The Cleantech Revolution

It’s exponential, disruptive, and now

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Executive Summary

- **The energy system is being transformed by the exponential forces of renewables, electrification, and efficiency.**
- **The orthodox view of slow change is wrong.** New clean technologies beat old fossil commodities because clean technologies' costs fall over time on learning curves, they are universal, and they grow quickly.
- **Exponential change has been remarkable in the past decade.** Cleantech costs have fallen by up to 80 percent, while investment is up nearly tenfold and solar generation has risen twelvefold. Electricity has become the largest source of useful energy, and the deep force of efficiency has reduced energy demand by a fifth.
- **Change is led by China.** Half the growth in cleantech is from China, but exponential growth is also happening in the OECD and across the Global South as Asia electrifies.
- **The drivers of growth are more powerful than the barriers.** Falling cleantech costs, the energy security of eternal renewables, Chinese leadership, and a race to the top will continue to overwhelm a fragile fossil fuel system which wastes two-thirds of its primary energy and fails to pay for its externality costs.

- **So exponential growth of cleantech will continue.** By 2030, we will be installing 1,000 GW of solar a year and selling 6,000 GWh of batteries a year, making possible the COP goal of tripling renewable capacity. Electrification rates will double to 0.5% a year, and efficiency gains will increase to over 3% a year.
- **The fossil fuel system faces inexorable decline.** Renewables will drive fossil fuels out of electricity generation, electrification will push fossils out of final energy, and efficiency will reduce fossil waste. Some 75% of fossil fuel demand is exposed to rapidly growing cleantech alternatives, so stranded assets are inevitable.
- **Wider implications of change.** The goals of the Paris Agreement are feasible, and the Global South will continue to leapfrog to cleantech.
- **This is the pivot decade.** When cleantech costs become irresistible, the renewable capacity is built, fossil fuel demand reaches the end of its plateau, and the transition is priced into markets.
- **Now is the time to act.** We need to build out renewables and electrify energy use, make good bets on small modular technologies, and harvest the enormous efficiency opportunity. The direction of change is inevitable, but the speed is up to us.
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1 Introduction

• There are two main perspectives on the energy transition: the old incumbent view of business-as-usual; and the new insurgent view of exponential change.

• At heart this is the longstanding battle of commodities versus technologies. Design and technologies beat commodities because they enjoy learning curves and are limitless. So costs fall over time, and growth is exponential.

• New energy comes from manufactured, modular, scalable, clean technologies; old energy is from centralized, heavy, dirty commodities.

• Old energy forecasting has failed in the face of the new energy reality. Linear forecasts constrained by barriers to growth have consistently been overwhelmed by exponential change.

• There are three key levers in the energy transition: Renewables; Electrification; and Efficiency.
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**

- **Fossil fuels**
- **Solar and wind**

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**

- **Fossil fuels**
- **Solar and wind**

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

- Nuclear: 39 years (1967)
- Gas: 28 years (1981)
- Coal: 32 years (1957)
- Hydro: 25 years (1978)
- Solar: 12 years (1983)
- Wind: 8 years (to 2021)

Years since generating 100 TWh

Source: Ember Global Electricity Review 2024; 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 inspired by a chart from Shell featured in Nat Bullard’s deck. In 2024, nuclear has a 10–15 year lead time.
New energy is fundamentally different to old energy

<table>
<thead>
<tr>
<th>THE AGE OF CARBON</th>
<th>THE AGE OF RENEWABLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite</td>
<td>Eternal</td>
</tr>
<tr>
<td>Fiery, heavy molecules</td>
<td>Obedient, light electrons</td>
</tr>
<tr>
<td>Geographically concentrated</td>
<td>Available everywhere</td>
</tr>
<tr>
<td>Wasteful</td>
<td>Efficient</td>
</tr>
<tr>
<td>Continuous material flow</td>
<td>Circular</td>
</tr>
<tr>
<td>Analogue</td>
<td>Digital</td>
</tr>
<tr>
<td>Trillions of dollars of annual rents to oligarchs</td>
<td>No superprofits</td>
</tr>
<tr>
<td>Malthusian commodity-based system</td>
<td>Schumpeterian technology-based system</td>
</tr>
<tr>
<td>Concentrates power</td>
<td>Localizes and distributes power</td>
</tr>
<tr>
<td>Kills millions from air pollution</td>
<td>Saves millions from air pollution</td>
</tr>
<tr>
<td>Produced the greatest externality in history¹</td>
<td>100 times lower impact on nature</td>
</tr>
</tbody>
</table>

¹ Sir Nicholas Stern, “The greatest market failure the world has seen.”

