X-Change: The Race to the Top

Cleantech competition between China, Europe, and the United States

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About RMI

RMI is an independent non-profit, 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 non-governmental organizations (NGOs) to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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Executive Summary

In the global "race to the top" to transition from fossil energy to clean energy, China is in the lead in many of the key areas of competition. However, the race is still at an early stage, Europe and the United States are back in the game, and everything is to play for.

We focus on the leading regions and races. We look at China, Europe, and the United States, which make up 80%–90% of deployment of key clean technologies. We focus on the competition in the clean technology supply chain, solar and wind deployment, electric vehicle (EV) sales, and electrification.

China dominates the supply chain, but change is happening. China has outspent the United States and Europe 10-fold in the past five years to achieve market share in manufacturing of over 90% in solar and 70% in batteries.[1] But United States and European capital expenditure is set to increase 16-fold by 2025, and opportunities for leadership abound; only 20% of final energy demand has been electrified; and technologies to enhance flexibility are still in the early stages.

Europe leads in solar and wind share of generation. Europe has the largest share of electricity from solar and wind,[2] and all three regions are moving rapidly up the S-curve towards solar and wind dominance.

China is leading in the EV race, and Europe is not far behind. Over one-third of Chinese car sales are already electric,[3] and this is likely to rise to 90% by the end of the decade.[4] In Europe, approximately one-quarter of vehicle sales are electric; and although the United States has been lagging, it is also moving rapidly up the S-curve.

China has leapfrogged in the electrification race. Over the past decade, China has leapfrogged a static United States and Europe to increase the electricity share of final energy by 1 percentage point every year to a level of 27% in 2022,[5] more than 5 percentage points higher than them. The main driver has been the electrification of Chinese industry, which has already driven a 2014 global peak[6] in industrial demand for fossil fuel energy.

This is a technology revolution led by China. Although the United States has driven technology revolutions for a century, the renewable revolution is currently driven by China, and needs to be understood through that lens. China is now an electrostate,[i] with half of primary energy going to electricity.[7]

Security needs will motivate the United States and Europe. In 2022, the United States and Europe woke up to the challenge of Chinese leadership in the energy technologies of the future,[ii] and now the race is more even. Barriers to change are barriers to geopolitical influence, and leaders will need to find solutions to deploy cleantech if they wish to avoid relative decline.

The competition will open up more opportunity for the Global South. Competition between the leading regions is stimulating more investment and innovation, and will drive down costs faster. That speeds up the technology transfer to the rest of the world and hastens the point where fossil fuel demand starts to decline.

Cooperation has a key role when we are facing a common crisis of climate change. Just as on the sports field, competition requires cooperation in standard setting, technology transfer, and trade.[8]

[i] There is no formal definition of electrostate, but one approach would be to argue that a country has become an electrostate when the majority of its primary energy is used to make electricity.

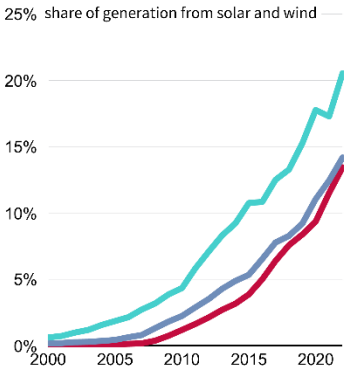
[ii] The wakeup call was Putin's illegal invasion of Ukraine, precipitating the worst energy crisis since 1973 and a new hunt for alternative sources to fossil fuels.

Exhibit 1: The Race to the Top in Six Charts

Three regions compete over three major clean tech markets

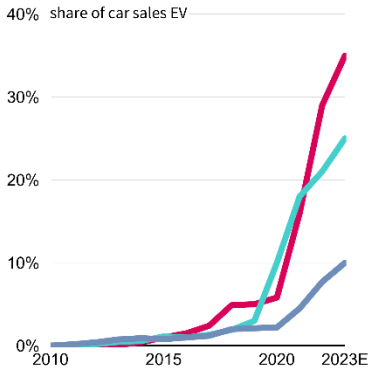
Renewable power

Europe is leading the United States and China



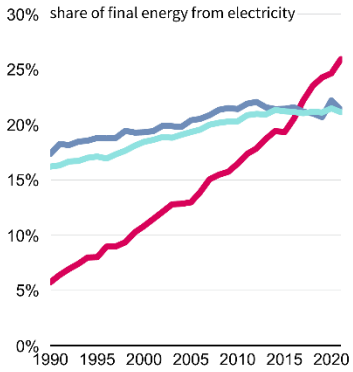
Electric Vehicles

China is ahead of Europe and the United States



Electrification

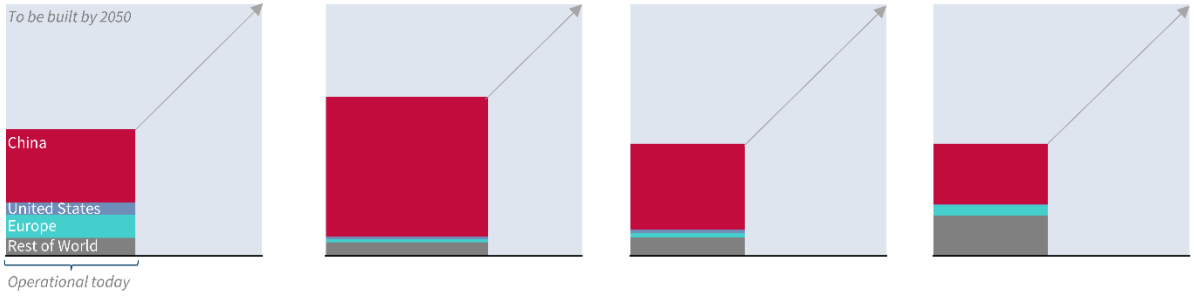
China leapfrogged Europe and the United States



China dominates production across clean tech markets today, but there is ample growth opportunity for Europe and United States to catch up

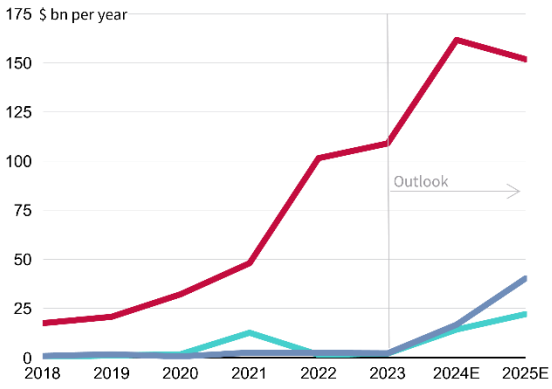
Wind | **Solar** | **Batteries/EVs** | **Other electrification**

Share of total production capacity by region today versus total final market size in zero-carbon economy



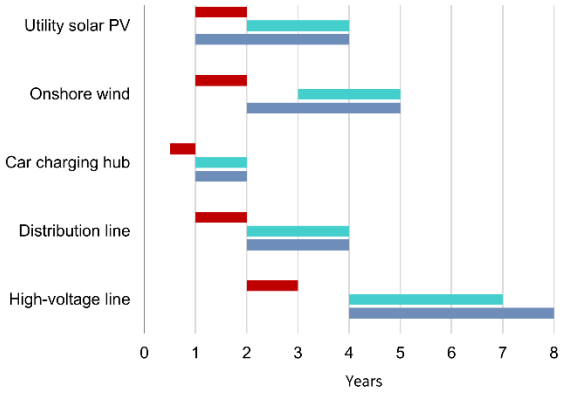
To get back in the game, the United States and Europe will need to pick up the pace of investment…

Clean energy supply chain investment



…and speed up deployment timelines

Typical deployment time

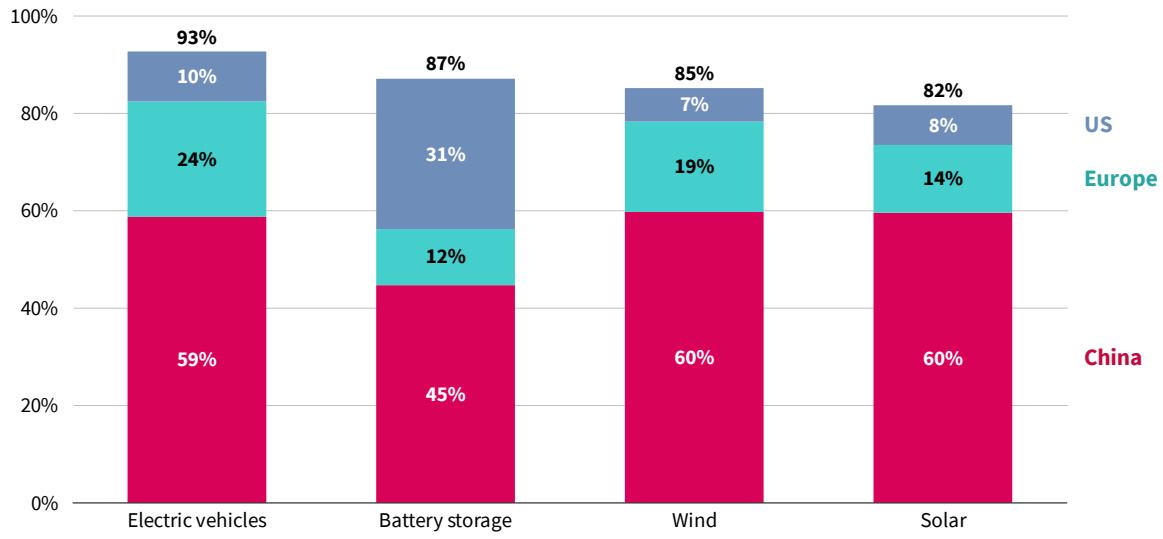


Source: Energy Institute, IEA EV outlook 2023, IEA World Energy Balance, BNEF Energy Transition Investment Trends, IEA World Energy Outlook (WEO) 2022

Introduction

In this piece we look at the three regions that dominate the deployment of renewable energy technologies — China, Europe and the United States.[iii] A subsequent piece will focus on the story in the Global South.[iv] The three regions also compete in many other areas, and in recent years the growth in US oil and gas production and Chinese coal production has been notable; but our focus is on the energy of the future not that of the past.

Exhibit 2: Share of global clean technology sales in 2023



Source: BNEF

There are dozens of areas of competition in cleantech, but for the purposes of this analysis it is possible to simplify the framing of them in two main horizontals (manufacturing and deployment) and two verticals (renewables and electrification).[v] Over time there will be a new vertical in the manufacturing of green molecules, but this vertical is still much smaller.

Exhibit 3: The framing of change

	Renewables	Electrification
Manufacturing	Making solar panels, wind turbines	Making EVs, batteries, electric machinery
Deployment	Solar and wind as share of electricity	EVs, electricity as share of energy

[iii] We use the word region to encapsulate China, Europe, and the United States, noting that China and the United States are countries. Europe is defined slightly differently in different databases, even by the same organization. Where possible we take a wide definition of Europe because it is best seen as a single energy market. Where data is only available for the EU, then we note that. Insofar as this comparative analysis is concerned, the gap between the EU 27, EU 28, and Europe is rarely material.

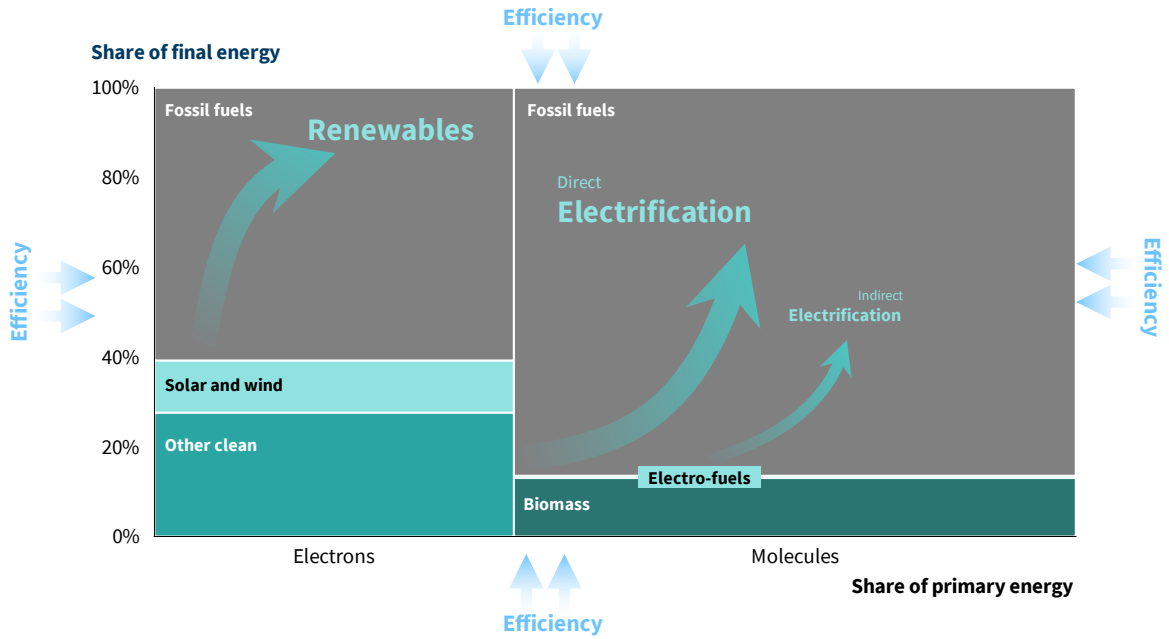
[iv] The Global South is of course not a monolith; each region — India, Africa, Southeast Asia, Latin America, and Island States — faces different issues.

[v] The IEA NZ Roadmap for example notes that 80% of emissions reductions to 2030 come from renewables, electrification, and efficiency.

As Amory Lovins pointed out,[9] efficiency is the overarching factor enabling and speeding up the transition, and we will look at the efficiency story in a separate piece.

The renewable revolution can be summarized in the Mekko chart below. Solar and wind are driving the growth of renewables, and at the same time electrification is reducing demand for fossil fuel molecules. EVs are only one aspect of electrification, but an area of especially rapid growth at present.

Exhibit 4: The energy transition and its key drivers 2022



Source: IEA WEO 2023, RMI. The primary energy split is the amount of primary energy going to electricity (electrons) or other (molecules). The final energy split is in Terawatt-hours (TWh) for electrons and exajoules (EJ) for molecules.

We can then synthesize this framing down to the four key races of the energy transition at present — supply chains, solar and wind deployment, EV sales, and electrification.

We split our analysis into three parts — the past, the future, and implications of the changes that are happening. It is useful to look at the actual data on the past to show both that exponential change is happening and the degree to which China has been able to take the lead. We set out in broad terms where the three markets are heading based on our S-curve analysis of electricity and cars and BloombergNEF's (BNEF's) framing of the future. And then we conclude by showing how the energy transition is a technology transition led by China, galvanized by competition between the three key regions, and likely to spread rapidly into the rest of the world in the manner of other technology transitions.

