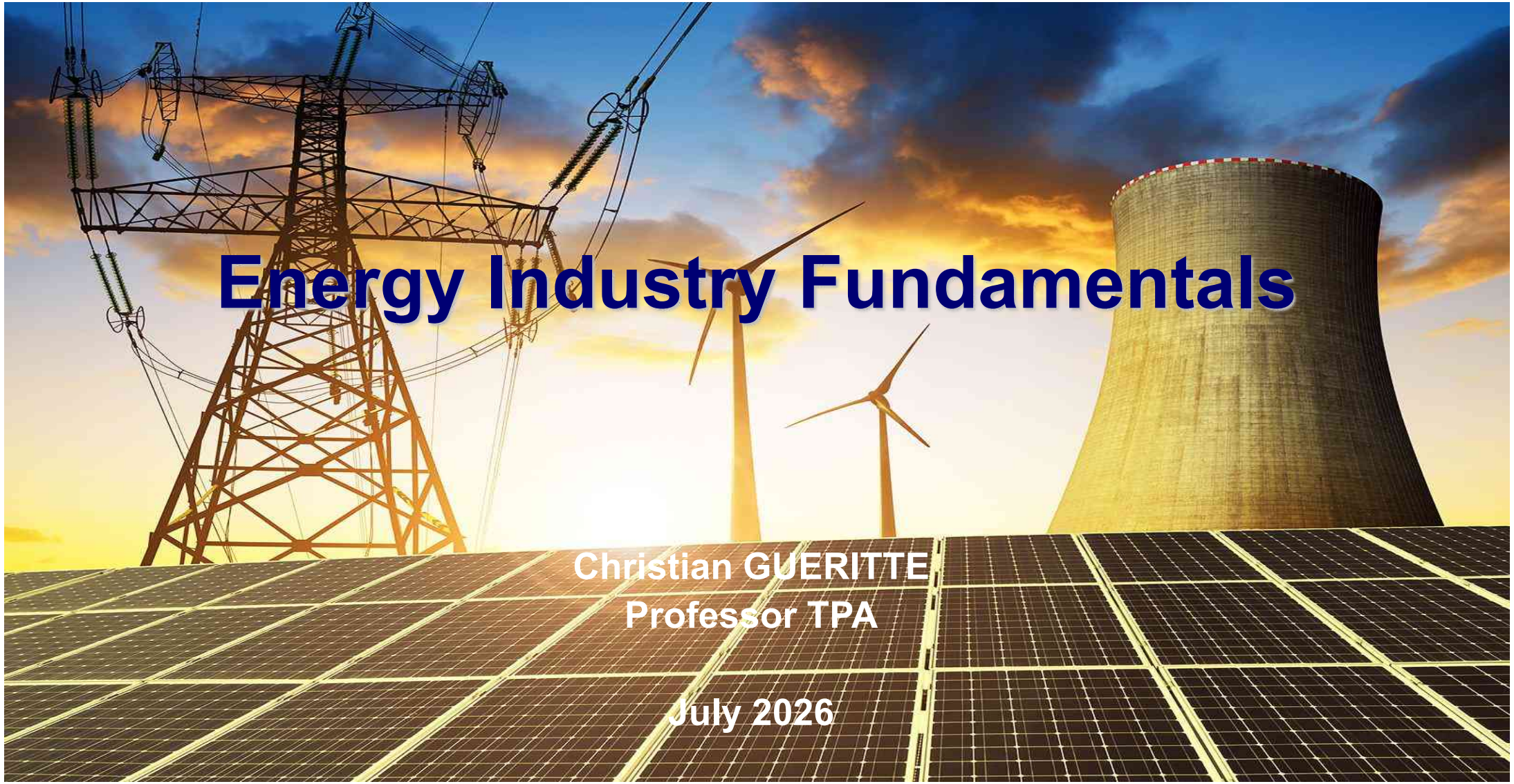
BOOK 2



Energy Industry Fundamentals

Christian GUERITTE
Professor TPA

July 2026





TPA
Sharing Experience

Building bridges between the oil industry and academic circles by delivering technical or business-related presentations by professors or experts.

OIL & GAS and ENERGY GLOBAL ISSUES
A Toolbox to understand the World of Energy in the Global Economy

The Toolbox is updated twice a year and benefits from the contributions of TPA Professors:

Coordination: GUÉRITTE Christian

LUC Benoît, PERSILLON Philippe, CORDIER Jean-Pierre, PAPÉE Jean, MULLER Isabelle, DEUTSCH Denis, FOURCADE Bernard, MICHAUD Olivier, SAINCRY Daniel, FOURNIÉ François, CHOUX Jean-Claude, BERA Jean, GUYS Philippe, DE MERVILLE Eric, DUMAY Jean-Michel, VALDELIÈVRE Michel, FONTAINE Jean-Marc, FERRIER Jérôme, BITEAU Jean-Jacques, PETTEAU Pascal, NOSJEAN Nicolas

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Energy



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1

Energy: a major element of economic development

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Let’s take into consideration the pertinent and powerful words from Adam Smith, scottish economist and philosopher of the 18th century, pioneer in the thinking of Political Economy

Adam Smith (1723 – 1790)



Theory of Moral Sentiments (1759)
The Wealth of Nations (1776)

Adam Smith - Human Nature & Economic Growth

- « The uniform, constant and uninterrupted efforts of every man to better his condition, the principle from which public and national as well as private opulence is originally derived, is frequently powerful enough to maintain the natural progress of things towards improvement, in spite both of the extravagance of government, and of the greatest errors of administration » (1)
- « Such is the delicacy of man alone, that no object is produced to his liking. He finds that in everything there is need for improvement…..The whole industry of human life is employed not in procuring the supply of our three humble necessities, food, clothes and lodging, but in procuring the conveniences of it according to the nicety and delicacy of our tastes » (2)

(1) Adam Smith -The Wealth of Nations, Book II, Chapter III

(2) Adam Smith - Lectures on Justice, Policy, Revenus and Arms

Adam Smith - The Invisible Hand

- « ….Every individual is continually exerting himself to find out the most advantageous employment for whatever capital he can command. It is his own advantage, indeed, and not that of the society which he has in view. But the study of his own advantage naturally, or rather necessarily, leads him to prefer that employment which is most advantageous to society….. He intends only his own game, and he is in this, as in many other cases, led by an invisible hand to promote an end which was not part of his intention » (3)

(3) Adam Smith -The Wealth of Nations , Book IV, chapter II

World macroeconomics features – Not a long quiet river!

The Covid-19 pandemia has fully affected macroeconomics data for the year 2020.
The World Economy has partially recovered in 2021.

The Russia-Ukraine war had and will have major effects in 2022 and later.

Also, the new turmoils affecting Middle-East in 2025 & 2026 together with the US president Trump's decisions (in particular affecting the US Effective Tariff Rates on imports) upsetting the world commercial activities in 2025 & 2026 will lead to important economical and geopolitical consequences for the world of Energy

World Economy in two pages – Year 2025 (1)

(GDP figures may vary according to sources, IMF, World Bank, UN and evolve upon time)

Basic World Statistics	EU-27	USA	Russia	Japan	China	India	World
Population (million) (Mid 2025) Rank	**451** (3)	**342** (4)	**144** (10)	**123** (12)	**1 407** (2)	**1 464** (1)	**8 215**
GDP, Nominal (T$) Year 2025 (Rank) (World Bank, July 2026)	**21,2*** (2)	**30,8** (1)	**2,6** (6)	**4,4** (4)	**19,5** (3)	**4,0** (5)	**118,3**
GDP, PPP (T$) Year 2025 (Rank) (World Bank, July 2026)	**29,6*** (3)	**30,8** (2)	**7,2** (5)	**6,8** (6)	**41,3** (1)	**17,2** (4)	**211,2**
GDP per capita (Year 2025) ($/Capita, nominal) ($/Capita, PPP) (World Bank, July 2026)	47 100* **65 500***	90 000 **90 000**	17 500 **49 600**	36 000 **55 400**	13 900 **29 300**	2 700 **11 700**	14 400 **25 700**

Source: Population: United Nations/World Bank, GDP: World Bank - July 2026, rounded figures.
For ranking purposes, EU-27 (excl. UK) considered as one block.
* EU GDP Nominal: 18,8 T€. Nominal per capita: 41600 €. Source: Eurostat July 2026. In the table, Values in US$. 1€=1,13$ Average rate 2025

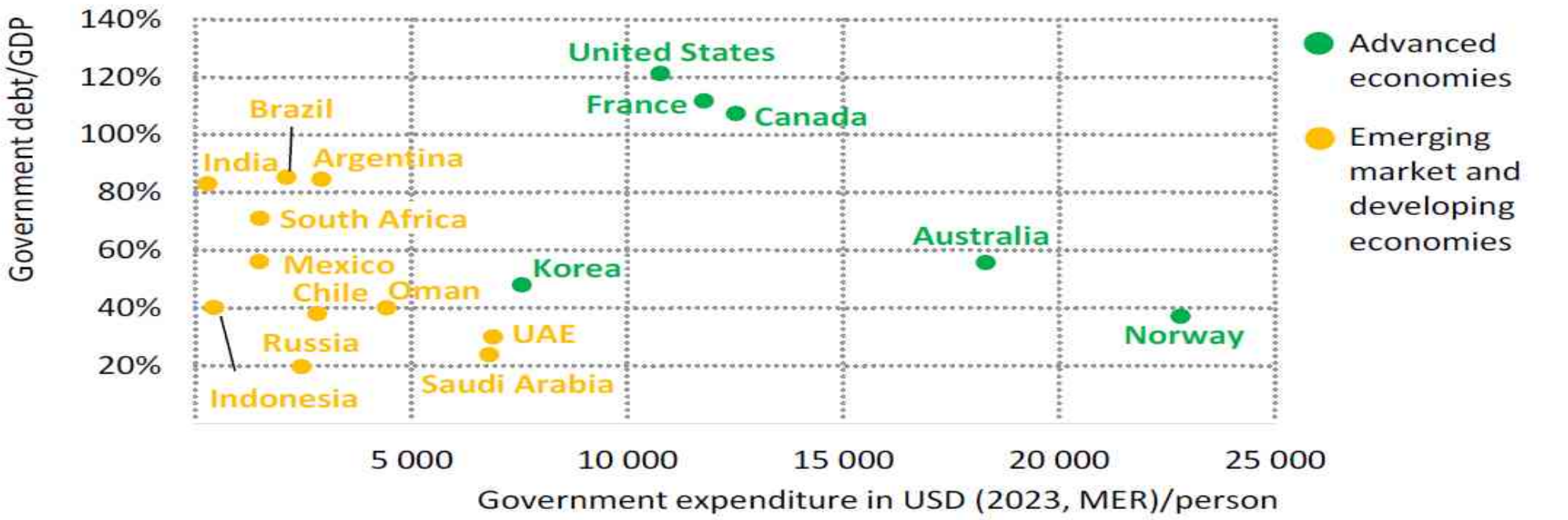
GDP : Gross Domestic Product
PPP : Purchasing Power Parity
T$: trillion $ (1T = 10^{12} $)

World Economy in two pages – Year 2025 (2)

Basic World Statistics	EU-27	USA	Russia	Japan	China	India	World
GDP (Nominal) 2025 (GUS$) Rank	21 200 (2)	30 800 (1)	2 600 (6)	4 400 (4)	19 500 (3)	4 000 (5)	118 300 211 200 PPP
National Budget Expenditures (2024)* (GUS$)	10 530 9 320 G€**	10 990	820	1 720	6 180	1 130	# 40 000
National Budget Expenditures (2024)* (% of GDP)	49,7	37,5	37,3	42,2	33,9	29,0	# 35
Public Debt 2025 (% of GDP) *	80**	124	17	206	99	84	
Military Spendings**** (2025) (GUS$)	443 392 G€	954	190	62	336	92	2 887 (+2,9% vs 2024
Current Account Balance (2025)*** (GUS $)	413 365 G€	-1116	43	216	735	-16	

* Source: IMF Data mapper June 2026
** Year 2025/Eurostat 2026
*** Current Account Balance = Net trade in goods & services + net transfer payments to and from the rest of the world. Source: IMF Data mapper 2026.
**** SIPRI (Stockholm International Peace Research Institute) 2026. For EU-27, European Commission 2026. For EU-27, +63% from 2020 to 2025.
Nota: The resulting Current Account Balance for the World should theoretically be equal to zero (For every surplus on a national current account there is, in principle, an equal deficit somewhere in the world) Actually, it is not the case due to many discrepancies in the evaluations of national Current Accounts Balances.

Reminder - Debt Ratios & Government Expenditures 2023



IEA. CC BY 4.0.

Some advanced economies have relatively high government debt burdens, but they also enjoy better access to debt than others, and are able access it at lower cost

Notes: GDP = gross domestic product; UAE = United Arab Emirates; MER = market exchange rate. "Government debt" = gross public debt.

Sources: World Development Indicators and IMF (2024a)

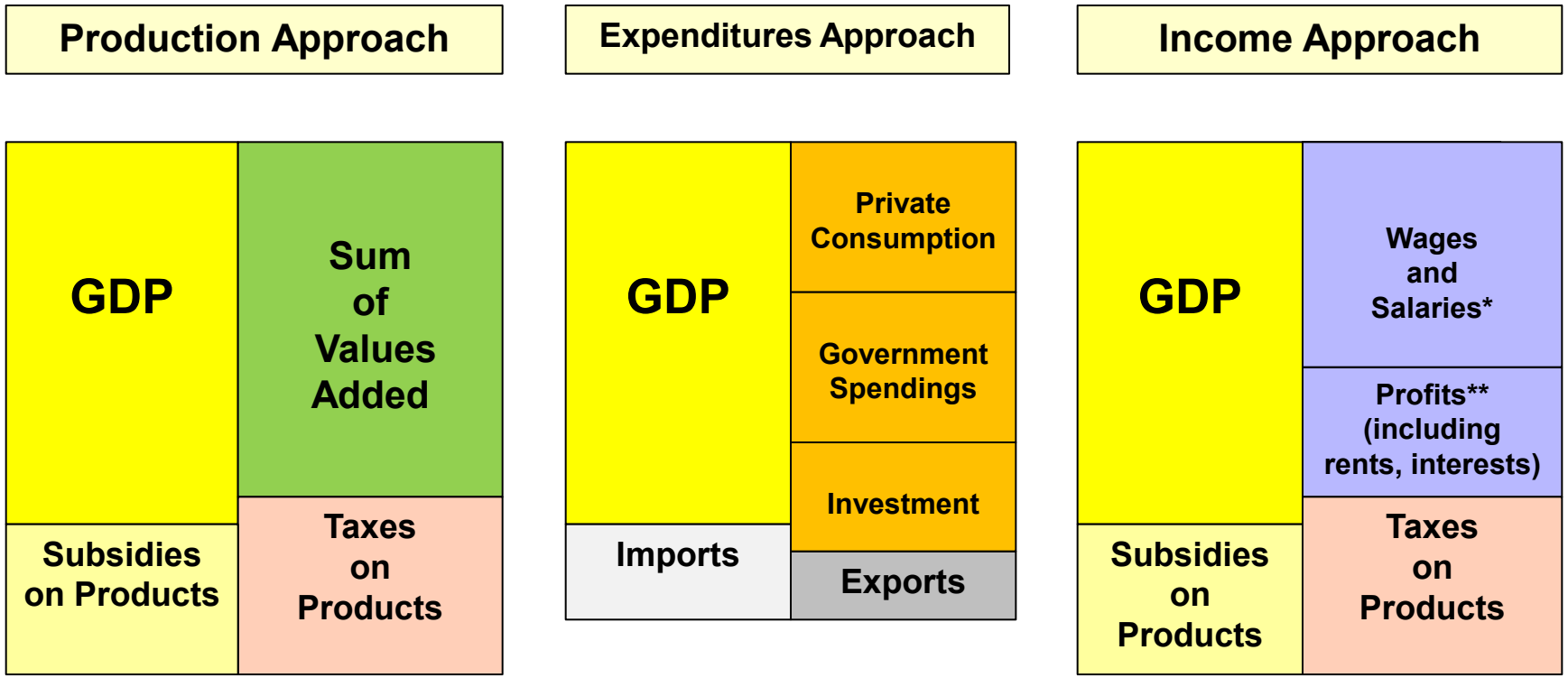
Source: IEA Strategies for Affordable and Fair Clean Energy Transition - June 2024
GDP expressed in nominal value

Reminder: European Union EU-27 & Euro Area EA-19

Countries EU-28	EA-19	Countries EU-28	EA-19
Belgium	*	Lithuania	*
Bulgaria		Luxembourg	*
The Czech Republic		Hungary	
Denmark		Malta	*
Germany	*	The Netherlands	*
Estonia	*	Austria	*
Ireland	*	Poland	
Greece	*	Portugal	*
Spain	*	Romania	
France	*	Slovenia	*
Croatia		Slovakia	*
Italy	*	Finland	*
Cyprus	*	Sweden	
Latvia	*	The United Kingdom	Exit in 2019

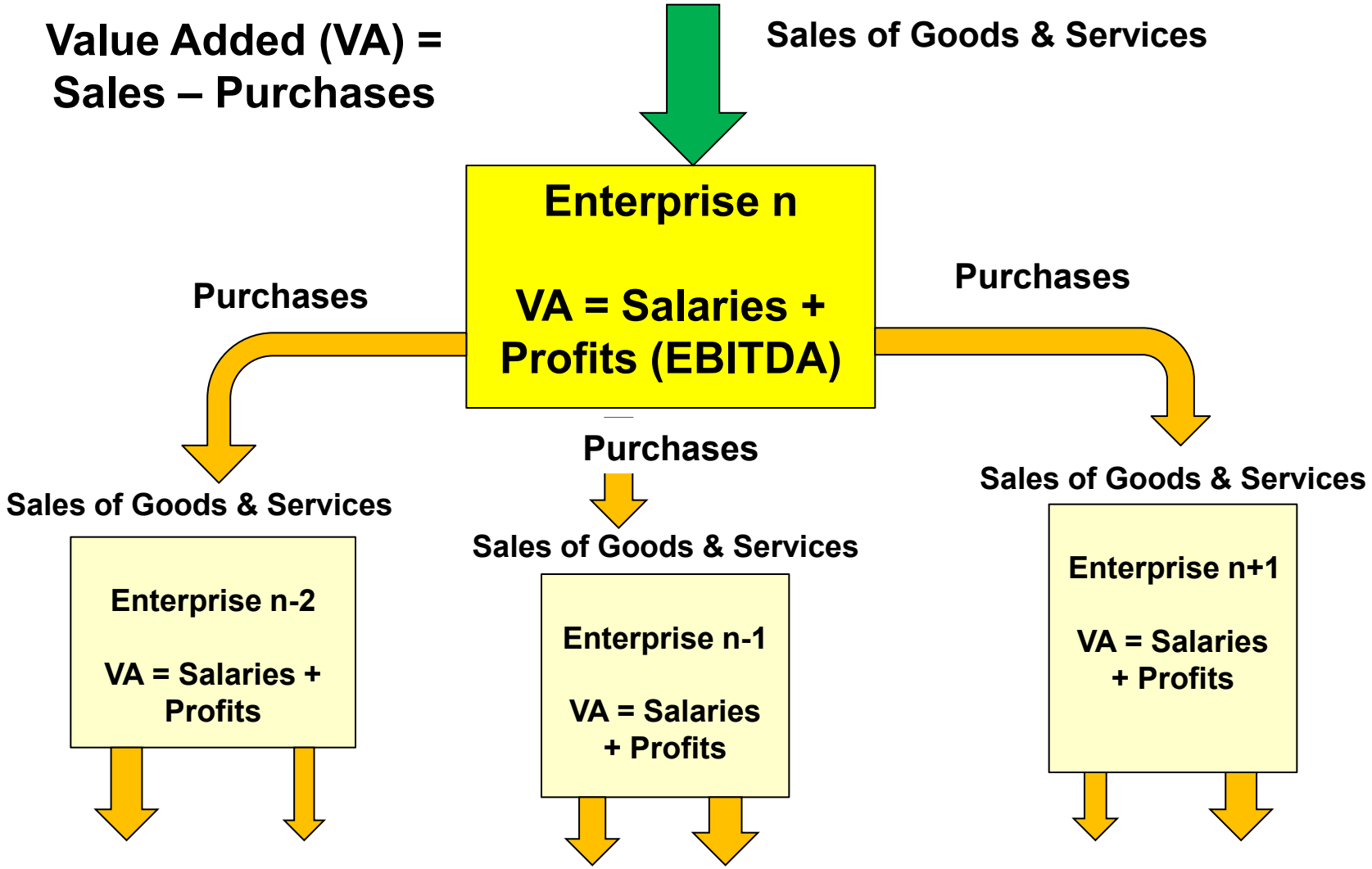
Nota: UK left EU in 2019

Definition of GDP (1)



* Gross salaries (Compensation of employees)
** Profits before Income Taxes and Depreciation (Gross operating surplus)
Nota: GDP can be expressed in nominal (current $ or constant $) or PPP (current $ or constant $)

Definition of GDP (2)
Production & Income approach



Definition of GDP (3)

GDP = Gross Domestic Product

VA = Value Added
S = Sales
P = Purchases (Internal Consumption)
COE = Compensation of Employees (Gross salaries, wages)
INT = Interests/rents
DEP = Depreciation
TOP = Taxes on Products
SOP = Subsidies on Products
EBIT = Earnings before Income Tax = Profit before Income Tax
EBITDA = Earnings before Inc. Tax, Deprec. & Amortization & incl. Inter. /rents

PC = Private Consumption
GS = Government Spendings
INV = Investment
E = Exports
I = Imports

Definition of GDP (4)

GDP = VA + TOP – SOP ***(Production Approach)***

VA = S – P

EBIT = S – P – COE – INT – DEP →
VA = S – P = COE + EBIT + INT + DEP →
VA = COE + EBITDA →
GDP = COE + EBITDA + TOP – SOP ***(Income Approach)***

Production = Consumption →
GDP = PC + GS + INV + E – I ***(Expenditures Approach)***

Definition of GDP (5)

1) PRODUCTION APPROACH

For any Enterprise/Business: Value Added = Sales - Purchases

For the National Economy: Value Added = ∑ (Sales – Purchases)

2) INCOME APPROACH

For any Enterprise/Business: Earnings before Income Tax = Sales - Purchases - Compensation of Employees - Interests/Rents - Depreciation

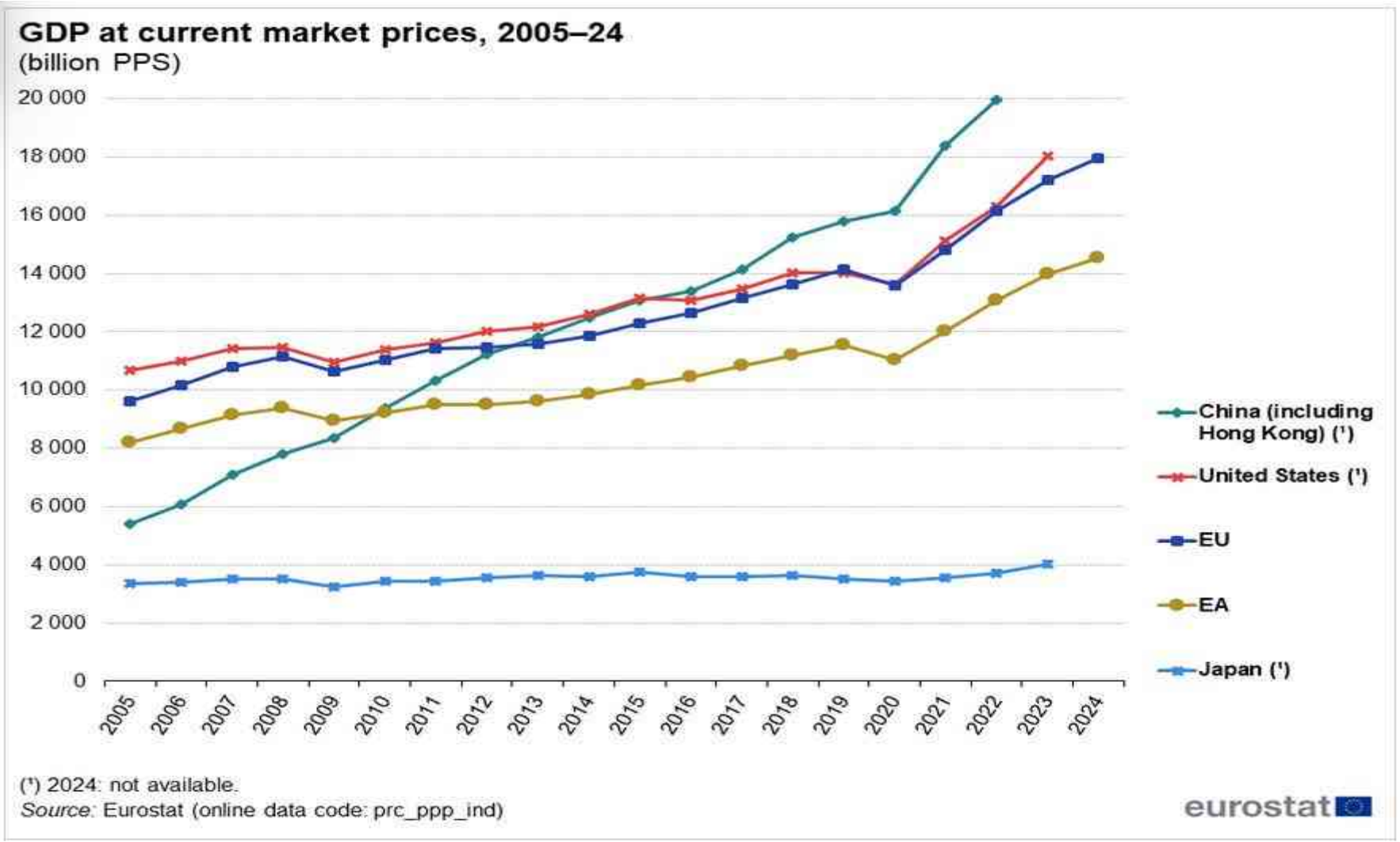
For the National Economy: Value Added = ∑(Sales - Purchases) = ∑Compensation of Employees + ∑Earnings before Income Tax and Depreciation (including Interests/Rents) + ∑(Taxes on Products – Subsidies on Products)

3) EXPEDITURES APPROACH

For the National Economy, Production = Consumption: Value Added = Private Consumption + Government Spendings + Investment + (Exports – Imports)

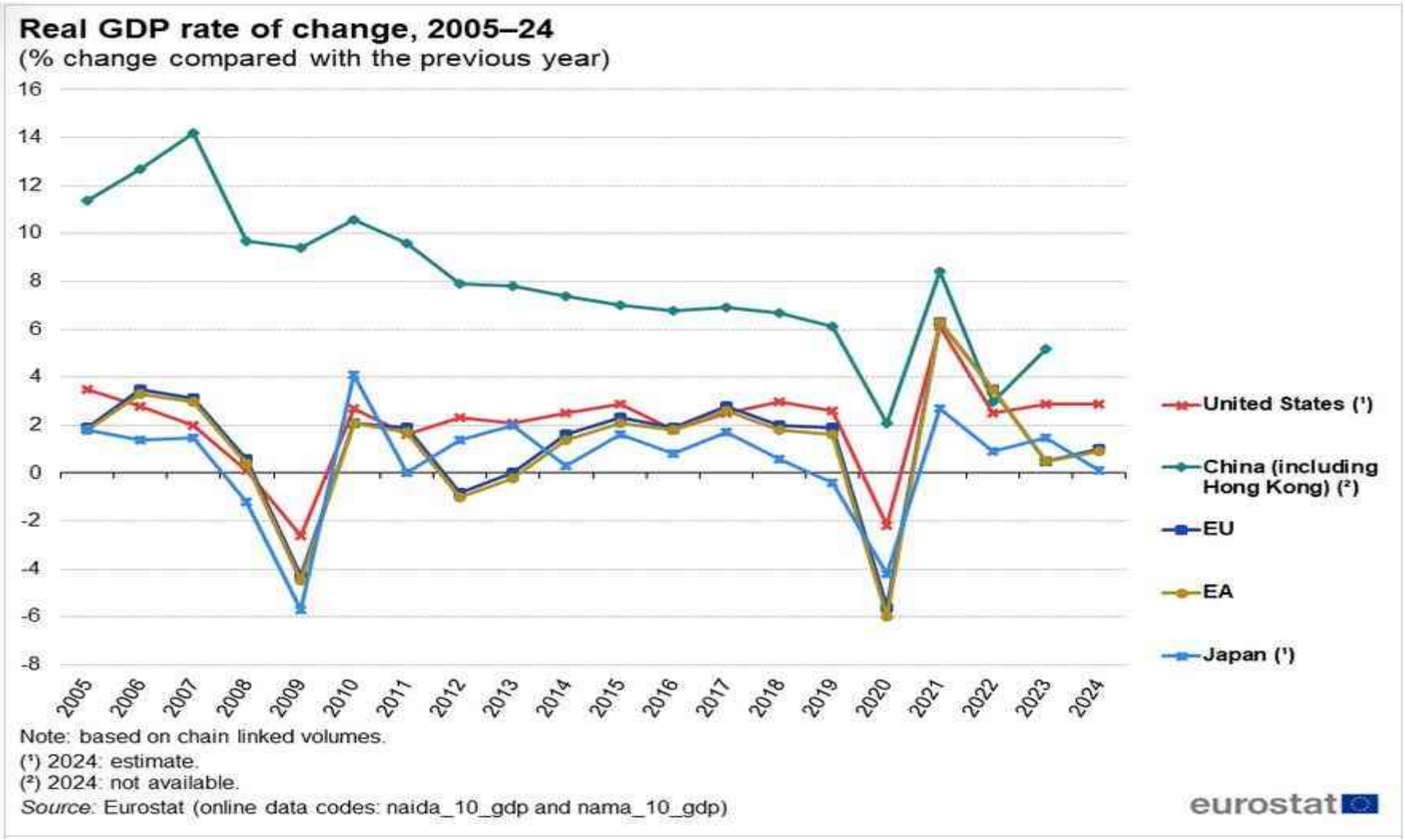
GDP at current Price of selected countries by Eurostat

Year 2005 to Year 2024 – Warning: GDP expressed in Euro PPS



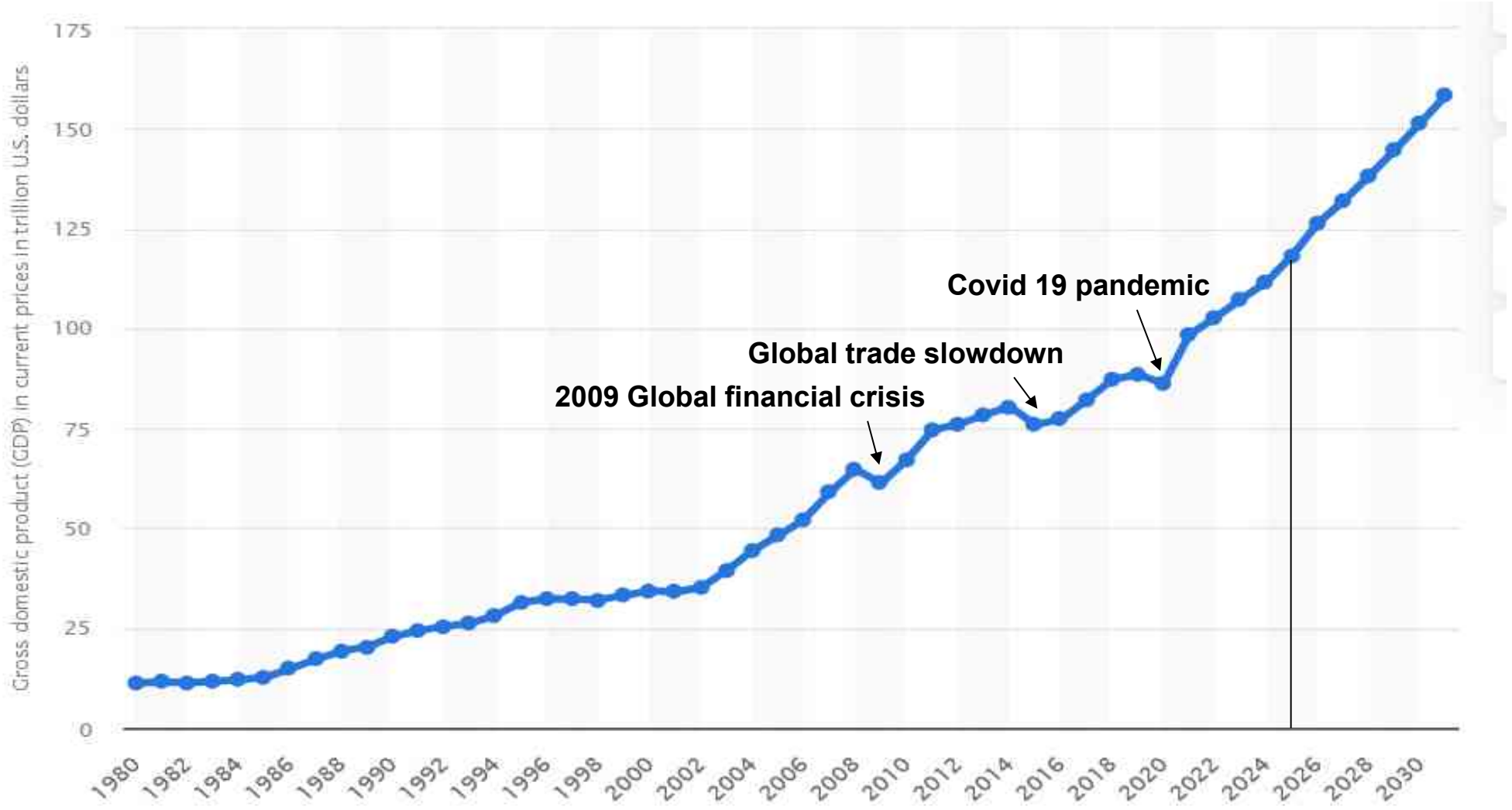
Source: Eurostat June 2025 - PPS: Purchasing Power Standards
PPS is an artificial, fictive currency which at the level of the EU equals one euro.
EU: European - Union EA: Euro Area

GDP rate of change of selected countries
Year 2005 to Year 2024



Source: Eurostat June 2025 - PPS: Purchasing Power Standards
PPS is an artificial, fictive currency which at the level of the EU equals one euro.
EU: European Union - EA: Euro Area

World GDP at current prices from 1980 to 2030 by Statista
World GDP nominal 2025 = 118 T$ (est.)

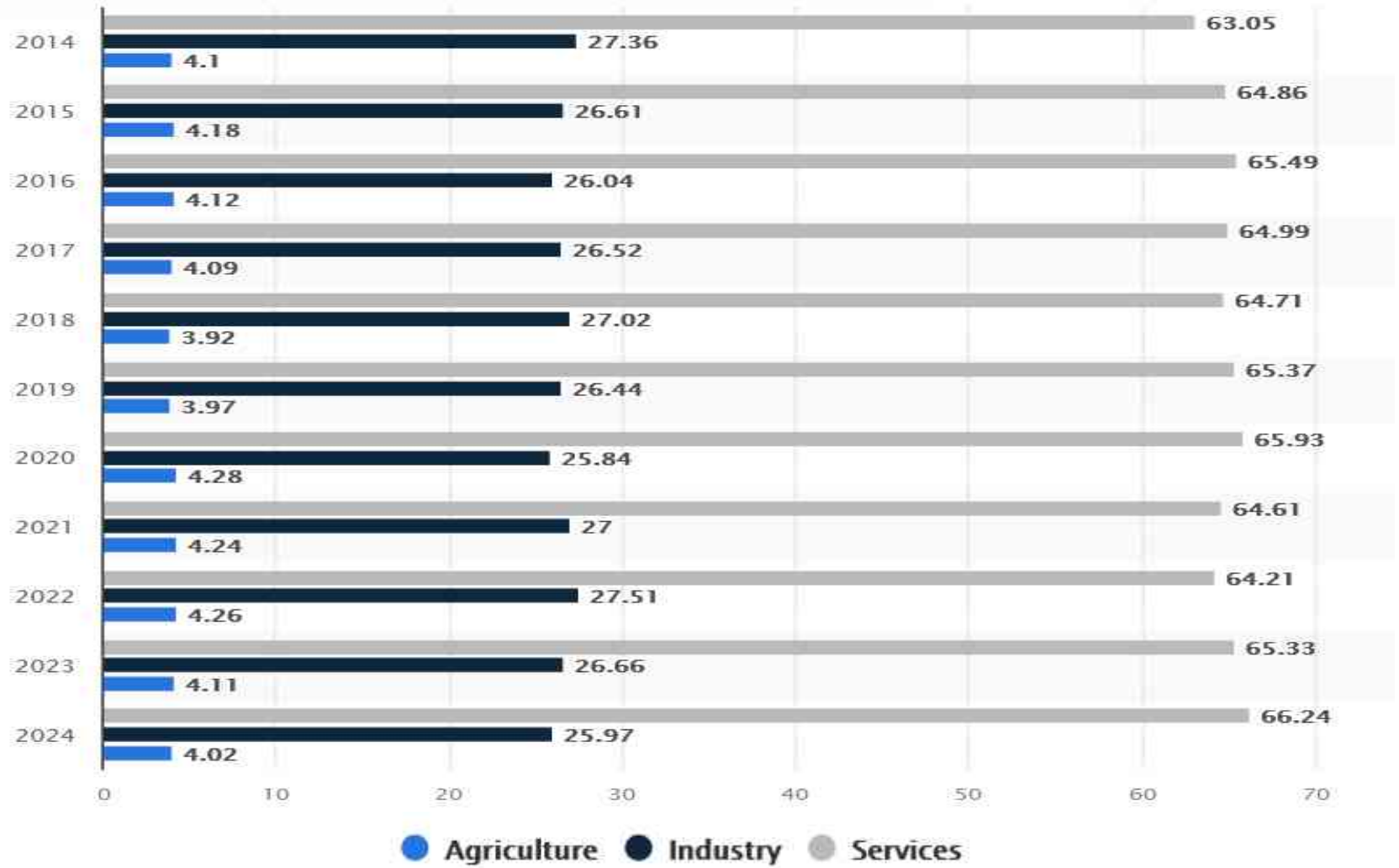


Source: Statista 2026
One scenario 2025 - 2030

Share of economic sectors in the world GDP

GDP at current price - Year 2014 to Year 2024

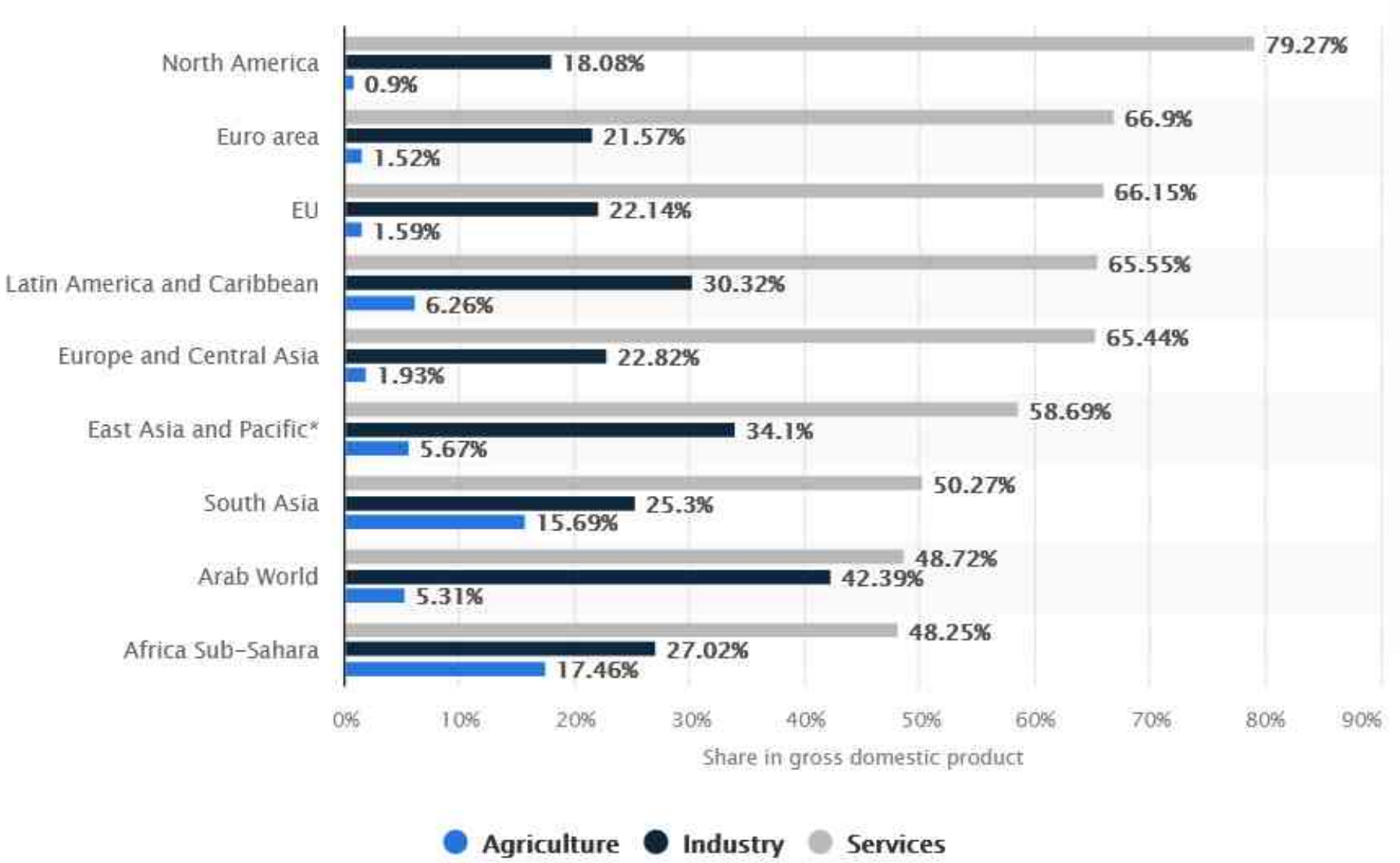
In 2024, Industry represents # 26% of the world GDP out of which # 6% from the Energy sector



Source: Statista July 2025

Share of economic sectors in the GDP for selected Regions

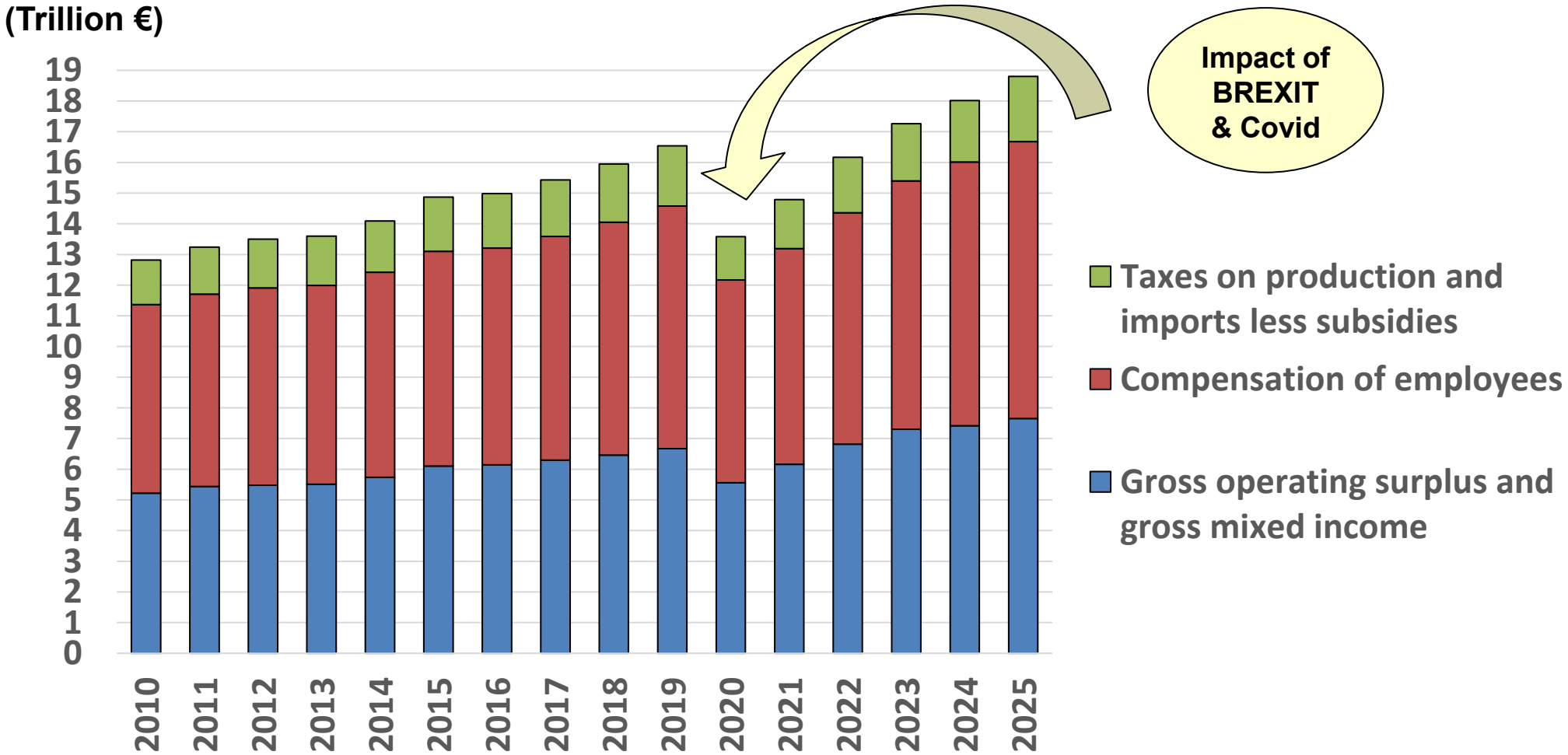
GDP at current price – Year 2024



Source: Statista July 2025

EU GDP Structure

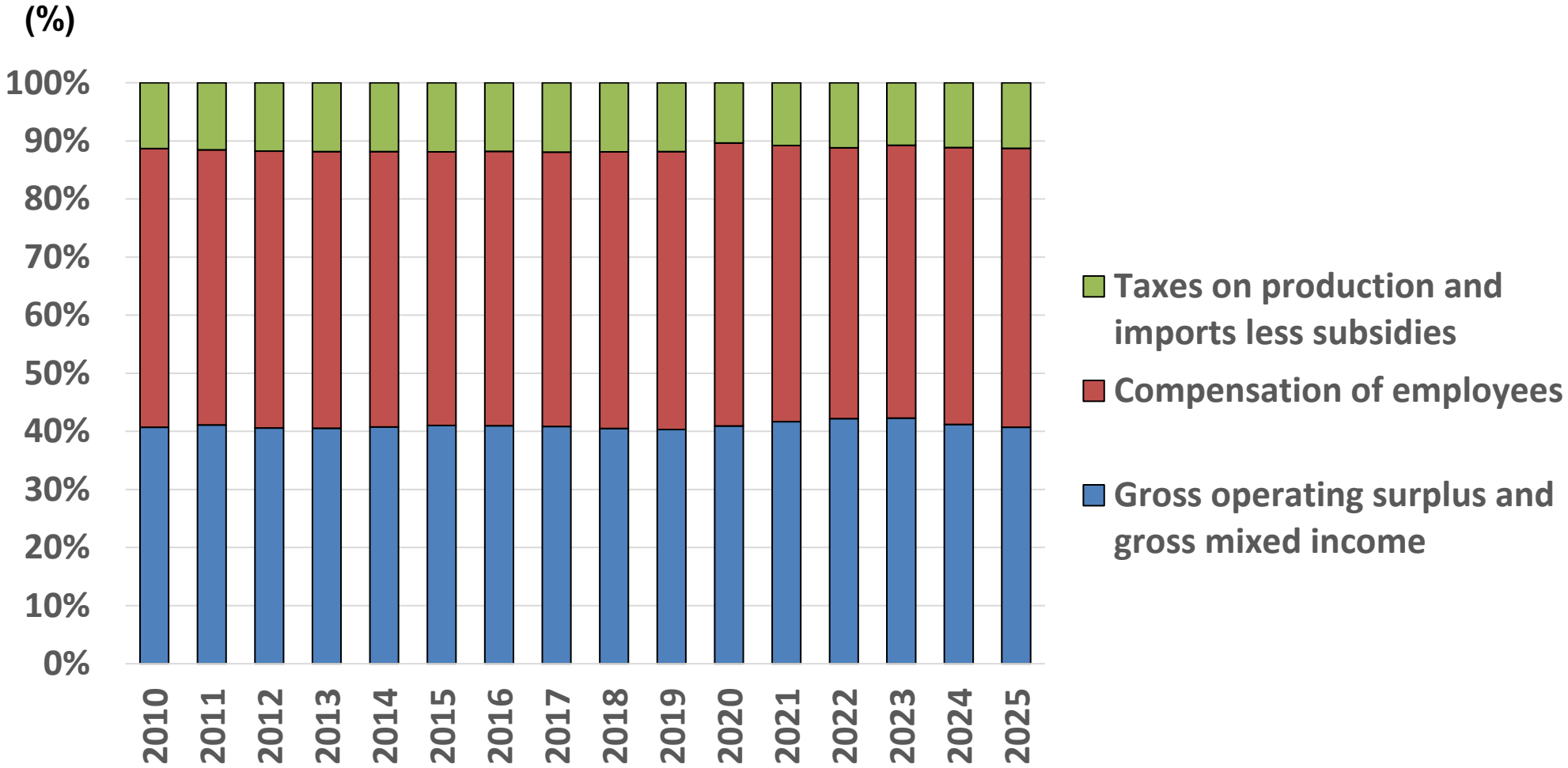
Income Approach / Share of Main Aggregates (Value)
EU-28/EU-27 – Evolution 2010-2025



Source: Data from Eurostat 2026
Nota: Croatia joined EU in 2013
UK left EU end 2019

EU GDP Structure

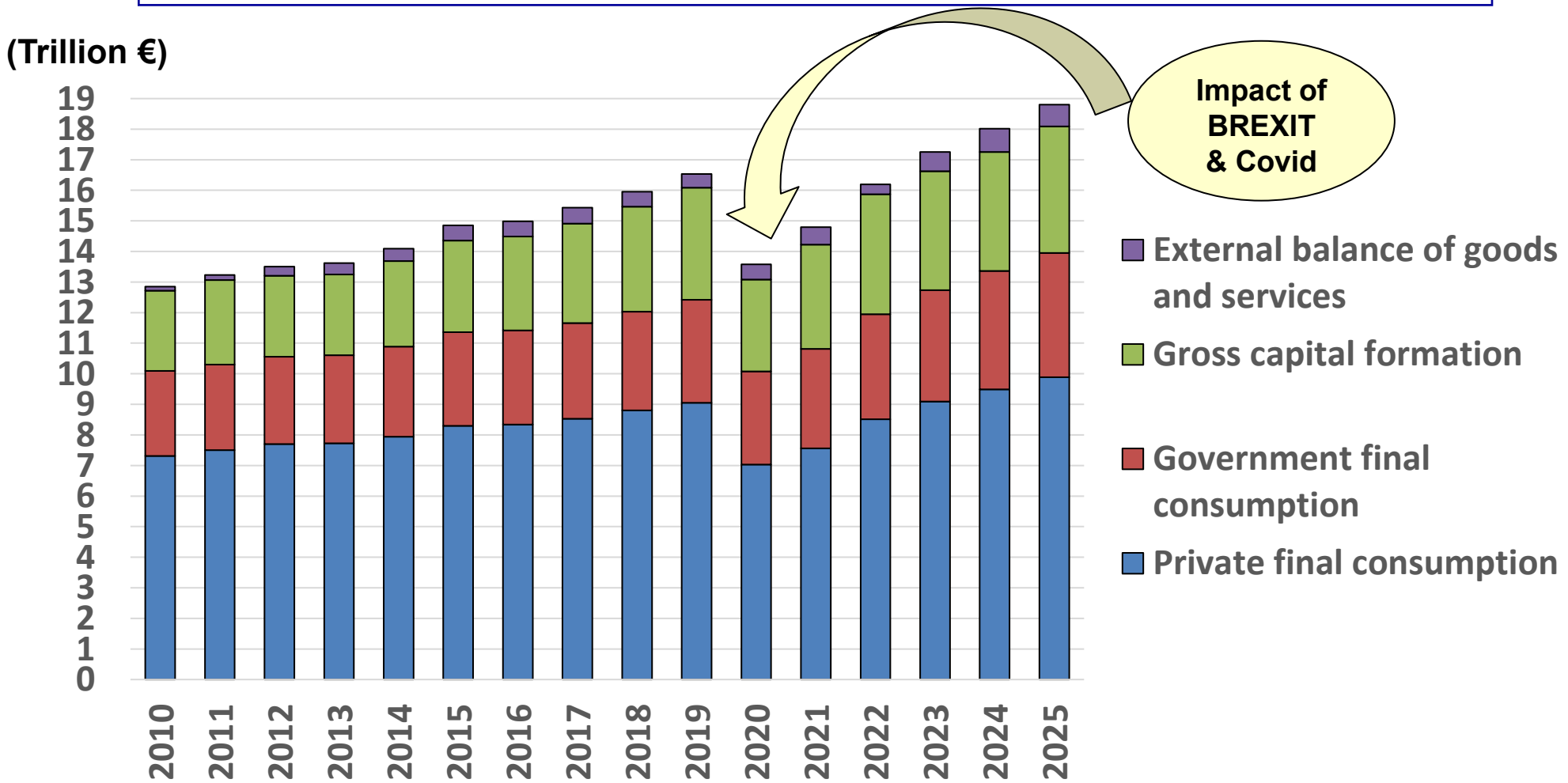
Income Approach / Share of Main Aggregates (Percentage)
EU-28/EU-27 – Evolution 2010-2025



Source: Data from Eurostat 2026
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EU GDP Structure

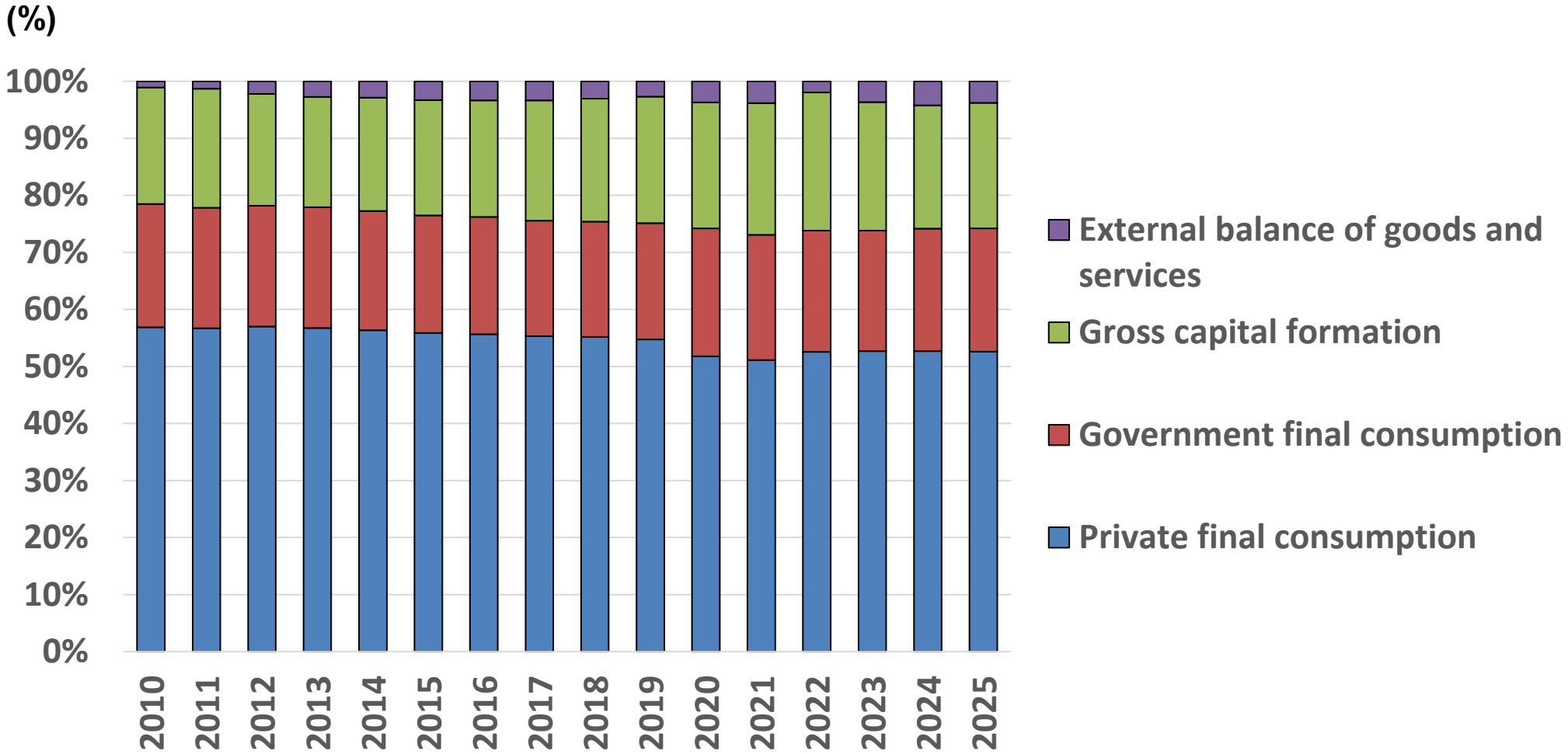
Expenditures Approach / Share of Main Aggregates (Value)
EU-28/EU-27 – Evolution 2010-2025



Source: Data from Eurostat 2026
Inventories changes included in Gross capital formation
Nota: Croatia joined EU in 2013 - UK left EU end 2019

EU GDP Structure

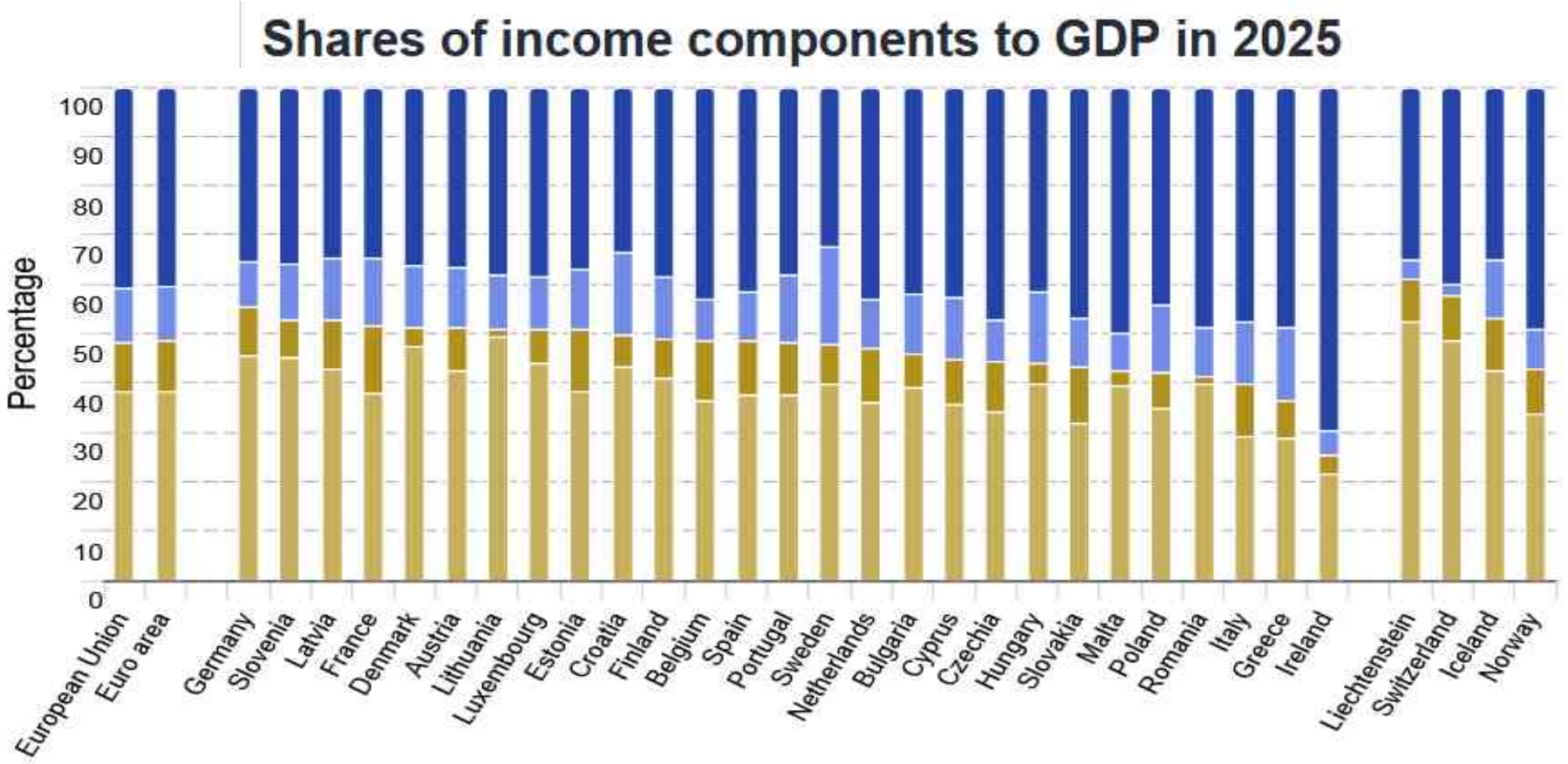
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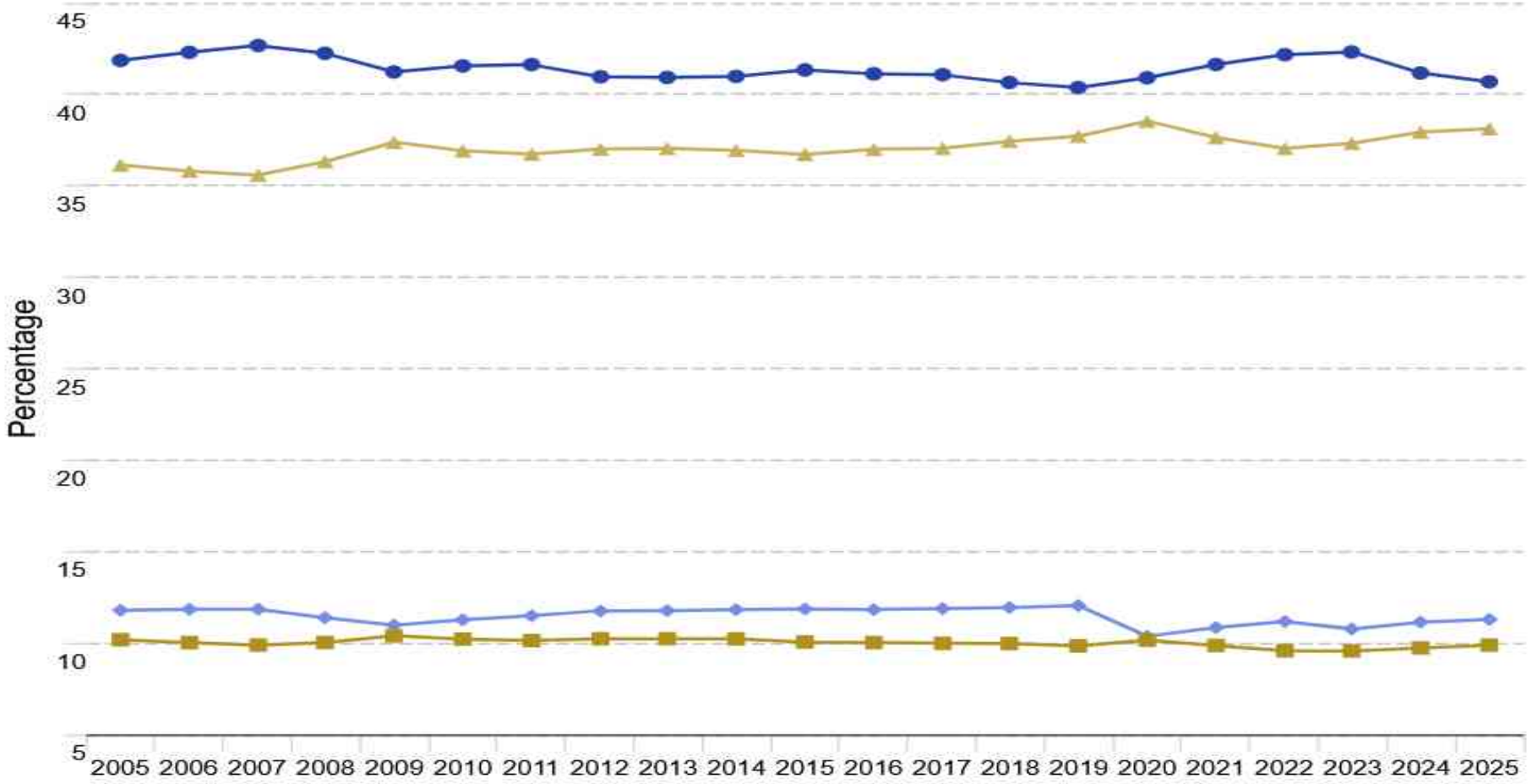
Income Approach / Share of Main Aggregates by countries
EU-27 – Year 2025



Source: Eurostat 2026

EU GDP Structure

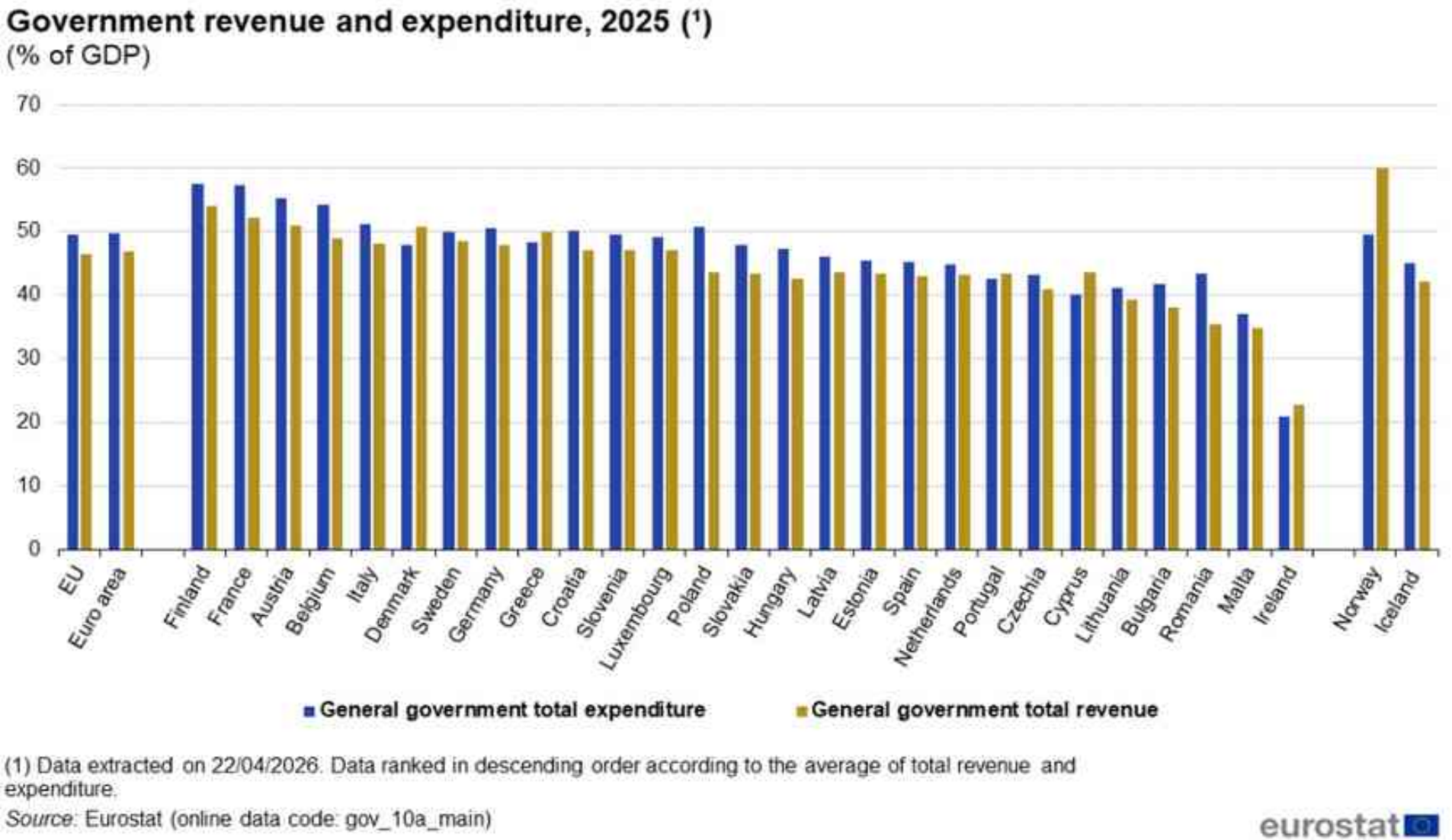
Income Approach / Evolution of Share of Main Aggregates 2005 - 2025



Source: Eurostat - nama_10_gdp

Source: Eurostat 2026

EU Government Revenue and Expenditure – 2025 (% of GDP)



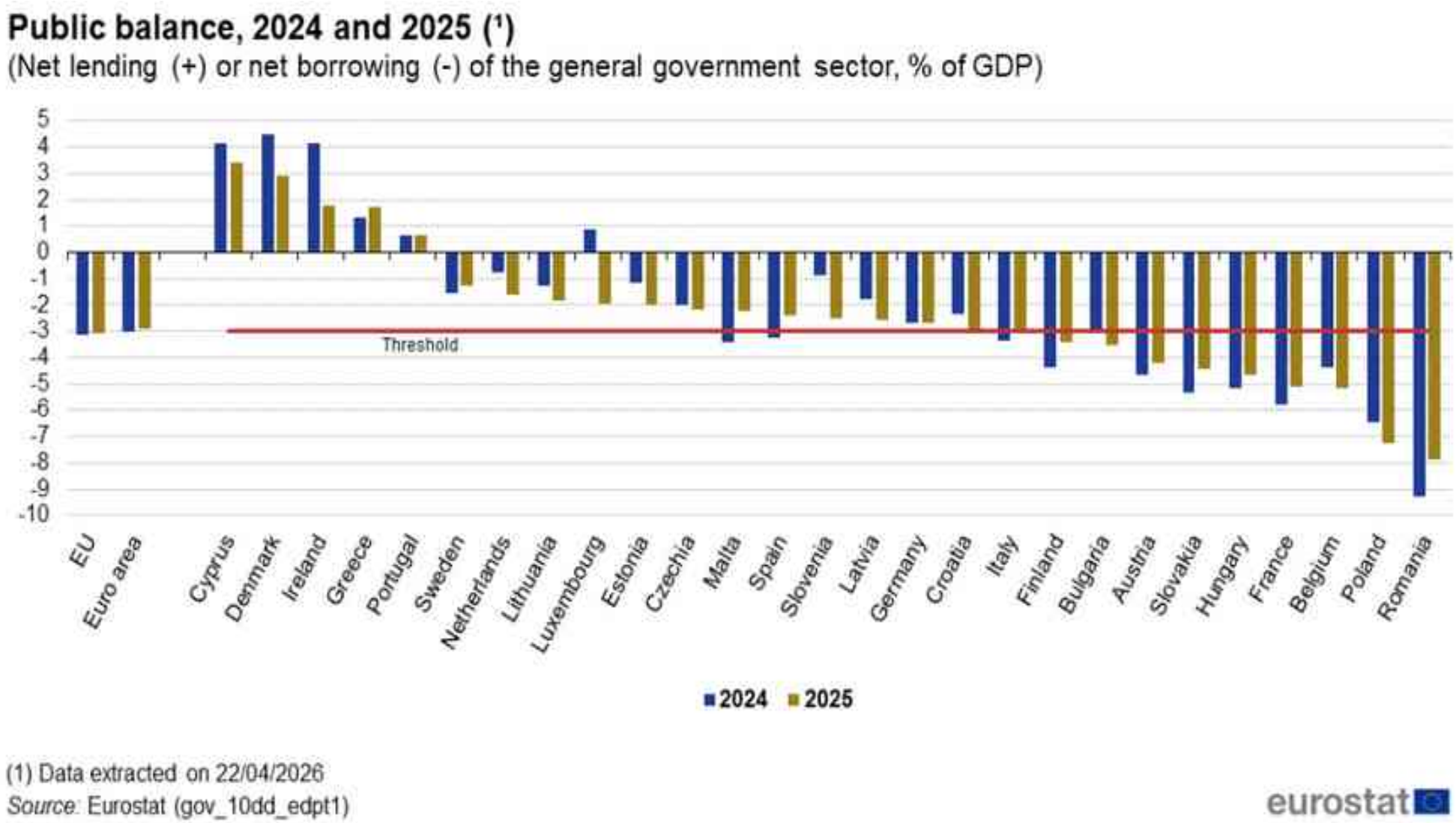
(1) Data extracted on 22/04/2026. Data ranked in descending order according to the average of total revenue and expenditure.

Source: Eurostat (online data code: gov_10a_main)

eurostat

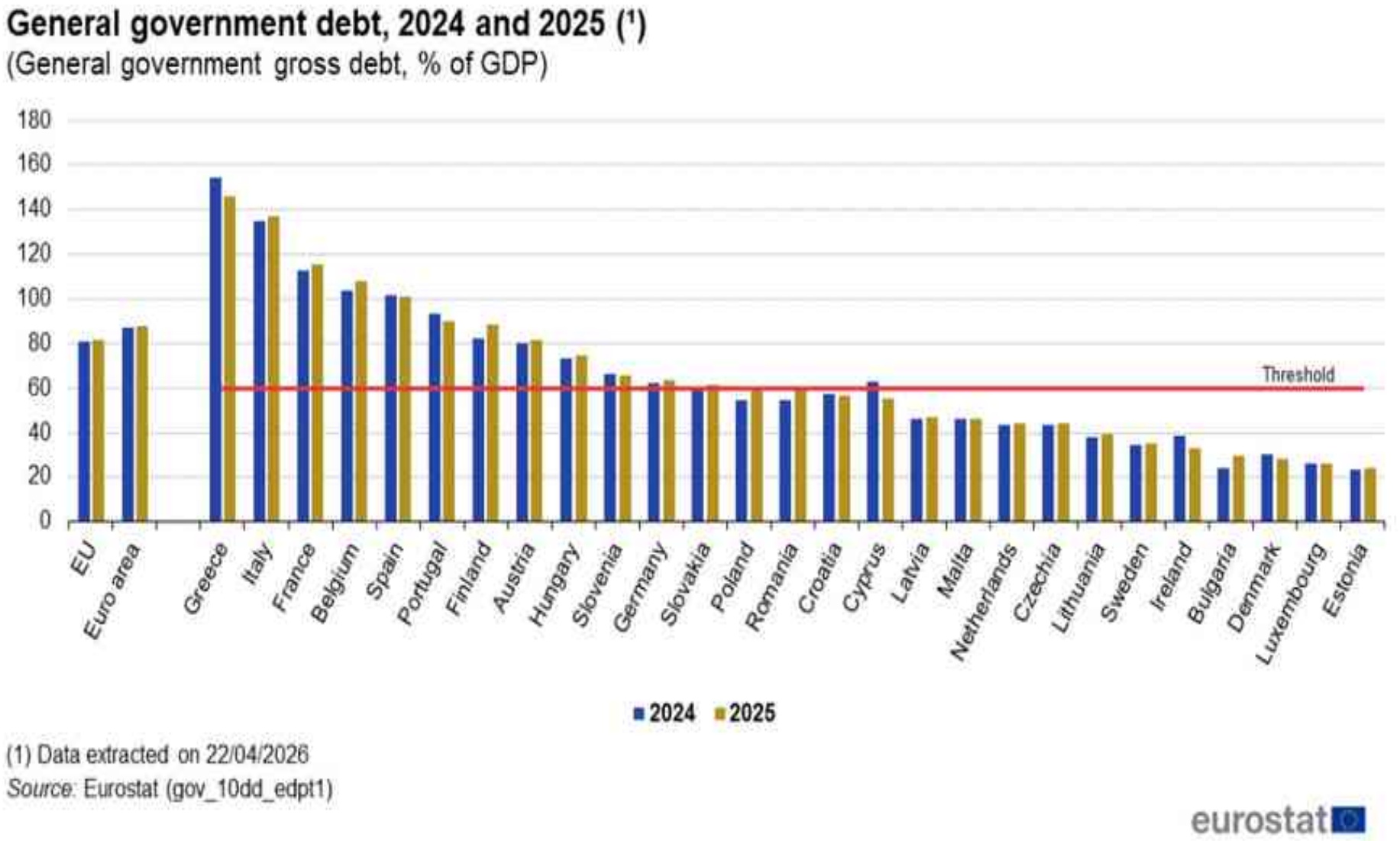
Source: Eurostat 2026

EU Public Balance, 2024 & 2025 (% of GDP)



Source: Eurostat 2026

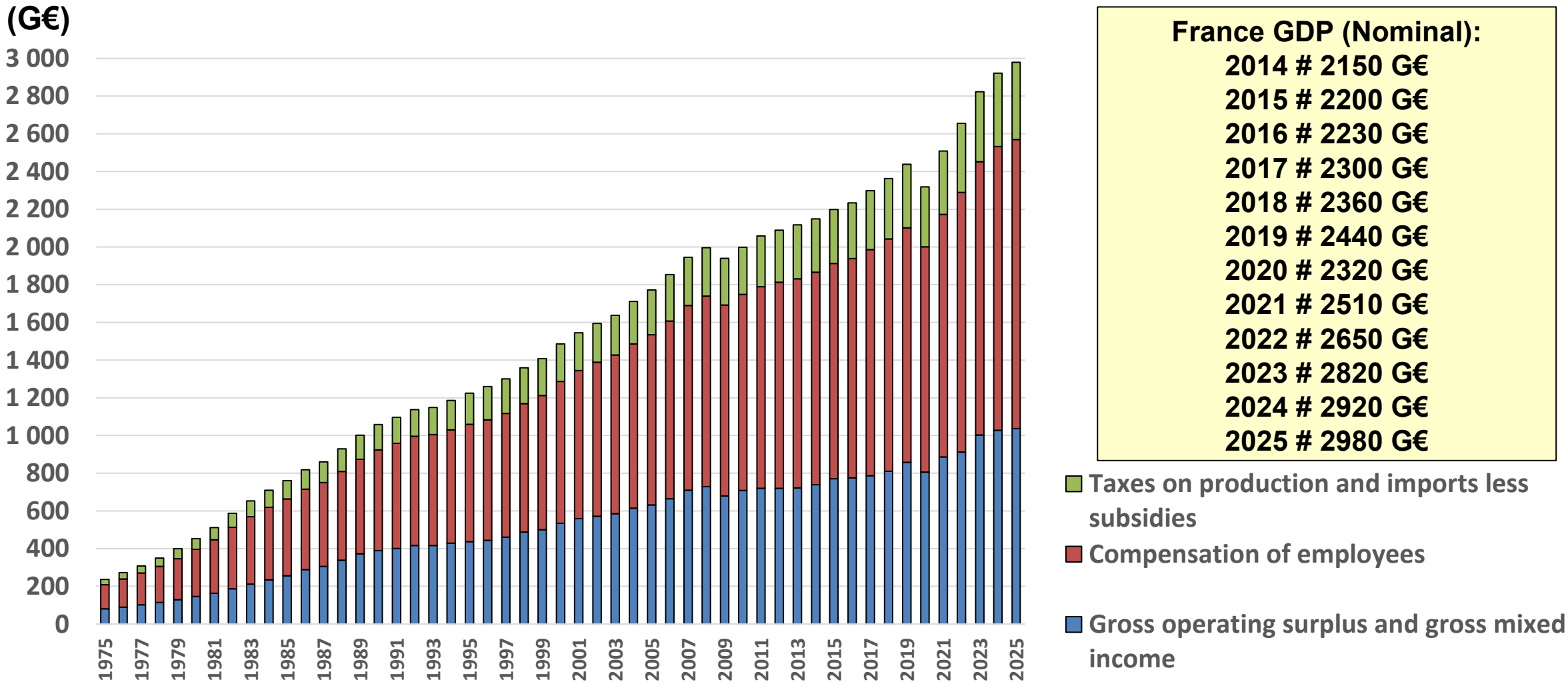
EU General Government Debt 2004 - 2025



Source: Eurostat 2026

France GDP Structure (Nominal) – Income Approach

Share of Salaries, Profits & Taxes (net) on Production in GDP France
Evolution 1975 – 2025 Real GDP Growth in 2025 = 0,9 %



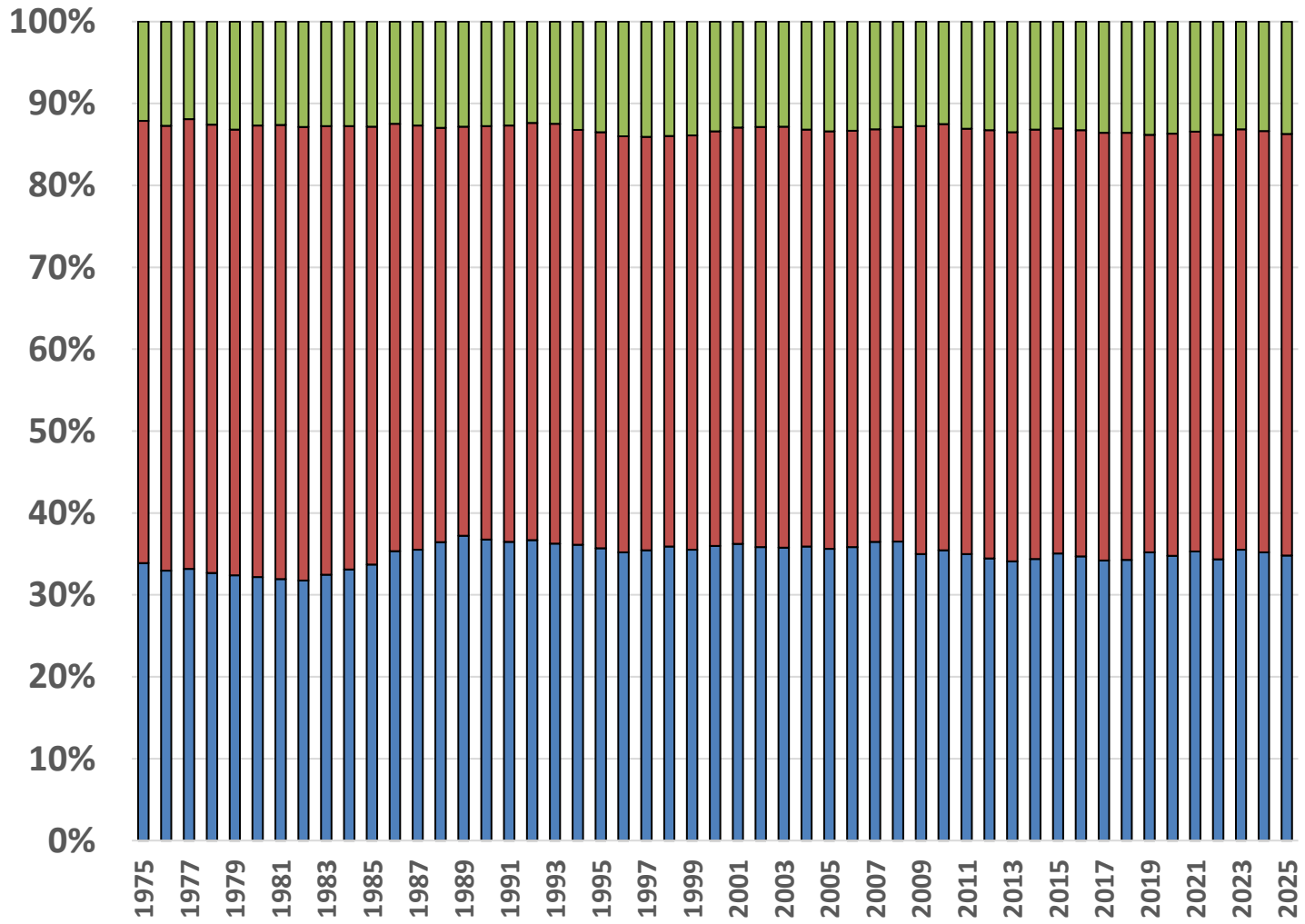
France GDP (Nominal):

2014 # 2150 G€
2015 # 2200 G€
2016 # 2230 G€
2017 # 2300 G€
2018 # 2360 G€
2019 # 2440 G€
2020 # 2320 G€
2021 # 2510 G€
2022 # 2650 G€
2023 # 2820 G€
2024 # 2920 G€
2025 # 2980 G€

Source: Data from Eurostat 2026

France GDP Structure – Income Approach

Share of Salaries, Profits & Taxes (net) on Production in GDP France
Evolution 1975 – 2025 Real GDP Growth in 2025 = 0,9 %



France GDP (Nominal):

2014 # 2150 G€
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2022 # 2650 G€
2023 # 2820 G€
2024 # 2920 G€
2025 # 2980 G€

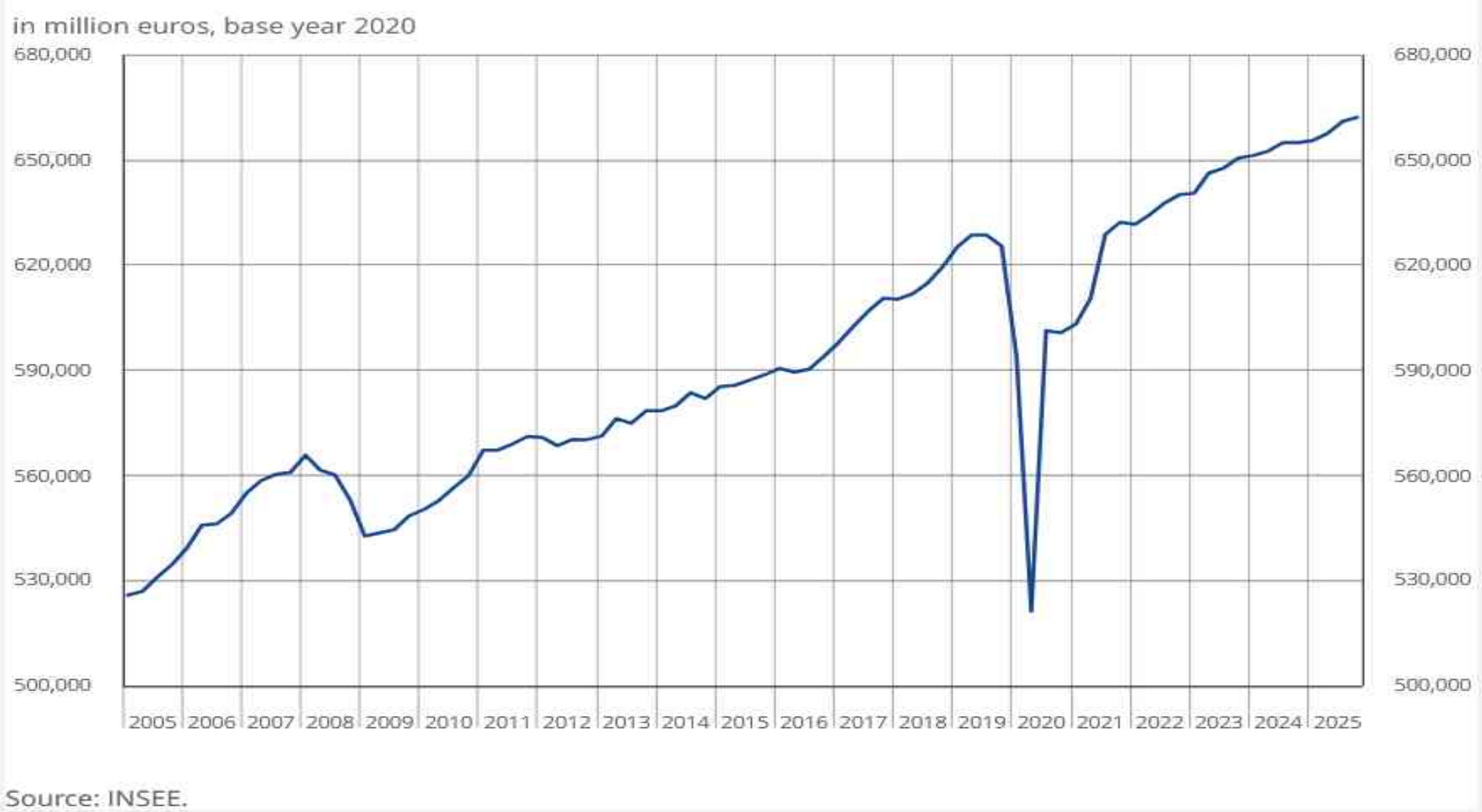
- Taxes on production and imports less subsidies
- Compensation of employees
- Gross operating surplus and gross mixed income

Source: Data from Eurostat 2026

France Economy 2025:

GDP # 2980 G€
Public Deficit # 153 G€ = 5,1% of GDP (-12% vs 2024)
General government Debt # 3450 G€ = 116% of GDP

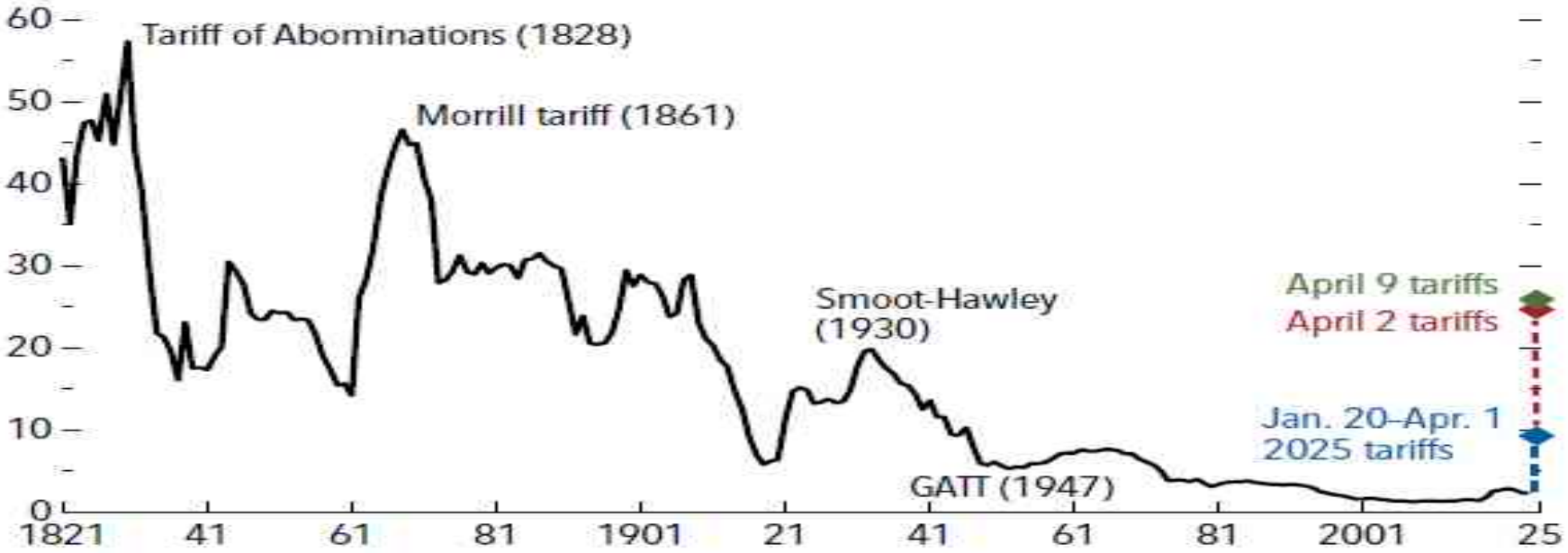
France quaterly GDP Evolution 2005 – 2025 (M€)



Source: INSEE 2026
SA-WDA : Adjusted for Seasonal variations and Working Days effects

Evolution of the Global Economy by IMF 2025 with an illustration of Tariff & Trade US conditions evolution (Reference to Trump's Administration decisions in 2025)

Tariff & Trade: Historical evolution: Up's and Down's! – The Trump's effect for 2025
US Effective Tariff Rates on All Imports (%) – Back to the Great Depression?!