Source: RMI.
Incumbents have underestimated the speed of change

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

**New solar additions**
- 800 GW of annual additions
- **S-curve trend**

**EV share of sales**
- 40% of car sales EV
- **S-curve trend**

**Battery sales**
- 3,200 GWh
- **S-curve trend**

**Forecasts**
- WEO2023
- WEO 2022
- WEO 2020
- WEO 2018
- WEO 2016

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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

1. Renewables
2. Electrification
3. Efficiency

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

• There is clear evidence three drivers of changes are growing exponentially: renewables, electrification, and efficiency.

• Cleantech costs fall by around 20% for every doubling in deployment and have fallen by up to 80% in a decade.

• Capital is pouring into cleantech. Getting to the first trillion of annual investment took decades; the second trillion will take only 4 years.

• Solar generation is doubling every 2-3 years and battery storage every year. Solar is poised to deploy the largest amount of generation capacity, and batteries are about to overtake pumped hydro.

• The supply chain is already in place for enough solar and batteries for net zero.

• Electricity supply has been growing inexorably for a century and is now the largest supplier of useful energy.

• Efficiency is the deep force of the energy transition, saving one fifth of total demand over the last decade.

• China leads the exponential story and is poised to be the first major electrostate. Exponential change is happening in the OECD and across the Global South as Asia leapfrogs the OECD in electrification.
Cleantech costs have fallen rapidly

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

Wind

<table>
<thead>
<tr>
<th>Year</th>
<th>Offshore</th>
<th>Onshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>$300</td>
<td>$100</td>
</tr>
<tr>
<td>2023</td>
<td>$100</td>
<td>$30</td>
</tr>
</tbody>
</table>

Solar

<table>
<thead>
<tr>
<th>Year</th>
<th>Fossil fuel range (LCOE)</th>
<th>Fossil fuel range (marginal cost)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>$300</td>
<td>$100</td>
</tr>
<tr>
<td>2023</td>
<td>$100</td>
<td>$30</td>
</tr>
</tbody>
</table>

Battery costs

<table>
<thead>
<tr>
<th>Year</th>
<th>ICE car TCO break-even</th>
<th>ICE car sticker price break-even</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>$500</td>
<td>$100</td>
</tr>
<tr>
<td>2023</td>
<td>$100</td>
<td>$50</td>
</tr>
</tbody>
</table>

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

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

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

**Solar module manufacturing capacity**

- 2,000 GW

**Battery manufacturing capacity**

- 16 TWh

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*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

- Buildings
- Industry
- Transport

Source: IIASA, IEA WEB.
Electricity is the new King of Energy

Electricity is the largest supplier of useful energy

Useful energy supply

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.
We are poised to electrify the rest of the system

The global stock of EV cars and digital devices has been doubling every 2 years

Source: IEA, Carbon Brief for heat pumps.
Efficiency is the Deep Force of change

Efficiency gains since 2010 have reduced energy demand growth more than any other factor

**Efficiency gains**

140 EJ per year avoided since 2010

Source: IEA WEB, IEA WEO, RMI calculations. Energy efficiency here is simply defined as the difference between GDP growth and energy demand growth.
China has become the first major electrostate

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

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

Source: Ember, IEA.
Exponential growth in emerging economies

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

- **Brazil wind**: 120 TWh
- **Vietnam solar**: 40 TWh
- **India solar**: 160 TWh
- **Morocco wind**: 8 TWh

Source: IEA.
Electric Asia

Asia is leading the charge to electrify everything

China

30% of final energy from electricity

Vietnam

20% United States and Europe share in 2022

Bangladesh

Korea

Source: IEA WEB
The era of peaking fossil fuel demand

• Pessimists keep raising barriers to change; optimists keep solving them.