1. The Past

We look at the dominance of China in the clean technology supply chain, the more balanced race for leadership in the deployment of solar and wind in the electricity sector, and the competition in the EV sector. However, the key differentiating factor over the past decade has been the rapid electrification of Chinese final energy demand in the face of stagnation in the United States and Europe.

Supply chain

As Gregory Nemet shows,[10] many countries over many decades contributed to the creation of clean technology supply chains. In recent years China has risen to dominate the supply chain for renewable energy hardware, but it should be noted that there are many more races in the energy transition; 20% of final energy demand has been electrified, but 80% has not. In other words, the energy transition is a series of marathons, not a single sprint; and we are only a few miles into the race. As we set out in more detail in the section on the future, there are many opportunities for others to participate in the supply chain.

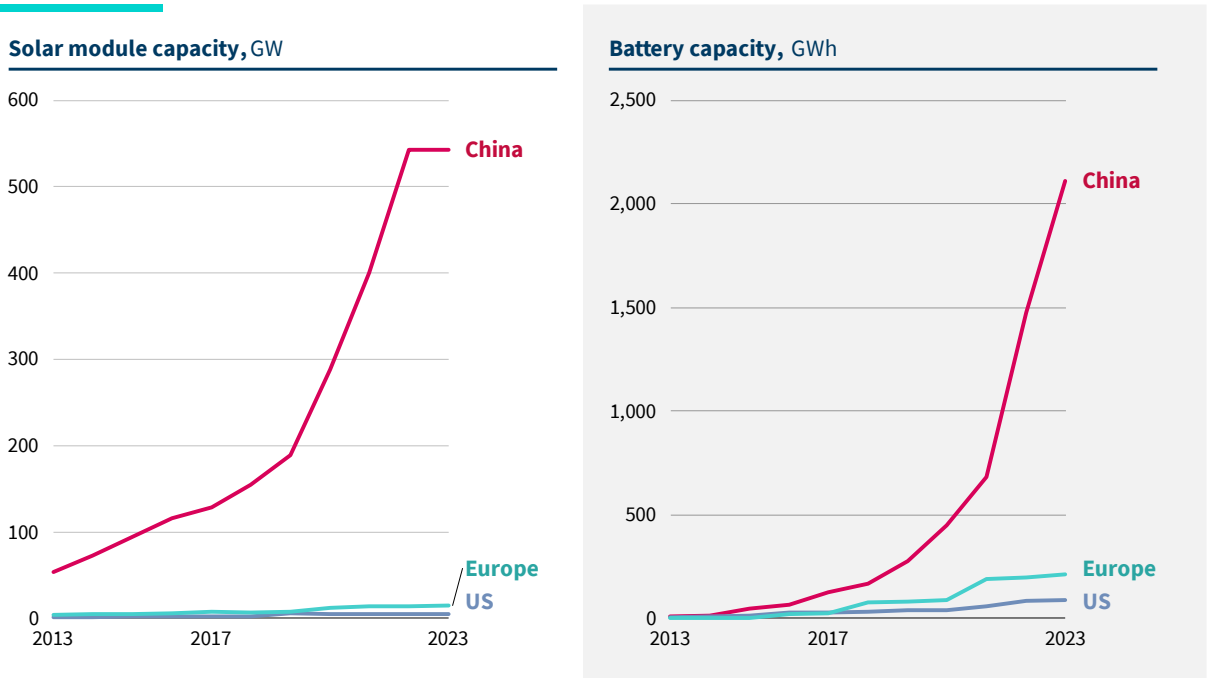
> **...the energy transition is a series of marathons, not a single sprint; and we are only a few miles into the race.**

Below we also look at capital expenditure and patents that lie behind Chinese dominance, and the consequences of that leadership in terms of trade.

Capacity

China dominates the hardware supply chains of key clean technologies. This is mainly because China took a strategic decision many years ago to invest heavily in research and capital expenditure in these sectors. For example according to BNEF data, from 2018 to 2023, China spent $329 billion on the clean technology supply chain while the United States and Europe spent $29 billion.[11]

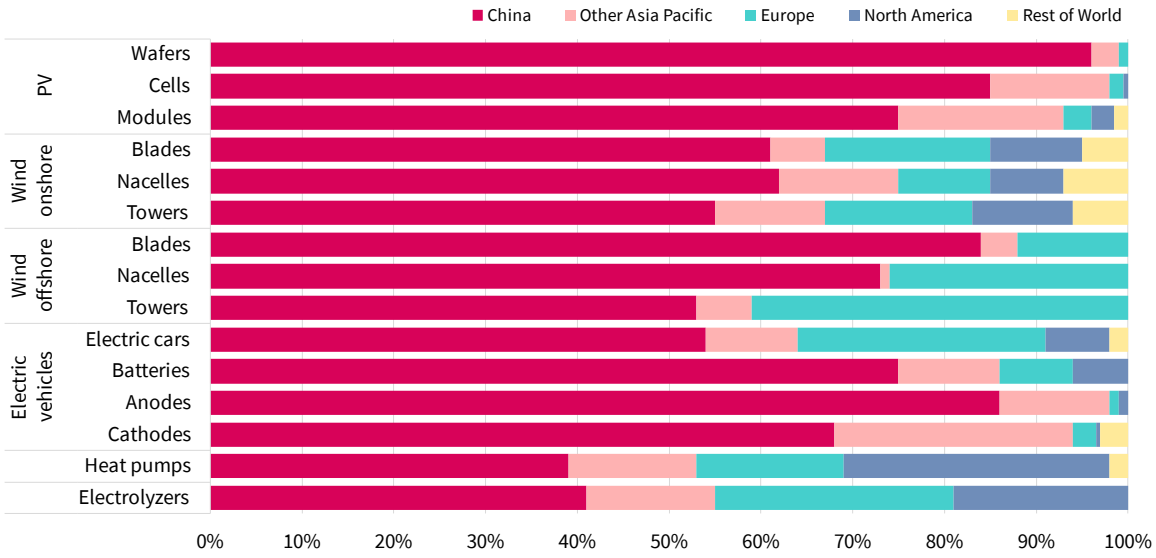
Exhibit 5: Solar and battery manufacturing capacity by region



Source: BNEF. Solar modules are crystalline silicon modules. Fully commissioned nameplate capacity.

China now dominates many aspects of the clean technology supply chain, especially in material processing and solar, as seen below in the chart from the International Energy Agency (IEA).

Exhibit 6: Share of manufacturing and refining capacity by region in 2021

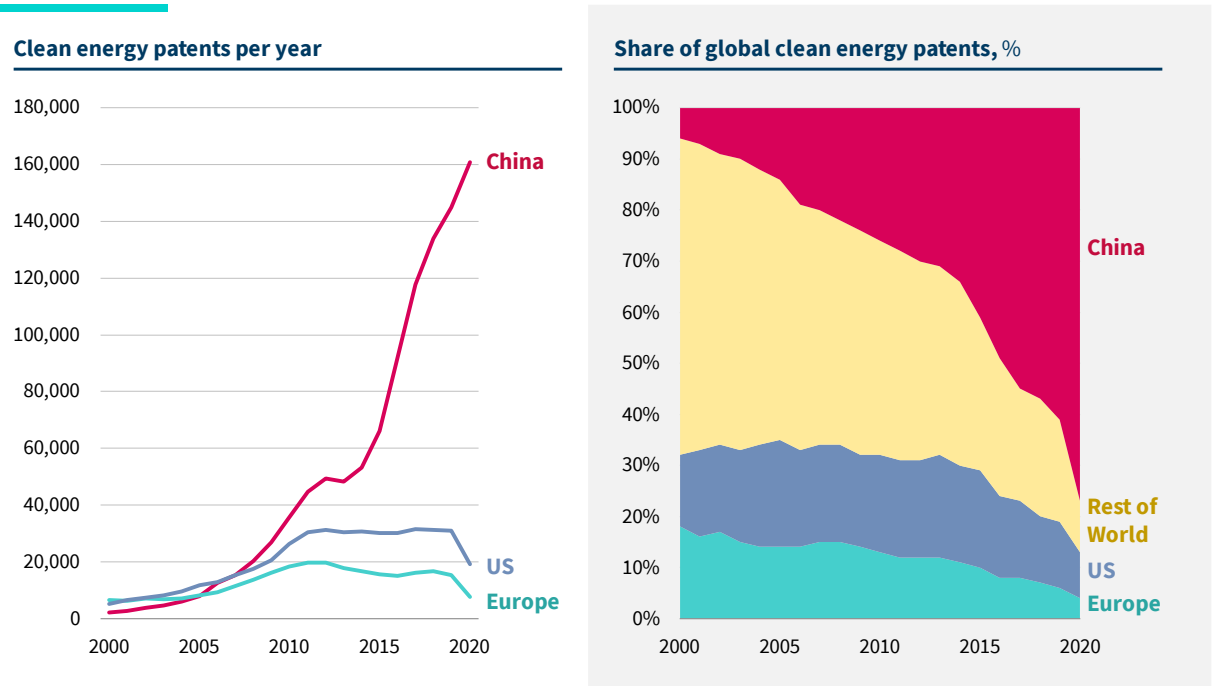


Source: IEA Energy Technology Perspectives 2023.

Patents

The IRENA INSPIRE database allows us to separate out patents by country in clean technology sectors like solar, batteries, or electrification.[12] China overtook Europe and the United States combined in 2014 in terms of number of renewable patents. By 2020, China was gaining six times as many renewable energy patents, nearly 80% of the global total. This is a feature across the whole range of renewable technology patents: in 2020, Chinese companies filed 84% of solar patents, 85% of wind, 78% of battery, 75% of EV, and 75% of other electrification technologies.

Exhibit 7: Clean energy patents per year (l) and share of global clean energy patents (r)

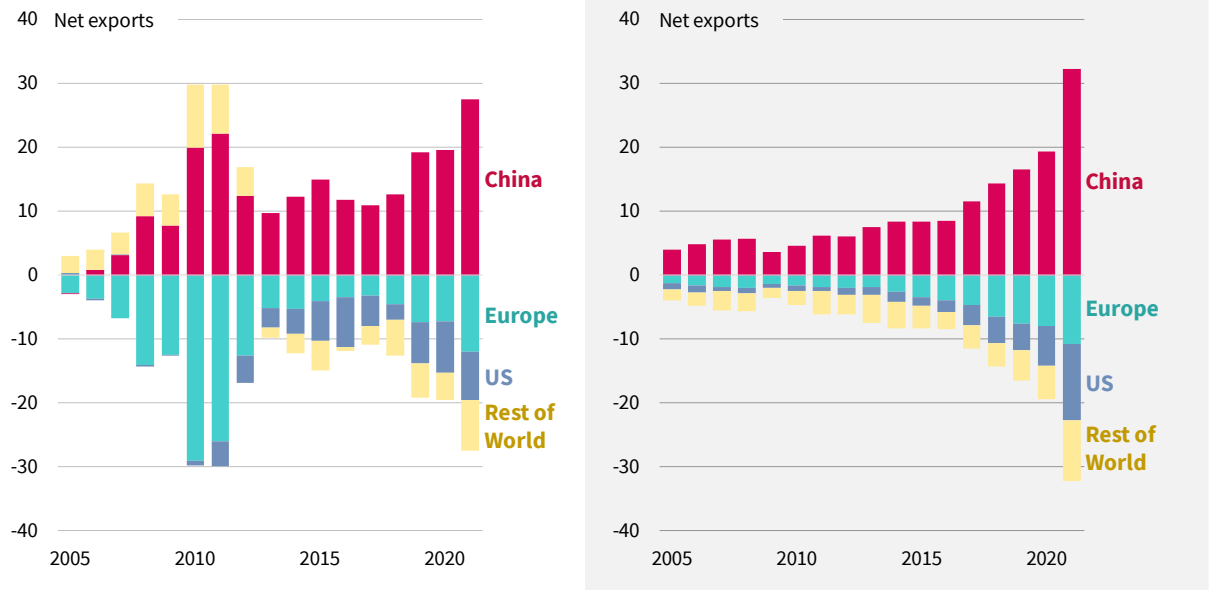


Source: IRENA INSPIRE database

Trade

China has become the dominant supplier of key clean technologies. We illustrate this below with data for battery and solar panel trade from the Comtrade Observatory of Economic Complexity (OEC) database.[13] Because the data is complex, we show specifically the net trade balance. China has become the key global producer, while Europe, the United States, and the rest of the world are all net importers.

Exhibit 8: Solar net trade balance (l) and battery net trade balance (r), $ billion

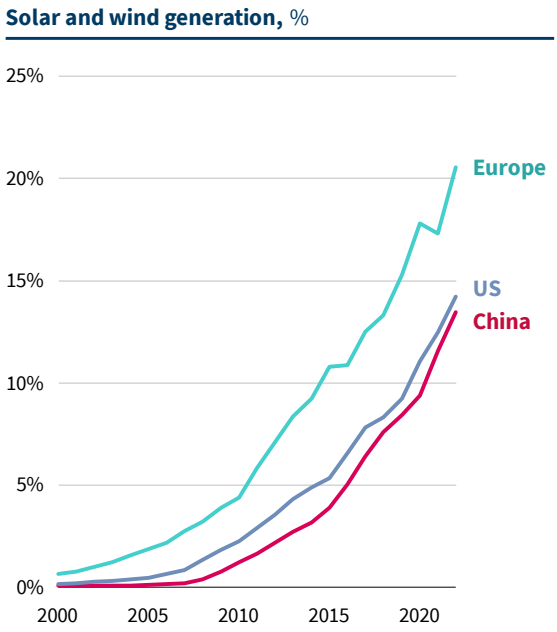


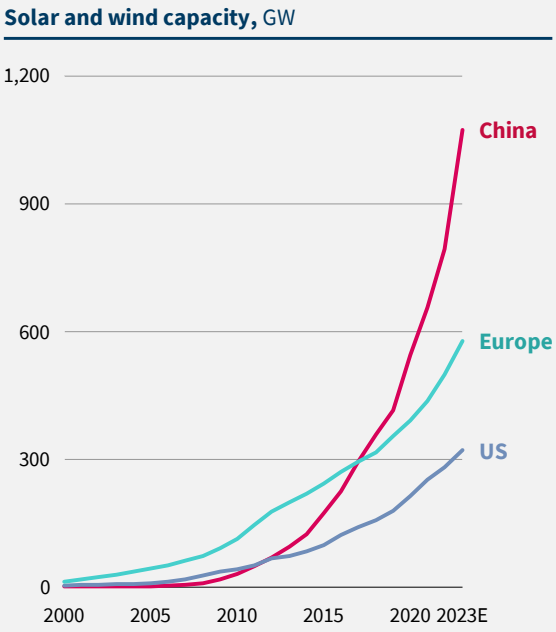
Source: OEC database

Renewable deployment

China has deployed the largest amount of solar and wind, with a notable surge in 2023, as new solar deployment more than doubled from 100 GW to 261 GW according to the IEA.[14] However, solar and wind are a much larger share of electricity generation in Europe, so it would be fair to say that Europe is leading this race.

