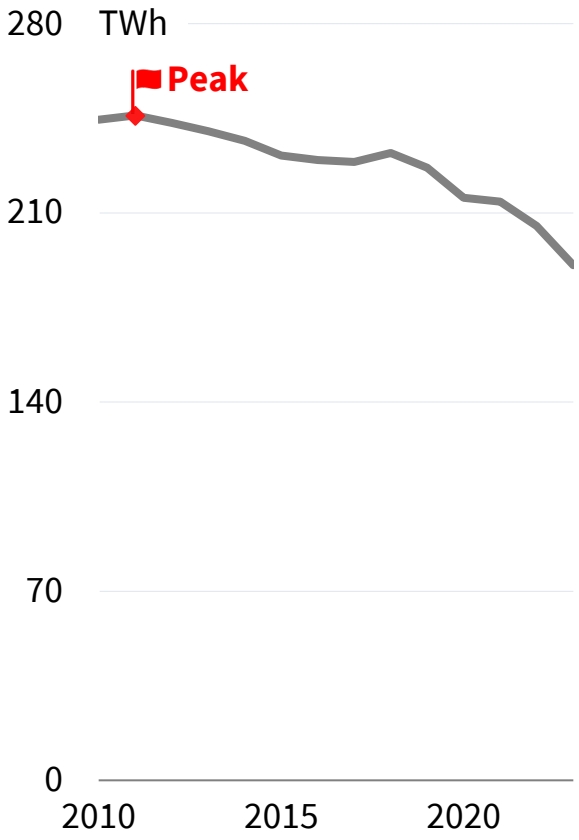
The Global South is not condemned to choose technologies the North is abandoning