• Early warning signals for fossils include peak new fossil fuel electricity capacity (2010), peak capex for oil and gas (2014), peak ICE demand (2017), and peak per capita fossil demand (2012–18).

• Global fossil fuel demand for industry peaked in 2014, and in buildings in 2018.

• Fossil fuel demand likely peaked in electricity in 2023 and will peak in transport before the end of the decade.

• OECD fossil fuel demand peaked in 2007, and every major area of demand has peaked in the United States.

• China is the pivot nation in the transition away from fossil fuels, and most areas of demand have clearly peaked there.

• Peaks are showing up across the Global South, from South America to South Africa and Thailand.
Pessimists sound clever; optimists change the world

The incumbents have been predicting the end of the transition for decades

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

14% of generation from solar and wind

THE PESSIMIST STORY

“Solar and wind don’t work”

“Solar and wind are too expensive”

“The grid can’t handle solar and wind intermittency”

THE OPTIMIST REALITY

China dramatically reduces costs

Leaders raise the deployment ceiling

Batteries, digitalization, and policy provide new solutions

Engineers solve the first suite of technical issues

“Grids and permitting will stop growth”

Source: Ember.
As growth turns to decline, flashing red lights all over the fossil fuel system.

**Fossil fuel capacity additions**
- 160 GW

**Oil and gas capex**
- 1,000 $ billion

**ICE sales**
- 90 million cars

**Fossil fuel demand**
- 66 GJ per capita

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

- **Industry**: Peaked in 2014
- **Buildings**: Peaked in 2018
- **Power and heat**: Peaked in 2023
- **Transport**: Peak imminent: 2024/25

Source: BNEF NEO 2024 NZS.
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

- Average increase in total electricity demand 2012–22
- Fossil power generation in decline
- A little room for fossil growth

Source: IEA Renewables 2023.
A plateau in road oil demand

Decades of growth stagnate before turning into rapid decline

Road oil demand

0 20 40 60 80 100 EJ


Decades of continuous growth

The demand plateau

Outlook

Rapid decline

Source: BNEF NEO2024 NZS.

Road share oil demand for transport, 2023

Aviation

Shipping

Rail

77%

Road

Road share oil demand, 2023

Other transport

Other sectors

53%

Road

53%
OECD fossil fuel demand peaked a generation ago

OECD fossil fuel demand for final energy peaked in 2005 and for electricity generation in 2007

Fossil fuels for final energy

Fossil fuels for electricity generation

Fossil fuels for non-energy

Source: IEA WEB.
United States — every major sector is past peak fossil demand

Fossil fuel demand across sectors peaked more than 15 years ago

**Electricity**
- Peak: 40 EJ

**Transport**
- Peak: 30 EJ

**Buildings**
- Peak: 12 EJ

**Industry**
- Peak: 10 EJ

Source: BNEF NEO 2024.
China is the global pivot nation

When China peaks, the world peaks

Primary fossil fuel demand by region

**OECD**

- **Peak**
- **From slow decline...**
- **...to fast decline**

**China**

- **Peak**
- **From rapid growth...**
- **...to fast decline**

**Global South**

- **From rapid growth...**
- **...to plateau**

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*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

Peaking behind us
- Fossil fuels in industry
- Fossil fuels in buildings

Peaking now
- Fossil fuels in electricity

Peaking shortly
- Fossil fuels in transport

Source: IEA WEB (past), Ember, IEA Electricity 2024 (electricity generation forecast), BNEF NZS (transport forward).
The first fossil peaks in the Global South

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

Fossil fuel generation

<table>
<thead>
<tr>
<th>Country</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thailand</td>
<td>200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>South Africa</td>
<td>280</td>
<td>Peak</td>
<td></td>
</tr>
<tr>
<td>Latin America</td>
<td>800</td>
<td>Peak</td>
<td></td>
</tr>
</tbody>
</table>

Coal capacity additions

<table>
<thead>
<tr>
<th>Country</th>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Ember; Note coal additions are a net figure — gross additions minus retirements.
4 Why rapid change will continue

• The three drivers of change — renewables, electrification and efficiency — are self-reinforcing.