Exhibit 9: Solar and wind share of electricity generation (l); Solar and wind deployment in GW (r)



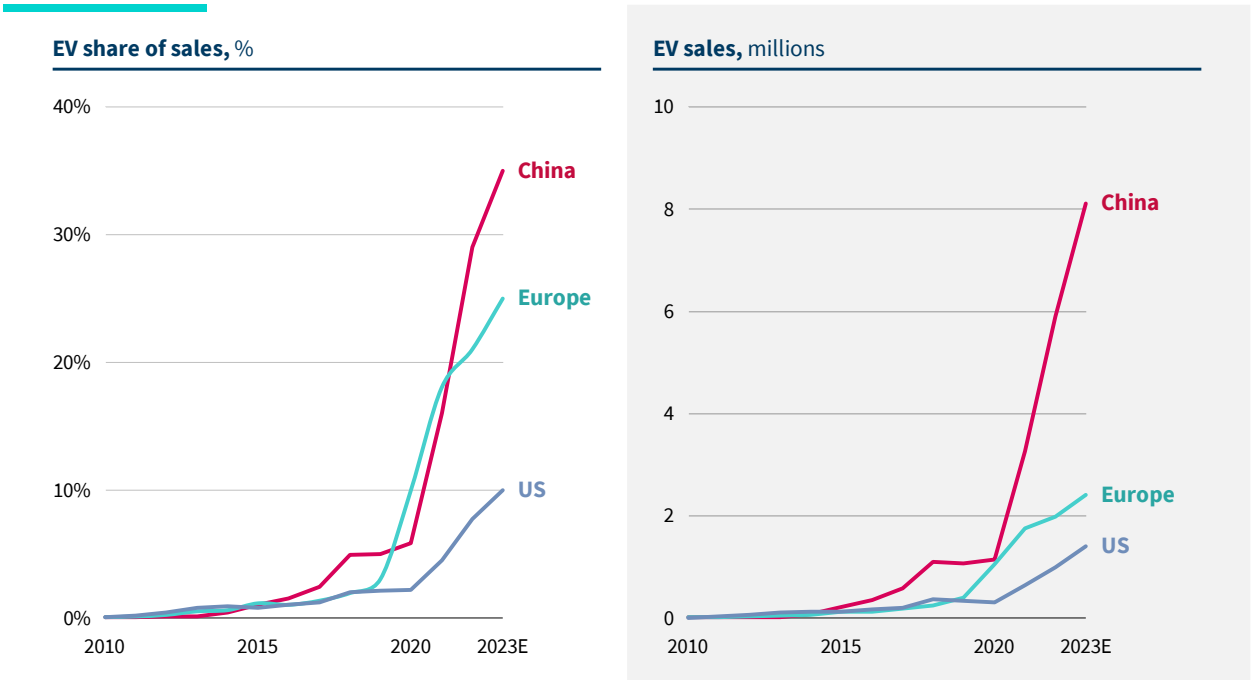


Source: Energy Institute (left); IEA Renewables 2023 (right)

EV sales

China has both the largest number of electric vehicle (EV) sales and the highest EV market share. Europe is rapidly following, and the United States is about four years behind in terms of market share. The latest IEA data indicates that the market share of EVs in 2023 was around 10% in the United States, 25% in Europe, and 35% in China.[15]

Exhibit 10: EV cars as share of sales (l); EV sales (r)



Source: IEA EV Outlook 2023, IEA Clean Energy Market Monitor 2024. Note: EU-27.

Electrification

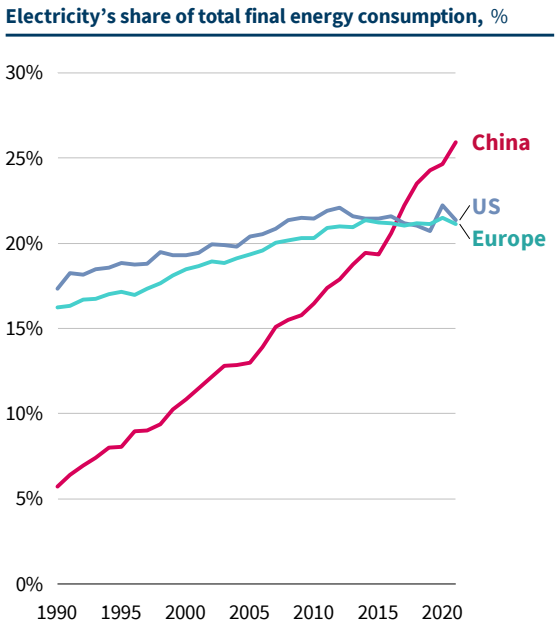
As noted above, electrification is the second key pillar of the energy transition. You decarbonize electricity and at the same time you electrify as much as you can. In the past decade, China has dramatically increased the share of electricity in final energy demand, and the United States and Europe have not. If we consider electricity as a share of final consumption, Europe and the United States have flatlined at just over 20% for over a decade while China has grown to 27%, increasing electricity as a share of final consumption at a rate of nearly 1 percentage point a year.

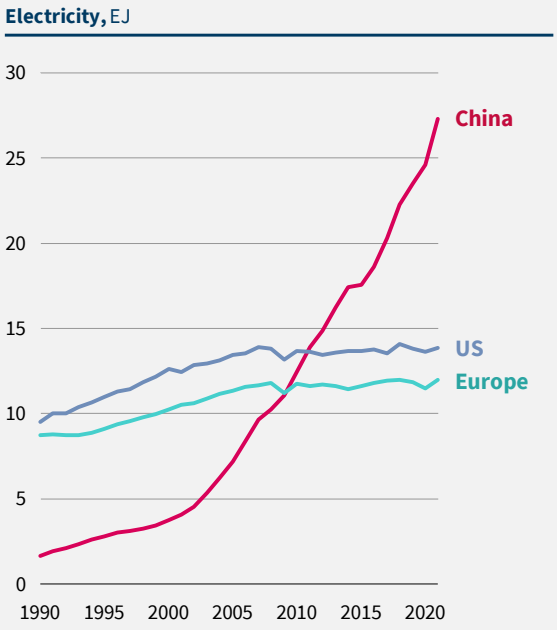
A decade ago, we might have argued that China was simply catching up with electrification in the United States and Europe. However, China reached those levels in 2016-17, and just kept growing its share of electricity.

Electrification has three main sub-stories within it — transport, industry, and buildings. We look first at the story in total and then by sector. We use data from the IEA's World Energy Balances (WEB) database. This has the great advantage of being comprehensive, although the data is only available until 2021 so we cannot yet see the detailed impact of Putin's war in Europe and the IRA in the United States.

Although China clearly leads in terms of electricity as a share of final energy demand, this is in large part the result of the different mix of demand; the United States for example has a much larger share of energy demand from the transport sector where electrification levels are very low, and this pulls down its total average. The United States leads in building electrification, and China and Europe are at similar levels in terms of industry electrification.

Exhibit 11: Electricity in total final energy consumption, % and EJ



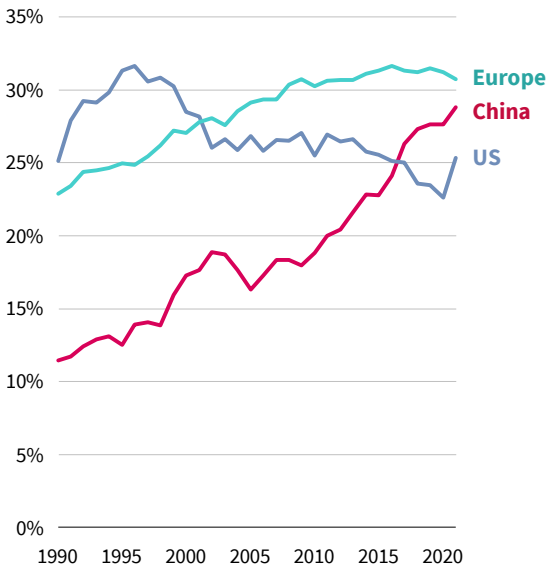


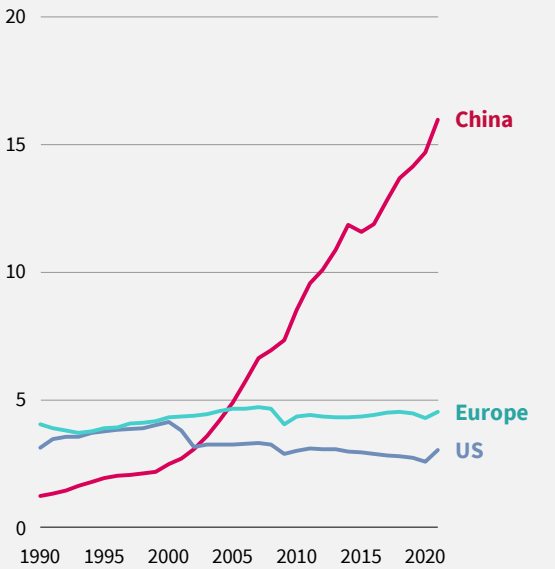
Source: IEA World Energy Balances (WEB)

Industry

China has electrified industry while the United States has been de-electrifying (the share of electricity within final energy demand has been falling) because of cheap gas, and Europe has been growing the share of electricity slowly because industrial electricity consumption is declining slower than fossil fuels. China has overtaken the United States and caught up with Europe.

Exhibit 12: Electricity in final industry demand, % and EJ



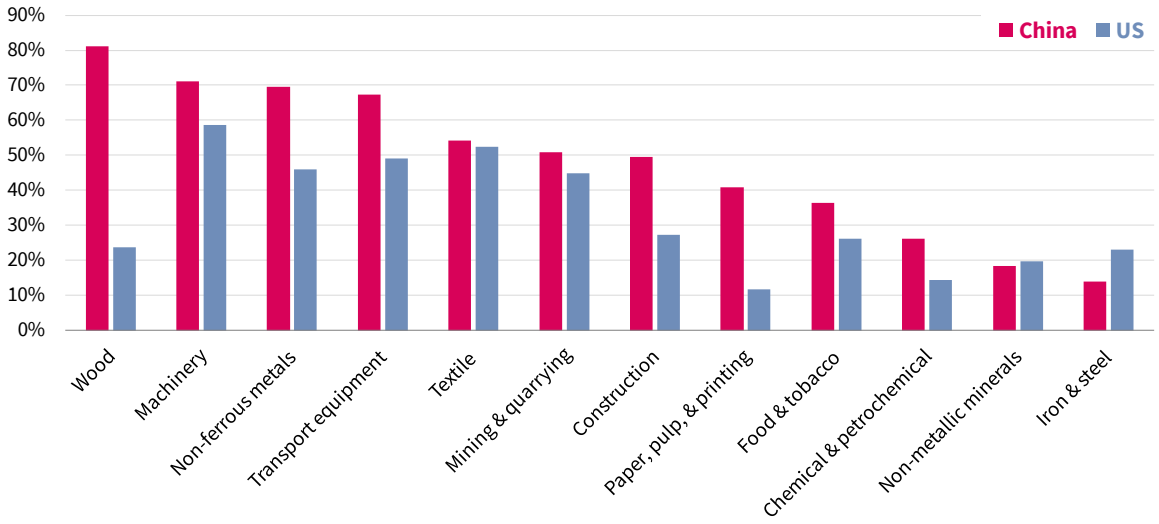


Source: IEA WEB

The assumption of many is that the electrification of Chinese industry is due to outsourcing of light industry to China. However, the industrial electrification story is much wider than that. In 2021, the share of electricity in final energy demand in industry was 6% higher in China than in the United States, both for heavy industry (24.3% versus 18.7%) and light industry (35% versus 29%).

This graph also serves to highlight that there are many areas of the energy transition where the winners are not yet clear. In sectors with a low share of electrification such as steel or chemicals, it is likely that the role of green molecules will be larger.

Exhibit 13: Share of industrial sector energy consumption from electricity 2021, %



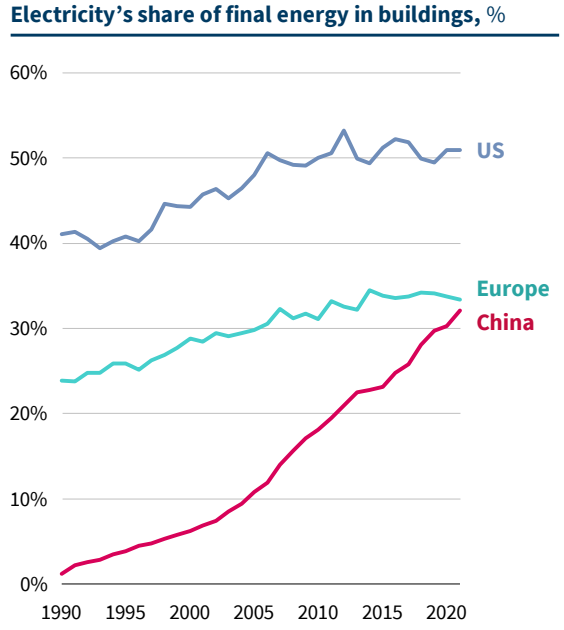
Source: IEA WEB

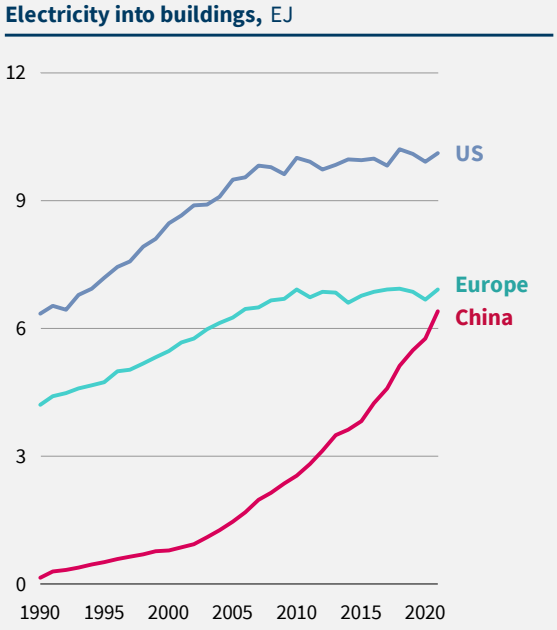
Buildings

Over the past decade, China has been electrifying its residential and commercial buildings while Europe and the United States have not significantly changed the share of electricity in building demand. China has caught up with Europe; the United States is still far ahead, but the United States building share of electricity within final energy has been flat over the past decade.

A large part of electrification in China has been the leapfrog from biomass to electricity as the main source of energy in buildings; this provides inspiration for other regions that will benefit from going through a similar shift. Forty years ago, biomass provided three-quarters of China's final energy demand in buildings;[16] now it is less than a fifth. Meanwhile, during the same period, electricity has grown at a 13% compound annual growth rate to provide nearly one-third of final demand in 2021.