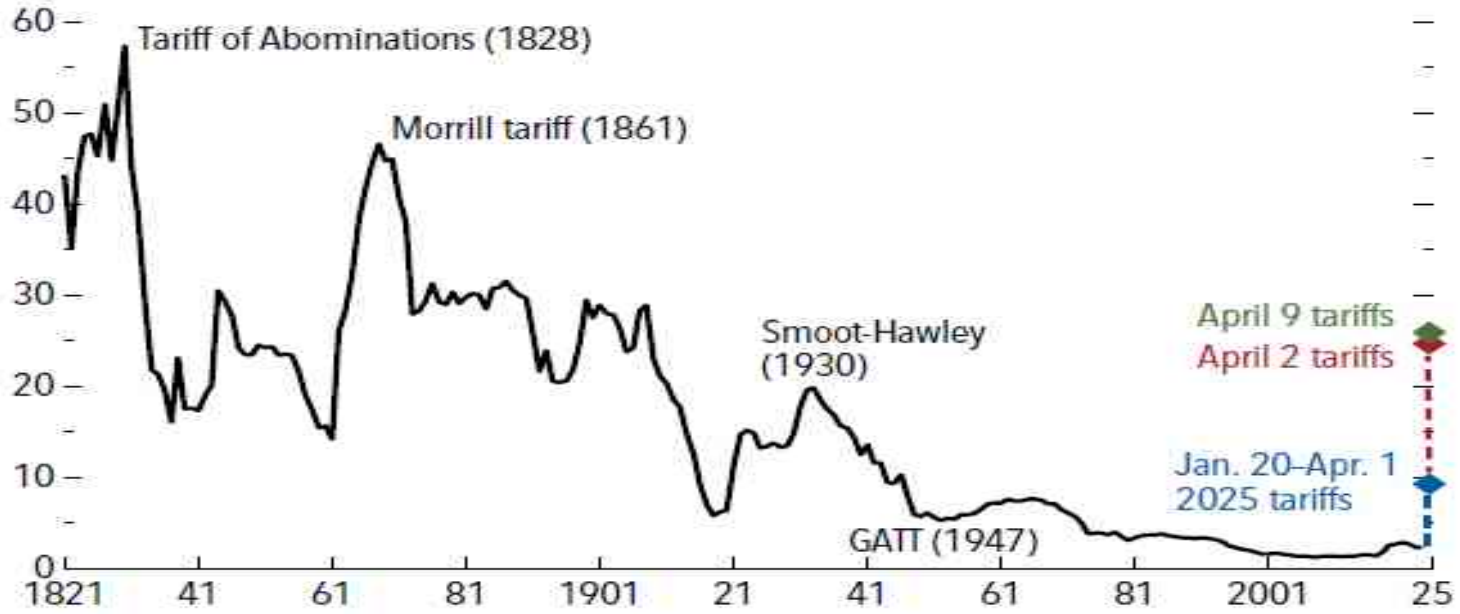


Sources: US Bureau of the Census, *Historical Statistics of the United States, 1789–1945*; US International Trade Commission; and IMF staff calculations.

Note: The Jan. 20–Apr. 1 tariffs in 2025 include 20 percent tariffs on China; 25 percent tariffs on steel and aluminum; 25 percent tariffs on Mexico and Canada; and a 10 percent tariff on Canadian energy imports. A United States–Mexico–Canada Agreement (USMCA) carve-out is assumed to halve the effective tariff increase for Canada and Mexico. The April 2 tariffs include auto sector tariffs and country-specific tariffs, applying exemptions provided in Annex II of the Executive Order per IMF staff judgment. The April 9 tariffs include an increase in the tariffs on China to 145 percent and a reduction in other country-specific tariffs to 10 percent. It also includes exemptions on some electronic products announced on April 11. GATT = General Agreement on Tariffs and Trade.

Source: IMF World Economic Outlook April 2025
A critical Juncture amid Policy Shifts

Tariff & Trade: Historical evolution: Up's and Down's! – The Trump's effect for 2025
February 2026: US Supreme Court invalidates Trump's Tariffs & Trades 2025 decrets



Sources: US Bureau of the Census, *Historical Statistics of the United States, 1789–1945*; US International Trade Commission; and IMF staff calculations.

Note: The Jan. 20–Apr. 1 tariffs in 2025 include 20 percent tariffs on China; 25 percent tariffs on steel and aluminum; 25 percent tariffs on Mexico and Canada; and a 10 percent tariff on Canadian energy imports. A United States–Mexico–Canada Agreement (USMCA) carve-out is assumed to halve the effective tariff increase for Canada and Mexico. The April 2 tariffs include auto sector tariffs and country-specific tariffs, applying exemptions provided in Annex II of the Executive Order per IMF staff judgment. The April 9 tariffs include an increase in the tariffs on China to 145 percent and a reduction in other country-specific tariffs to 10 percent. It also includes exemptions on some electronic products announced on April 11. GATT = General Agreement on Tariffs and Trade.

February 2026:

US Supreme Court invalidates Trump's Tariffs & Trades as illegal ➡ Important conséquences for the World Trading Business

Source: IMF World Economic Outlook April 2025
A critical Juncture amid Policy Shifts

Tariff & Trade: Historical evolution - Some specific events

Tariff of Abominations:

The bill was passed in the US Congress in 1828. The goal was to protect the US factories by taxing imports from Europe. But the law was vehemently contested by the South arguing that the tariffs enhanced the interests of the North at their detriment. The tariffs were replaced in 1833.

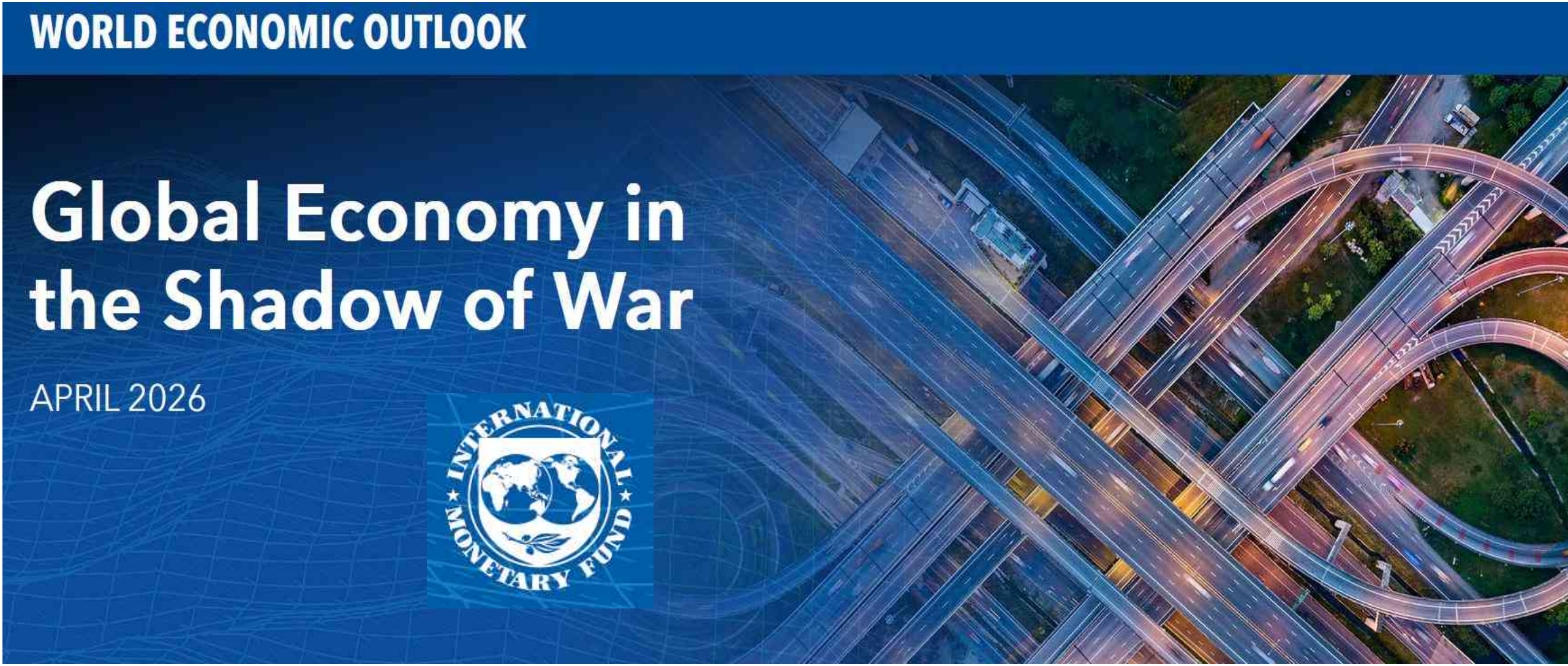
Morrill tariff:

An increased import tariff promoted by Justin Smith Morrill adopted in March 1861 during the presidency of the Democrat James Buchanan. It was put in place for the benefit of industrialists and factory workers to implement a rapid industrial growth.

Smoot-Hawley tariff:

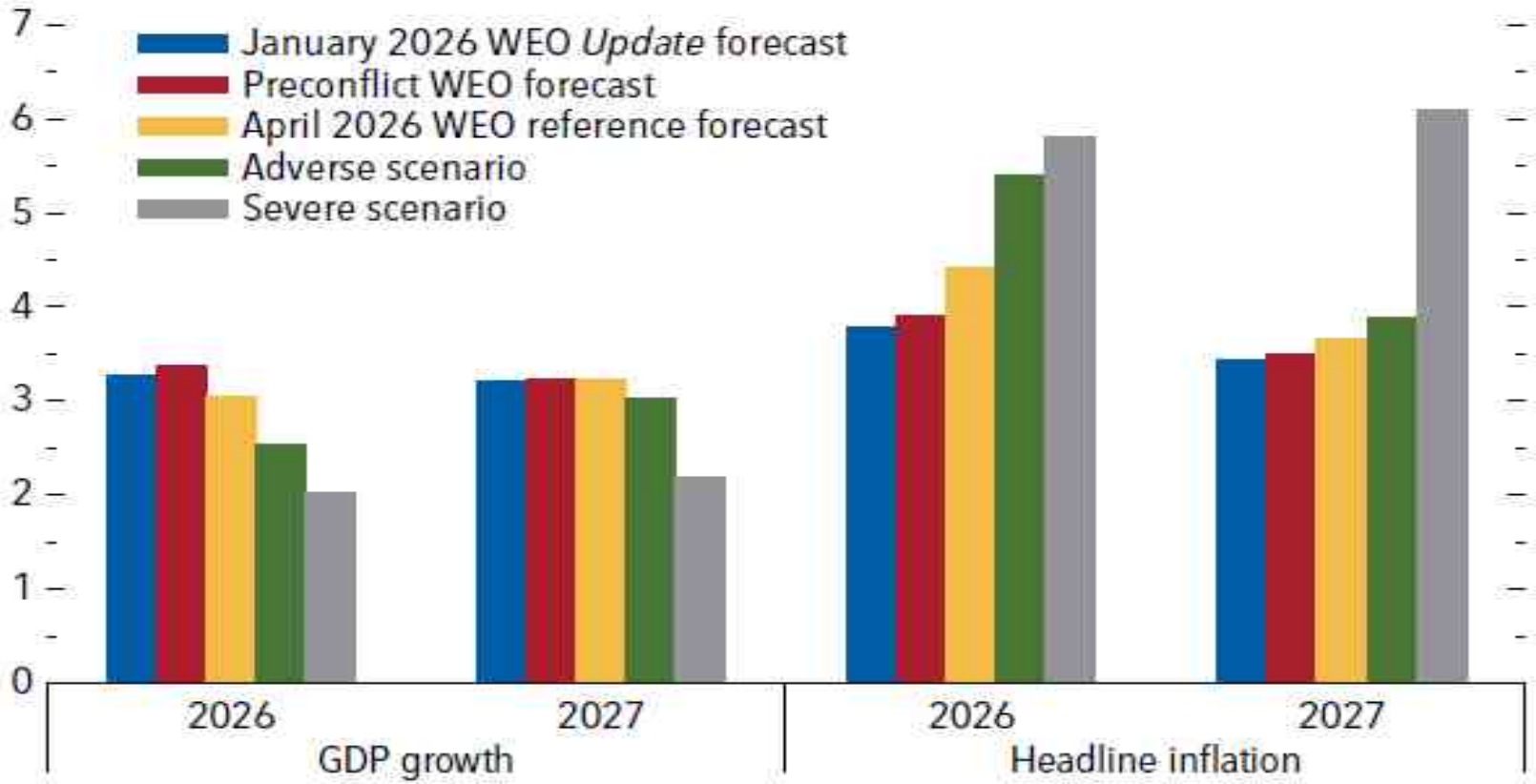
A protectionist measure signed into law in June 1930 under the presidency of Herbert Hoover, in order to shield American industries from foreign competition during the onset of the Great Depression.

International Monetary Fund – World Economic Outlook



World Growth and Inflation Forecasts

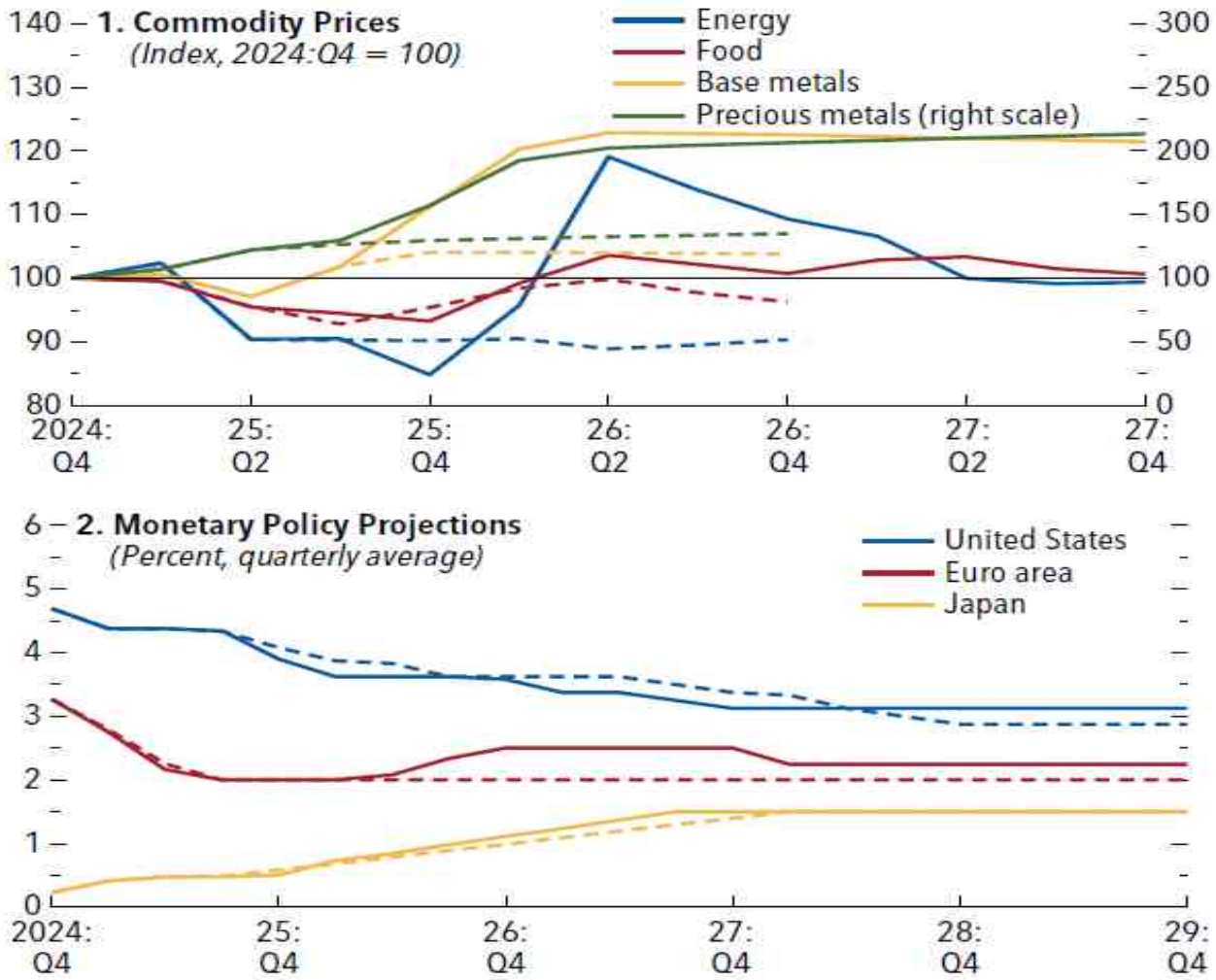
Figure 1.8. Global Growth and Inflation Forecasts
(Percent)

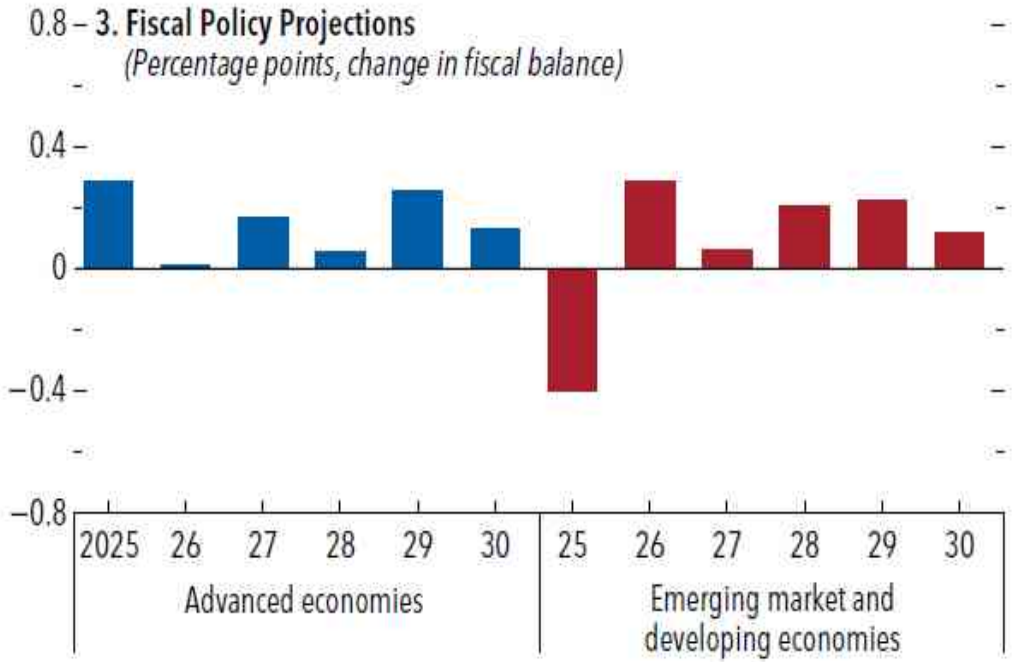


Source: IMF staff estimates.

Commodity Prices, Monetary Policy, Fiscal Policy

Figure 1.7. Global Assumptions





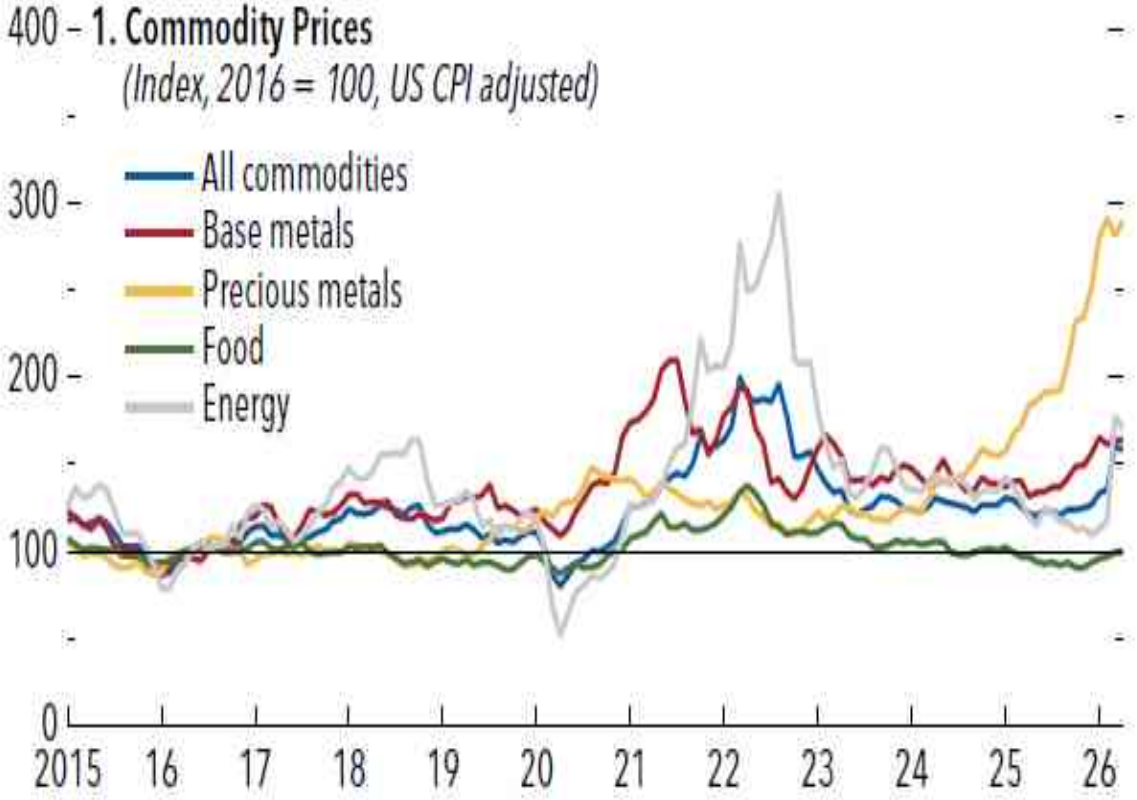
Source: IMF staff calculations.

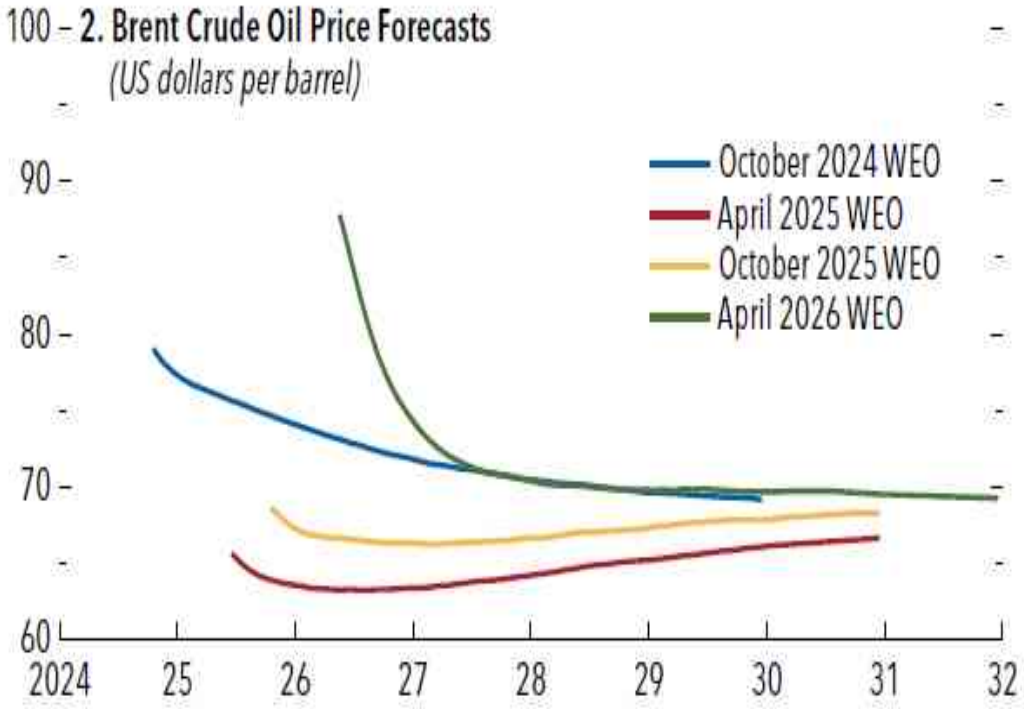
Note: In panels 1 and 2, solid lines denote projections from the April 2026 *World Economic Outlook* (WEO) and dashed lines those from the October 2025 WEO. In panel 3, the fiscal balance used is the general government structural primary balance in percent of potential GDP. The structural primary balance is the cyclically adjusted primary balance excluding net interest payments and corrected for a broader range of noncyclical factors such as changes in asset and commodity prices.

Source: IMF World Economic Outlook April 2026

Commodity Prices and Oil Prices Development

Figure 1.SF.1. Commodity Market Developments



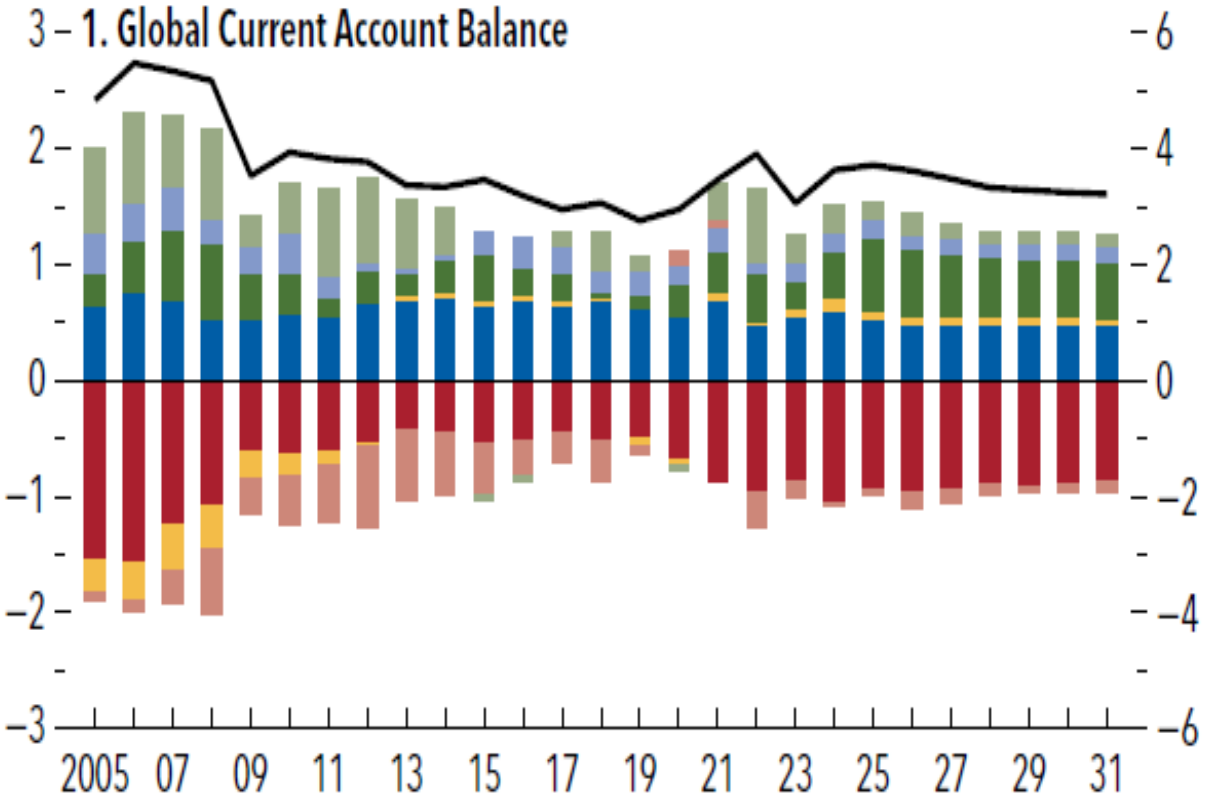


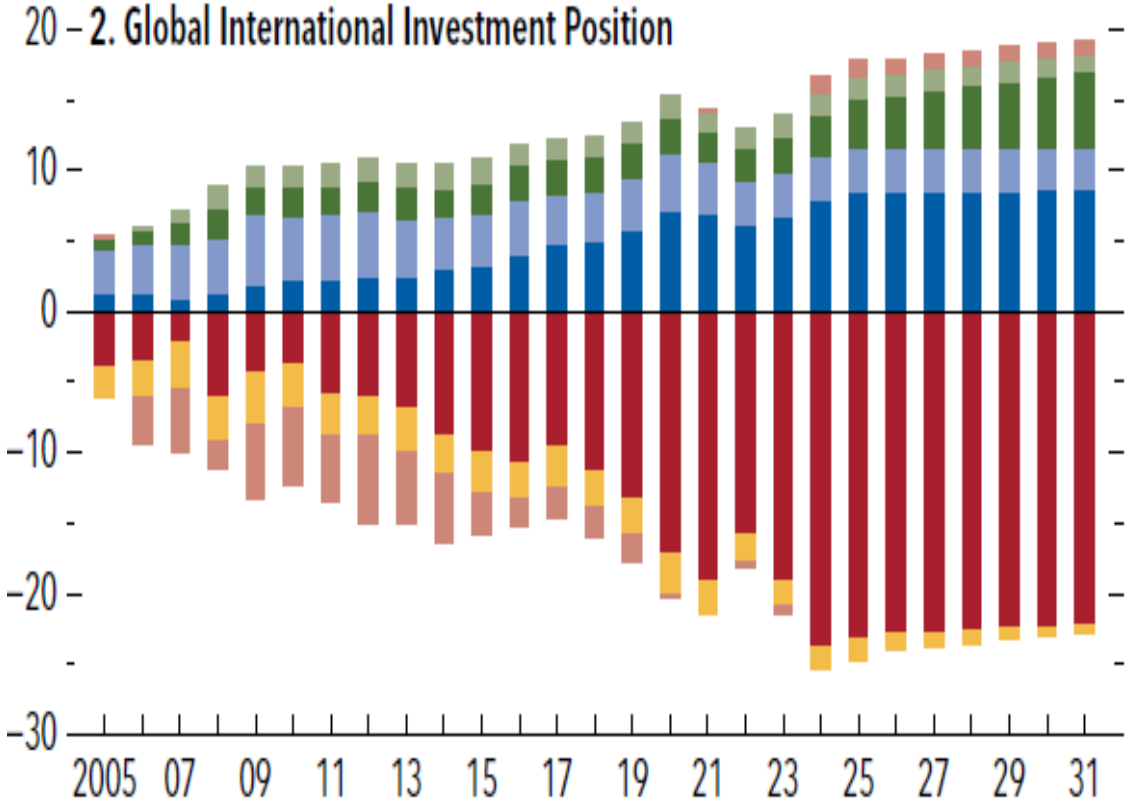
Sources: Bloomberg Finance L.P.; Haver Analytics; IMF, Primary Commodity Price System; International Energy Agency; and IMF staff calculations.

Note: In panel 2, expiration dates are on the *x*-axis. CPI = consumer price index; WEO = *World Economic Outlook*.

Source: IMF World Economic Outlook April 2026

Global Current Account Balance & Investment position (% of GDP)



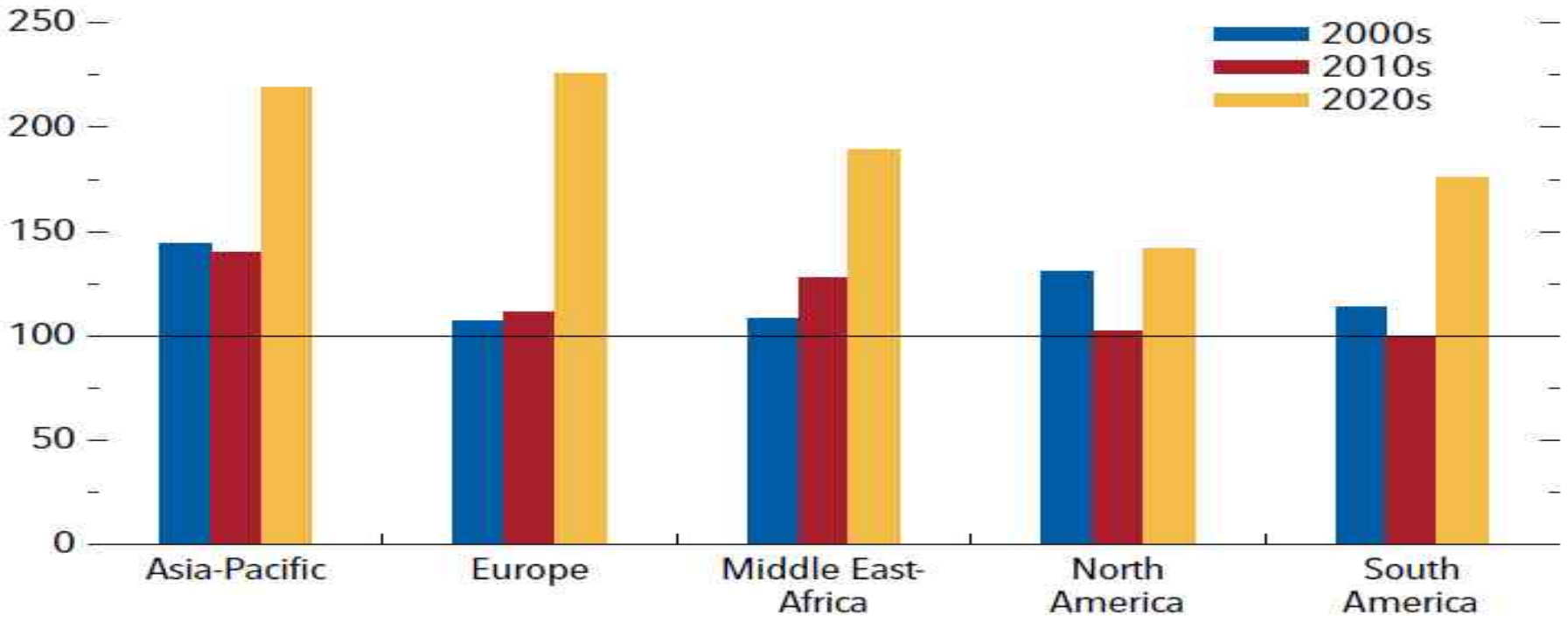


Source: IMF staff calculations.

Note: "European creditors" are Austria, Belgium, Denmark, Finland, Germany, Italy, Luxembourg, The Netherlands, Norway, Slovenia, Sweden, and Switzerland. "European debtors" are Cyprus, Greece, Ireland, Portugal, and Spain. "Oil exporters" are Algeria, Azerbaijan, Iran, Kazakhstan, Kuwait, Nigeria, Oman, Qatar, Russia, Saudi Arabia, United Arab Emirates, and Venezuela.

Regional Geopolitical Risk by IMF

Figure 1.1. Regional Geopolitical Risk
(Index, 1990s = 100)

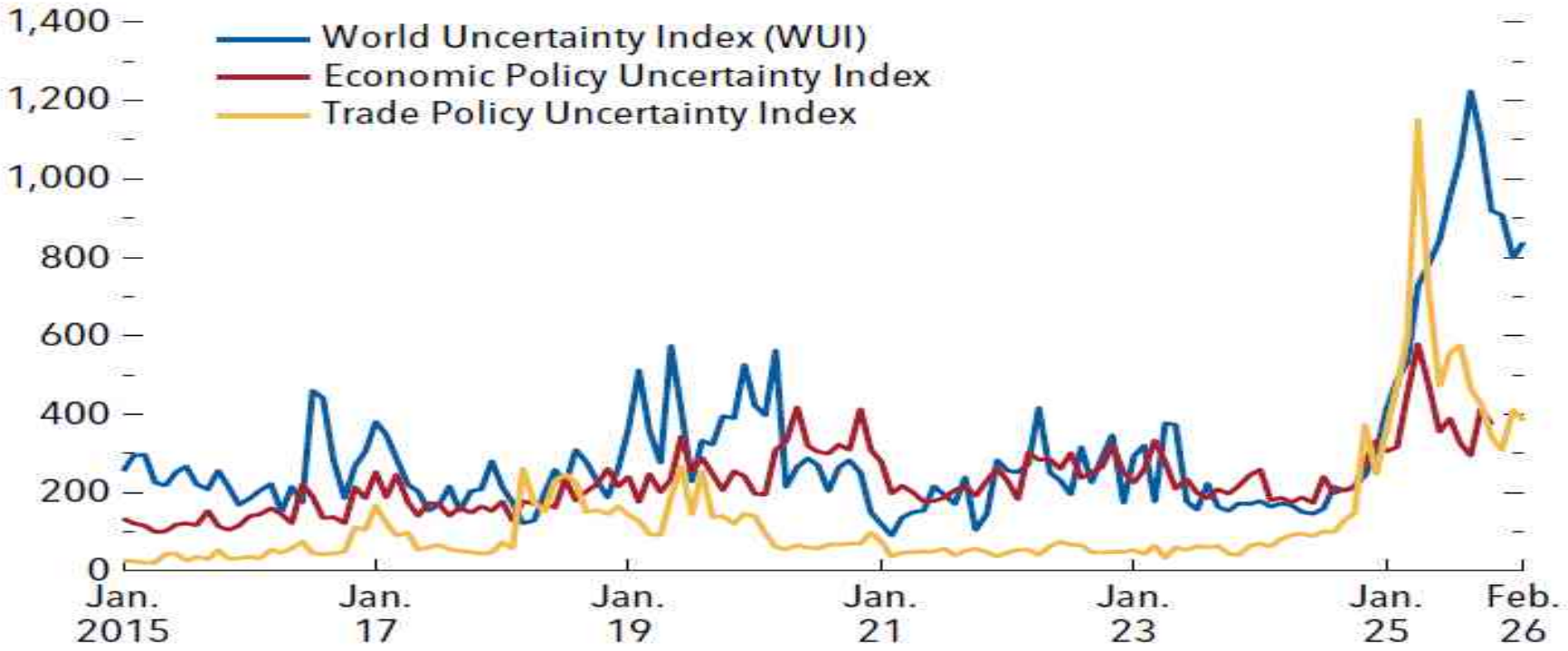


Sources: Caldara and Iacoviello 2026; and IMF staff calculations.

Note: This figure presents the country-specific geopolitical risk index of Caldara and Iacoviello (2026), a news-based measure of adverse geopolitical events that covers 10 major newspapers in Canada, the United Kingdom, and the United States. The country-level data were downloaded from https://www.matteoiacoviello.com/gpr.htm and averaged at the regional and decadal levels and normalized to 100 for the 1990s.

Global Uncertainty Index by IMF

Figure 1.3. Global Uncertainty
(Index)



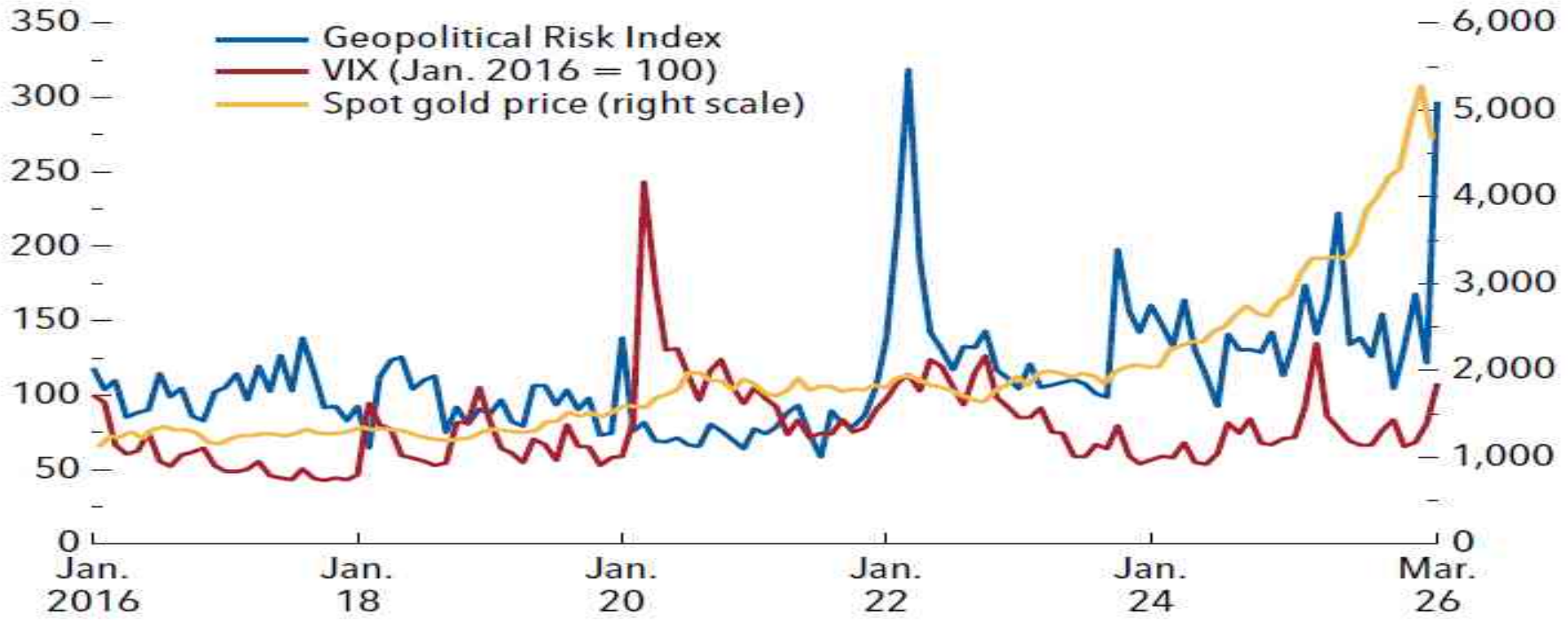
Sources: Ahir, Bloom, and Furceri 2022 (worlduncertaintyindex.com); Baker, Bloom, and Davis 2016 (policyuncertainty.com); and Caldara and others 2020 (matteoiacoviello.com/tpu.htm).

Note: The uncertainty measures are news- and media-outlets-based indices that quantify media attention to global news related to overall uncertainty (WUI), economic policy uncertainty, and trade policy uncertainty. WUI is divided by 100.

Source: IMF World Economic Outlook April 2026

Geopolitical Risk Index by IMF

Figure 1.6. Global Geopolitical Risk
(Index; US dollars per ounce)



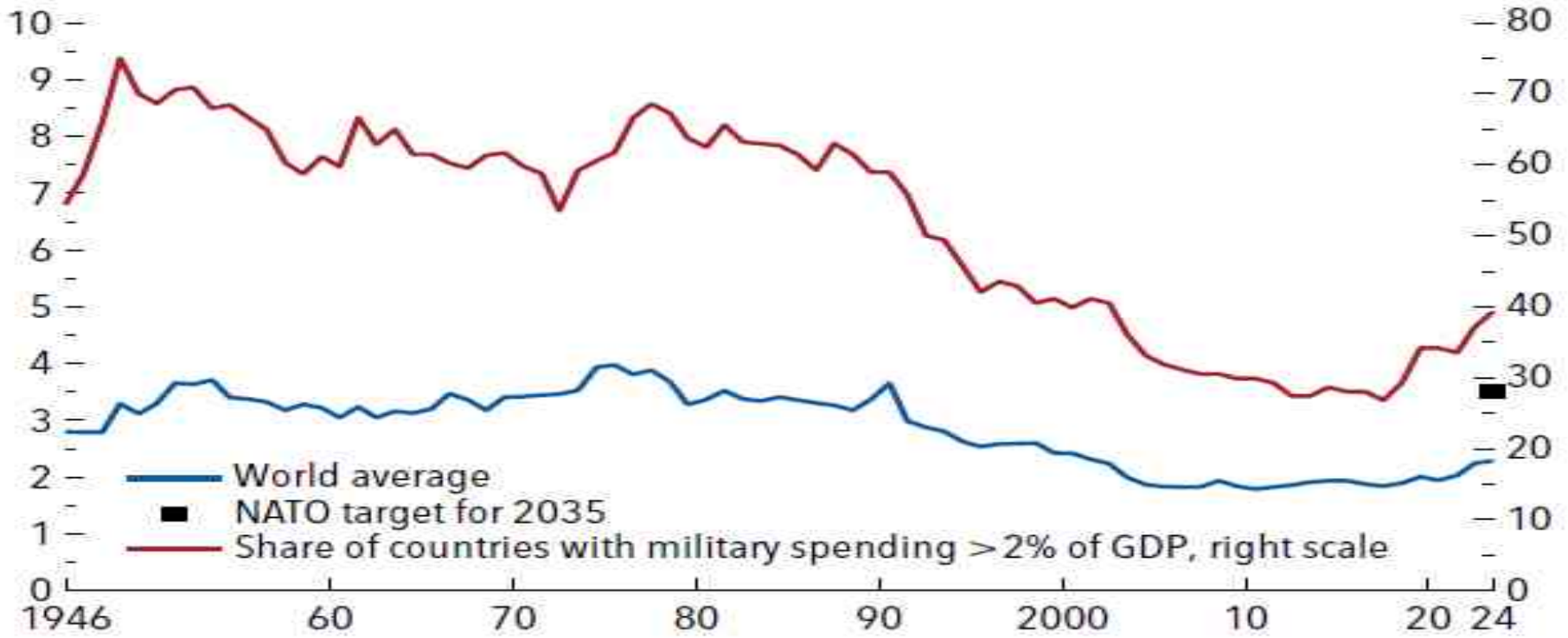
Sources: Caldara and Iacoviello 2022; Chicago Board Options Exchange (CBOE); London Stock Exchange Group, Datastream; and IMF staff calculations.

Note: This figure plots the monthly global geopolitical risk index of Caldara and Iacoviello (2022), a news-based measure of adverse geopolitical events that covers 10 major newspapers in Canada, the United Kingdom, and the United States. Data were downloaded from https://www.matteoiacoviello.com/gpr.htm on April 02, 2026. VIX = CBOE Volatility Index.

Source: IMF World Economic Outlook April 2026

Defense Spendings on the Rise

Figure 2.1. Defense Spending on the Rise
(Percent of GDP, left scale; percent, right scale)



Sources: Gethin 2024; Stockholm International Peace Research Institute Military Expenditure Database; World Human Capital Expenditure Database; and IMF staff calculations.

Note: NATO = North Atlantic Treaty Organization.

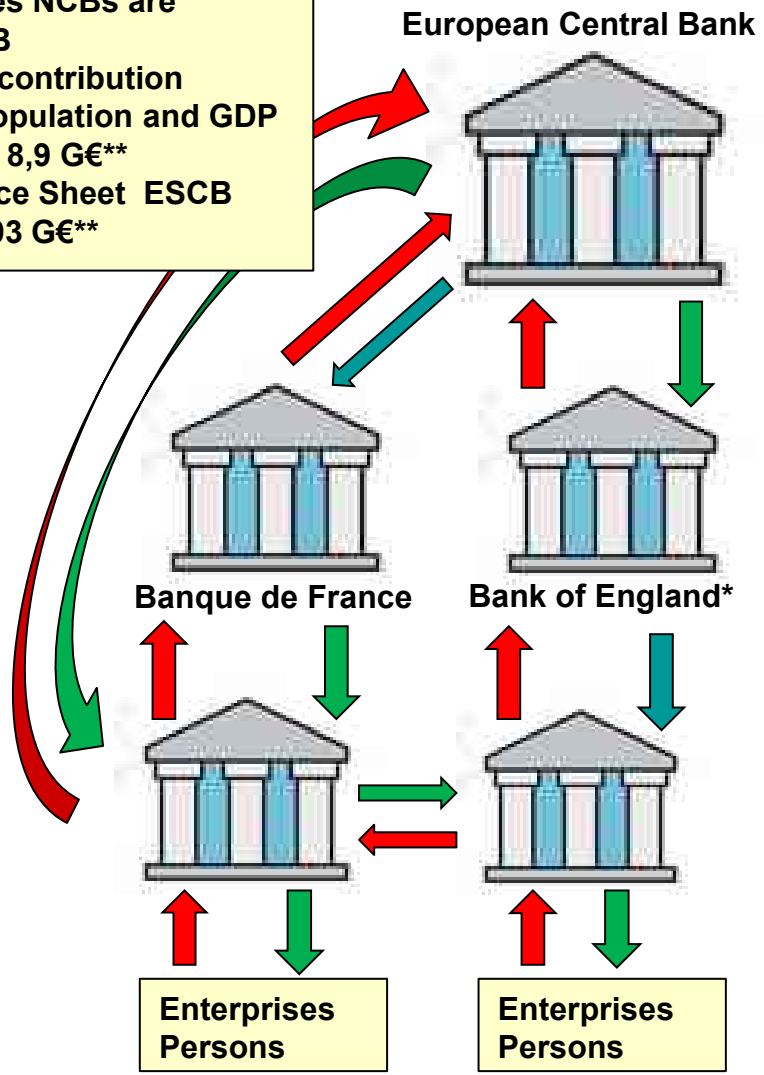
Source: IMF World Economic Outlook April 2026

European Union - GDP Evolution
Financing the Global Economy

The Banking System – One Example

European Union – European Central Bank & European System of Central Banks (ESCB)

- All EU member states NCBs are shareholders of ECB
- Each member state contribution depends upon its population and GDP
- Share capital ECB = 8,9 G€**
- Consolidated Balance Sheet ESCB (ECB + NCBs) # 6 293 G€**



European Central Bank (ECB)
Banque Centrale Européenne (BCE)

- Defines Monetary Policy
- Controls National Central Banks activities
- Fix interest rate to ensure price stability
- Receives deposits from Commercial Banks
- Lends money to Commercial Banks

National Central Banks (NCBs)

- Create fiduciary money and issue notes
- Receive deposits from Commercial Banks without limits (Permanent facilities)
- Lend to Commercial Banks without limits (Permanent facilities)
- Apply Interest rates fixed by BCE

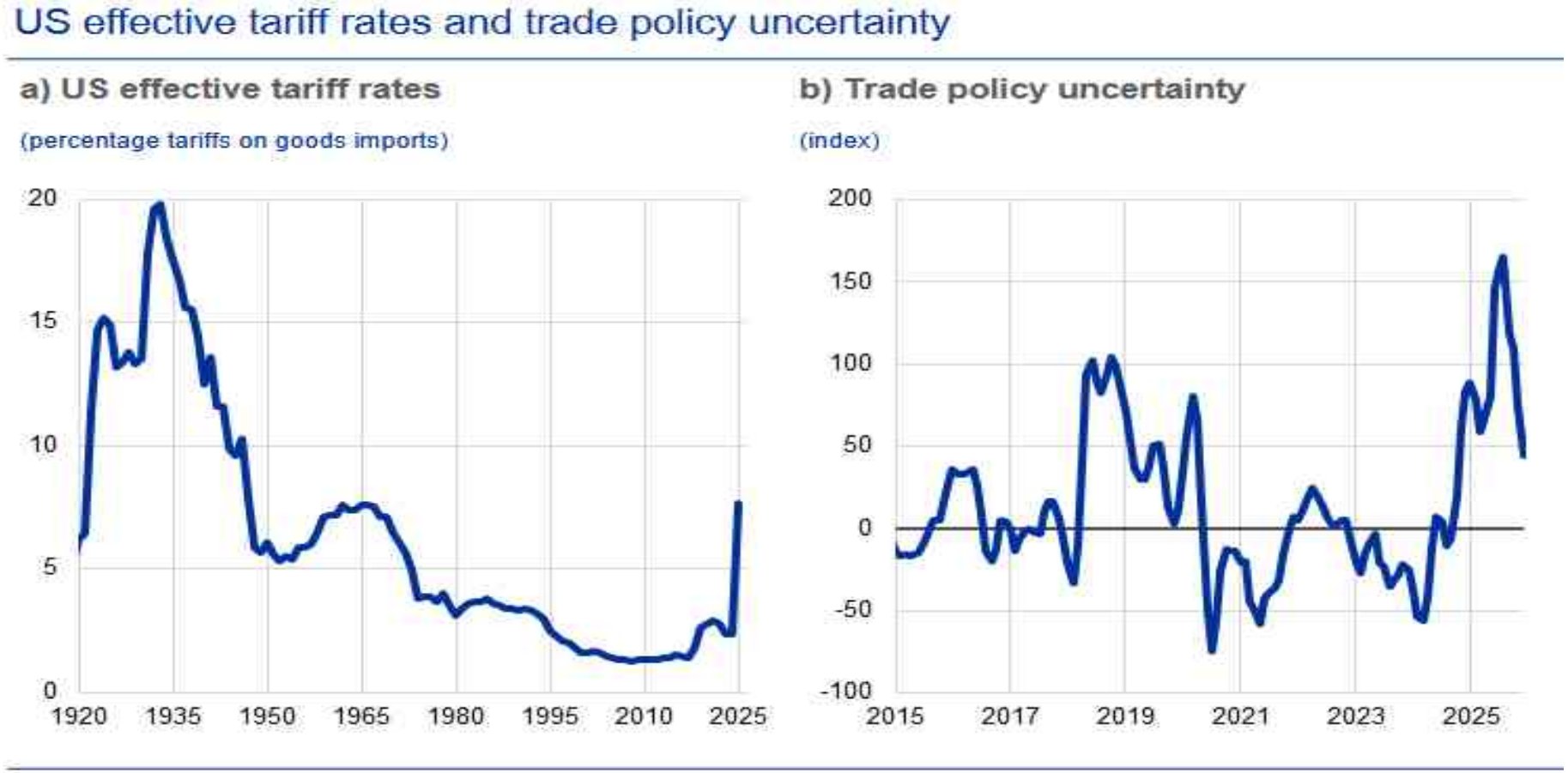
Commercial Banks

- Receive deposits from Enterprises and Persons
- Lend to Enterprises and Persons
- Can borrow from others Commercial Banks, National Central Bank or ECB (Open Market)
- Assume the obligation to deposit 1% of credits to ECB (Compulsary reserves)

• Will leave the ESCB after Brexit
** At 31/12/2025

ECB Annual Report 2025
April 2026

US Tariff Rates & Trade Policy Uncertainty



Sources: Panel a): US International Trade Commission, US Census Bureau and ECB staff calculations; panel b): ECB staff calculations and Caldara et al. (2020)[1].
Notes: Panel a): Effective tariff rates are calculated using the revenue approach, i.e. by dividing the duties collected by the value of goods imported. The data are annual averages. The latest observation is for 2025. Panel b): The index is an adjusted version of the index proposed by Caldara et al. (2020) which measures the monthly share of articles discussing trade policy uncertainty in seven international newspapers. The adjusted series removes influences from broader sources of uncertainty (such as general economic policy uncertainty, geopolitical tensions and market stress) to better isolate uncertainty specific to trade policy.[2] The index is a three-month moving average. The latest observation is for December 2025.

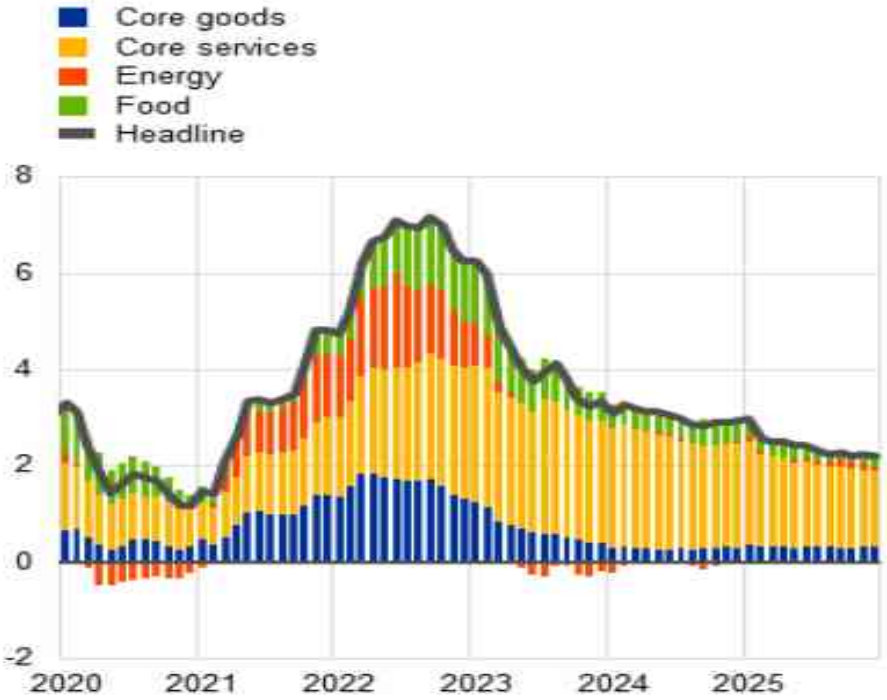
Source: ECB Annual Report 2025 – April 2026

Global Headline Inflation 2020 – 2025, 2% in 2025 in Euro area

Headline and core inflation rates

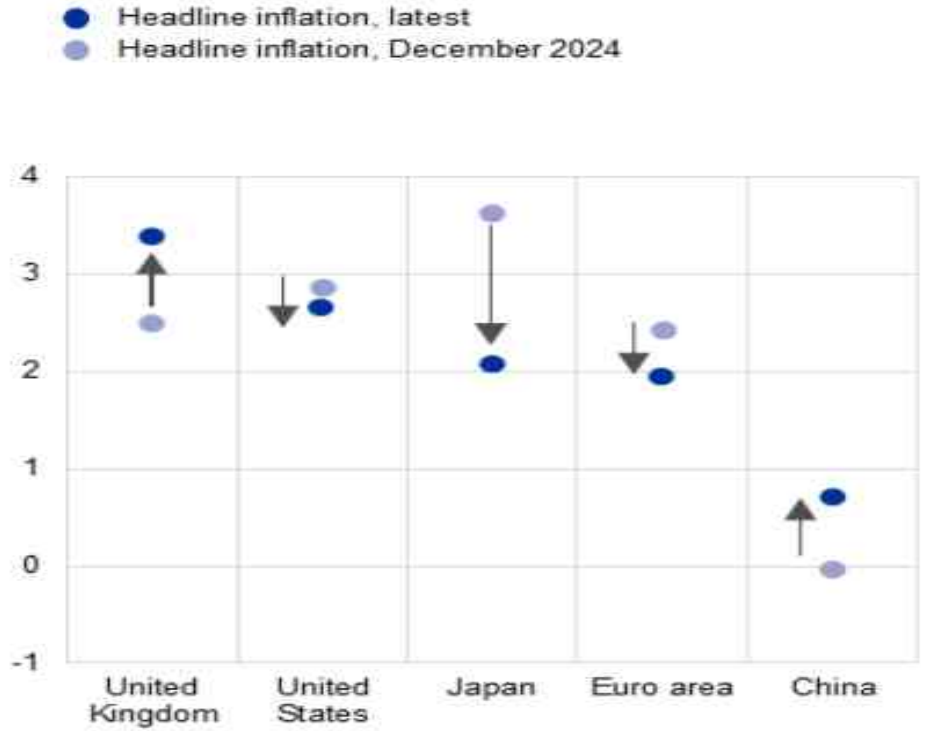
a) Global headline inflation and its components

(annual percentage changes, monthly data)



b) Inflation in major economies

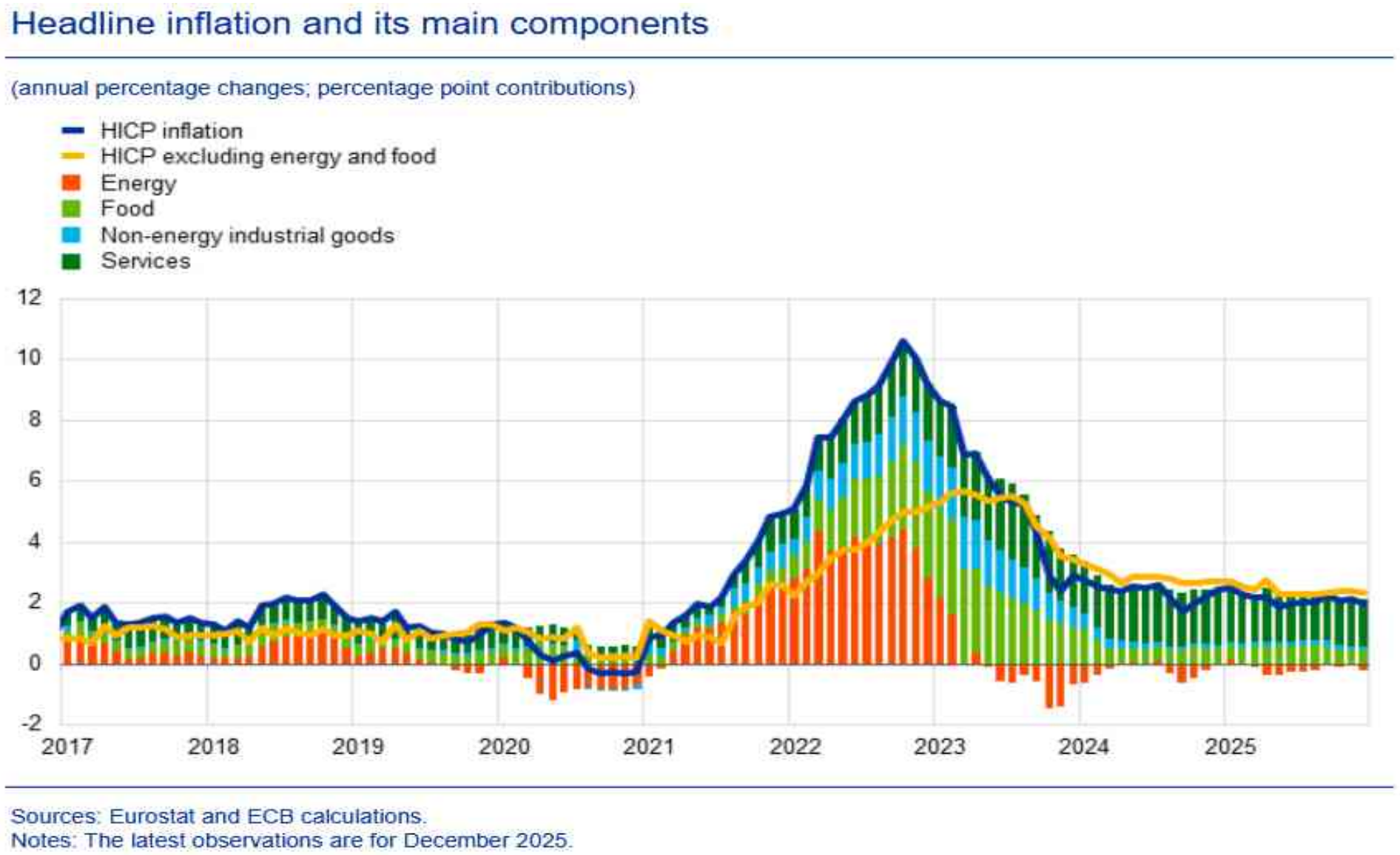
(annual percentage changes, monthly data)



Sources: National sources and OECD via Haver Analytics, and ECB staff calculations.
Notes: Panel a) Global inflation is computed on the basis of national CPIs and annual GDP weights expressed in purchasing power parity (PPP) terms. The aggregate is calculated on the basis of 22 countries and the euro area, covering 81% of global GDP in PPP. The contributions of components to headline inflation are computed using OECD CPI weights. Core goods inflation and core services inflation exclude energy and food. The latest observations are for December 2025. Panel b): the latest observations are for December 2025.

Source: ECB Annual Report 2025 – April 2026

Euro area Headline Inflation 2017 – 2025, 2% in 2025 in Euro area

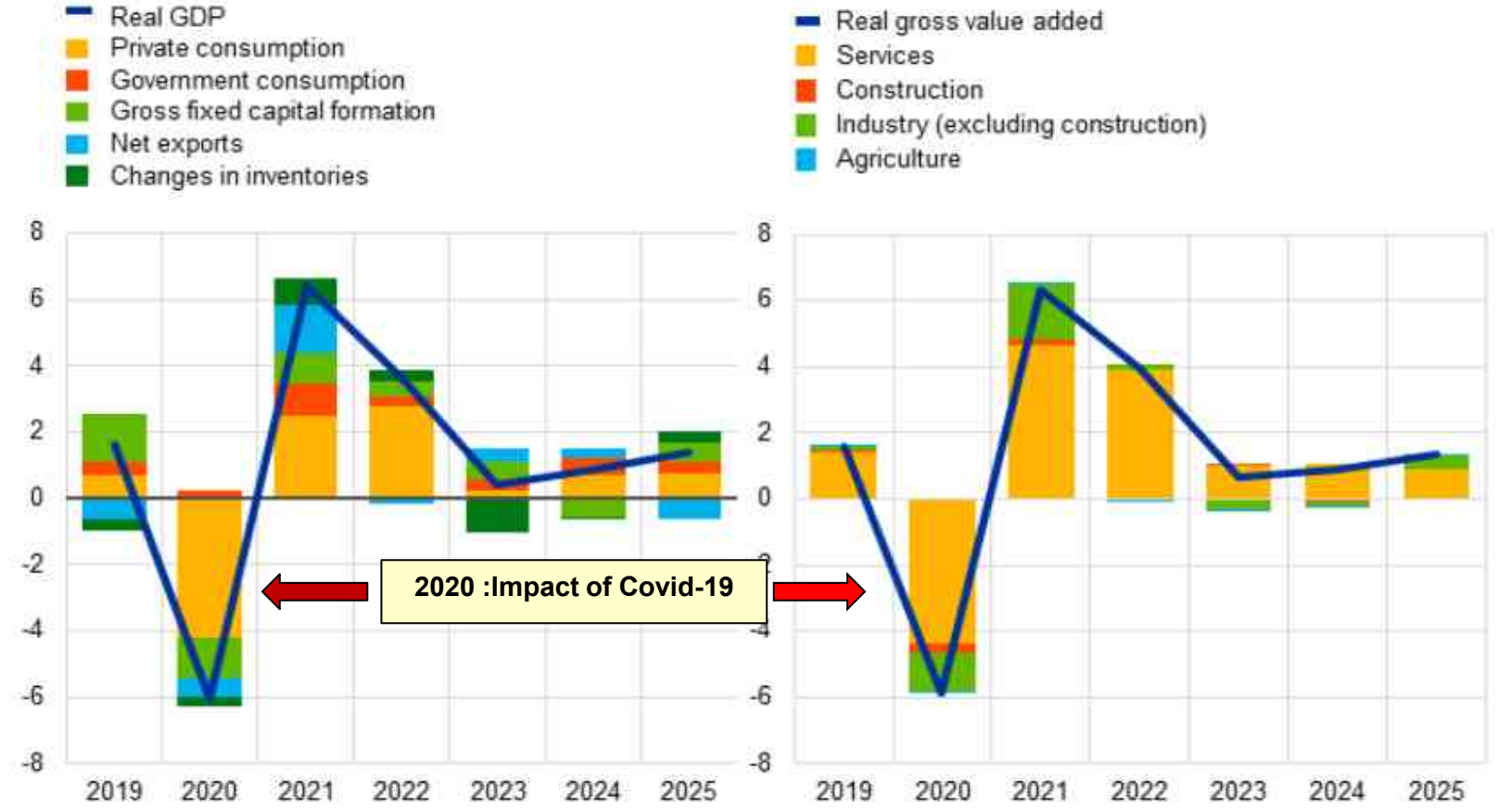


Source: ECB Annual Report 2025 – April 2026
Nota: HICP: Harmonized Indes of Consumer Price

Euro Zone GDP Growth Evolution 2019 - 2025

Euro area real GDP and gross value added

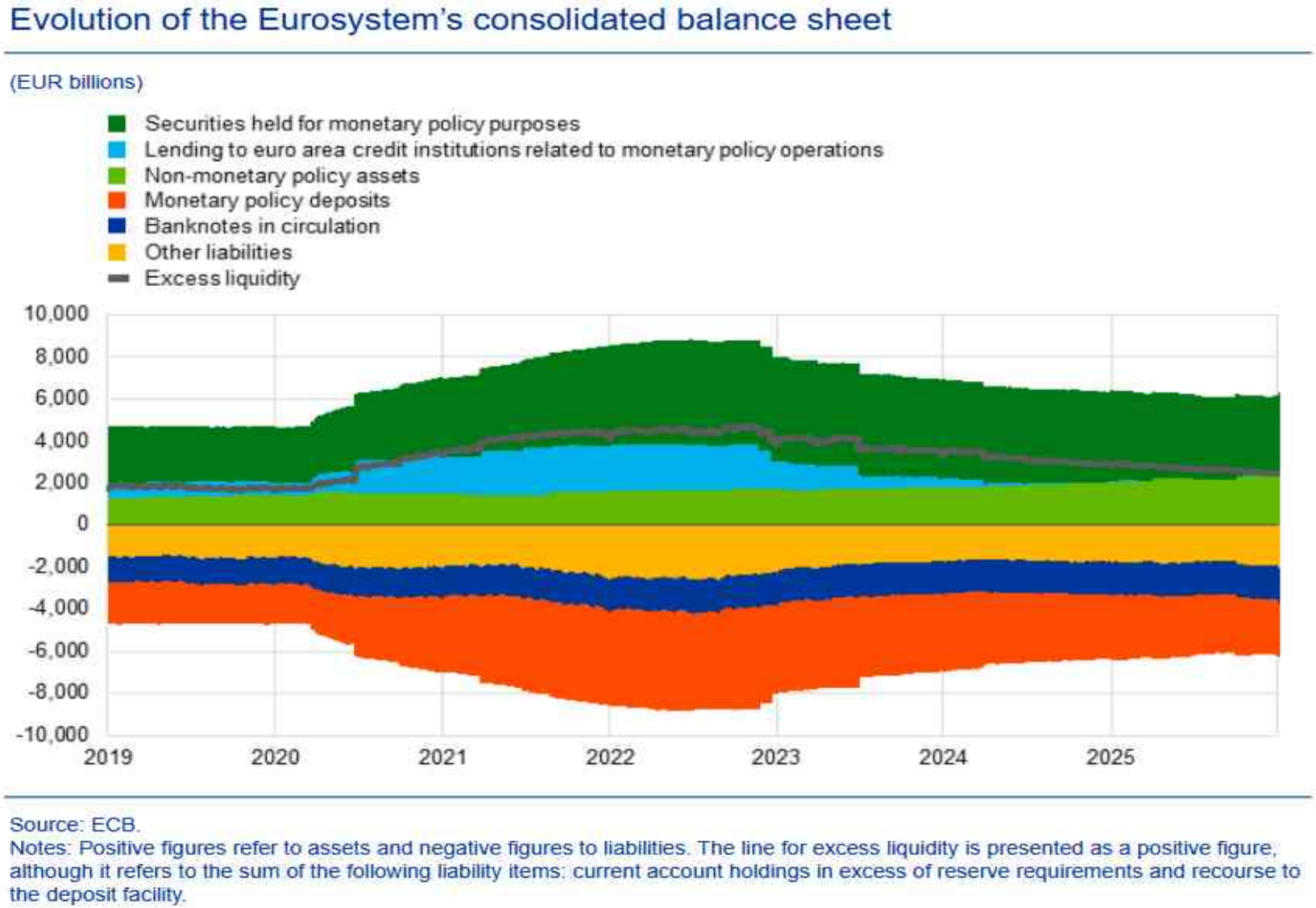
(annual percentage changes; percentage point contributions)



Source: Eurostat.
Note: The latest observations are for 2025.

Source: ECB Annual Report 2025 – April 2026

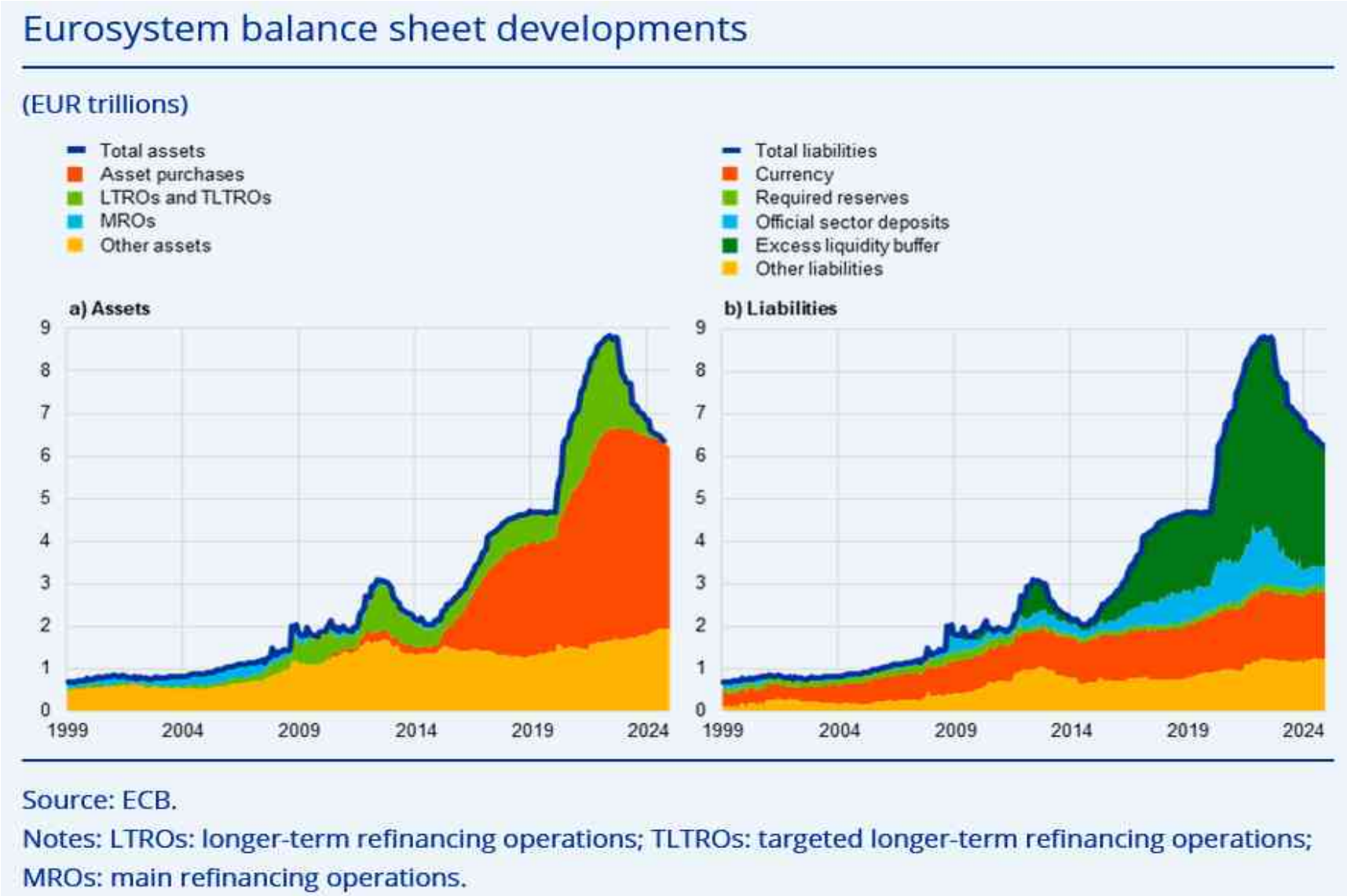
Eurosystem's consolidated balance sheet 2019 - 2025



Source: ECB.
Notes: Positive figures refer to assets and negative figures to liabilities. The line for excess liquidity is presented as a positive figure, although it refers to the sum of the following liability items: current account holdings in excess of reserve requirements and recourse to the deposit facility.

Source: ECB Annual Report 2025 – April 2026

Eurosystem's consolidated balance sheet 2014 - 2024



Source: ECB Annual Report 2024 – April 2025

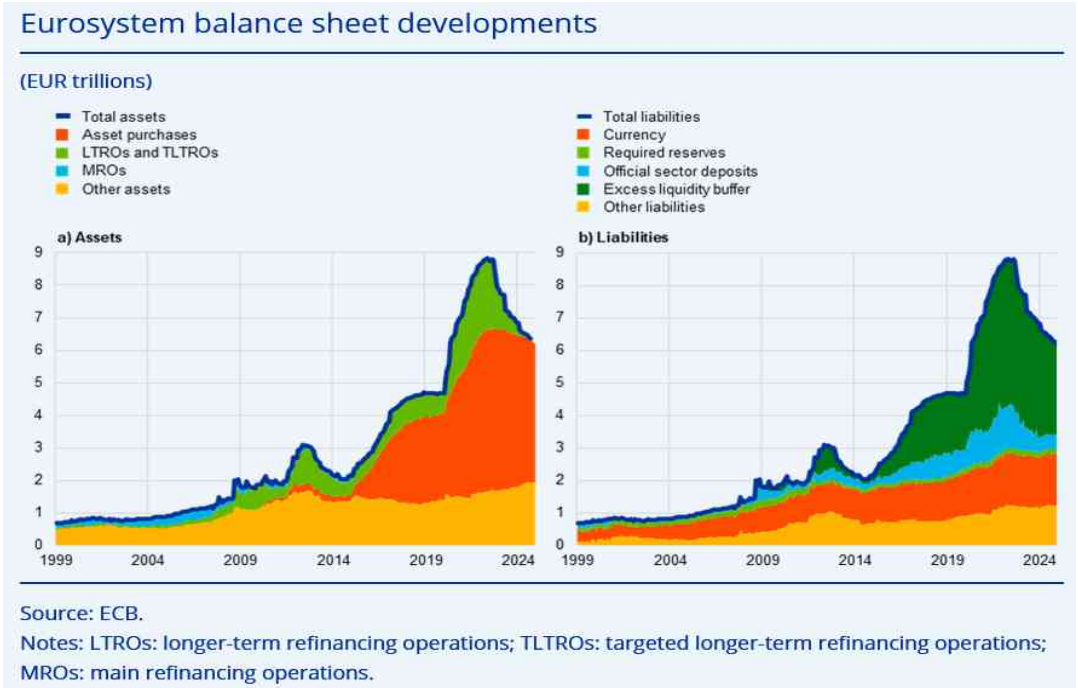
The support of European Economies by ECB

Effect of he Covid-19 pandemia in 2020

Balance Sheet: 4 700 G€ end 2019 → 8 600 G€ end 2021! - 6290 G€ end 2025

- To support the European Member States Economies, ECB has injected considerable amount of money in the economic network through the mechanism of « Quantitative Easing » (QE) by purchasing massive amounts of long-term securities from Member States NCBs.
- In exchange, it issues credit to the Banks reserves.
- Therefore, massive amount of money is injected in the Economy in order to mitigate the effect of any kind of financial crisis.

Euro system Assets/Liabilities



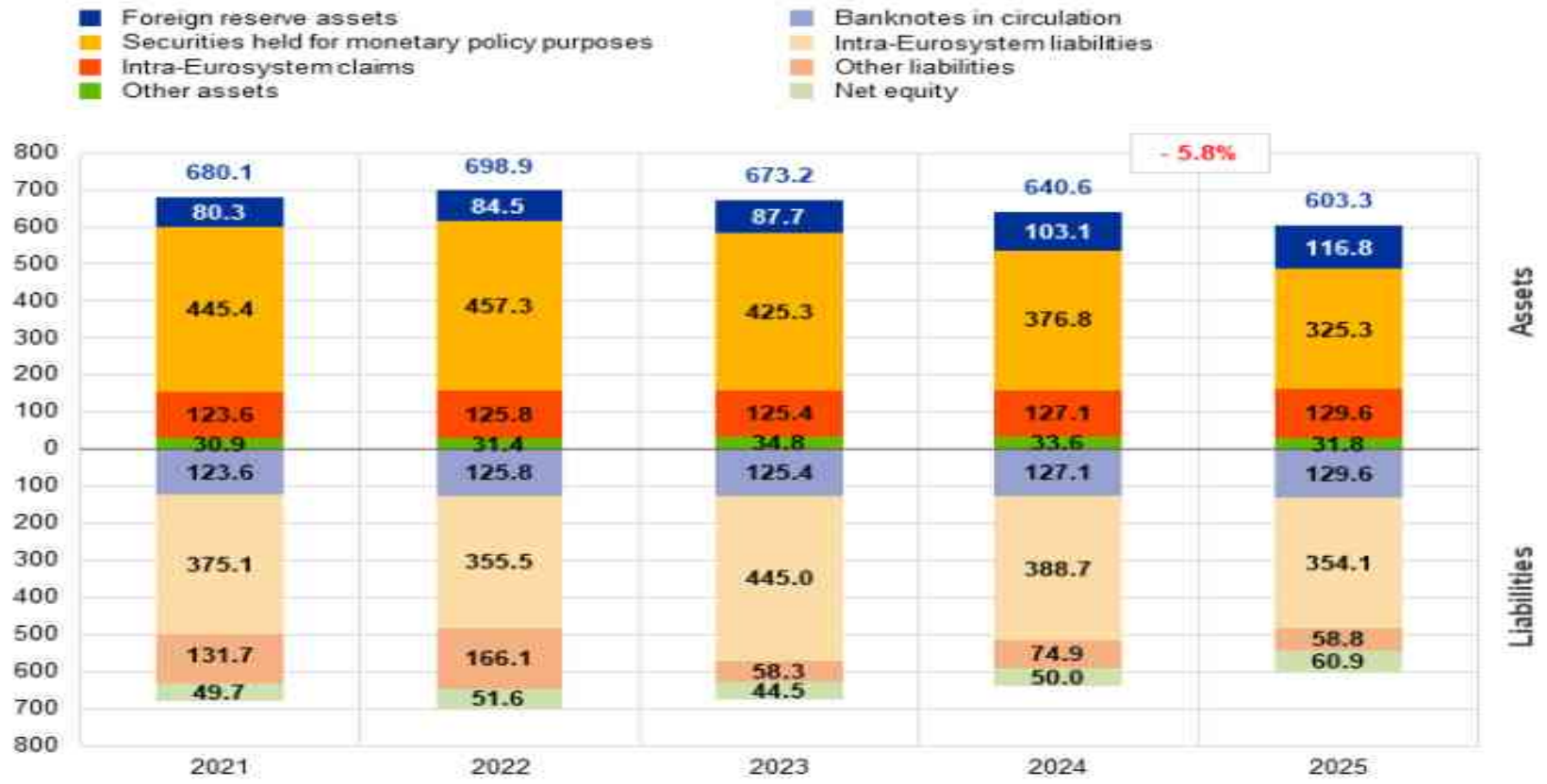
- Who will repay the debt?
- To write off part of the totality of the debt is illegal, contrary to the european treaty which forbids financing state deficits
- To put in place a perpetual debt?
- A lot of debates on this subject

Source: ECB Consolidated Balance Sheet – February 2024

ECB Annual Accounts 2021 - 2025

Main components of the ECB's balance sheet

(EUR billions)



Source: ECB.
Note: For the purpose of preparing the ECB's Annual Accounts, the ECB's net equity consists of its paid-up capital, any amounts held in the provision for financial risks and the general reserve fund, the revaluation accounts (excluding the revaluation account for post-employment benefits), any accumulated losses from previous years and any profit/(loss) for the year.
For information on the adjustments of the figures for 2023, see "Changes to presentation in the financial statements" in Section 2.3 "Accounting policies" of the ECB's Annual Accounts 2024.