• Cleantech costs will keep falling at around 20% for every doubling of deployment as technology gets better and spreads around the world.

• Fossil fuels are vulnerable because they have huge unpaid externalities (up to $7 trillion a year), get large subsidies ($1 trillion a year), and waste two-thirds of their energy.

• Cleantech provides energy security: 86% of people live in fossil-importing countries today; renewable resources are 100 times larger than fossil fuels, and available everywhere.

• The world’s largest energy consumer, China, lacks oil and gas, and cleantech is a path to leadership, clean air, and zero emissions. So, China will continue to deploy cleantech rapidly.

• There is a race to the top as others try to catch up. Cleantech is now 10% of global GDP growth, and there is a race to lead the cleantech industries of the future. Meanwhile, as the world burns, so policy pressure will rise.

• Clean technologies will continue to follow S-curves, cascading across sectors and geographies. Change at the frontier is hard, but most countries can copy the leaders.
Three drivers of self-reinforcing change

There are positive feedback loops between renewables, electrification, and efficiency

1. **Renewables**
   - 100% of electricity generation from wind and solar
   - Allows renewables to replace end-use demand of coal, oil, and gas
   - Drives out inefficient fossil supply technology

2. **Electrification**
   - 100% of useful energy demand from electricity
   - Reduces the amount of cleantech needed to replace fossil fuels
   - Drives out inefficient fossil end-use technology

3. **Efficiency**
   - 75% of primary demand turned useful

Source: Rystad Energy scenarios, RMI analysis.
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

Top-tier battery cell density

Wind rotor diameter

Solar cell efficiency

More innovation

Denser batteries open up new sectors for batteries to play in

Bigger rotors reduce cost per MWh

More efficient solar panels reduce cost per MWh

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.
The fossil fuel system is fragile
Fossil fuels impose major externalities, while collecting large rents and subsidies

<table>
<thead>
<tr>
<th>Amount</th>
<th>Description</th>
<th>Percentage/Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.6\text{ trillion}$</td>
<td>In annual waste from energy efficiency losses</td>
<td>86% of people live in fossil fuel-importing countries</td>
</tr>
<tr>
<td>$2\text{ trillion}$</td>
<td>In annual fossil fuel rents</td>
<td>5–6 million annual air pollution deaths as the result of burning fossil fuels</td>
</tr>
<tr>
<td>$1.3\text{ trillion}$</td>
<td>In annual explicit subsidies ($7\text{ trillion}$ with implicit subsidies)</td>
<td>75% of greenhouse gases come from burning fossil fuels</td>
</tr>
</tbody>
</table>

Sources: RMI, World Bank, IMF, OWID, IRENA, Lelieveld et al. (2023), BMJ, IEA, IIASA.
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 Inefficiency of the Fossil Fuel System.
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

**Energy use**

**Heating**

- **Gas boiler**
  - 85% efficiency
- **Heat pump**
  - 300%–400% efficiency

**Transport**

- **Internal combustion engine**
  - 25%–40% efficiency
- **Electric vehicle**
  - 80%–90% efficiency

**Notes:**
- Solar and wind’s 100% efficiency represents the fact that there are no conversion losses from primary to secondary energy.
- Source: IEA, IIASA, RMI analysis, Adapted from Prof. Tomas Kåberger.
Renewables provide energy security

They are 100x bigger than fossil fuels, and every country has them

Renewable potential as a multiple of energy demand

- Superabundant: >1,000x
- Abundant: >100x
- Replete: >10x
- Stretched: <10x
- No data

Share of population living in countries that import fossil fuel

Fossil fuel exporters
- 14%

Fossil fuel importers
- 86%

Share of population endowed with replete or better renewable resource

- Stretched: 6%
- Replete to superabundant: 92%

Source: Carbon Tracker, IRENA, Comtec, NREL, Solargis, RMI.
The world’s largest energy consumer is moving fast

China is leading the way to patent, make, and deploy the energy technologies of the future

**Patent**

**Clean energy patents**

- China: 180,000s
- US: 100,000s
- Europe: 50,000s

**Make**

**Battery manufacturing capacity**

- China: 2,500 GWh
- US: 1,500 GWh
- Europe: 1,000 GWh

**Deploy**

**Renewables**

- China: 1,200 GW solar and wind capacity
- US: 800 GW solar and wind capacity
- Europe: 600 GW solar and wind capacity