Exhibit 14: Electricity in final buildings demand, % and EJ



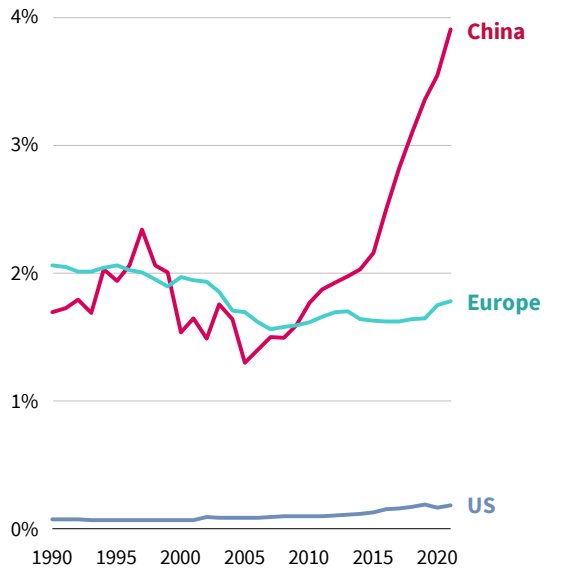


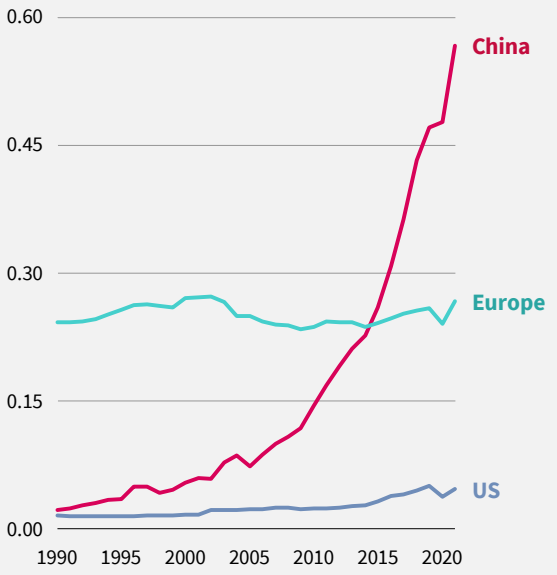
Source: IEA WEB

Transport

EV sales are rapidly increasing, indicating an upcoming shift toward electricity as a share of transport energy. Currently, the share of electricity within transport is still low, despite the large amount of interest in the rapid scaling of EV sales globally. The historical drivers of electrification have been industry and buildings.

Exhibit 15: Electricity in final transport demand, % and EJ





Source: IEA WEB

2. The Future

We seek to illustrate the most likely direction of travel in the period to 2030 for the three regions. We use our own S-curve modeling for the electricity and EV sectors,[17] and BNEF framing,[18] and cross-check these against a variety of other sources. There are many other reports that look in detail at the likely future of each country's energy system,[19] but our goal is to set out the comparative positioning of the three regions.

The overall conclusion is that China is set to maintain its leadership position but that the other regions are also moving up the S-curve. One key area of uncertainty is whether the United States and Europe will be able to increase their electrification rate. Another is which region will be able to harness the power of Artificial Intelligence most effectively to increase efficiency, enable variable renewables to increase their share of generation, or speed up technology development in some of the harder-to-solve sectors.

Supply chain

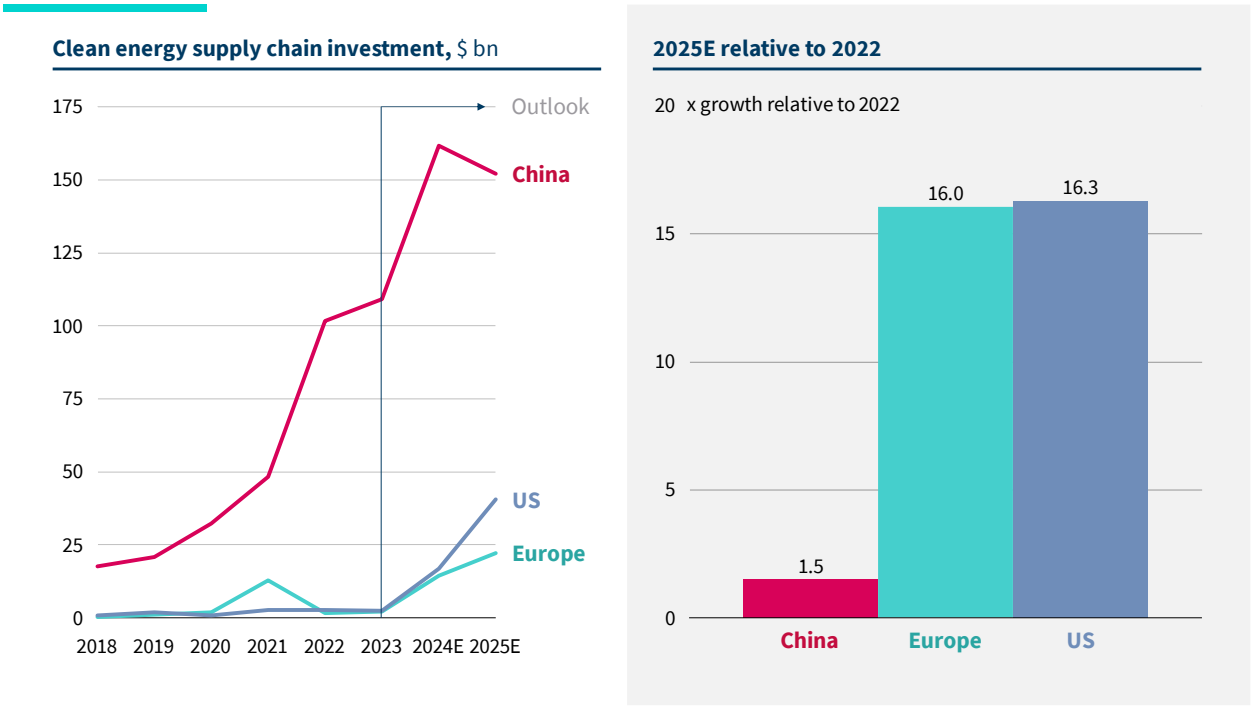
As we set out in the chart on the first page, we are a long way from peak capacity even in hardware. We estimate that the solar sector is at around 40% of peak capacity, the wind sector at 25%, and the battery sector at 20% of peak capacity.

China will continue to dominate investments in renewable technology supply chains, with BNEF noting plans for $469 billion of surplus investments in factories planned for 2024-27.[20] However the United States and Europe are back in the game. Since Putin's invasion of Ukraine, the United States has passed the Inflation Reduction Act (IRA) and Europe has passed a wide swathe of legislation — most notably the RePowerEU plan.[21]

The IRA has driven a surge in investment in US cleantech, with the American Clean Power Association noting[22] that 280 clean energy projects have been announced in the first year of the IRA, with $282bn of investment. BNEF calculate[23] that is likely to be enough to enable the United States to be self-sufficient in key elements of cleantech. A part of this has been investment into the clean energy supply chain, and that money is spent over time; BNEF expects total US supply chain capital expenditure to be $40bn in 2025, [24] although Rhodium Group data imply that it will be more than this.[25] In total BNEF expects a 16-fold increase in supply chain capital expenditures in the United States and Europe in the period to 2025, from $4 billion in 2022 to over $60 billion expected in 2025.

From BNEF data, in 2022, China spent 26 times as much on the clean energy supply chain as Europe and the United States combined;[26] in 2025 that multiple is forecast to fall to a level of just 2.4. The surge in capital expenditures in the United States and Europe is not enough to replace Chinese leadership, but it should be enough to provide them with much of their own clean technology demand.

Exhibit 16: Supply chain investment



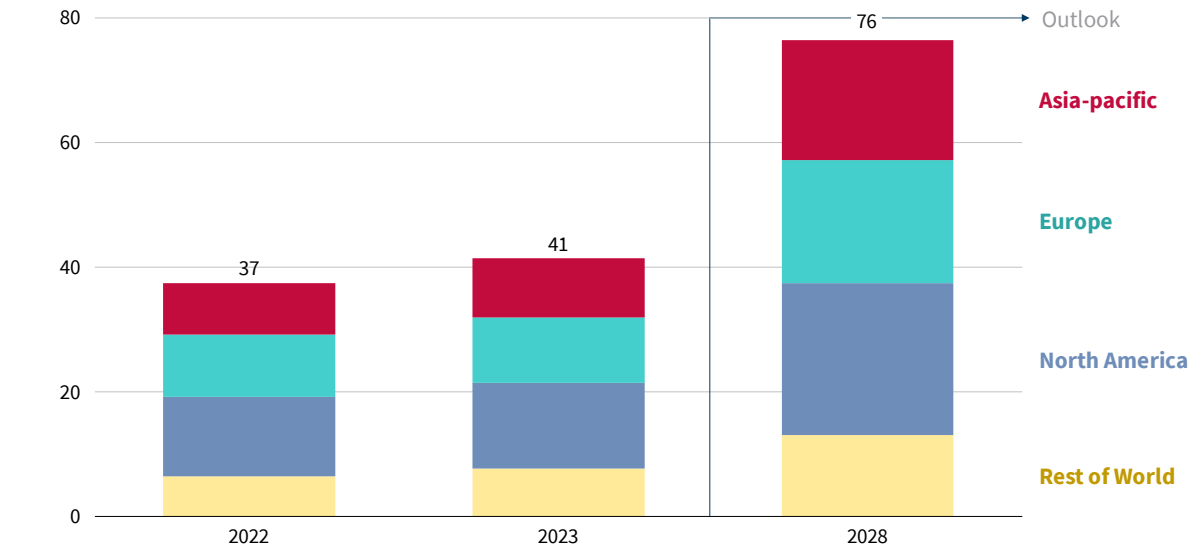
Source: BNEF. Note this includes upstream factories for solar, batteries, electrolyzers, and wind turbines.

Moreover, this data only looks at capital expenditures on specific clean technology hardware. As in other sectors like smartphones, it is likely that the highest returns on capital will be enjoyed in software and services.

There are considerable opportunities to provide the software and services that will enable flexibility, such as the work being done in the United States on virtual power plants.[27] Meanwhile every area of final demand requires electrification. The United States famously has a large and successful venture capital industry well used to identifying and supporting technologies of the future.

The figure below illustrates that Europe and the United States are well positioned for the energy management software market. The majority of the energy management software market today lies in Europe and North America. Market outlooks show that these regions also host the main pockets of growth in the coming years.

Exhibit 17: Energy management software market outlook, $ billion



Source: Markets & Markets Energy Management System Report

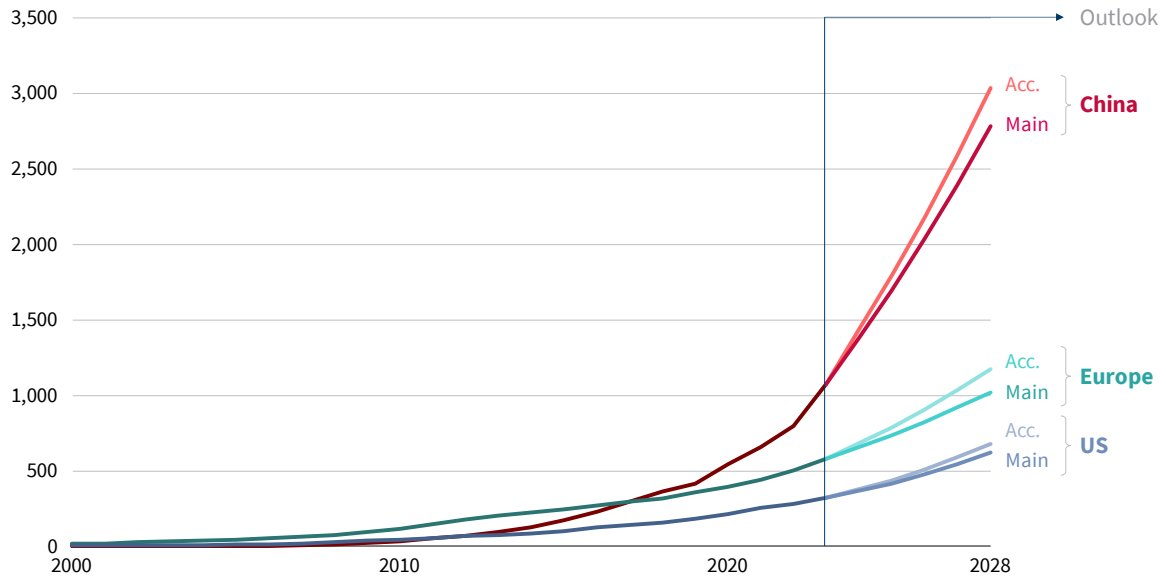
Renewable deployment

We show below the IEA's short-term forecasts from 2024, BNEF's 2022 forecasts (after the passage of the IRA), and our own S-curve model. While the details differ, they all paint a clear picture of continued rapid growth to 2030, with Europe retaining the leading position in terms of the share of electricity from solar and wind.

The IEA provides useful data on what is expected in each market in the next five years.[28] These illustrate the remarkable story of continuous rapid growth in China to reach nearly 3,000 GW of solar and wind capacity by 2028.[vi] Given the IEA's well-known conservatism in forecasting solar and wind deployment,[29] this should be seen as a floor not a ceiling.

[vi] To be clear, we are not suggesting that any of this change will be easy. There are many barriers to change, from grids to market structures to the differing priorities of regional leadership. Nevertheless, so far these challenges have been solved and the likelihood is that they will continue to be solved.

Exhibit 18: Projected solar and wind capacity by the IEA, GW



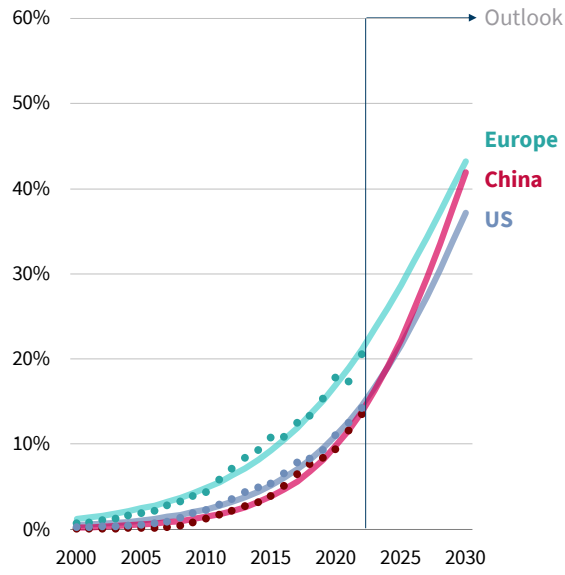
Source: IEA Renewables 2023. The two lines are the IEA's two scenarios of Main and Accelerated

In *X-Change: Electricity* we modeled the likely share of solar and wind using a fast and faster model.[30] We summarize below the expected share of solar and wind using the fast model, based on a logistics model most appropriate to a stock-based S-curve. It implies that China is likely to overtake the United States and nearly catch up with Europe by the end of the decade, and that by 2030 all three regions will enjoy solar and wind at around 40% of electricity generation.