Source: ECB Annual Accounts – April 2026

2

Energy Consumption vs Gross Domestic Product

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- 4. Energy: past evolution, present situation
- 5. Energy: A zoom on France
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- 7. Global Energy Growth – Scenarios from various organizations
- 8. Global Energy Growth – Mobility/Transport
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- 19. Reminder - The 2008/2009 economic crisis, the 2020 Covid-19 sanitary crisis
- 20. Some geopolitical considerations – Impact of Ukraine invasion by Russia & geopolitical events – Iran/Israel/US war
- 21. Reminder: Basic Thermodynamics
- 22.Equivalences and conversion factors

The links between CO_2, Energy and the Global Economy

Two independant parameters:

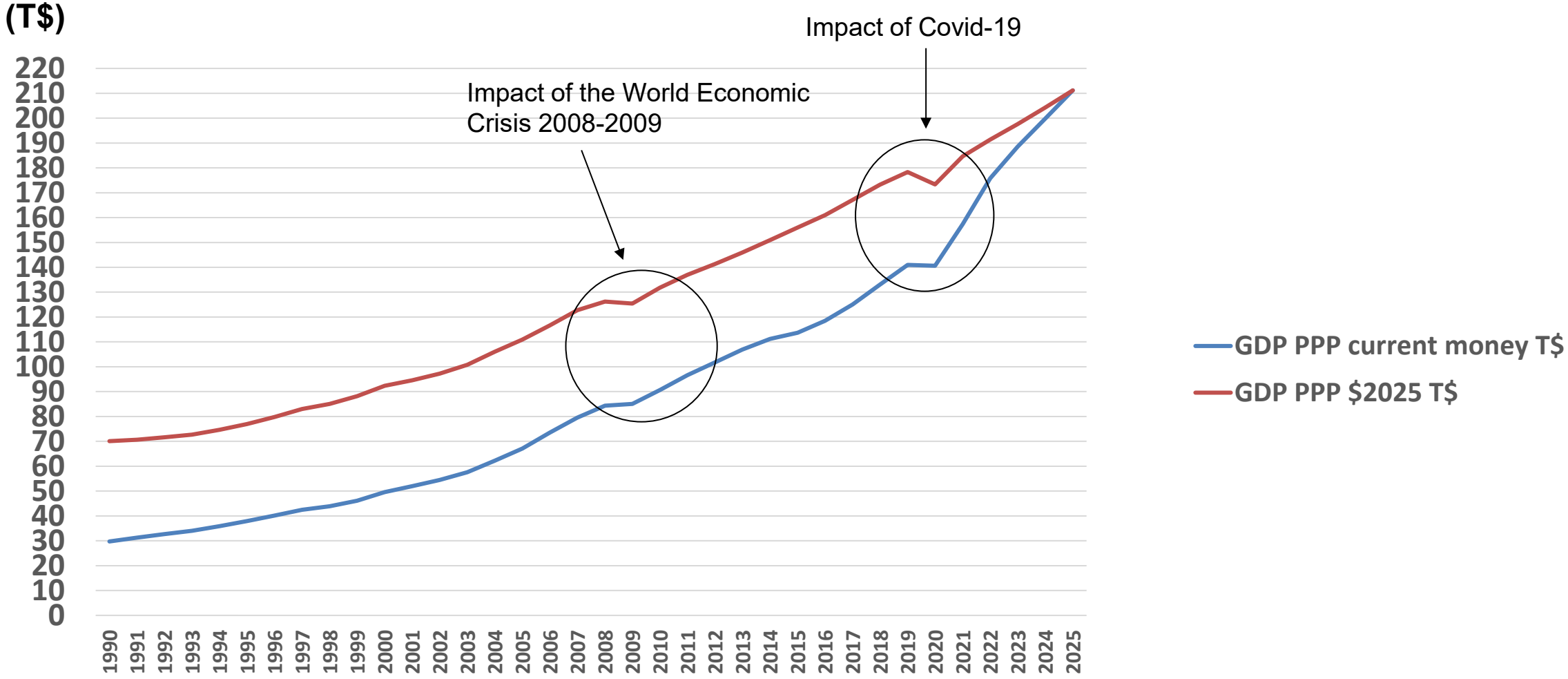
- **CO_2 vs Primary Energy:**

Carbon Intensity = tCO_2/toe

- **Primary Energy vs GDP:**

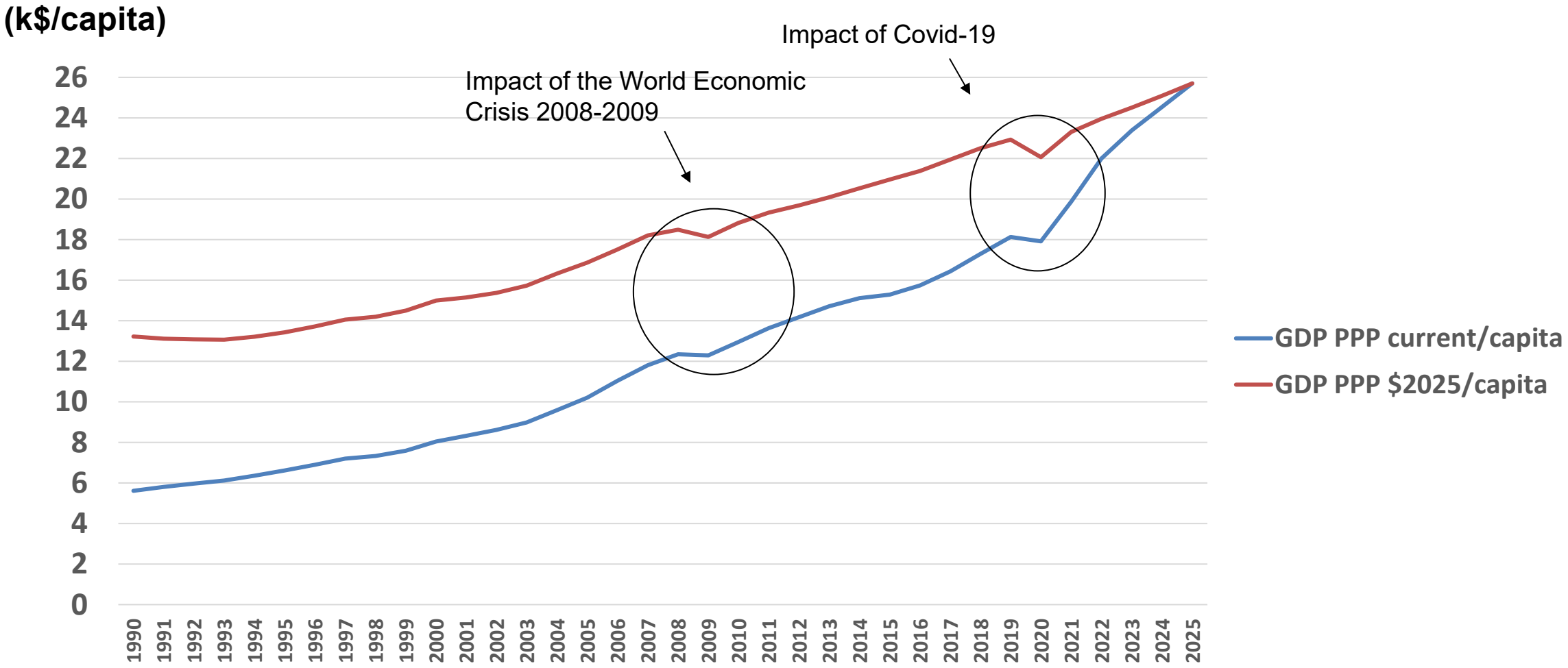
Energy Intensity = toe/k$GDP

World GDP PPP 1990 – 2025
Probability to continue on that trend?



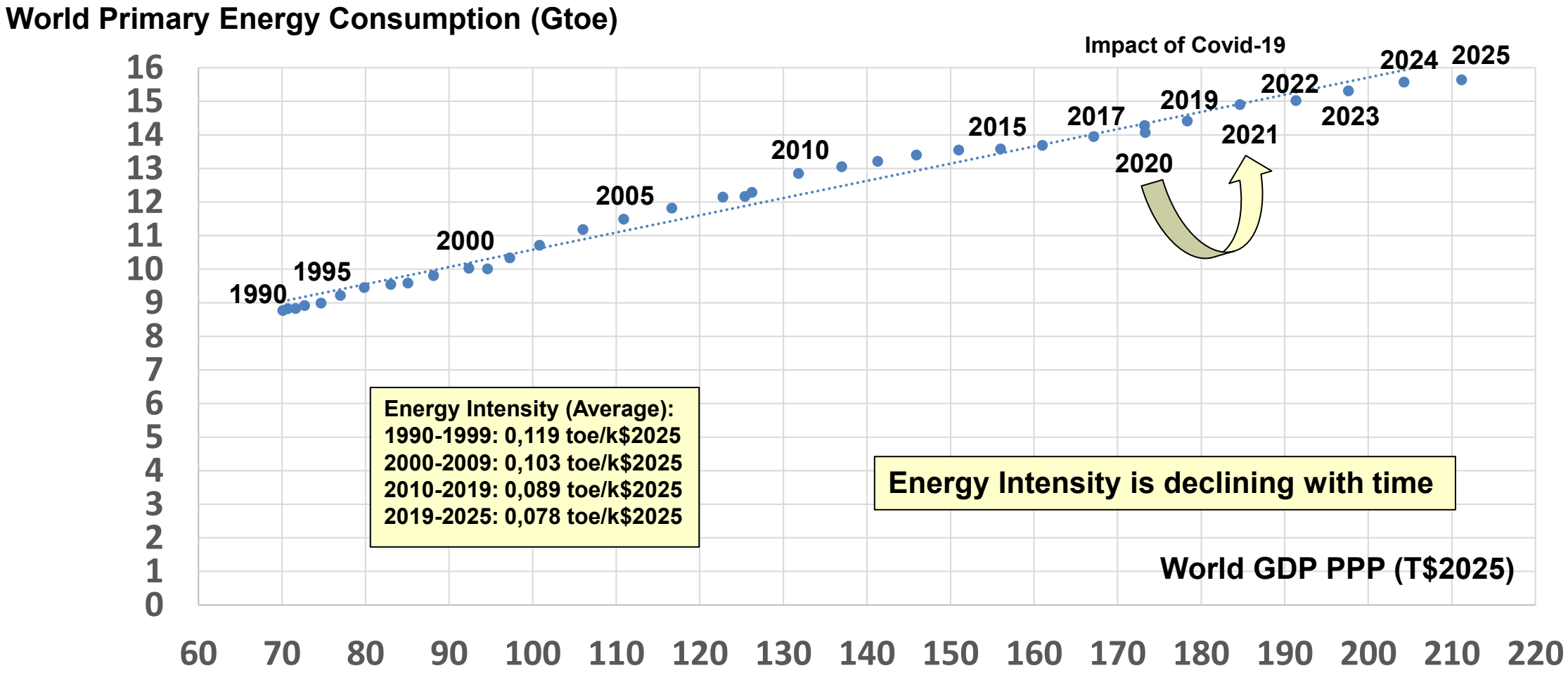
Source: Ch.Guéritte/Data from World Bank July 2026 - $2025: US CPI
GDP: Gross Domestic Product
PPP: Purchasing Power Parity

World GDP PPP per capita 1990 - 2025
Probability to continue on that trend?



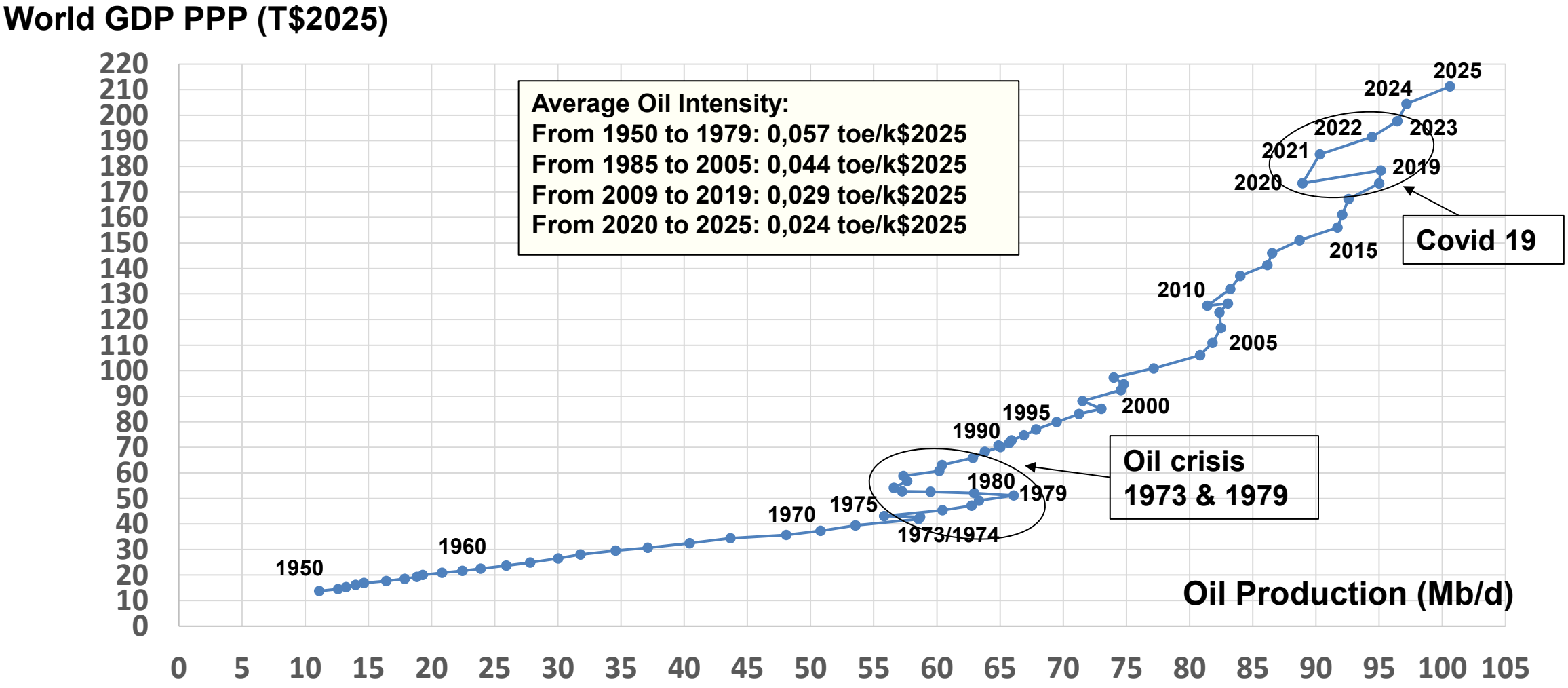
Source: Ch.Guéritte/Data from World Bank July 2026 - $2024: US CPI (Consumer Price Index)
GDP: Gross Domestic Product
PPP: Purchasing Power Parity

Energy is perfectly correlated to Global Economy through the Energy Intensity



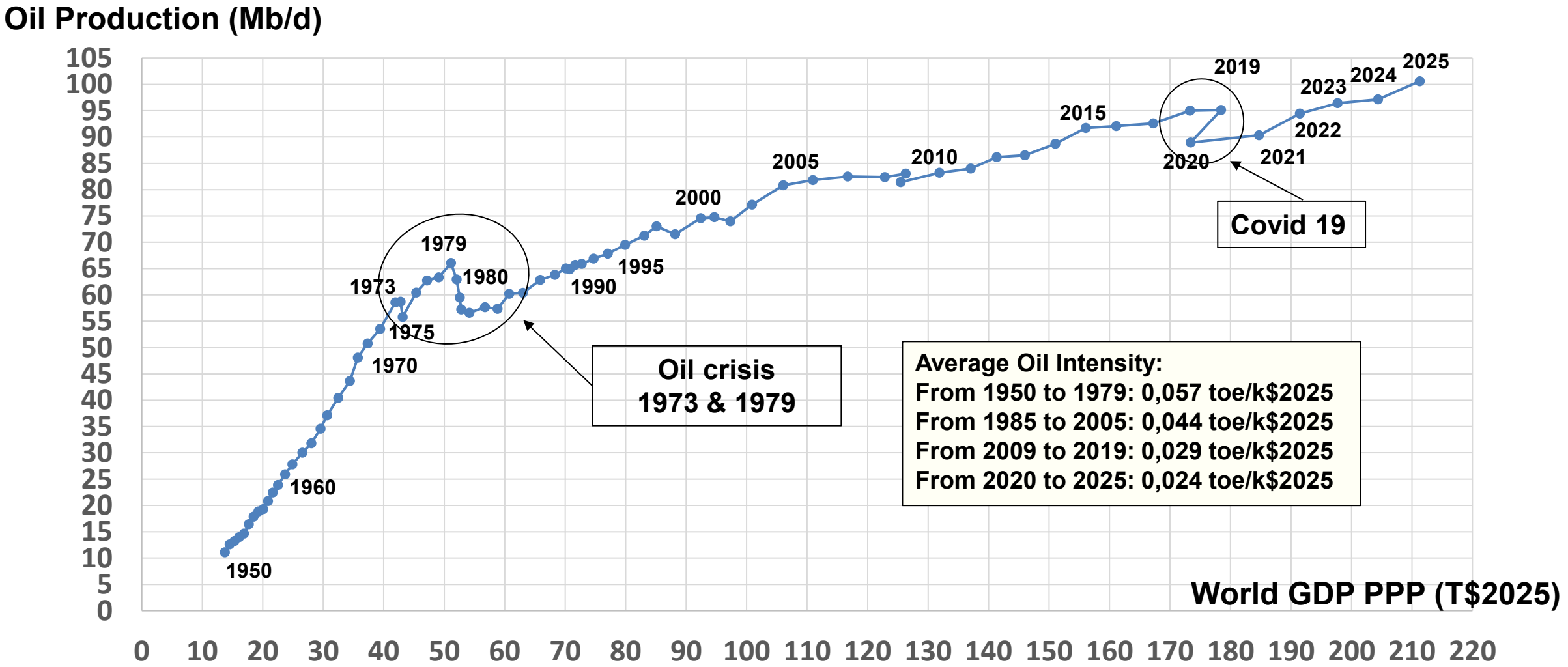
Nota: Source Ch.Guéritte. Data from World Bank 2026 & IEA Global Energy Review 2026.
The environmental economic conditions are important when defining GDP.

World GDP PPP ($2025) vs Oil Production (1)
A good correlation, with impacts of external events



Source: Ch.Guéritte/Data from World Bank July 2026, Maddison, EI Stat.Review 2026
Oil includes condensates, NGL, Tight Oil, Shale Oil, Xtra heavy Oil
GDP expressed in PPP, constant money US$ 2025, using US CPI

Oil Production vs World GDP PPP ($2025) (2)
A good correlation, with impacts of external events



Source: Ch.Guéritte/Data from World Bank July 2026, Maddison, EI Stat.Review 2026
Oil includes condensates, NGL, Tight Oil, Shale Oil, Xtra heavy Oil
GDP expressed in PPP, constant money US$ 2025, using US CPI

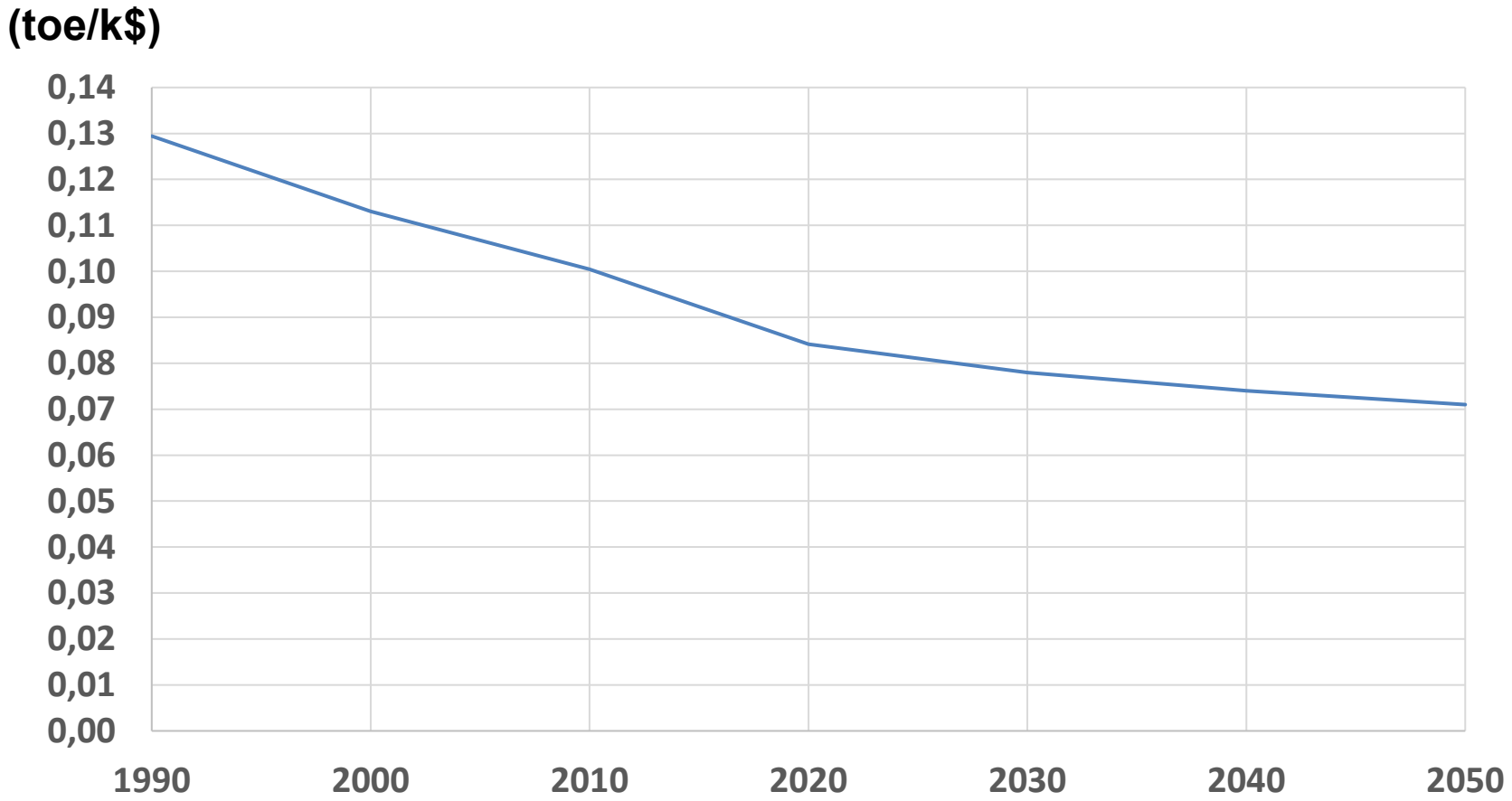
As of now, one question:
What about the World GDP Growth for the next decades?

Energy Consumption evolution is very well correlated with the World GDP Growth.

The fullfillment of Energy Transition goals means stabilization and decline of the World Energy consumption (see chapter 7)

Does'it mean that the the GDP per capita will decline in the future? Or Will there be a complete decorrelation between Energy and Global Economy?

Evolution of Energy Intensity (EI) (toe /k$ GDP PPP $2024)
2020 – 2050: IEA WEO 2025 STEPS
Assuming an attenuated decrease of EI until 2050 (Covid19 in 2020)



Nota: Source Ch.Guéritte. The environment economic conditions are important when defining GDP.
Data: History & IEA WEO 2025

Energy Intensity & Primary Energy will decrease
What about Purchasing Power?

Primary Energy Consumption/capita: PEc
GDP/capita: Purchasing Power/capita: PPc
Energy Intensity: EI = PEc/PPc

→ **dEI/EI = dPEc/PEc – dPPc/PPc**

→ **dPPc/PPc = dPEc/PEc – dEI/EI**

Data:

GDP is expressed in PPP and in US$2024

- **From 2010 to 2024**

Growth of EI: -1,77%/year
Growth of PEc: +0,23%/year
Growth of PPc: +2,00%/year

- **From 2024 to 2050 IEA STEPS:**

Growth of EI: - 2,14%/year
Growth of PEc: - 0,18%/year
Growth of PPc: + 1,96%/year

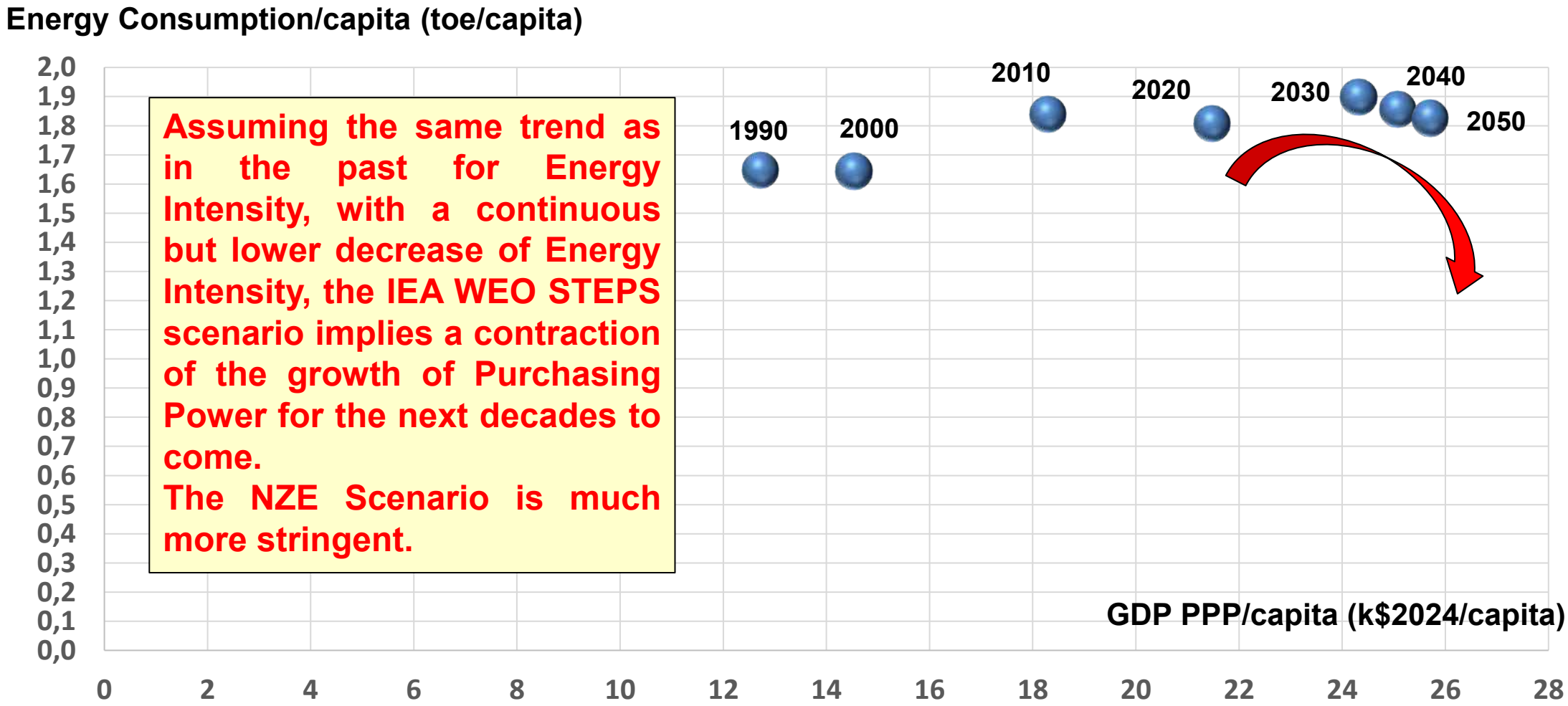
Past Data

IEA WEO 2025 STEPS

Annual Growth of PP vs Annual Growth of EI & PE

E I / PE	-1,70%	-2,00%	-2,30%	-2,50%
+0,25%	+1,95%	+2,25%	+2,55%	+2,75%
+0,00%	+1,70%	+2,00%	+2,30%	+2,50%
-0,25%	+1,45%	+1,75%	+2,05%	+2,25%
-0,50%	+1,20%	+1,50%	+1,80%	+2,00%
-0,75%	+0,95%	+1,25%	+1,55%	+1,75%
-1,00%	+0,70%	+1,00%	+1,30%	+1,50%

Purchasing Power vs Primary Energy (IEA WEO 2025)
Assuming an attenuated decrease of Energy Intensity until 2050
The Growth of GDP for the future could be at stake!

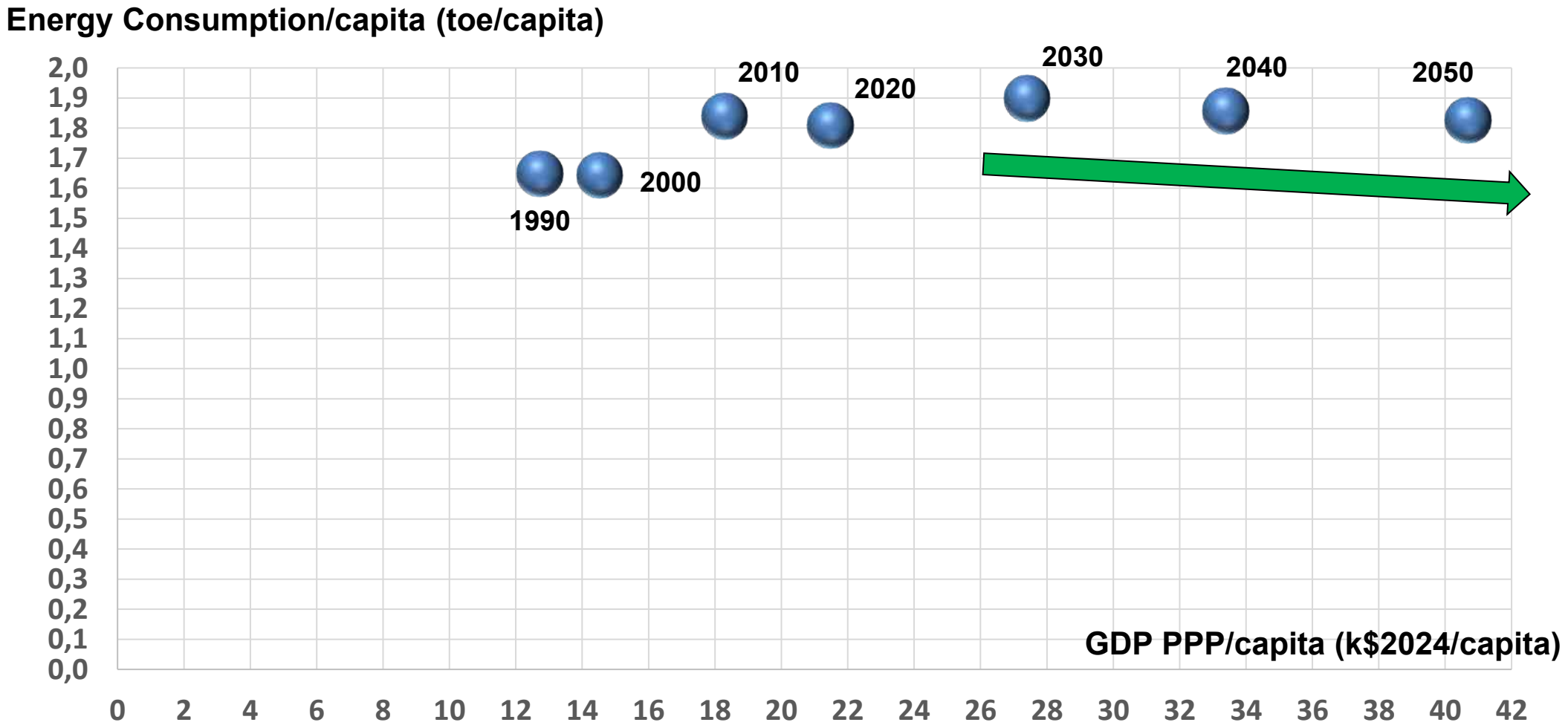


Nota: Source Ch.Guéritte. The environment economic conditions are important when defining GDP.

Purchasing Power vs Primary Energy (IEA WEO 2025)

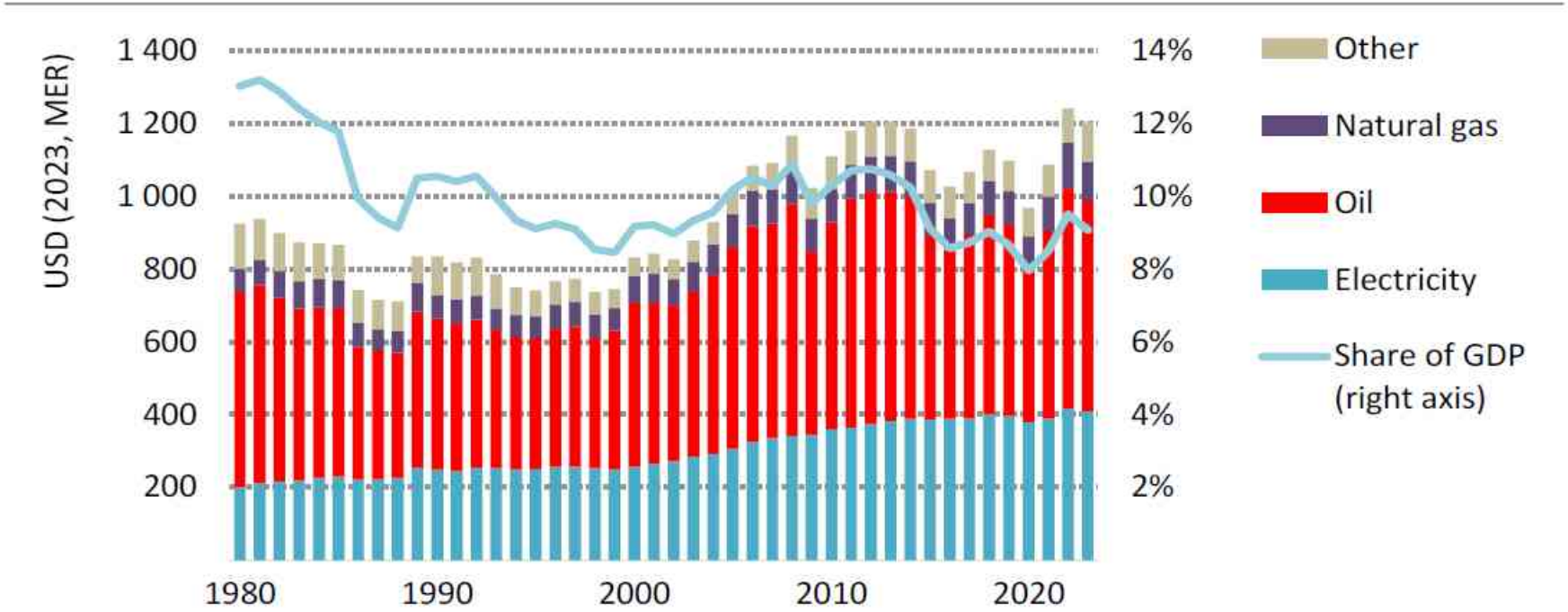
IEA WEO 2025 considers a continous trend for GDP, same for all scenarios

(+3,0/2,6% per annum for all scenarios) for the period 2024 – 2050 …… Questionable??



Nota: Source Ch.Guéritte. The environment economic conditions are important when defining GDP.

Reminder - Global Energy bill per capita evolution Represents # 9% of GDP in 2023



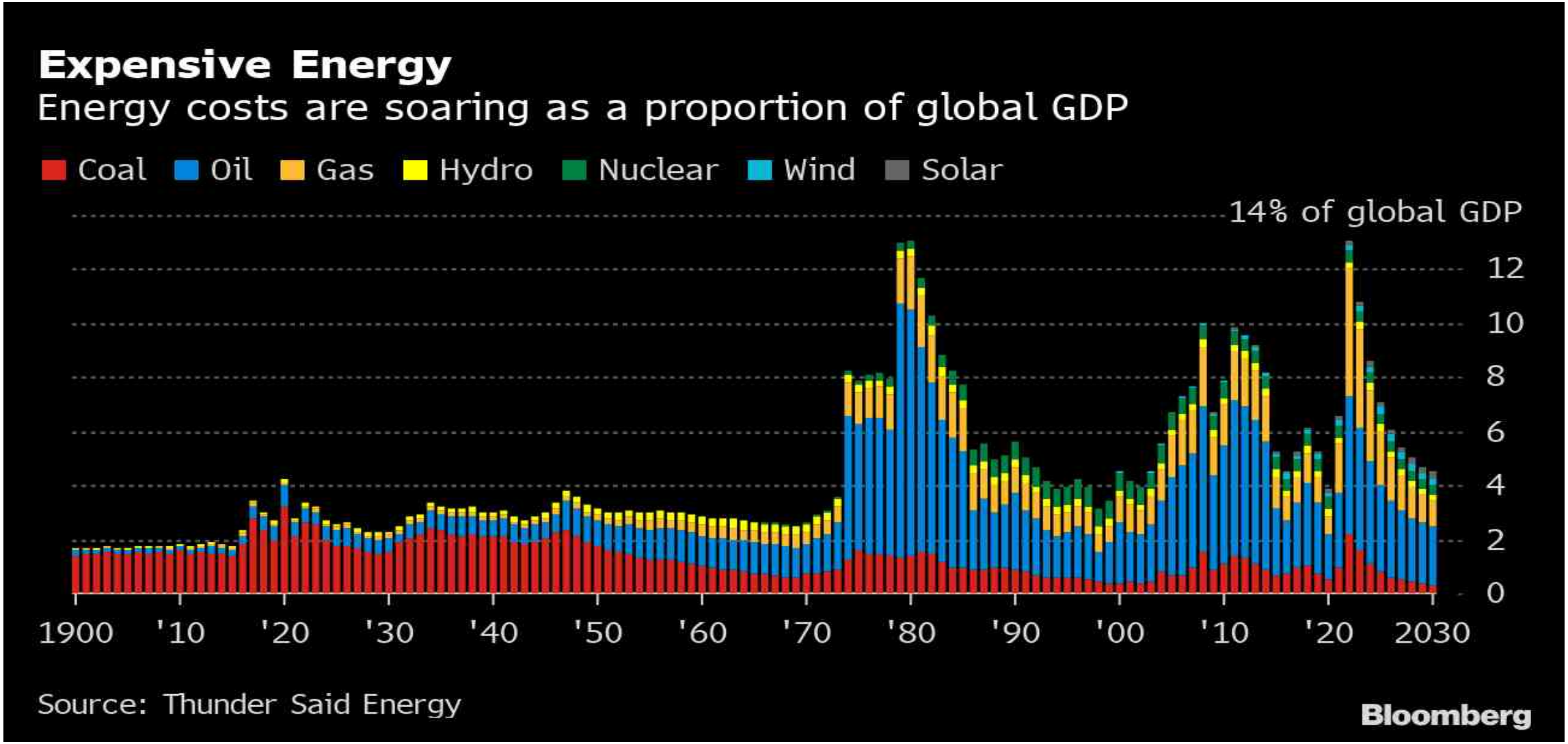
IEA. CC BY 4.0.

Consumer spending on energy made up around 8-10% of global GDP in recent years; oil price volatility has a significant impact on consumer energy bills

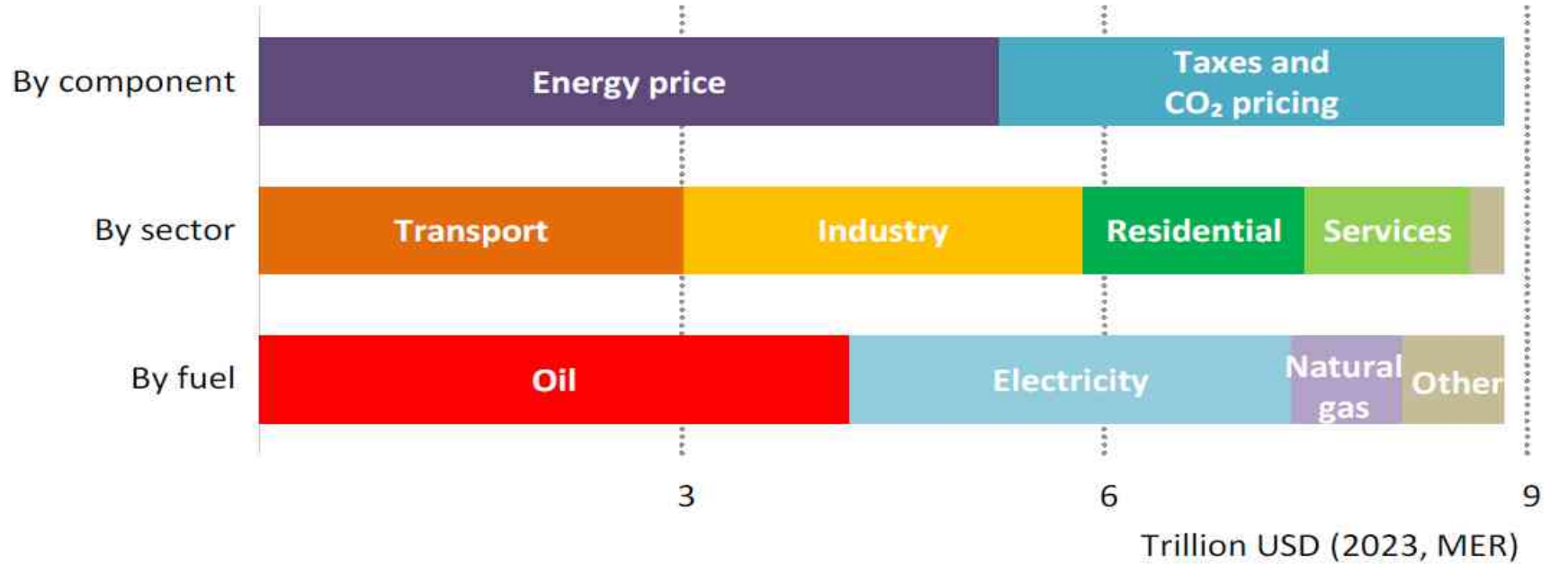
Notes: Other includes coal, modern bioenergy and district heat. The figure excludes traditional use of biomass.

Source: IEA Strategies for Affordable and Fair Clean Energy Transition - June 2024
GDP expressed in nominal value

Global Energy bill evolution - World
During the recent decades, it represented between 4 & 14% of GDP



Breakdown of Global Energy bills 2019 - 2023



IEA. CC BY 4.0.

Consumers pay, on average, around USD 9 trillion for energy each year, with roughly equal amounts spent on energy use in transport, industry and buildings (residential and services)

Notes: Taxes and CO_2 pricing include upstream royalties; fuel duties; and value-added, environmental and excise taxes, and are net of consumer subsidies. Oil, natural gas and other fuels used for power generation are included in electricity.

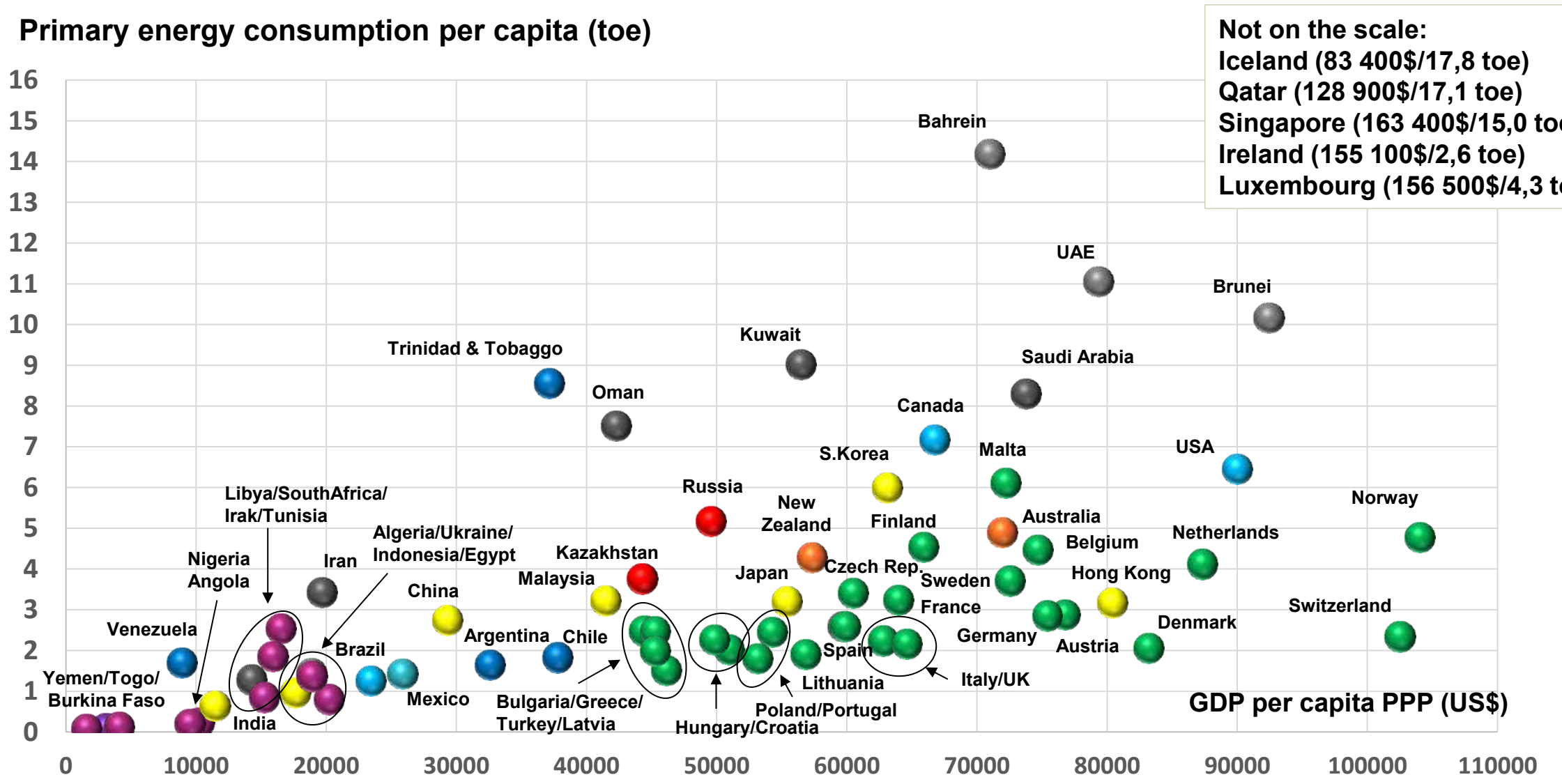
Source: IEA Strategies for Affordable and Fair Clean Energy Transition - June 2024
GDP expressed in nominal value

To fight against Climate Change means less Energy consumption Does it mean a GDP per capita decrease for the future?

- In 2025, Energy represents less than 6% of the World GDP (variable upon time) Despite this, Energy is actually an essential, vital element for the Global Economy.
- Energy and GDP are strictly correlated: Human activities depend upon machines which consume Energy. Correlation coefficient # 99%
- The GDP per capita has regularly increased in the past, but there exist great disparities among the countries in the World. GDP per capita increases with the Energy consumption per capita.
- Since 1990, Energy Intensity has been permanently decreasing. The trend is the same for all countries. Will there be a common limit?
- The fight against Climate Change requires Energy Consumption restrictions for the next decades to come. Therefore, the world GDP Growth could be at stake. It might result in a contraction/stabilization of the World average Purchasing Power per capita for the future?!

A Clear Correlation between Energy and GDP

Primary Energy Consumption and GDP PPP/capita in 2025



Source: Ch.Guéritte/Data from World Bank 2026 & Our World in Data 2026 (Original data in kWh/capita), El Stat. Review 2026. Figures can be slightly different according to sources

Human Development Index (HDI)

Human Development Index (HDI): A statistical composite index including:

Life expectancy (Life expectancy at birth)
Education (Expected years of schooling & mean years of schooling)
GDP per capita PPP

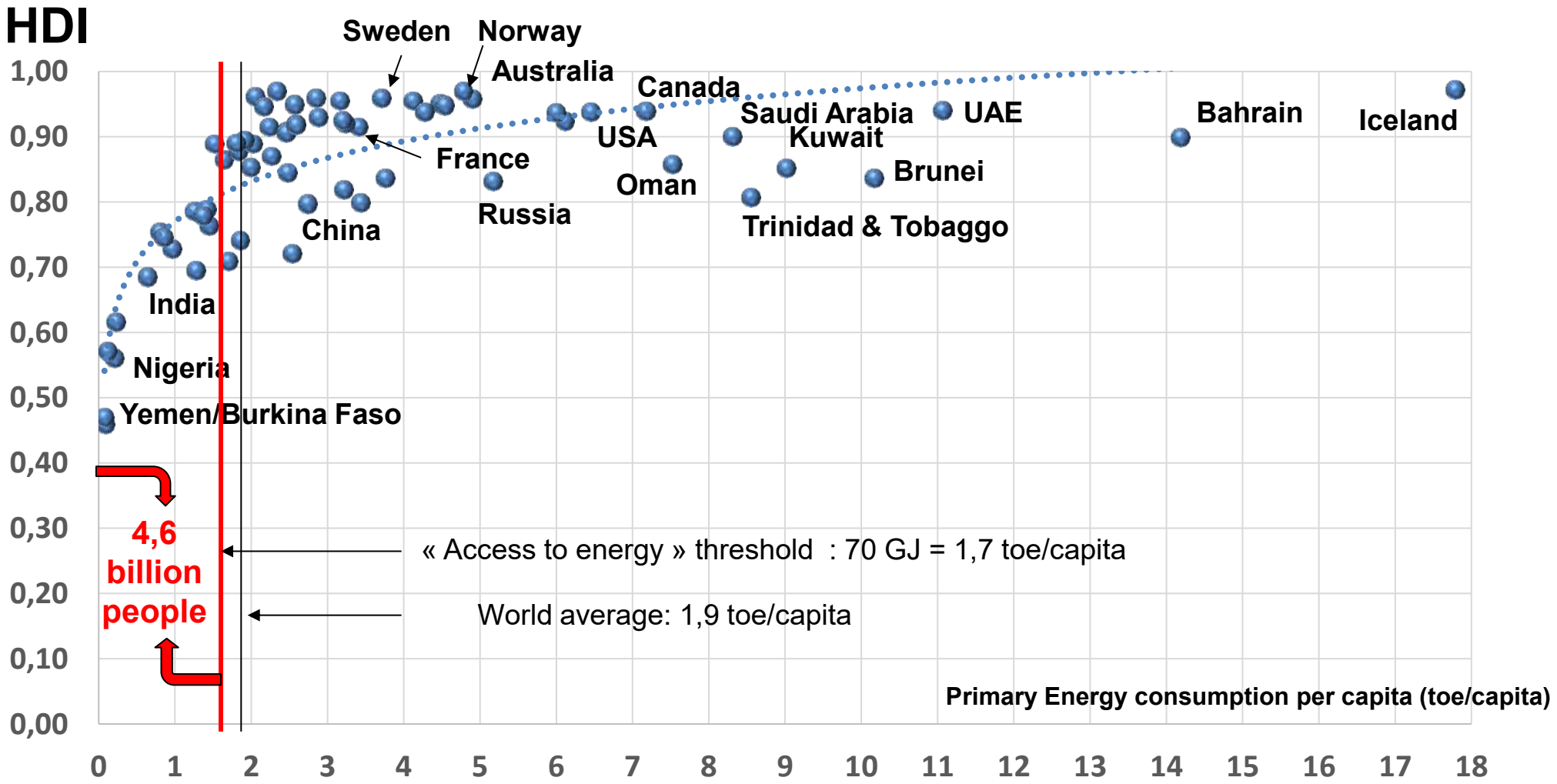
LEI: Life Expectancy (LE) Index = (LE - 20)/(85 - 20)
When LE = 85 years, LEI = 1, when LE = 20 years, LEI = 0

EI: Education Index = (MYSI + EYSI)/2 where
MYSI: Mean Years of Schooling (MYS) Index = MYS/15 (15 years maximum)
EYSI: Expected Years of Schooling (EYS) Index = EYS/18 (18 years maximum)

II = Income Index = GDPc Index = GDP per capita Index = ((Ln(GDPc) - Ln(100))/((Ln(75000)-Ln(100))
= ((Ln(GDPc) – Ln(100)/Ln(750))
When GDPc = 75000$, II = 1, when GDPc = 100$, II = 0

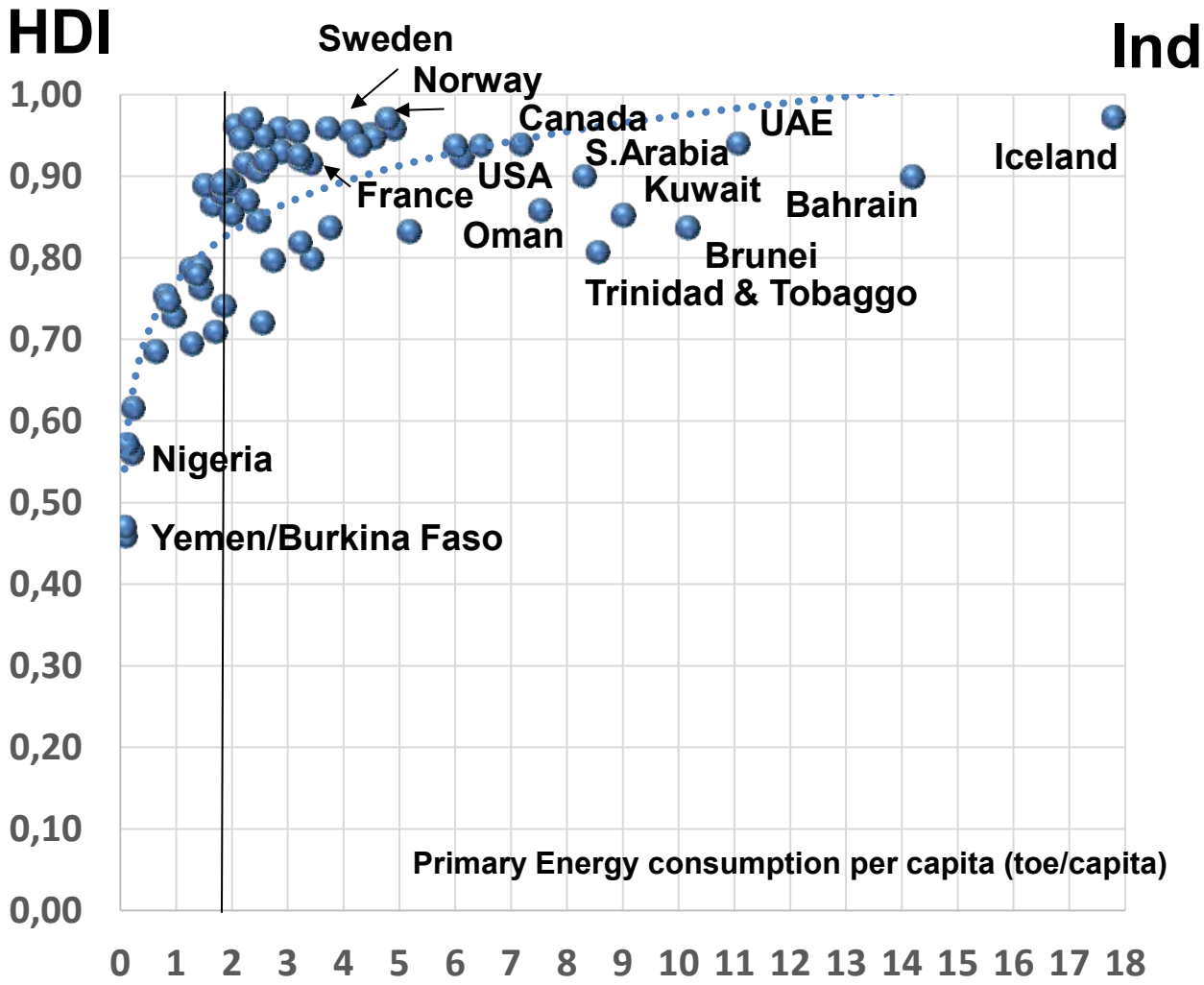
HDI = Geometric mean of the three index = $(LEI*EI*II)^{1/3}$ 0<HDI<1

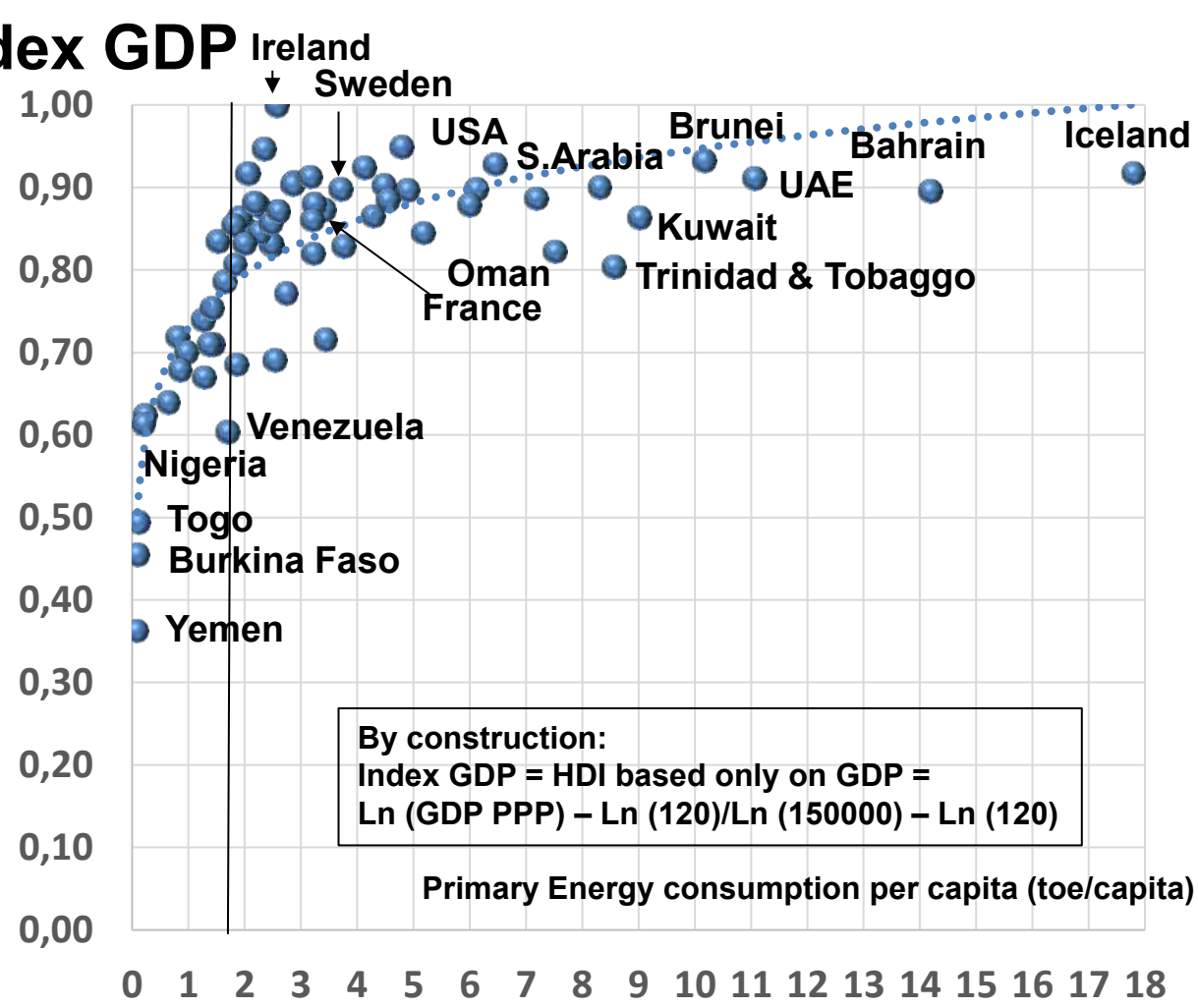
Primary Energy Consumption, GDP and Human Development Index (HDI) in 2025 – A Good Correlation



Source: Ch. Guéritte/Data from World Bank July 2026, EI Stat. Review 2026 & UN 2026
1 toe = 41,858 GJ = 11,632 MWh

Primary Energy Consumption, GDP and Human Development Index (HDI) in 2025 – A Good Correlation

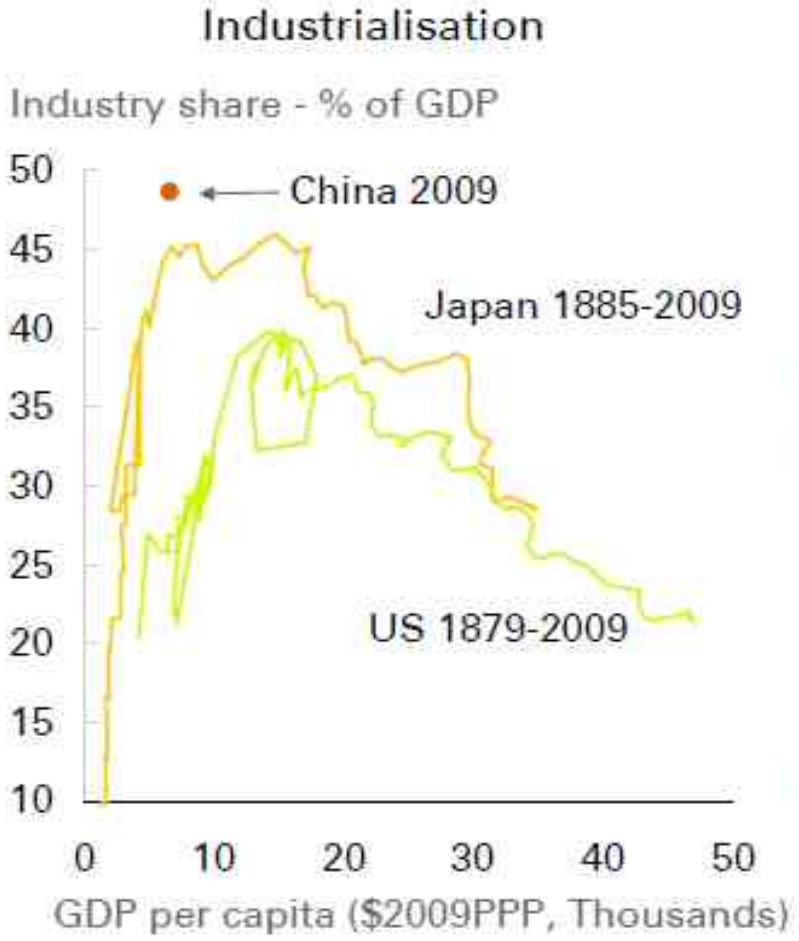




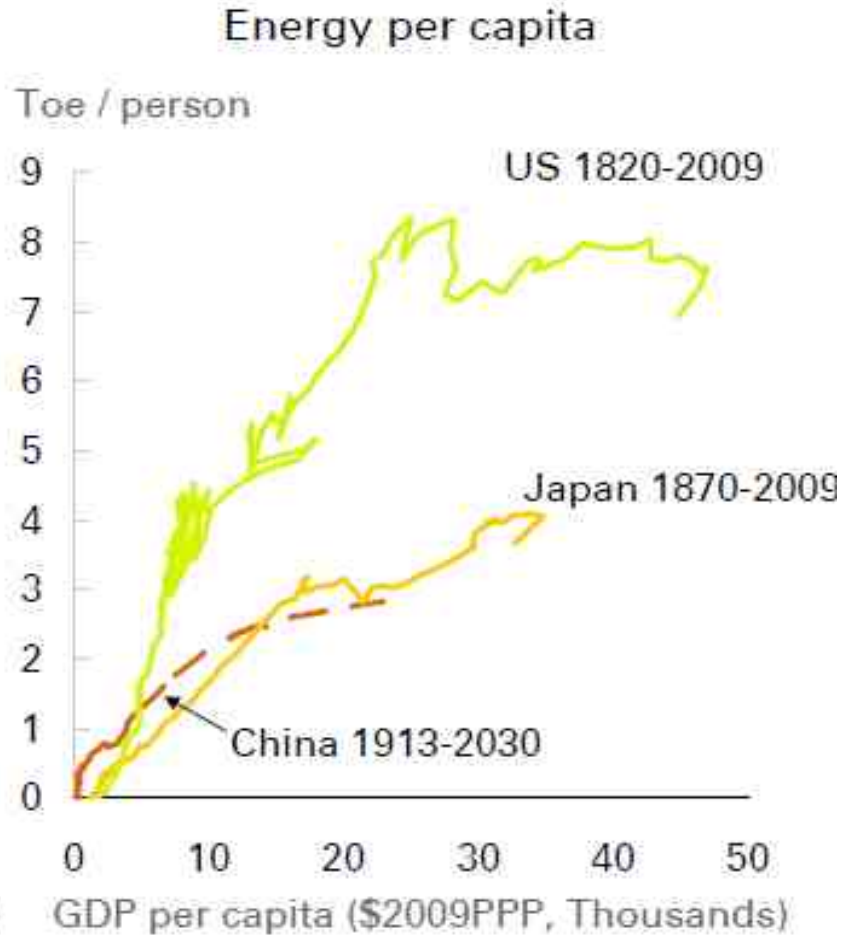
Source: Ch. Guéritte/Data from World Bank July 2026, EI Stat. Review 2026 & UN 2026
1 toe = 41,858 GJ = 11,632 MWh

Evolution of Industrialisation and Energy per capita
Reminder - A view from BP - 2011

Growth, plateau then decline

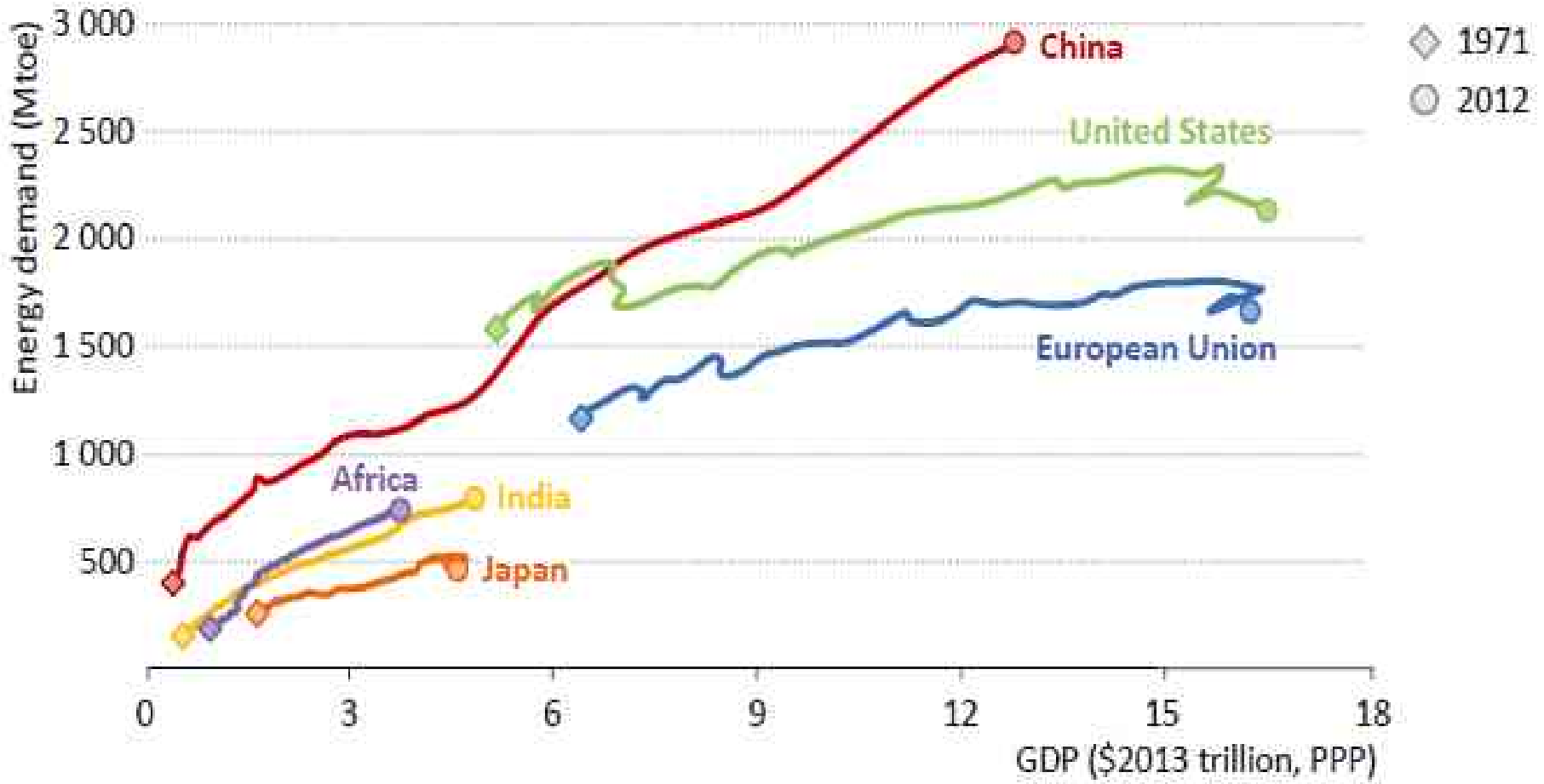


Growth, then stabilization



Source: BP 2011 Energy Outlook 2030

Reminder - Primary Energy Demand vs GDP 1971 – 2012
A view by IEA 2014 - Growth, then stabilization for OECD



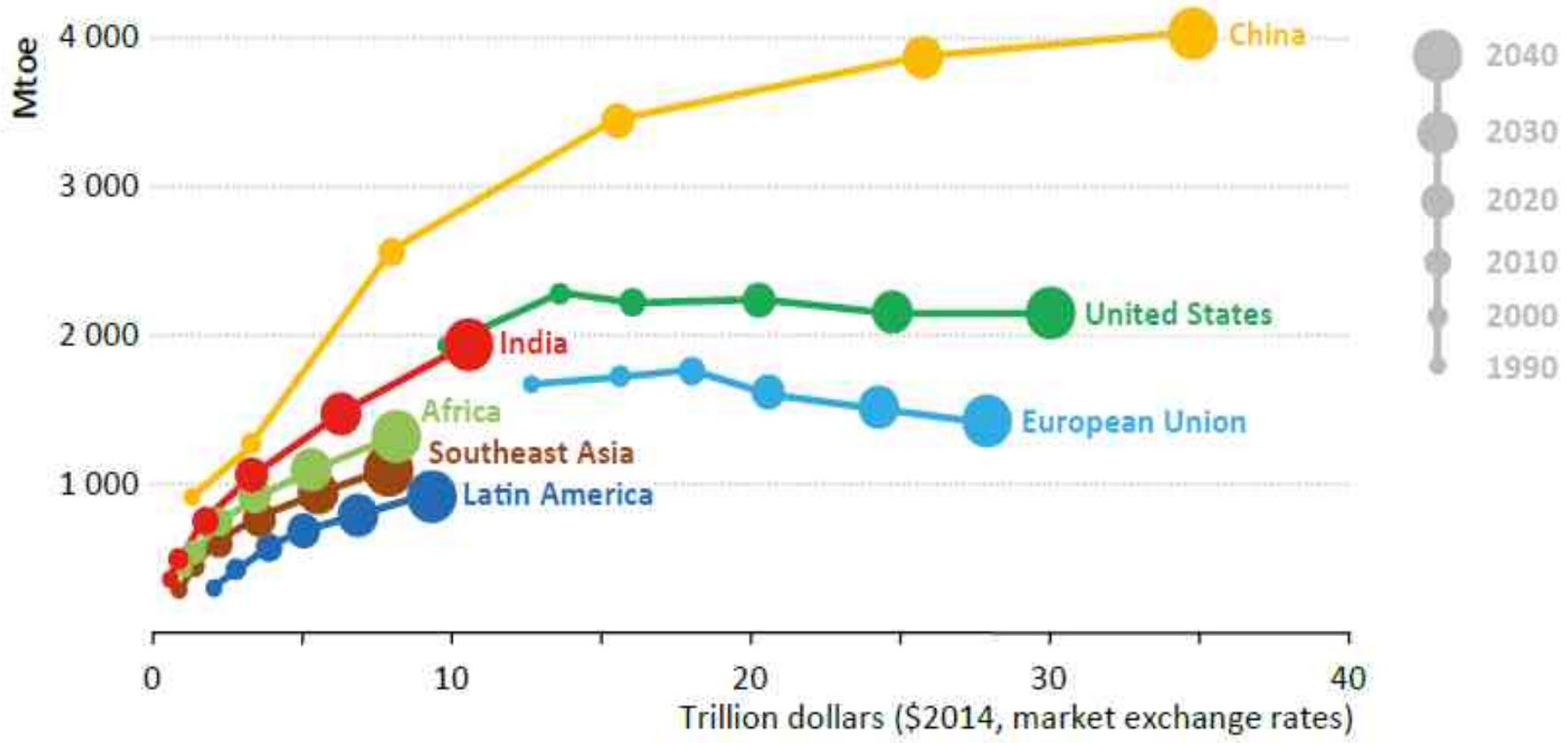
Note: Mtoe = million tonnes of oil equivalent.

Source: IEA World Energy Outlook (WEO) 2014

Primary Energy Demand and GDP 1990 – 2040

Reminder: IEA 2015 Central Scenario

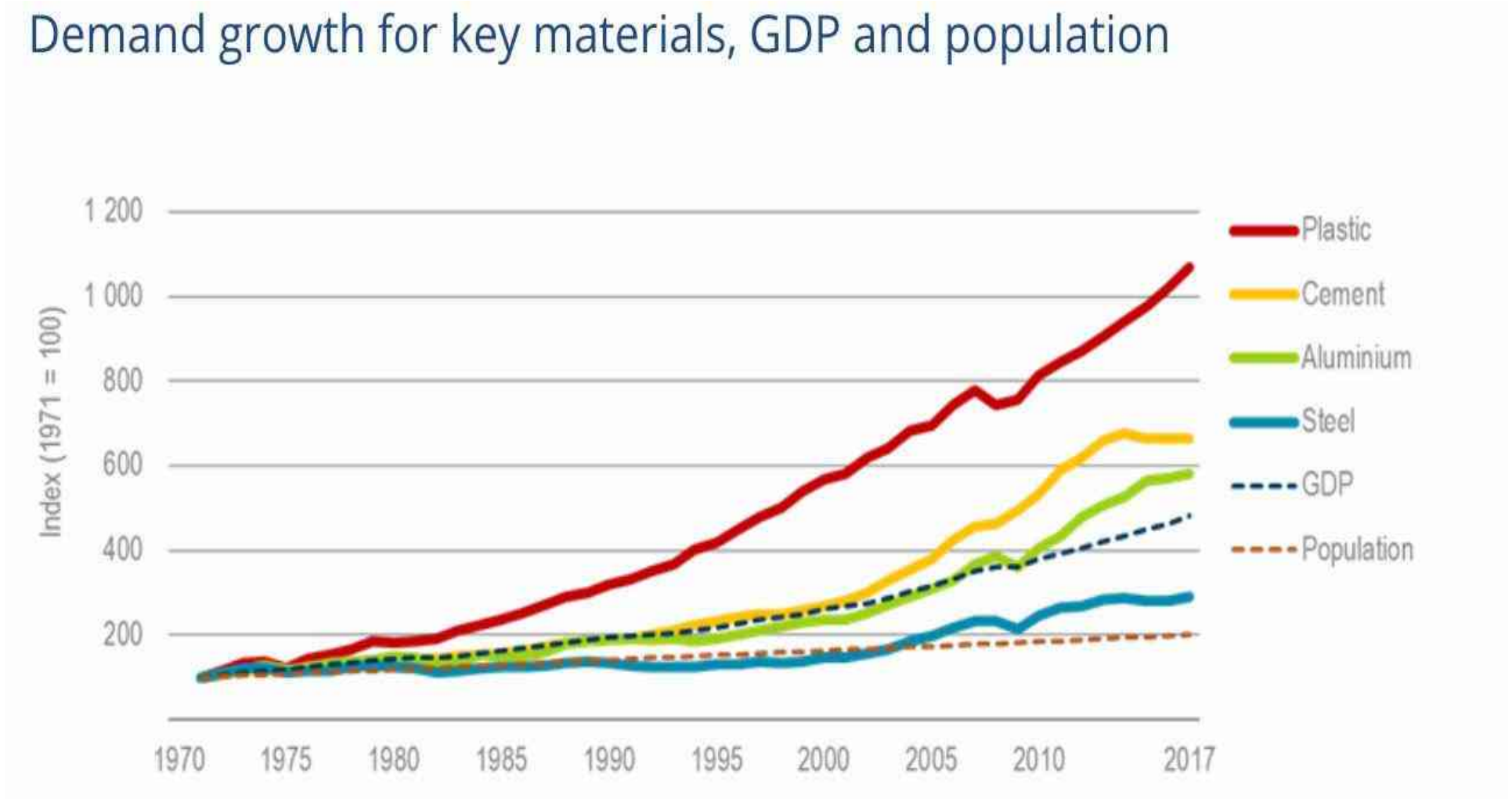
Energy Demand: Growth for Developing Countries, Stabilization for Developed Countries



Source: IEA WEO 2015

Reminder - World Demand Growth for Key Materials x by 3 to 11 from 1970 to 2017

In 2022, the Russia – Ukraine war will exacerbate Prices inflation for Key Materials



Source: IEA WEO 2019

Fossil Fuels: a large contribution to Energy Demand

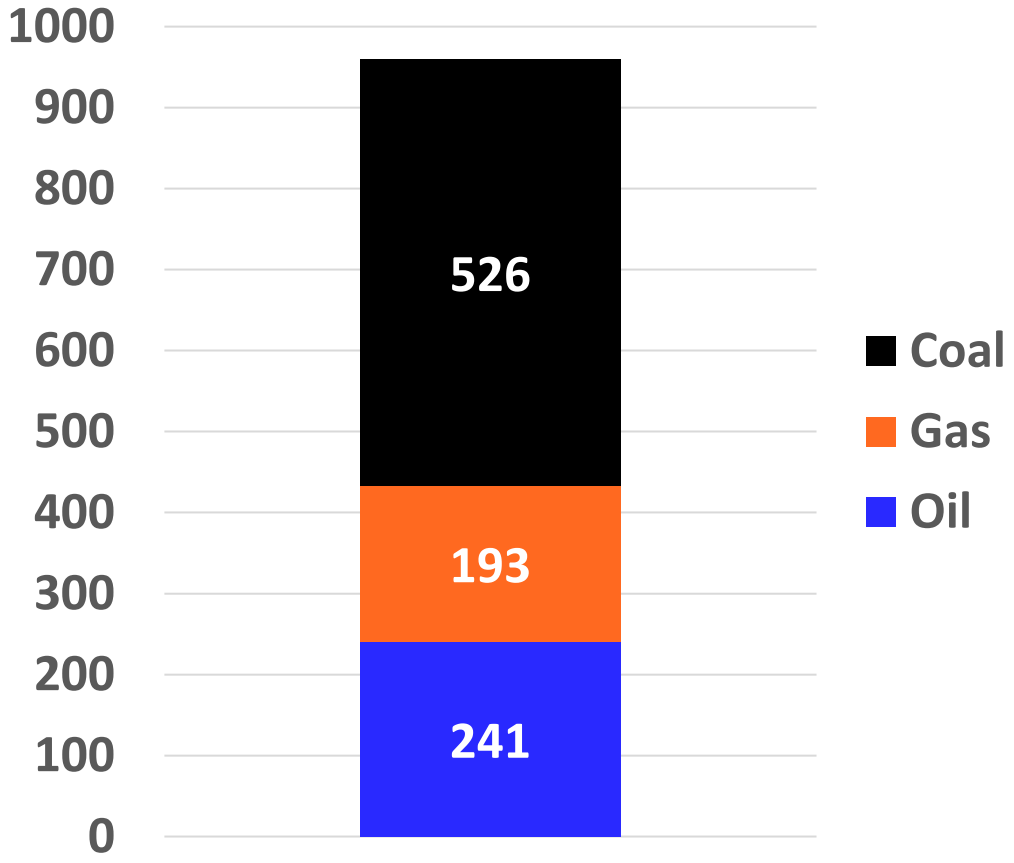
Proven Reserves, Ultimate Production,…..
Different Evaluations, Different Forecasts,…
But Similar Trends

Since 2022, BP & EI do not produce anymore data on Oil, Gas & Coal Reserves – Last figures: end 2020.