**Electrification**

- China: 30 EJ electricity consumption
- US: 25 EJ electricity consumption
- Europe: 15 EJ electricity consumption

Source: IRENA, IEA, BNEF. For more see X-Change: The Race to the Top.
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**

35 % of GDP growth

- **United States**
  - Manufacturing of clean energy technologies
  - Deployment of clean power capacity
  - Sales of EVs and heat pumps

- **China**
  - Manufacturing of clean energy technologies
  - Deployment of clean power capacity

- **European Union**
  - Manufacturing of clean energy technologies
  - Deployment of clean power capacity
  - Sales of EVs and heat pumps

- **India**
  - Manufacturing of clean energy technologies

Source: IEA.
The world burns…

Record temperatures

17 °C

15.8 °C

1940 1960 1980 2000 2010 2023

Source: C3S. Surface temperatures.

…so policy pressure will continue to rise

Change is not uniform, but it is relentless at a global level

Net-zero targets

Combustion car bans

Carbon prices

Source: IEA, BNEF, World Bank/OWID.

Share of emissions covered

Regional & municipal

National

Net-zero targets

Combustion car bans

Carbon prices

Source: IEA, BNEF, World Bank/OWID.

Share of emissions covered

Record temperatures
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**

- North America
- Europe and Central Asia
- Middle East and North Africa
- Latin America and Caribbean
- World
- South Asia
- Sub-Saharan Africa

**Solar and wind as a share of generation**

- EU
- China
- North America
- South America
- World
- Africa
- Middle East
- CIS

Source: OWID, Energy Institute.
Rapid exponential growth along S-curves is a standard characteristic of successful new technologies.

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

**Infrastructure systems**

Share of maximum size in the United States

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

S-curve-type growth even applies to infrastructure.

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

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.
The ceiling of the possible keeps rising

Leading countries and companies keep opening up new opportunities for the rest of the world

Solar and wind as share of electricity generation

- Innovation raises the ceiling of the possible
- The leaders are here
- The world is here

Source: RMI
5 Implications for the energy system

• If change continues on S-curves, then by 2030 we expect solar sales of over 1,000 GW a year and battery sales of over 6,000 GWh a year.

• S-curves imply that by 2030 solar and wind generation will triple to over 12,000 TWh and EVs will be two-thirds of car sales.

• The annual electrification rate is likely to more than double to 0.5% in 2030 as transport joins the party, and success in China drags up electrification rates elsewhere.

• Annual efficiency gains are likely to double from the 1.5% average of the past two decades to at least 3% as the result of the rising share of renewables, electrification, and a greater focus on end-use efficiency.

• Renewables will push out fossil electricity, electrons will push out molecules, and efficiency will reduce waste. In a typical X shaped pattern.

• Over 75% of fossil fuel demand today is threatened by rapidly growing cleantech alternatives.

• Fossil fuel demand will be squeezed between efficiency and cleantech. The demand plateau will last until the end of the decade, and then clear decline will set in.
Super-fast growth in solar and battery sales

Solar sales are on track for over 1,000 GW per year by 2030

Global solar sales

- Past
- Fast
- Faster

Battery sales are likely to be over 6,000 GWh a year by 2030

Global battery sales

- Past
- Fast
- Faster

Source: BNEF historical and 2024E for solar (high), RMI S-curves. For more see X-Change: Batteries.
Renewables will keep rising up their S-curves

As the renewable revolution will continue to solve barriers to change

**Solar and wind generation**

- 15,000 TWh
- Outlook

**Battery stationary storage**

- 5,000 GWh
- Outlook

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

80% of useful energy from electricity
Efficiency will be pulled up the S-curve

Faster cleantech deployment will speed up efficiency improvements

**Electricity generation efficiency**

Driven by renewables which are about 2.5x more efficient than fossil-fueled electricity

**End-sector efficiency**

Driven by higher efficiency of electricity versus fossil fuels

Source: Rystad Energy 1.6°C. Electricity efficiency is final as a share of primary. Sector efficiency is useful as a share of secondary.
Tripling renewables by 2030