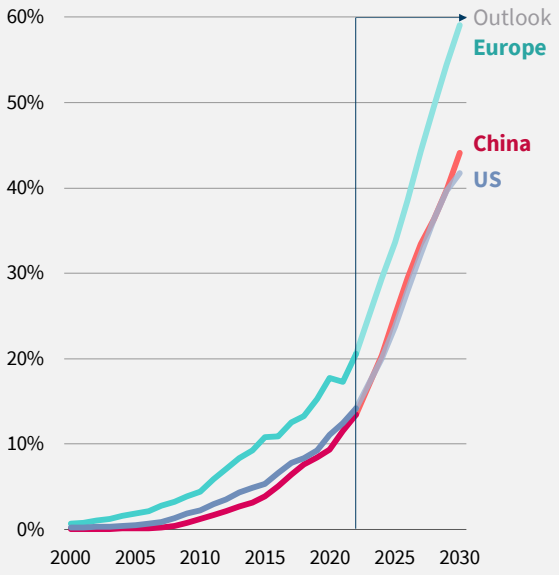
The BNEF forecasts from 2022 are significantly more aggressive than our S-curve for Europe, a little more aggressive for China, and in line with the S-curve for the United States.

Exhibit 19: Solar and wind share of electricity generation, %

S-curve solar and wind share of generation, %



BNEF solar and wind share of generation in ETS, %



Source: Energy Institute (past); RMI *X-Change: Electricity* (left), BNEF New Energy Outlook (right). ETS is BNEF's Economic Transition Scenario.

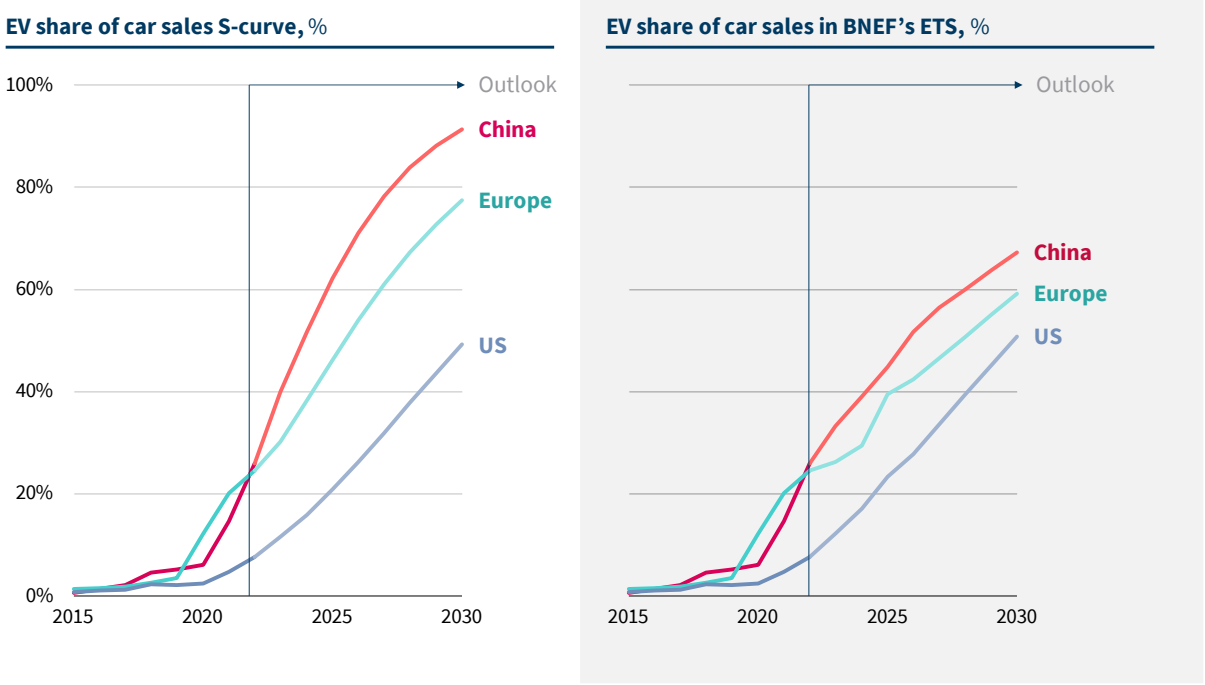
EV sales

EV sales in all three regions are moving up the S-curve. We set out below the implied market share of EVs based on our S-curve as well as the BNEF forecast. Again, the broader picture is clear — all three regions are likely to continue to move rapidly up S-curves.

Our S-curve analysis as set out in *X-Change: Cars* implies that EVs as a share of sales will be nearly 90% in China and below 50% in the United States by the end of the decade.[31] We again take the "Fast change" scenario from that report, using a Gompertz S-curve most suitable for a flow-based analysis.

This S-curve is higher than the BNEF 2030 expected range for EV sales in China and Europe but in line with its expected range for the United States.

Exhibit 20: EV share of sales, %



Source BNEF, RMI X-Change: Cars. ETS is BNEF's Economic Transition Scenario.

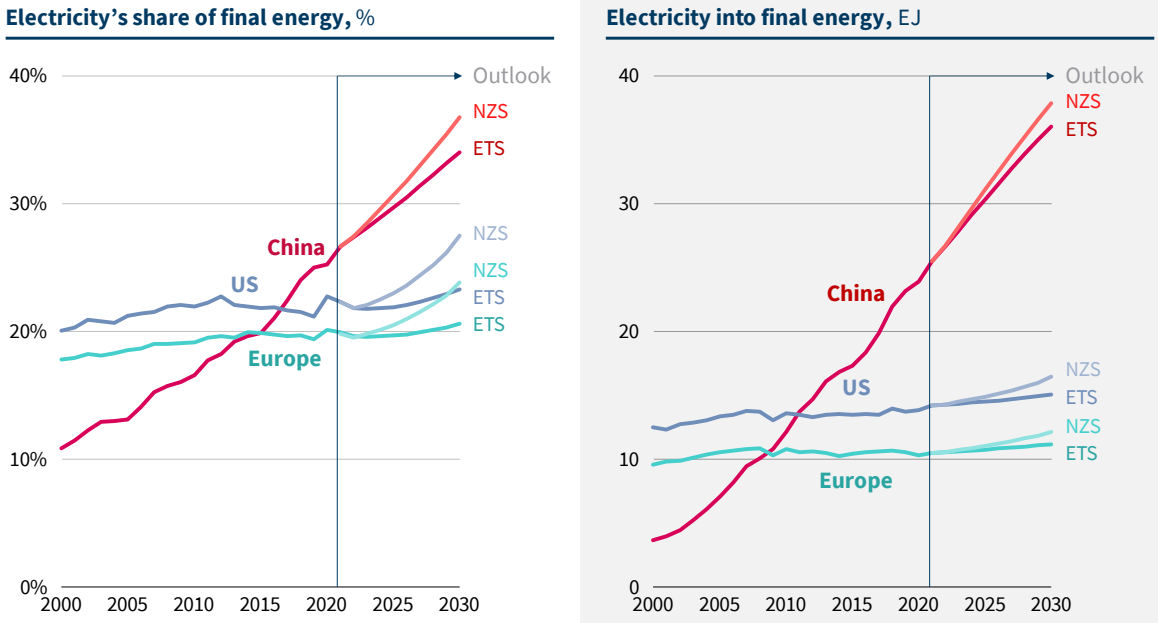
Where cars are leading, we are seeing light-duty and then heavy-duty trucks move up the same type of S-curve, as set out in more detail in our report on the battery domino effect.[32]

Electrification

China is expected to maintain its recent leadership in the electrification of end-use sectors. Under the BNEF net zero (NZS) scenario, China continues to electrify final energy demand at a rate of around one percentage point each year. The Chinese electricity sector plan is to get to 30% electrification by 2025,[33] and over recent years China has been electrifying at one percentage point a year. This suggests that 35% by 2030 is feasible, which is the high end of the BNEF curve.

Future electrification rates for Europe and the United States are more uncertain and will depend on whether they are able to break out of a decade's inability to increase the share of electricity in final energy demand. Given very low gas prices in the United States and high gas prices in Europe, Europe is more likely to be able to electrify at speed.

Exhibit 21: Electricity in total final consumption, % and EJ



Source: BNEF NEO 2022. NZS is the Net zero scenario and ETS is the Economic transition scenario.

It is a similar story in each of the subsectors within electricity demand: China is likely to continue to grow the share of electricity by around 1 percentage point each year, and there is the hope that the United States and Europe will follow. Only in the EV sector, as noted above, do we see concrete evidence of the necessary S-curves of change outside China.

> **Only in the EV sector (…) do we see concrete evidence of the necessary S-curves of change outside China.**

3. Implications

We set out below the implications of this analysis, in three sections. First, we show how the technology transition is a technology shift led by China, in the same way as the past three technology transitions were led by the United States. Then we show that Chinese leadership will continue to spark a reaction in the other major economic blocs, lest they fall too far behind in the energy technologies of the future. The desire for leadership and energy security are powerful forces that will help to overcome the barriers to change in those markets.

This competition for leadership will in itself stimulate change, and will speed up the dissemination of renewable technologies into the rest of the world. That means there are reasons to be optimistic about change in the Global South and there is a clear decline path for fossil fuels.

Chinese leadership will continue to spark a reaction in the other major economic blocs, lest they fall too far behind

A technology revolution led by China

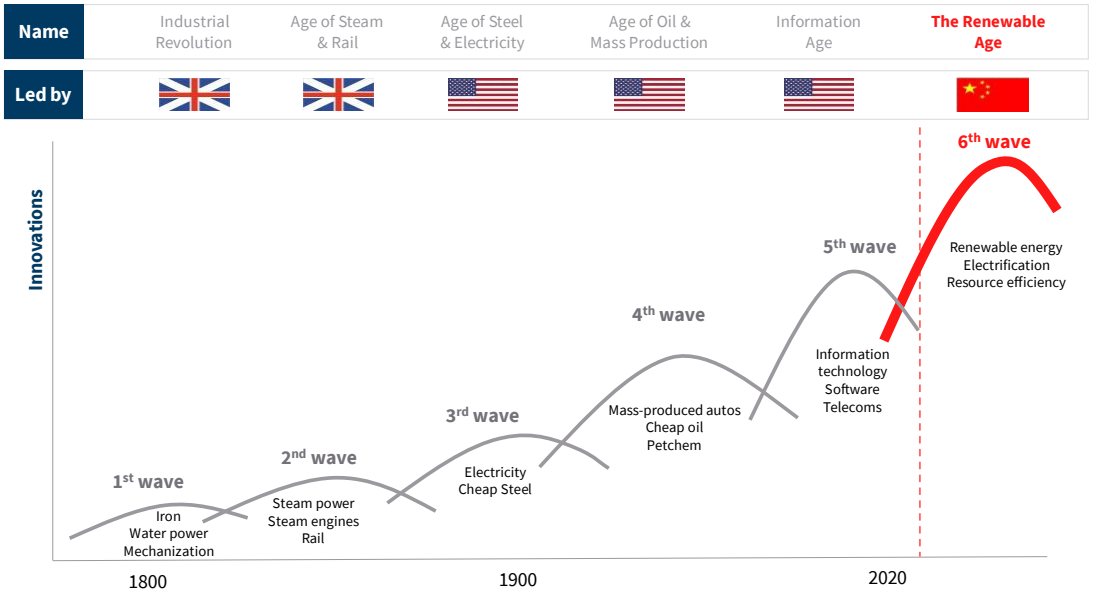
This section describes how technology revolutions work, notes that China can now be classified as an electrostate, and shows the importance of taking China as a reference point for understanding the energy transition.

How technology revolutions work

Carlota Perez sets out a framework for thinking about technology change in waves,[34] with each wave taking place every 40–60 years and led by a central country. The first two technology revolutions were led by the United Kingdom, most notably the Industrial Revolution. The next three technology revolutions were led by the United States, most recently the Information Technology revolution.

We argue that the Renewable Revolution is the next major technology wave, and is clearly being led by China at present.

Exhibit 22: The Renewable Revolution as the sixth major technology revolution



Source: Carlota Perez (first five), RMI (renewable age)

China is now an electrostate

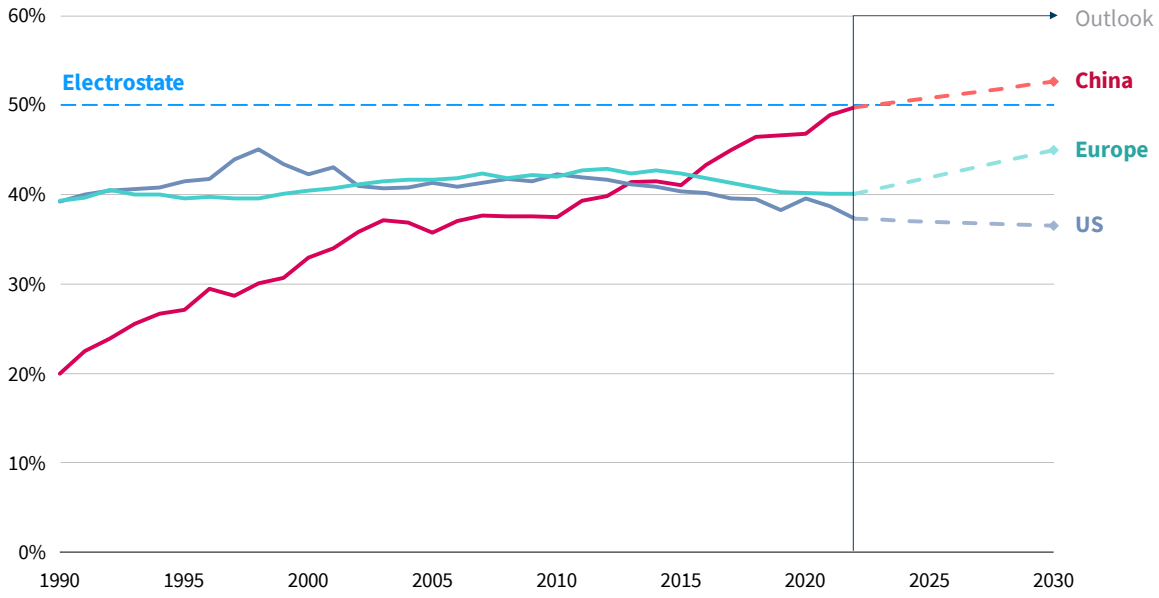
China has shifted from an export-led growth strategy (for solar panels a decade ago) to a domestic-led strategy (for EVs today). China has reaped the benefits of its success in cleantech, and Chinese policymakers speak of a new era of prosperity led by the export of solar batteries and EVs, referred to as the "New Three."[35]

This brings new weight to the idea that China is becoming an electrostate.[vii] The concept of China as a potential electrostate was popularized by the *Economist* in 2020 when they looked both at the supply chain and at demand.[36] There is no formal definition of electrostate, but one approach would be to argue that a country has become an electrostate when the majority of its primary energy is used to make electricity.