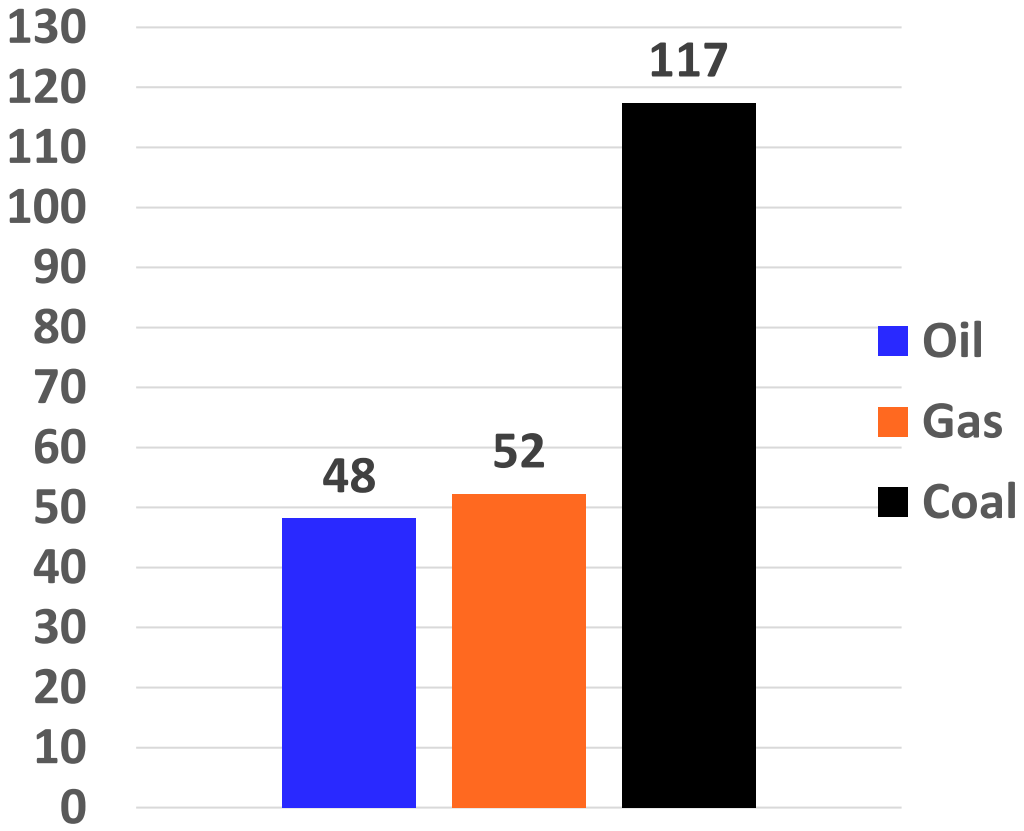
In their annual World Energy Outlook, IEA provides estimates for proven reserves and resources

Fossil Fuels – « Proven Reserves » end 2024
960 Gtoe # 7,0 Tboe (Drastic decrease in China Coal Reserves vs end 2016)

Proven Reserves (Gtoe)

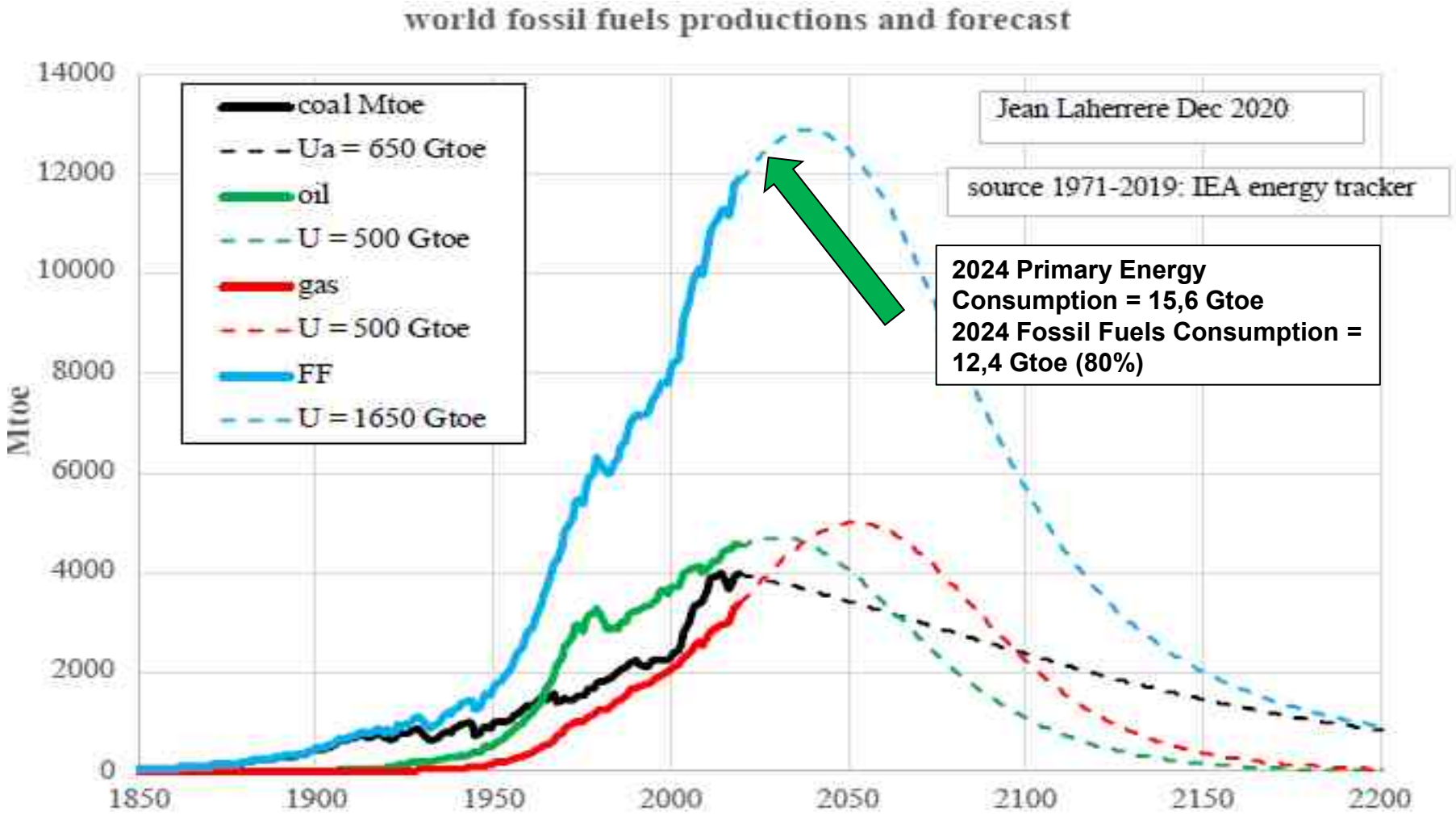


R/P Ratio (Nb of years)



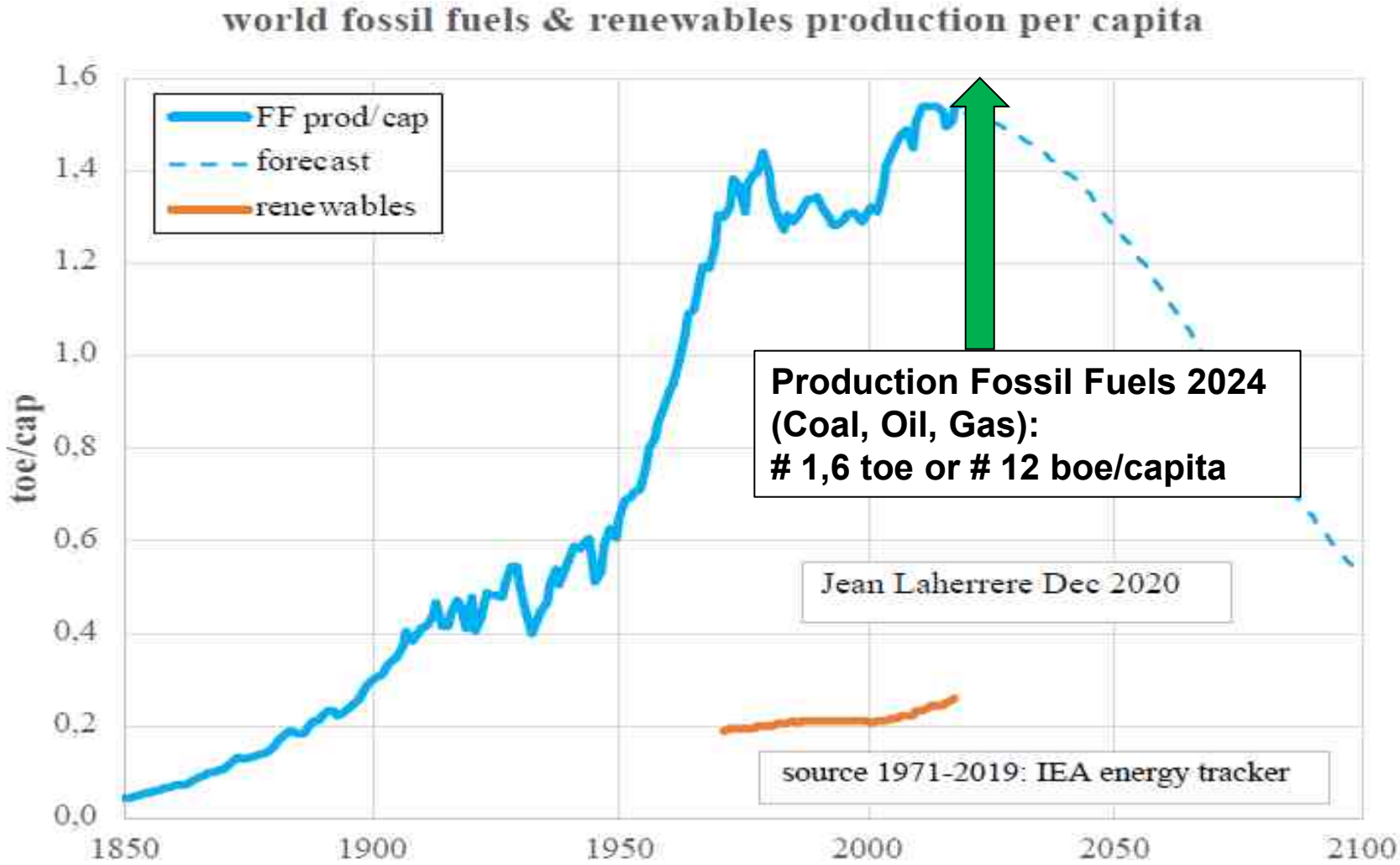
Source;: Data from IEA 2025
toe: tonne oil equivalent
boe: barrel oil equivalent

Fossil Fuels – Ultimate cumulative production
with no constraints # 1 650 Gtoe # 12 Tboe (# 140 years of production & 4 800 $GtCO_2$ potential emissions!)



Source: Jean Laherrère – ASPO 2020

World Fossil Fuels Production per capita
Actual figures till 2019. What next?



Source: Jean Laherrère – ASPO 2020

3

Evolution of Energy Intensity

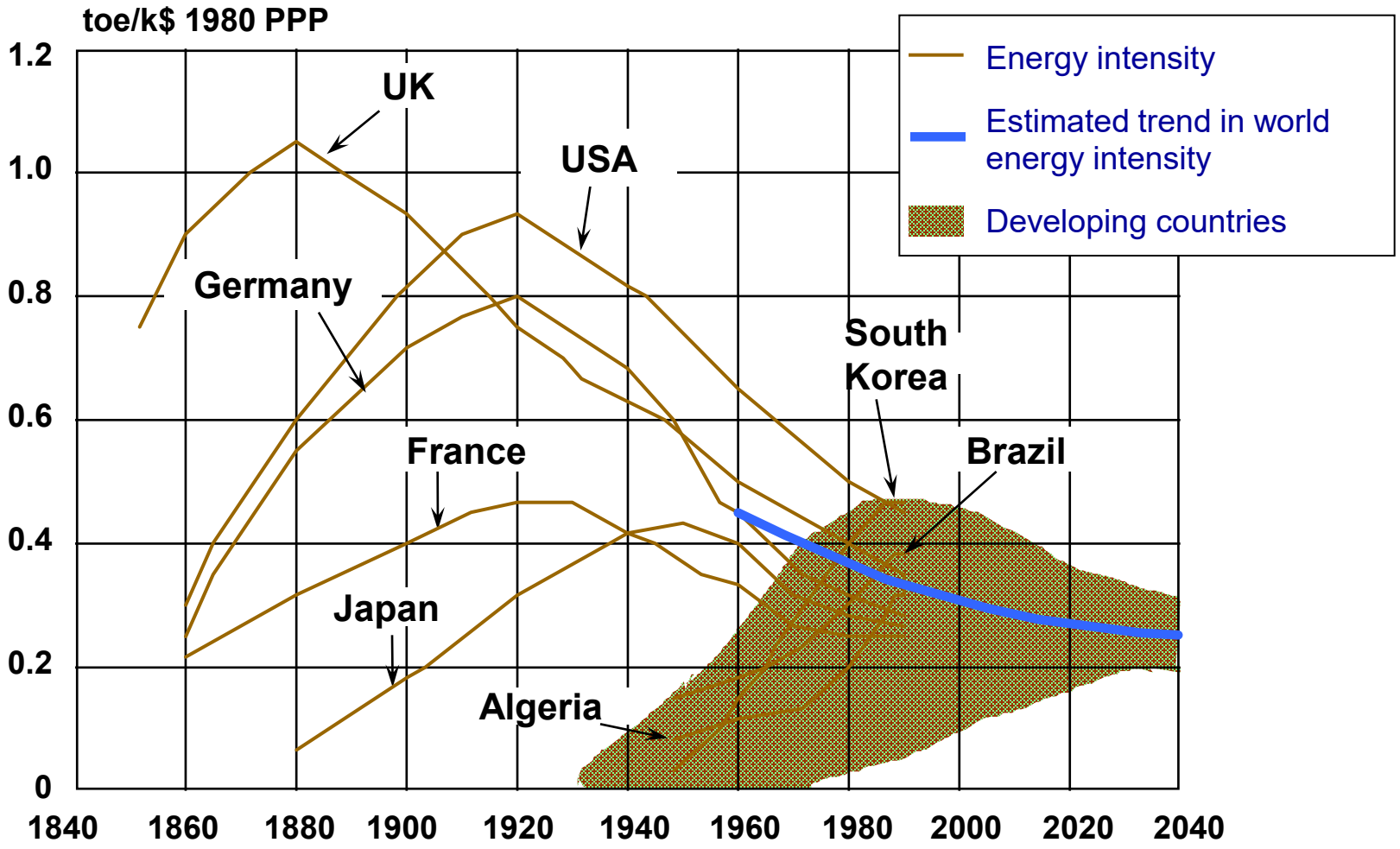
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- 11. Global Energy Growth – Electricity storage
- 12. Global Energy Growth – Petrochemicals

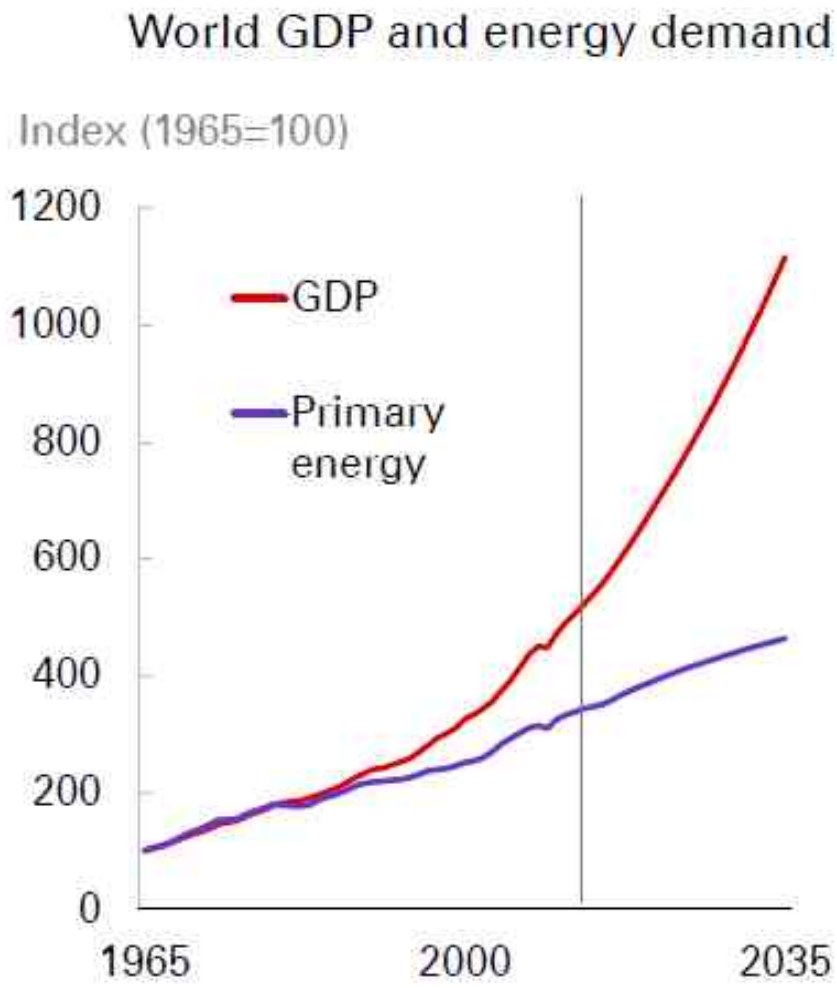
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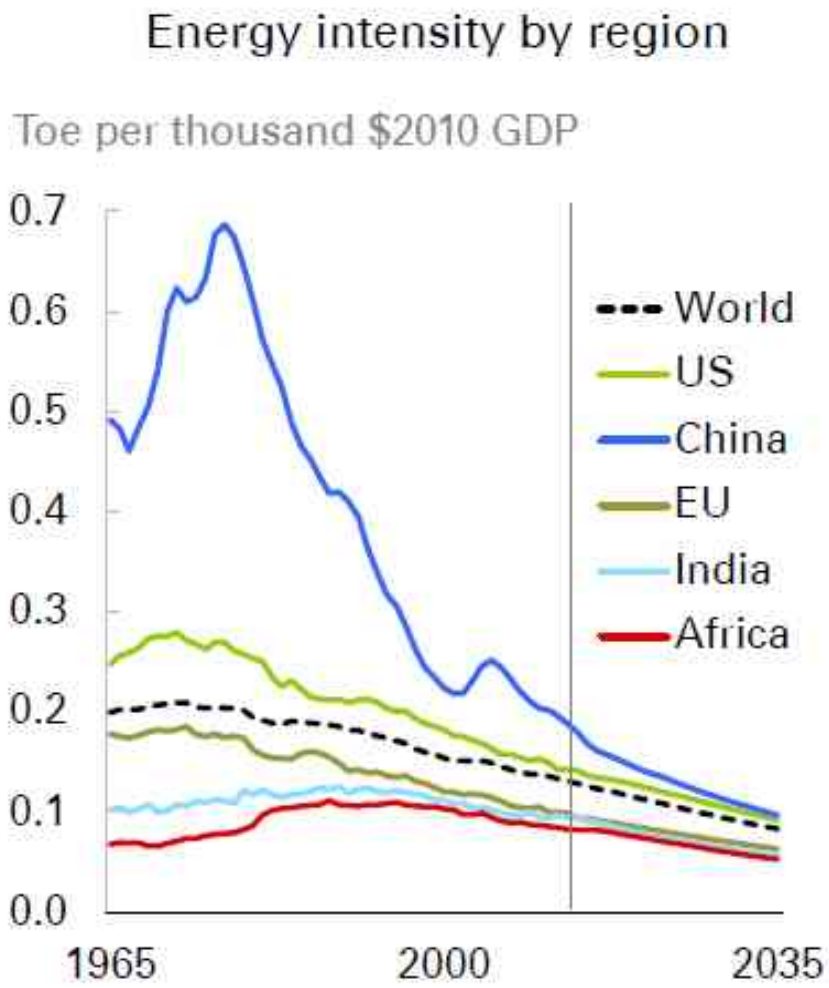
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- 21. Reminder: Basic Thermodynamics
- 22.Equivalences and conversion factors

Evolution of Energy Intensity (p.m. a vision 2000)
In the graph below, Energy Intensity is expressed in toe per k$1980 GDP
In all Countries, Energy Intensity is declining with time



Energy Intensity – Reminder: BP 2016 Scenario
In all Countries, Energy Intensity is declining with time

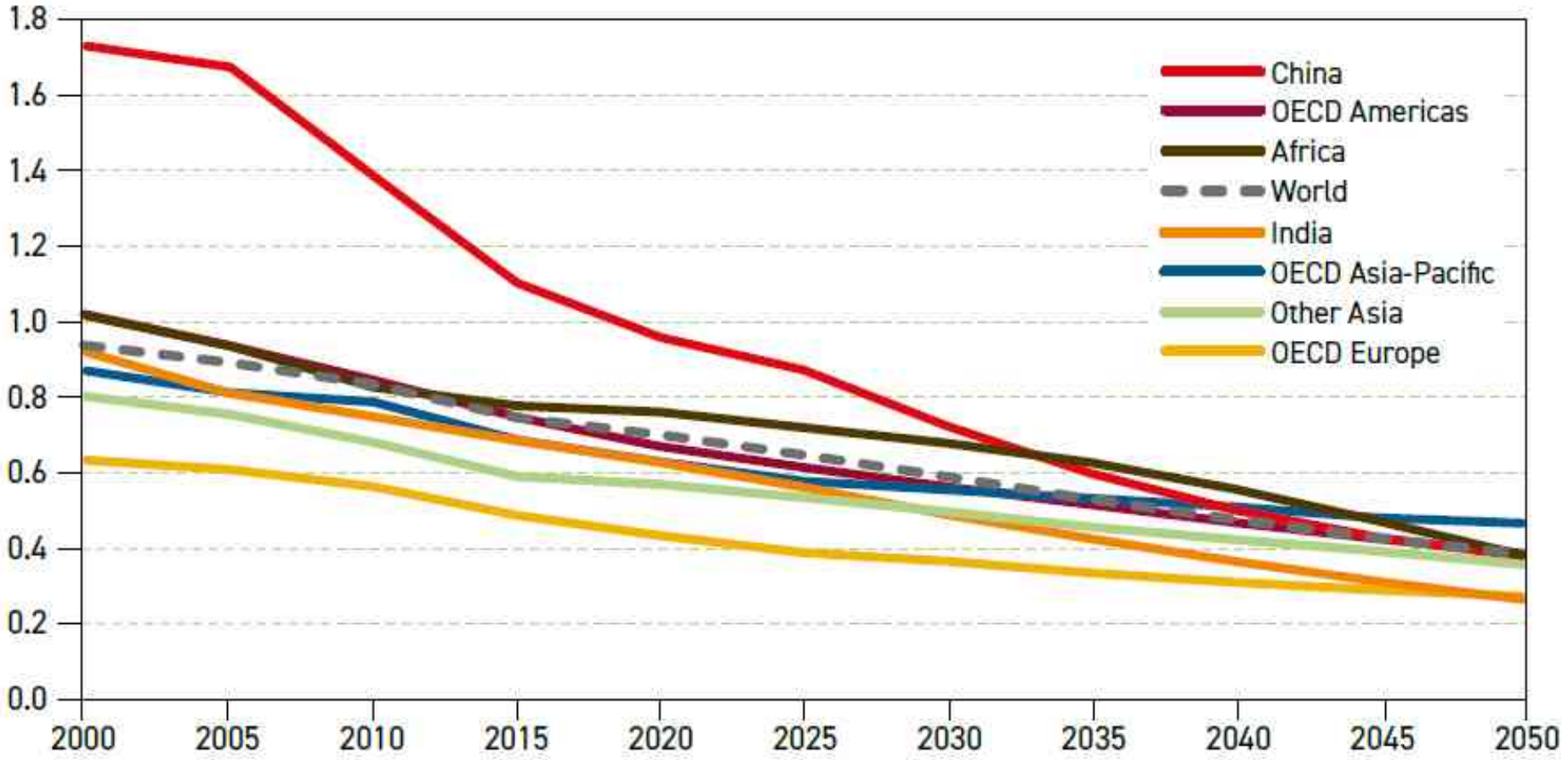




Source: BP 2016 Energy Outlook 2035

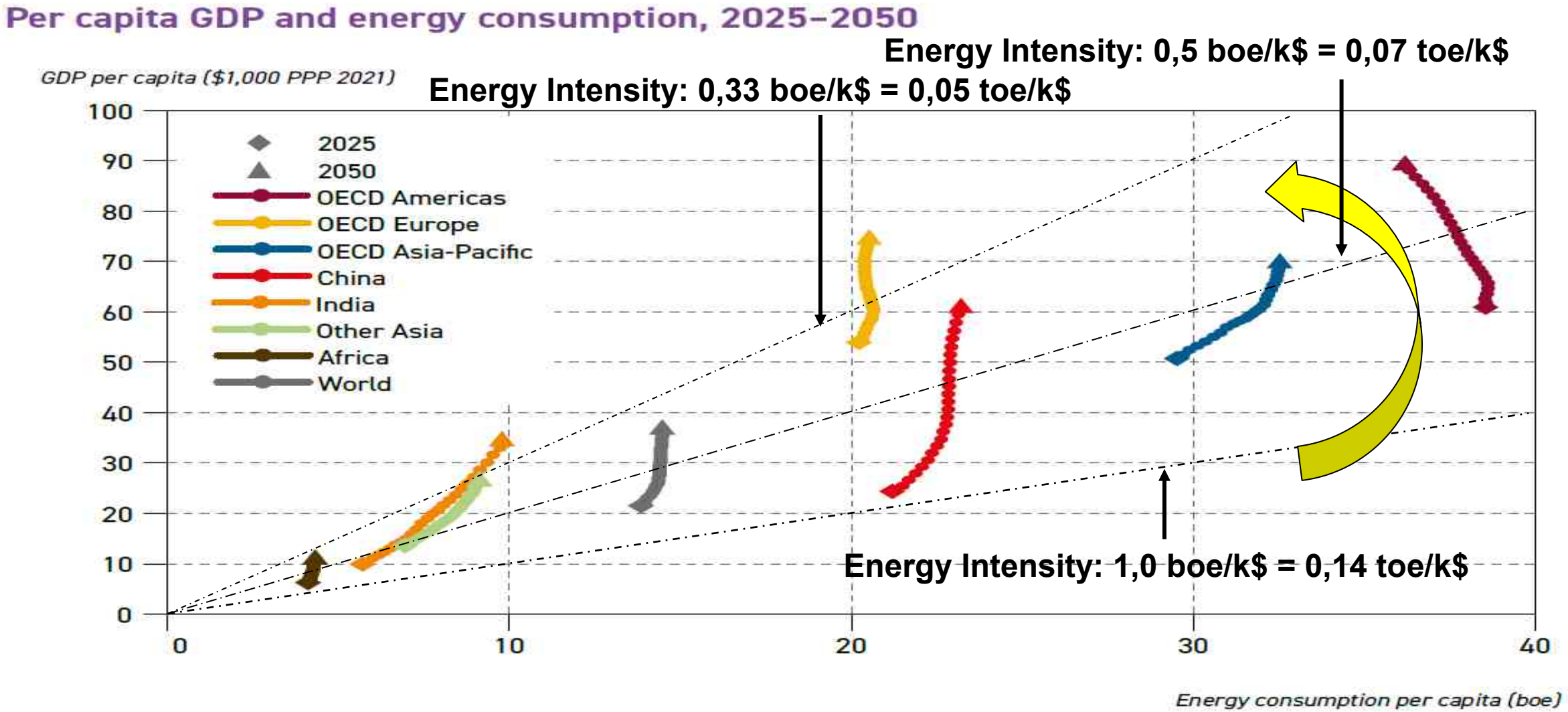
Energy Intensity 2000 – 2050 By OPEC 2026
In all Countries, Energy Intensity is declining with time

Evolution and projections of energy intensity in major regions, 2000–2050, boe/$1,000 (PPP 2021)



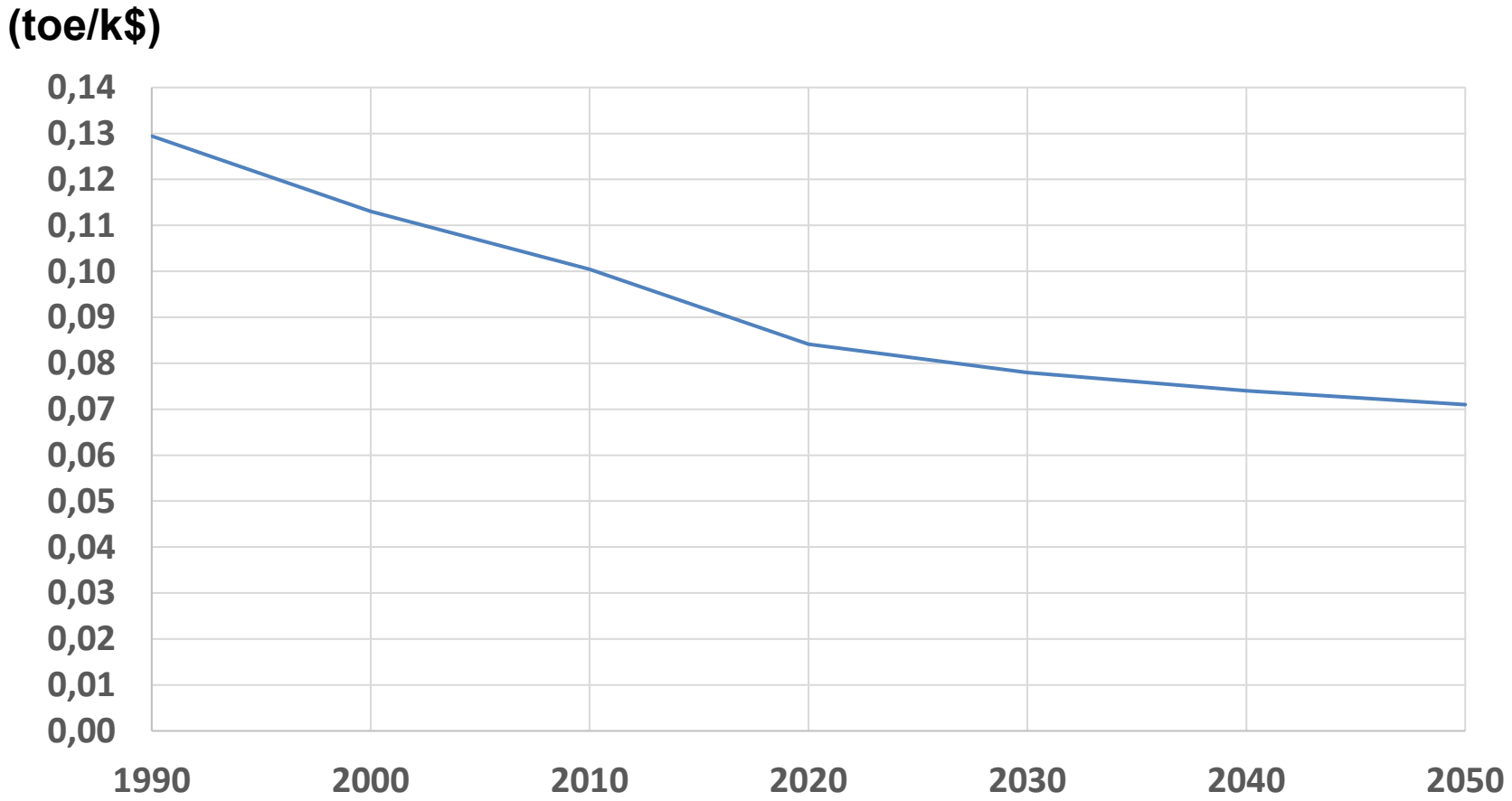
Source: OPEC WOO 2026 – June 2026

GDP (PPP) per Capita vs Energy Consumption per Capita 2025 – 2050 by OPEC 2026



Source: OPEC WOO 2026 – June 2026
1 toe # 7,3 boe

Evolution of Energy Intensity (EI) (toe /k$ GDP PPP $2024)
2020 – 2050: IEA WEO 2025 STEPS
Assuming an attenuated decrease of EI until 2050 (Covid19 in 2020)



Nota: Source Ch.Guéritte. The environment economic conditions are important when defining GDP.
Data: History & IEA WEO 2025

4

Energy: past evolution, present situation

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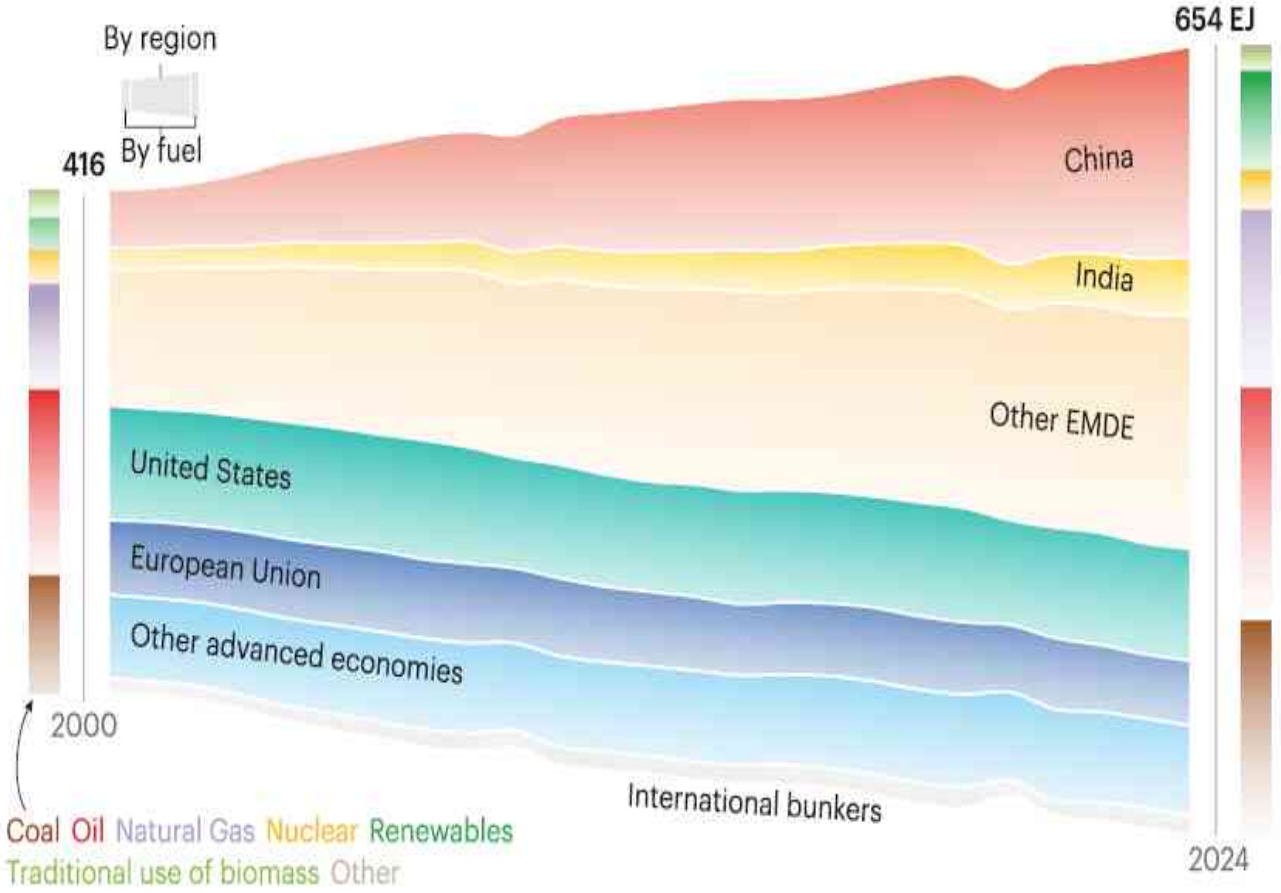
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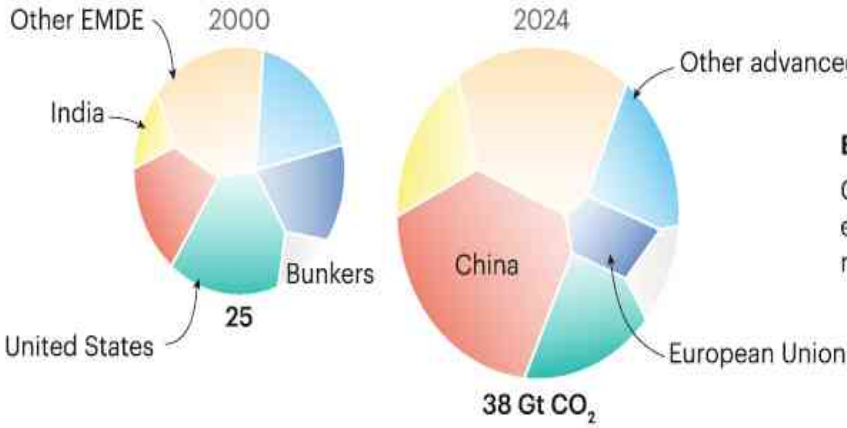
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Evolution of World Primary Energy Demand 2000 - 2024 by IEA 2025

Global energy demand and emissions continue to grow

Global demand has grown by nearly 60% since 2000, with all the increase coming in emerging market and developing economies. All major energy sources grew over the period.



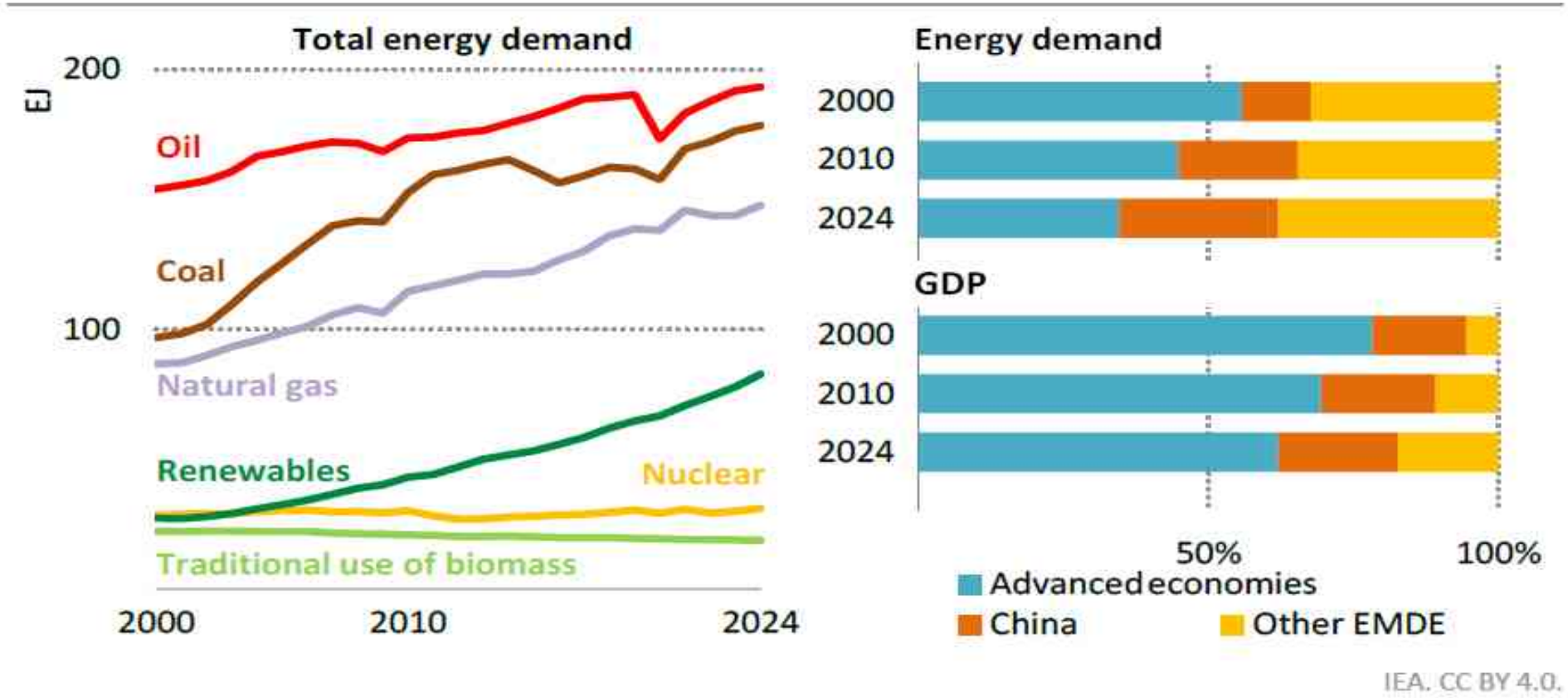


Emissions

Global energy-related CO_2 emissions have increased by more than 50% since 2000.

Source: IEA WEO 2025

Evolution of World Primary Energy Demand 2000 - 2024 by IEA 2025

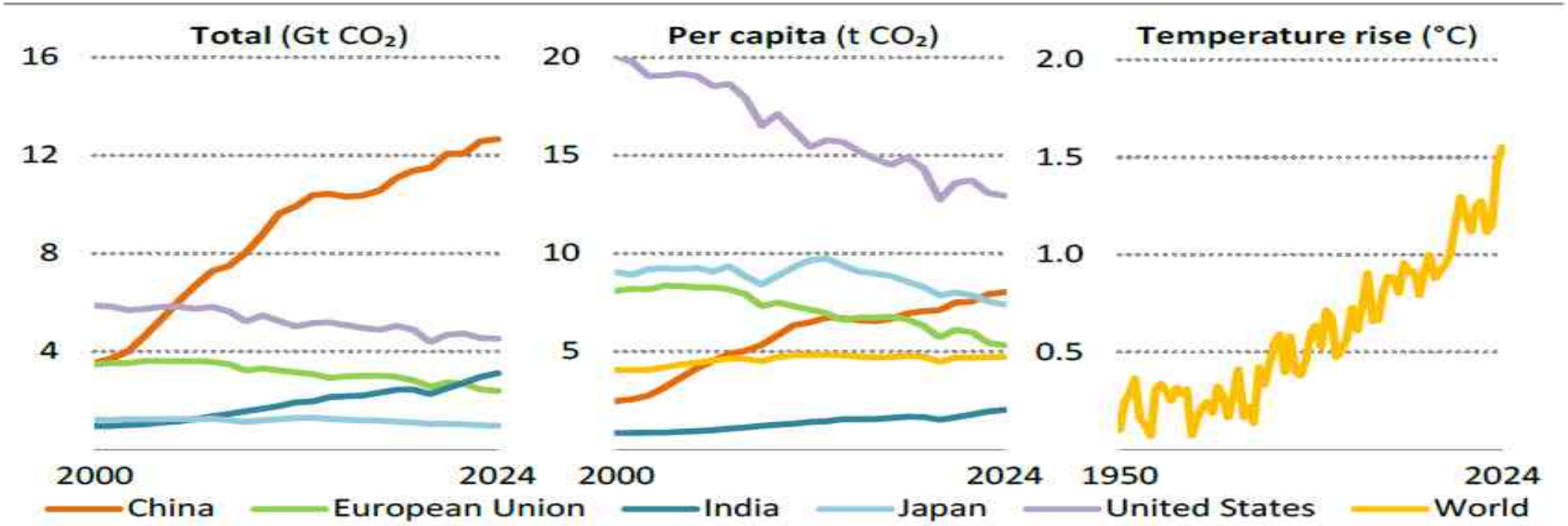


Global energy demand has increased 20% since 2010,
with all the increase taking place in emerging market and developing economies

Notes: EJ = exajoule; EMDE = emerging market and developing economies. GDP is measured in market exchange rates.

Source: IEA WEO 2025

Evolution of World CO_2 Emissions & Temperature rise by IEA



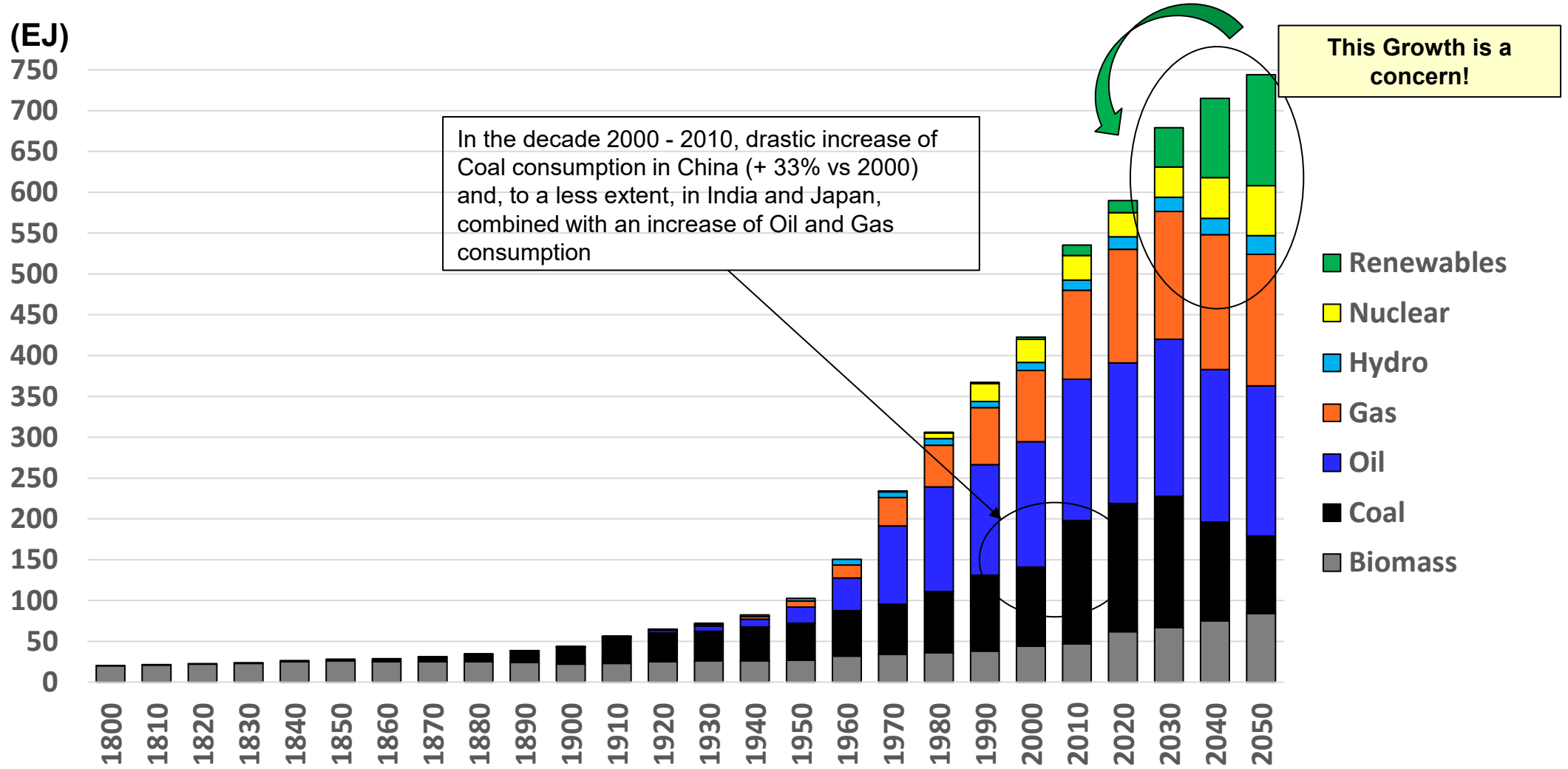
Energy-related emissions reached another all-time high in 2024, which was the hottest year ever recorded, with temperatures of over 1.5 °C above pre-industrial levels

Notes: Gt CO_2 = gigatonnes of carbon dioxide; t CO_2 = tonnes of carbon dioxide; °C = degree Celsius. Temperature rise is the average of HadCRUT5, Berkeley Earth, NOAA GlobalTemp v6, GISTEMP, ERA5, and JRA-3Q datasets adjusted by the World Meteorological Organisation so that each dataset is relative to the period 1850-1900.

Sources: IEA analysis and WMO (2025).

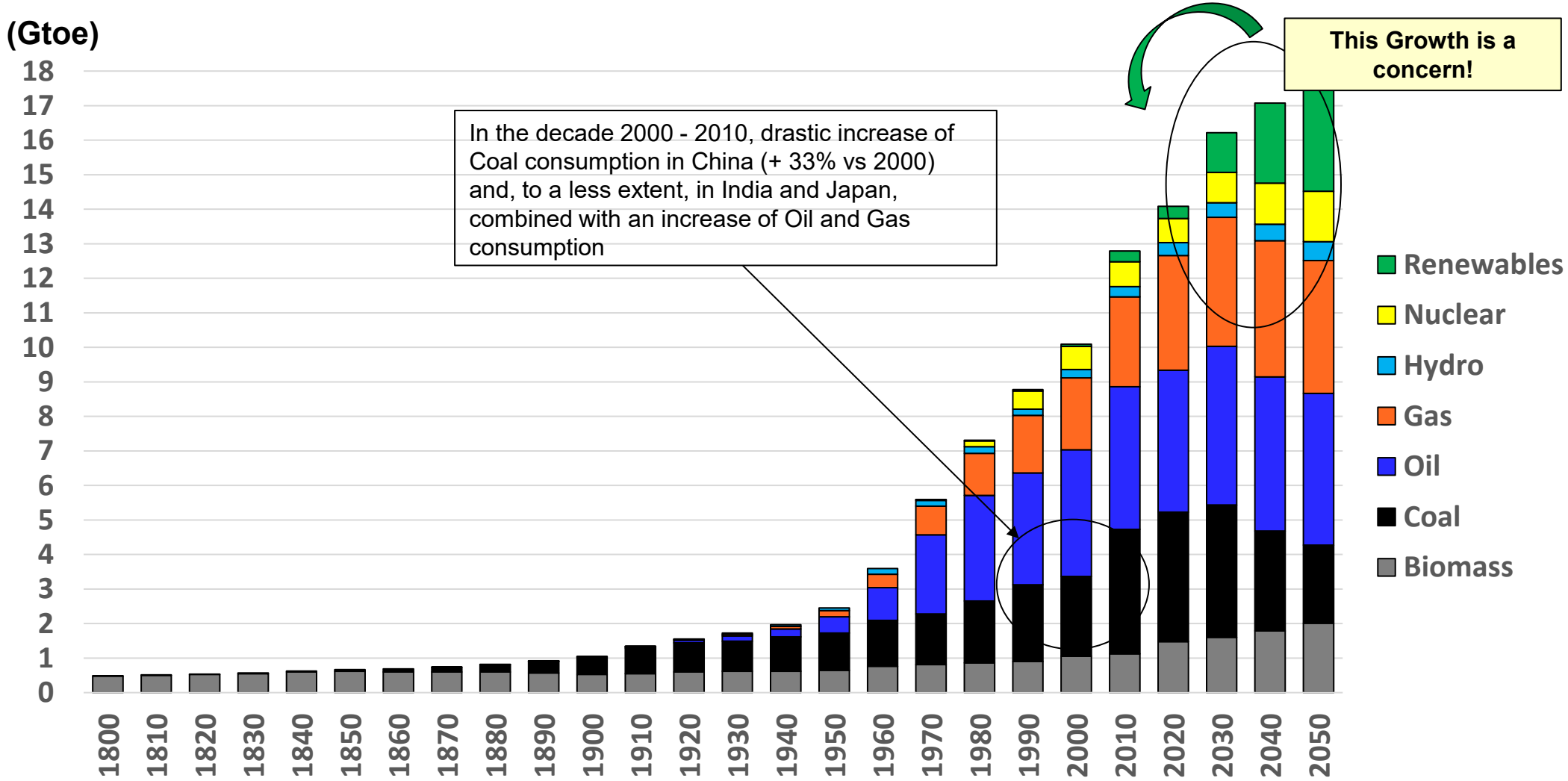
Source: IEA WEO 2025

History of World Primary Energy Demand (EJ)
(2030 – 2050: IEA STEPS 2025)



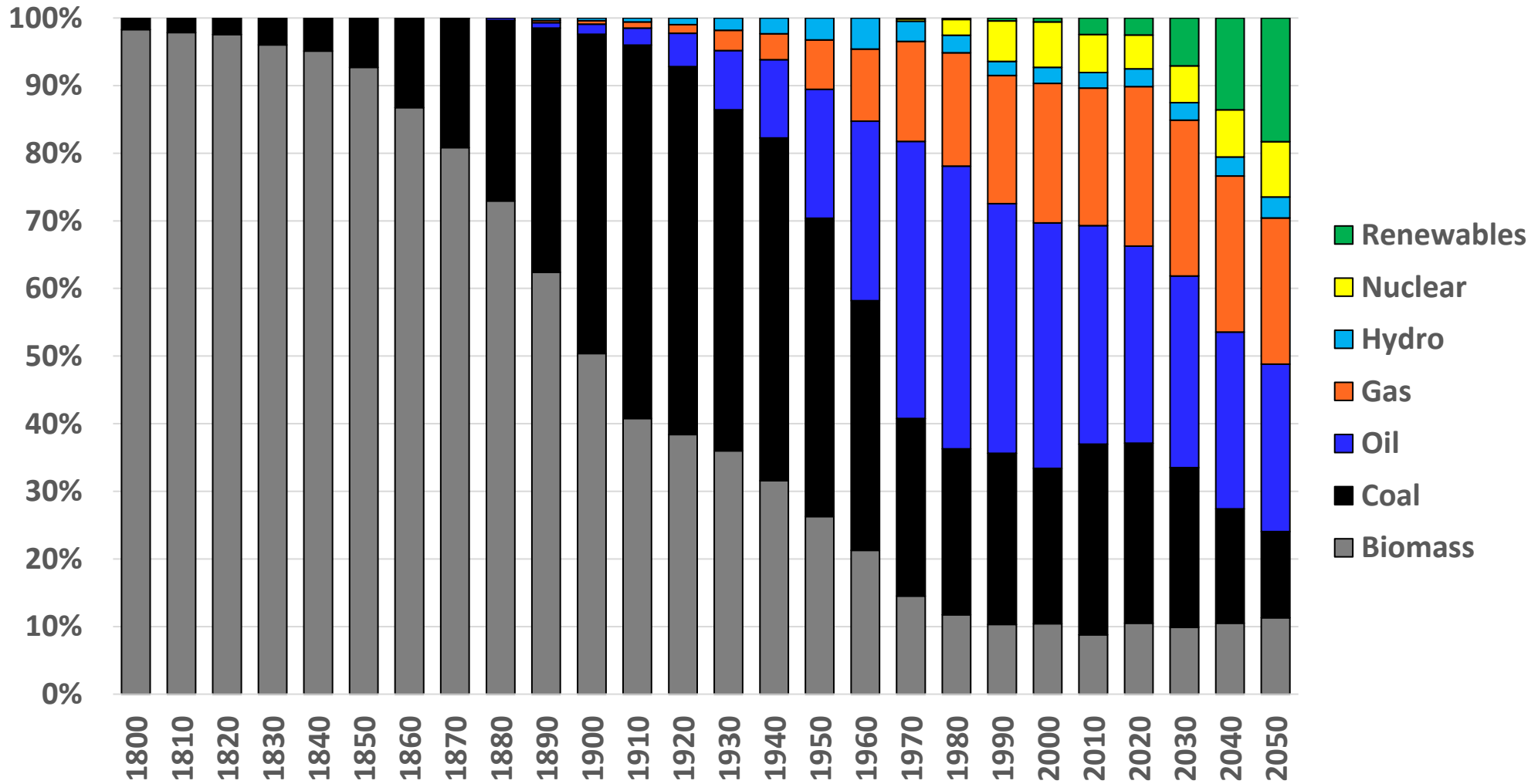
STEPS: IEA WEO 2025 Stated Policies Scenario - Actual data till 2024, estimates as from 2025.
Biomass includes modern solid, liquid, gaseous bioenergy
EJ = Exajoules = 10^{18} J = 23,88 Mtoe

History of World Primary Energy Demand (Gtoe) (2030 – 2050: IEA STEPS 2025)



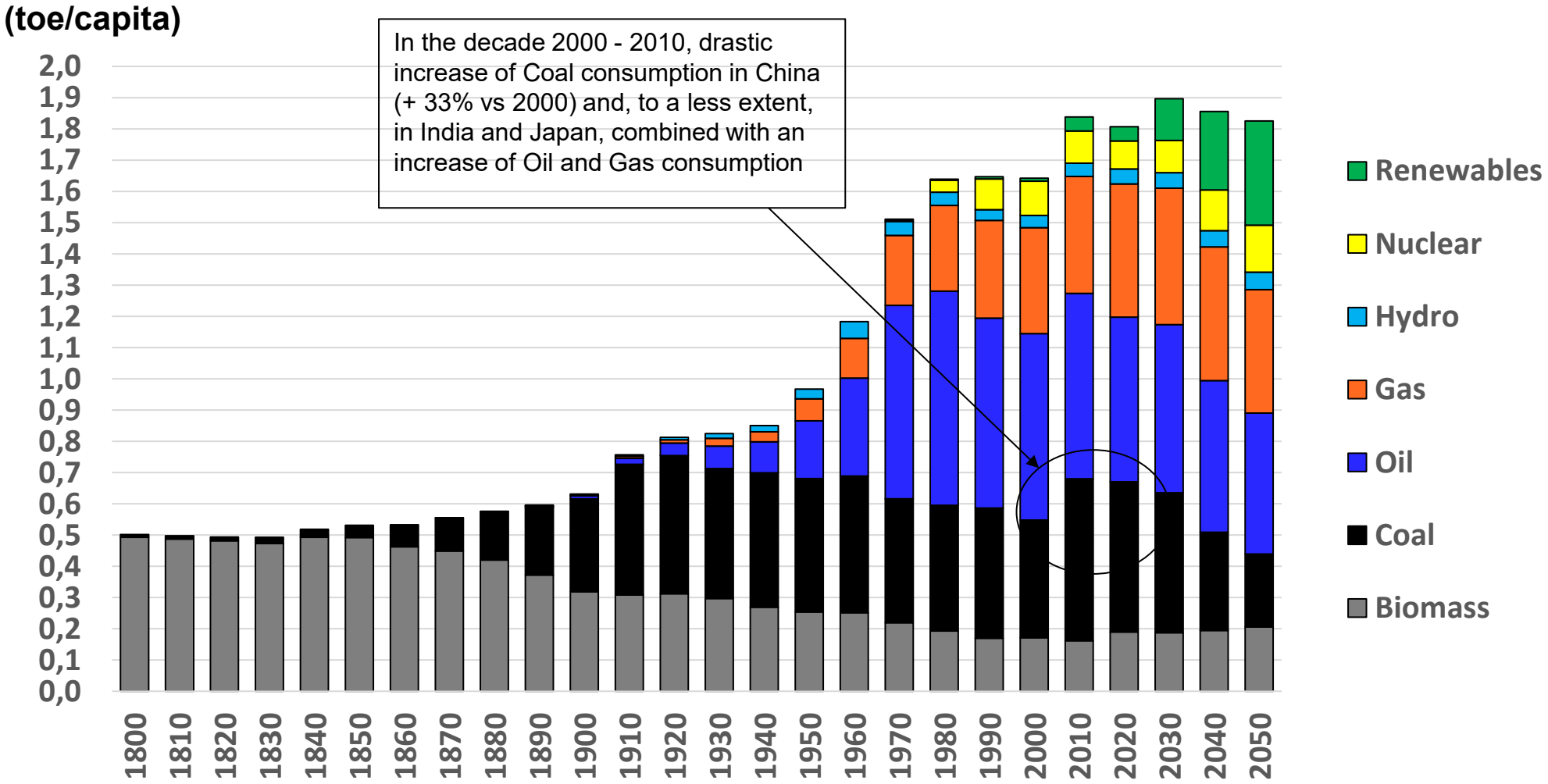
Actual data till 2024, estimates as from 2025
Biomass includes modern solid, liquid, gaseous bioenergy

Global Fuel mix by decade
(2030 – 2050: IEA STEPS 2025)



Actual data till 2024, estimates as from 2025
Biomass includes modern solid, liquid, gaseous bioenergy

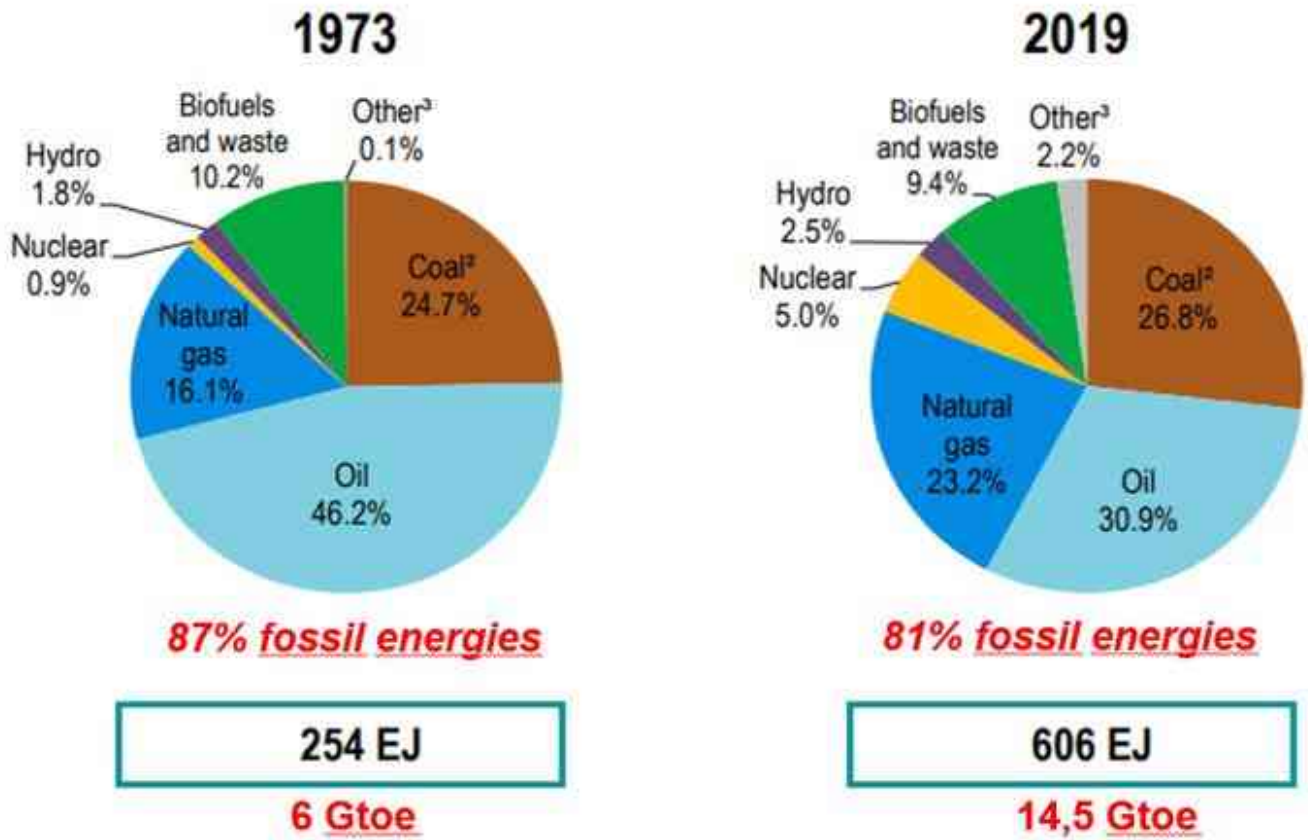
History of World Primary Energy Demand per Capita (2030 – 2050: IEA STEPS 2025) Regular Increase, then a recent stabilization



Actual data till 2024, estimates as from 2025
Biomass includes modern solid, liquid, gaseous bioenergy

Every year n, IEA is delivering its World Energy Outlook Report.
This report describes the World Energy situation for year n-2, estimates for year n-1, and perspectives/scenarios for the next decades.

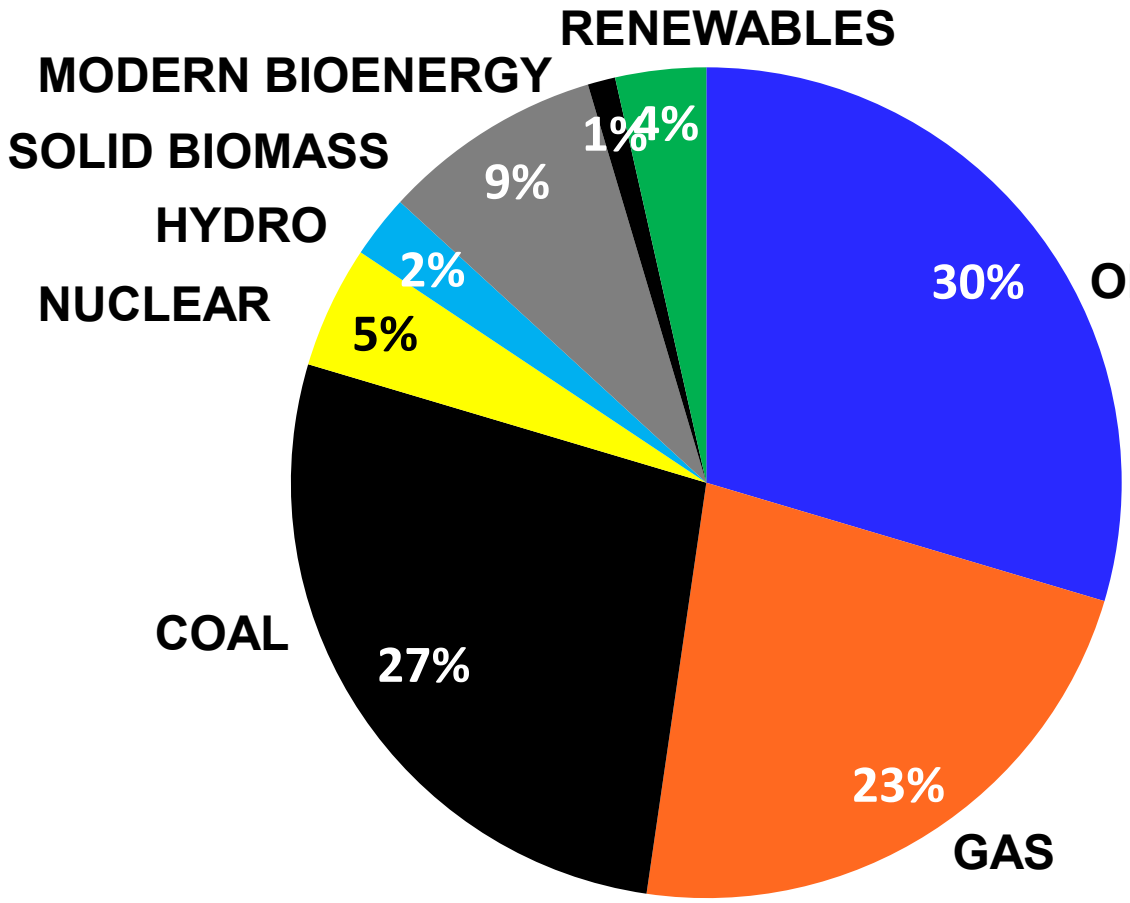
World Primary Energy Demand
Reminder - Evolution 1973 - 2019



1. World includes international aviation and international marine bunkers.
2. In these graphs, peat and oil shale are aggregated with coal.
3. Includes geothermal, solar, wind, tide/wave/ocean, heat and other sources.

Source: IEA, World Energy Balances, 2021.

World Primary Energy Demand – 2024
+ 2,0% vs 2023



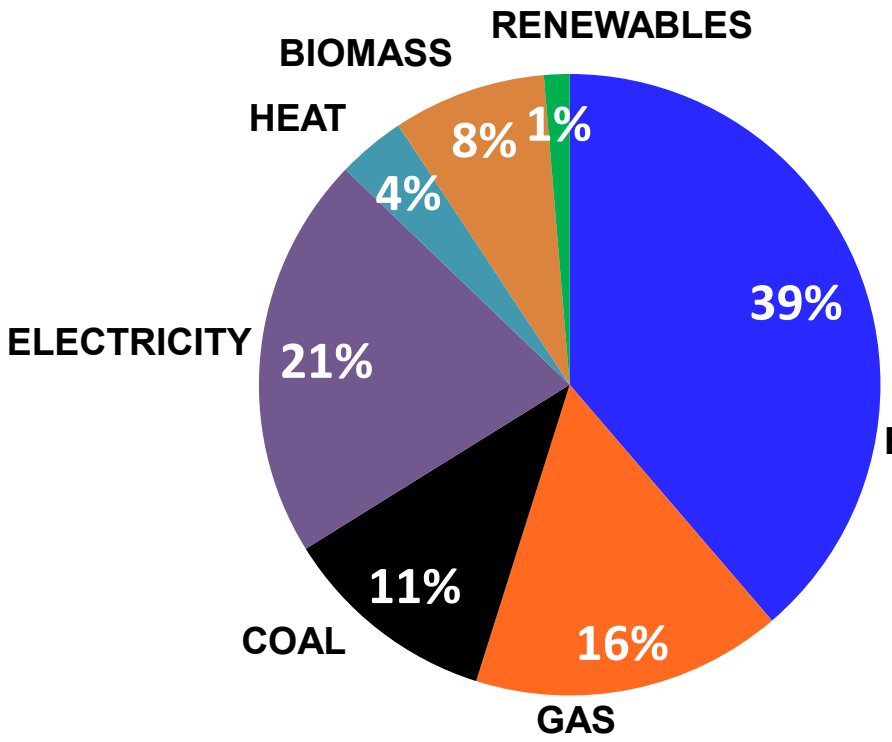
654 EJ
= 15,6 Gtoe*

*** out of which electricity generation # 6,5 Gtoe # 31 100TWh (eq. Primary Energy)**

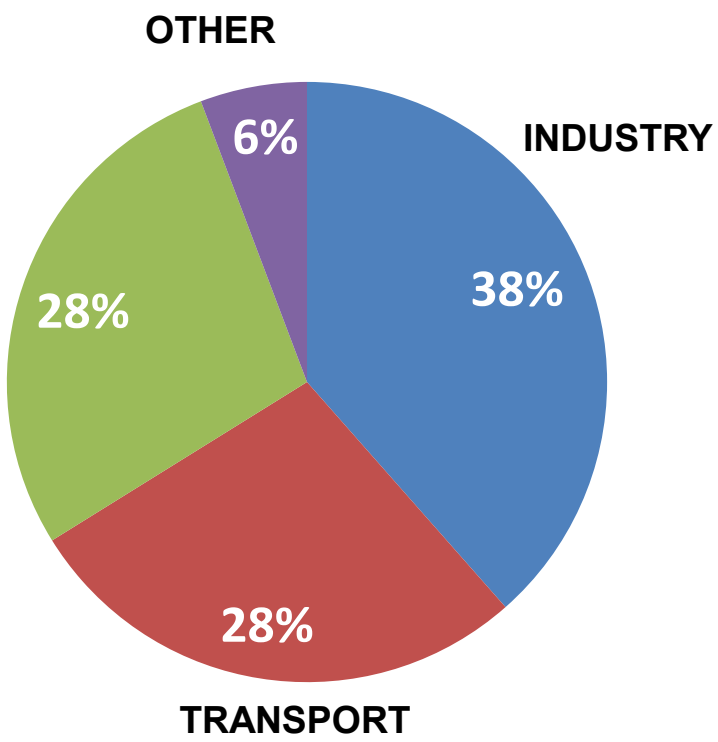
Source: Data from IEA WEO 2025. Nota: Sums might not be equal to 100% due to rounding
Solid Biomass: tradit. wood & charcoal & solid residues. Modern Bioenergy: liquid & gaseous bioenergy (biofuels & biogases) Renewables: Solar, Wind, Geothermal, Marine Energy,…

Total Final Consumption – 2024
+ 2,0% vs 2023

By type of Fuels



By sectors



453 EJ = 10,8 Gtoe

Nota: Sums might not be equal to 100% due to rounding
OTHER relates to agricultural sector & other non-energy use

Source: Data from IEA WEO 2025

How to explain the difference between 15,6 & 10,8 Gtoe?

To produce final end-used Energy products, it is necessary to transform them.

1) Oil products are fabricated from crude Oil in refineries where industrial processes generate losses.

2) Electricity is an important part of final consumption. Electricity is not a primary Energy, it must be produced through thermal or nuclear Power Plants, renawable energies which have each a limited Efficiency ratio.

3) Other type of losses exist in transmission & distribution systems.

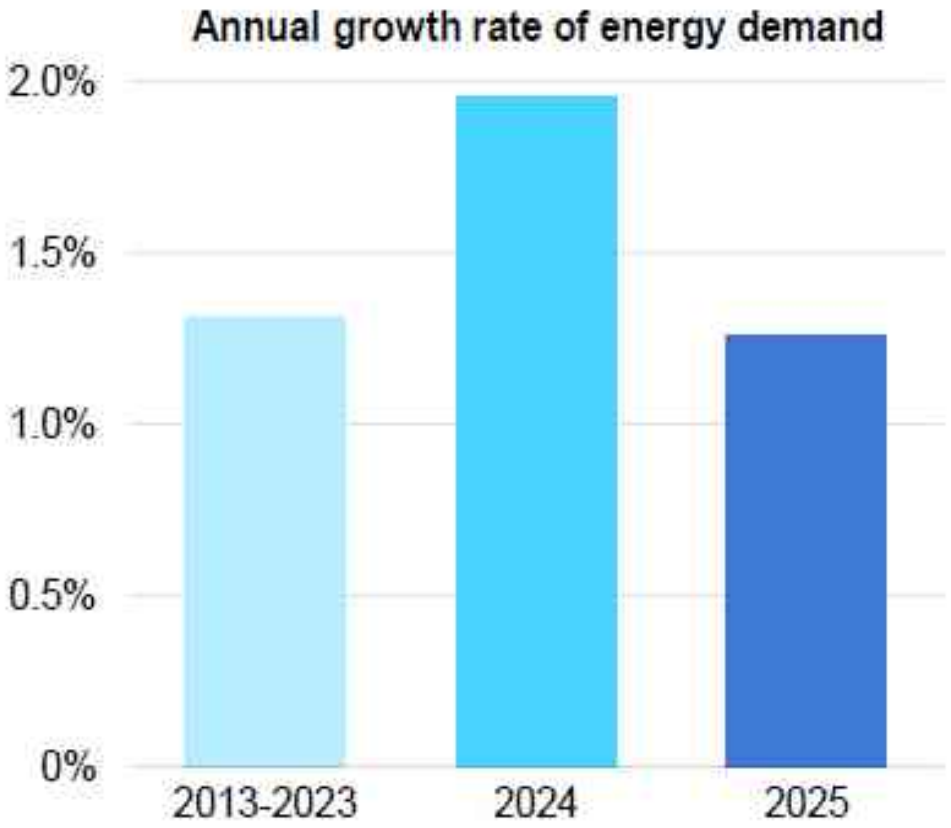
Losses in Power Plants # 3750 Mtoe
Other losses # 1050 Mtoe
Total losses # 4800 Mtoe

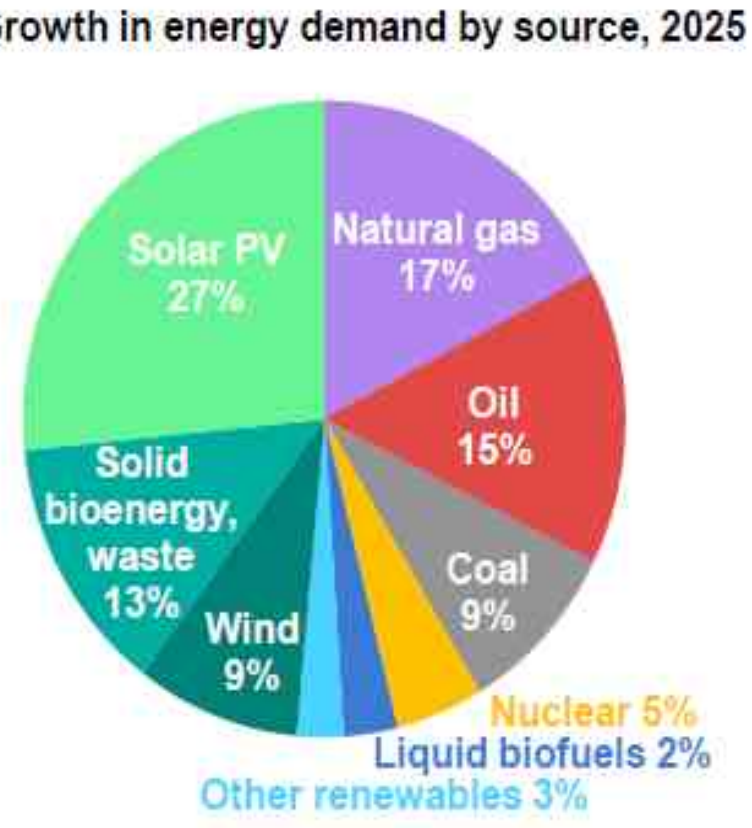
	Electricity generation 2024 by fuel				Equivalent Primary Energy		
	Mtoe	TWh		EJ	Mtoe	TWh	Conv. Coeff.
Oil	65	757	2%	3	197	2294	33%
Gas	583	6785	22%	24	1576	18338	37%
Coal	928	10798	35%	39	2813	32721	33%
Nuclear	244	2835	9%	10	739	8591	33%
Hydro	382	4448	14%	16	382	4448	100%
Bioenergy	65	760	2%	3	251	2923	26%
Solar PV	178	2073	7%	7	178	2073	100%
Solar CSP	2	20	0%	0	2	20	100%
Wind	218	2533	8%	9	218	2533	100%
Geothermal	9	100	0%	0	86	1000	10%
Marine	0	1	0%	0	0	1	100%
Renewables	406	4727	15%	17	484	5627	84%
Total	2675	31110	100%	112	6443	74942	42%

Source: Data from IEA WEO 2025. 1TJ = 0,2778 GWh = 23,88 toe
For the conversion from Final Energy to Primary Energy, international standards are used for Plants Energy Efficiency

World Primary Energy Demand Growth

Global energy demand: average annual growth, 2013-2025, and share of growth by source, 2025



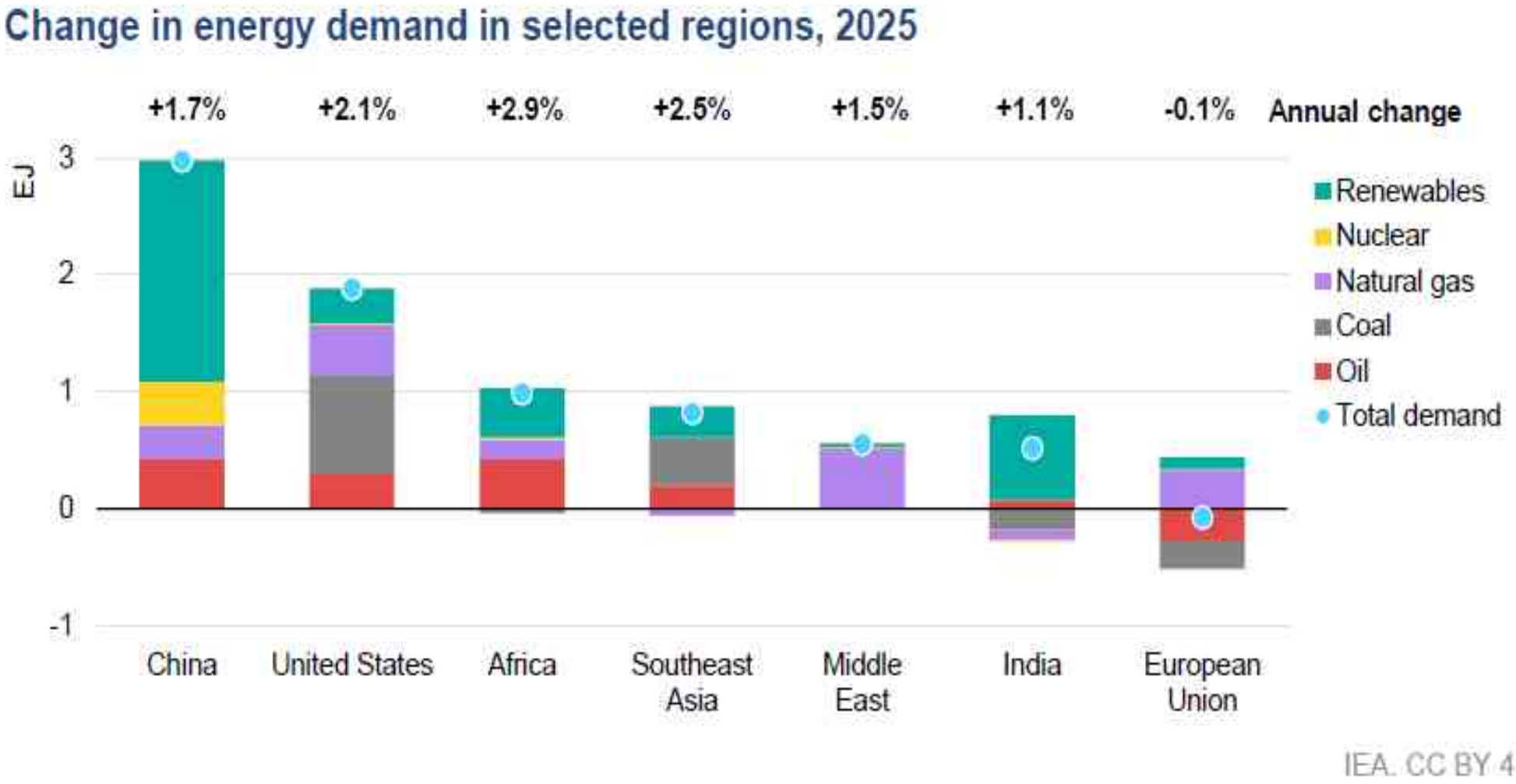


IEA. CC BY 4.0.

Note: "Other renewables" include hydropower, solar thermal, geothermal and biogases.

Source: IEA Global Energy Review 2026 – May 2026

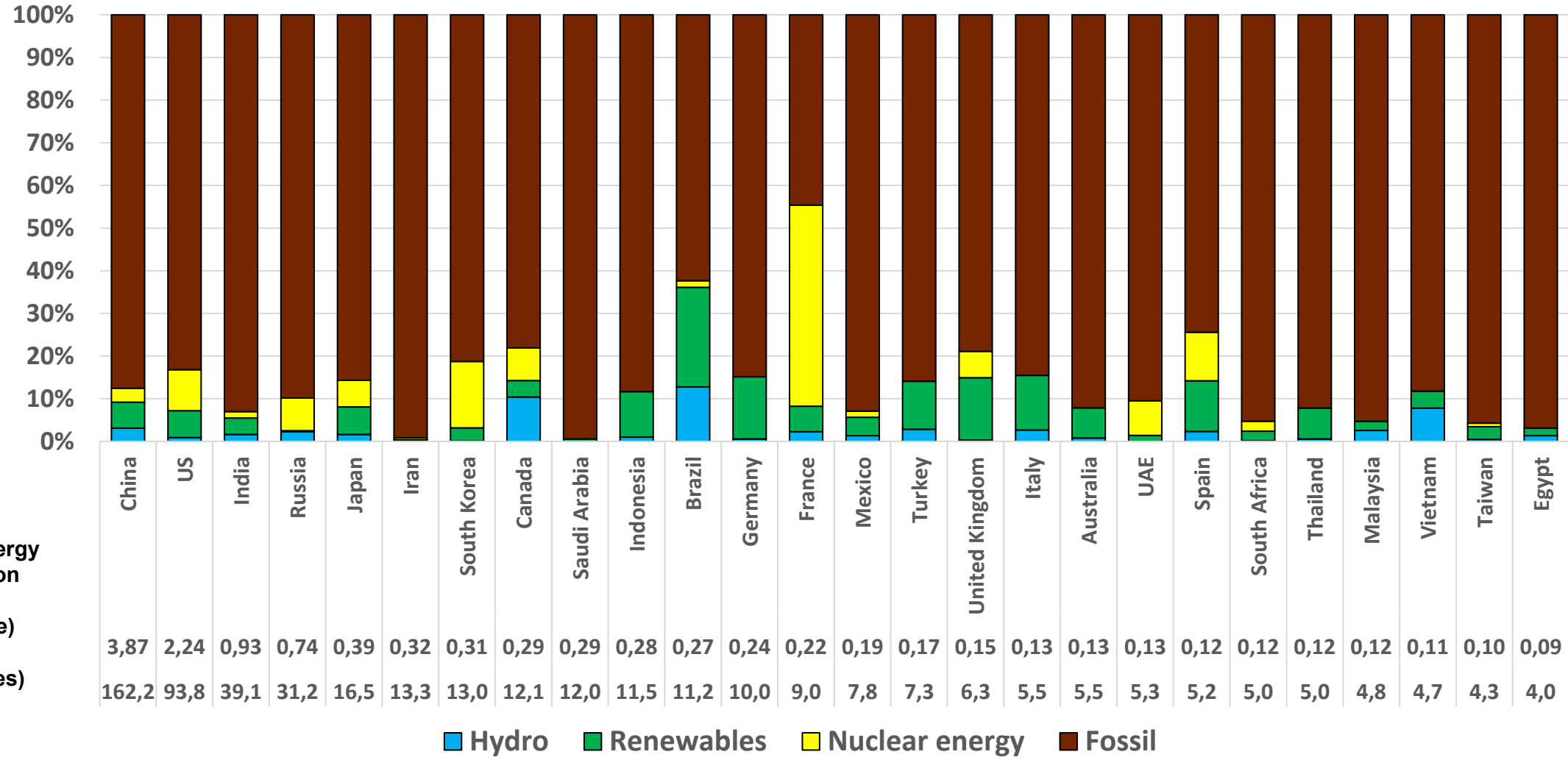
Change in World Primary Energy Demand 2024 - 2025
Growth for Renewables in China, decline of Coal & Oil in EU



Note: EJ = exajoule.