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

### Renewable capacity

<table>
<thead>
<tr>
<th>Year</th>
<th>Likely</th>
<th>Feasible</th>
</tr>
</thead>
<tbody>
<tr>
<td>2022</td>
<td>3 TW</td>
<td>0 TW</td>
</tr>
<tr>
<td>2030</td>
<td>9 TW</td>
<td>12 TW</td>
</tr>
</tbody>
</table>

**COP goal**

- **triple up** renewables from 2022
- **doubling down** on annual efficiency improvement rate versus 2022

### Annual rate of electrification

- **2022**:
  - Likely: 0.0%
  - Feasible: 1.0%
- **2022-30**:
  - Likely: 0.2%
  - Feasible: 0.6%

### Annual primary efficiency gains

- **2000-22**:
  - Likely: 4%
  - Feasible: 3%
- **2022-30**:
  - Likely: 5%
  - Feasible: 4%

Source: IEA APS scenario as likely (Announced Pledges Scenario); NZE as feasible (net zero emissions).
A new energy system is coming

Fast or faster; either we are off the fossil plateau by the late 2020s or by the early 2030s

**Fast, 1.8°C**

- Solar & wind
- Other
- Fossil fuels

**Faster, 1.6°C**

- Solar & wind
- Other
- Fossil fuels

Source: Rystad 1.6° & 1.8°C degree scenario.
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*

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).
The largest areas of fossil fuel demand are most at risk

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

Source: IEA, IIASA, RMI.
Fossil fuel demand gets squeezed

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

Primary energy supply

Source: IEA WEB, IEA APS scenario, RMI.
So fossil fuel demand is on the brink of rapid decline

Fossil fuel demand faces a cliff edge. The key variable is the length of the plateau — short or very short

Source: Rystad Energy (Fast 1.8°C, Faster 1.6 °C).
Wider implications of the transition

- Paris is achievable because we are at the pivot point in the 300-year history of fossil fuel use.
- The race for the top is on fire. A battle for leadership is taking place in every area of energy supply and demand. Competition will drive change.
- The Global South can continue to leapfrog to cleantech. Witness the success of Kenya, Barbados, Morocco, Vietnam or Bangladesh.
- We are at peak waste, so we can reduce the pressure on nature.
- The great capital reallocation will continue. Capital will shift into areas of growth and out of those in decline.
- Stranded fossil fuel assets will result from the gap between the expectations of incumbents for business-as-usual and the reality of exponential change.
- Since the fossil fuel system is huge ($50 trillion of fixed assets), this asset stranding has profound implications for the financial system.
- As China is leading this transition, we need to benchmark to China.
- The debate will be very different by 2030 and the transition will be priced into markets.
Paris is feasible

This is the pivot decade from growth to decline

Global CO₂ 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.
The race for the top is on fire

Nobody wants to miss out on the technologies of the future

Renewables

60% generation from solar and wind

Electric vehicles

100% car sales EV

Electrification

40% of final energy from electricity

Note: Solar, wind, and EVs in an S-curve outlook based on RMI modeling; electrification is from BNEF’s ETS.
Source: Energy Institute, IEA, BNEF, RMI analyses. For more see X-Change: The Race to the Top.
The Global South can continue to leapfrog

Falling costs open up new opportunities to bring energy to those who lack it

**Solar**
- 40% of generation
- 2010 to 2020
- Countries: Namibia, Yemen, Chile, Jordan, Vietnam, Barbados, India, US

**Wind**
- 45% of generation
- 2010 to 2020
- Countries: Uruguay, Kenya, Morocco, Brazil, Chile, US

**Electrification**
- 30% of final energy supply from electricity
- 2000 to 2020
- Countries: Vietnam, Malaysia, Bangladesh, Philippines, United States, Kenya, Morocco, Brazil, Chile, US

Source: Ember, IEA
We are at peak waste

So we can massively reduce the strains of the energy system on nature

Solar & wind reduces losses from generation

Electrification reduces end-use losses

Source: Rystad Energy 1.6 °C Scenario.
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**