In our analysis above we used the standard measure of final energy which is useful for inter-country comparisons. However, comparing final electricity demand with final fossil fuel demand is comparing apples with pears. Electricity is a superior energy source to fossil fuels, which are subject to thermodynamic losses of around 60% on conversion into electricity. There are various ways to solve for this issue, ranging from the thermal equivalence method used by BP[37] (the data is now provided by the Energy Institute) to simply taking the share of the supply of primary energy used to make electricity. We take the latter as it requires no adjustment to the data, and is easy to calculate.

According to IEA data for China in 2022, primary energy inputs into electricity as a share of total primary energy reached 49.7% (primary energy demand was just under 160 EJ and of that, 79 EJ was used for electricity and heat generation). Given the surge in renewable deployment in 2023, it is highly likely that China has already crossed the 50% barrier and become an electrostate.

Exhibit 23: Primary energy used for electricity as a share of total primary energy IEA APS, %



Source: IEA WEB, IEA WEO 2023, RMI annotation. APS is the IEA's Announced Pledges Scenario.

Why Chinese leadership matters

Naturally enough, the debate on the future of energy in the United States and Europe tends to revolve around the issues faced in those markets. There is much discussion for example about the travails of

[vii] Albeit an electrostate that will need to decarbonize its grid.

the US offshore wind industry, the supposed slowdown in EV sales, or how hard it is to build grids. However, when seen from the perspective of Chinese leadership of the energy transition, these issues are more of a problem for the specific country than an impediment to global change. For example:

- **Offshore wind.** Some have focussed on the rising cost of US offshore wind projects[38] to argue that these somehow invalidate the falling cost driver of the energy transition. However, Chinese renewable deployment in 2023 was more than 300 times larger than US offshore wind, which is still at an early stage. And costs continue to fall in China for both wind and solar. US offshore wind plans are for 1 GW of potential deployment in 2024 compared to the 2023 actual China deployment data of 8 GW of offshore wind, 54 GW of onshore wind, and 260 GW of solar.[39]
- **EV sales.** Some have argued that the United States will not embrace electric vehicles and that the EV transition is stalling. However, as set out in *X-Change: Cars*,[40] there is a clear global pathway to the deployment of electric vehicles. China is the largest car market in the world and is clearly blazing a trail that others can follow. A large number of countries have moved along an S-curve growing rapidly after reaching 5% share of sales. So far, the United States is pretty much following this pattern.
- **Grids.** There is much debate about how hard it is to build grids. This is not in doubt, but it is also clear that China has been able to build dozens of ultra-high-voltage grids to integrate large amounts of renewables, including those from its planned 225 mega bases.[41]
- **Electrification.** The share of electricity in final energy demand has not changed for a decade in the United States and Europe. However, it is increasing by 10 percentage points a decade in China. Clearly there are solutions being found in China which can be applied elsewhere.

The United States and Europe will compete for leadership

The future is not yet determined and there are many reasons why the United States and Europe will compete with China for leadership. This in turn will help to solve barriers to change.

The future is not yet determined

China is the current leader, but there are many races in the energy transition still to play for. We are still at an early stage in the race - only 15% of electricity comes from solar and wind, and only 20% of final energy comes from electricity.

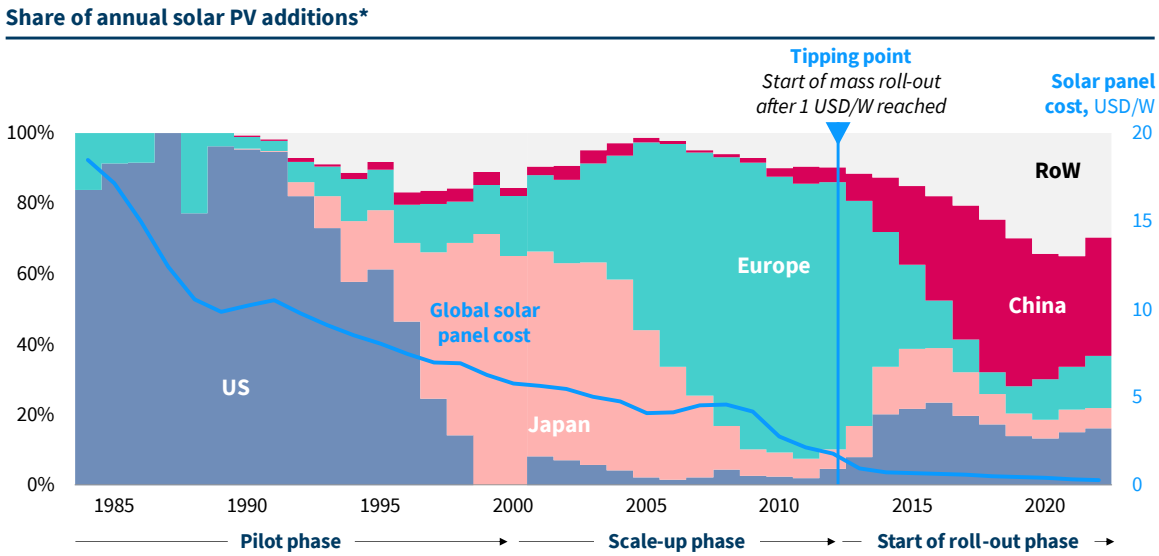
That means there is a race to develop the technologies of the future in every single end-use sector, from steel to cement, from heating to flying. There is also a race to develop the technologies to tie together end markets most effectively, because flexibility is key. Further, many of the raw materials for the energy transition come from outside China, most notably lithium from Australia and Chile. Much raw material processing is in China, but could be done closer to where it is extracted. Moreover, recycling offers the opportunity to turn demand centers into raw mineral supply centers — mining minerals from clean tech at end-of-life. This can turn regions devoid of natural resources but hosting large energy demand into the future material supply hubs as well.

The IRA has brought the United States back into the game, and it is highly likely that the United States will lead in many areas of the energy transition.[42] Meanwhile, innovation is happening everywhere, both in the three markets we identify here and across the world. In Japan, Korea, India, and across the Global South there is a huge incentive to solve the barriers of the energy transition and build new businesses.

The IRA has brought the United States back into the game, and it is highly likely that it will lead in many areas of the energy transition.

Moreover, in the modern world change can happen fast. Other countries have led the solar supply chain in the past, most notably the United States, Japan, Australia, and Germany.[43] China has been able to rise to dominance over the past decade only.

Exhibit 24: Share of solar installation versus panel cost by country over time



Source: Our World in Data (OWID), RMI analysis. * three-year rolling average which therefore slightly understates the degree of Chinese leadership in 2024

There are many reasons to compete

There are many reasons for China, Europe, and the United States to compete. The advantages of energy technology leadership are many. They include:

- **Industrial leadership.** Those who build the technologies reap the rewards. In every sector there is now a race to build and deploy clean technology solutions the fastest. And if incumbents do not disrupt themselves, then someone else will. The classic example of this is Tesla. While the car companies dawdled, Tesla built up a commanding lead and now sells the majority of all electric vehicles in the United States.[44] The best way to compete in 2024 is to build up the electricity-powered industries of the future before your competition does.[45]

> **There is now a race to build and deploy renewable solutions the fastest. And if incumbents do not disrupt themselves, then someone else will.**

- **Jobs.** IEA data shows that more people are already employed in the green energy sector than in fossil fuels, and all the job growth in energy comes from green jobs.[46] The incumbent argument that we need to preserve fossil fuel jobs misses the point: as the world shifts to renewable energy, the number of these jobs will gradually decline, in the same way we no longer employ large numbers of people to repair gas lighting, maintain transport canals, or service horse buggies.
- **Equity.** It is overwhelmingly the rich who use expensive fossil fuel energy and the poor who suffer the consequences of global warming and pollution.[47] Cheap, clean, and universal renewables provide us with new tools to help solve these issues. Lower costs and lower imports mean more resources to deploy on key tasks such as reducing poverty. Cheaper local energy means more energy for energy-poor households.

- **Geopolitical influence**. Energy is power. It follows that those who provide you with your energy have some influence over you. In the past, this energy was fossil fuels, and the ability to control supply handed enormous power to OPEC; but in the future, energy will come from clean technologies. A key competition of the future is likely to be over the deployment of clean technologies in the Global South.
- **Energy independence**. Eighty percent of people live in countries that import fossil fuels,[48] but every country in the world has renewables, and almost all have huge amounts. The world as a whole has 100 times as much renewable potential as fossil fuel production.[49] Harvesting the sun will provide countries with energy independence in a way that fossil fuels never could.
- **Resilience**. Local energy also provides resilience because it is available even if central facilities are damaged by the rising tide of damage linked to global warming.
- **Lower pollution**. Fossil fuels burn 15,000 million tons of fuel every year,[50] pouring nearly 40 gigatons of carbon dioxide and other pollutants into the biosphere. As the World Health Organization notes, 7 million people a year die of polluted air, making it one of the largest killers in the world.[51] Countries that deploy renewables enjoy cleaner air, cleaner water, and cleaner land.
- **Efficiency.** Fossil fuels lose two-thirds of their energy as wasted heat.[52] Renewables and electrification technologies are simply more efficient, providing the same services with around half the primary energy.[53]
- **Lower costs**. Renewables and electrification are technologies on learning curves, so they provide a cheaper solution than continuing with fossil fuels. That is already the case in electricity and low temperature heat and is about to be the case in transport.[54] These sectors are well over half of fossil fuel demand.
- **Lower greenhouse gas emissions**. Deploying renewables means emissions will fall, enabling countries to meet their obligations under the Paris Agreement, and making possible a livable planet.

If Europe and the United States fail to deploy new technology, they will fall behind

Countries that deploy new technologies faster will prosper, and those that do not will fall into decline, in the same way as those which deployed fossil fuels 200 year ago prospered while those that did not fell into relative decline.[55] Those that sought to block the growth of electricity or cars after 1900 held back development in their countries.[56] A clean technology system is coming and it is better, cheaper, cleaner, and faster. Costs fall each year, and more and more sectors and countries are able to deploy renewable technologies to their advantage. It follows that the attempts made by some in the United States and Europe to block change will only end up weakening those nations.

There are some siren voices seeking to expand fossil fuel production as a supposed tool of resilience. This would be like expanding canals as a transport tool when we have invented railways or trying to expand fixed line telecommunications rather than building mobile stations. The primary function of fossil fuels in 2024 is to provide a platform from which the best and the brightest can build a renewable future. The starting gun has been fired, and if countries deploy their fossil fuels to maintain the old system, they face stagnation and decline.

The primary function of fossil fuels in 2024 is to provide a platform from which the best and the brightest can build a renewable future.

Competition for leadership will help solve barriers to change

There are many barriers to the energy transition. It is hard to put up solar panels or grids in the face of local opposition; it is difficult to change pricing regimes in the face of opposition from incumbents; and it is hard to electrify sectors that run on fossil fuels.

All of this is true, but as the cleantech race between China and its strategic competitors widens, we are highly likely to see a push to electrify sectors that have struggled to change. The reason why countries will solve these barriers is because of strong economic forces as well as geopolitical necessity; they will be left behind if they fail to act. A powerful solvent that tends to appeal across the political divide is the desire for energy security and geopolitical influence. We already see echoes of this as military forces start to electrify vehicles and build renewables and microgrids to enhance resilience,[57] and politicians seek to make supply chains domestic.[58]

The technology revolution will spread

We show how it is normal for technology to diffuse to the rest of the world. The implication is that regulators are likely to take a more proactive stance in United States and Europe.

Technology will diffuse out to the rest of the world

Carlota Perez describes how technology revolutions tend to diffuse out from the leading country into the rest of the world.[59] In the days before universal communication, this process happened slowly. Now it happens much faster.

There is a standard pattern of deployment of technology which will be familiar to most readers. Companies deploy new technology in the easy places first and then they sell it to more challenging geographies. This is the logic of capitalism. It is also the way that the internet and mobile phone revolutions have played out in recent years: first they were deployed at scale in the United States and other wealthy locations; then as costs came down and barriers were solved, they were deployed elsewhere as well.[60] In the energy transition, that means we should expect the major producer of renewable energy technology — China — to sell its technology first at home, and next to wealthy locations.

In the same way that China was able to speed up technology transfer from the West to build up its domestic industry, the United States and Europe should encourage Chinese solar and battery companies to build facilities in their home markets.

And as those markets start to saturate and costs continue to come down, we would expect China to sell its renewable technologies to less wealthy countries.

We should expect (…) China to sell its technology first at home, and next to wealthy locations. And as those markets start to saturate (…) we would expect China to sell its renewable technologies to less wealthy countries.

As China builds up capacity to produce 1,000 GW per year of solar panels, we should expect a large part of these solar panels to end up in the Global South. In the 2030s, the Chinese market for new solar will saturate and start to fall, and at that point there will be more overcapacity, and an even greater incentive to sell solar panels to the Global South.

Developments in the Caribbean provide a signal of the future that is coming; solar panels are now being offered to retail consumers in the Caribbean at $120 per kW.[61] The payback time for home solar can be as little as a year. It is not surprising therefore that solar retail has taken off in the past two years.[62]

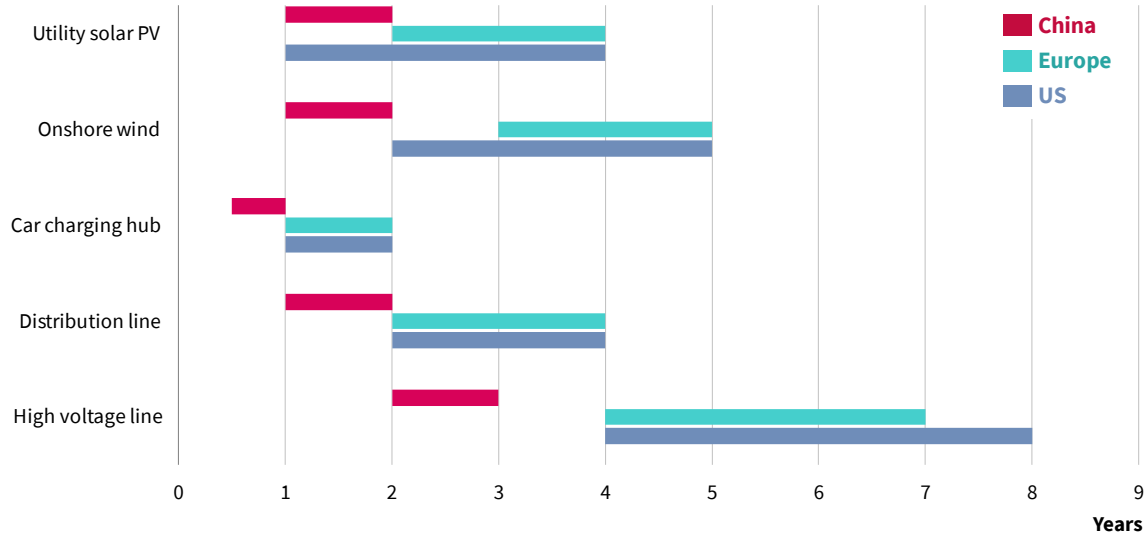
Technology diffusion allied to the rising availability of development capital and local policy initiatives will all be needed to enable the Global South to deploy renewables at scale.[63] This does not mean that countries cannot deploy these technologies faster than the leaders, nor that they are condemned to change slowly. Across the world, from Vietnam to Barbados, from Uruguay to Morocco, we are seeing a rapid shift to renewables.[64]

Regulatory change is likely

There are many drivers of Chinese leadership: strategic focus; capital investment; manufacturing prowess; technology innovation; and so on. But the one most easily fixed by competitors in the United States and Europe is regulatory action. China is simply faster to get stuff done. If Europe and the United States wish to compete, then regulators need to up their game in order to speed up renewable deployment and drive down electricity prices.