Fossil fuel generation

Thailand



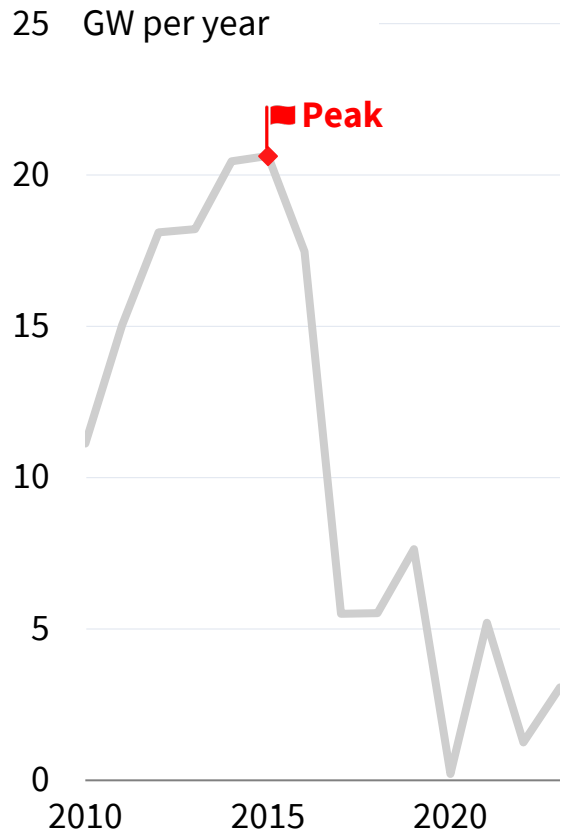
South Africa



Latin America

Coal capacity additions

India

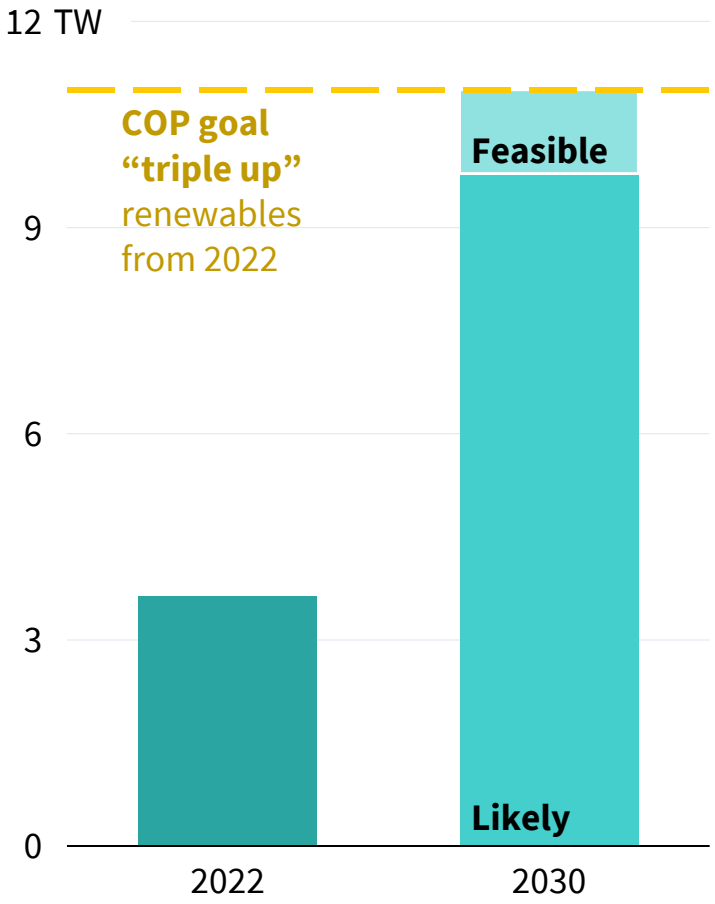


Source: Ember; Note coal additions are a net figure — gross additions minus retirements.

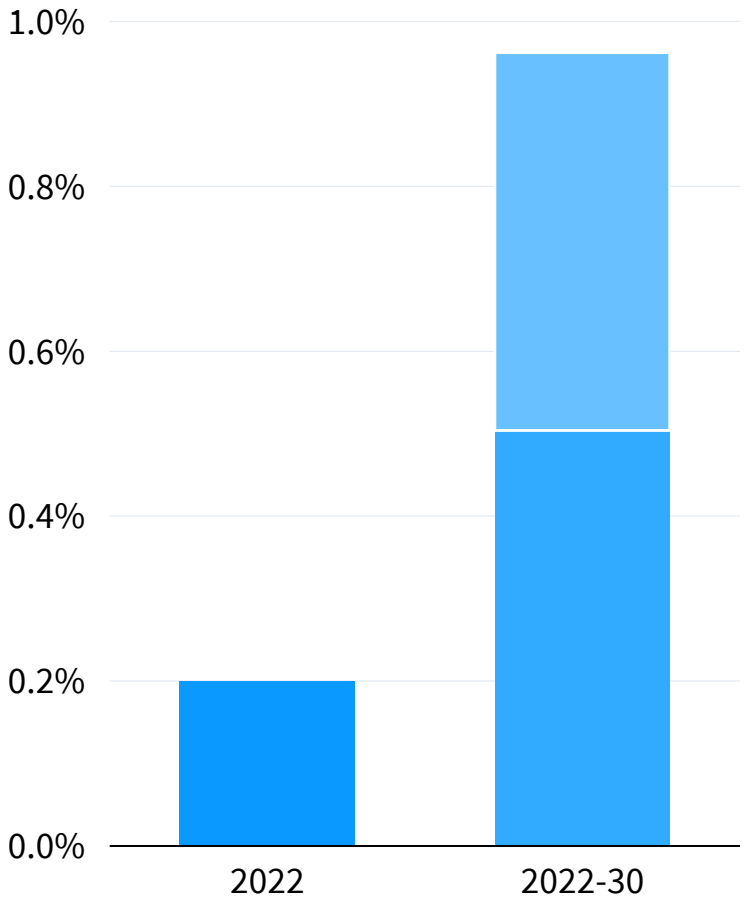
Tripling renewables by 2030

S-curves suggest we will triple renewables, and more than double electrification and efficiency rates