- **CAGR 9%**
- **CAGR 2%**

**Share of total investment**

- **Cleantech**
- **Fossil**

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

Oil demand

Source: Rystad Energy, OPEC, RMI.
We need to change our framework of reference to China

China is leading this technology revolution, and others need to catch up or fall behind

<table>
<thead>
<tr>
<th>Transition</th>
<th>Industrial Revolution</th>
<th>Age of Steam &amp; Rail</th>
<th>Age of Steel &amp; Electricity</th>
<th>Age of Oil &amp; Mass production</th>
<th>Information Age</th>
<th>The Renewable Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Led by</td>
<td>🇬🇧</td>
<td>🇬🇧</td>
<td>🇺🇸</td>
<td>🇺🇸</td>
<td>🇺🇸</td>
<td>🇨🇳</td>
</tr>
</tbody>
</table>

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

1st wave
- Iron
- Waterpower
- Mechanization

2nd wave
- Steam engines
- Steam power
- Rail

3rd wave
- Electricity
- Steel
- Heavy engineering

4th wave
- Mass-produced automobiles
- Cheap oil
- Petrochem

5th wave
- Information technologies
- Telecomms
- Software

6th wave
- Renewable energy
- Electrification
- Resource efficiency

1800 1900 2020
The debate will be very different in 2030

When the facts change, people change their minds. Repricing follows.

<table>
<thead>
<tr>
<th>Area</th>
<th>2015</th>
<th>2024</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost of renewables</td>
<td>Expensive</td>
<td>Cheap</td>
<td>Super cheap</td>
</tr>
<tr>
<td>Societal pressure for change</td>
<td>Niche</td>
<td>Moderate</td>
<td>Intense</td>
</tr>
<tr>
<td>EVs</td>
<td>Toy for the rich</td>
<td>A second car for the rich</td>
<td>A cheaper car for all</td>
</tr>
<tr>
<td>Renewables</td>
<td>Grid can’t take 20%</td>
<td>Grid can’t take 70%</td>
<td>Leaders enjoy cheap energy</td>
</tr>
<tr>
<td>Net zero</td>
<td>&lt;1% of world has targets</td>
<td>90% of world has targets</td>
<td>90% of world has plans</td>
</tr>
<tr>
<td>Global fossil fuel demand</td>
<td>Growth</td>
<td>Plateau</td>
<td>Decline</td>
</tr>
<tr>
<td>Hard-to-solve areas</td>
<td>CCS</td>
<td>Lots of technological solutions</td>
<td>Lots of commercial solutions</td>
</tr>
<tr>
<td>Geopolitics</td>
<td>Climate makes good speeches</td>
<td>Renewables nice to have</td>
<td>Renewables a key tool of power</td>
</tr>
<tr>
<td>United States vs. China</td>
<td>China pollutes too much</td>
<td>China makes too many climate solutions</td>
<td>China and United States compete</td>
</tr>
<tr>
<td>Financial markets</td>
<td>ESG</td>
<td>Carbon offsetting</td>
<td>ESG</td>
</tr>
<tr>
<td>Corporations</td>
<td>Greenwash</td>
<td>Green premium</td>
<td>Green prize</td>
</tr>
</tbody>
</table>

Source: RMI.
What we need to do now

- This is the pivot decade when cleantech manufacturing capacity is built, renewables get too cheap to resist, and fossil fuel demand reaches the end of its plateau.

- Focus on the signal not the noise. We need to prepare for change, not hide behind denial.

- We need to continue building out the renewable system, speed up electrification in the OECD, and increase focus on efficiency.

- We should make good bets on solutions that work: small modular technologies and efficiency measures. Equally, we need to avoid high-cost, inefficient, and unproven bets.

- Companies need to move from tactics to strategy.

- Investors should retool for the megatheme of the energy transition.

- Energy modelers need to change their approach or become stranded experts.

- And we need to get on with it. We are in a race between climate and economic tipping points. The direction is inevitable, but speed is up to us.
The 2020s are the pivot decade

You snooze, you lose

Manufacturing capacity is built: Batteries
15 TWh manufacturing capacity

Cleantech goes up the steep part of the S-curve: EV
100% EV share of car sales

Renewables get too cheap to resist: Solar
80 $/MWh LCOE

Fossil fuel demand enters terminal decline
520 EJ fossil fuel demand

Sources: BNEF, RMI, Rystad Energy.
Focus on the signal not the noise

There are always barriers to change. Those who solve them get rich.