The data below from the IEA illustrates the point. It takes far longer to deploy renewables in the United States and Europe than in China. For example, it takes 2–3 years to put up a high voltage line in China, but 4–7 years in Europe and 4–8 years in the United States.

Exhibit 25: Typical deployment time for new technologies, years



Source: IEA WEO 2022

Furthermore, the latest data from the IEA shows that industrial electricity prices in 2023 were much lower in China and the United States (around $60 per MWh) than in Europe (around $110 per MWh).[65] In the race to the top, it is vital for industries to have competitive prices for electricity, and this will put additional pressure on policymakers in Europe in particular to change regulatory structures in order to get closer to their competition.

4. Appendix

Rising renewables means falling fossil fuels

The Chinese electricity sector uses more fossil fuels than any other country sector in the global economy.[66] Changes in that sector will therefore have global implications. Below we explain why some commentators are arguing that Chinese fossil fuel demand is peaking, and what that means for Chinese coal demand. We then set out why China is the pivot nation that will push global fossil fuel demand into decline.

Fossil fuel demand in China

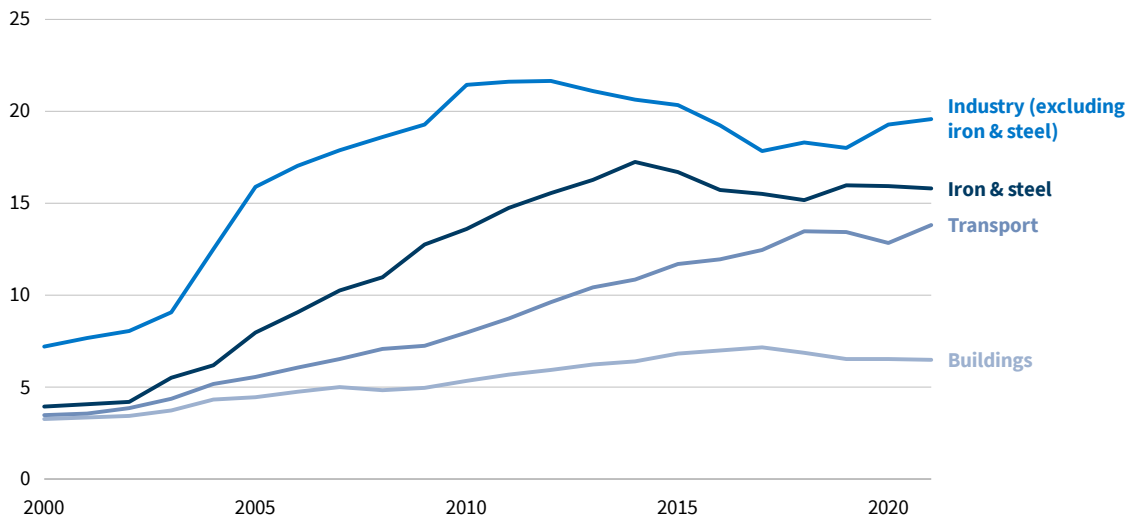
At the end of 2023, Lauri Myllyvirta, lead analyst at the Centre for Research on Energy and Clean Air, argued that Chinese emissions (and hence fossil fuel demand) had likely reached a structural peak in 2023 because of the rapid growth of renewables and electrification.[67] We summarize below the evidence for this, using the detailed WEB database.

Peak demand for industry, buildings, and transport

It is highly likely that electrification has driven peak fossil fuel demand in the buildings and industry sectors in China. As the chart below shows, final fossil fuel demand in industry excluding iron and steel peaked in 2010, in iron and steel it peaked in 2014, and in buildings it peaked in 2017.

The only major sector enjoying growth in fossil fuel demand is transport, and there the rapid growth of EVs means that transport demand for oil will shortly peak. Sinopec for example argued at the end of 2023 that gasoline demand had already peaked and that oil demand would peak by 2030.[68]

Exhibit 26: Final fossil fuel demand in China by sector, EJ



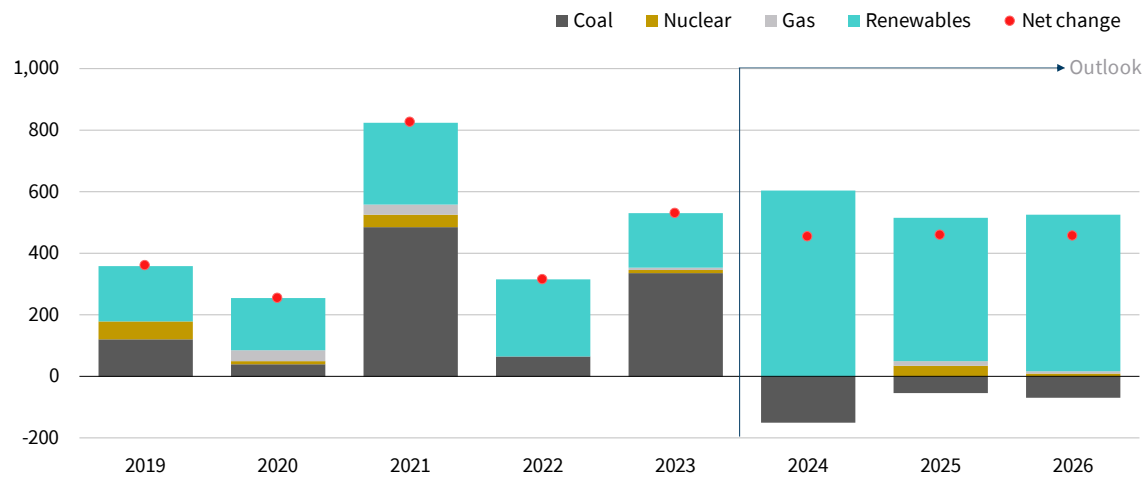
Source: IEA WEB

Peak demand in electricity

The rapid growth of renewables has been supplying a rising share of the total demand growth in electricity. If hydro supply had not fallen in 2023 due to the lack of rain, then the growth in Chinese demand for fossil fuels in electricity would have been tiny. Looking forward, it is likely that normal rain

patterns will return this year, implying a bounce back in hydro. Meanwhile, renewable supply continues to grow rapidly and the surge in solar supply from the end of 2023 will be seen in the annual numbers. There is simply very little room for fossil fuels to increase their net production of electricity. The IEA recent global electricity review therefore argues that Chinese demand for fossil fuels for electricity has therefore peaked in 2023.[69] All growth in electricity supply in China in the foreseeable future comes from renewables.

Exhibit 27: Growth in electricity supply in China, TWh

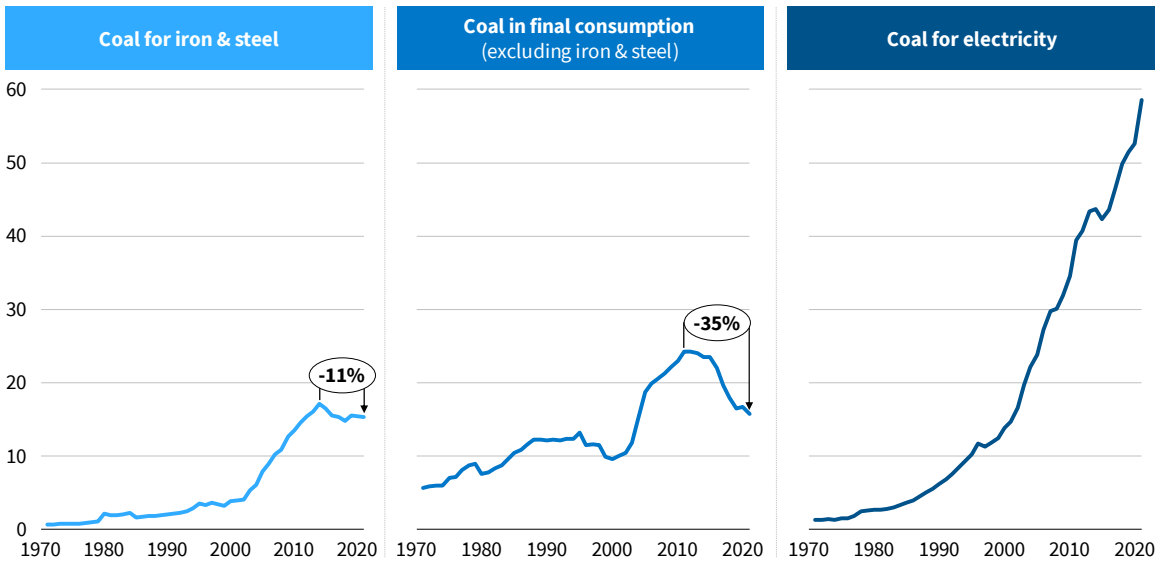


Source: IEA Electricity 2024

Peak demand for coal

There are three parts to Chinese coal demand: electricity, iron and steel, and other. Chinese coal demand for iron and steel peaked in 2014 and is down 11%. For other sectors it peaked in 2012, and is down 35%. The only area of demand growth for coal in China has been electricity, as the chart below sets out.

Exhibit 28: Coal demand in China, EJ



Source: IEA WEB.

As noted above, it is likely that all the net growth in electricity demand in 2024 will be supplied by renewables. That implies that there will be no room for demand growth for coal.

Meanwhile, the government has pledged to peak coal demand by 2025,[70] and as a rule they achieve their pledges early.

What about the new coal capacity?

Given the math of peaking demand for coal-fired electricity, it is worth asking why China is still building coal-fired power stations. As Hannah Ritchie explained in a recent article,[71] the purpose of the new coal plants is to provide backup as peaker plants. The implication as argued by the IEA[72] is that capacity utilization will fall below 50% and that coal demand will not rise.

The global implications

China is the pivot nation in global demand for fossil fuels. The moment that it shifts from growth to decline, global fossil fuels demand will also enter into decline.

China is the pivot nation in global demand for fossil fuels. The moment that it shifts from growth to decline, global fossil fuels demand will also enter into decline.

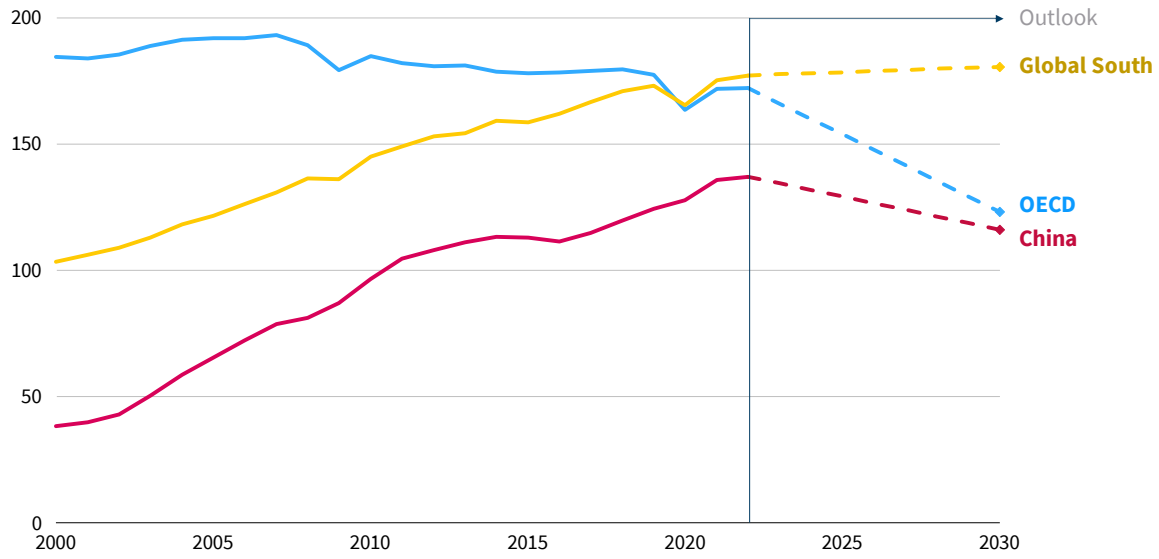
In broad terms it is possible to split global fossil fuel demand into three buckets — OECD, China, and the Global South.[viii] Fossil fuel demand peaked in the OECD in 2007 and since then has fallen by around 10%. Meanwhile, the main driver of fossil fuel demand growth has been China.

When China moves from growth to decline, the balance shifts. Since 2008 there have been two drivers of growth (China and the Global South) and one driver of decline (OECD). As soon as China pivots from growth to decline, there will be two groups with falling demand and just one (the Global South) with rising demand. The Global South alone is not growing fast enough to offset decline in the other two groups.

We set out the framing below, using IEA APS data which allows us to split out the three regions. In both the IEA APS and STEPS scenarios, Chinese and OECD decline in fossil fuel demand is greater than the growth in Global South demand in the period to 2030.

[viii] Technically China is also part of the Global South. But in this instance it makes more sense to split it out.

Exhibit 29: Primary fossil fuel demand in China, developed markets and the Global South IEA APS, EJ



Source: IEA WEB, IEA WEO 2023 APS. APS is the IEA's Announced Pledges Scenario.