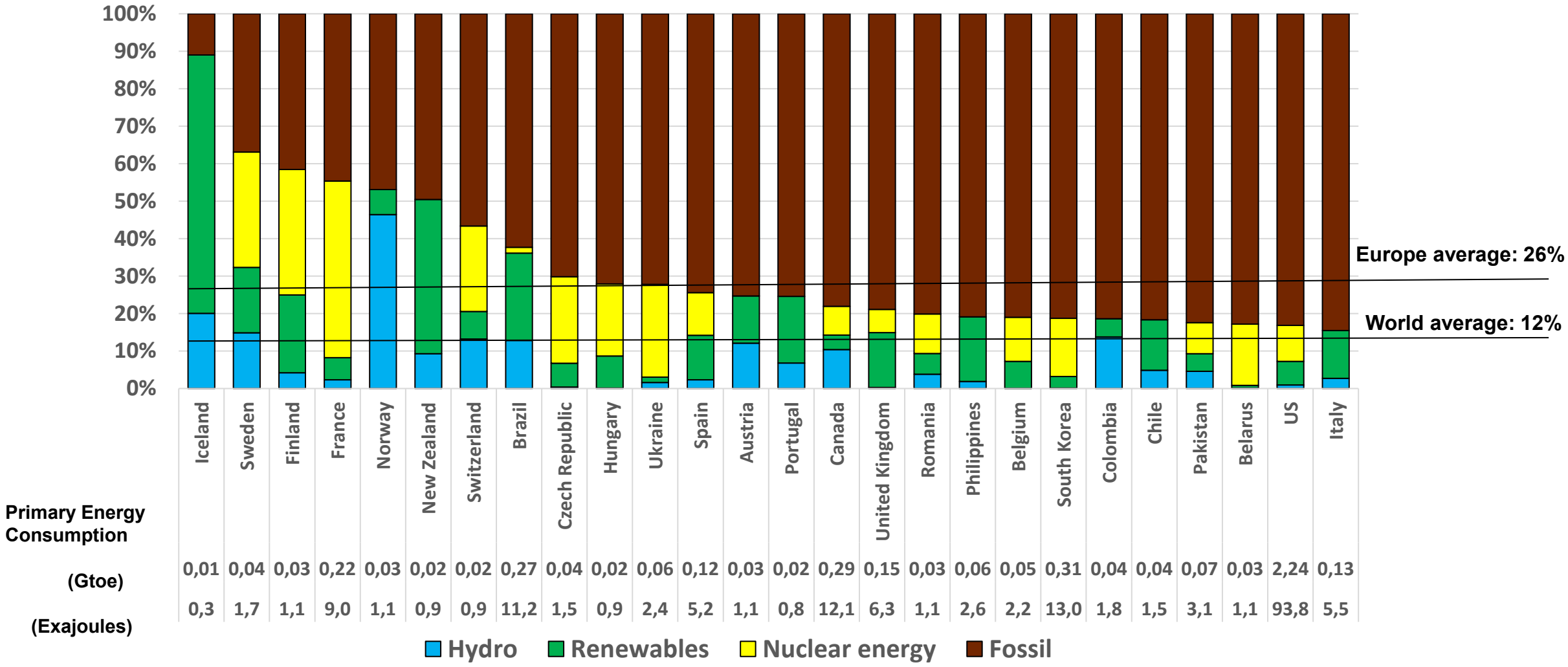
Source: IEA Global Energy Review 2026 – May 2026

Share of decarbonated Primary Energy in the Energy mix by countries – 2025, ranked by total Energy Consumption



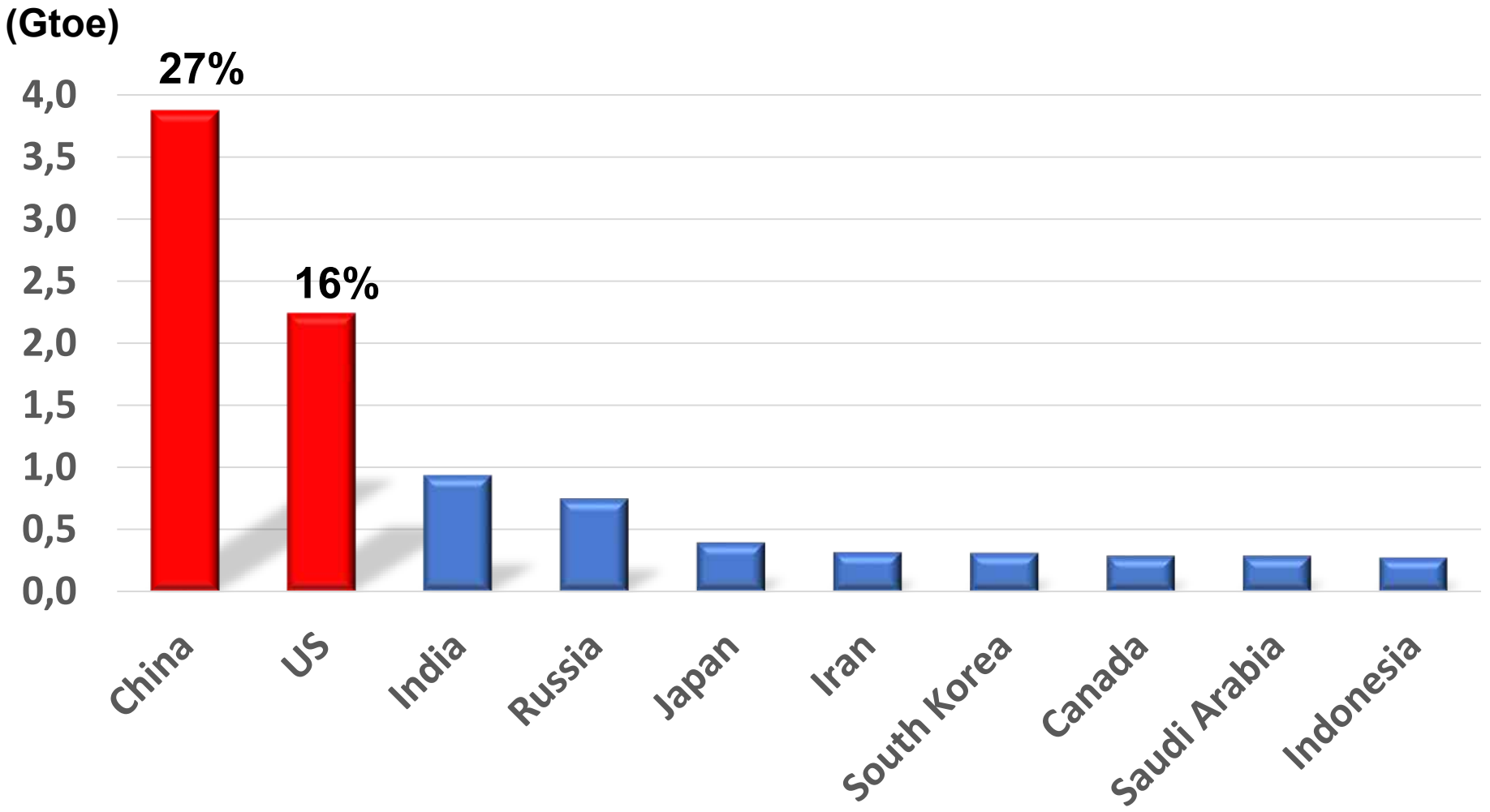
Source: Ch.G/Data from EI Stat. Review 2026 - 1 EJ = 23,88 Mtoe
Commercially-traded Fuels, traditional biomass not included

Share of decarbonated Primary Energy in the Energy mix by countries – 2025, ranked by decarboned Energy Consumption



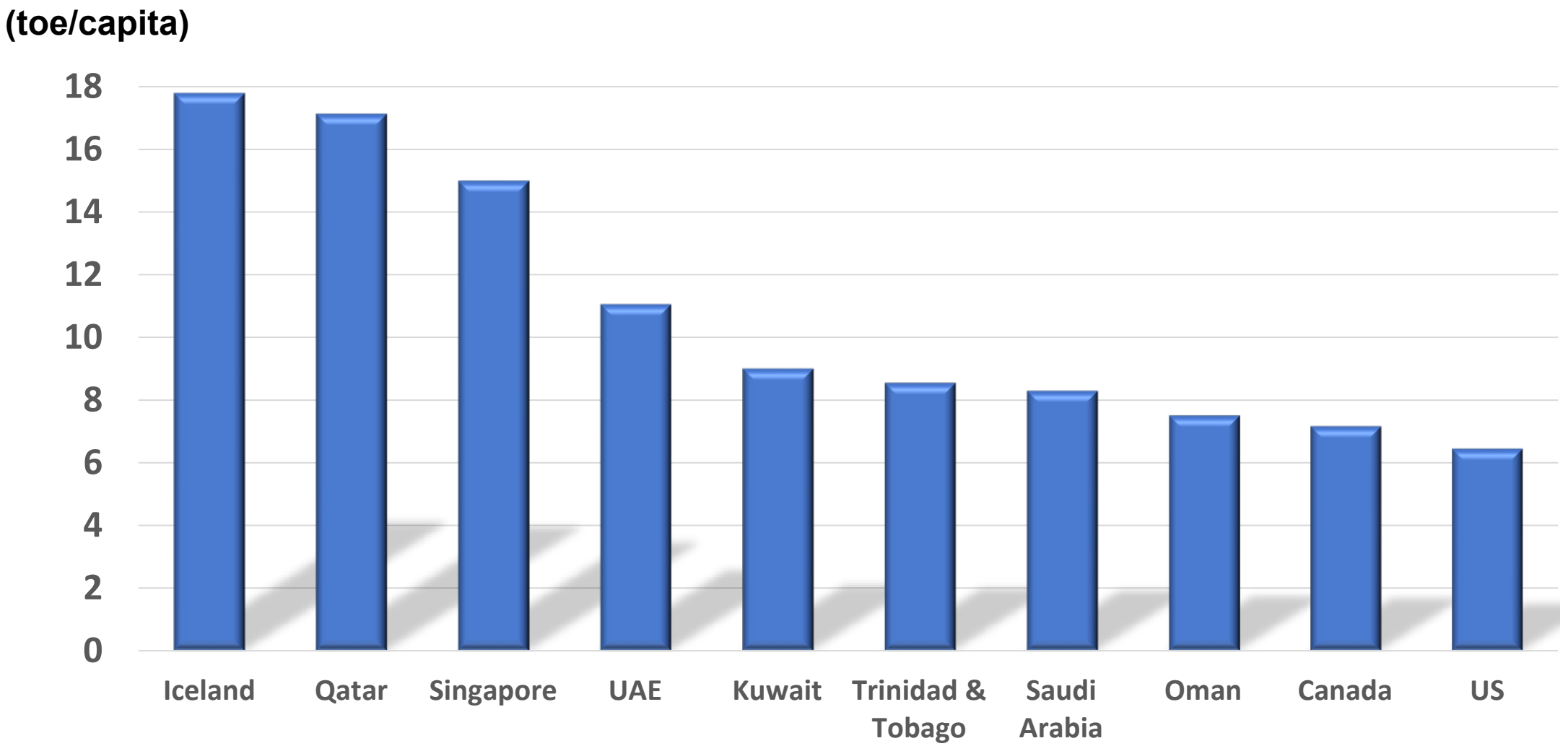
Source: Ch.G/Data from EI Stat. Review 2026 - 1 EJ = 23,88 Mtoe
Commercially-traded Fuels, traditional biomass not included

10 first countries by Primary Energy Consumption Year 2025 - N°1 China, N°2 USA



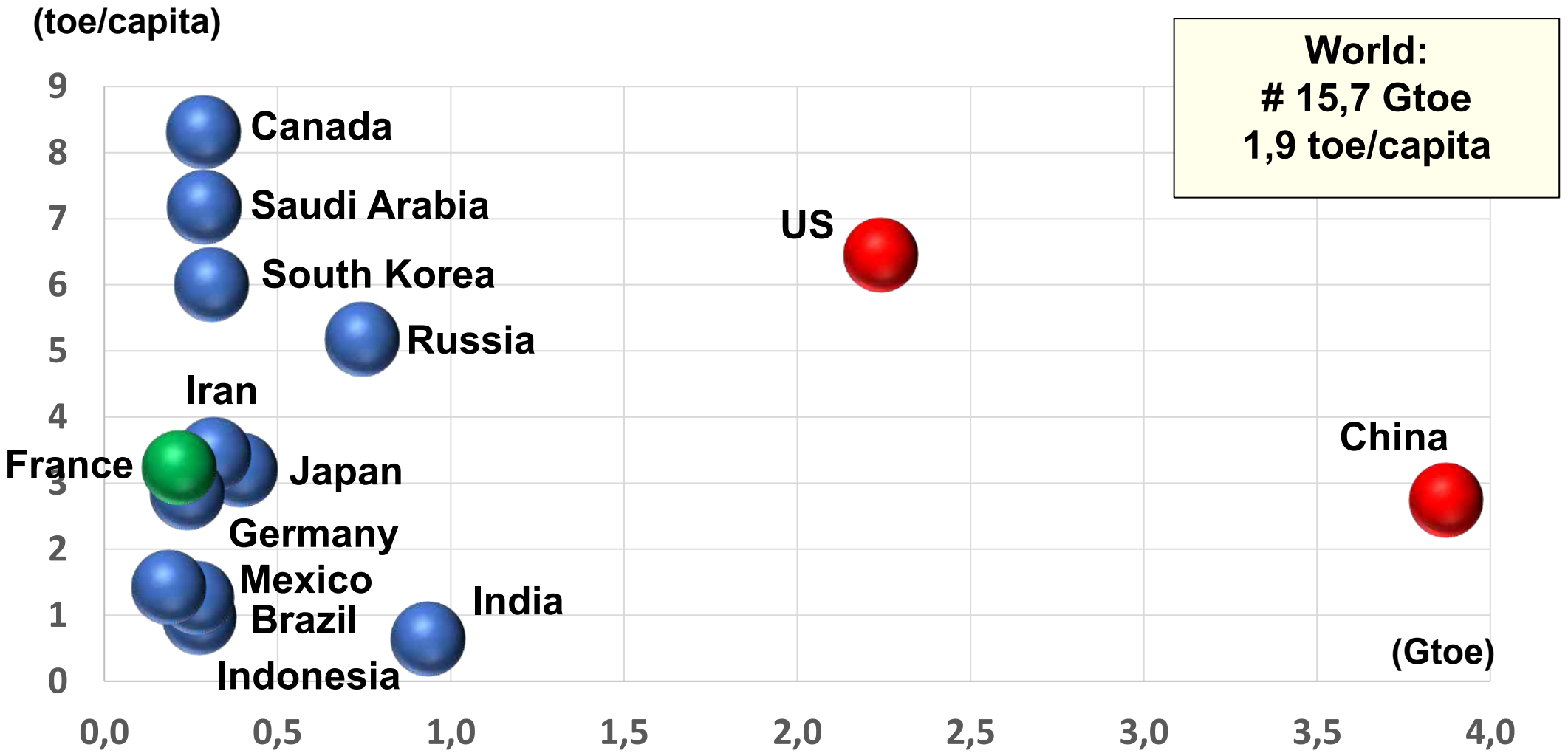
Source: Data from EI Statistical Review 2026

10 first countries by Primary Energy Consumption/capita Year 2025 - N°1 Iceland, N°2 Qatar



Source: Data from EI Statistical Review 2026

Primary Energy Consumption – Year 2025
Ranking is different for toe & toe per capita



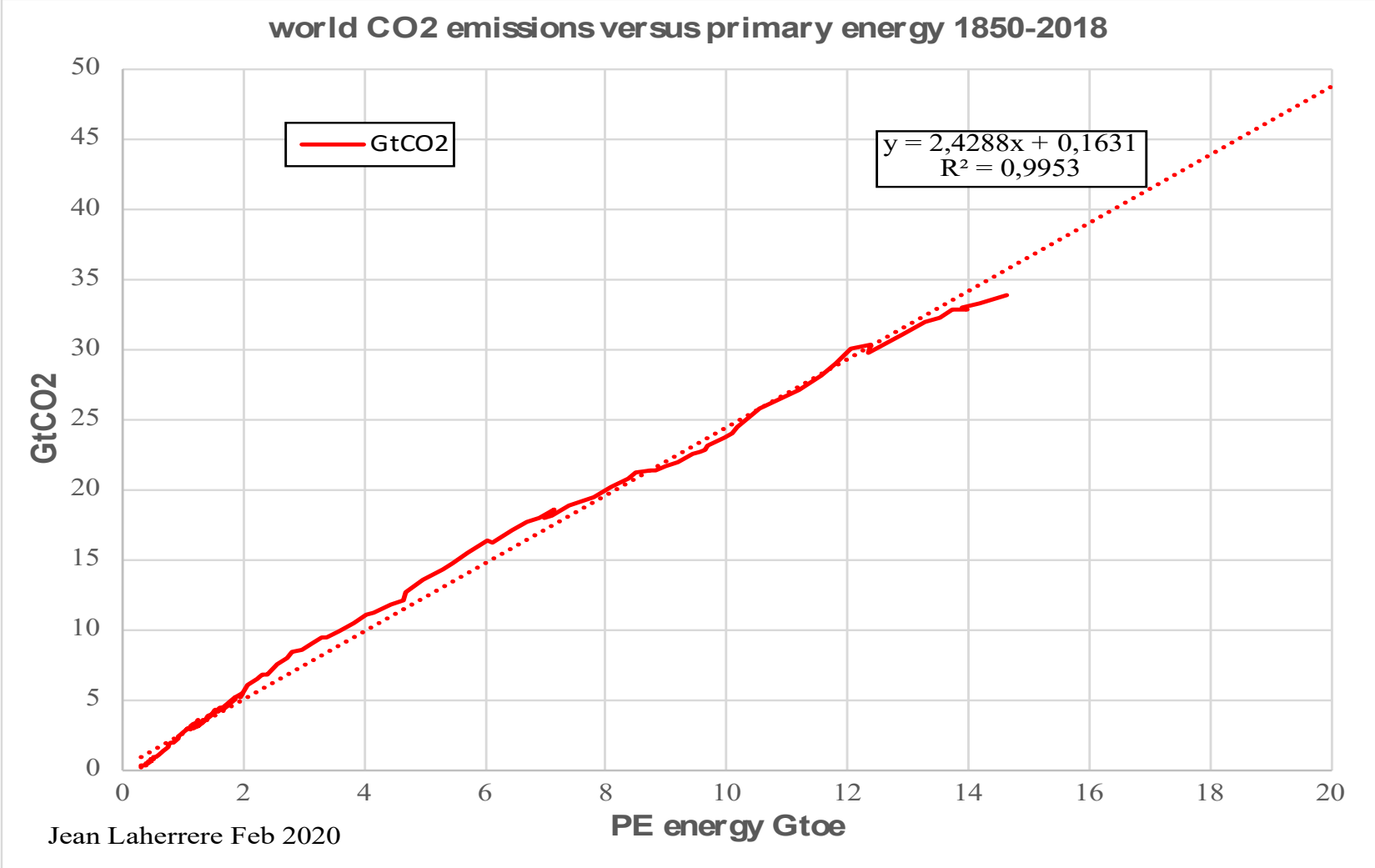
Source: Ch.Guéritte/Data from IEA Global Energy Review 2026 & EI Stat. Review 2026

10 first countries by GDP/Energy Consumption/CO_2 Emissions per capita – Year 2025

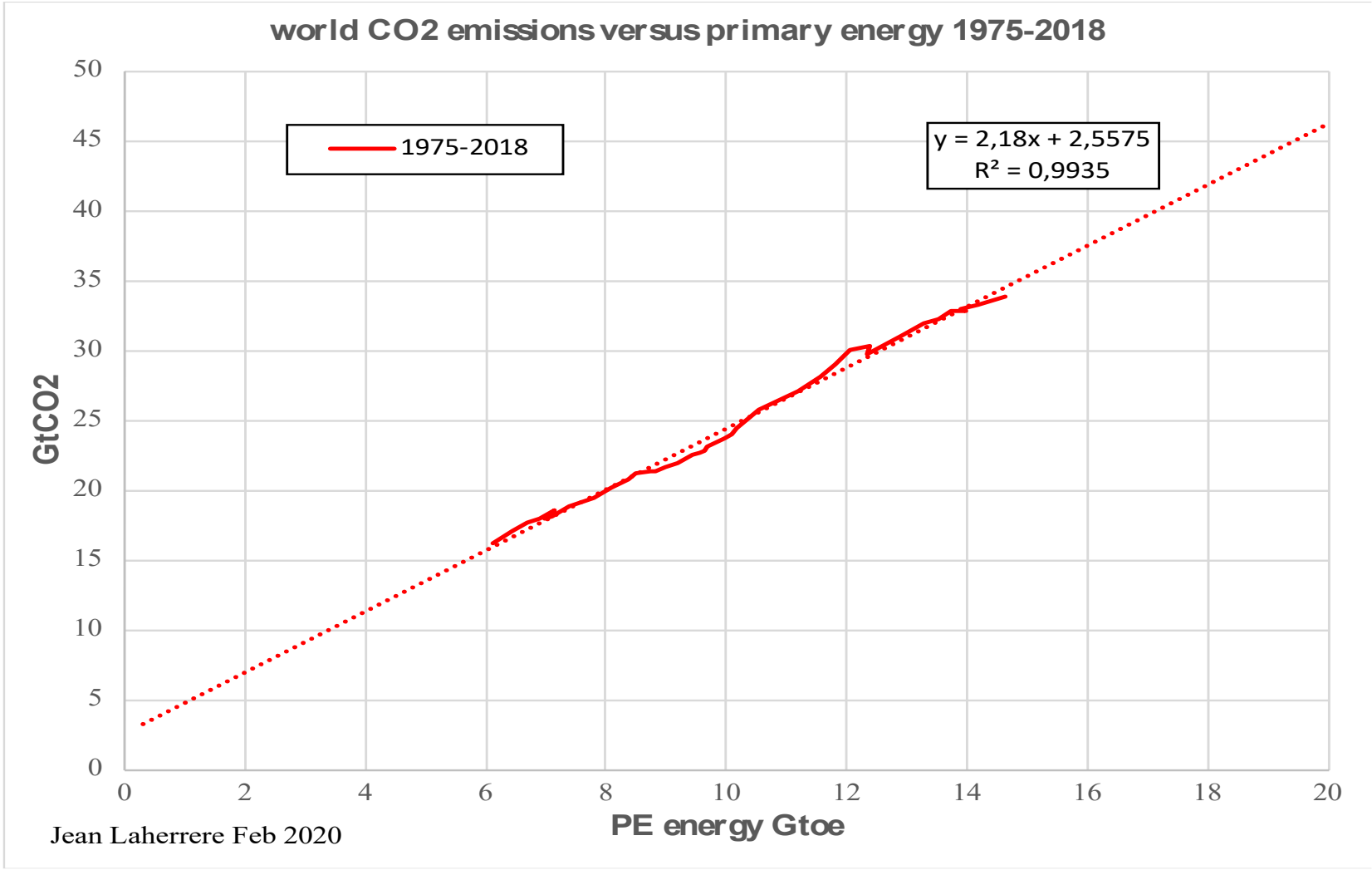
Countries	Population 1st July 2025 (Million)	Countries	GDP PPP /capita 2025 (US$)	Countries	Energy /capita 2025 (toe)	Countries	CO2 energy emissions /capita 2025 (tCO2)
India	1464	Singapore	163 400	Iceland	17,8	Qatar	43,6
China	1407	Luxembourg	156 500	Qatar	17,1	Singapore	41,8
USA	342	Ireland	155 100	Singapore	15,0	UAE	25,4
Indonesia	286	Qatar	128 900	UAE	11,1	Kuwait	21,1
Pakistan	255	Norway	104 000	Kuwait	9,0	Saudi Arabia	18,2
Nigeria	238	Switzerland	102 500	Trinidad and Tobaggo	8,6	Oman	17,3
Brazil	213	Brunei	92 400	Saudi Arabia	8,3	Australia	13,9
Bangladesh	176	USA	90 000	Oman	7,5	US	13,7
Russia	144	Netherlands	87 300	Canada	7,2	Canada	13,2
Mexico	132	UAE	79 300	US	6,5	Kazakhstan	12,0
Total World	8 215	**Total World**	25 700	**Total World**	1,9	**Total World**	4,3

Source: Population: UN, GDP PPP/cap.: World Bank July 2026
Energy/cap. & CO_2/cap.:EI Stat. Review 2026/Rounded figures

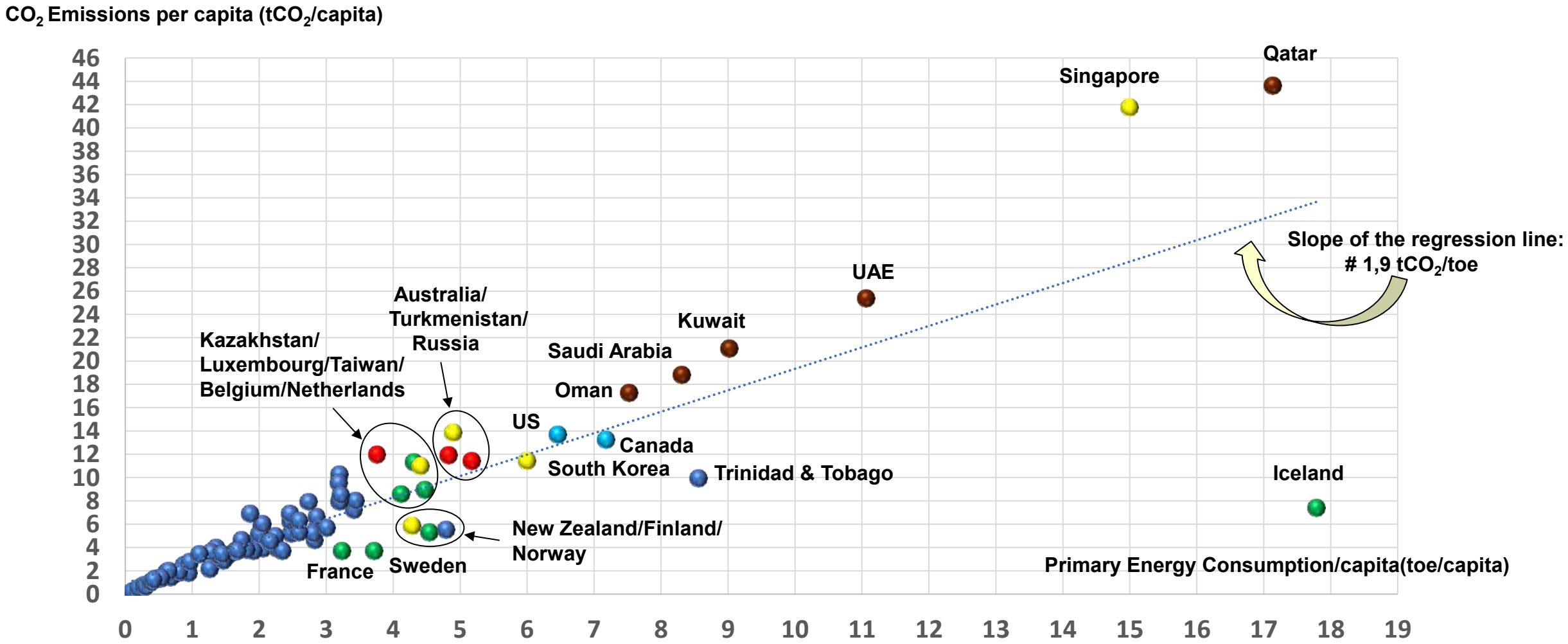
A clear correlation between Energy consumption and CO_2 emissions



A clear correlation between Energy consumption and CO_2 emissions



A clear correlation between Energy Consumption and CO_2 Emissions by selected Countries – Year 2025



Source: Ch.Guéritte/Data from EI Statistical Review 2026

Indicators of Global Progress towards the SDG targets

INDICATOR		2015	LATEST YEAR
7.1.1 Proportion of population with access to electricity		**957.5 million** people without access to electricity	**685 million** people without access to electricity (2022)
7.1.2 Proportion of population with primary reliance on clean fuels and technology for cooking		**2.7 billion** people without access to clean cooking	**2.1 billion** people without access to clean cooking (2022)
7.2.1 Renewable energy share in total final energy consumption		**16.7%** share of total final energy consumption from renewables	**18.7%** share of total final energy consumption from renewables (2021)
7.3.1 Energy intensity measured as a ratio of primary energy and GDP		**4.9 MJ/USD** primary energy intensity	**4.6 MJ/USD** primary energy intensity (2021)
7.a.1 International financial flows to developing countries in support of clean energy research and development and renewable energy production, including in hybrid systems		**12.3 USD billion** international financial flows to developing countries in support of clean energy	**15.4 USD billion** international financial flows to developing countries in support of clean energy (2022)
7.b.1 Installed renewable energy-generating capacity in developing and developed countries		**250 watts per capita** Installed renewables capacity	**424 watts per capita** Installed renewables capacity (2022)

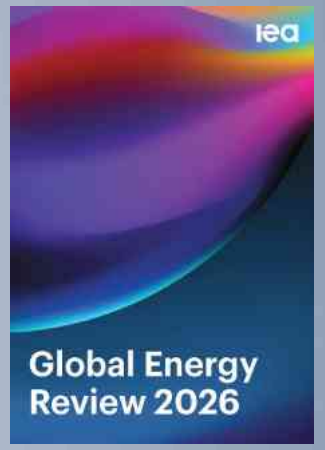
Source: IEA June 2024 – Tracking SDG 7 The Energy Progress Report
SDG: Sustainable Development Goals

2025 key figures to keep in mind

World population ≈ **8,2 billion December 2025, 8 billion reached in Nov.2022**
World GDP (PPP) ≈ **211 TUS$**
Average GDP (PPP) ≈ **25 700 $ per capita**

World primary Energy Consumption ≈ **15,7 Gtoe**
Average Energy Consumption/capita ≈ **1,9 toe**
Average Energy Intensity ≈ **0,075 toe/kUS$** (PPP)

CO_2 Emissions (**CO_2 Energy**) ≈ **35,4 $GtCO_2$**
Global CO_2 Emissions* ≈ **38,1 $GtCO_2$**
Average CO_2 Emissions ≈ **4,3 tCO_2** per capita



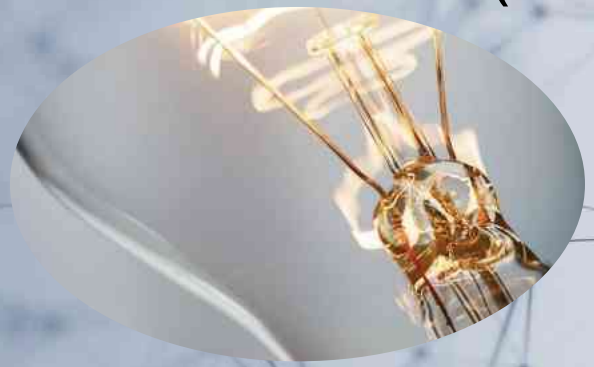
Large disparities between countries

Rounded figures Source: World Bank July 2026, IEA Global Energy Review 2026
*** Includes emissions from industrial process & flaring**

2025 key figures to keep in mind

World population ≈ **8,2 billion December 2025, 8 billion reached end November 2022**

World GDP (PPP) ≈ **211 TUS$**



730 million people

have no access to electricity in the world

vs 1,3 billion in 2013



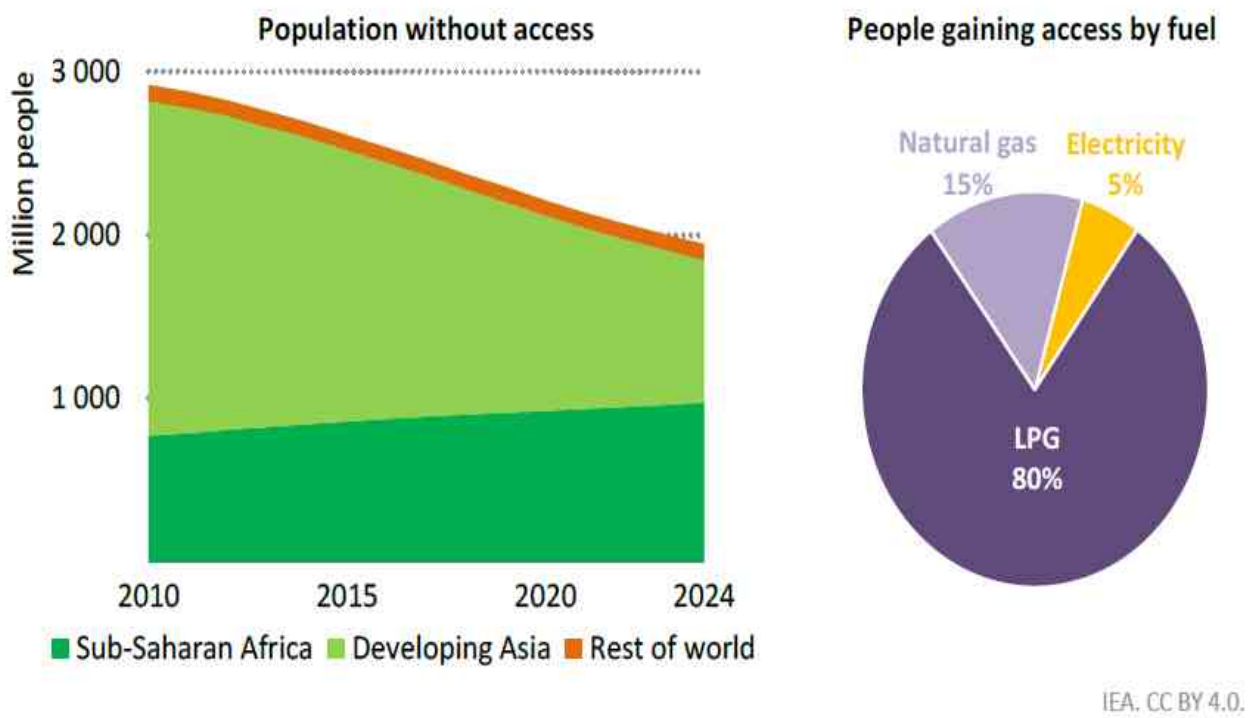
2,0 billion people

have no access to clean cooking

Rounded figures Source: World Bank July 2026, IEA WEO 2025

People without access to Gas & Electricity

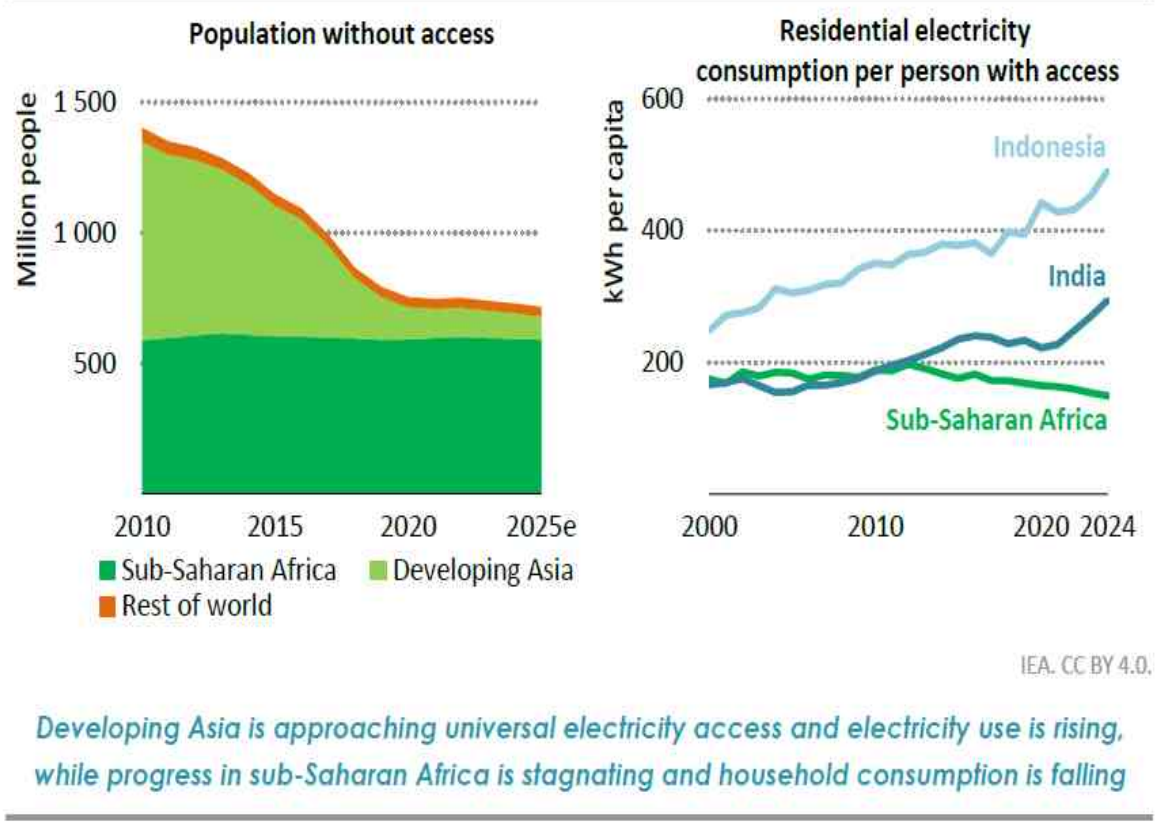
People without access to Clean Cooking (Gas)



LPG drives access gains, while Africa's population without access continues to expand

Note: LPG = liquified petroleum gas.

People without access to Electricity



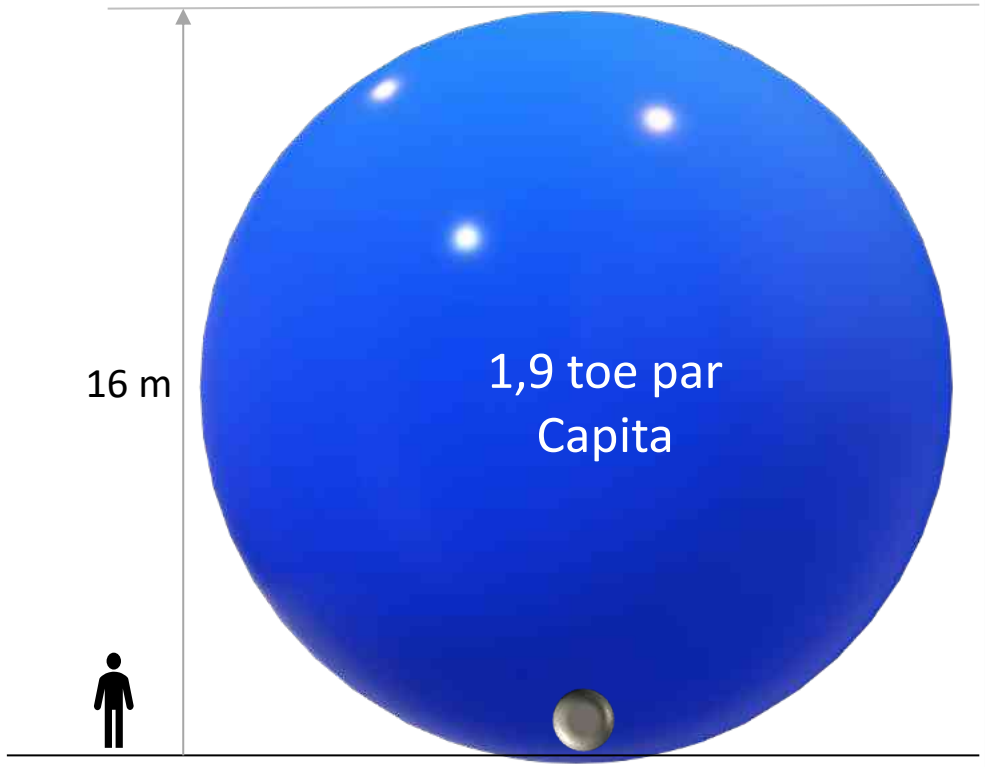
Developing Asia is approaching universal electricity access and electricity use is rising, while progress in sub-Saharan Africa is stagnating and household consumption is falling

Note: 2025e = estimated values for 2025.

Source: IEA WEO 2025

World Primary Energy Consumption per Capita – Year 2025

Illustrated in Natural Gas Volume equivalent at 1 atmosphere and 15°C and in Crude Oil Volume equivalent



Primary Energy Consumption per Capita

- **World average: 1, 9 toe**
- **France: 3,2 toe**
- **US: 6,4 toe**
- **India: 0,6 toe**

5

Energy: A zoom on France

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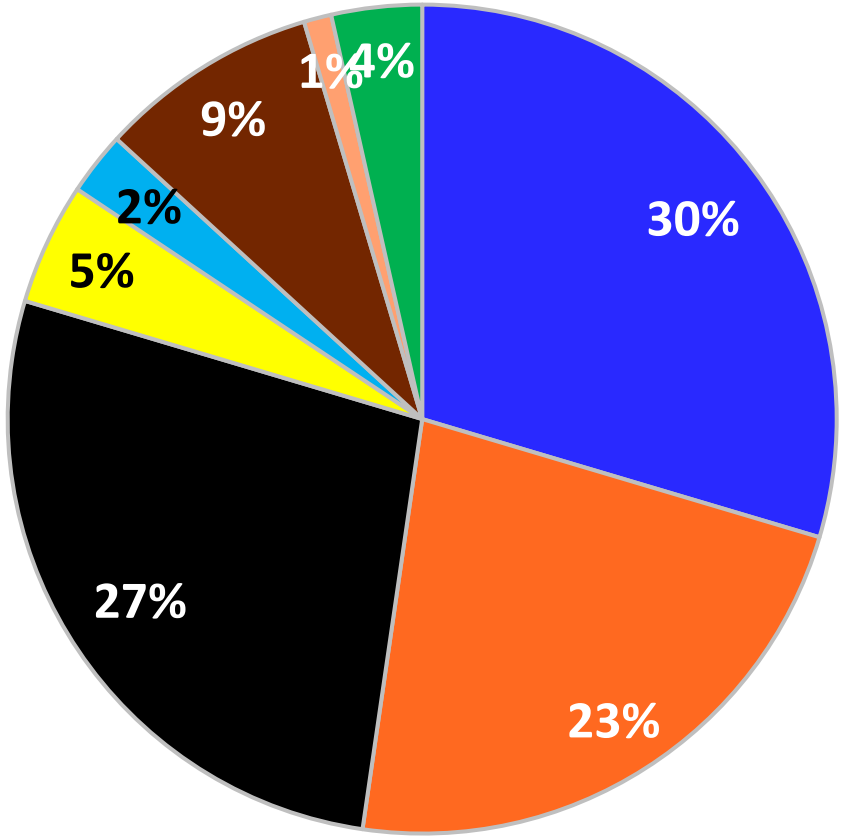
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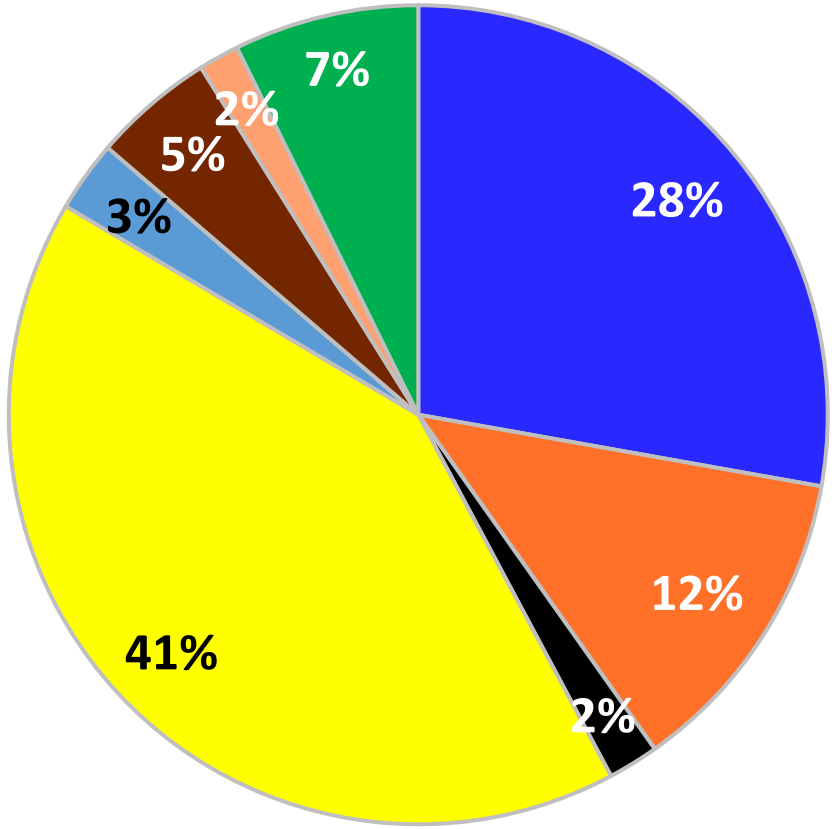
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A Zoom on France

Demande en énergie primaire: Monde & France - 2024

Monde: 654 EJ # 15,6 Gtep # 180000 TWh **France**: 9,3 EJ # 0,22 Gtep # 2600 TWh (1,4%)



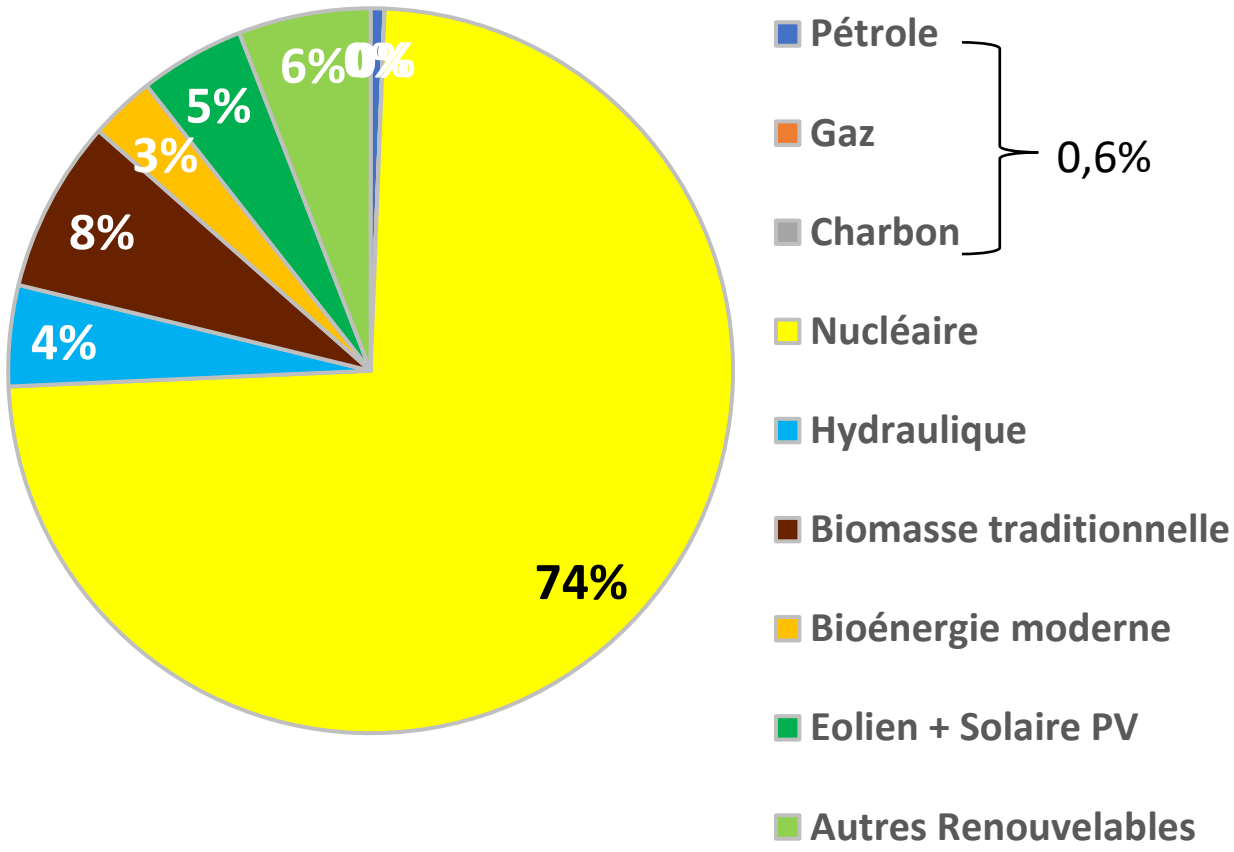


Pétrole
Gaz
Charbon
Nucléaire
Hydraulique
Biomasse traditionnelle
Biomasse moderne
Autres Renouvelables

Source: Données de l'IEA WEO 2025 & SDES Chiffres clés de l'Énergie 2025
EJ: Exajoules (10^{18} J), tep: tonnes équivalent pétrole, TWh: TeraWattheures (10^{12} Wh)

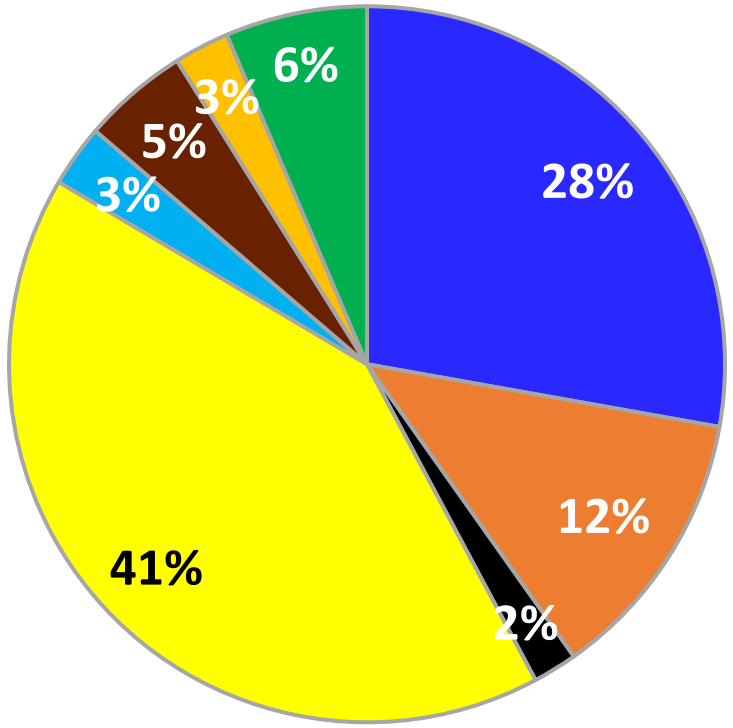
Production et consommation d'énergie primaire France - 2024

Production: # 5,6 EJ # 0,13 Gtep # 1600 TWh



Pétrole
Gaz
Charbon
0,6%
Nucléaire
Hydraulique
Biomasse traditionnelle
Bioénergie moderne
Eolien + Solaire PV
Autres Renouvelables

Consommation: 9,3 EJ # 0,22 Gtep # 2600 TWh

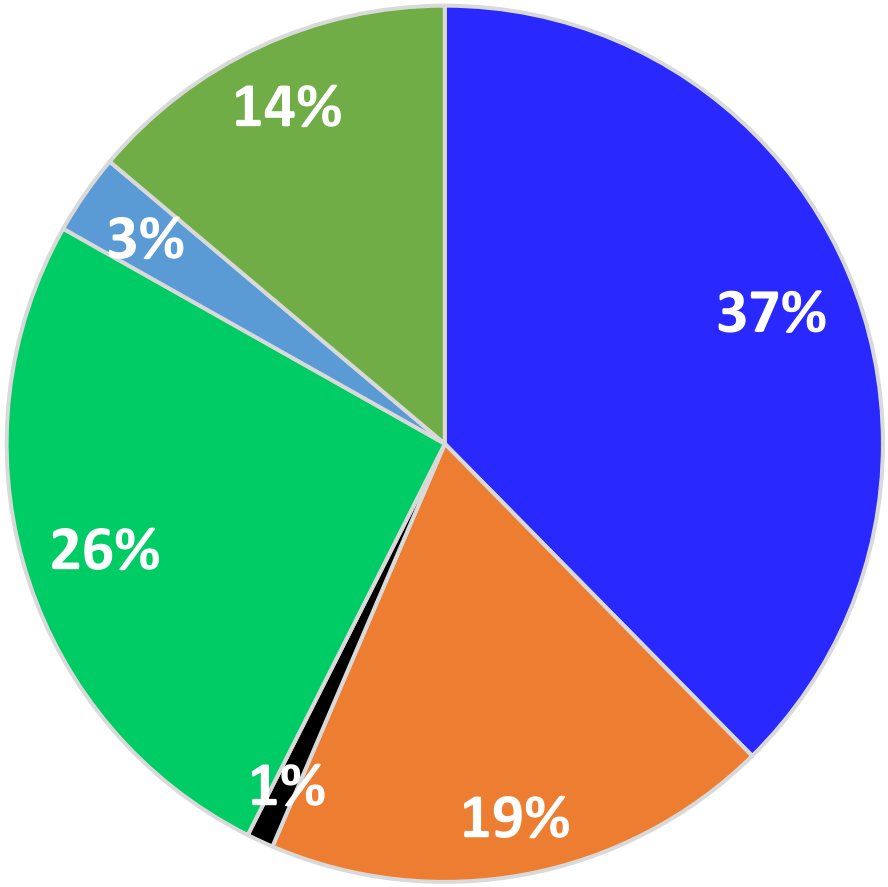


Pétrole
Gaz
Charbon
Nucléaire
Hydraulique
Biomasse traditionnelle
Bioénergie moderne
Autres Renouvelables

Source: Données de SDES/Bilan annuel de l'Énergie - Chiffres clés de l'Énergie 2025
EJ: Exajoules, tep: tonnes équivalent pétrole, TWh: TeraWattheures
Autres renouvelables inclut géothermie et déchets renouvelables

Consommation d'énergie finale France - 2024

Consommation énergie finale: 5,6 EJ # 0,13 Gtep # 1550 TWh (Équivalent de 135 EPR)

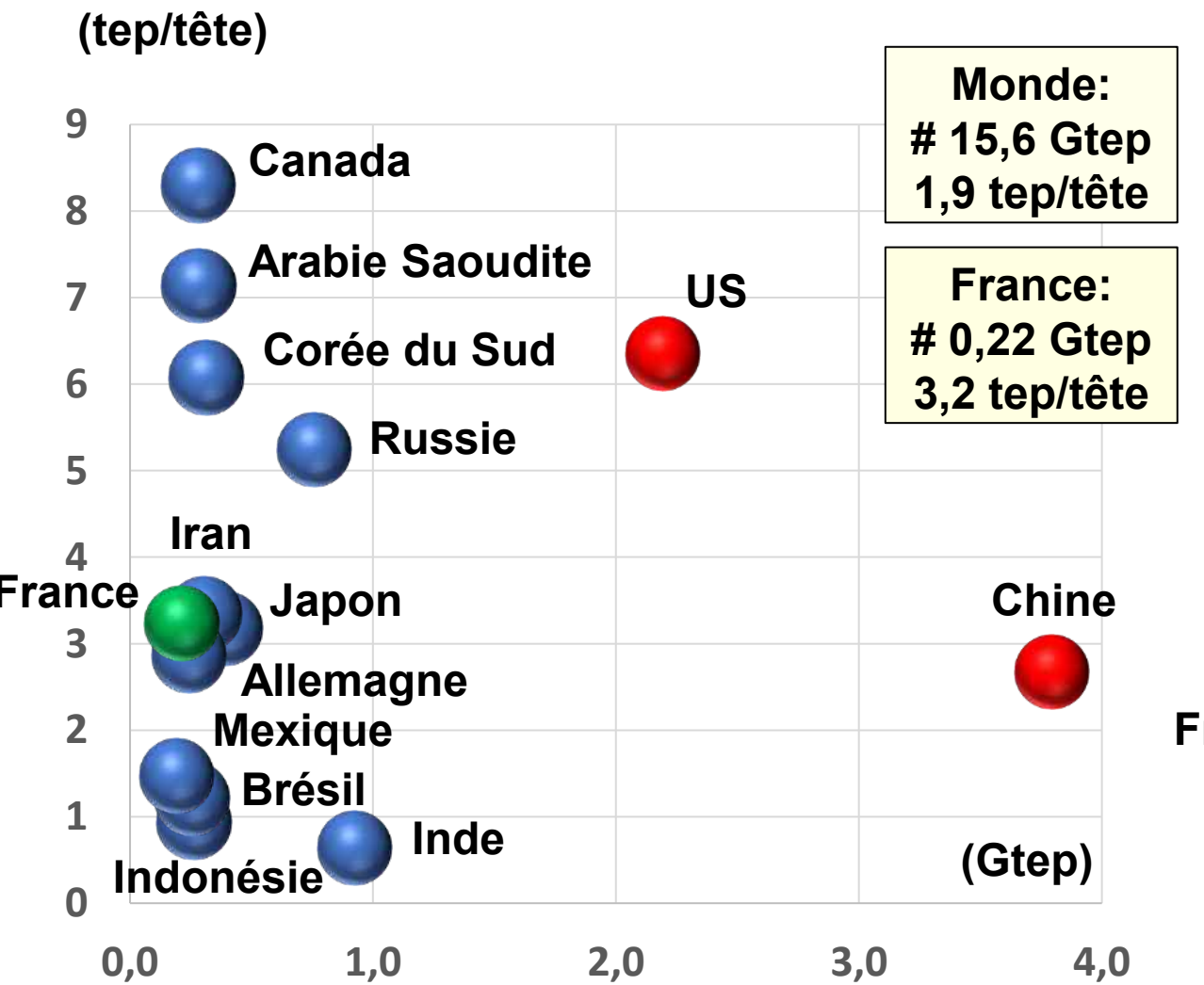


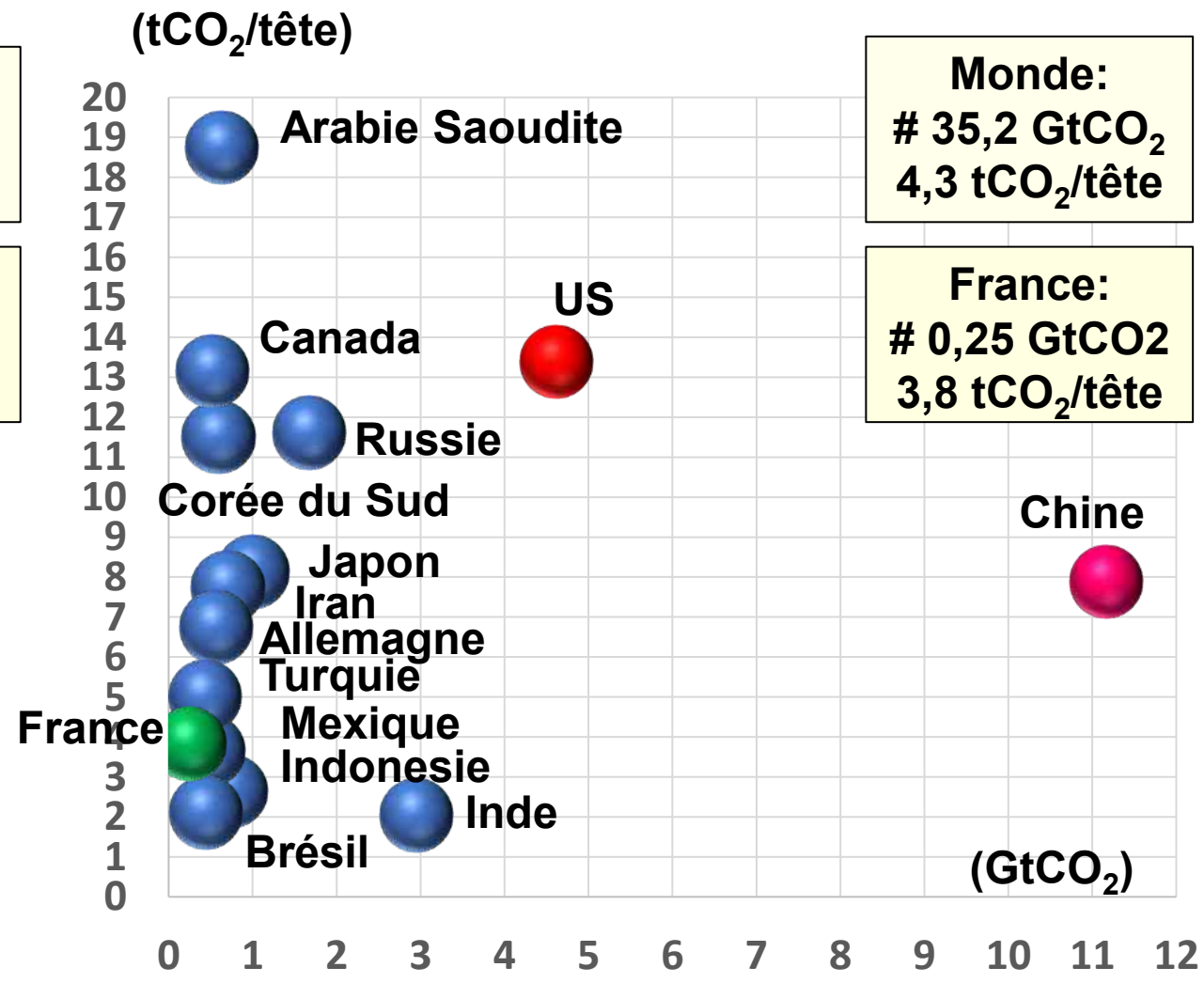
- Pétrole
- Gaz naturel
- Charbon
- Electricité
- Chaleur commercialisée
- EnR thermique et déchets

Consommation électricité France 2025 # 450 TWh

Source: Données de SDES/Bilan annuel de l'Énergie - Chiffres clés de l'Énergie 2025 - ADEME
EJ: Exajoules, tep: tonnes équivalent pétrole, TWh: TeraWattheures
EnR: Energie renouvelable EPR: Evolutionnary Power Reactor

Consommation d'énergie primaire et émissions de CO_2 – Année 2024
Le classement est différent selon valeurs nominales & par habitant

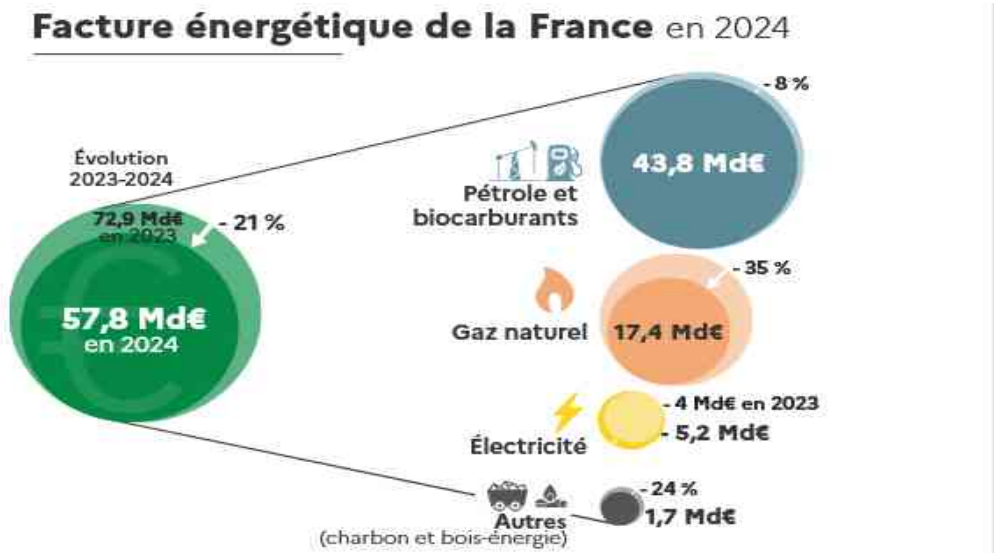


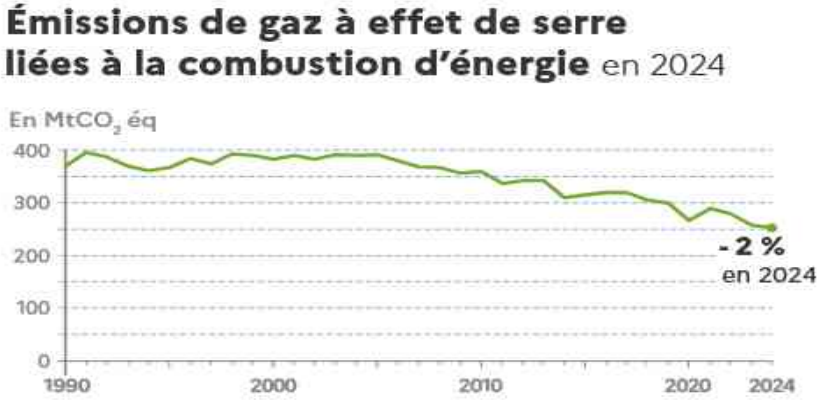


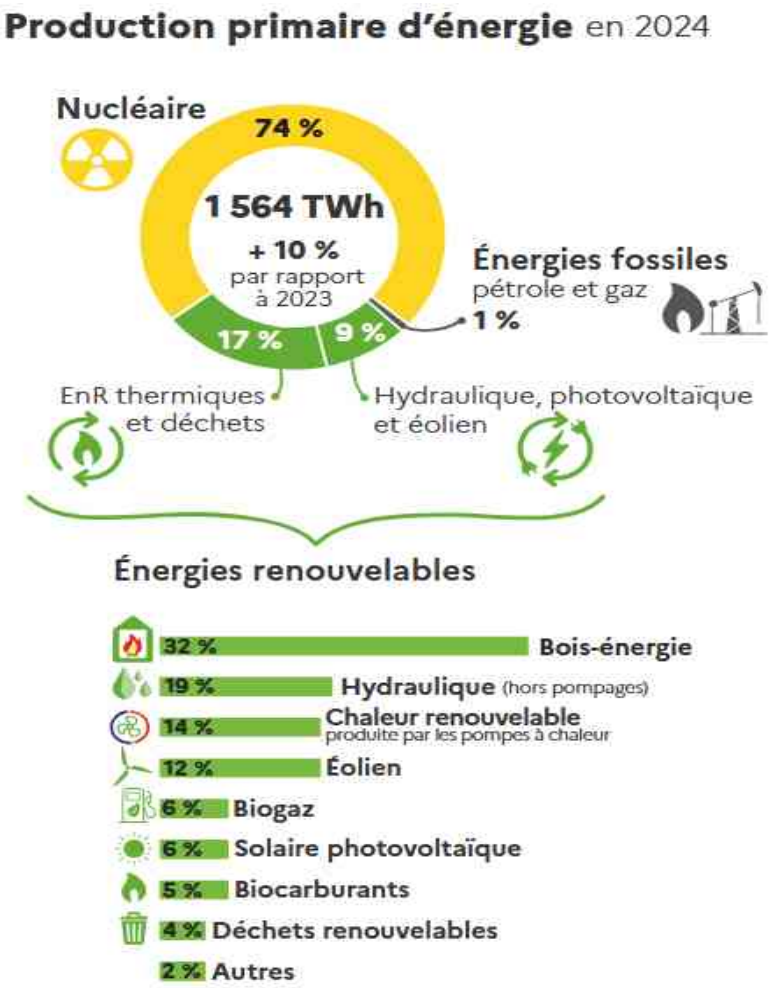
Source: Ch.Guéritte/Données de EI Stat. Review 2025, IEA WEO 2025

Nota: émissions de CO_2 énergie. Les chiffres peuvent varier légèrement selon les sources

A Zoom on France







Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

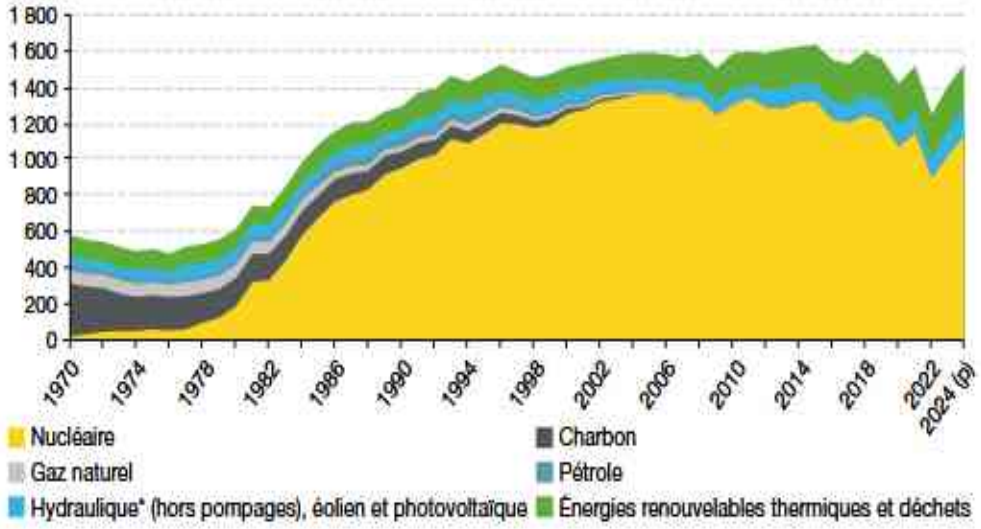
A Zoom on France
Nuclear: 41% of Primary Energy Consumption

Bilan énergétique de la France

PRODUCTION D'ÉNERGIE PRIMAIRE PAR ÉNERGIE

TOTAL : 1 564 TWh en 2024

En TWh

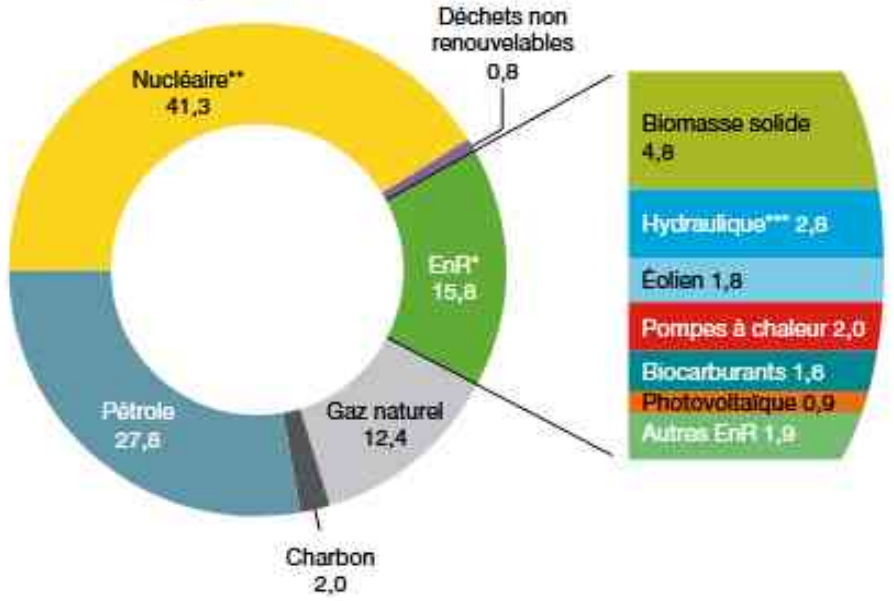


(p) = provisoire.
** Y compris énergies marines.*
Note : la production nucléaire correspond à la chaleur dégagée par la réaction nucléaire évaluée par convention à environ le triple de la production d'électricité obtenue au final.
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine. À partir de 2011, il inclut en outre les cinq DROM.
***Source** : SDES, Bilan énergétique de la France*

RÉPARTITION DE LA CONSOMMATION D'ÉNERGIE PRIMAIRE PAR ÉNERGIE

TOTAL : 2 575 TWh en 2024[1] (donnée non corrigée des variations climatiques)

En % (données non corrigées des variations climatiques)



[1] Données 2024 provisoires.
** EnR = énergies renouvelables.*
*** Correspond pour l'essentiel à la production nucléaire, déduction faite du solde exportateur d'électricité. On inclut également la production hydraulique issue des pompages réalisés par l'intermédiaire de stations de transfert d'énergie, mais cette dernière demeure marginale comparée à la production nucléaire.*
**** Hydraulique hors pompages.*
Note : la production nucléaire correspond à la chaleur dégagée par la réaction nucléaire évaluée par convention à environ le triple de la production d'électricité obtenue au final.
Champ : France.
***Source** : SDES, Bilan énergétique de la France*

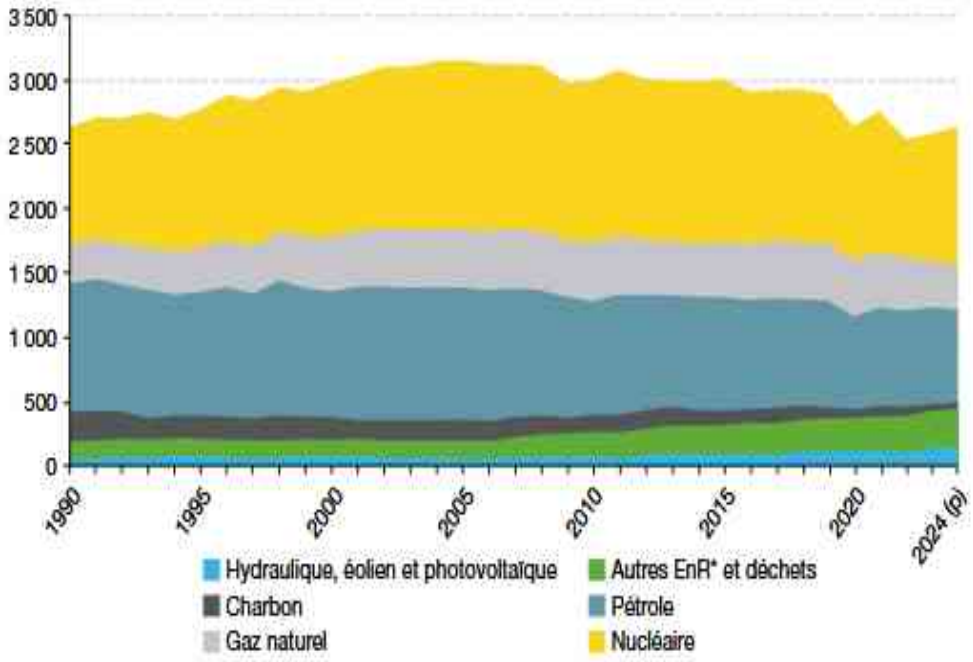
Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

A Zoom on France

ÉVOLUTION DE LA CONSOMMATION D'ÉNERGIE PRIMAIRE

TOTAL : 2 630 TWh en 2024 (donnée corrigée des variations climatiques)

En TWh (données corrigées des variations climatiques)

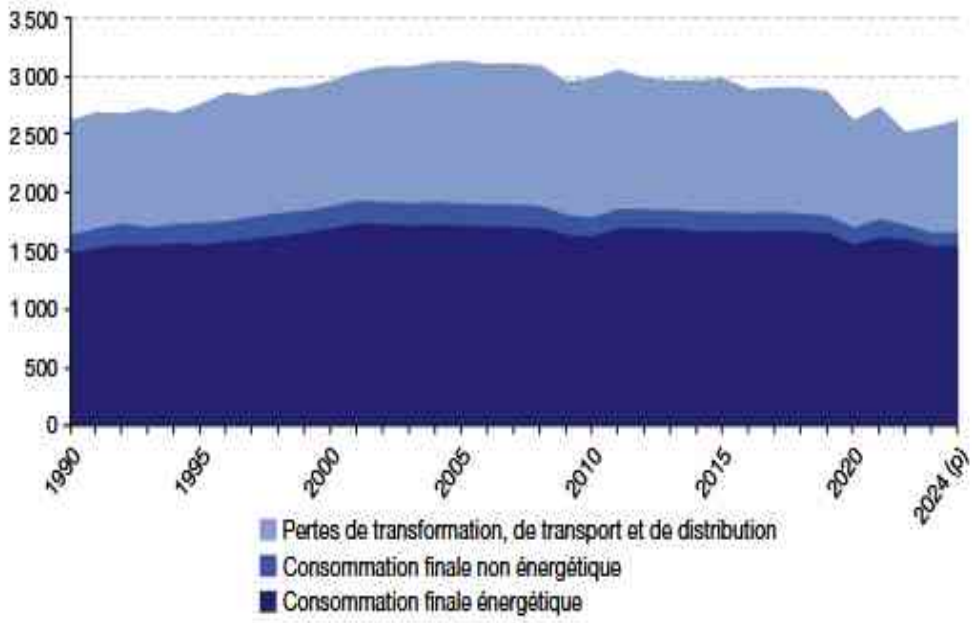


(p) = provisoire.
** EnR = énergies renouvelables.*
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine.
À partir de 2011, il inclut en outre les cinq DROM.
***Source** : SDES, Bilan énergétique de la France*

CONSOMMATION D'ÉNERGIE PRIMAIRE PAR USAGE

TOTAL : 2 630 TWh en 2024 (donnée corrigée des variations climatiques)

En TWh (données corrigées des variations climatiques)



(p) = provisoire.
Note : les pertes de transformation, de transport et de distribution intègrent la consommation d'énergie des entreprises du secteur de la transformation pour leur usage propre ainsi qu'un écart statistique.
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine.
À partir de 2011, il inclut en outre les cinq DROM.
***Source** : SDES, Bilan énergétique de la France*

Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

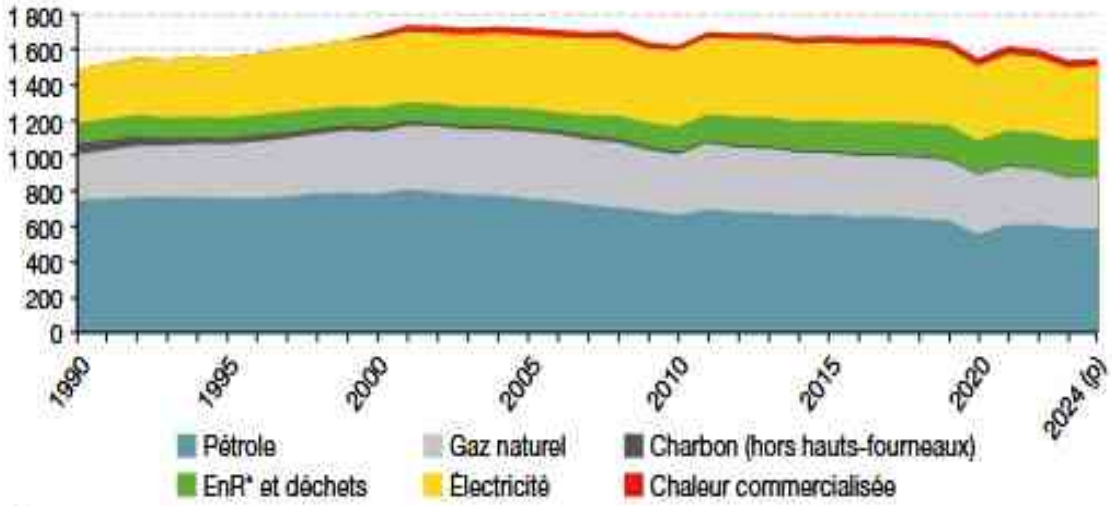
A Zoom on France

Consommation finale d'énergie par secteur et par énergie

CONSOMMATION FINALE À USAGE ÉNERGÉTIQUE PAR ÉNERGIE

TOTAL : 1 550 TWh en 2024 (donnée corrigée des variations climatiques)

En TWh (données corrigées des variations climatiques)

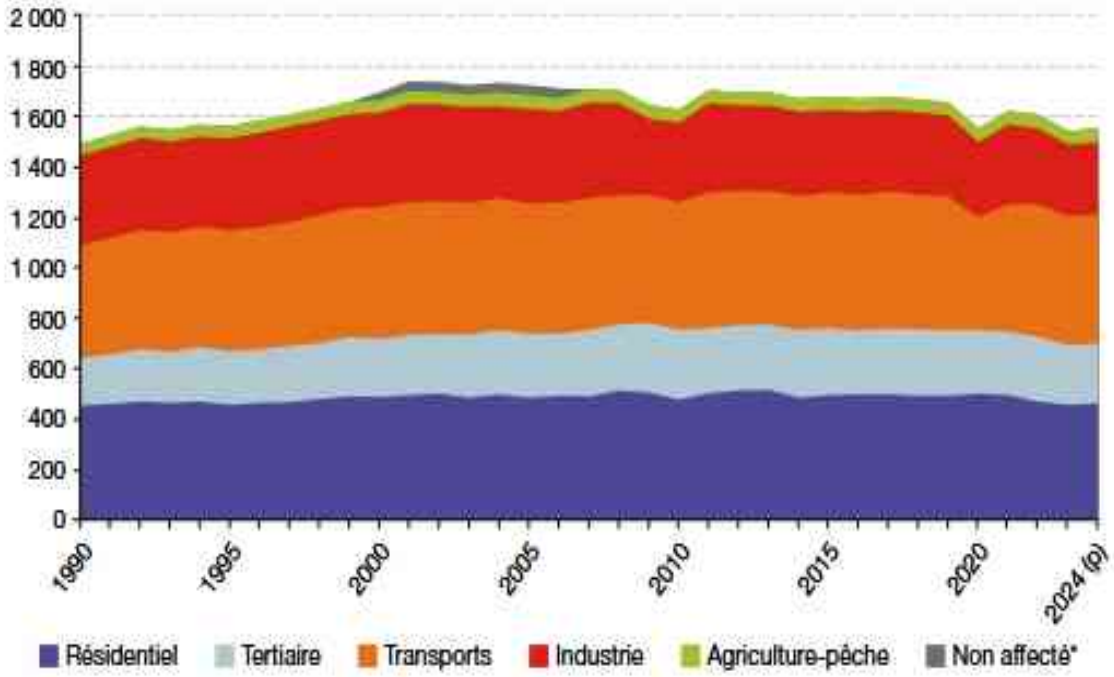


(p) = provisoire.
** EnR = énergies renouvelables.*
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine. À partir de 2011, il inclut en outre les cinq DROM.
***Source** : SDES, Bilan énergétique de la France*

CONSOMMATION FINALE ÉNERGÉTIQUE PAR SECTEUR

TOTAL : 1 550 TWh en 2024 (donnée corrigée des variations climatiques)

En TWh (données corrigées des variations climatiques)



(p) = provisoire.
** La répartition de la chaleur par secteur consommateur n'est pas disponible entre 2000 et 2006.*
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine. À partir de 2011, il inclut en outre les cinq DROM.
***Source** : SDES, Bilan énergétique de la France*

Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

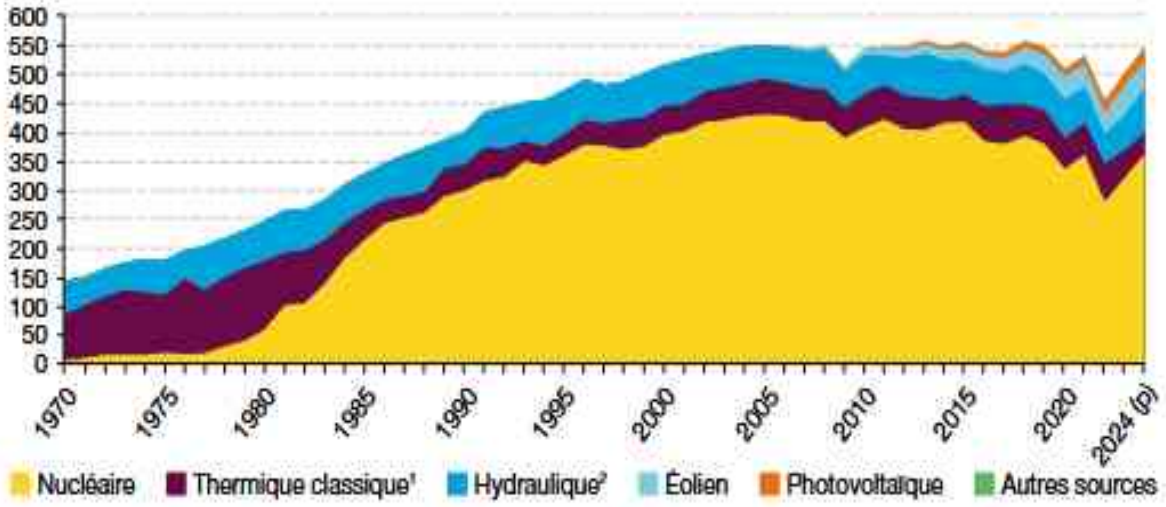
A Zoom on France

Électricité

PRODUCTION NETTE D'ÉLECTRICITÉ

TOTAL : 548 TWh en 2024

En TWh

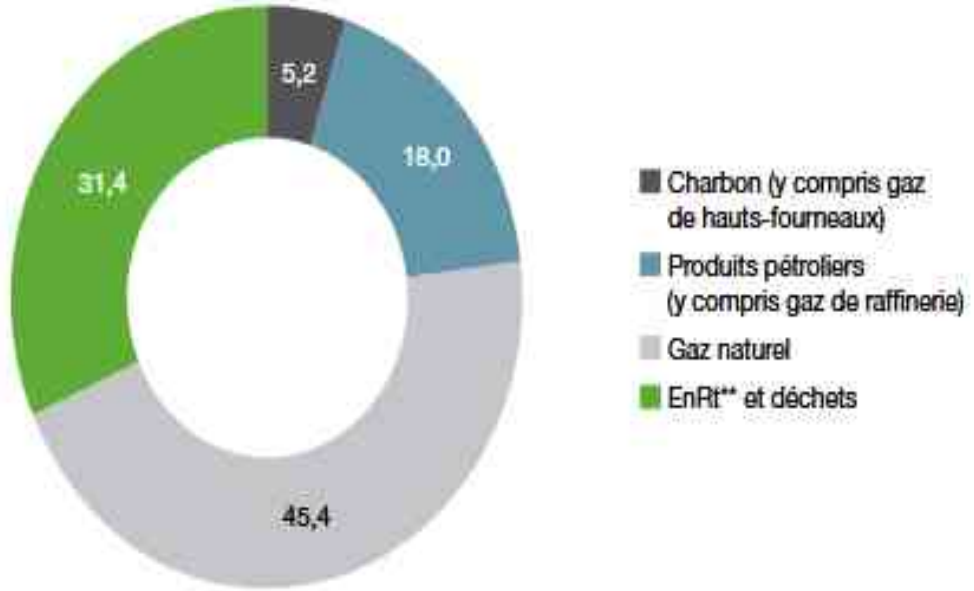


(p) = provisoire.
¹ Thermique à combustibles fossiles (charbon, fioul, gaz naturel), biomasse ou déchets.
² Y compris énergie marémotrice.
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine. À partir de 2011, il inclut en outre les cinq DROM.
***Source** : SDES, Bilan énergétique de la France*

PRODUCTION THERMIQUE CLASSIQUE NETTE PAR TYPE DE COMBUSTIBLE

TOTAL : 37 TWh en 2024*

En %



** Données provisoires.*
*** EnRt = énergies renouvelables thermiques.*
Champ : France.
***Source** : SDES, Bilan énergétique de la France*

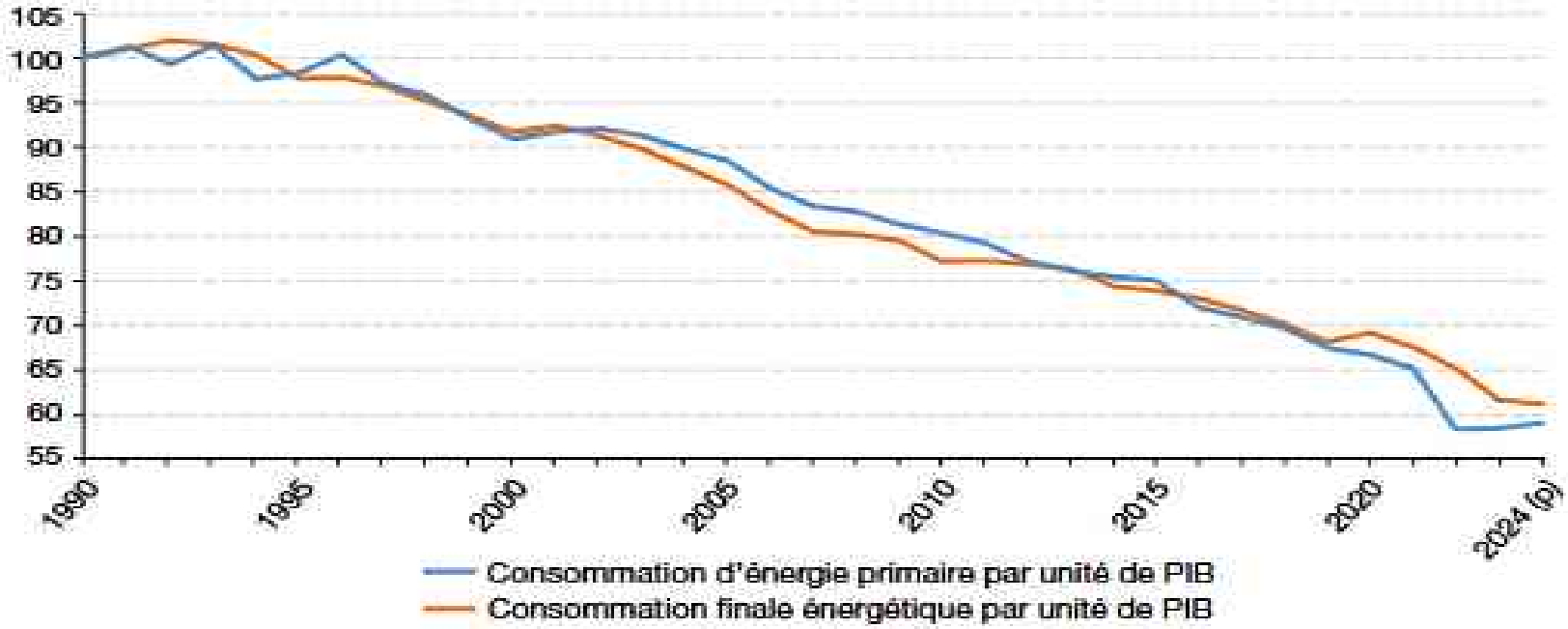
Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

A Zoom on France

Efficacité énergétique

INTENSITÉ ÉNERGÉTIQUE (DONNÉE CORRIGÉE DES VARIATIONS CLIMATIQUES)