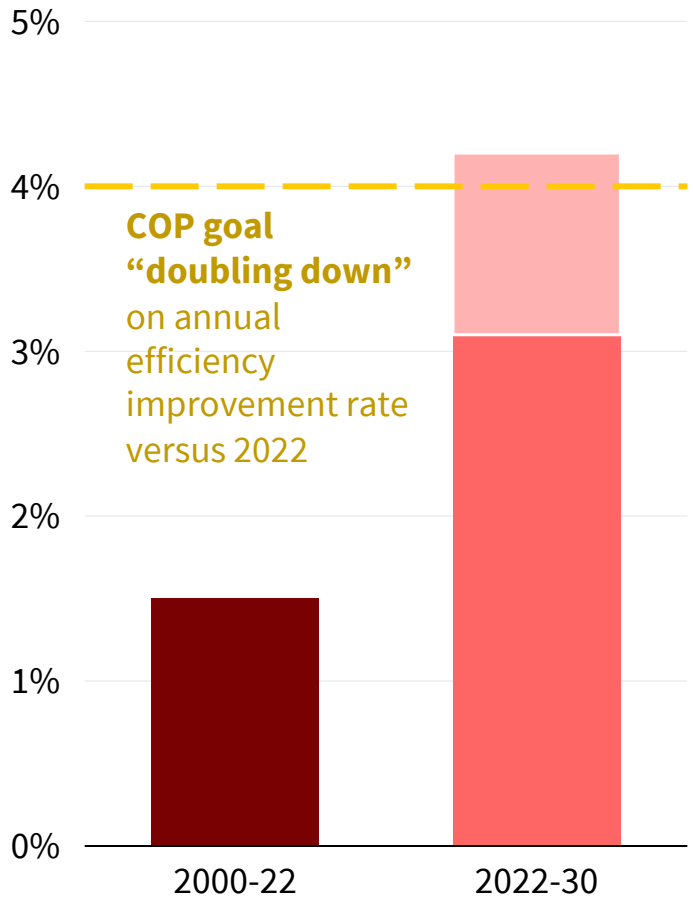
Renewable capacity



Annual rate of electrification



Annual primary efficiency gains

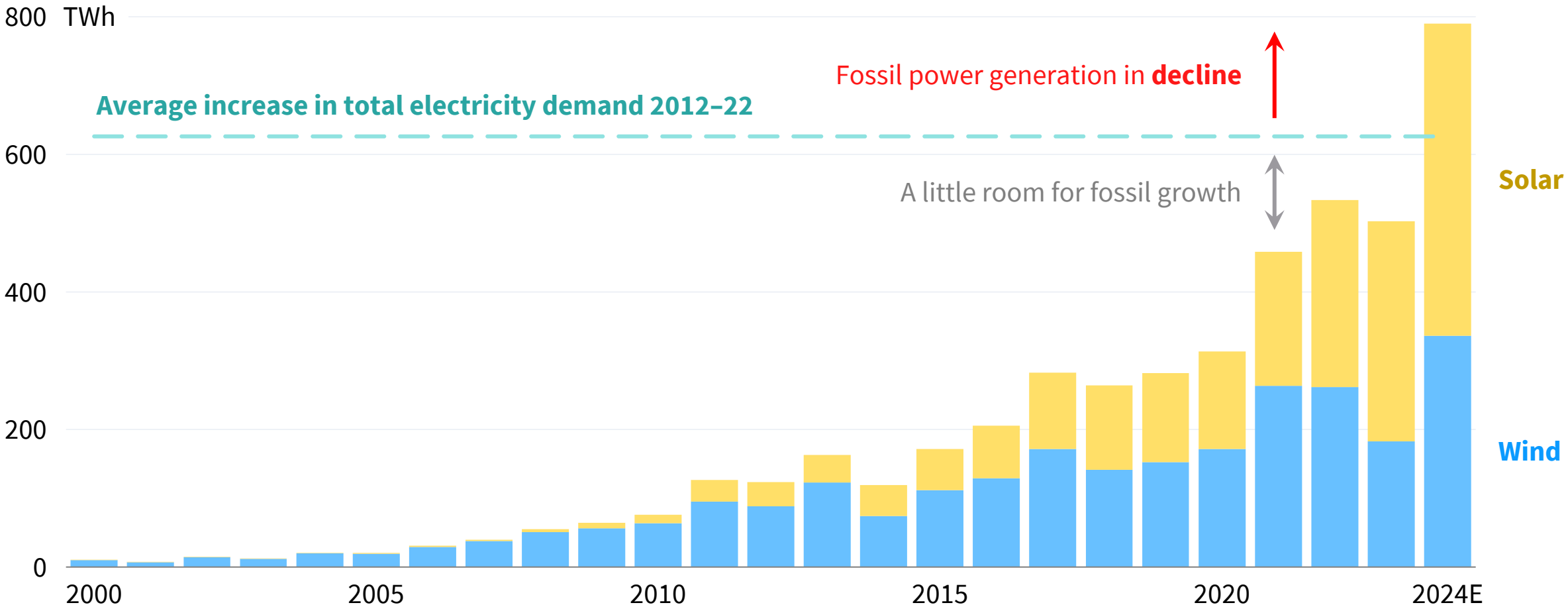


Source: IEA APS scenario as likely (Announced Pledges Scenario); NZE as feasible (net zero emissions).