The balance between renewable and fossil resources

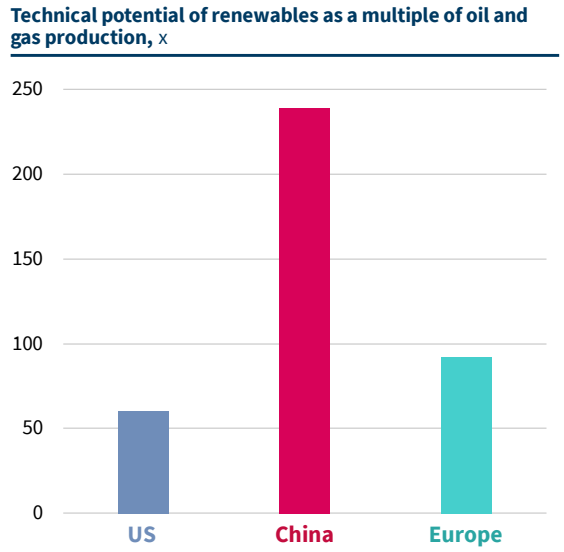
As we set out below, renewable resources in all three regions are far higher than fossil fuel resources. We focus on oil and gas because it is more valuable than coal and because all three regions are committed to phase out coal in any event. The United States does export fossil fuels, but it is no petrostate, and the direct impact of oil and gas production is only 3% of GDP.

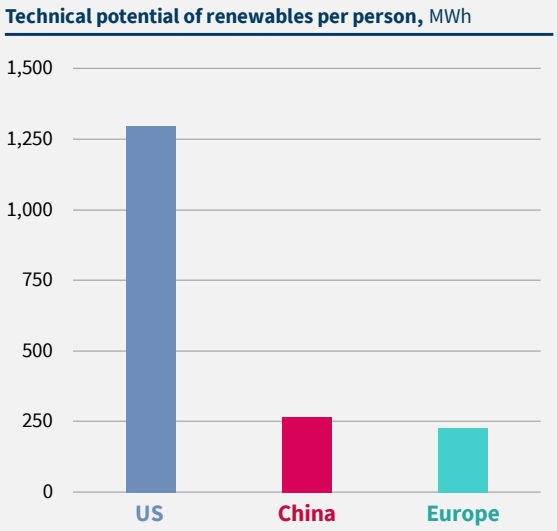
Renewable potential

All three regions have huge renewable resources, far greater than their fossil fuel supply. The United States has the largest solar and wind resource per person of the three, with the opportunity to generate over 1,200 MWh per person per year.

To calculate the technical potential of renewables we take data from NREL and Solargis on how much energy could be produced by solar and wind once you screen out croplands, mountains, national parks, cities, and so on. And we compare with the amount of energy in equivalent terms which is produced by oil and gas.[73] Even in the United States, the technical potential is more than 60 times greater than the annual oil and gas production. In China that rises to over 200 times, and in Europe it is nearly 100 times larger.

Exhibit 30: Technical potential of renewables versus oil and gas





Source: NREL, Solargis, Carbon Tracker for 2019.

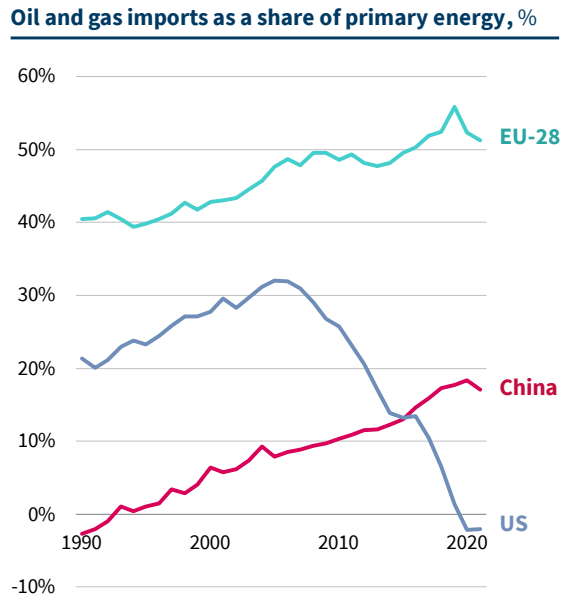
Oil and gas supply

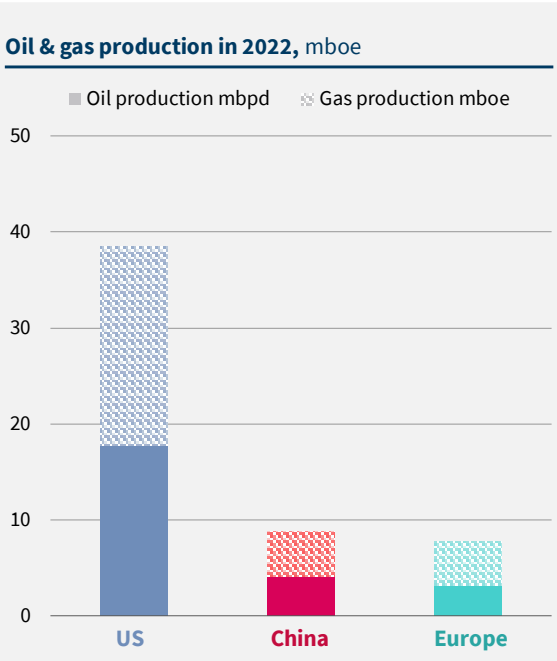
The United States produces nearly 40 million barrels per day (mbpd) of oil and gas while China produces less than 10 mbpd and Europe 8 mbpd (in large part thanks to Norway).

The United States is the only net exporter of oil and gas. Imported oil and gas make up 20% of Chinese energy demand, and 50% in the EU 28.

Of the three, Europe thus has the strongest incentive to embrace renewables for reasons of political economy.

Exhibit 31: Oil and gas imports and production





Source: IEA (left), Energy Institute (right).

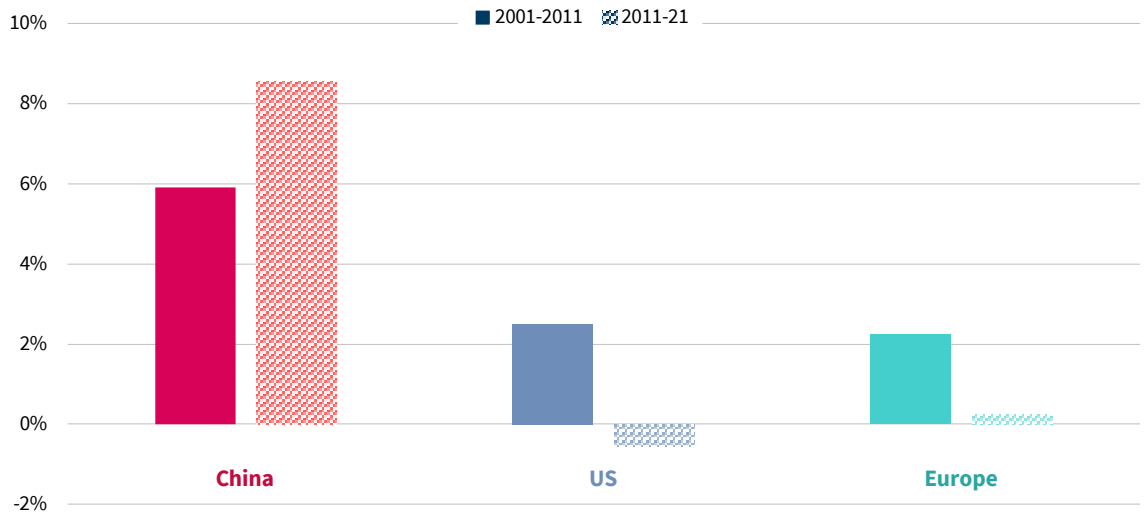
Drivers of electrification

We look below in more detail at electrification. We first set in context the change in electrification over the past couple of decades. Then we look in detail at how industry and buildings in China have been the main drivers of change in the past seven years, driven more by electrification than by growth in final demand. And we then look forward at the drivers of the growth of electricity demand in the period to 2030.

Change in the past

China has increased its electrification rate (electricity as a share of final energy) by nearly 1 percentage point every year in the past decade, while that of Europe has essentially been flat and the United States has fallen.

Exhibit 32: Change in electricity's share of final energy by decade, %



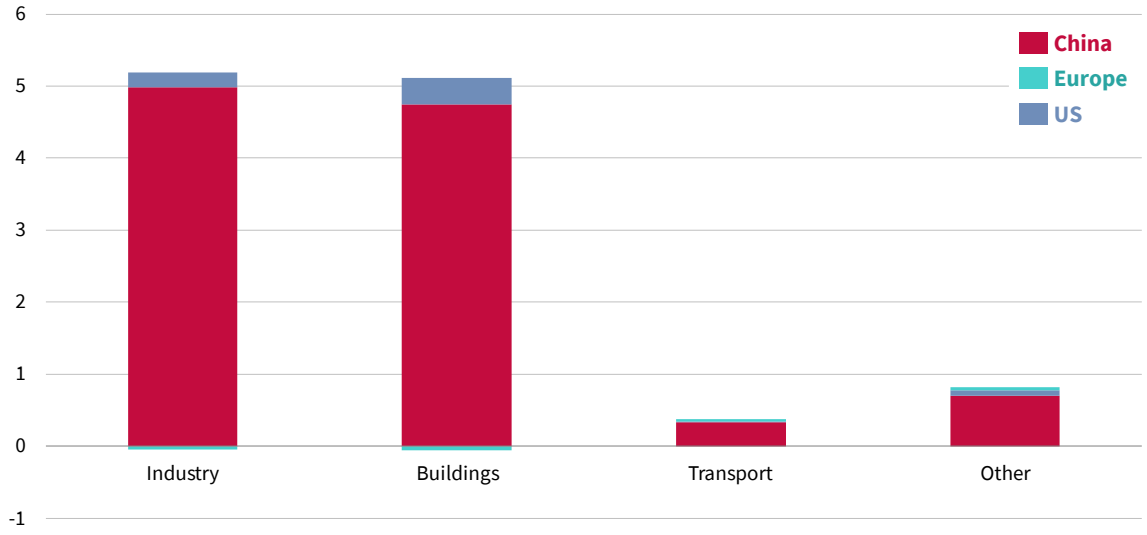
Source: IEA WEB

Drivers of change

Although the attention of the world has been focused on the electrification of the Chinese transport sector, the real story over the past seven years has been the electrification of Chinese industry and buildings.

Chinese industry for example was 44% of the increase in the total demand for electricity in the top three regions. Since these three made up 72% of the global increase in electricity demand, Chinese industrial demand was 31% of the global increase in electricity demand over this period.

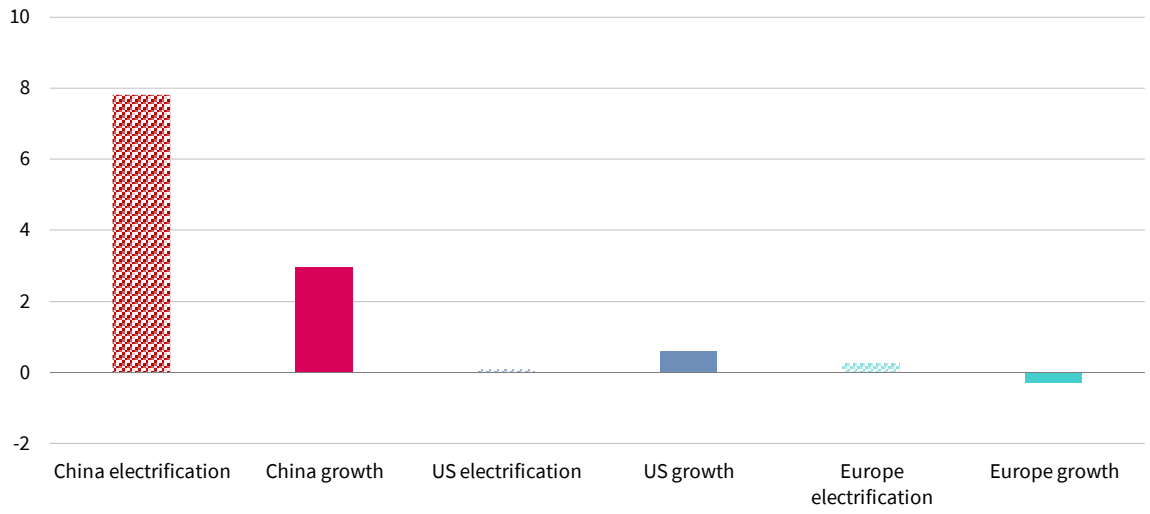
Exhibit 33: Increase in electricity usage by sector 2015-2022, EJ



Source: IEA WEO 2023

It is also possible to split out whether the increase in electricity usage was the result of growth in energy demand or an increase in the share of electricity for electrification. Of the total increase in electricity usage, 68% was from electrification in China and most of the rest was from growth of energy demand in China.

Exhibit 34: Drivers of the increase in electricity usage 2015-22, EJ

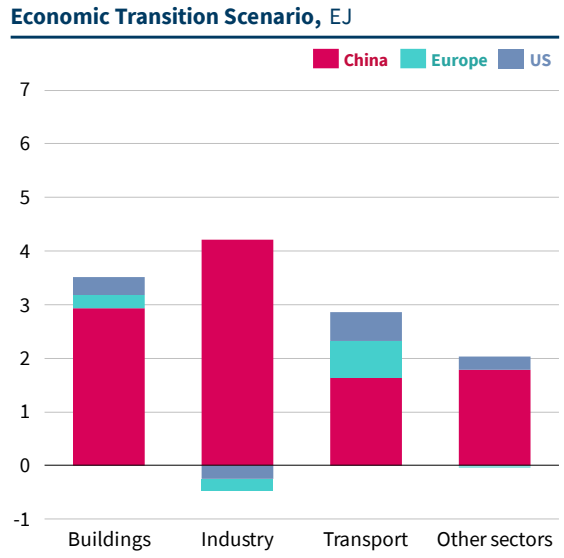


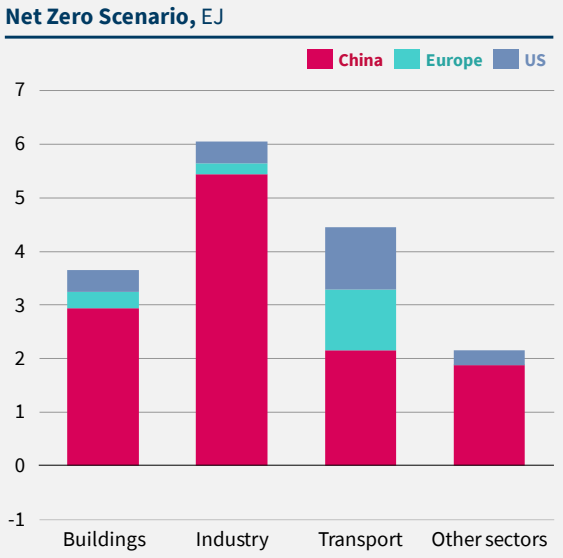
Source: IEA WEO 2023

Drivers till 2030

We set out below the expected growth in electricity usage in the three key regions under BNEF's two core scenarios to give a sense of what is expected. The implications are that China will continue to dominate the electrification of building and industry, but that transport will be more evenly matched.

Exhibit 35: The increase in electricity usage by sector 2021–30, EJ





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