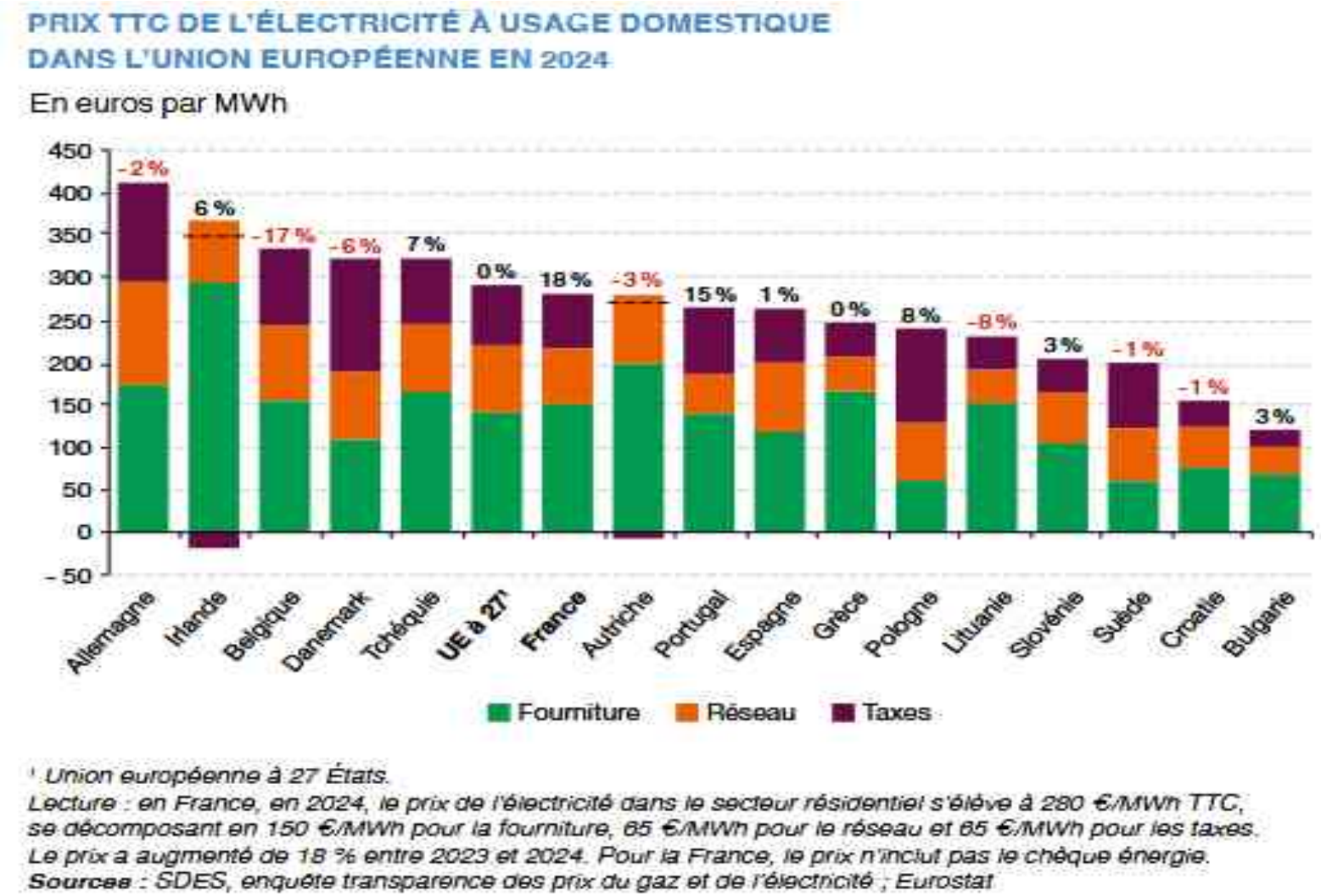
En indice base 100 en 1990 (données corrigées des variations climatiques)



(p) = provisoire.
Champ : jusqu'à l'année 2010 incluse, le périmètre géographique est la France métropolitaine. À partir de 2011, il inclut en outre les cinq DROM.
***Sources** : SDES, Bilan énergétique de la France ; Insee*

Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

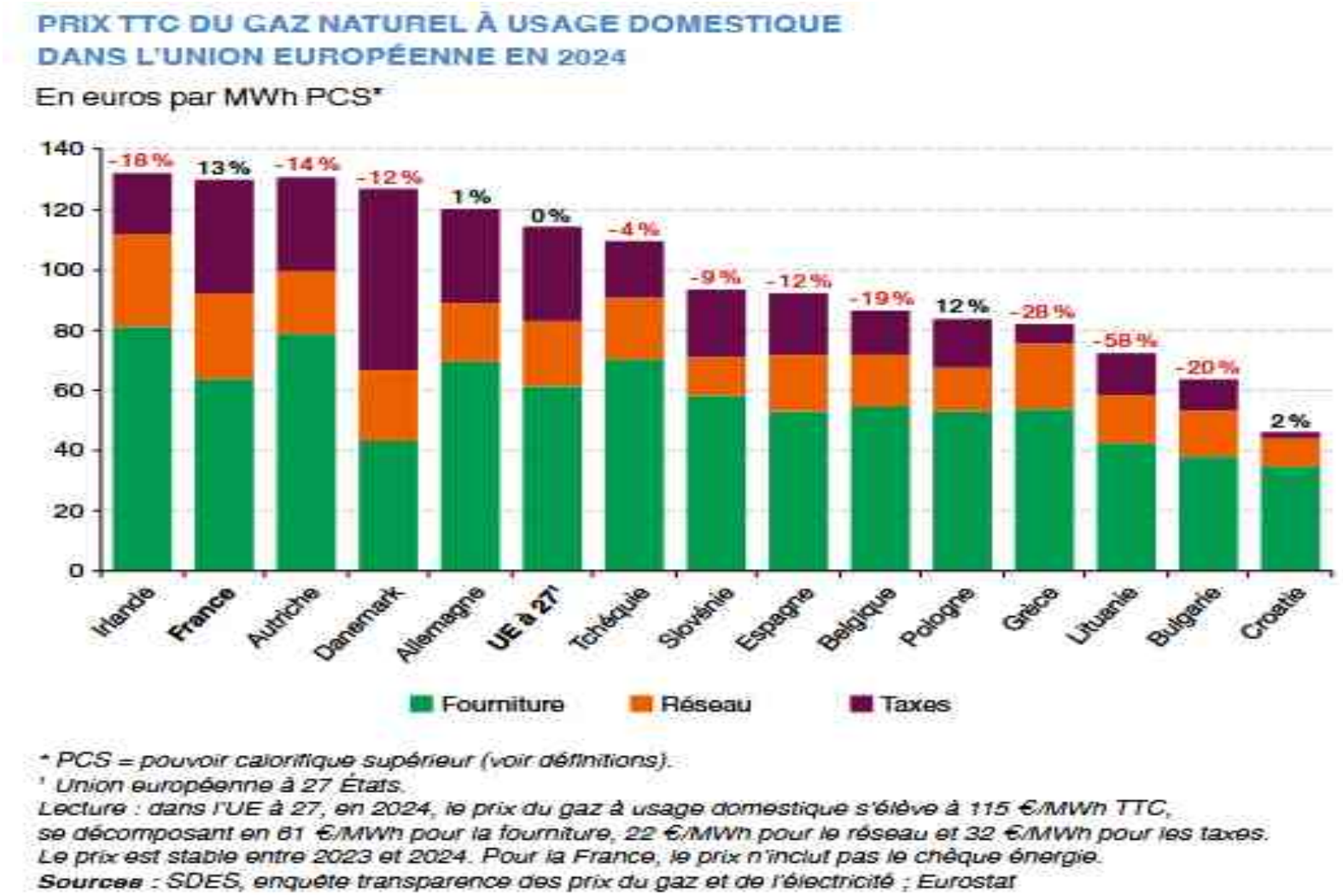
A Zoom on France



¹ *Union européenne à 27 États.*
Lecture : en France, en 2024, le prix de l'électricité dans le secteur résidentiel s'élève à 280 €/MWh TTC, se décomposant en 150 €/MWh pour la fourniture, 65 €/MWh pour le réseau et 65 €/MWh pour les taxes. Le prix a augmenté de 18 % entre 2023 et 2024. Pour la France, le prix n'inclut pas le chèque énergie.
***Sources** : SDES, enquête transparence des prix du gaz et de l'électricité ; Eurostat*

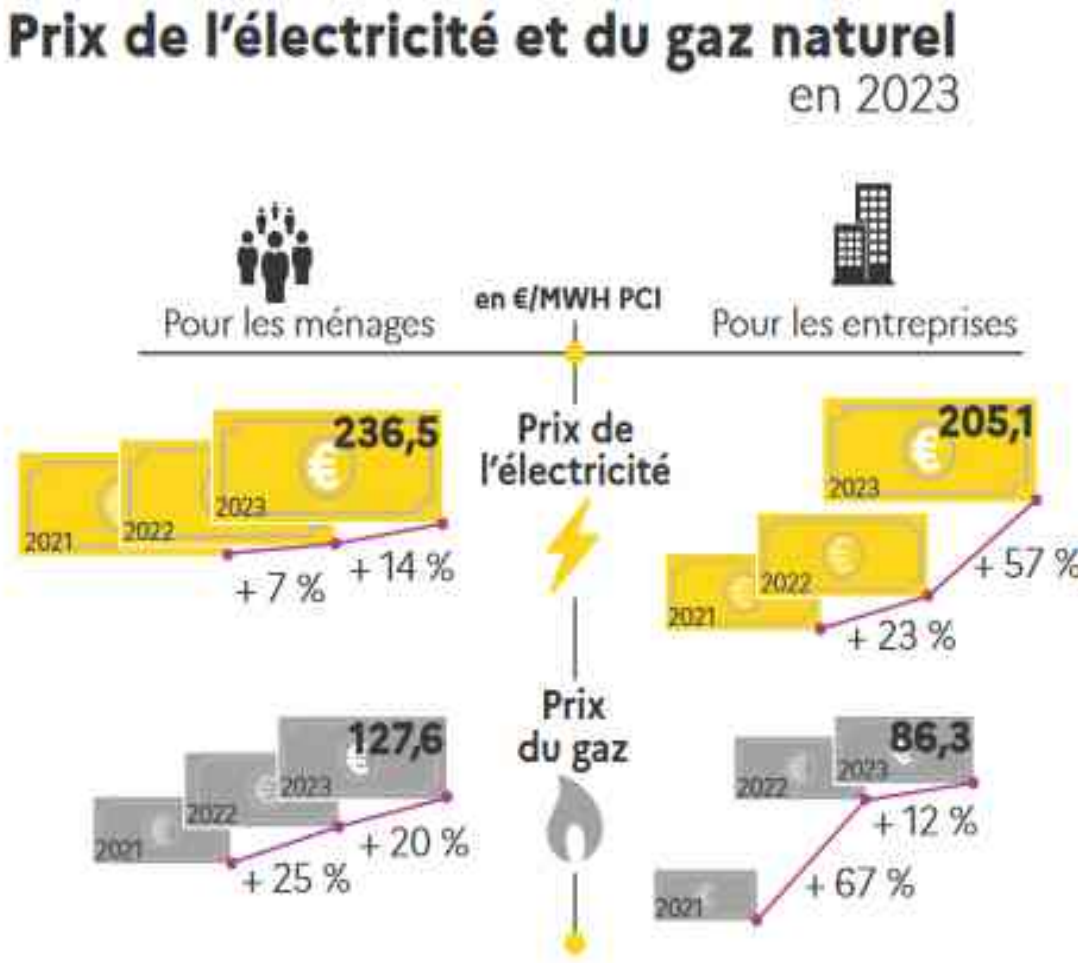
Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

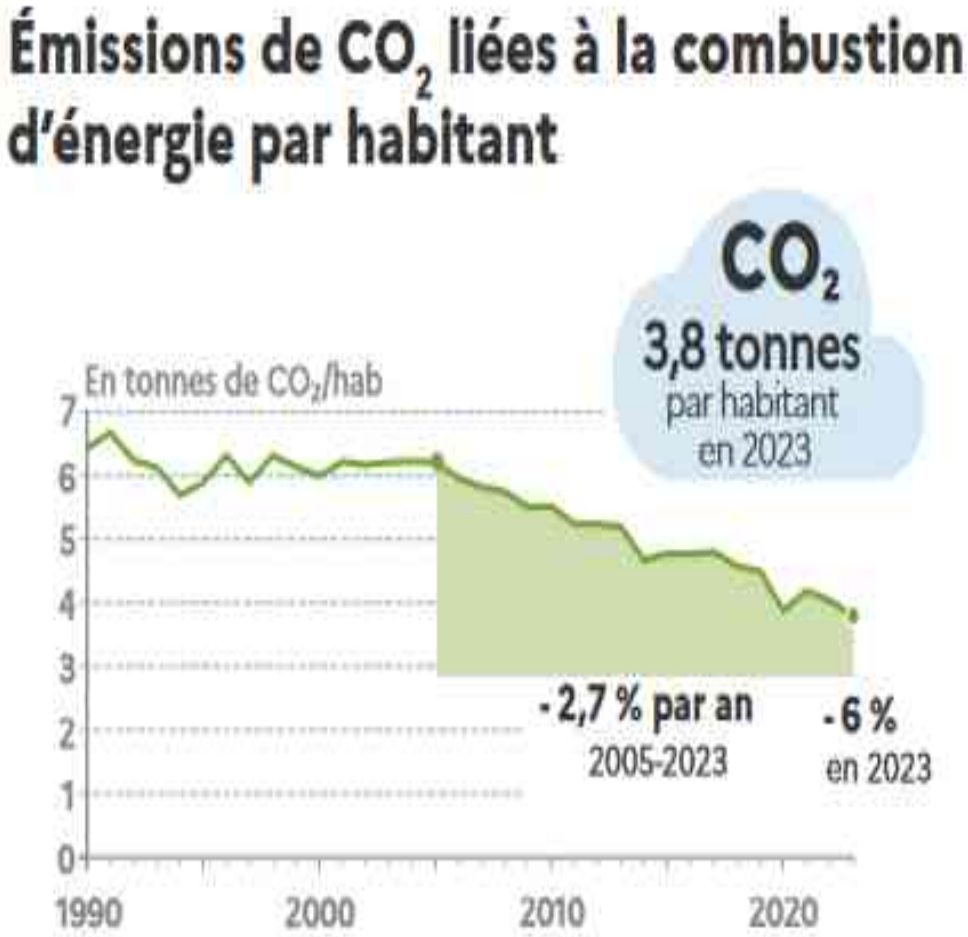
A Zoom on France



Source: SDES, Service des Données et des Etudes Statistiques - Commissariat du Développement Durable - Octobre 2025

A Zoom on France





Source: SDES, Service de la Donnée et des Etudes Statistiques Ministère du Développement Durable 2024

France – Programmation Pluriannuelle de l'Énergie Published in February 2026



Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026 – PPE3

La programmation pluriannuelle de l'énergie, une stratégie pour la souveraineté énergétique de la France

Le Gouvernement déploie, à travers la 3e Programmation Pluriannuelle de l'Énergie (PPE3), un plan ambitieux visant à accroître la production d'énergie décarbonée, souveraine et à prix compétitif en France. Ce plan fixe les orientations énergétiques pour les dix prochaines années et trace la voie vers la neutralité carbone à horizon 2050.

Face à l'urgence climatique et la nécessité d'indépendance géostratégique : la PPE3 projette la France vers une production énergétique indépendante et performante. Elle répond ainsi à 3 objectifs : souveraineté énergétique, neutralité carbone et compétitivité des prix.

La PPE3 fixe un cap clair : accroître la production énergétique décarbonée notamment électrique (entre 650 et 693 TWh en 2035, contre 544 TWh en 2025) et réduire la consommation d'énergies fossiles (environ 330 TWh en 2035 contre 900 TWh en 2023). Cette augmentation permettra d'inverser la tendance actuelle, passant de 60 % d'énergies fossiles dans la consommation à 60 % d'énergie décarbonée d'ici 2030, et 70 % en 2035.

La PPE3 dessine une trajectoire fondée sur un bouquet énergétique diversifié, combinant production électrique de différentes sources (nucléaire, hydroélectricité, éolien en mer et terrestre, photovoltaïque), électrification des usages et développement de substituts bas carbone aux énergies fossiles (réseaux de chaleur, biométhane, biocarburants, hydrogène), afin de réduire la dépendance aux énergies fossiles (pétrole, gaz).

Main trends:

- To pursue nuclear production with prolongation of reactors operational life to 50/60 years
- To develop 6 EPR2
- To promote SMR (Small Moduler Reactors)
- To develop Hydroelectricity by increasing pumping stations (STEP) and dam's capacities
- To slow down Wind onshore, optimize existing sites
- To develop Wind offshore farms
- To pursue development of solar Energy

Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie: PPE 3 Published in in February 2026

Chiffres clés

Les objectifs par filière à horizon 2035

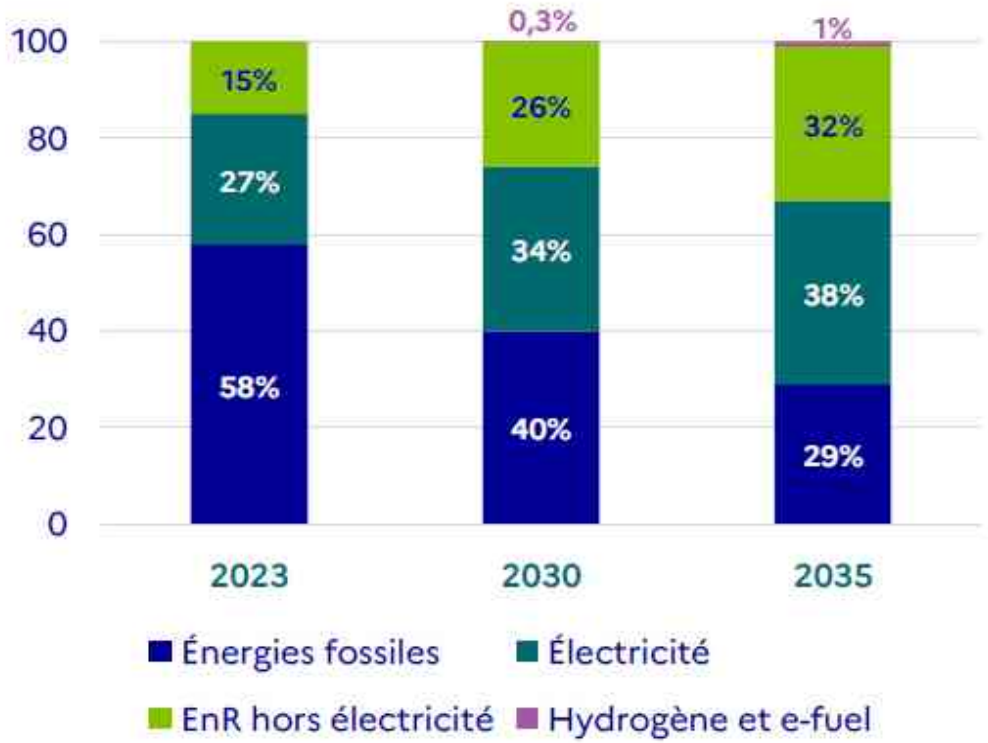
		2023	2030	2035
Filières électriques	PRODUCTION D'ÉLECTRICITÉ DÉCARBONÉE[1]	458 TWh	585 TWh	Entre 650 et 693 TWh
	PRODUCTION NUCLÉAIRE	56 réacteurs 320,4 TWh	57 réacteurs en service 380 TWh (Cible haute à 420 TWh)	
	PHOTOVOLTAÏQUE	19,3 GW[2] 22,7 TWh	48 GW ~59 TWh	55 – 80 GW ~67 – 98 TWh
	ÉOLIEN TERRESTRE	21,9 GW[3] 48,7 TWh	31 GW ~68 TWh	35 – 40 GW ~80 – 91 TWh
	ÉOLIEN EN MER	0,84 GW[4] 1,9 TWh	3,6 GW ~14 TWh	15 GW[5] ~59 TWh
	HYDRO-ÉLECTRICITÉ	25,9 GW (avec STEP)[6] 54,2 TWh[7]	26,3 GW (avec STEP) ~54 TWh	28,7 GW (avec STEP)[8] ~54TWh
Filières non électriques	CHALEUR ET FROID RENOUVELABLES ET DE RÉCUPÉRATION	172 TWh chaleur[9] 1 TWh froid livré par les réseaux	297 TWh chaleur 2 TWh froid livré par les réseaux	328-421 TWh chaleur 2,5 – 3 TWh froid livré par les réseaux
	BIOMÉTHANE injecté dans les réseaux de gaz naturel (objectifs en TWh PCS)	9 TWh	44 TWh*	47 – 82 TWh
	BIOCARBURANTS dans le transport	38 TWh dans le transport	55 TWh dans le transport	70 – 90 TWh (transport et hors transport)
	HYDROGÈNE (capacité d'électrolyse installée)	0 GW	Jusqu'à 4,5 GW (9-19 TWh pci)	Jusqu'à 8 GW (16-40 TWh pci)

Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

La décarbonation de l'économie française dans la PPE

Accroître les énergies décarbonées et diminuer la part des énergies fossiles, fortement émettrices de carbone



Il est essentiel de réduire le poids des énergies fossiles dans notre bouquet énergétique.

En 2023, nous consommions près de **60 % d'énergie finale fossile**

Notre objectif est de n'en consommer plus que **40 % en 2030**

Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Relance du nucléaire : une rupture avec la précédente programmation pluriannuelle de l'énergie

La PPE3 marque une rupture : alors que la PPE précédente prévoyait la fermeture de 14 réacteurs, la PPE3 acte la relance du nucléaire et garantit les investissements sur le long terme.

Conformément aux orientations définies par le président de la République lors du discours de Belfort du 10 février 2022, elle établit de nouveaux objectifs afin de donner un coup d'accélérateur à la filière.

- Sur le parc existant, elle vise à prolonger la durée de vie des réacteurs à 50 ou 60 ans, en respectant l'ensemble des exigences de sûreté, et à augmenter la puissance disponible des réacteurs existants.
- Dans le prolongement du discours de Belfort, elle confirme le lancement de la construction de six réacteurs EPR2 et fixe pour objectif d'être en mesure de décider en 2026 du lancement de la construction de huit réacteurs supplémentaires.

Elle propose de soutenir les petits réacteurs modulaires (« SMR ») et des petits réacteurs innovants avec l'objectif d'un premier réacteur au début de la décennie 2030.

Elle transcrit l'objectif de renouvellement des usines de l'aval du cycle, à travers le programme « Aval du futur ».

Elle comprend la poursuite des travaux sur la fermeture du cycle (usines de fabrication de combustible, réacteurs à neutrons rapides, usine de retraitement des combustibles), avec l'objectif de définir une feuille de route stratégique en vue d'une décision en 2026.

Elle vise la poursuite de la recherche dans le secteur du nucléaire.

Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Énergies renouvelables : un développement ambitieux et réaliste

La PPE3 poursuit le développement des énergies renouvelables en privilégiant les technologies le plus compétitives.

Les objectifs ont été définis en prenant en compte des critères de coûts, de disponibilité, d'acceptabilité locale et sociale et de souveraineté.

1. La réforme de l'hydroélectricité : redémarrage d'une filière souveraine

L'hydraulique occupe une place importante dans le bouquet énergétique de la France. Ce procédé représente en 2024 près de 15 % de la production d'électricité en France, se plaçant ainsi deuxième filière de production électrique après le nucléaire, et la première parmi les filières renouvelables.

La PPE3 et les nouveaux investissements permettront de développer le parc de stations de transfert d'énergie par pompage (STEP). Les sites existent déjà, ce qui rend cette solution à la fois pérenne et largement acceptée par l'écosystème, sans nécessiter la création de nouveaux sites.

La PPE3 fixe ainsi un objectif de développement ambitieux :

- **Augmenter à hauteur de 1,7 GW** les capacités de STEP
- **Augmenter de 1,1 GW la puissance installée** des ouvrages existants, notamment par l'optimisation et le suréquipement d'aménagements.

Une étape importante a été franchie dans la résolution des précontentieux avec la Commission européenne sur l'hydroélectricité à l'été 2025.

La Commission européenne a donné son accord de principe sur les modalités permettant une relance massive des investissements dans les barrages et les vallées au bénéfice de la transition énergétique et de la gestion de l'eau. Le régime juridique des concessions hydroélectrique va ainsi évoluer en faveur de la modernisation et l'extension d'installations essentielles au système énergétique.

La proposition de loi Battistel-Bolo visant à relancer les investissements dans le secteur de l'hydroélectricité pour contribuer à la transition énergétique a été adoptée par l'Assemblée nationale le 5 février 2026. Elle doit permettre la mise en œuvre de cette réforme.

2. Accélération sur l'éolien en mer : la montée en puissance d'une aventure industrielle

La PPE poursuit le développement de l'éolien en mer en prenant en compte les réalités industrielles de la filière et les besoins d'infrastructures. **Avec 5 000 emplois industriels et 3 des 11 sites européens de fabrication des grands composants de turbines, la France est leader européen dans la fabrication des équipements de l'éolien en mer.**

Le Gouvernement réitère son engagement pour développer avec ambition une **filière industrielle complète dans le domaine de l'éolien en mer et de son raccordement** :

- Une cible de 15 GW de puissance installée d'ici 2035 ;
- Un ajustement du calendrier pour l'objectif de 18 GW, désormais fixé à 2037, afin de mieux intégrer les réalités industrielles, notamment celles liées au raccordement des parcs au réseau électrique ;
- Des appels d'offres supplémentaires pour initier de nouveaux projets sur l'ensemble des façades maritimes.

La PPE permet la publication des prochains appels d'offres. L'introduction de critères de résilience issus du règlement « Industrie zéro net » (*Net Zero Industry Act*) européen dans les appels d'offres pour l'éolien en mer permettra de maximiser les retombées industrielles du développement de l'éolien en mer sur le territoire européen.

Concernant les autres énergies renouvelables marines, un tournant décisif sera pris pour la filière hydrolienne avec un premier appel d'offre de 250 MW au raz Blanchard ; l'usine marémotrice de la Rance de 240 MW continuera sa production.

3. Poursuite raisonnée du développement des énergies renouvelables électriques terrestres

Les objectifs d'installations des énergies renouvelables électriques ont été ajustés pour tenir compte de l'évolution de la consommation électrique sur les dernières années.

Depuis la version mise à la consultation du public, les cibles en 2030 et 2035 ont été adaptées pour tenir compte du rythme réel d'électrification du pays. Dans l'attente d'une accélération sur l'électrification des usages, **le Gouvernement a décidé de maintenir stable les objectifs d'octroi de soutien public par appel d'offres inscrits dans la PPE 2 pour les énergies renouvelables terrestres jusqu'en 2028.** En gardant le rythme établi par la PPE précédente, elle maintient le niveau de déploiement propice à l'émergence de projets industriels souverains, notamment dans l'industrie photovoltaïque.

Pour l'éolien terrestre, l'ambition est claire : privilégier les projets visant à l'augmentation de la puissance des parcs existants, avec une cible de 31 GW en 2030, 35-40 GW en 2035, contre environ 24 GW en 2025.

En ce qui concerne la trajectoire photovoltaïque, le Gouvernement maintient une trajectoire ambitieuse avec une cible de 48 GW en 2030 et 55-80 GW en 2035, contre un peu plus de 31 GW en 2025.

4. Poursuite du développement des énergies bas carbone non-électriques

Grâce à l'électrification, la France pourra considérablement réduire son recours aux énergies carbonées : il s'agit d'inverser la part des énergies fossiles dans la consommation du pays qui s'élève aujourd'hui 60 % pour passer à 60 % d'énergie décarbonée en 2030.

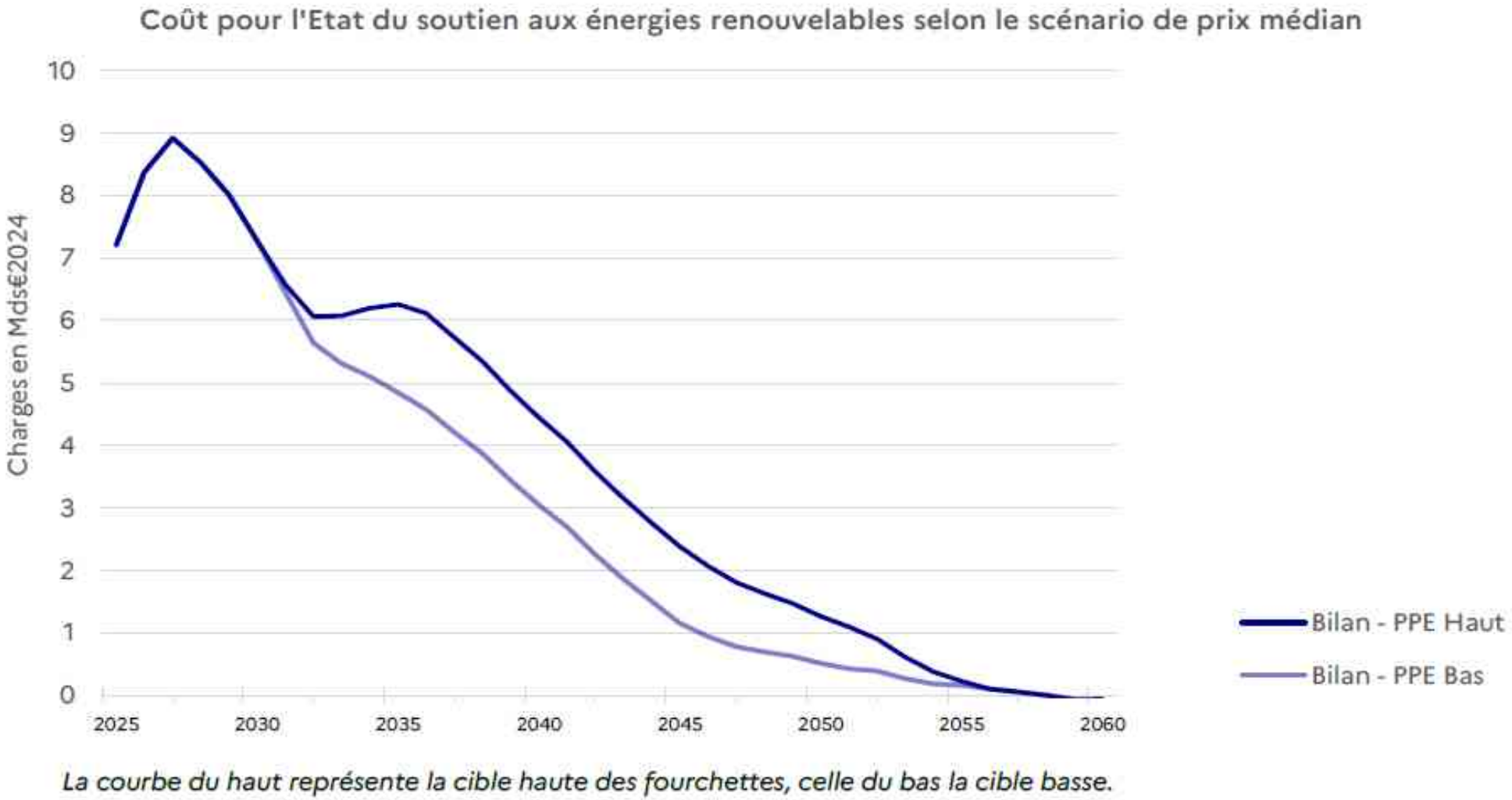
L'électricité nucléaire et renouvelable et l'électrification massive des usages permettront d'accomplir près de 70 % de la réduction d'énergies fossiles prévue par la PPE en 2035. Toutefois, certains usages nécessitent des combustibles aujourd'hui assurés par des énergies fossiles, principalement le pétrole et le gaz.

À travers cette PPE, pour les usages de l'énergie que l'on peut difficilement électrifier, le Gouvernement promeut le recours à des substituts décarbonés tels que le biométhane, l'hydrogène décarboné, la chaleur renouvelable et les biocarburants.

Compte tenu du coût de ces substituts relativement plus élevés que les hydrocarbures, afin de répondre à une ambition forte de déploiement des énergies bas carbone, l'État a mis en place plusieurs dispositifs incitatifs et de soutien.

Source: GOUVERNEMENT
Liberté
Égalité
Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026



Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Plus de 100 000 nouveaux emplois dans la transition énergétique

Les cibles d'énergies décarbonées de la PPE impliqueront des besoins importants en emplois, notamment dans le nucléaire, le photovoltaïque et l'éolien en mer. Le tableau ci-dessous fournit des estimations par filière des besoins en emploi à l'horizon 2030[10].

Emplois par filières	Emplois en 2022[11]	Trajectoire 2030[12]
Réseaux de chaleur	3 740	8 690
Réseaux de froid	210	420
Hydroélectricité	14 720	14 720
Éolien terrestre	14 670	21 656
Éolien en mer	5 080[13]	33 867[14]
Solaire thermique	2830	11 320
Solaire photovoltaïque	18 920	56 760
Géothermie	2 780	8 237
Biogaz	5 290	14 944
Filière nucléaire	125 000[15]	156 000[16]
Total énergies (hors biocarburant, hydrogène et dérivés, énergie fossile et filière réseaux)[17]	**~ 193 200**	**~326 600**

Source: GOUVERNEMENT Liberté Égalité Fraternité

France – Programmation Pluriannuelle de l'Énergie Published in February 2026

Comparaison avec les cibles du Bilan prévisionnel de RTE

Le scénario de la PPE a été préparé par le Gouvernement sur le fondement d'une grande consultation et dans une logique de minimisation des coûts, d'acceptabilité sociale et de souveraineté industrielle.

Il ne se positionne pas exactement sur l'un des scénarios du bilan prévisionnel de RTE publié en décembre 2025, mais s'inspire du scénario R3, en y intégrant des contraintes industrielles et d'acceptabilité.

	R1	R2	R3	R4	PPE 3	Scénario RTE correspondant
Eolien en mer						
Objectif 2035	7 GW	10 GW	13 GW	15 GW	15 GW	R4 (objectif industriel)
Eolien terrestre						
Objectif 2030	27 GW	27 GW	32 GW	35 GW	31 GW	R3 (cohérence avec la proposition de loi Gremillet)
Objectif 2035	30 GW	30 GW	40 GW	45 GW	35-40 GW	R2 – R3
Photovoltaïque						
Objectif 2030	35 GW	42 GW	47 GW	54 GW	48 GW	R3 (cohérence avec la proposition de loi Gremillet)
Objectif 2035	40 GW	55 GW	65 GW	90 GW	55 - 80 GW	R2 – R« 3,5 » (objectif industriel)

Source: GOUVERNEMENT Liberté Égalité Fraternité

Reminder - France PPE March 2025 - Renewables Incentive Costs Additional Commitments 2025-2035 to fulfill PPE3 objectives

Estimation des coûts de soutien entre 2025 et 2060 ($Md€_{2024}$)	Scénario de prix bas	Scénario de prix médian	Scénario de prix haut
Photovoltaïque	30,1 à 55,3	20,8 à 38,4	9,4 à 17,6
Éolien terrestre	21,6 à 27,6	6,1 à 7,6	-16,0 à -11,9
Éolien en mer	36,3	4,5	-35,2
Hydraulique	4,2	2,2	-0,2
Hydrolien	1	0,8	0,5
Biométhane	5,0 à 10,9	4,4 à 9,4	3,7 à 7,8
Total PPE 3	**98,2 à 135,2**	**38,7 à 62,9**	**-33,7 à -25,5**
Déjà engagé avant la PPE 3	114,3	90,1	60,1
Total	**212,5 à 249,6**	**128,8 à 152,9**	**26,4 à 34,6**

Nota: PPE = Programmation Pluriannuelle de l'Énergie
Costs estimates vs various Energy prices scenarios

Zoom sur le PPE3/Éolien Offshore – Qu'en penser?

Projets PPE3	AO10 – 10ème Appel d'offres pour le soutien de l'éolien en mer	Nucléaire - Programme pour les EPR2
Date de lancement	12 Juin 2026	9 Novembre 2021
Programme	Construction de 10 GW (15 GW cumulés 2035) 5 GW éolien flottant + 5 GW éolien posé	Construction de 6 EPR2, 1750 GW par unité 3 paires de 2 réacteurs
Sites	Ensemble des façades maritimes	3 sites: Penly, Gravelines, Bugey
Attribution des contrats	Février 2027	Plusieurs contrats attribués
Démarrage travaux	?	Entre été 2024 et Avril 2028 selon les sites
Mise en service prévue	?	Entre 2037 et 2042 selon les sites
Durée	25 ans, à démanteler et renouveler tous les 25 ans	60 ans+
Production attendue	Intermittente – # 30 TWh/an pendant 25 ans Tenant compte du facteur de charge	# 70 TWh/an pendant 60 ans+
Coût	Prix d'achat moyen pondéré = 100 €/MWh *(p.m. Parc Yeu/Noirmoutier: 61 éoliennes x 8MW = 488 MW - Invest. 2,5 G€ - 167 €/MWh)*	73 G€ (Source EdF)

6

Demography: A key element

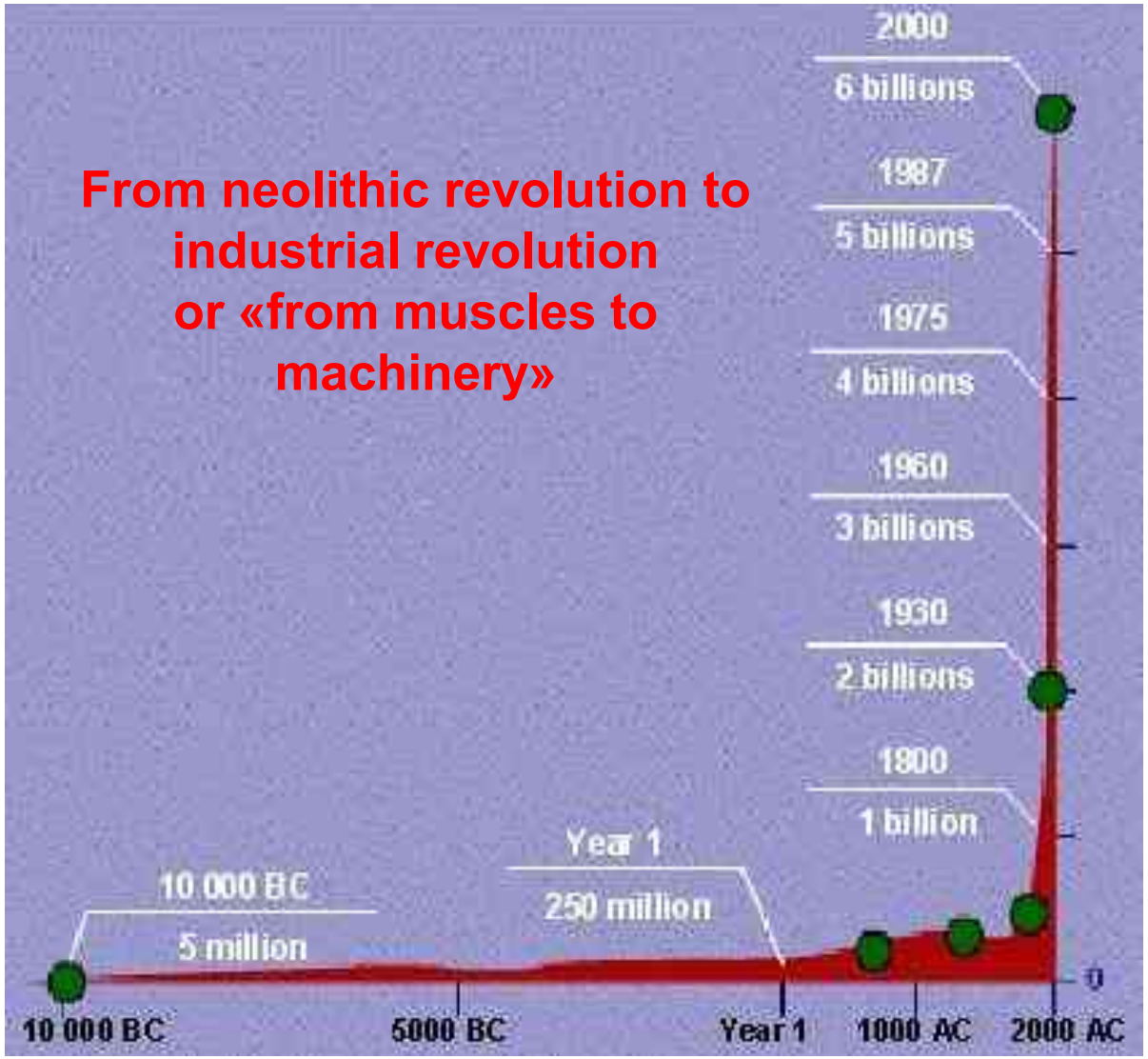
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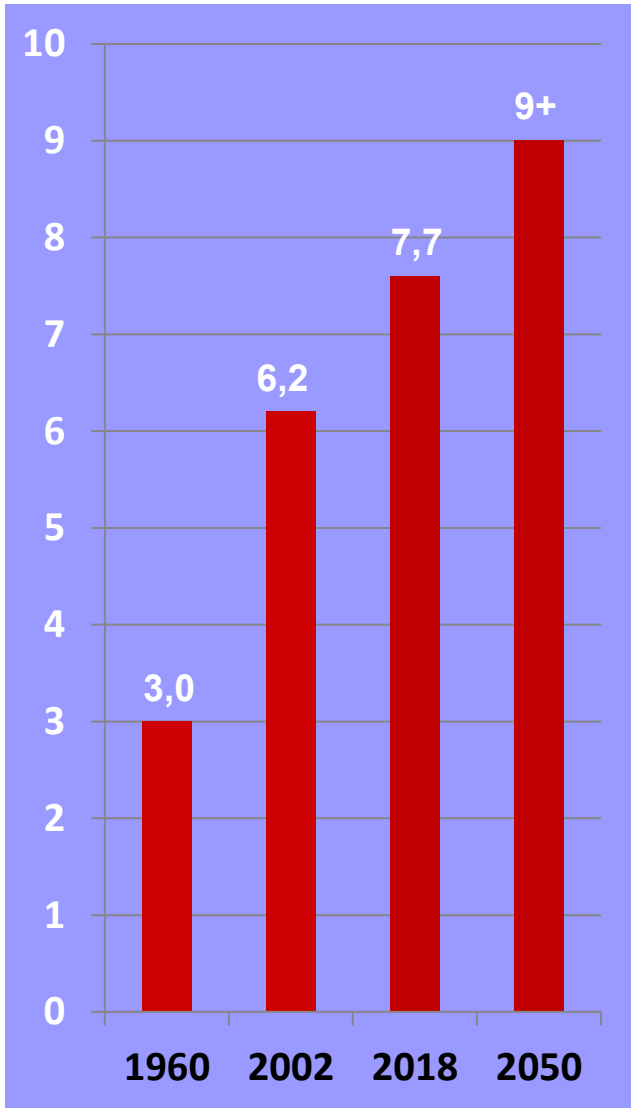
- 1. Energy: a major element of economic development
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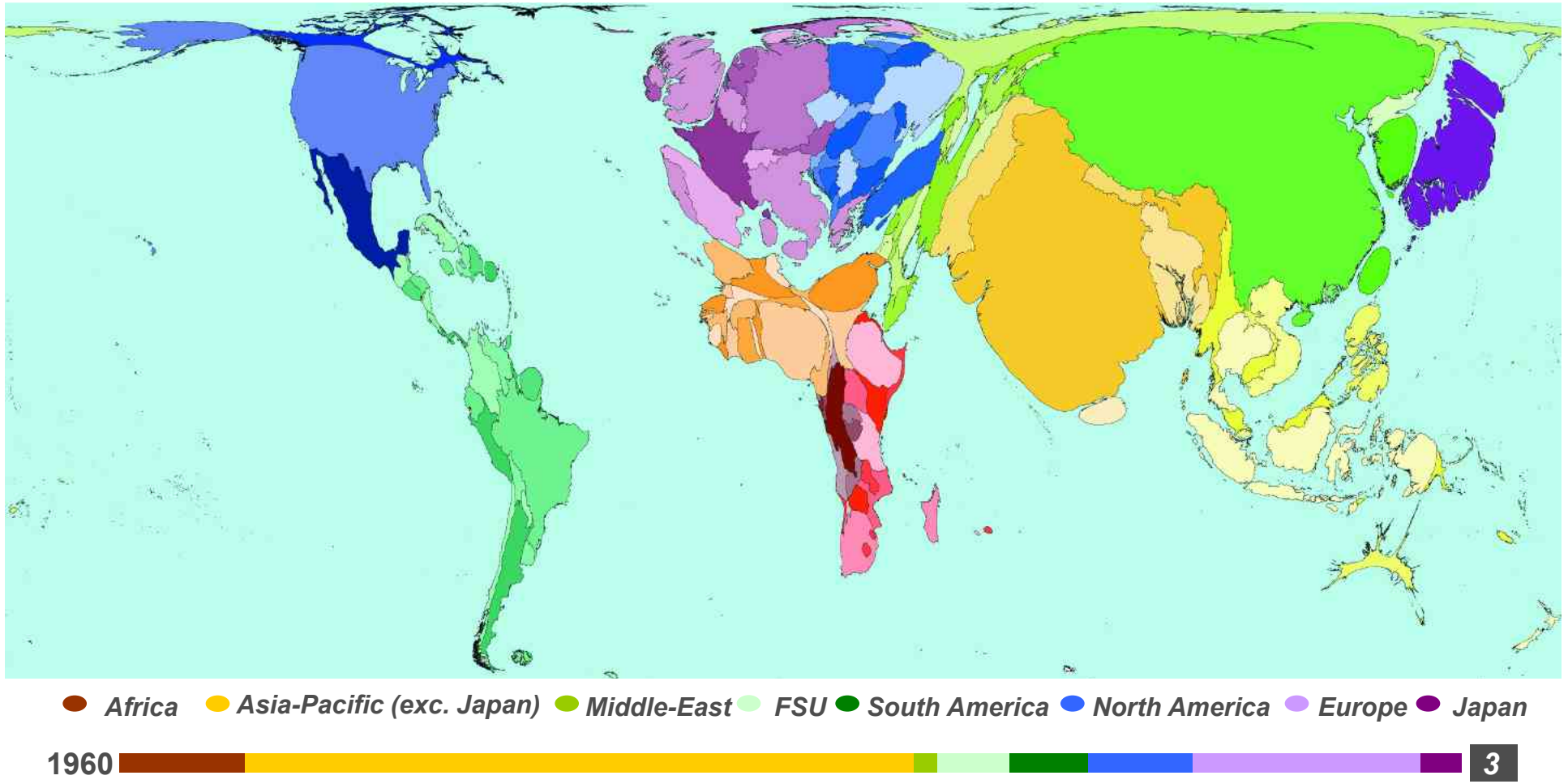
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World Population Evolution over a 12 000 years period



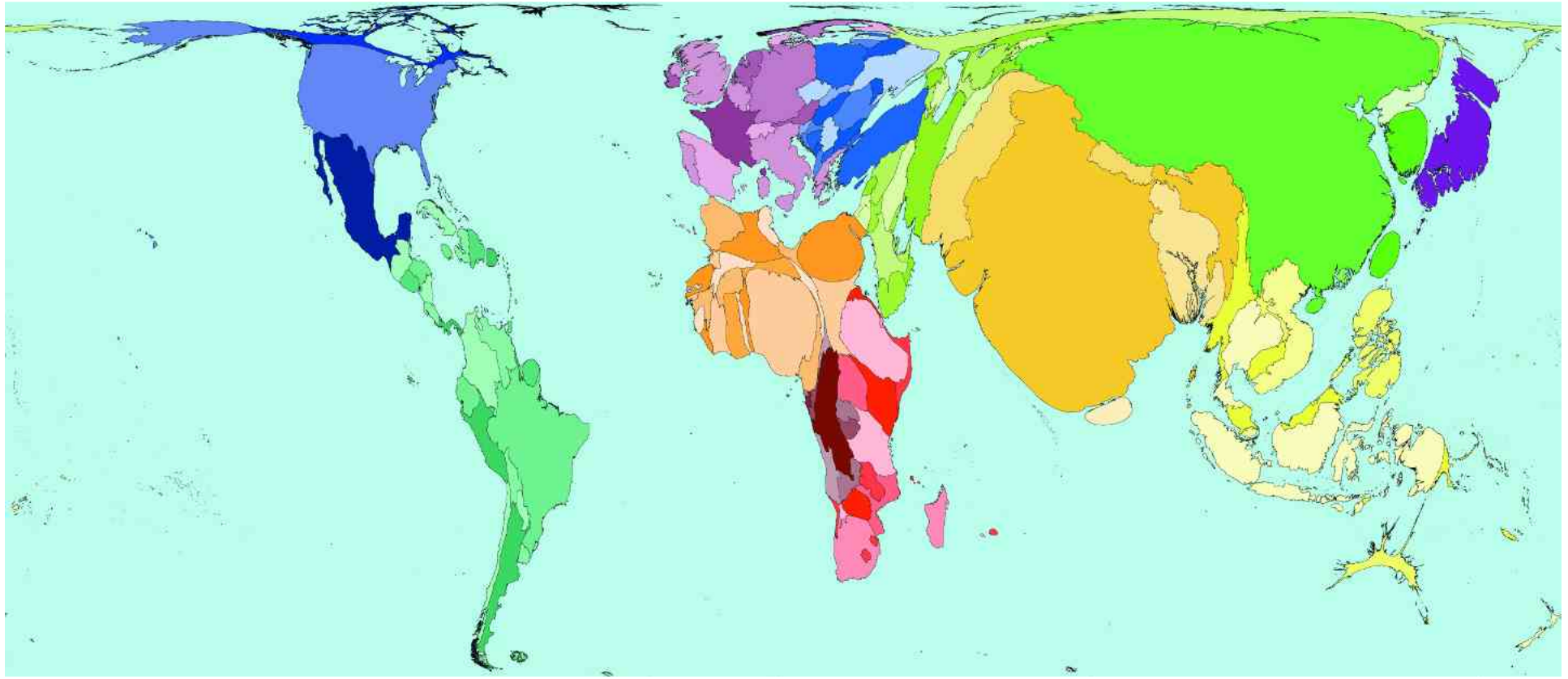


World Population (billions) - 1960



Sources : UN / worldmapper

World Population (billions) - 2002



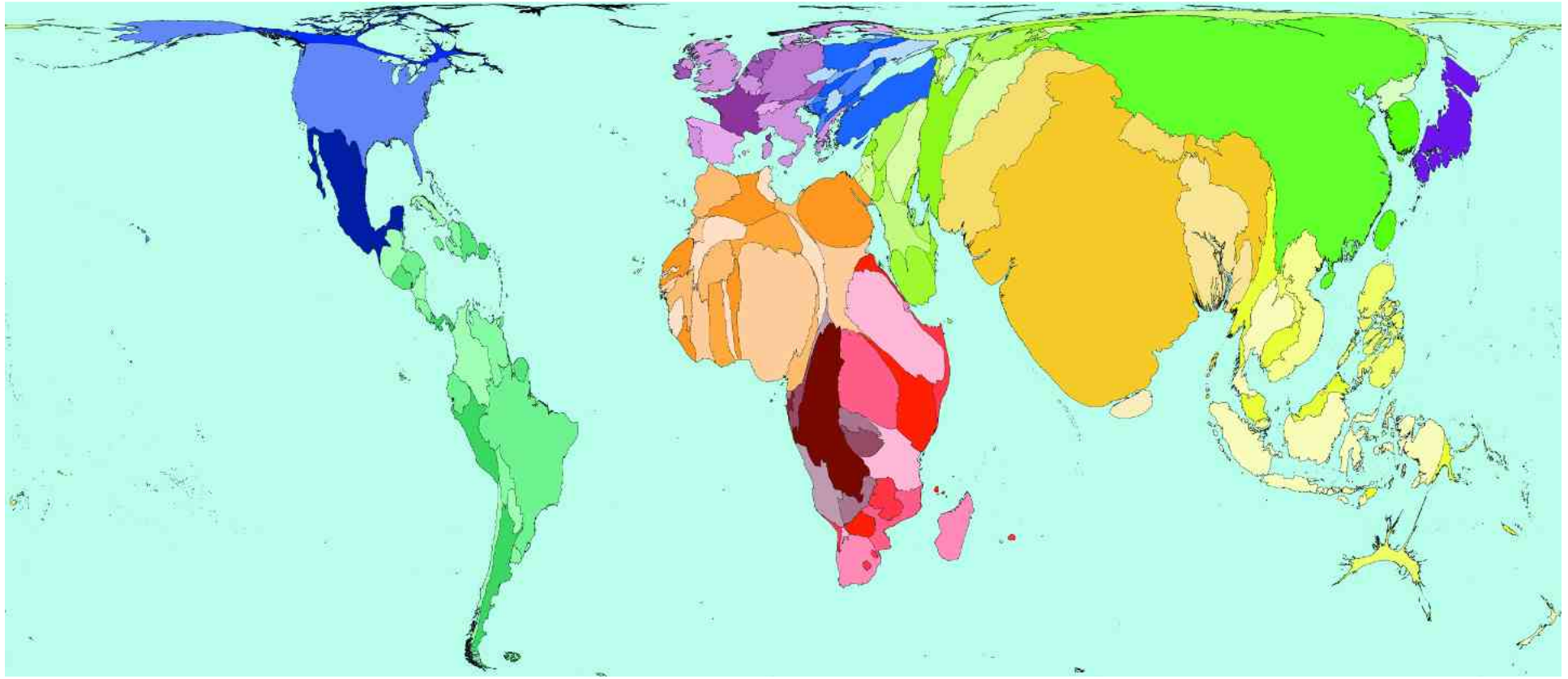
Africa Asia-Pacific (exc. Japan) Middle-East FSU South America North America Europe Japan

2002 >6,2

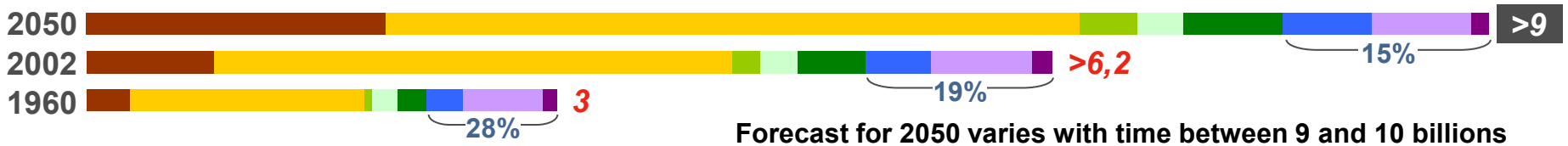
1960 3

Sources : UN / worldmapper

World Population (billions) - 2050



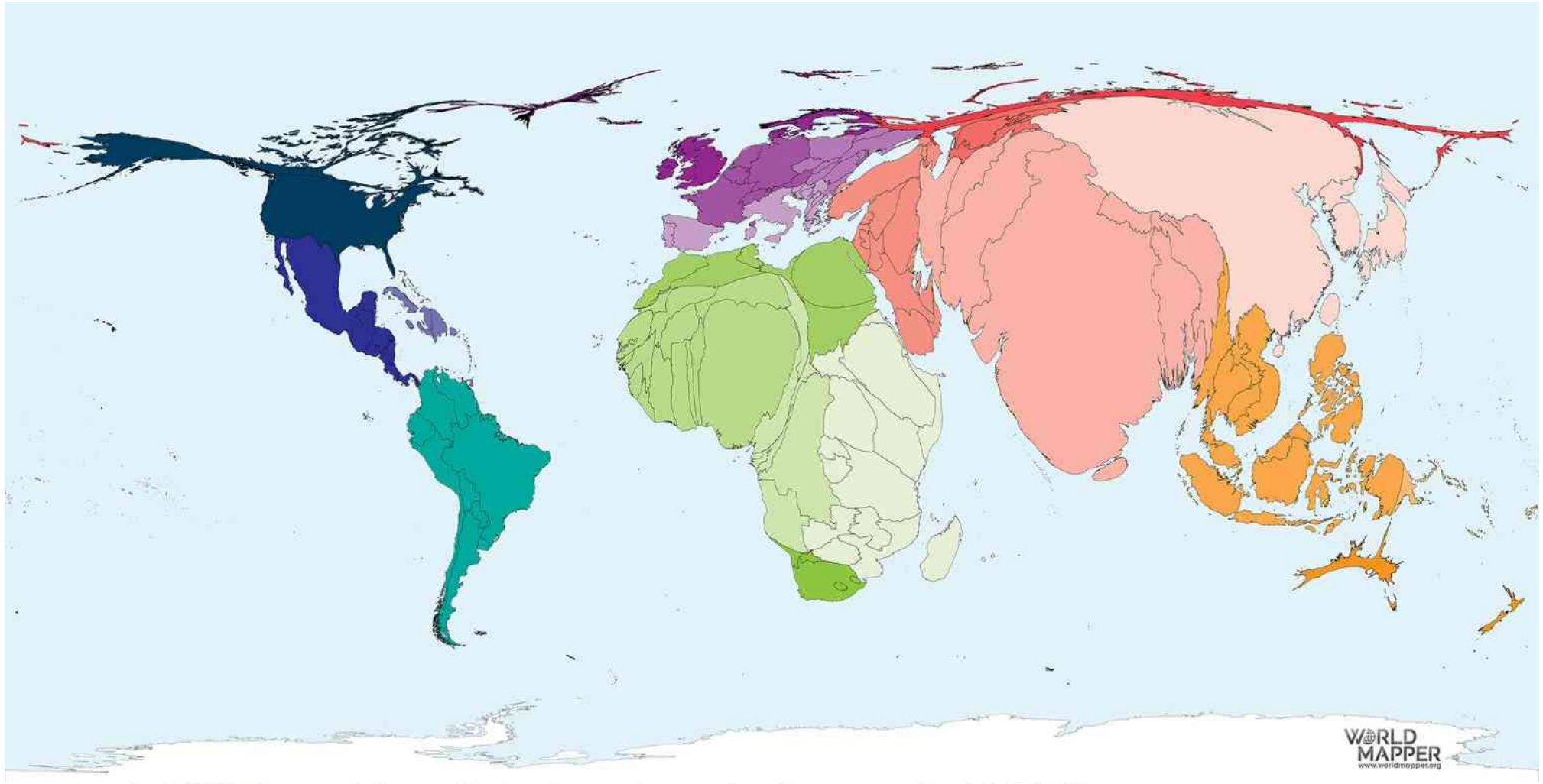
Africa · Asia-Pacific (exc. Japan) · Middle-East · FSU · South America · North America · Europe · Japan



Forecast for 2050 varies with time between 9 and 10 billions

Sources : UN / worldmapper

World Population (billions) - 2050



In 2050 the world population is estimated to have reached 9.8 billion.

India will then be the largest country by population (1.7 billion), followed by China (1.4 billion). The USA will no longer be the third-largest country in the world. This position will then be taken by Nigeria, with a population of 411 million.

Sources : UN / worldmapper 2026

Demography is key element in Energy Growth

World Urbanisation rate will grow from 58% in 2024 to 68% in 2050

	Compound average annual growth rate (%)			Population (million)			Urbanisation (share of population, %)		
	2000-24	2024-35	2024-50	2024	2035	2050	2024	2035	2050
North America	0.9	0.5	0.4	513	543	571	83	86	89
United States	0.7	0.4	0.4	340	357	374	84	86	89
C & S America	1.0	0.5	0.3	537	567	586	82	85	88
Brazil	0.9	0.3	0.1	217	224	223	88	90	92
Europe	0.3	-0.1	-0.1	692	687	668	76	80	84
European Union	0.2	-0.2	-0.3	448	438	420	76	79	84
Africa	2.5	2.1	1.9	1 494	1 884	2 434	45	51	59
Middle East	2.1	1.5	1.3	274	323	380	73	76	81
Eurasia	0.4	0.3	0.3	241	250	264	65	68	73
Russia	-0.1	-0.3	-0.2	143	138	135	76	79	83
Asia Pacific	1.0	0.4	0.3	4 340	4 549	4 670	52	57	64
China	0.5	-0.3	-0.5	1 415	1 369	1 256	66	74	80
India	1.3	0.8	0.6	1 441	1 568	1 669	37	43	53
Japan	-0.1	-0.6	-0.6	124	116	105	92	93	95
Southeast Asia	1.2	0.6	0.4	690	736	769	52	59	66
World	**1.2**	**0.8**	**0.6**	**8 091**	**8 805**	**9 572**	**58**	**62**	**68**

Notes: C & S America = Central and South America. See Annex C for composition of regional groupings.

Sources: OECD (2025); UN DESA (2018, 2024); World Bank (2025a); IEA databases and analysis.

Source: IEA WEO 2025/OECD/United Nations/World Bank

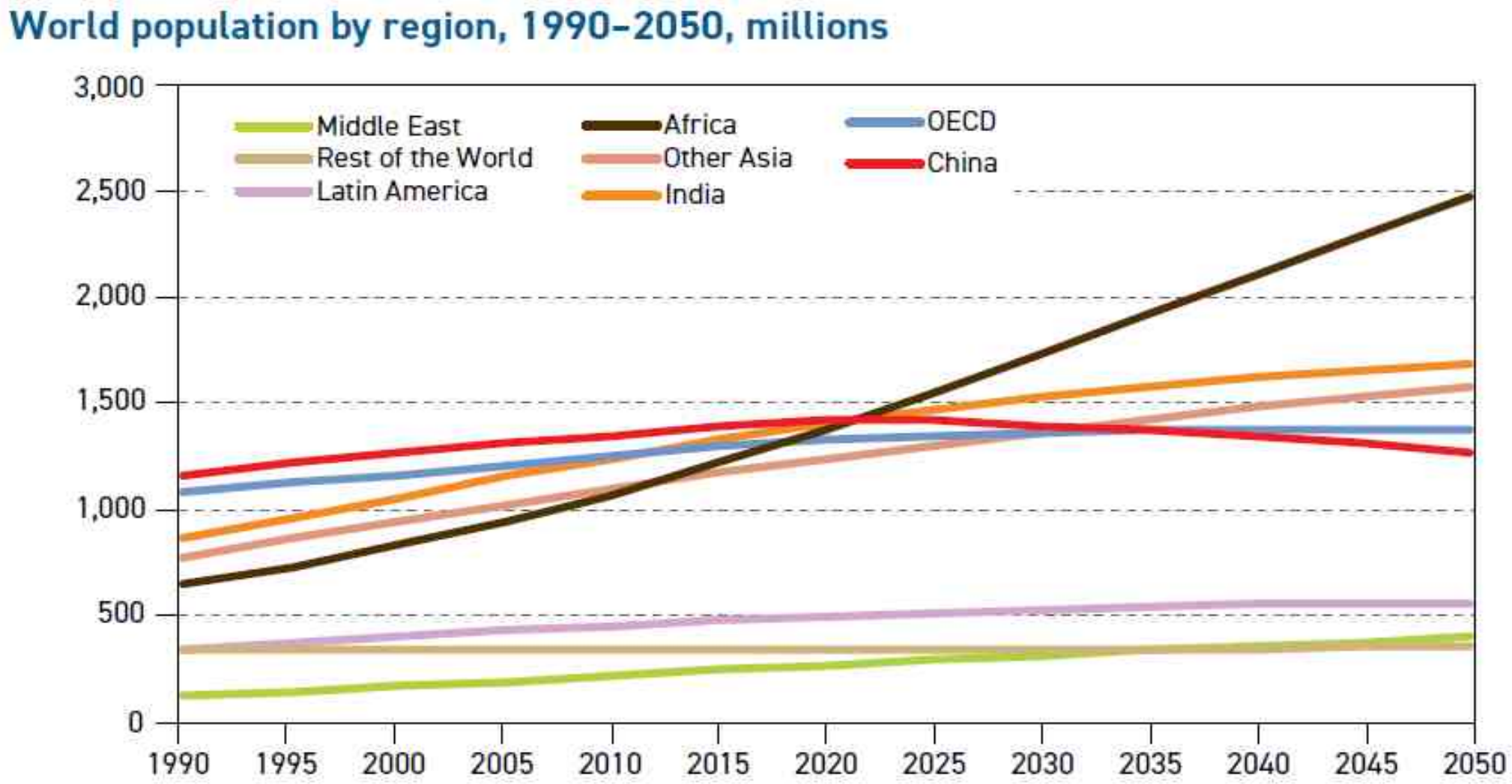
Demography is key element in Energy Growth

World population by region, millions

	2025	2030	2035	2040	2045	2050	Growth 2025–2050
OECD Americas	543	558	571	582	592	599	56
OECD Europe	590	590	589	587	583	577	–13
OECD Asia-Pacific	217	215	212	209	205	202	–15
OECD	**1,350**	**1,363**	**1,372**	**1,378**	**1,380**	**1,377**	**28**
China	1,416	1,398	1,373	1,343	1,306	1,260	–156
India	1,464	1,525	1,579	1,623	1,656	1,680	216
Other Asia	1,304	1,367	1,428	1,484	1,533	1,575	270
Latin America	513	527	540	549	555	558	45
Middle East	291	315	337	359	379	398	107
Africa	1,550	1,727	1,910	2,096	2,282	2,467	917
Russia	144	142	140	138	137	136	–8
Other Eurasia	152	157	161	165	169	173	21
Other Europe	48	47	45	44	42	41	–7
Non-OECD	**6,882**	**7,206**	**7,513**	**7,799**	**8,060**	**8,287**	**1,405**
World	**8,232**	**8,569**	**8,885**	**9,177**	**9,440**	**9,664**	**1,433**

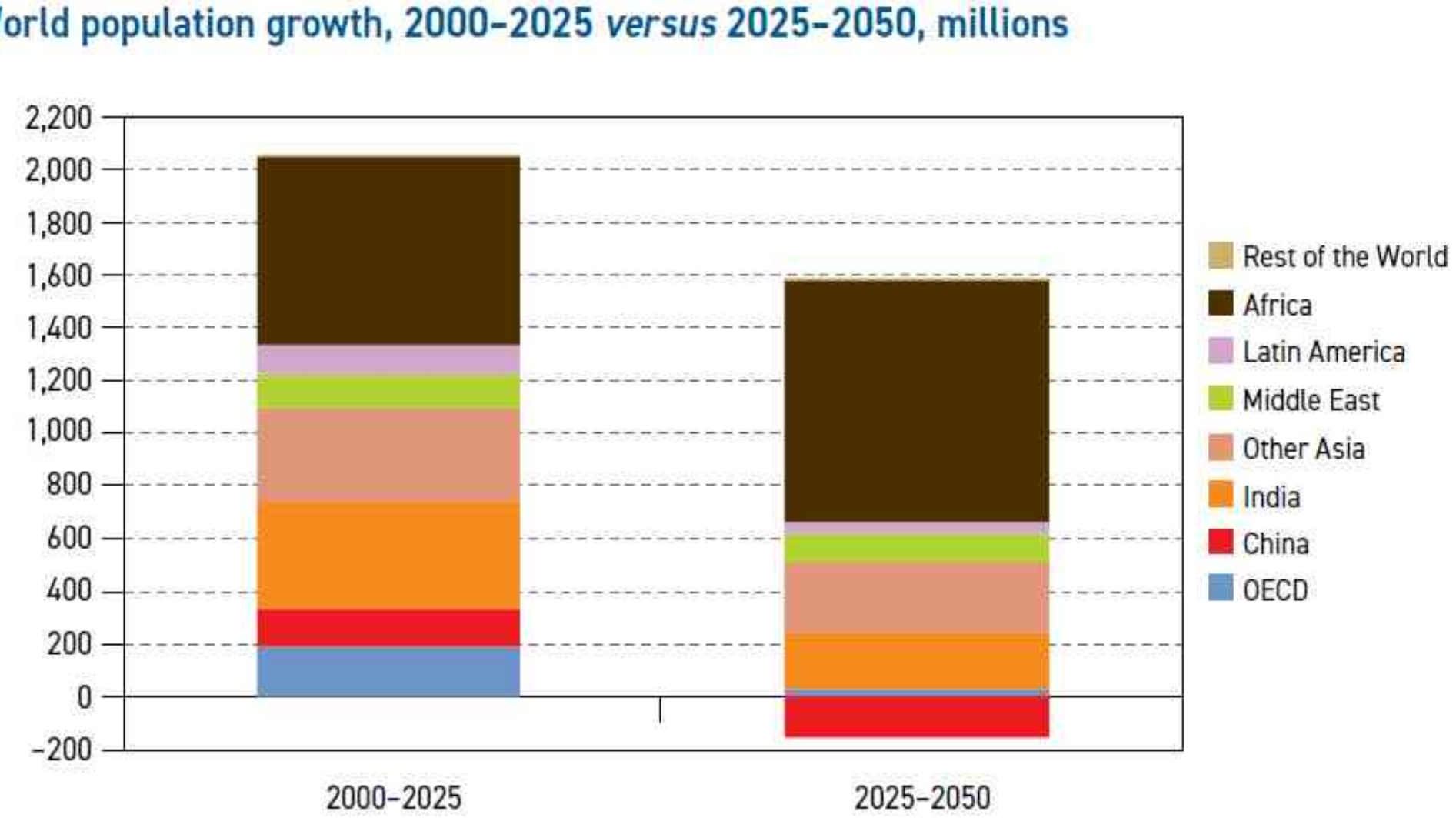
Source: United Nations/OPEC WOO 2026 – June 2026

World Population trends 1990 – 2050
Growth in Middle East & Africa, India, Asia, decline in China & OECD



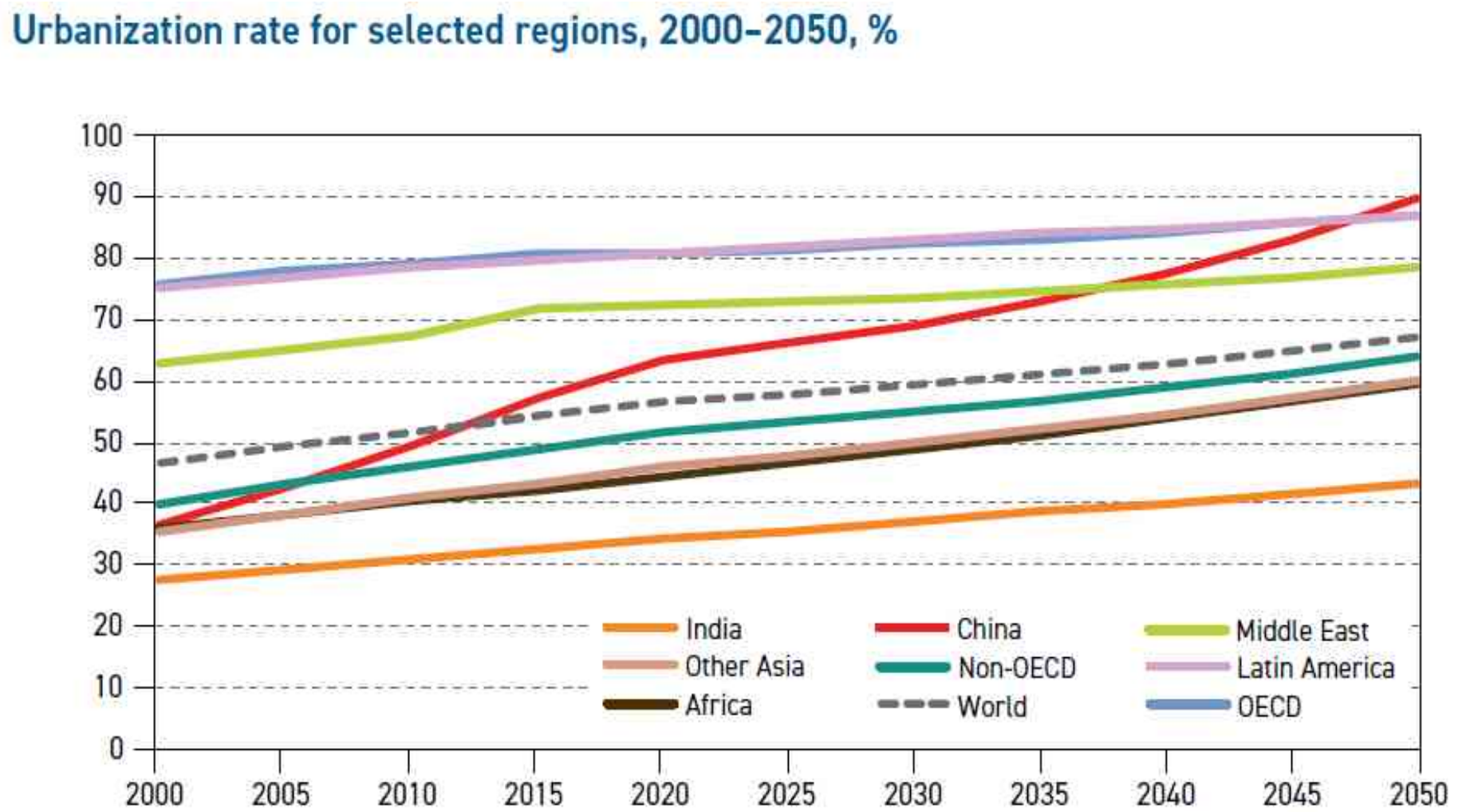
Source: United Nations/OPEC WOO 2026 – June 2026

Demography Growth will be less in the next decades than before



Source: United Nations/OPEC WOO 2026 – June 2026

Urbanization rate is increasing worldwide
From 47% in 2000 to # 70% in 2050



Source: United Nations/OPEC WOO 2026 – June 2026

World Population, Living Standards and Energy



Carbon-based Energy represents
80% of the World Primary Energy Consumption

7

Global Energy Growth
Scenarios from various organizations

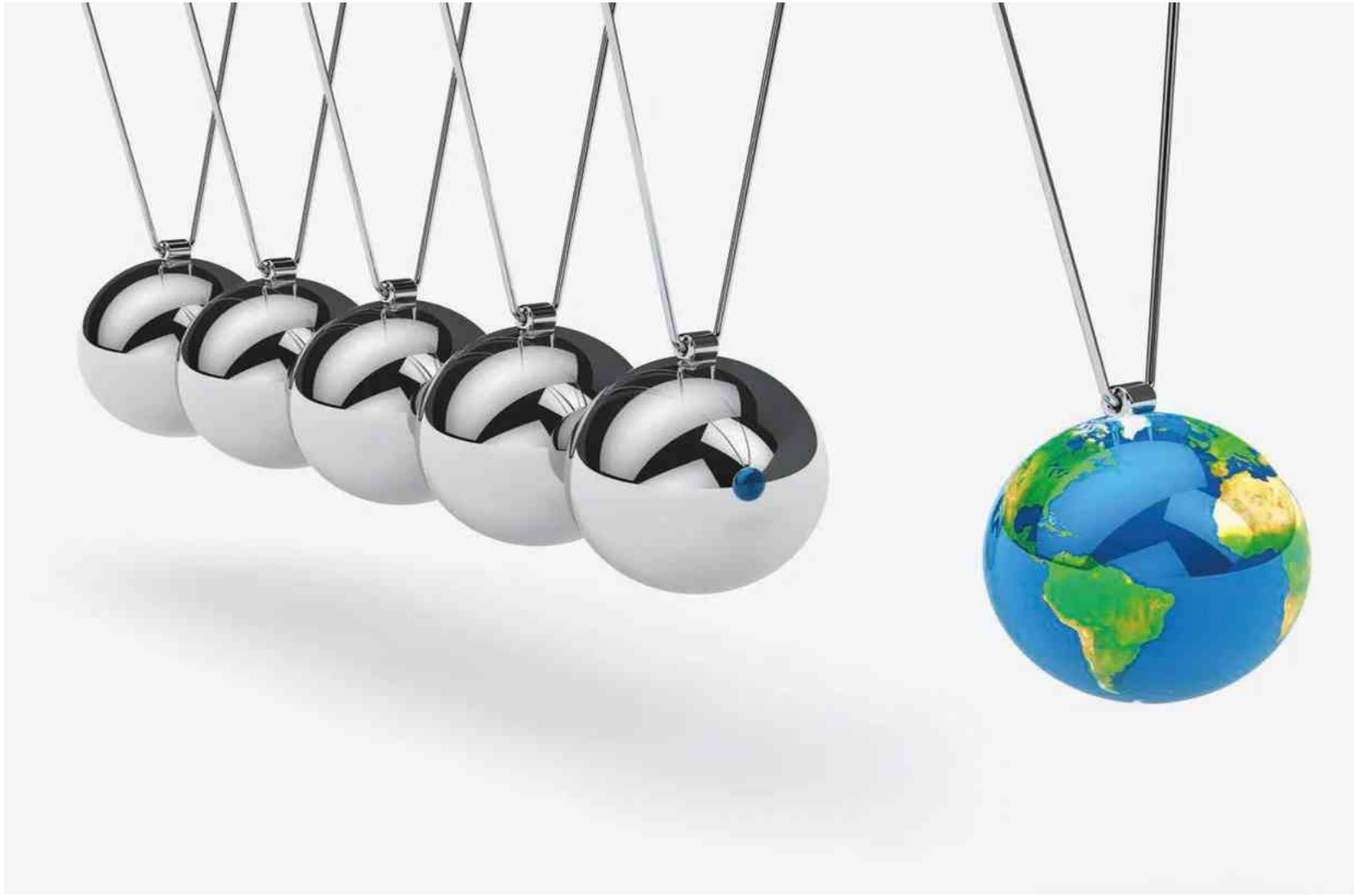
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Global Energy Growth – Scenarios from various organizations



Global Energy Demand Growth
Scenarios for the Future from different Entities - Similar Visions
(When not specified, Scenarios which are presented represent the Business as Usual Scenario)

Preliminary remark:

In the following, the scenarios from the various organizations have been established taking into account the year 2020 Covid-19 sanitary crisis economic consequences (impacting mainly year 2020 & 2021) as well as the Ukraine/Russia war with its impacts on the Energy world.

Also, the new policies dictated by Trump administration in the US have an impact.

In the following:

- TotalEnergies Energy Outlook 2025
- A new momentum for Energy Companies - Different strategies for Majors
- International Energy Agency – World Energy Outlook 2025
- ExxonMobil Global Outlook 2025
- BP Energy Outlook 2025
- US Energy Information Administration – International Energy - Outlook 2023 (No updates in 2024 & 2025)
- OPEC World Oil Outlook 2025
- IRENA World Energy Transition Outlook 2024
- Bloomberg NEF New Energy Outlook 2025

TotalEnergies Energy Outlook November 2025

In order to cope with the 2°C/1,5°C objective, a Rupture Scenario is necessary!



TotalEnergies

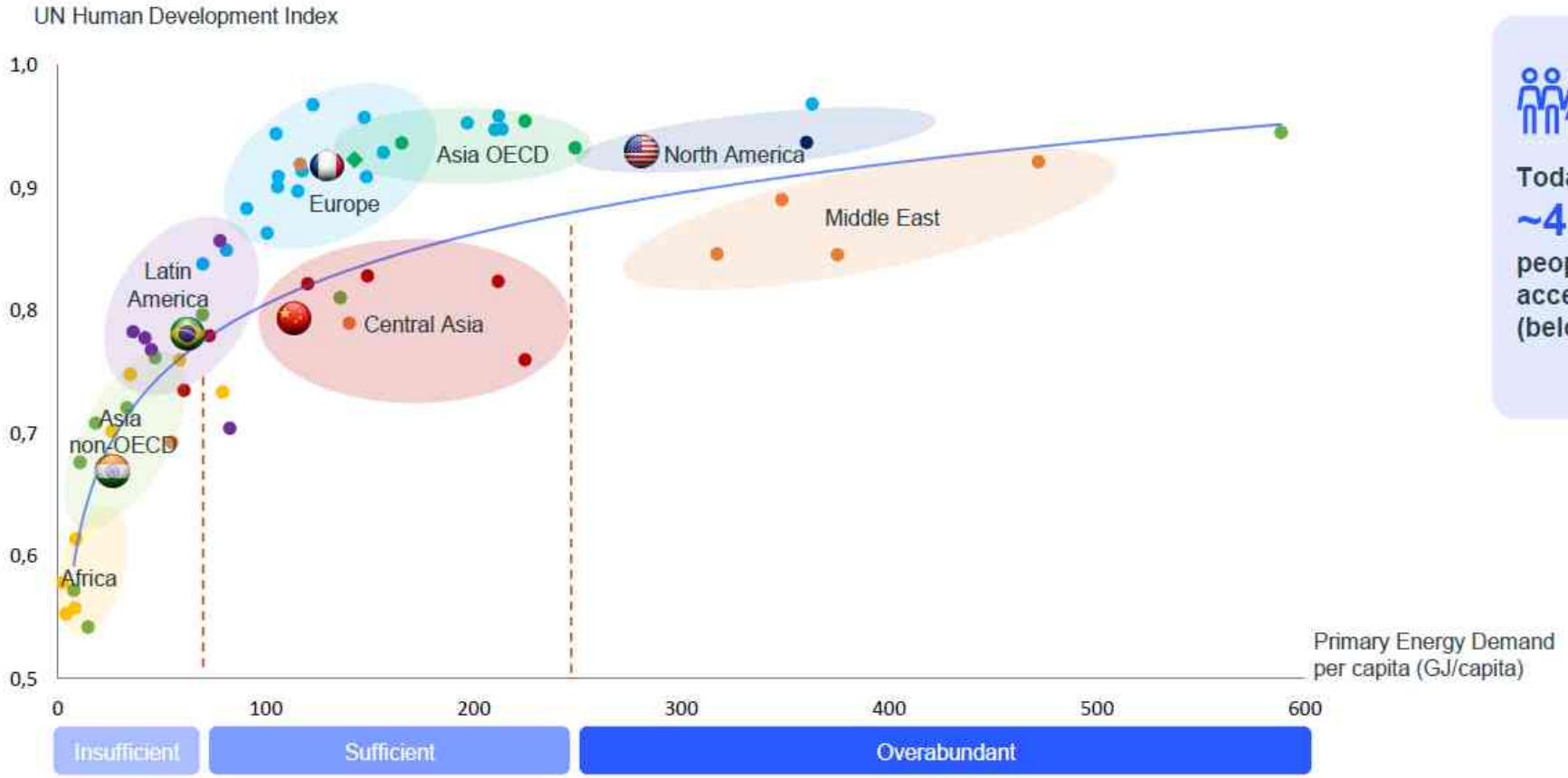
TotalEnergies Energy Outlook 2025

November 4th, 2025

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

Energy access is essential to human development



Today
~4.6 bn
people lack access to energy (below ~70 GJ/capita)

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

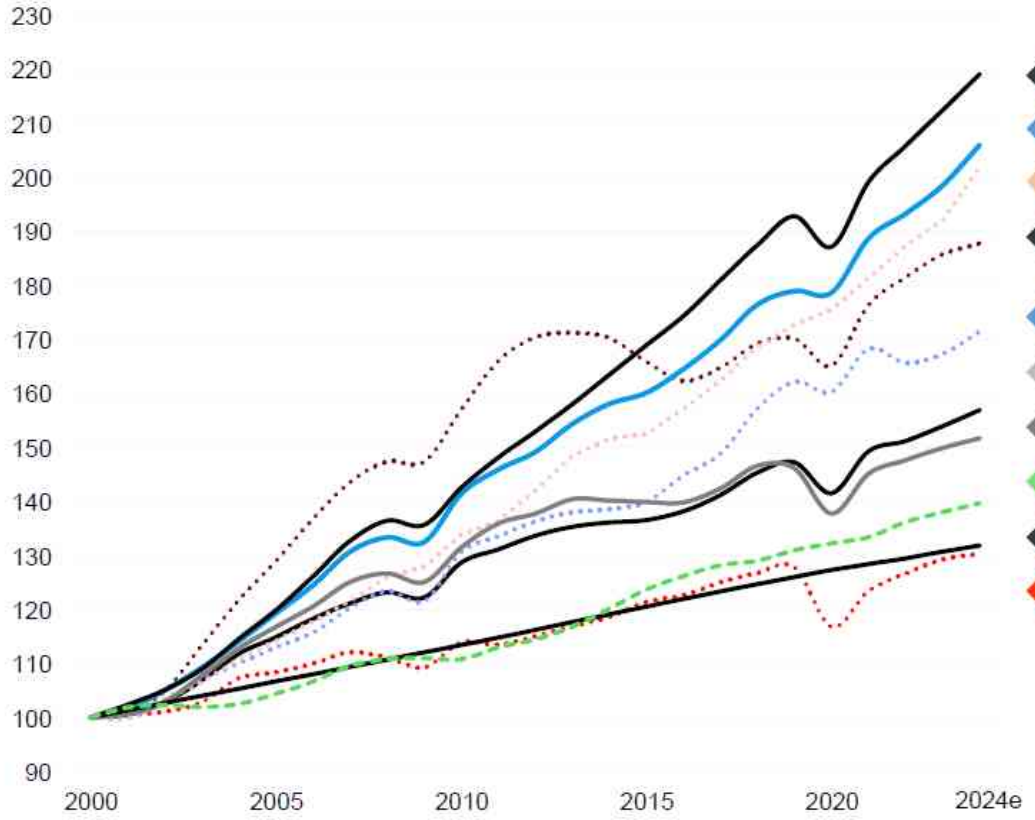
ENERGY AND EMISSIONS

Evolution of global energy indicators since 2000

Primary energy demand grows slower than GDP as CO_2 emissions start to decouple

Evolution since 2000

2000=100



Compound Annual Growth Rates (CAGR)

	2000-2024e	2023-2024e
GDP	3.3%	3.2%
Electricity demand	3.1%	4.3%
Renewable energy supply	3.0%	5.8%
Coal demand	2.7%	1.0%
Natural gas demand	2.3%	2.7%
Total primary energy demand	1.9%	2.2%
CO_2 emissions	1.7%	0.8%
Energy efficiency	1.4%	1.0%
Population	1.2%	0.9%
Oil products demand	1.1%	0.8%

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

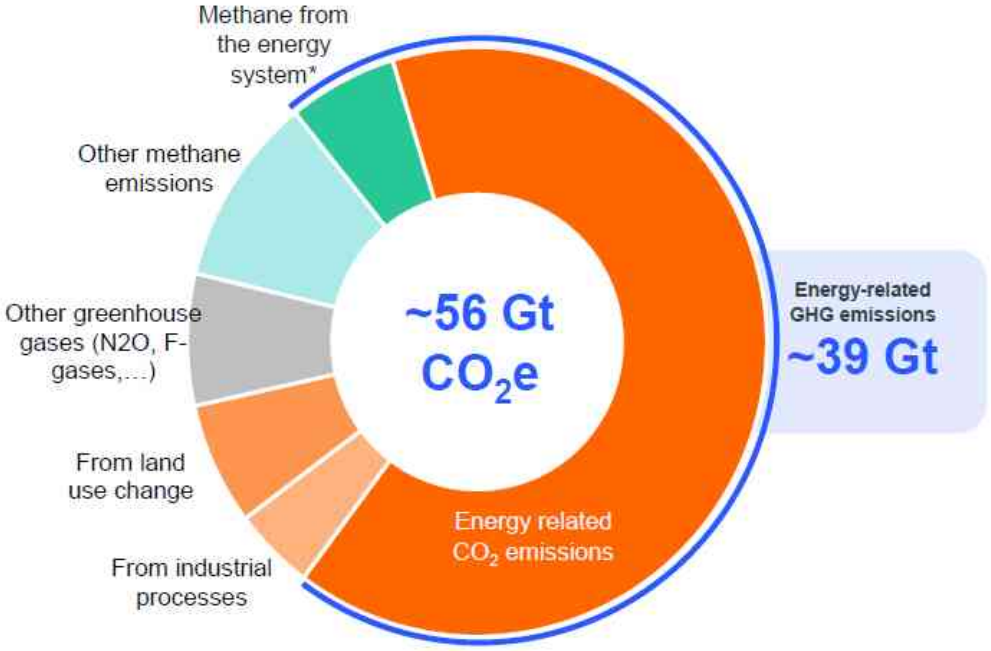
ENERGY AND EMISSIONS

Global and Energy-related GHG emissions

Coal in electricity generation is the single largest source of emissions

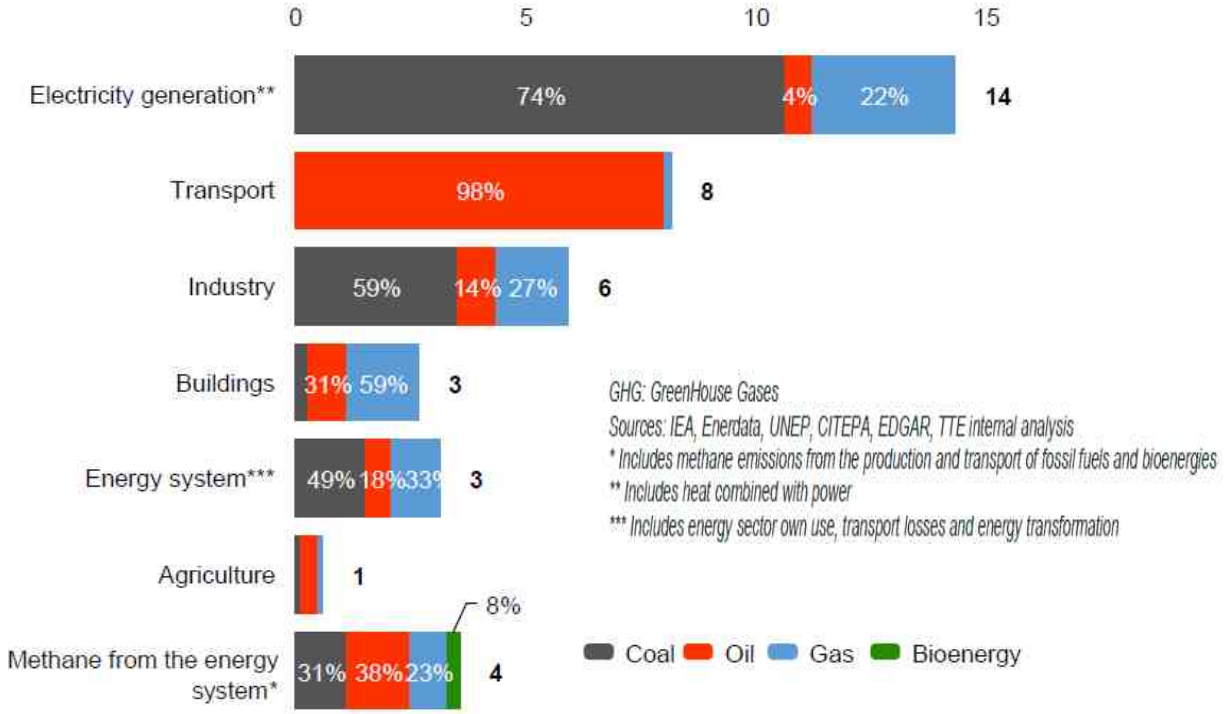
Global anthropogenic GHG emissions in 2023

$GtCO_2e$



Global energy-related GHG emissions in 2023

$GtCO_2e$



TotalEnergies Energy Outlook November 2025

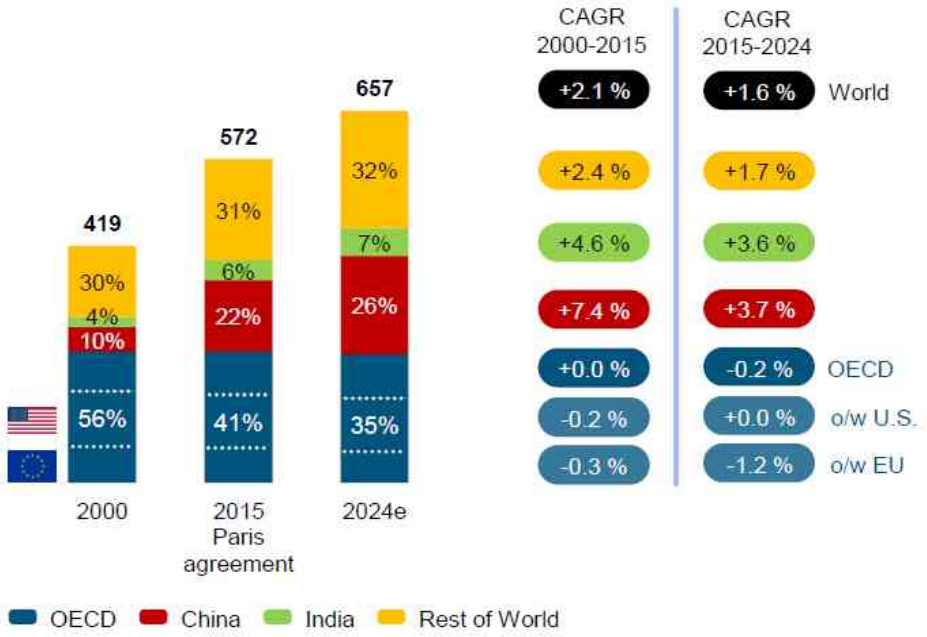
ENERGY AND EMISSIONS

Recent trends across regions

Emissions have grown less than energy demand since 2015

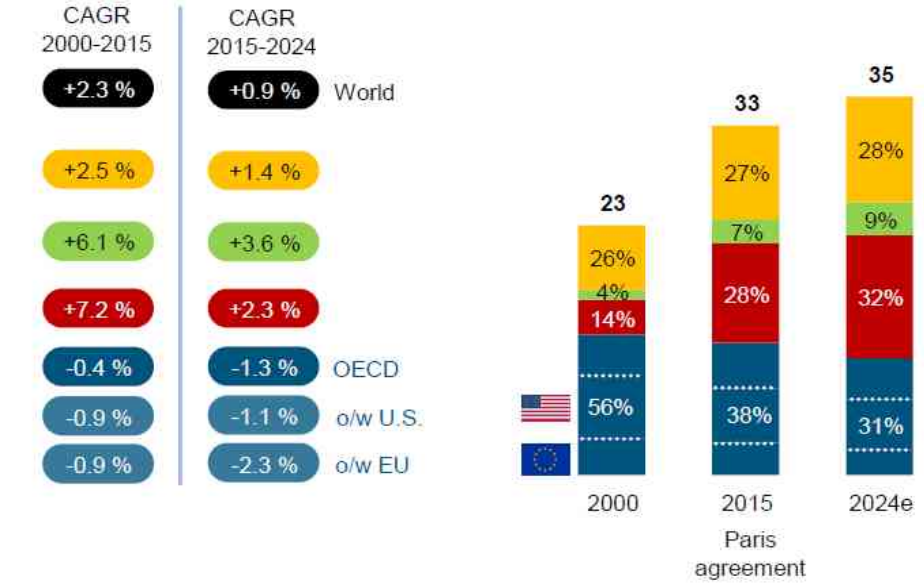
Total Primary Energy Demand (TPED) growth

EJ



Energy-related CO_2 emissions evolution

$GtCO_2$



Energy demand in OECD countries has broadly remained flat since 2000, while China, India, and the Rest of World have grown from less than half to almost two-thirds of global energy demand.