Peak fossil fuel demand in electricity

Solar and wind provided 500 out of 600 TWh of demand growth in 2023, and will break through average growth this year

Change in electricity generation

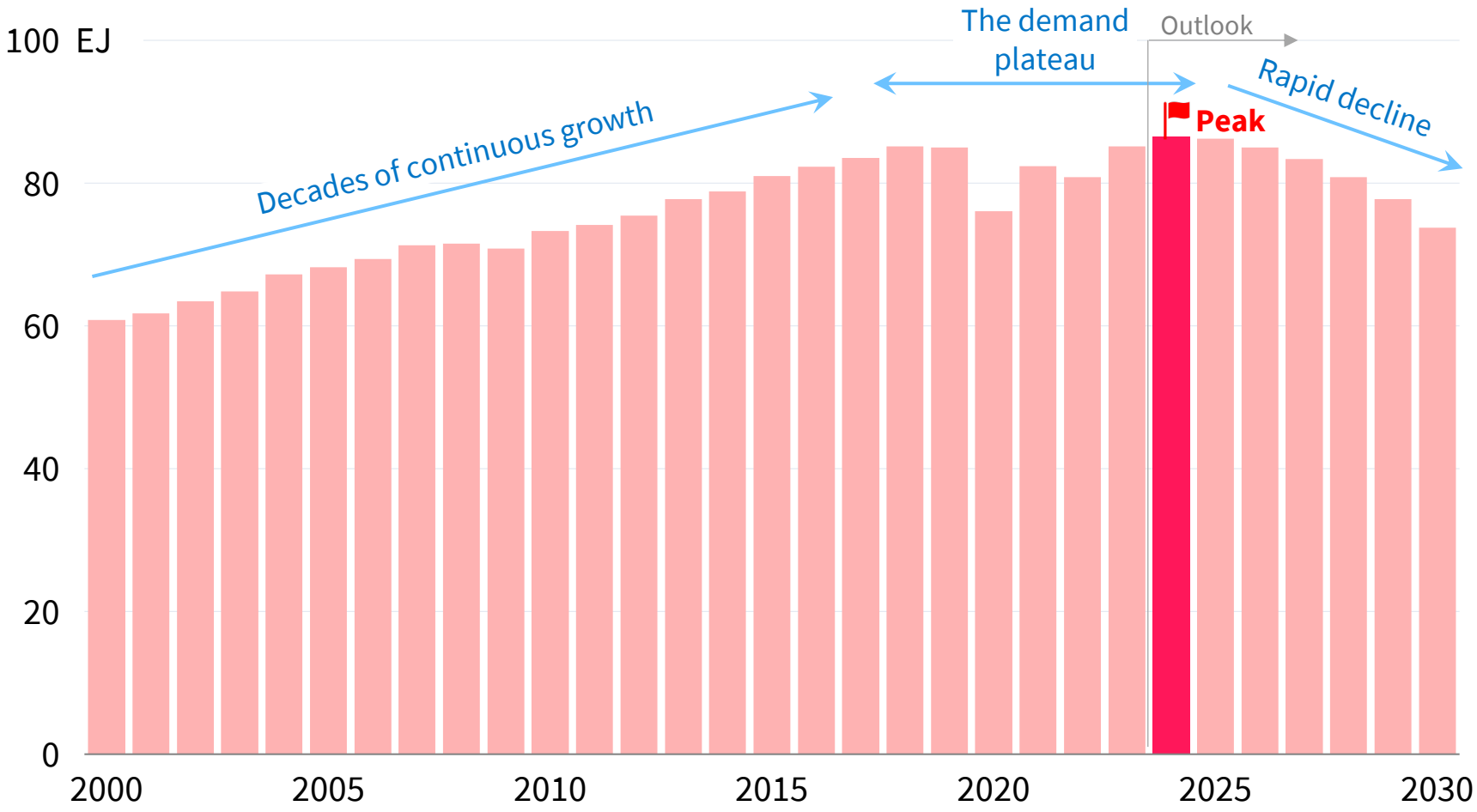


Source: IEA Renewables 2023.