EV adoption versus headlines

- Are Electric-Car Enthusiasts a Little Too Enthusiastic?
- Electric Vehicles for Everyone? The Impossible Dream
- Power Failure: Automakers Are All in on Electric Cars, But US Infrastructure Is Unprepared
- Ten reasons electric cars still suck: We unplug the EV hype

Media headlines are centered around their year of publication.
Sources: IEA, CNET, Time, Forbes, InsideHook, Manhattan Institute.
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

- Utility-solar PV
- Onshore wind
- Car charging hub
- Distribution line
- High-voltage line

Source: IEA.
Speed up electrification in the OECD

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

**Electricity share of final energy**

- China
- France
- Spain
- US
- Italy
- UK
- Germany

**Electricity multiple of natural gas prices in 2023**

- In the US & Europe, natural gas is cheaper than electricity
- In China, electricity is cheaper than gas

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

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

<table>
<thead>
<tr>
<th>Degree of design complexity</th>
<th>Complex</th>
<th>Simple</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design-intensive</td>
<td><strong>Platform-based complex product systems</strong> e.g., Small modular reactors, carbon capture &amp; storage</td>
<td><strong>Mass-produced complex products</strong> e.g., Electric vehicles</td>
</tr>
<tr>
<td>Complex</td>
<td><strong>Complex product systems</strong> e.g., Nuclear power plants, BECCS</td>
<td><strong>Platform-based complex products</strong> e.g., Wind turbines, concentrating solar power, standardized asset retrofits</td>
</tr>
<tr>
<td>Simple</td>
<td><strong>Standardized complex product systems</strong> e.g., Combined-cycle gas turbine power plants</td>
<td><strong>Complex-customized products</strong> e.g., Biomass power plants, geothermal power</td>
</tr>
</tbody>
</table>

**Need for customization**

Source: Adapted from Malhotra and Schmidt, "Accelerating Low-Carbon Innovation."
Harvest the vast fields of efficiency

The efficiency potential is huge, and proven

**Energy demand from primary energy to value added 2019**

- Primary energy: 600 EJ
- Final energy: 400 EJ
- Useful energy: 200 EJ
- Value added: 100 EJ

**Emissions avoided by efficiency, in context**

- 8,000 million tons CO₂ per year

Source: IEA, IIASA, RMI assumptions, Amory Lovins.
Companies: time to move from tactics to strategy

The energy transition is not a box-ticking exercise

<table>
<thead>
<tr>
<th>Type</th>
<th>Future</th>
<th>What to do</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuel producers</td>
<td>Decline of core products</td>
<td>Reinvention; rundown</td>
</tr>
<tr>
<td>Heavy fossil fuel users</td>
<td>Need to find a new energy source</td>
<td>Retool for the new energy source</td>
</tr>
<tr>
<td>Renewable companies</td>
<td>Rapid growth, rapid innovation</td>
<td>Innovate and expand</td>
</tr>
<tr>
<td>Entrepreneurs</td>
<td>A brave new world of opportunities</td>
<td>Solve barriers and get rich</td>
</tr>
<tr>
<td>Others</td>
<td>A new environment</td>
<td>Rethink areas of focus</td>
</tr>
</tbody>
</table>

Source: RMI.
Finance: Retool investment strategies

The energy transition is a megatheme, like the industrialization of China or the growth of the internet.

- **Allocate capital to sectors with growth**
- **Exit sectors in decline. Or trade the volatility on the way down**
- **Go long-short winners and losers from change. Disruption is coming, so separate reality from lip service**
- **Pick winners. The Gartner hype curve is the standard tool**
- **Beware of fossil Minsky moments the coming decade**
Adjust energy models to capture reality

Incumbent modelers need to up their game or become stranded experts

Annual renewable deployment concept chart

Who is where?

The group

Source: RMI.
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

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

Actual solar additions vs. consensus outlooks

- Source: Lenton et al based on IPCC reports
- 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).
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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