Emissions growth has slowed markedly since 2015. The OECD share of global emissions has declined from more than half in 2000 to around one-third in 2024.

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

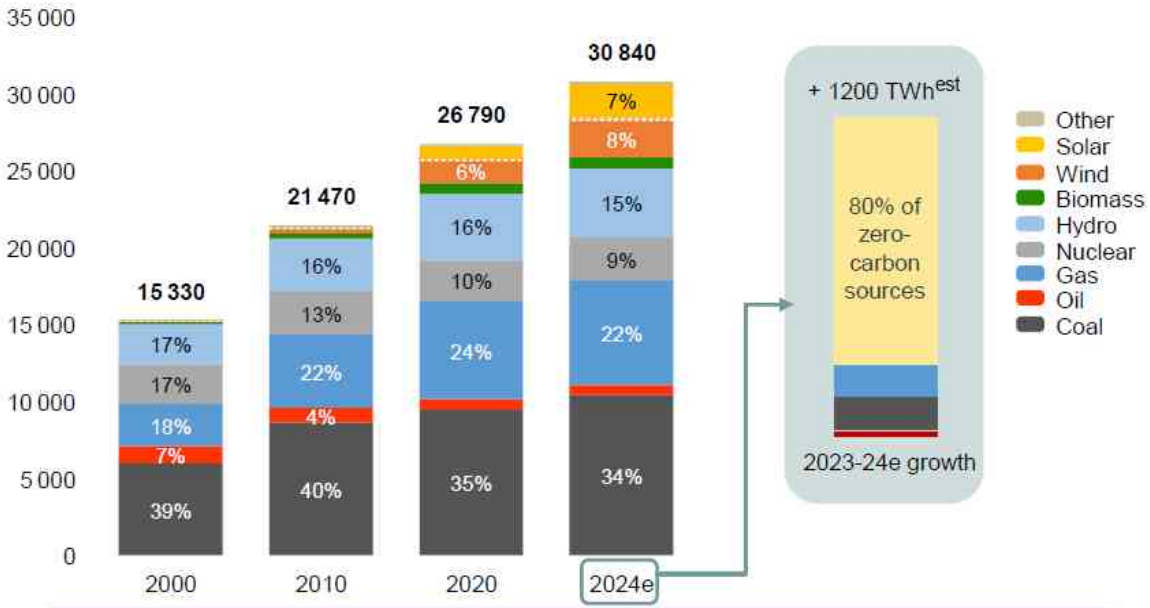
TECHNOLOGY

Electricity generation mix

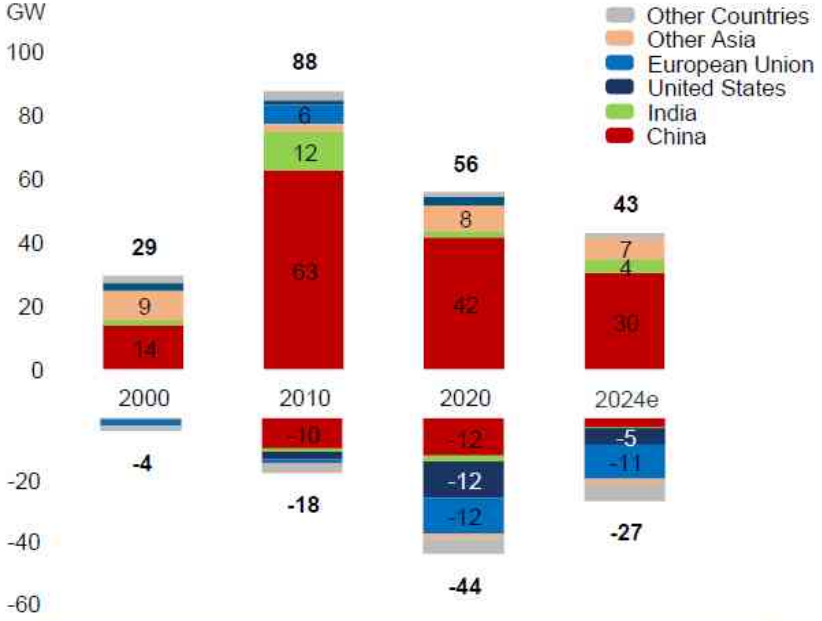
Energy security and affordability supported by coal in emerging countries, with CO_2 intensity reduction driven by renewables and increased coal efficiency

World electricity generation by fuel*

TWh



Coal-fired generation capacity annual additions and retirements***



2020-2024: Power generation emissions increase from 8.1 to 14.6 Gt CO_2, with carbon intensity falling from ~530 to ~470 g CO_2e/kWh**

More efficient new coal power plants: average carbon intensity from ~940 to ~900 gCO_2e/kWh since 2000 - Load factor from 62% to 51%**

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

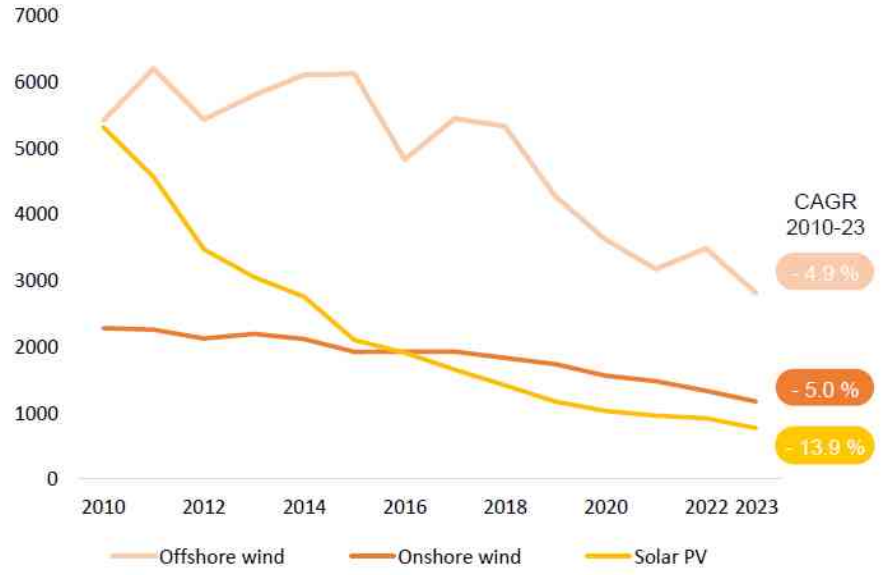
TECHNOLOGY

Cost of producing 24/7 reliable electricity

While costs have fallen sharply, solar PV remains more expensive than natural gas for delivering 24/7 reliable electricity

Cost of wind and solar capacity*

$/kW (2010-2023)

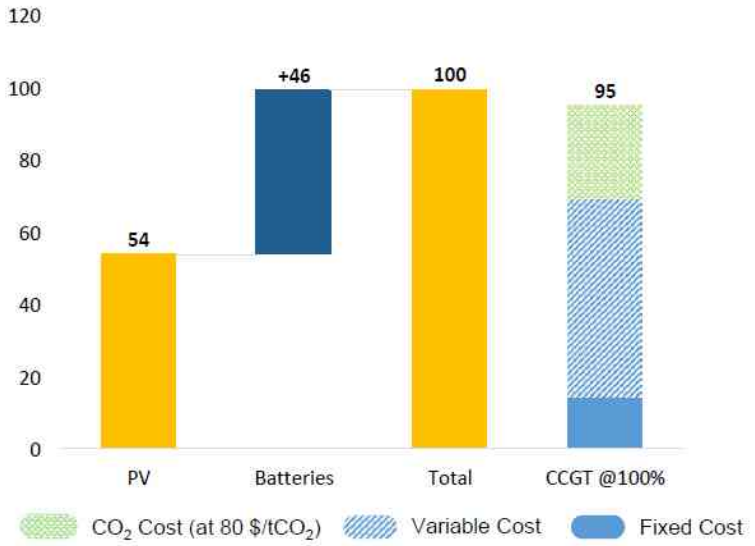


Note: The total installed costs represent the total cost of completing a project (including project development costs, grid connection, equipment, installation, civil engineering, contingency, etc.)

Cost of a 24/7 reliable electricity – EU example**

PV (20%) + Batteries (80%)

$/MWh



CO_2 pricing is essential for decarbonizing the electricity grid

Note: Cost estimates refer to newly installed capacities in EU27 countries in 2025

*Sources: * IRENA, "Renewable Power Gene*

*** Internal calculations based on a* Directetproche Frogdp-web01 130929 *enzie, IHS, and BNEF*

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

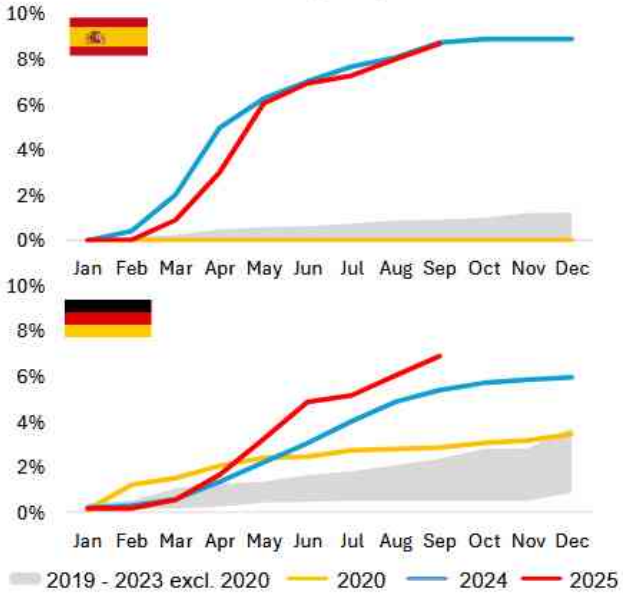
TECHNOLOGY

System transformation required to integrate renewables

Effective renewables deployment now limited by the absorption capacity of the electricity system

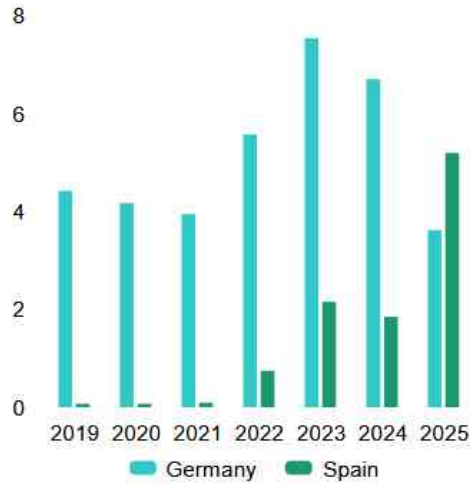
Frequency of negative electricity prices*

Share of annual hours with negative prices



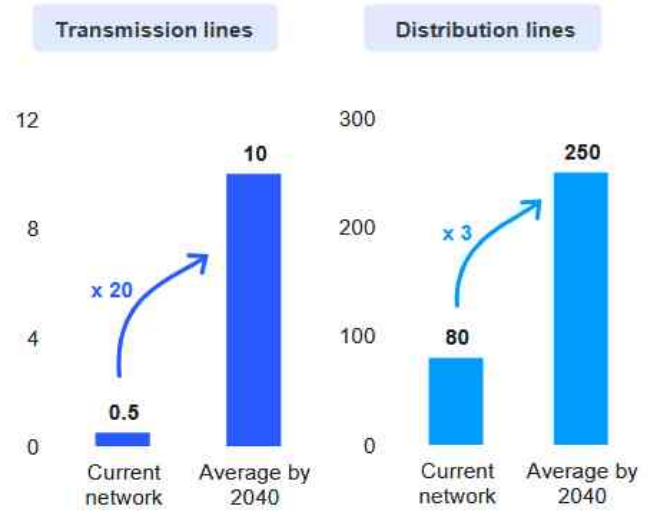
Annual variable renewables technical curtailment**

TWh



Annual network buildout required for Europe's energy transition***

Thousand kilometer of new lines per year



Massive deployment of demand flexibility and storage capacities is needed

Expansion of transmission and distribution networks, along with transformation in planning and operation, is required

*Sources: * ENTSO-E transparency platform, TTE internal analysis*
*** IEA, Renewables 2025 (Variable renewables refer to solar PV and wind) and TTE internal analysis*
**** Compass Lexecon for CurrENT (2024) based on ENTSO-E Distributed Energy Scenario, BNEF ETS (2025), TTE internal analysis*

TotalEnergies Energy Outlook November 2025

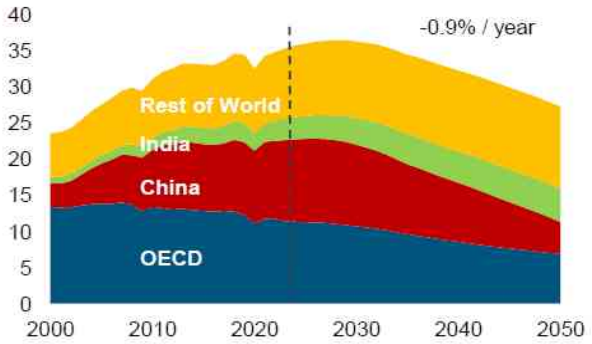
THREE SCENARIOS

Comparing emission pathways across the scenarios

Trends

Emissions ($GtCO_2$*)

Reference: assuming recent trends in policies and technologies hold



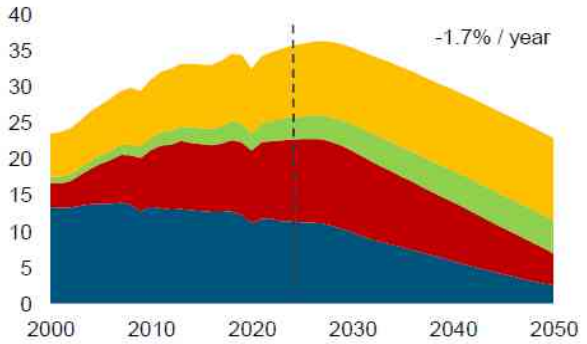
If current trends hold, China advances toward its 2060 goal while OECD countries reduce emissions but fall short of their 2050 Net Zero targets. India and the Rest of World continue to develop with limited decarbonization

~ +2.6-2.8°C** by 2100

Momentum

Emissions ($GtCO_2$*)

Goal-driven: OECD near Net Zero 50, China near Net Zero 60



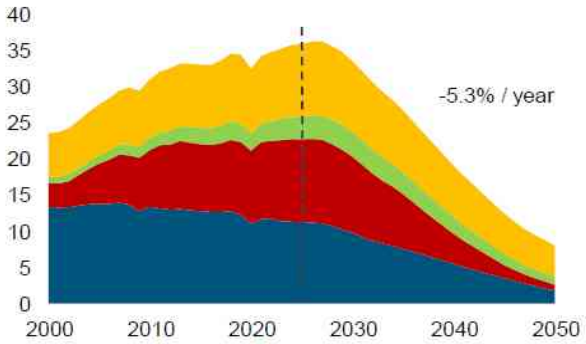
OECD countries are closer to their 2050 Net Zero targets, and China to its 2060 goal. In India and the Rest of World, nearly half of energy demand growth is met by low-carbon sources

~ +2.2-2.4°C** by 2100

Rupture

Emissions ($GtCO_2$*)

Goal-driven: well-below 2°C



Geopolitical fragmentation and tensions make this scenario out of reach as it would require a stronger international cooperation to stay well below 2°C: OECD countries and China need to support low-carbon growth in emerging economies

~ +1.7-1.9°C** by 2100

Rest of World India China OECD

Our collective challenge is to accelerate global decarbonization without compromising growth in emerging and developing economies

* CO_2 emissions related to energy combustion

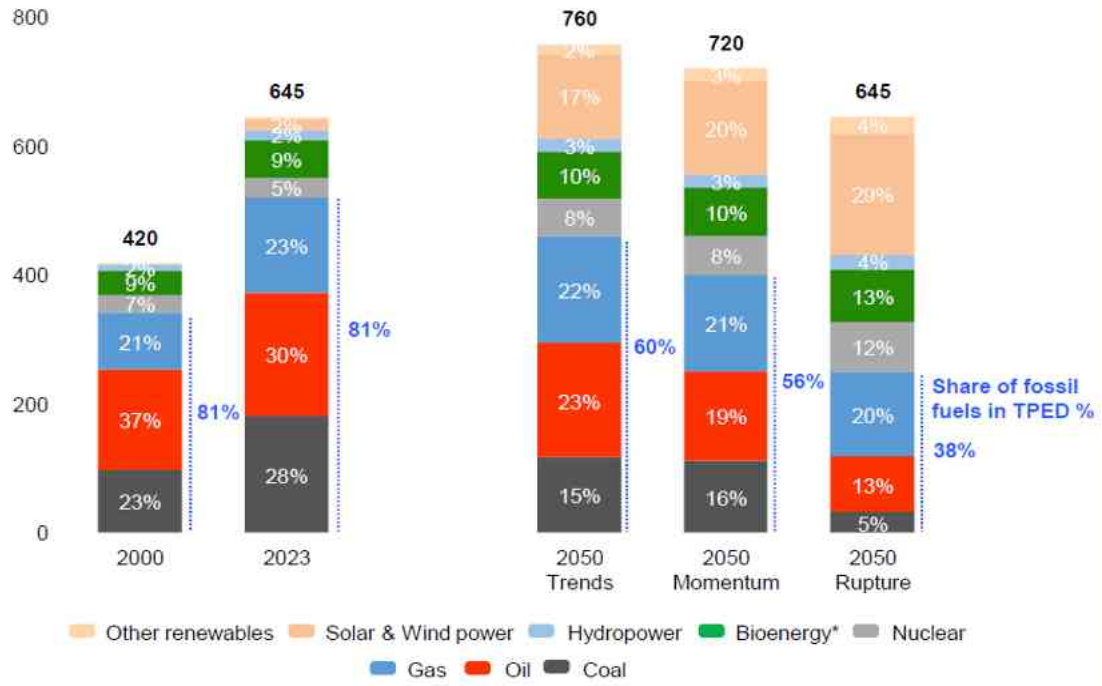
** Temperature increases estimated at P66-P83, evaluation conducted by MIT

TotalEnergies Energy Outlook November 2025

THREE SCENARIOS

Primary Energy Demand in 2050

From sustained transition to global transformation



The *Trends* scenario assumes that Coal demand gradually declines, particularly in China's power sector. Governments policies supporting electric vehicle adoption remain in place (e.g., ICE 2035 ban in the EU).

The *Momentum* scenario assumes the 2050 targets set by the OECD countries and the 2060 targets set by China are met.

The *Rupture* scenario assumes significantly enhanced multilateral cooperation towards global decarbonization. Geopolitical fragmentation and tensions make this scenario out of reach.

Variable renewables expected to play a central role in electricity generation, which requires:

- a profound transformation of the operations of electricity systems
- massive investment in electricity grids

Gas maintains a stable share in the TPED, notably as an energy source in industry.

Source: Enerdata, TTE internal analysis
** Bioenergy includes biomass, waste, biofuels and biogas*

Source: TotalEnergies Energy Outlook November 2025

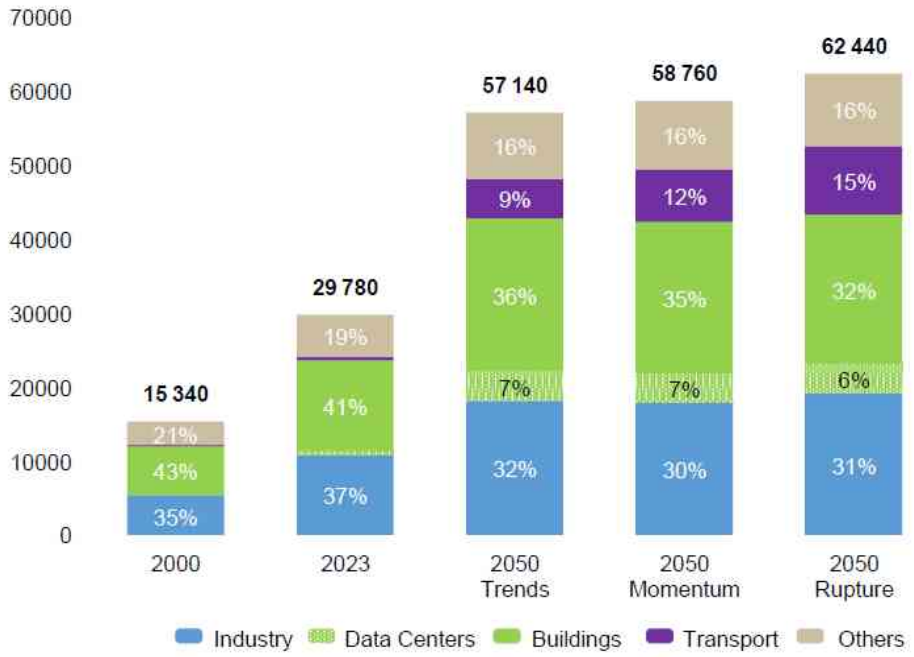
TotalEnergies Energy Outlook November 2025

COMMON FEATURES

Electricity demand by sectors

In all scenarios, electricity demand increases, driven by new uses

Electricity demand evolution by sectors
TWh, excluding H_2 production use



TotalEnergies

Historically, electricity demand has been largely driven by GDP. In the future, new uses, in addition to economic growth, will further increase demand.

Transport : +5 000 TWh in *Trends*, mostly in China, Europe, and to a lesser extent the U.S.

Buildings:
+3 500 TWh for data centers, mainly in the U.S. and China
+2 700 TWh for cooling, mainly in India, the Middle East and Indonesia

In *Rupture*, electrification advances further across all sectors reaching 35% in industry compared to 29% in *Trends*

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

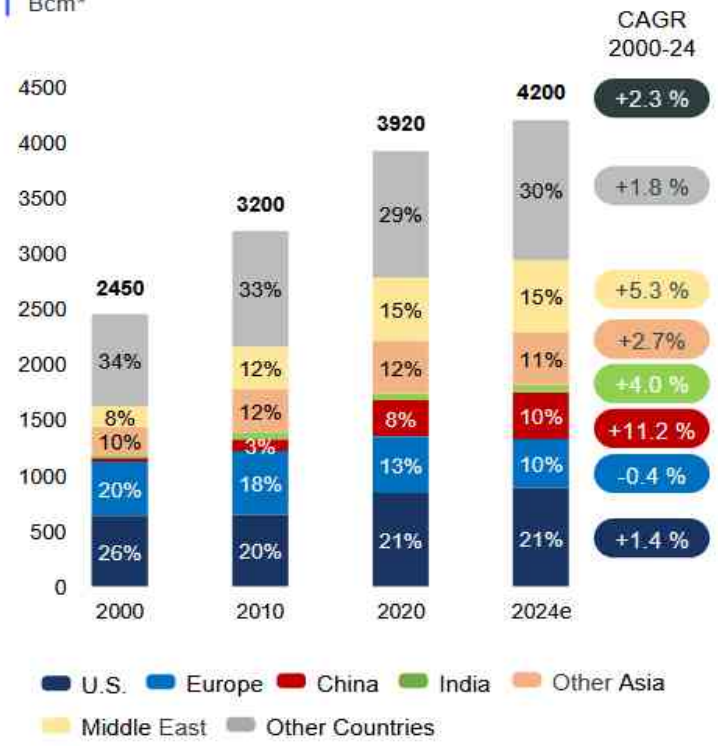
COMMON FEATURES

Gas demand growth over the last 20 years

Gas demand has increased across all regions and sectors, except in Europe

Gas demand by regions

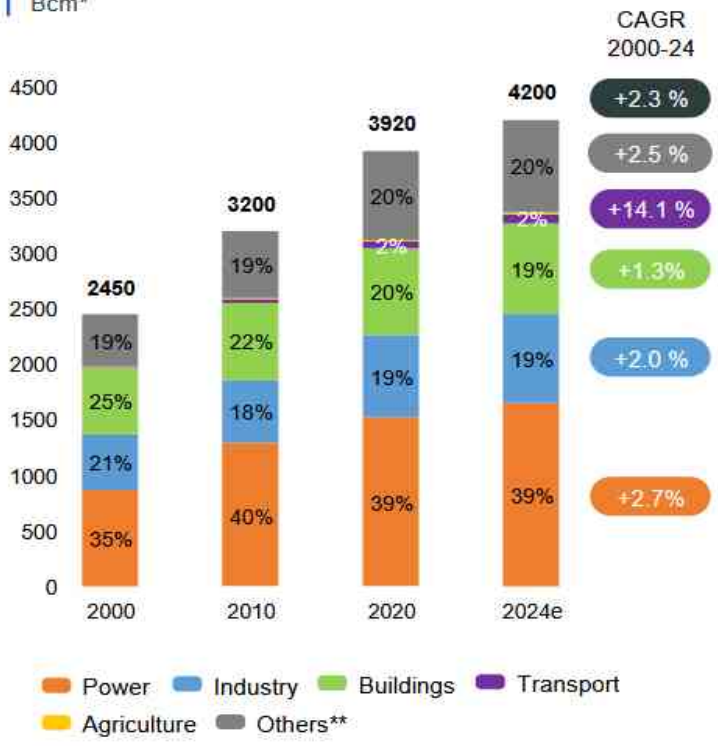
Bcm*



Recent global gas demand growth mainly driven by China and the Middle East

Gas demand by sectors

Bcm*



Recent gas demand growth led by electricity generation, in particular coal-to-gas switching in the U.S., and by industrial use

** Bcm normalized at 36 MJ/m³*
*** Energy system uses (3/4), and non-energy uses (1/4)*

Source: TotalEnergies Energy Outlook November 2025

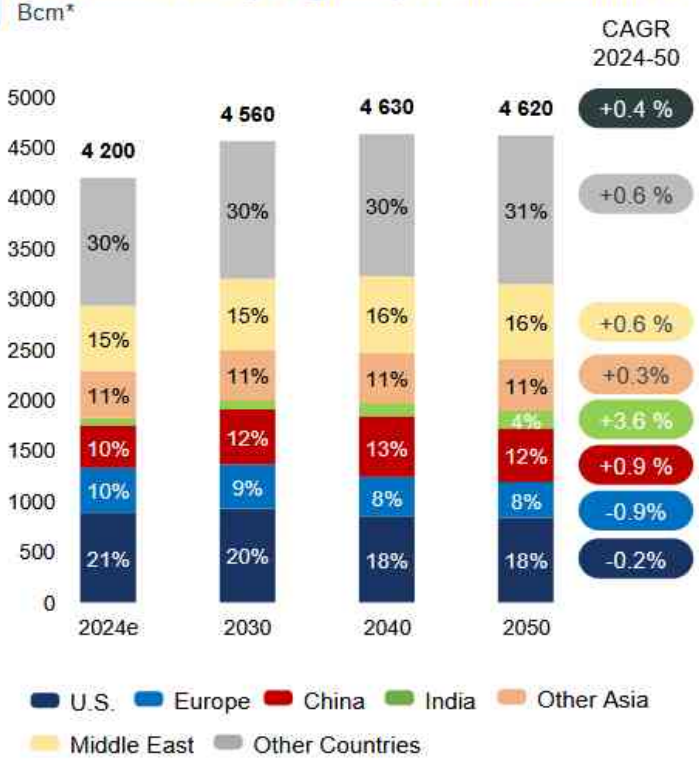
TotalEnergies Energy Outlook November 2025

COMMON FEATURES

Gas demand growth over the next 25 years

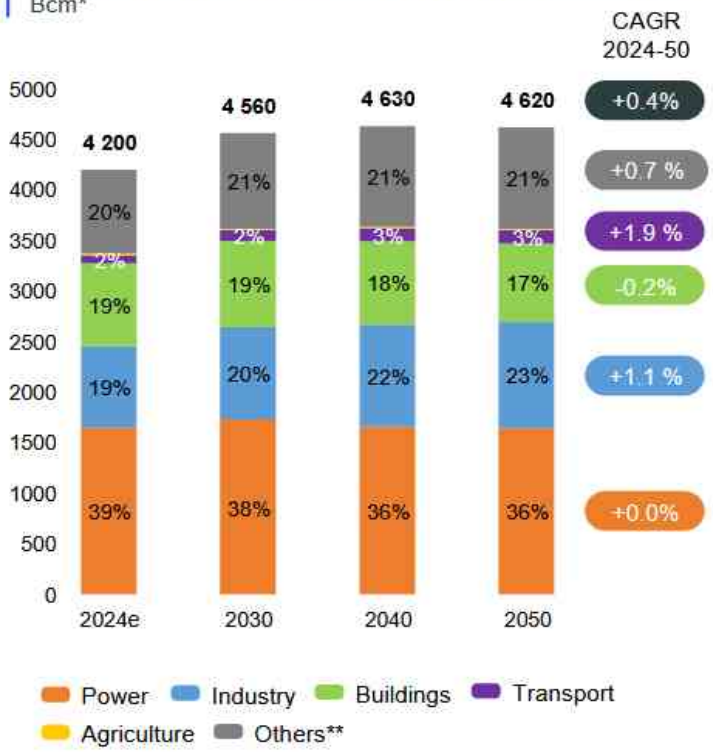
Demand is expected to grow until the 2040s, then plateau

Gas demand by regions, *Trends* scenario



Expected global gas demand growth underpinned by China, India and the Rest of World, offsetting a slight decline in OECD countries

Gas demand by sectors, *Trends* Scenario



Expected gas demand growth led by industry, supported by economic growth and coal-to-gas switching to reduce air pollution

** Bcm normalized at 36 MJ/m³*
*** Energy system uses (3/4), and non-energy uses (1/4)*

Source: TotalEnergies Energy Outlook November 2025

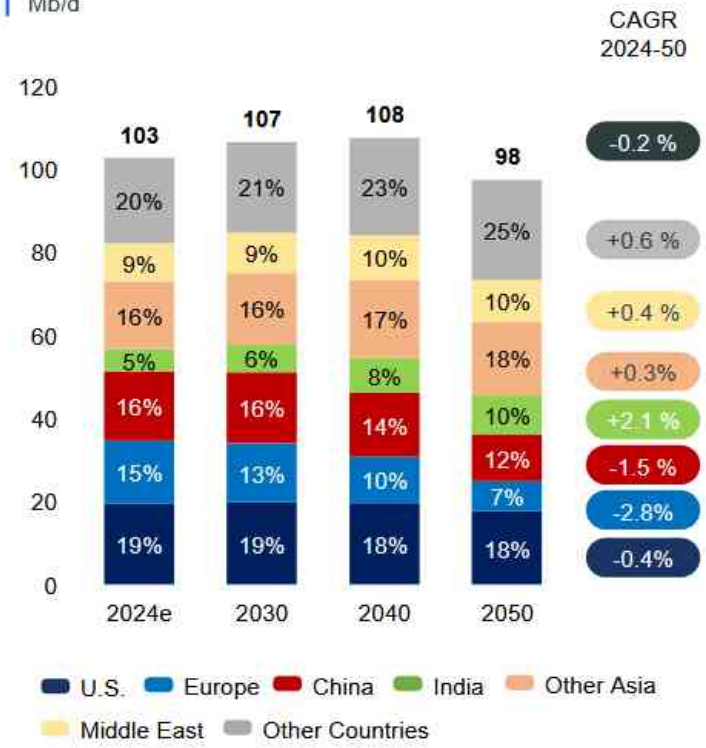
TotalEnergies Energy Outlook November 2025

COMMON FEATURES

Oil products demand growth over the next 25 years

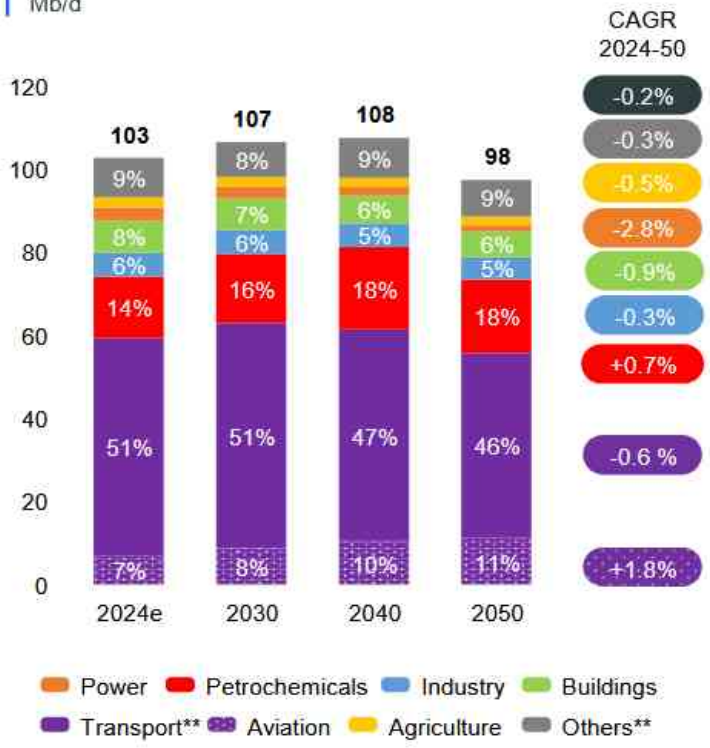
Demand is expected to remain stable until 2040, then slowly decline

Oil products* demand by regions, *Trends* scenario



India is the primary growth driver of global demand, along with the Middle East and Other Asia, offsetting decline in Europe and China

Oil products* demand by sectors, *Trends* scenario



Demand from aviation and petrochemicals grows over the period. Post-2040, EV penetration leads to a slow decline

** Oil products include all refined products and biofuels*
*** Transport : Aviation excluded; Others: Non-energy uses (2/3), and energy system uses (1/3)*

Source: TotalEnergies Energy Outlook November 2025

TotalEnergies Energy Outlook November 2025

THREE SCENARIOS

From *Trends* to *Momentum* and *Rupture* – in 2050

All decarbonization levers would have to be pushed further to remain well-below 2°C

	Trends	Momentum	Rupture
Strong electrification of end-use	~33% of final demand	~36%	~43%
Deep decarbonization of electricity grid	30 740 TWh* (~54% of power generation)	33 100 TWh* (~56%)	40 500 TWh* (~65%)
Energy efficiency acceleration**	+1.9%/yr 2023-50	+2.1%/yr	+2.5%/yr
Sustainable mobility	~44% Zero Emission Vehicles in light vehicles fleet	~55%	~73%
	Sustainable aviation fuels (SAF) @ ~8% of demand	SAF @ ~24%	SAF @ ~54% (~41% biofuels,~13% e-Fuels)
Gas going greener	~10% green gases*** in gas supply	~14%	~23%
Increasing plastics' circularity	~18% of gross demand coming from recycled materials	~30%	~40%
CCS to abate remaining emissions	~1.6 Gt (~6% CO_2 emissions)	~2.8 Gt (~11%)	~5.4 Gt (~40%)
Support to India and Rest of World	~30% of non-fossil sources in primary energy demand (vs. ~44% in OECD countries)	~30% (vs. ~64% in OECD countries)	~54% (vs. ~64% in OECD countries)

** Solar & wind – excluding renewable electricity generation for green H_2*
*** Energy efficiency is defined here as the decrease in primary energy required to produce 1$ of GDP*
**** Green gases include biogas and H_2, excluding H_2 share for liquid e-fuels production*

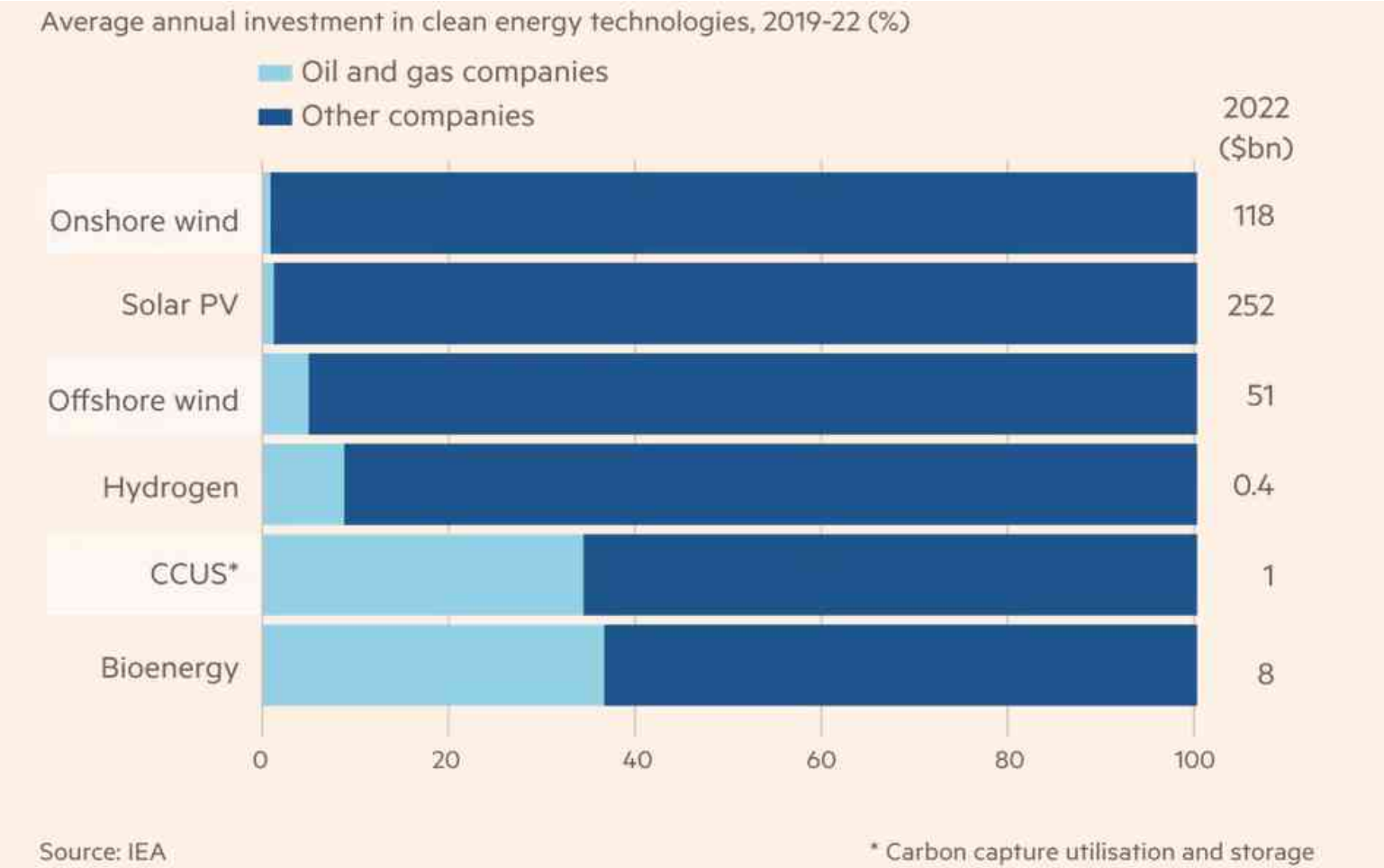
Source: TotalEnergies Energy Outlook November 2025



A new momentum for Energy Companies

Different strategies for Majors

Oil & Gas Investments in Clean Energy Technologies – Average 2019-2022



Investments Wind, Solar & Bioenergy	Yearly aver. 2019-2022
Total World	# 430 G$
Oil & Gas companies	# 9 G$
Share	2,1%

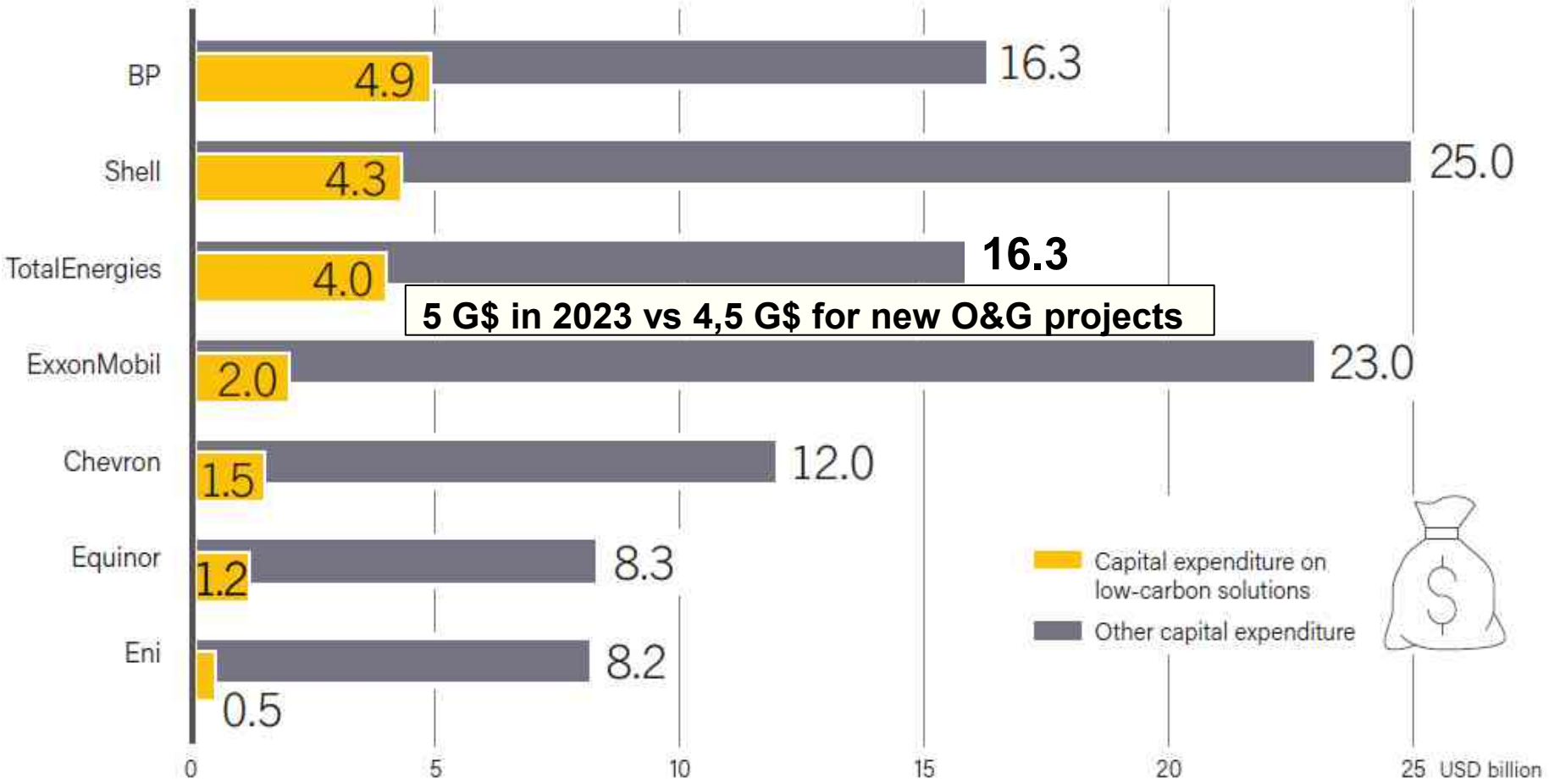
Low Carbon Invest. Incl. Power & Grids	Year 2022
Total World	# 1750 G$
Oil & Gas companies	# 18 G$
Share	1,0%

Worldwide, a lot of specialized companies of various sizes are involved in Renewables. O&G companies have now been involved for some years. Their contribution will be more and more important in the decades to come

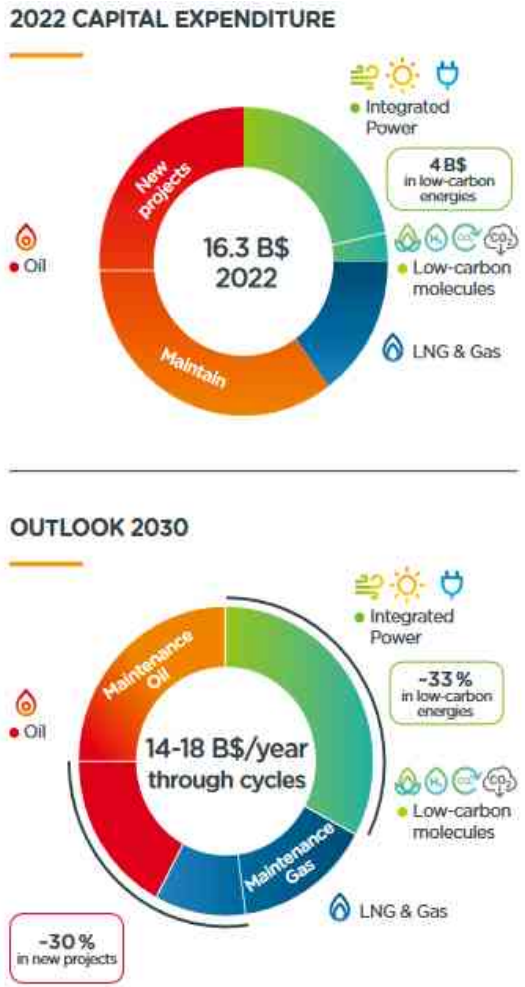
Source: Financial Times/IEA 2023
IEA 2023 & Annual Reports

Investments in Renewable Energy & Power made by 7 IOC in 2022 (# 18 G$ vs 110 G$ total Capex = 16%)

In 2023, TotalEnergies plans to invest 5 G$ in Low Carbon Energy vs 4,5 G$ for new O&G projects excluding maintenance



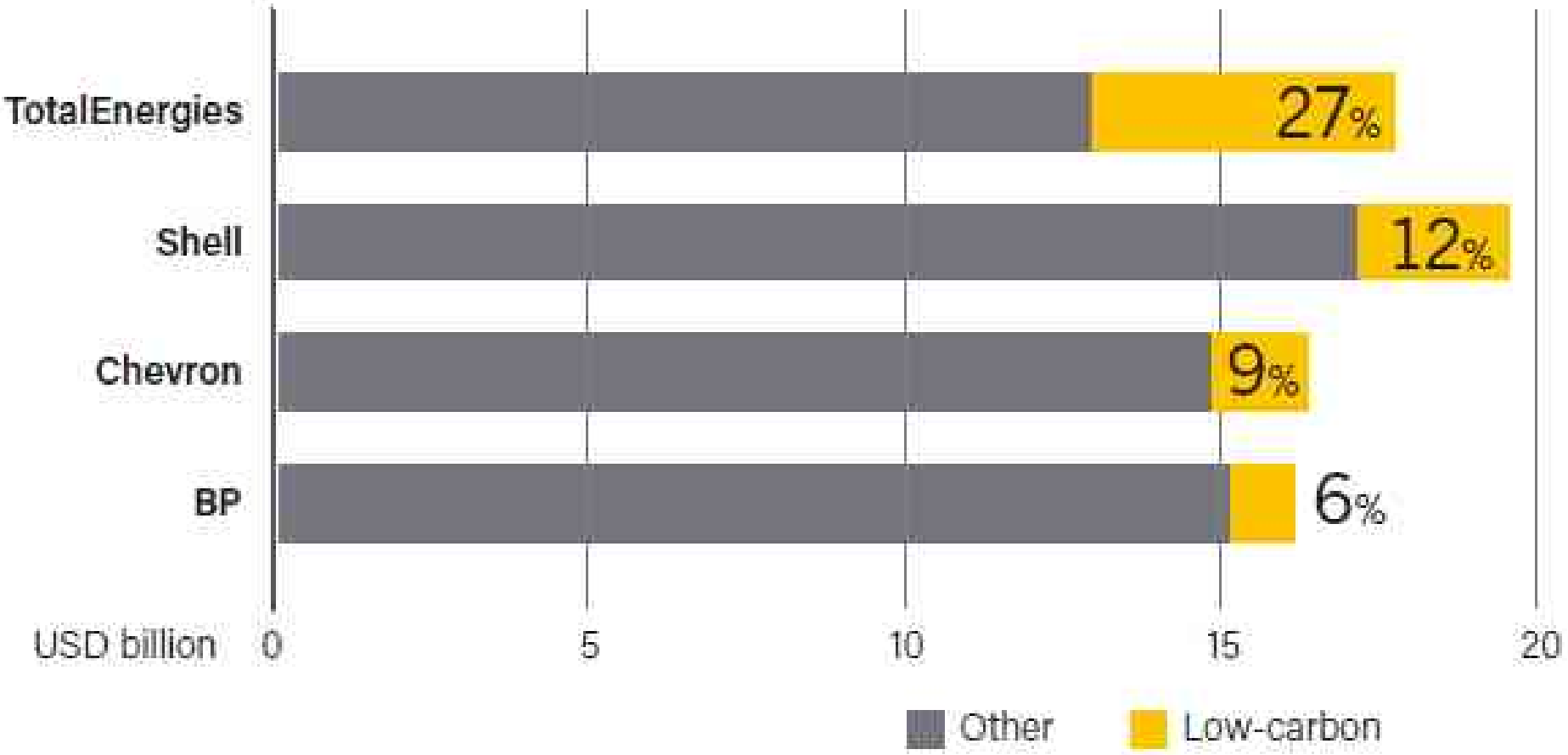
TotalEnergies Capex



Note: Equinor defines "low carbon" as renewable energy and low-carbon solutions, including hydrogen and carbon capture, utilisation and storage; BP defines it as transition growth investment (including power trading and marketing); Shell uses the term low carbon energy solutions, ExxonMobil uses low carbon solutions, and TotalEnergies refers to low carbon energies (excluding new molecules).

Source: REN21 2023 and TotalEnergies Sustainibility & Climate 2023 Progress Report
IOC: International Oil Companies

Low-carbon & total Capex made by 4 IOC in 2024 (G$)



Note: Low-carbon options are defined differently by company and may include renewable energy, carbon capture and storage, low-emission fuels and electric vehicle charging.

Source: REN21 2025
IOC: International Oil Companies

International Oil Companies and Energy Transition - 2023

Companies	Country	Activities
BP	UK	Bioenergy, EV charging, Renewable Power, Hydrogen, CCS
Shell	UK/NL	Electricity, Wind, Solar, EV charging, Hydrogen Fuel Cell
TotalEnergies	France	Renewables, Solar, Wind, Biomass, Electricity, EV charging, Batteries/Storage, Hydrogen, CCS
Equinor	Norway	Solar, Wind offshore, EV, Hydrogen
ENI	Italy	Bioenergy, Wind
ExxonMobil	US	Focus on Oil & Gas, CCS
Chevron	US	Focus on Oil & Gas

International Oil Companies and Energy Transition

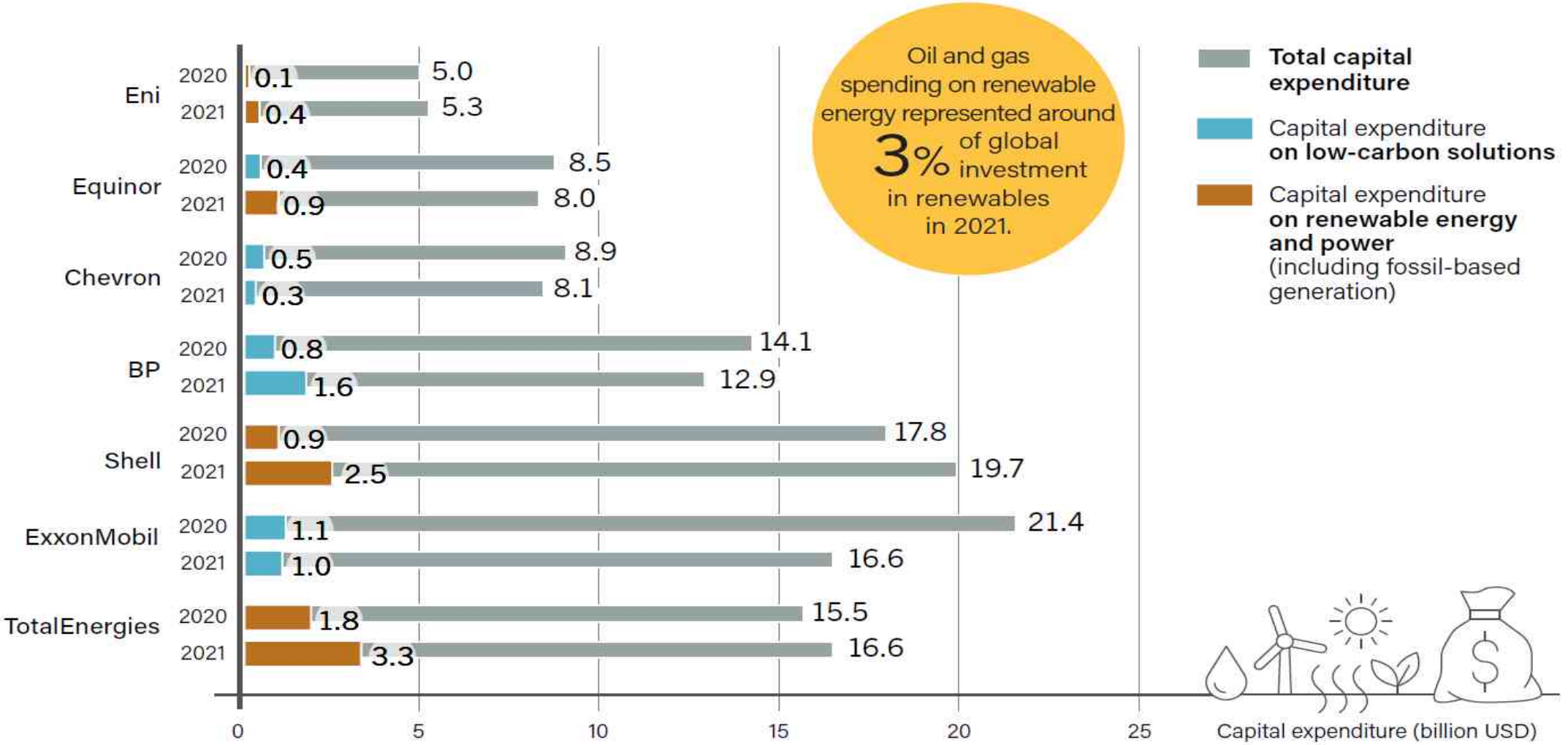
COMPANIES	EXPANDING BEYOND OIL PRODUCTION TO CLEAN ENERGY TECHNOLOGIES	INTEGRATING LOW-CARBON TECHNOLOGIES IN OIL PRODUCTION	AIMING TO LOWER OPERATIONAL EMISSIONS	RENEWABLE ENERGY TECHNOLOGY MAIN INVESTMENTS	INVESTMENTS IN DOWNSTREAM ELECTRICITY	RENEWABLE ENERGY TARGETS	OTHER ENGAGEMENTS IN LOW-CARBON INITIATIVES (I.E. JOINT VENTURES OR FUNDS)
BP plc	✓	✓		Onshore wind, solar, biofuels, EVs infrastructure, batteries		50 gigawatts (GW) by 2030	Joint ventures with renewable companies
Chevron Corporation		✓	✓	N/A		N/A	Future Energy Fund to invest in breakthrough low-carbon emission technologies
Eni S.p.A	✓	✓		Solar, wind, hydrogen, EVs batteries and chargers, biofuels	✓	15 GW by 2030 and 55 GW by 2050	Venture capital fund for R&D in renewables with universities and research centres
Equinor ASA	✓	✓		Solar, offshore wind, hydrogen, EVs	✓	4-6 GW by 2026 and 12-16 GW by 2035	Joint ventures with renewable companies
ExxonMobil Corporation		✓	✓	N/A		N/A	N/A
Royal Dutch Shell plc	✓	✓		Offshore wind, hydrogen, biofuels, EVs	✓	Invest USD 3 billion in renewable energy (including hydrogen) per year by 2030	Investments in renewable start-ups and innovation hubs
Total SE	✓	✓		Solar, wind, hydrogen, biofuels	✓	35 GW of renewable electricity by 2025	Joint ventures with renewable companies

Sources: (Holder, M., 2021), (Equinor, 2021a), (Jewkes, S., 2020a), (Nasralla, S. and Twidale, S., 2020), (Total, 2020a) and companies strategies

European Oil & Gas Companies are much more involved in Energy Transition than US Companies which remain focused on Oil & Gas activities

Source: IRENA 2021 – International Oil Companies and Energy Transition

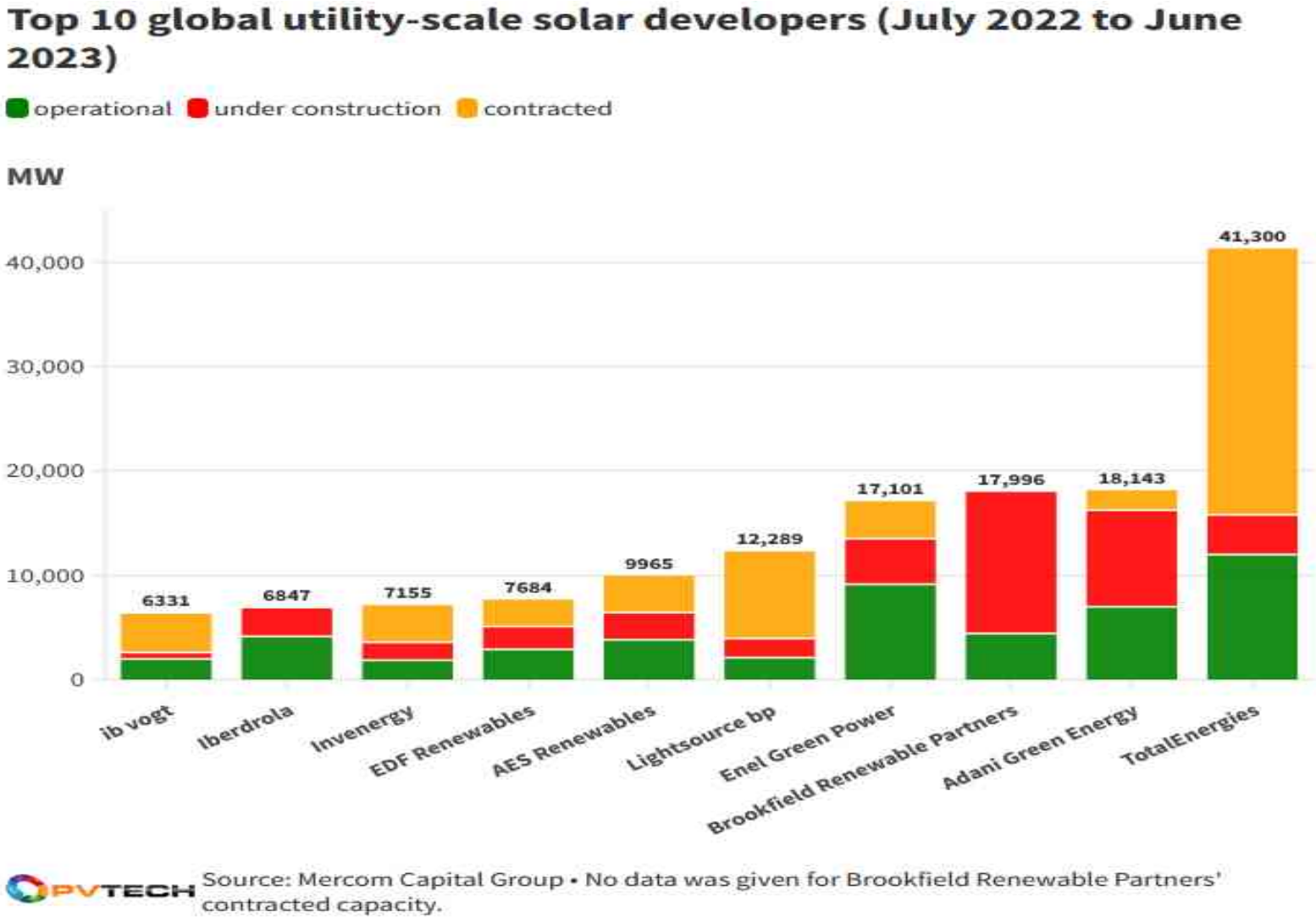
Global Investment for Renewable Energy & Power made by Oil & Gas companies in 2020 & 2021



Source: REN21 2022

TotalEnergies is among the most dynamic companies committed in Energy Transition
See Book 4 Oil – Chapter 13

TotalEnergies is the top leader for utility-scale solar capacities in the World, including operational, under construction and contracted projects # 41 GW

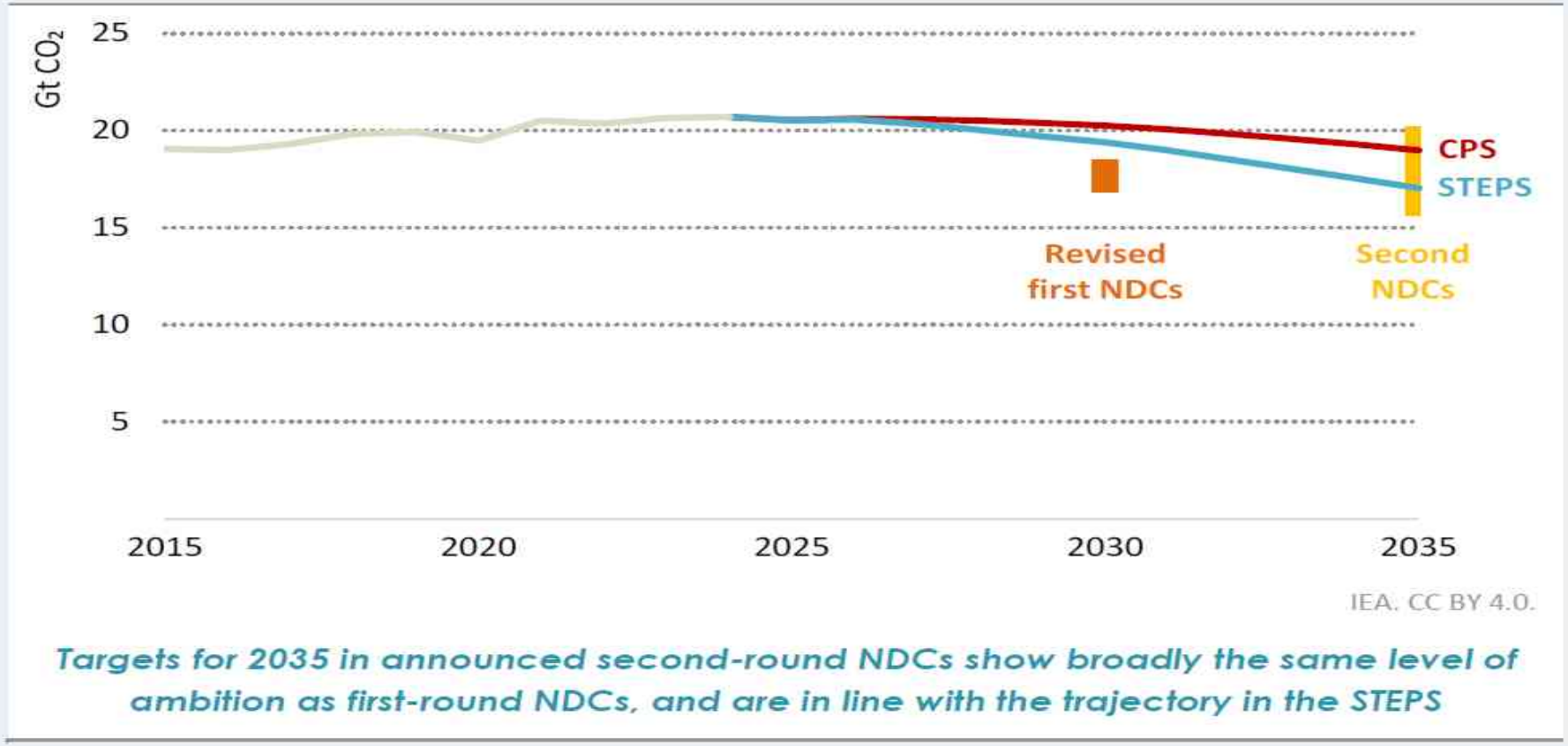


International Energy Agency (IEA) Scenarios
World Energy Outlook (WEO) 2025

IEA 2025 Scenarios – Preliminary remarks

- Compared to the last period of time, the general considerations on Energy Transition et Climate Change issues have substantially changed.
- The US Trump's administration has confirmed its position to quit the 2015 Paris Agreement and to promote strongly the development of Oil & Gas production (« Drill, baby, drill! »)
- A large number of countries have put the priority on Energy security, sometimes delaying the continuous use of fossil energy.
- Demand for Oil is continuing to grow and the time for the peak oil is still delayed.
- The development of new renewable Energy projets is facing some reservation in connection with both economics and acceptability of people (Ex.: New Wind farms projects, EV developments,…)
- Developing countries are in growing demand for huge financial contributions from the developed countries.
- The COP 30 in Belem, Brazil in November 2025 has adressed all these issues. US are not represented. India and China will probably become the more important actors to contribute in some ways to the Energy transition. The new round of National Determined Contributions (NDCs) that were due this year has not been completed because many countries are yet to announce or update their targets.
- US Administration has criticized the work done by IEA, arguing that this organization works against America's Economy. US is presently the greatest contributor in financing IEA (IEA 2024 budget = 78 M€, US financing # 7 M€.

Energy related CO_2 emissions trajectories from NDC submissions delivered by some countries before COP 30 in Belem
Globally, targets for 2035 are in line with the STEPS Scenario described below



Targets for 2035 in announced second-round NDCs show broadly the same level of ambition as first-round NDCs, and are in line with the trajectory in the STEPS

Notes: Gt CO_2 = billion tonnes of carbon dioxide; NDCs = Nationally Determined Contributions. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario. The estimates aggregate selected countries with 2035 indicative targets announced at the United Nations Climate Summit on 24 September 2025 and the Nationally Determined Contributions submitted to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat as of mid-October 2025.

Source: IEA WEO 2025

IEA World Energy Outlook - November 2025

3 Scenarios

CPS

Current Policies Scenario



STEPS

Stated Policies Scenario



NZE

Net Zero Emissions by 2050 Scenario



IEA World Energy Outlook - November 2025

3 Scenarios

CPS

Current Policies Scenario



- No change in Energy-related policies is assumed beyond what is already in place.
- The evolution of the Energy sector is based on a detailed review of existing legislation.
- Similar to a “Business as Usual “ scenario, but slowing down in the future due to potential constraints like insufficient infrastructure, lack of institutional capacity or financing, absence of continued policy support.
- Associated with a temperature rise of 3,0°C in 2100 (with a 50% probability)

IEA World Energy Outlook - November 2025

3 Scenarios



- Takes into account those policies that have been formally tabled but not yet adopted as well as other official strategy documents that indicate the direction of travel.
- Such targets such as those defined by the existing NDCs and those declared by the Paris Agreement are not automatically assumed to be met.
- Consistent with a temperature rise of 2,5°C in 2100.

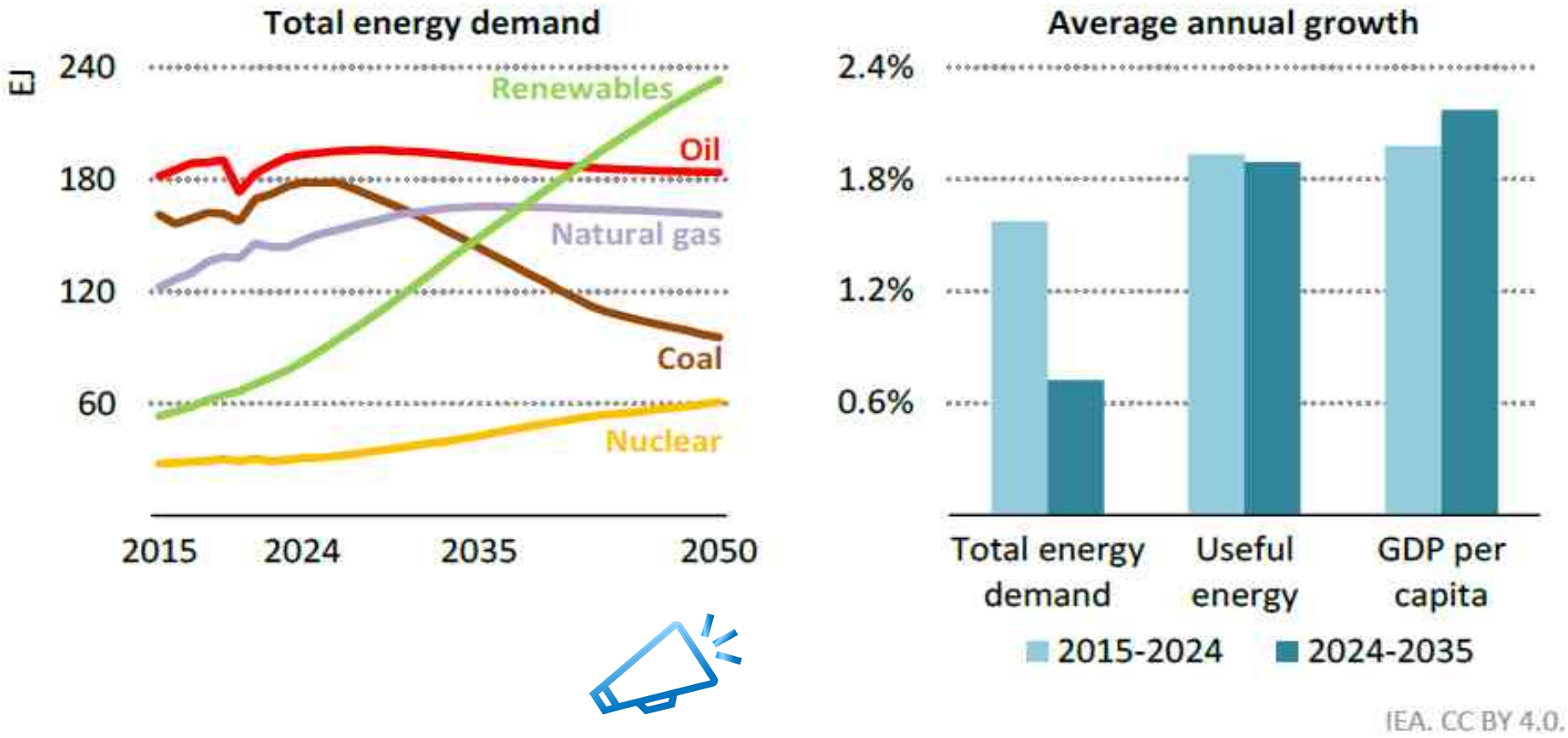
IEA World Energy Outlook - November 2025

3 Scenarios



- Based on a narrow pathway for the global Energy sector to achieve Net Zero Emissions by 2050
- Advanced economies reaching this objective in advance of the other scenarios.
- Implies massive use of CCUS, reforestation, direct air capture & Storage,...etc.
- Consistent with a global temperature rise of 1,5°C in 2100 (50% chance to be achieved) Warming peaks already above 1,6 °C and could exceed 1,5°C for decades before returning to 1,5°C in 2100.

Total Energy Demand by IEA WEO 2025 - STEPS Scenario

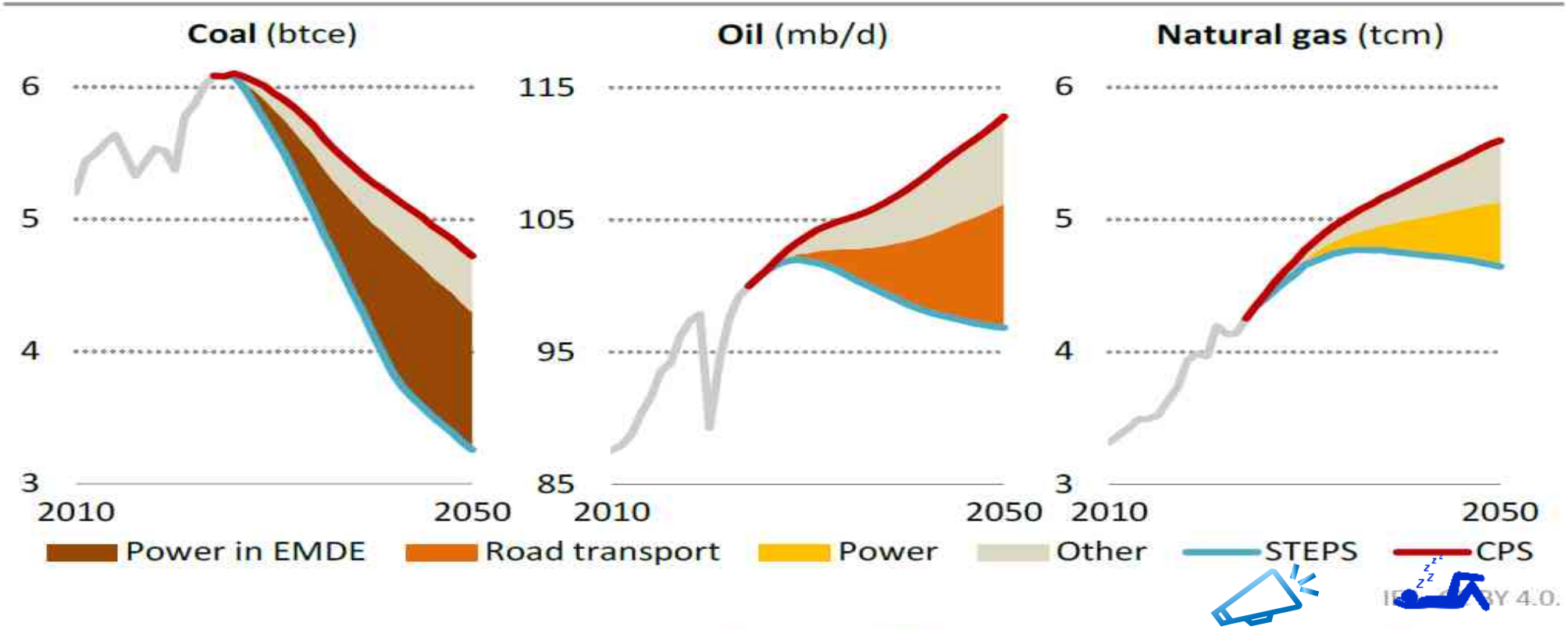


Fossil fuels reach high points in the next decade before being overtaken by renewables as total demand growth slows, but the energy available to end-users does not

Note: EJ = exajoule.

Source: IEA WEO 2025

IEA WEO 2025 STEPS & CPS Scenarios
Global Demand for Coal, Oil & Gas

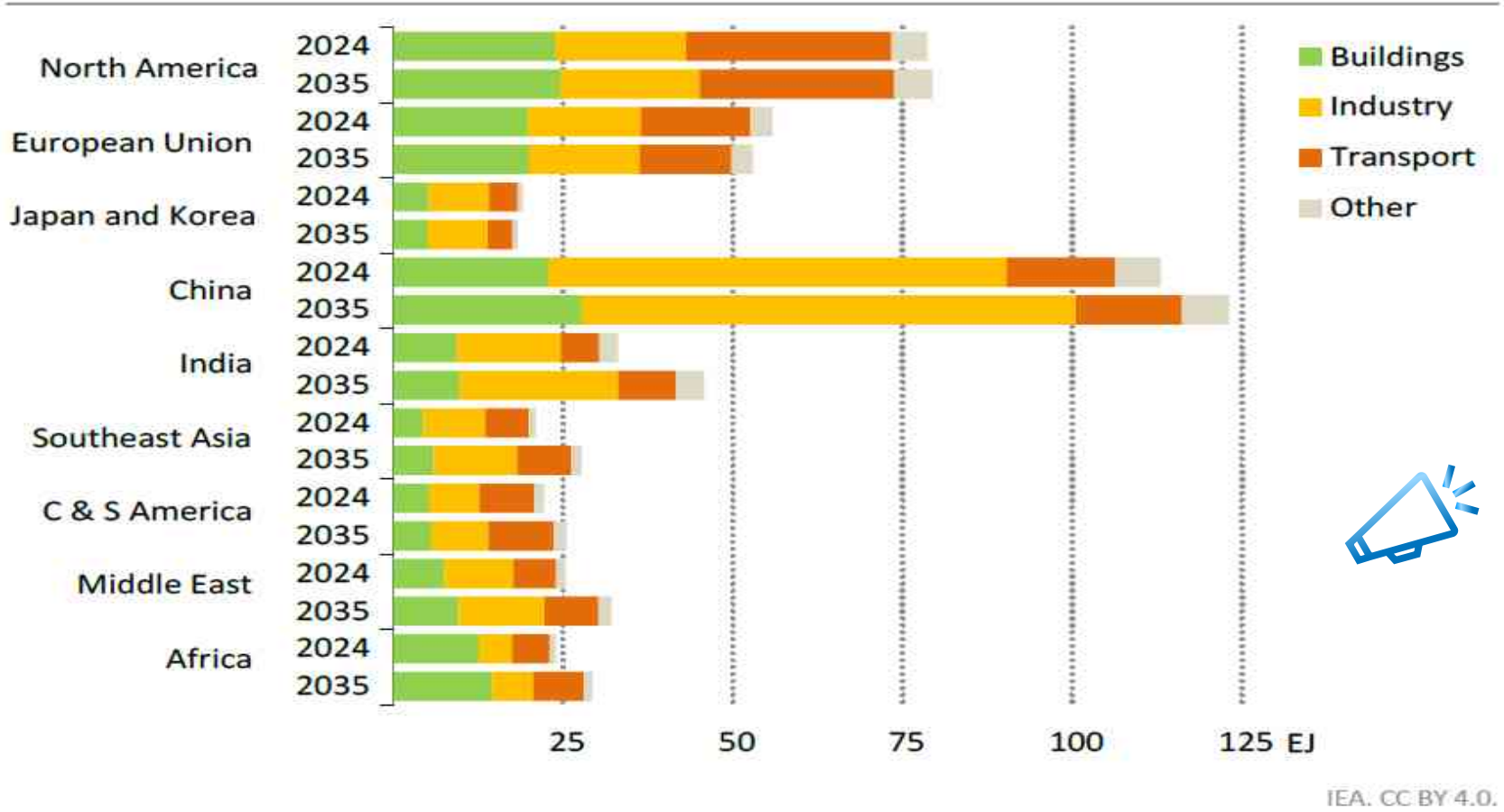


Coal and oil demand peak by 2030 in the STEPS; growth is higher in the CPS due to slower uptake of technologies such as renewables and EVs

Note: btce = billion tonnes of coal equivalent; mb/d = million barrels per day; tcm = trillion cubic metres. EMDE = emerging market and developing economies; CPS = Current Policies Scenario; STEPS = Stated Policies Scenario.