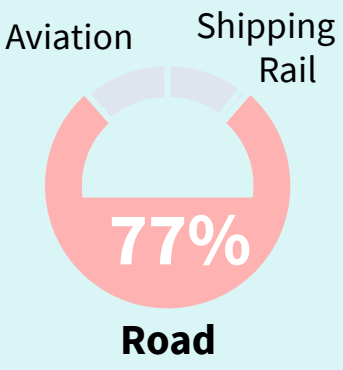
A plateau in road oil demand

Decades of growth stagnate before turning into rapid decline

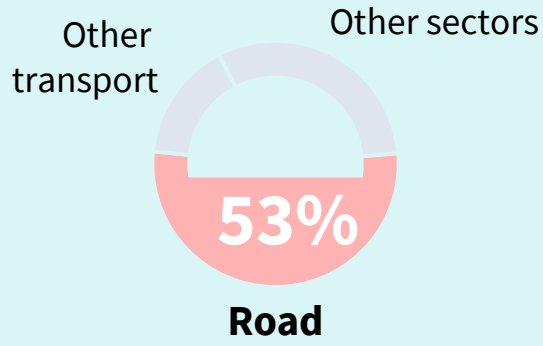
Road oil demand



Road share oil demand for transport, 2023



Road share oil demand, 2023



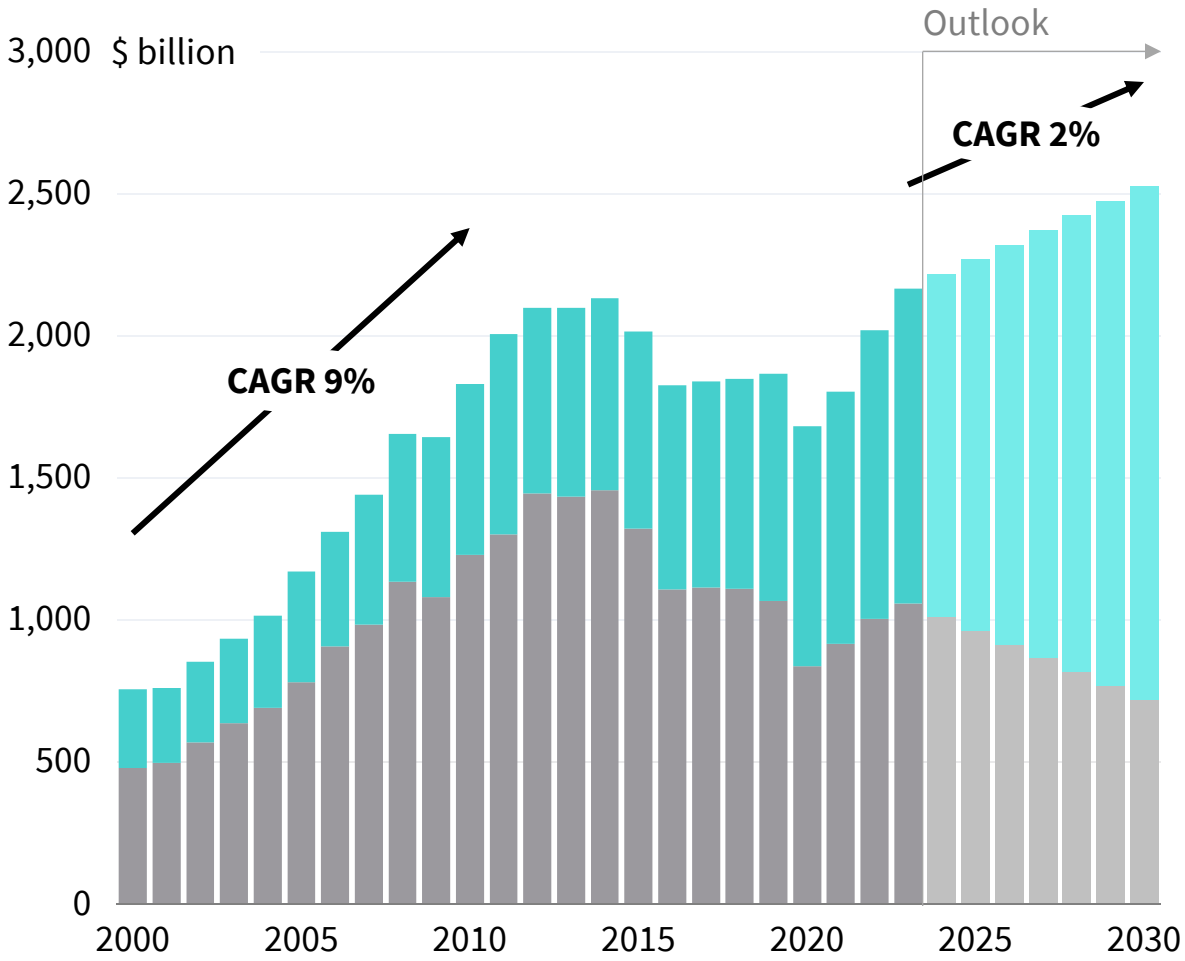
RMI

Source: BNEF NEO2024 NZS.

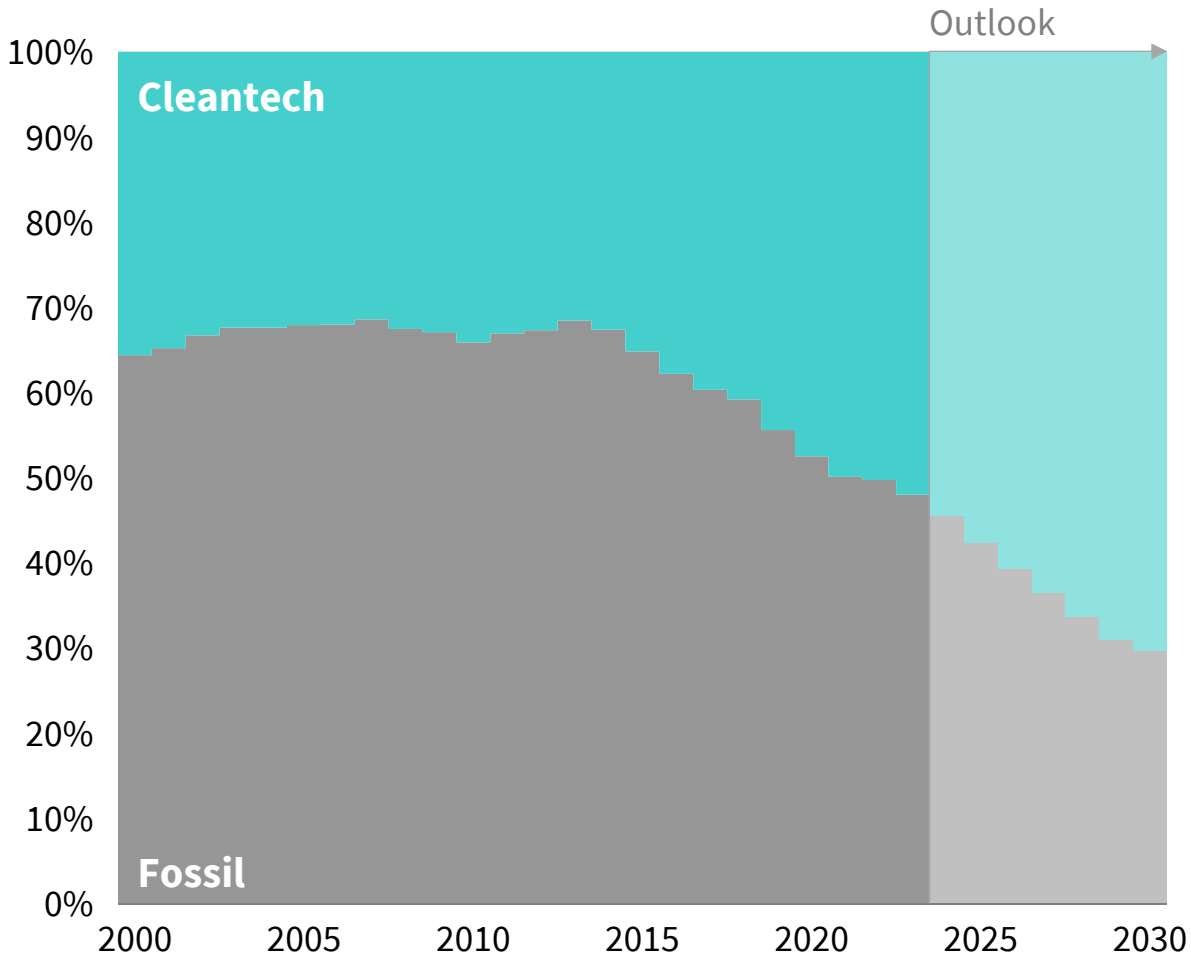
We are halfway through a Great Capital Reallocation

The required growth in investment is achievable, and reallocation from fossil to cleantech is well underway

Total investment in primary energy supply



Share of total investment



RMI

Source: IEA, RMI. For more see The Great Reallocation: Capital expenditure on energy production.