Source: IEA WEO 2025

IEA WEO 2025 STEPS Scenario
Final Consumption by Regions 2024 - 2035

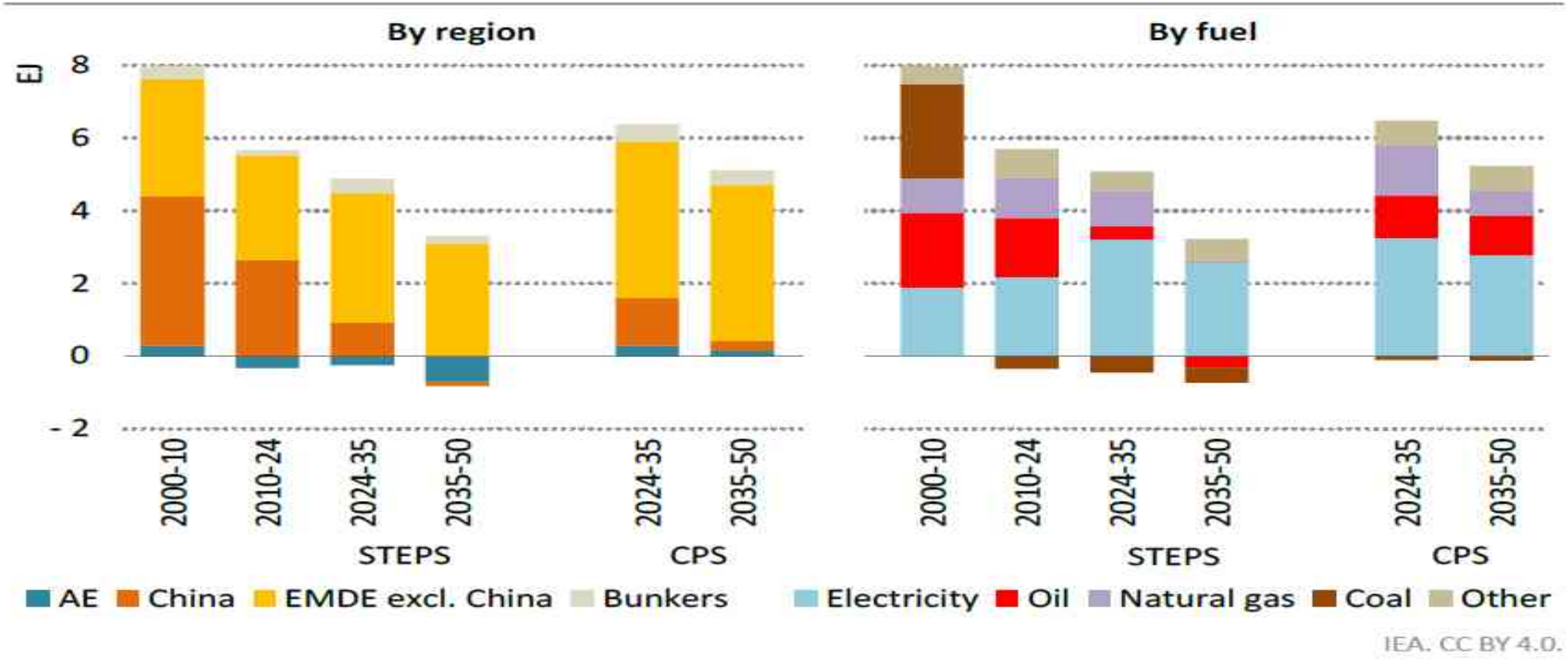


Total final consumption remains relatively evenly split across the main end-use sectors in advanced economies, while it is dominated by industry in Asia and by buildings in Africa

Notes: EJ = exajoule; C & S = Central and South America. Other includes agriculture and non-energy use.

Source: IEA WEO 2025

IEA WEO 2025 STEPS & CPS Scenarios
Final Consumption annual increase

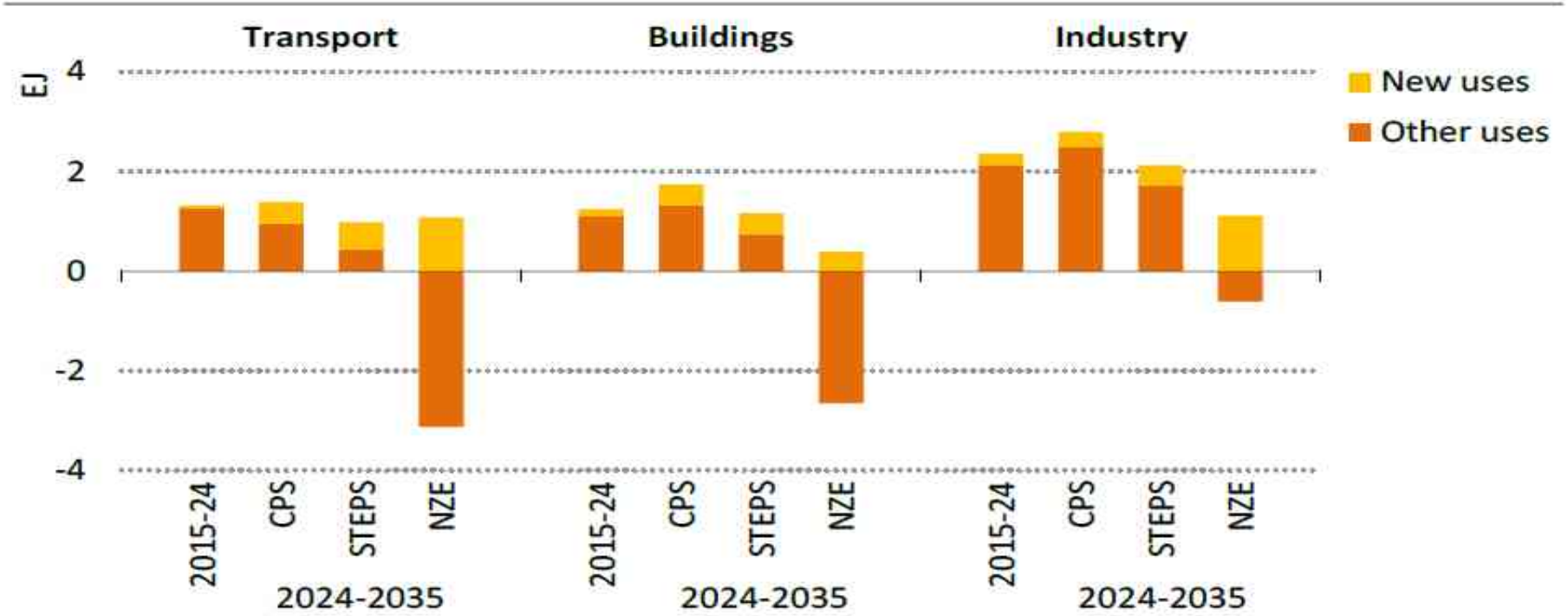


Engine of growth shifts from China to other emerging market and developing economies, with electricity meeting most of the growth; fossil fuels play a larger role in the CPS

Notes: EJ = exajoule. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario. AE = advanced economies; EMDE excl. China = emerging market and developing economies excluding China. Other includes district heating, solar thermal and geothermal, bioenergy and waste.

Source: IEA WEO 2025

IEA WEO 2025 - Three Scenarios
Final Consumption Growth by sectors



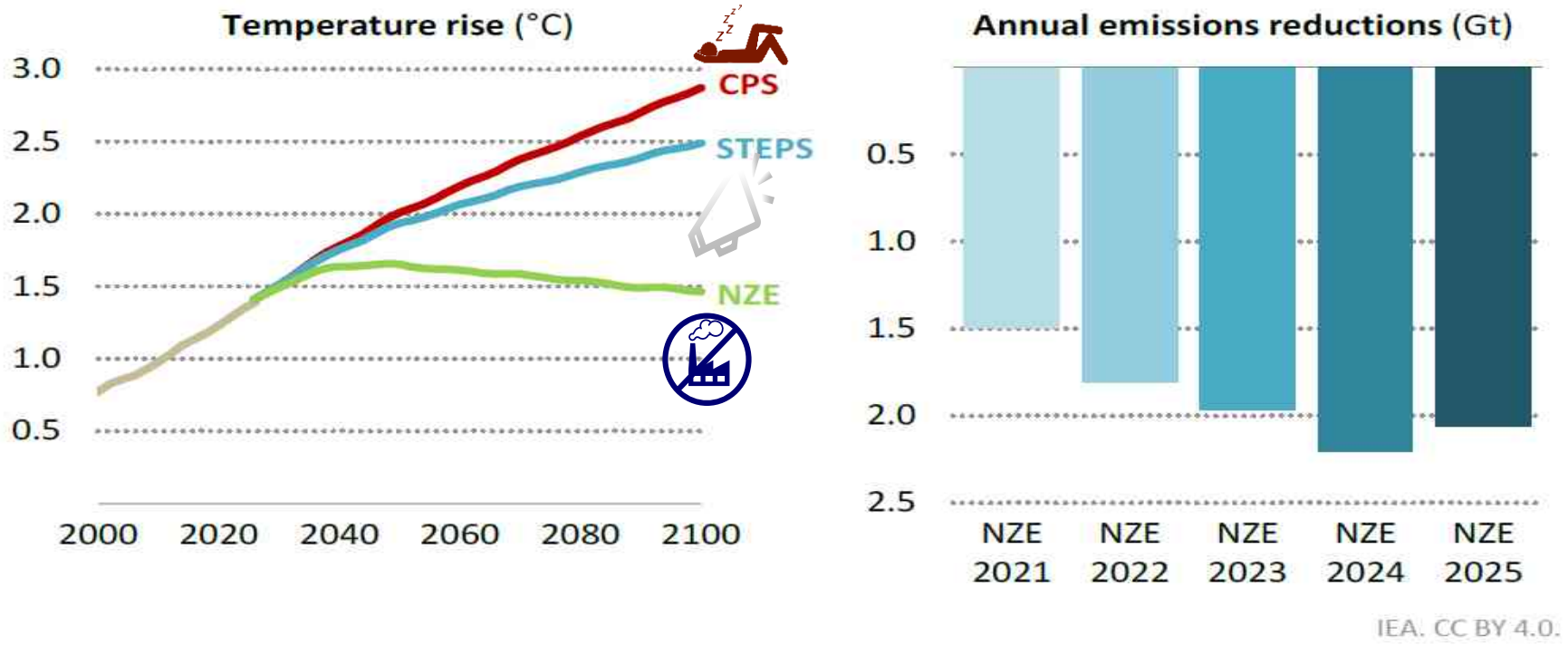
IEA. CC BY 4.0.

End-uses that were marginal in the last decade account only for a small part of the growth in the CPS, an increasing share of it in the STEPS, and nearly all of it in the NZE Scenario

Notes: EJ = exajoule. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. In transport, new uses include hydrogen and EVs; in buildings it includes heat pumps, data centres and electric desalination; in industry it includes heat pumps, hydrogen and clean technology manufacturing.

Source: IEA WEO 2025

Three IEA Scenarios vs their consequences in term of temperature rise in 2100

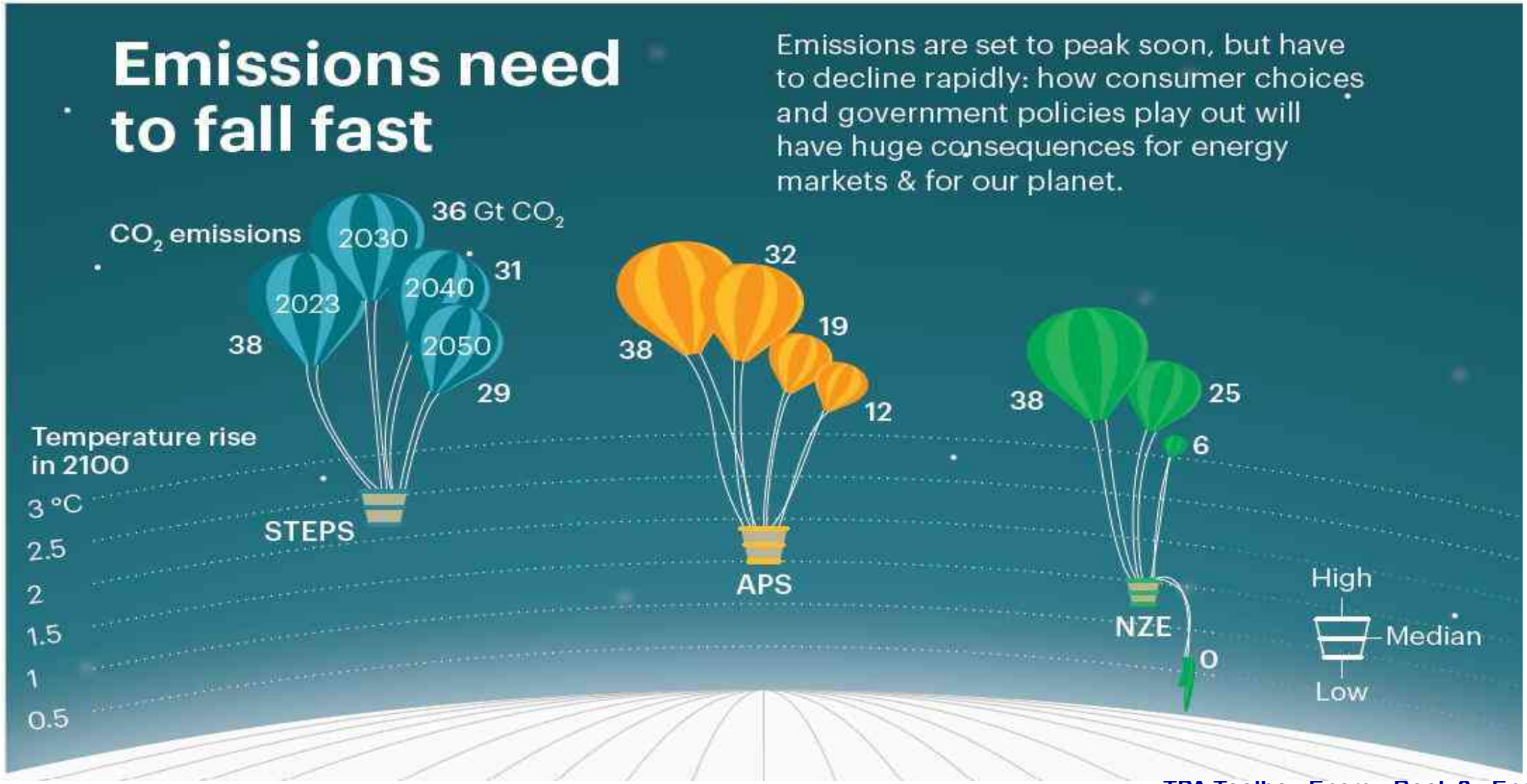


The average temperature rise reaches 2.9 °C in 2100 in the CPS, 2.5 °C in the STEPS, and in the NZE Scenario it peaks at around 1.65 °C in 2050 and falls below 1.5 °C in 2100

Notes: Gt = gigatonnes. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario; NZE 20xx = NZE Scenario in the *World Energy Outlook* of the specified year. The figure shows median long-term average global temperature anomaly relative to 1850-1900 and matches the Intergovernmental Panel on Climate Change Sixth Assessment Report definition of warming of 0.85 °C between 1995-2014.

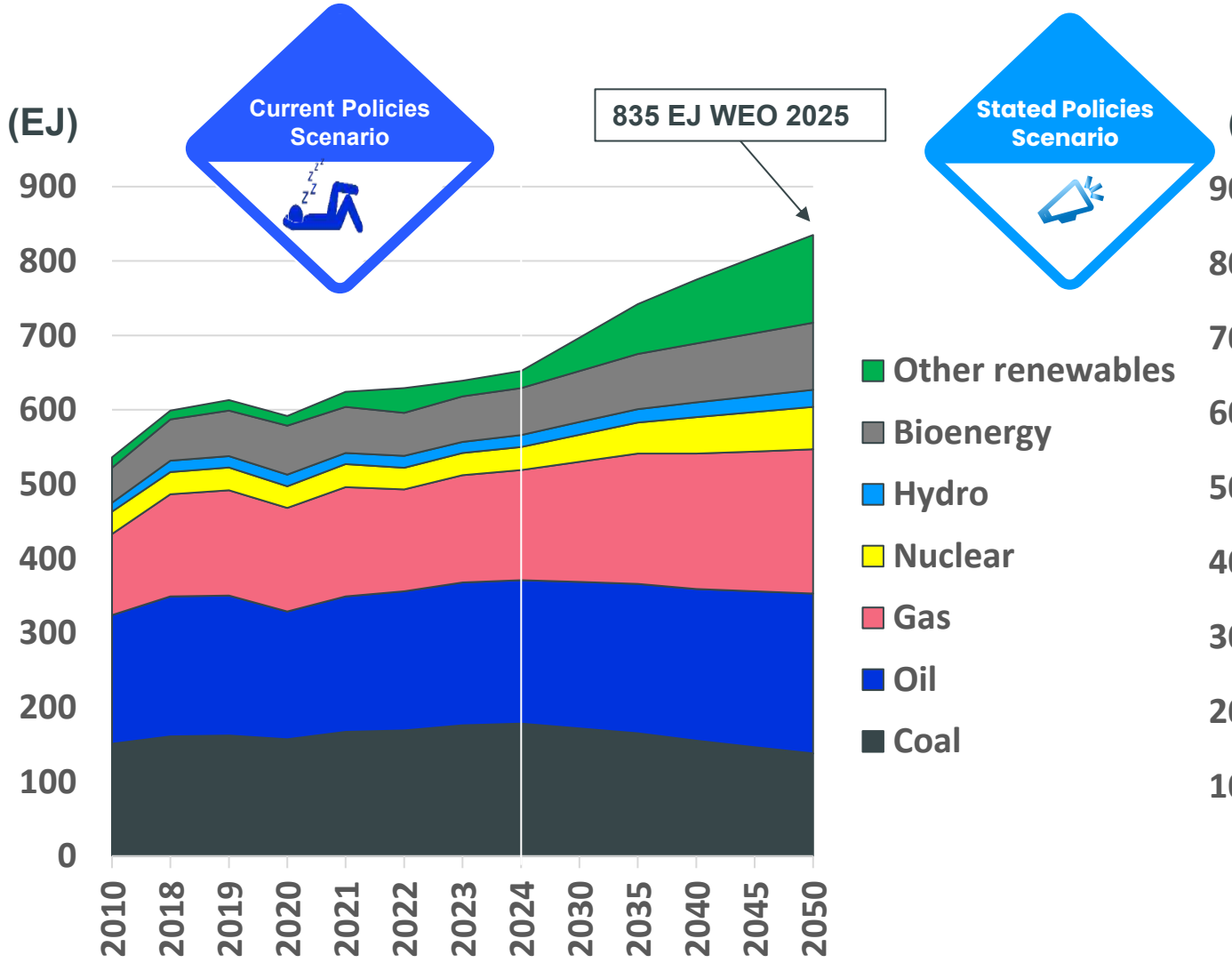
Source: IEA WEO 2025

Reminder - Three IEA WEO 2024 Scenarios vs their consequences in term of CO_2 emissions & temperature rise in 2100



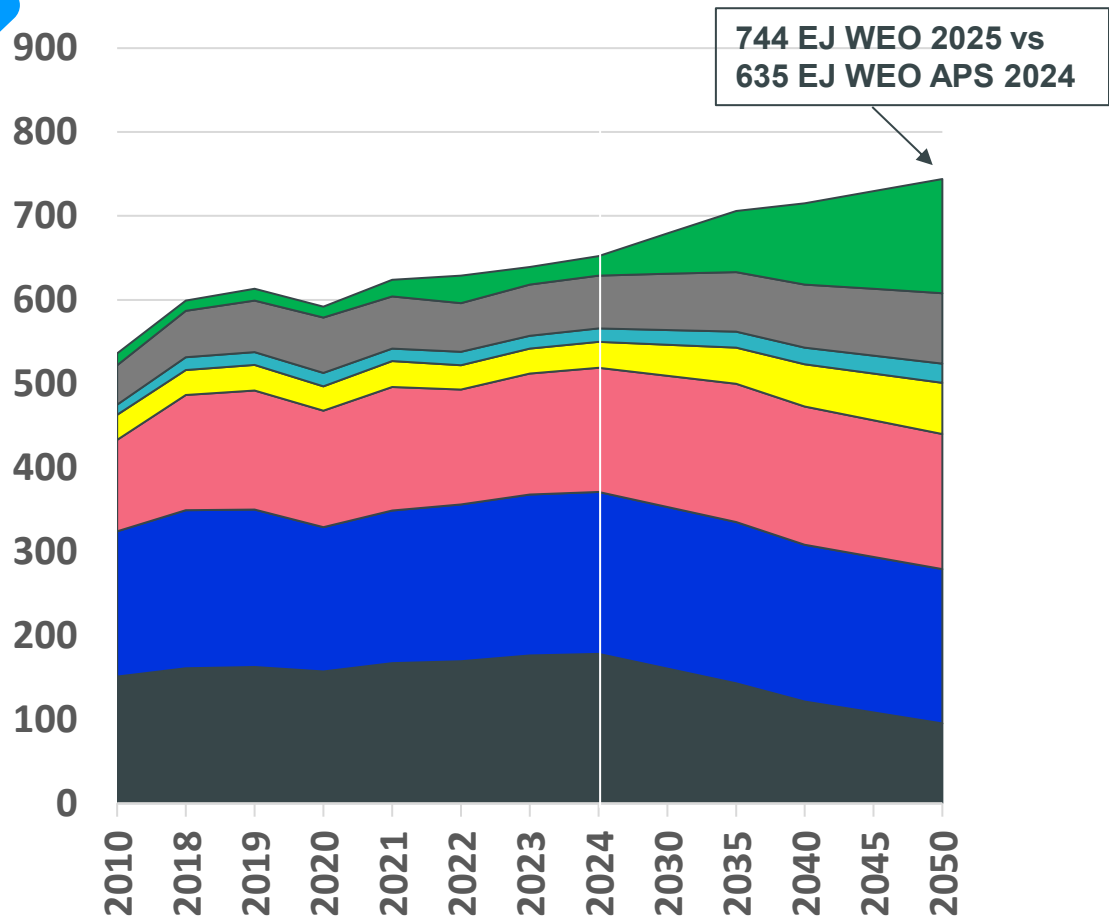
Source: IEA WEO 2024

Primary Energy Demand
IEA 2025 CPS and STEPS Scenarios (EJ)



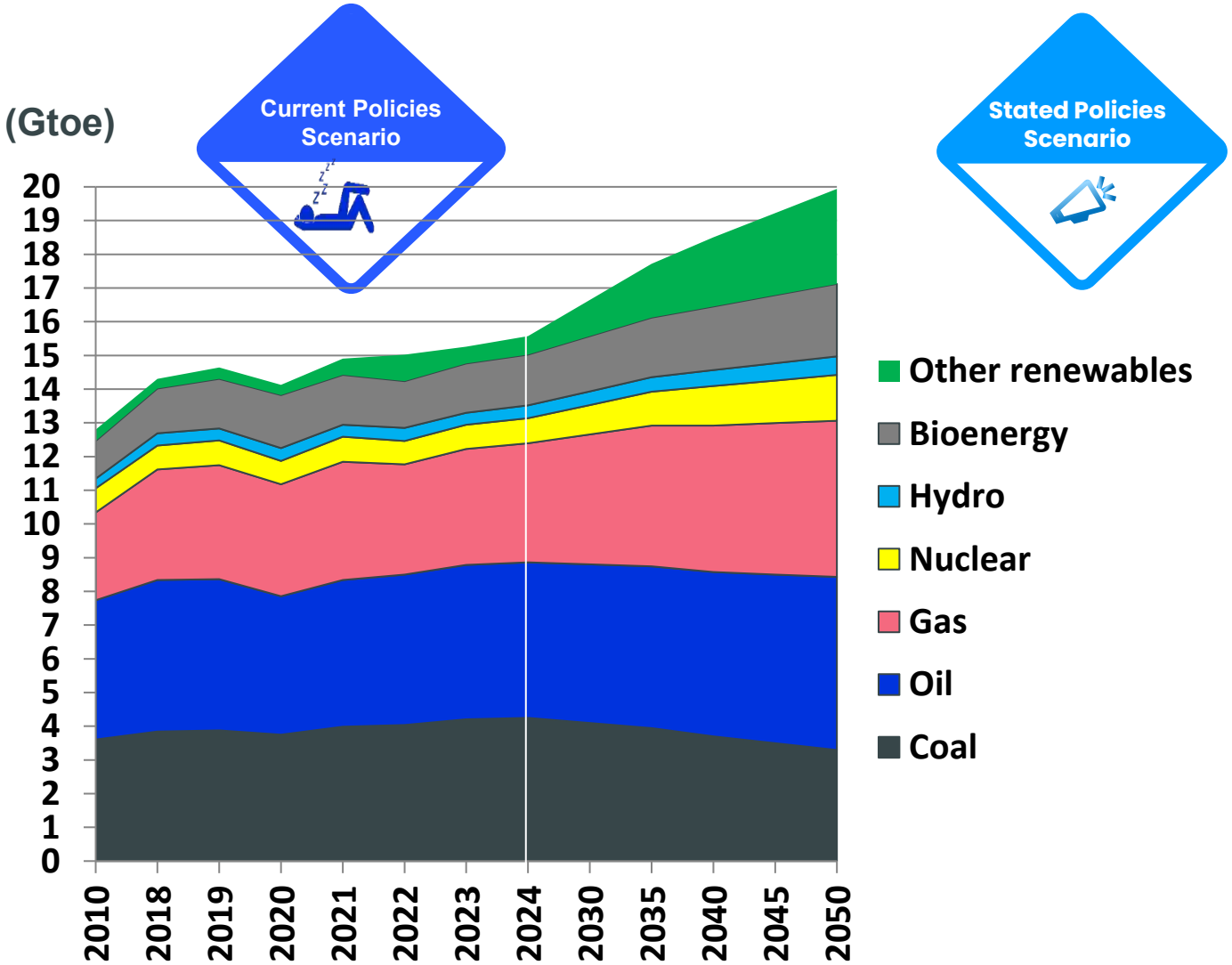
Other renewables
Bioenergy
Hydro
Nuclear
Gas
Oil
Coal

In the STEPS, Energy Demand continues to grow after 2024

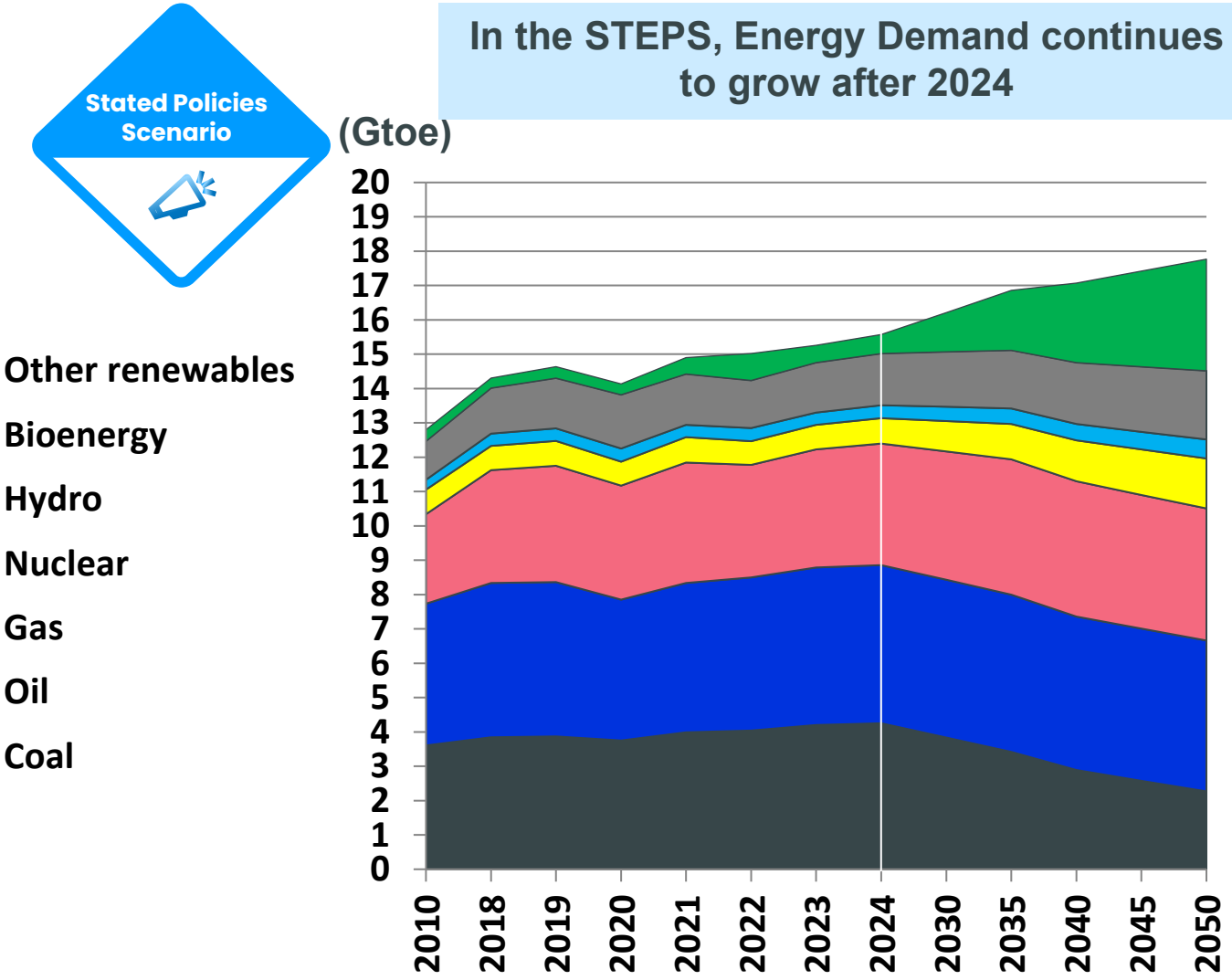


Source: Ch.Guéritte/Data from IEA WEO 2025
1 EJ = 10^{18} J = 23,88 Mtoe

Primary Energy Demand
IEA 2025 CPS and STEPS Scenarios (Gtoe)



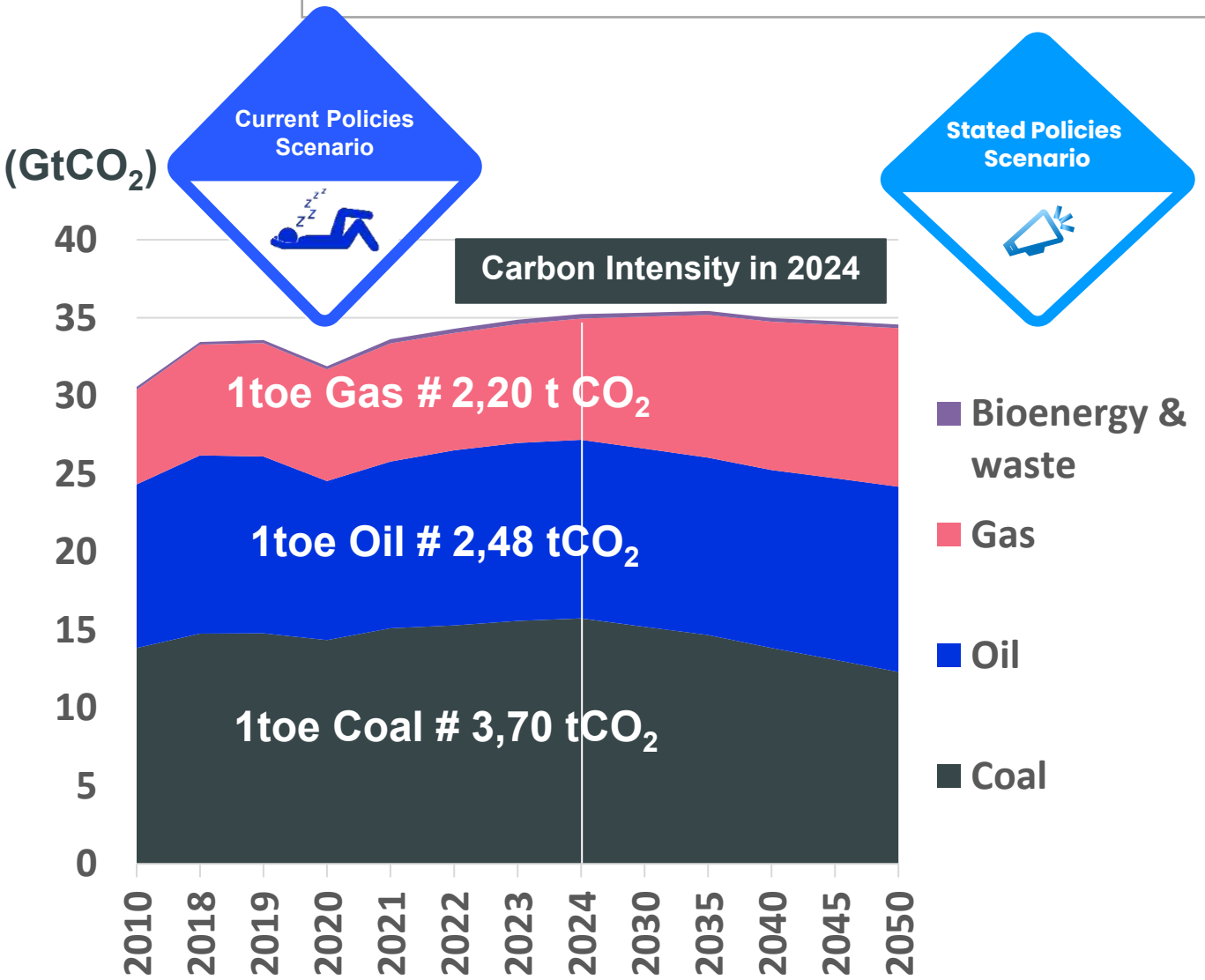
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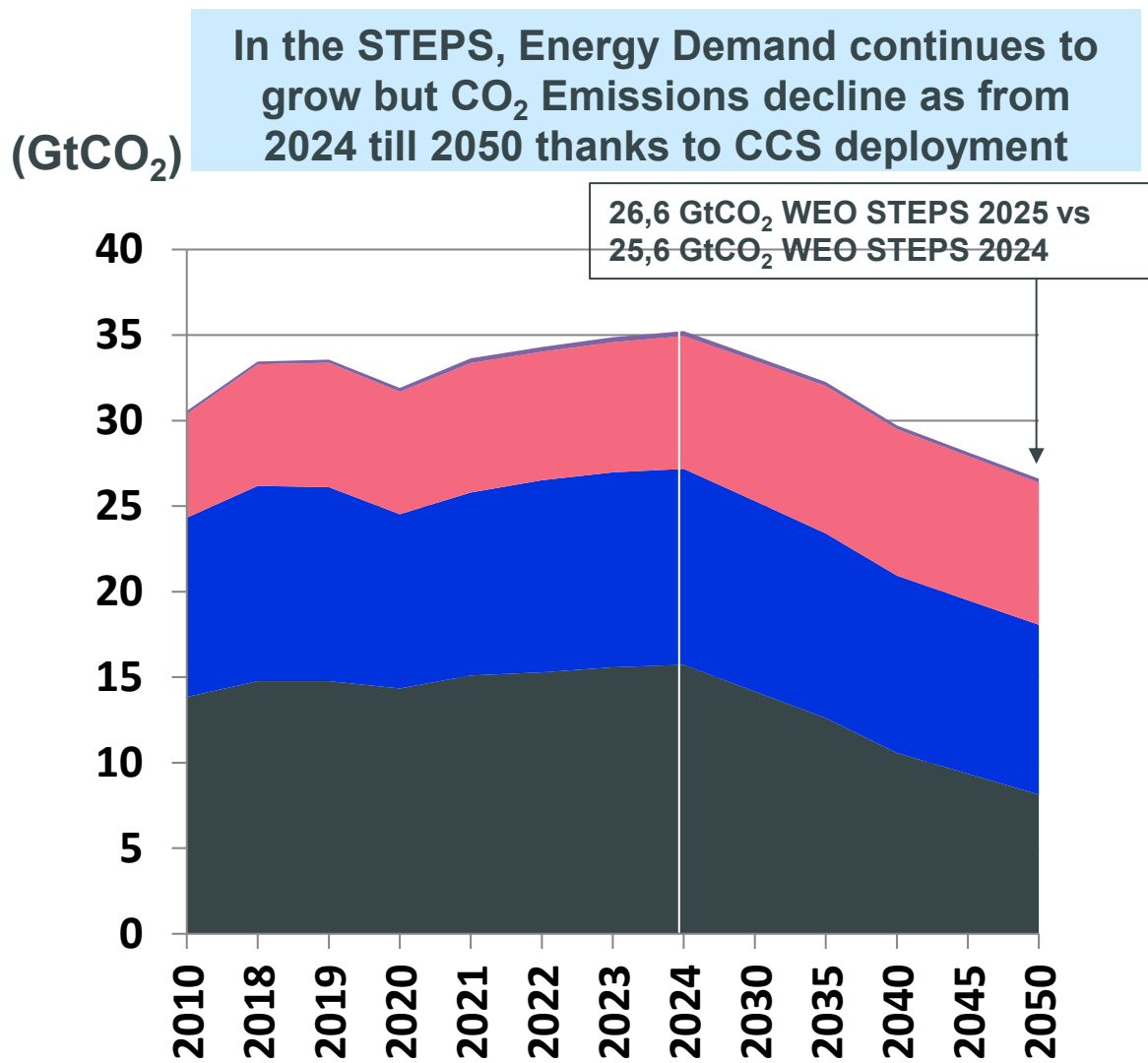


In the STEPS, Energy Demand continues to grow after 2024

Source: Ch.Guéritte/Data from IEA WEO 2025
1 EJ = 10^{18} J = 23,88 Mtoe

CO_2 Energy Emissions (Combustion activities) IEA 2025 CPS and STEPS Scenarios ($GtCO_2$)





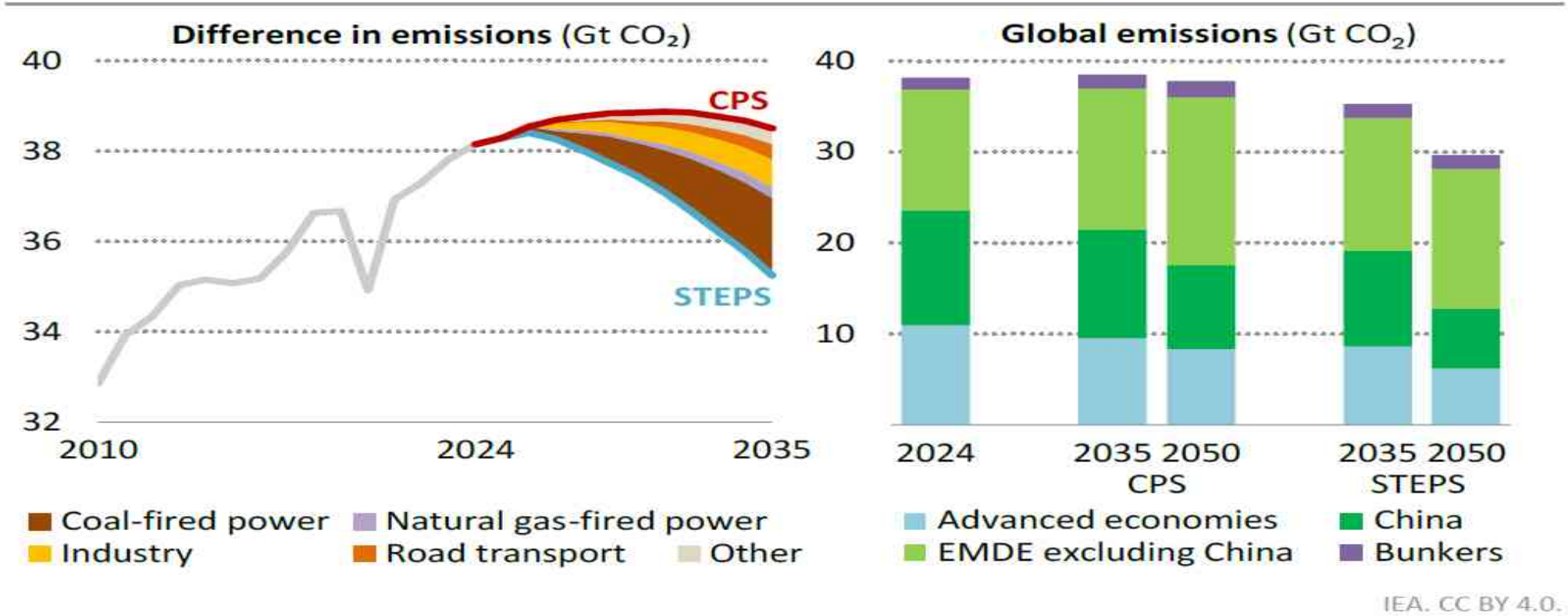
In the STEPS, Energy Demand continues to grow but CO_2 Emissions decline as from 2024 till 2050 thanks to CCS deployment

Source: Ch.Guéritte/Data from IEA WEO 2025

Example of specific measures to be actively launched to build-up a Sustainable Development

- Increasing energy efficiency in the industry, buildings and transport sectors (performance of industrial tools and equipments, heating and cooling systems, buildings isolation, changes in transport modes, use of more efficient vehicles, improvement through digitalisation,….)
- Stopping the use of least-efficient coal-fired power plants and banning their construction.
- Implementing massively CCUS (Carbon Capture Utilization & Storage) projects.
- Implementing efficient carbon pricing.
- Increasing investment in renewable technologies in the power sector.
- Accelerating the use of nuclear energy.
- Phasing out of fossil-fuels subsidies to end-users.
- Reducing methane emissions in oil & gas production.
- & Drastic changes in people's behaviour and way of life.

CO_2 Energy Emissions By IEA WEO 2025



Emissions from coal-fired power generation in emerging market and developing economies account for most of the difference between the two scenarios to 2035

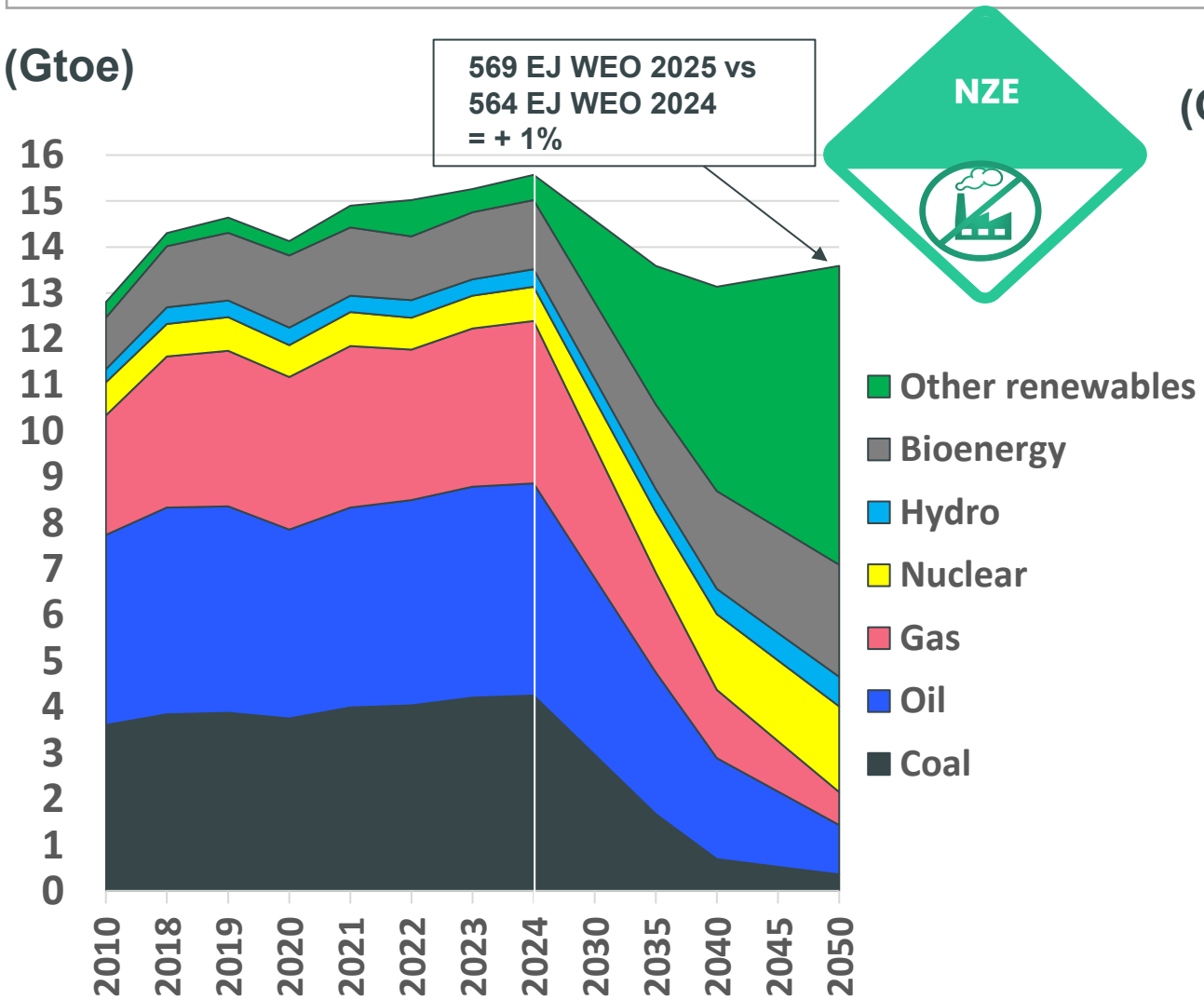
Note: Mt CO_2 = million tonnes of carbon dioxide. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; EMDE = emerging market and developing economies.

Source: IEA WEO 2025

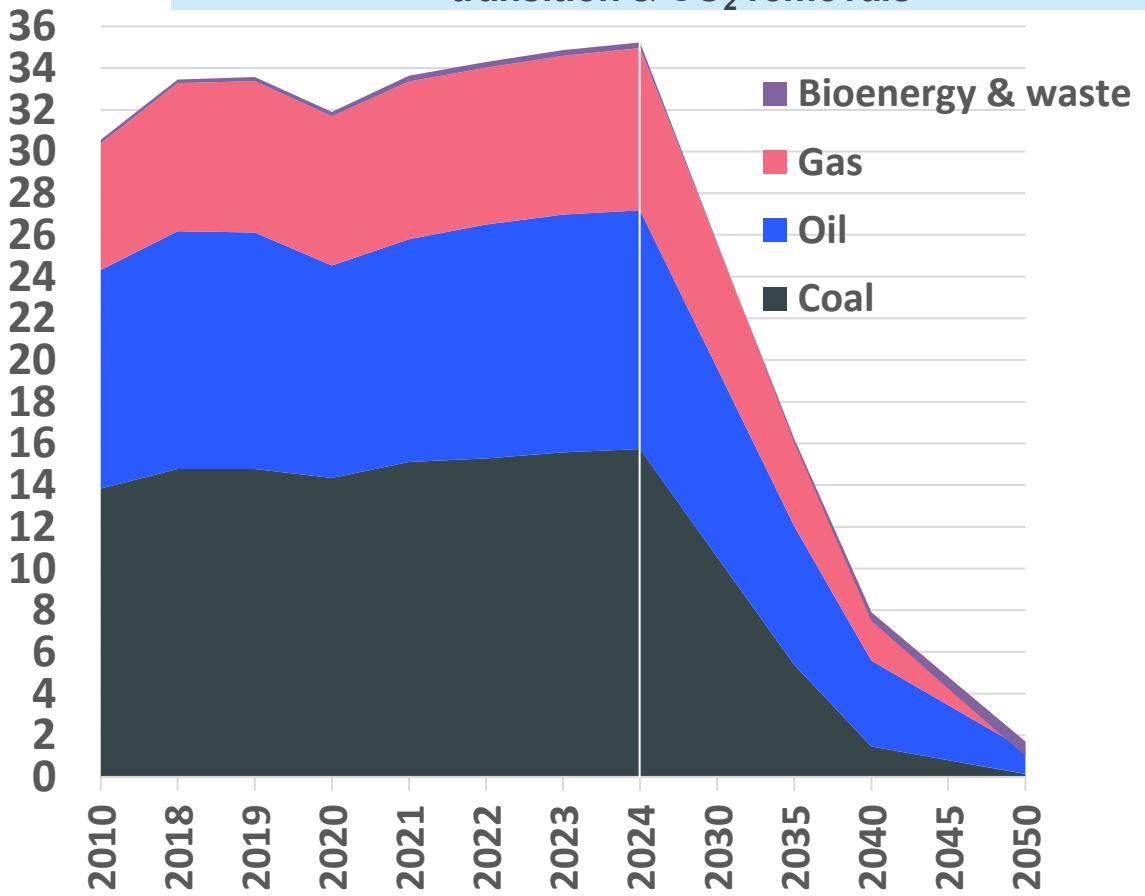
Nota: CO2 Energy emissions include industrial process and flaring

The IEA NZE Scenario 2025

Energy Consumption & CO_2 Net Emissions (Combustion activities)
IEA 2025 NZE 2050 Scenario – Clearly impossible to achieve



In the NZE, Energy Demand decreases and CO_2 Emissions decline strongly as from 2024 to reach almost 0 in 2050 thanks to agressive Energy transition & CO_2 removals



Source: Ch.Guéritte/Data from IEA WEO 2025

Comments on the NZE Scenario by IEA 2025

Why an increase of Energy Consumption from 2040 to 2050?

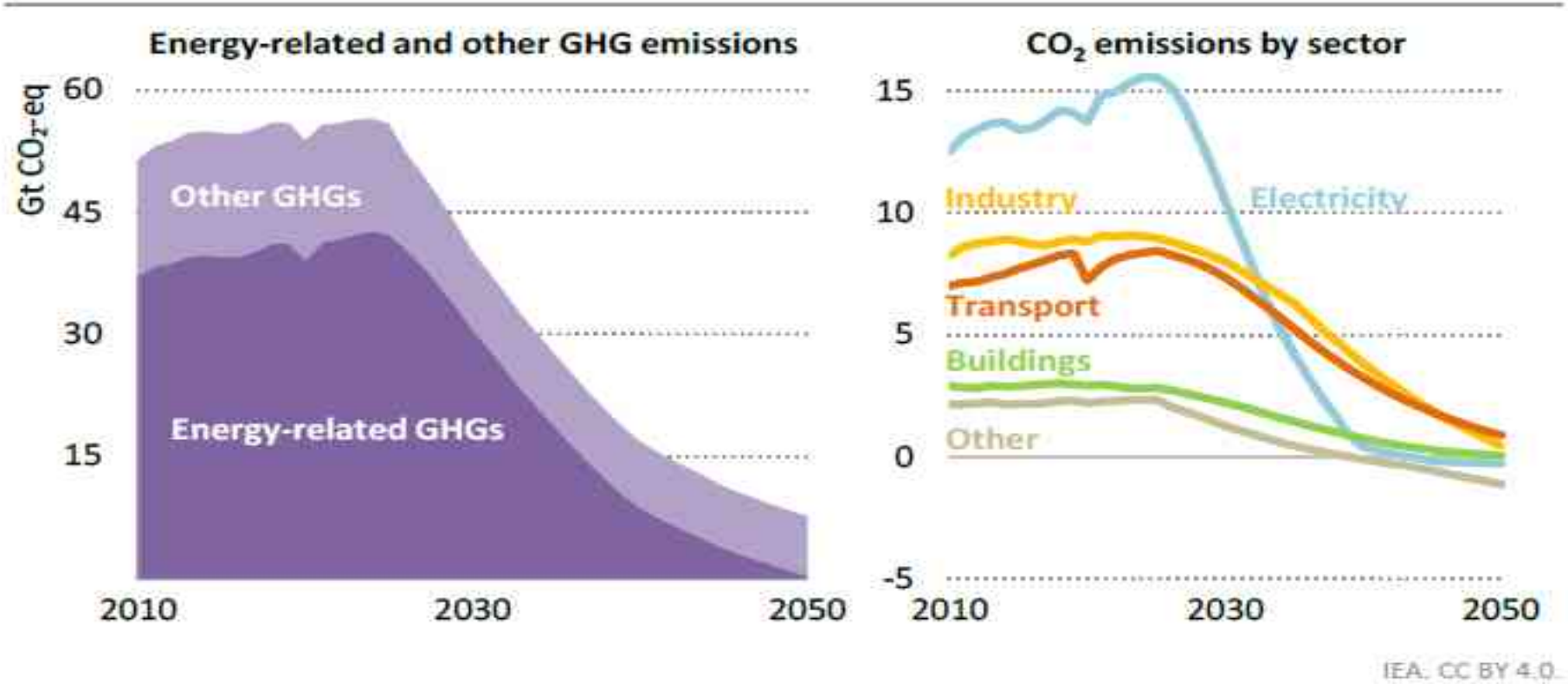
In the IEA 2025 NZE Scenario,

Final Energy Consumption decreases
from 380 EJ (9,1 Gtoe) in 2040 to 352 EJ (8,4 Gtoe) in 2050,

while
Total Energy Supply increases
from 551 EJ (13,2 Gtoe) in 2040 to 570 EJ (13,6 Gtoe) in 2050.

This due to the huge increase of decarbonated Final Electricity Demand from 2040 to 2050 which, translated into Primary Energy, increases the global Energy Supply during this period.

GHG Emissions in the NZE Scenario



Global energy-related GHG emissions fall by around 55% by 2035, led by rapid reductions in the electricity sector and in methane emissions

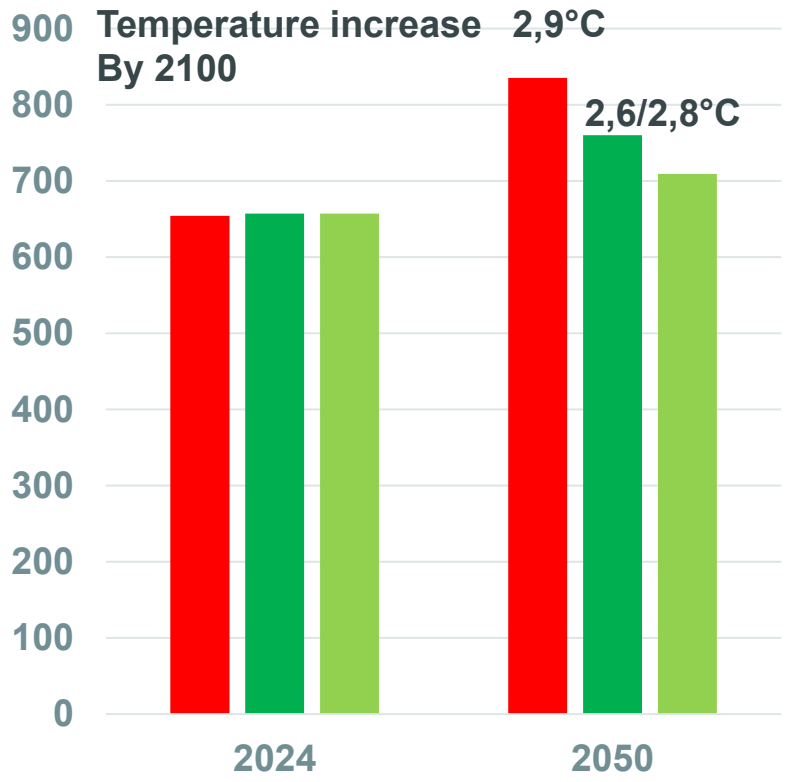
Note: GHG = greenhouse gases; CO_2-eq = carbon-dioxide equivalent. Other includes agriculture, forestry and other land use (AFOLU) and waste.

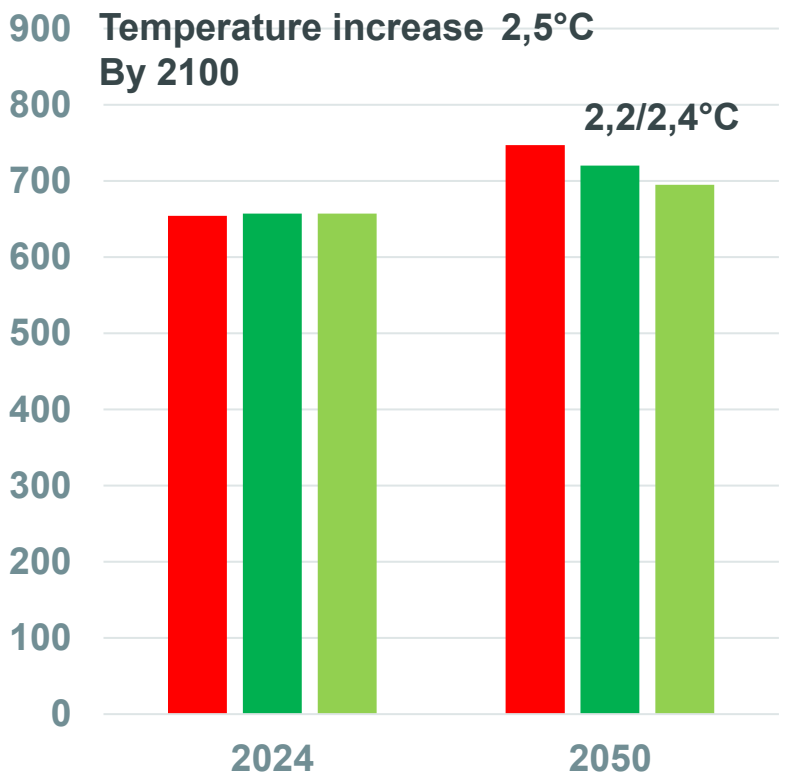
Sources: AFOLU emissions based on IEA modelling and Land-Use Analytic.

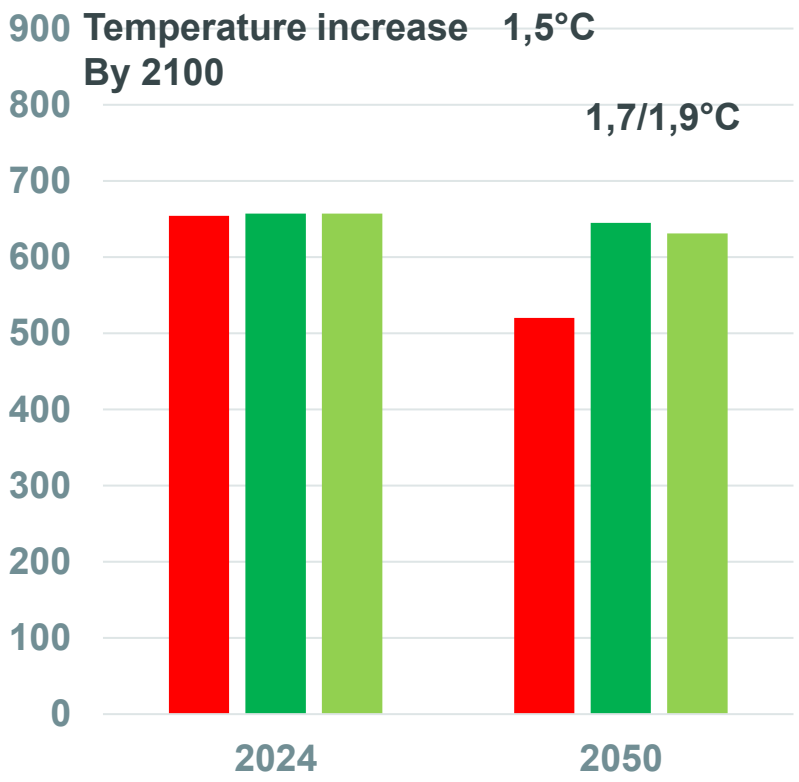
Source: IEA WEO 2025

Comparison TotalEnergies Scenarios vs IEA Scenarios

Primary Energy Demand - TotalEnergies vs IEA Scenarios – Outlooks 2025 (EJ)







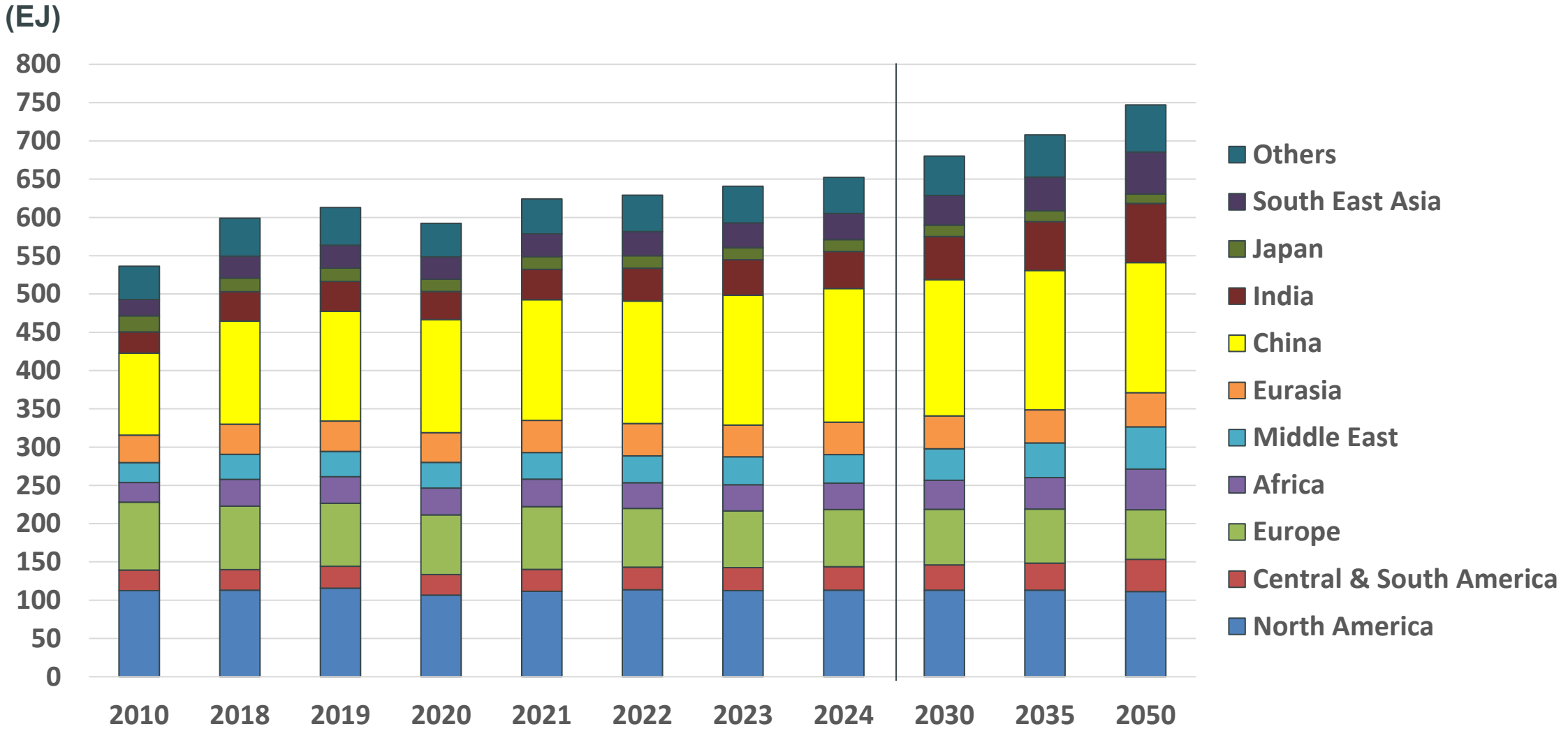
IEA WEO CPS 2025 (EJ)	IEA WEO STEPS 2025 (EJ)	IEA WEO NZE 2025 (EJ)
TotalEnergies Outlook Trends 2025 (EJ)	TotalEnergies Outlook Momentum 2025 (EJ)	TotalEnergies Outlook Rupture 2025 (EJ)
TotalEnergies Outlook Trends 2024 (EJ)	TotalEnergies Outlook Momentum 2024 (EJ)	TotalEnergies Outlook Rupture 2024 (EJ)

Source: Ch.Guéritte/Data from IEA WEO 2025
& TotalEnergies Energy Outlook 2025 – EJ: Exajoules

A Zoom on IEA Scenarios
By Sources & by Regions

Global Energy Demand by Regions – IEA 2025 STEPS

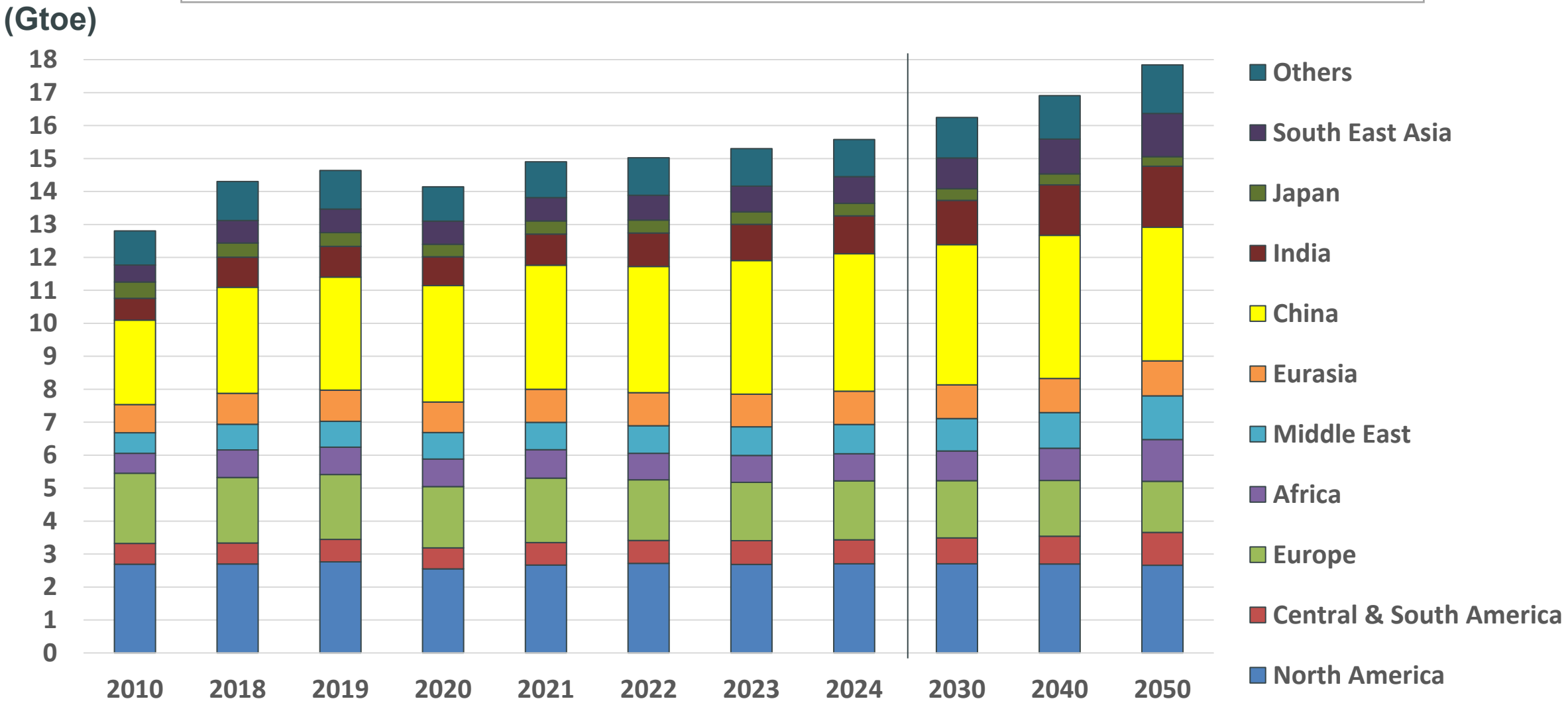
The Geography of Energy Demand in the STEPS implies a global increase worldwide in particular in Non-OECD regions



Source: Ch.Guéritte/Data from IEA WEO 2025

Global Energy Demand by Regions – IEA 2025 STEPS

The Geography of Energy Demand in the STEPS implies a global increase worldwide essentially in Non-OECD regions



Source: Ch.Guéritte/Data from IEA WEO 2025

ExxonMobil – 2025 Global Outlook

ExxonMobil 2025 Global Outlook (1)

Increasing global energy supply *and* reducing emissions is not only possible – **It's essential.**



Nothing happens without energy. Society will need to produce enough of it to support a bigger population, larger economies, and higher living standards for everyone.

By 2050, the world also has ambitious goals to reduce emissions. But the world is not on track to meet global emissions targets, climate policies have largely failed, and critical technologies are underdeveloped.

There are opportunities to change course.

With the right policy and technology advancements, the world can meet rising energy demand *and* reduce emissions by 2050.

2025 Global Outlook
Our view to 2050

Key takeaways:

All energy types are needed for a more prosperous, lower-emission future.
- Renewables grow the fastest
- Coal declines the most
- Oil & natural gas still make up more than half of the global energy mix

Rising living standards increase energy use 25% in developing countries.
- Half the world's population currently lacks the energy needed to address basic human needs.

Industry and transport underpin the global economy and will require growing supplies of energy.[1]

Global CO_2 emissions fall 25%; affordability will drive the pace of any transition.

Sustained oil and natural gas investment is more important than ever.

Source: ExxonMobil 2025

ExxonMobil 2025 Global Outlook (2)



Fueling the future

In 2050, developing countries will use 25% more energy as living standards improve.

Global Outlook projections:
The world will be bigger in 2050.

More people.
The world's population will grow by more than 1.5 billion people, mostly in developing countries.

Larger global economies.
Global gross domestic product (GDP) will double. Developing nations will expand their economies twice as fast as developed nations.

Higher living standards.
Personal income will rise nearly 80% by 2050, driven by rising economic growth and affordable, available energy.

Currently 4 billion people – half the world's population – lack access to the energy needed for housing, infrastructure, jobs, and other basic human needs.

Our analysis estimates that the most basic living standards require a person to use at least 50 million British thermal units (MMBtu) per year. To put that in perspective, people in developed countries around the world use more than three times that amount – about 160 MMBtu per person.

Energy use correlates with longer lifespans and higher levels of education. Energy enables people to cook with cleaner fuels, heat and cool their homes, access better healthcare, and buy modern products and many other necessities.



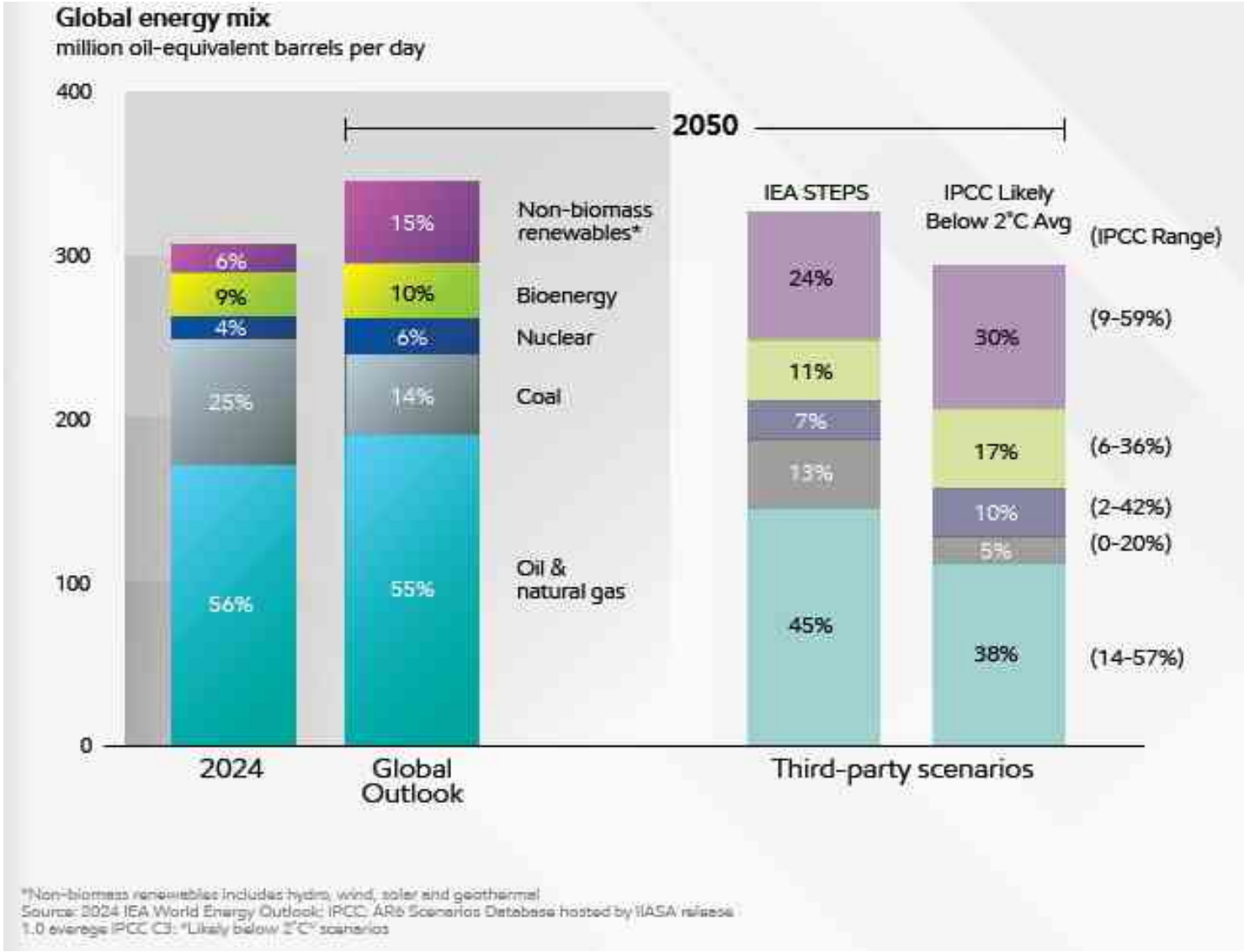
Source: ExxonMobil 2025

ExxonMobil 2025 Global Outlook (3)

What sources of energy are needed to fuel economic **growth?**

Today: Traditional fuels like coal, oil, and natural gas
2050: Natural gas will continue to grow and displace coal. Renewables and lower-emission technologies like hydrogen, carbon capture and storage, and biofuels will become more important. Oil and natural gas will remain key to powering the 2050 economy.

All solutions will be necessary long-term.



Source: ExxonMobil 2025

ExxonMobil 2025 Global Outlook (3)

Affordability will drive the pace of any energy transition

In today's world, lower-emission technologies are expensive. That's part of the reason why today's efforts to reduce emissions have fallen behind.

1.5x



Bio-diesel for long-haul trucking is **1.5x more expensive** than traditional diesel.[1]

3x



Sustainable aviation fuel is **3x more expensive** than traditional jet fuel.[2]

Lessons from Europe

Heavy industry and commercial transportation are the backbone of the European economy, according to the European Commission.[3] Europe's high-regulation, high-cost approach to lowering emissions has hurt its economy.

Under Europe's decarbonization approach:

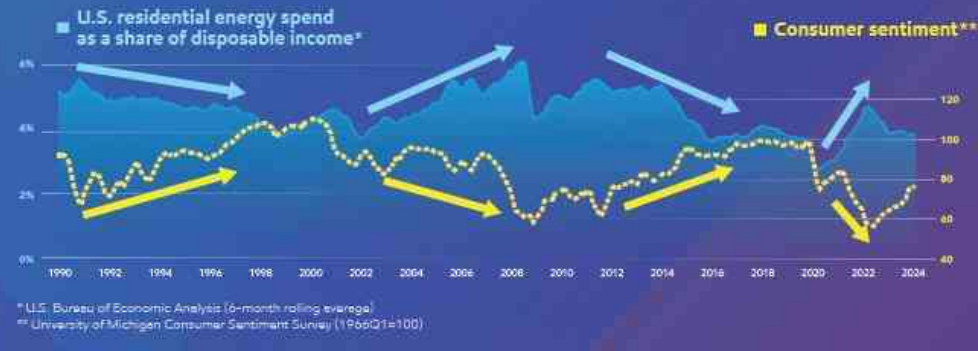
- Industrial production, a critical sector in Europe's economy, is declining.[4]
- Energy prices in heavy industry and commercial transportation are rising.[5]

As a result, public support for lower-emissions technology needed to reach EU climate goals is wavering.[6]

Higher energy costs affect the whole economy. Historically, when consumers spend more on energy, their confidence in the economy falls.

When consumers lose confidence in the economy, they lose confidence in the social and political institutions around them. If a political administration implements policies that make energy too expensive, it will lose the support of the electorate. If the electorate stops supporting policies that advance an energy transition, that will hurt the overall progress of lower-emissions technology.

However, the opposite is also true. When lower-emission options are cost competitive, they are more readily adopted. This is where supportive policy can help in the early stages.



ExxonMobil 2025 Global Outlook (4)

What's needed to make lower-emissions technology **affordable?**

It's been 20 years since the Kyoto protocol came into force and 10 years since the Paris climate agreement. Yet, global energy-related CO_2 emissions continued to rise at ~1% per year in 2024 — unchanged vs the 20-year average. Clearly, a different policy approach is needed.

Public policy support

Policy should be designed in such a way to avoid energy price spikes that will shake consumer confidence. That means policy frameworks that support all solutions and focus on reducing carbon intensity of energy and products, rather than wholesale replacement or constraining supply. Policies that unnecessarily raise cost by increasing tax burdens or otherwise reduce financial support can pinch supply below the point needed to meet demand. This can drive up costs for everyone and create unnecessary energy shortages.



Technology advancements

Only 3 out of more than 50 technologies needed to reach net-zero are "on track," according to the International Energy Agency.[1] The reasons why include technology challenges, policy and regulatory barriers, market readiness, and insufficient investments. The right policy framework can incentivize technology advancements that will help drive costs down long term.



Market-driven solutions

Where no market exists and initial costs are high, incentives make sense to get things started. But government incentives should only be used as a bridge to market-driven incentives. Markets must develop to naturally select the most cost-effective technologies for companies and for consumers. One fundamental requirement for any market to work is a transparent and consistent accounting system, where participants can evaluate both the cost and carbon intensity of products and energy.



Source: ExxonMobil 2025

ExxonMobil 2025 Global Outlook (5)



Direct Air Capture pilot unit in Baytown, Texas.

Advancing an energy transition

Carbon emissions are expected to fall by 2050, but more progress is needed

In 2050, oil and natural gas will still make up more than half of the world's energy supply. But the world will also use more lower-emission technologies than it does today. This shift will help drive down emissions by 2050, even as energy demand grows.

	2024 levels:	Global Outlook 2050 projected levels:	Level needed to meet global emission goals in 2050 (according to IPCC)**
Global CO_2 emissions*	36 billion metric tons	27 billion metric tons	11 billion metric tons
Solar generation	2,000 TWh	11,000 TWh >5x today	22,000 TWh >10x today
Carbon capture and storage	24 MMT CO_2	3,100 MMT CO_2 130x today	7,000 MMT CO_2 ~290x today
Low-carbon hydrogen production	1 MTA	80 MTA ~80x today	170 MTA ~170x today

*Energy-related CO_2 emissions
**IPCC: AR6 Scenarios Database hosted by IIASA release 1.0 average IPCC C3: "Likely below 2°C" scenarios

Efficiency improvements and renewables are necessary but not a complete solution.

By 2050, CO_2 emissions are expected to fall ~25%, driven by efficiency improvements and a bigger shift toward lower-emission solutions.

Source: ExxonMobil 2025

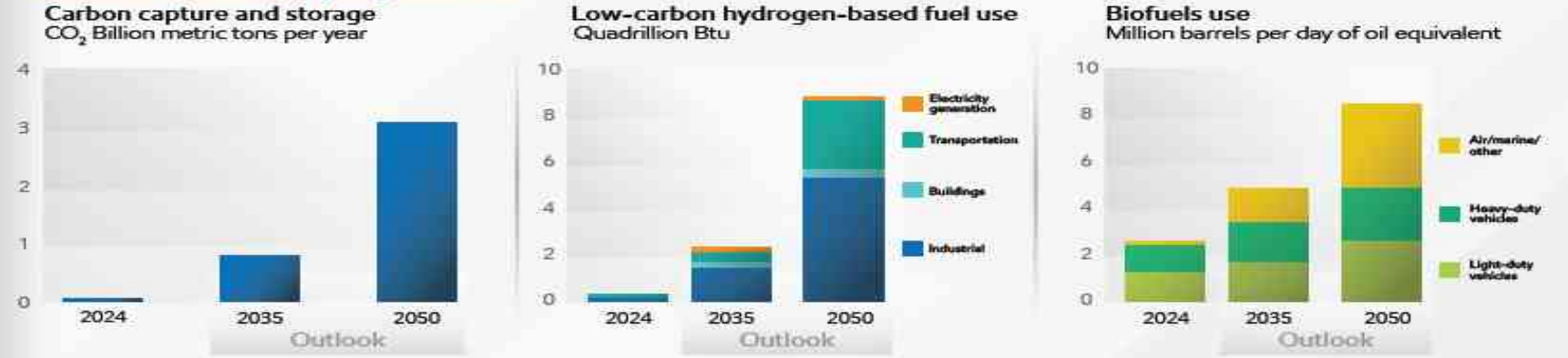
ExxonMobil 2025 Global Outlook (6)

It will take **all solutions** to help drive faster progress on **reducing emissions.**

Technologies like low-carbon hydrogen, carbon capture and storage, and biofuels are nowhere near reaching their full potential to reduce emissions on a global scale.

With the right climate policies and technology advancements, these solutions can help move society closer to achieving its climate goals.

Global Outlook projections



A proven and safe technology that captures CO_2 emissions at the source and permanently stores them deep underground. One of the few proven technologies to help reduce emissions in critical, hard-to-decarbonize industrial sectors.

Hydrogen generates water vapor when combusted. Expected to become a key for replacing traditional furnace fuel. Has potential to lower emissions when used in commercial transportation in the long-term.

A lower-emission alternative to fossil fuels when combusted. Expected to become especially important in aviation, where electric batteries are too heavy to be feasible.

Source: ExxonMobil 2025

ExxonMobil 2025 Global Outlook (7)

Changes in the world's energy mix **are coming**

A broad array of energy types will be vital to a prosperous, lower-emissions future in 2050

Renewables will grow the most.

Solar and wind will grow from 3% today to more than 11% of the world's energy mix by 2050.

Oil production remains essential.

Demand for oil to make gasoline for cars will shrink by ~25% by 2050, but most of the world's oil is used for other things like manufacturing, plastics and other chemicals, and heavy-duty transport — all of which drive economic growth.

Coal use will decline the most.

By 2050, the world's use of coal will fall to levels not seen since before 2005. Many developing countries rely heavily on coal today, but over time it will be replaced by other alternatives as technology improves.

Demand for natural gas will grow significantly.

Growing electricity demand and industrial activity in developing countries drives a 20% increase in natural gas, which emits much less CO_2 than coal.

Electricity demand will expand, a lot.

Electricity demand will grow 70% by 2050, driven by population growth and improved living standards in developing countries. It will take all types of energy to meet this demand.

Commercial transportation and industrial activity will make up 50% of emissions in 2050 (up from 40% today).

To decarbonize these sectors, the world will have to deploy lower-emissions technologies such as biofuels, CCS, and hydrogen.

Oil and natural gas are essential. There's no other viable way to meet the world's energy needs.

Our Global Outlook projects that oil and natural gas will make up more than half of the world's energy supply in 2050. We project that oil demand will stabilize after 2030, remaining above 100 million barrels per day through 2050. However, demand for natural gas will rise by more than 20% — driven by higher electricity demand in developing countries.

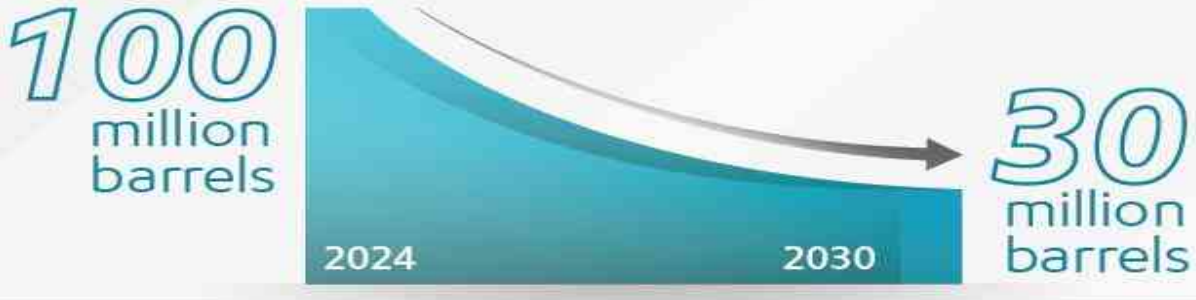
All major credible scenarios include oil and natural gas as a dominant energy source in 2050. Even in the average IPCC Likely Below 2° Scenario, where renewables will grow to 30%, oil and natural gas will still retain the biggest share of the global energy mix.

ExxonMobil 2025 Global Outlook (8)

Sustained oil and natural gas investment is **more important** than ever



Oil supply declines with no new investment (Sensitivity Analysis)



Our Global Outlook estimates oil production naturally declines at a rate of about 15% per year. This decline rate reflects the world's shift toward "unconventional" sources of oil supply, which are produced mainly from shale and dense rock formations that have a faster rate of decline versus other sources of supply.

With no new investment, global oil production would drop from roughly 100 million barrels per day currently to 85 million in the first year alone. By 2030, it would fall below 30 million barrels daily – 70 million short of projected demand.

As our Outlook shows, sustained investment in oil and natural gas development is needed to meet the world's needs. This is true even as companies like ExxonMobil invest billions to lower greenhouse gas emissions in their products, their operations, and for their industrial customers.

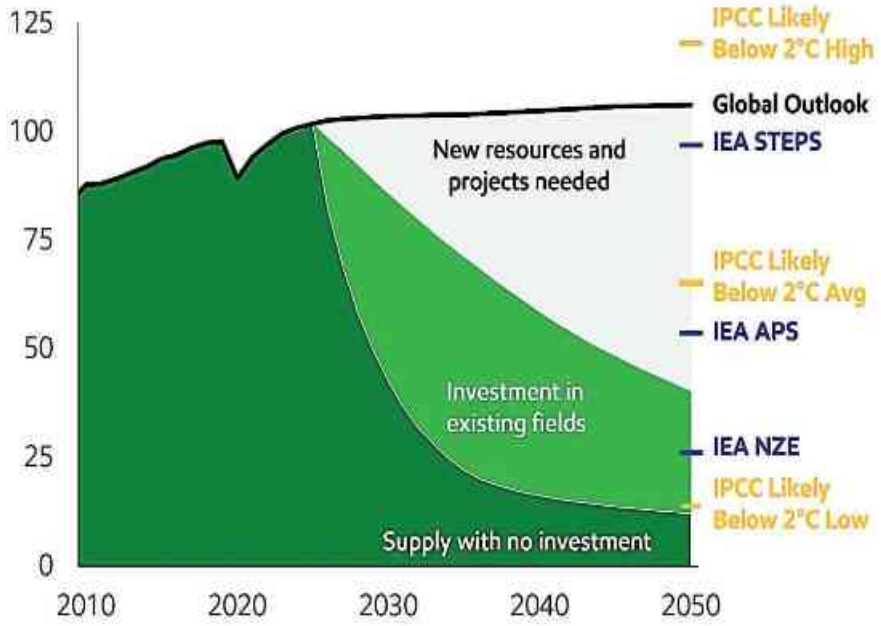
Source: ExxonMobil 2025

ExxonMobil 2025 Global Outlook (9)

Significant oil and natural gas investment needed to meet projected global demand

Projected global oil supply and demand

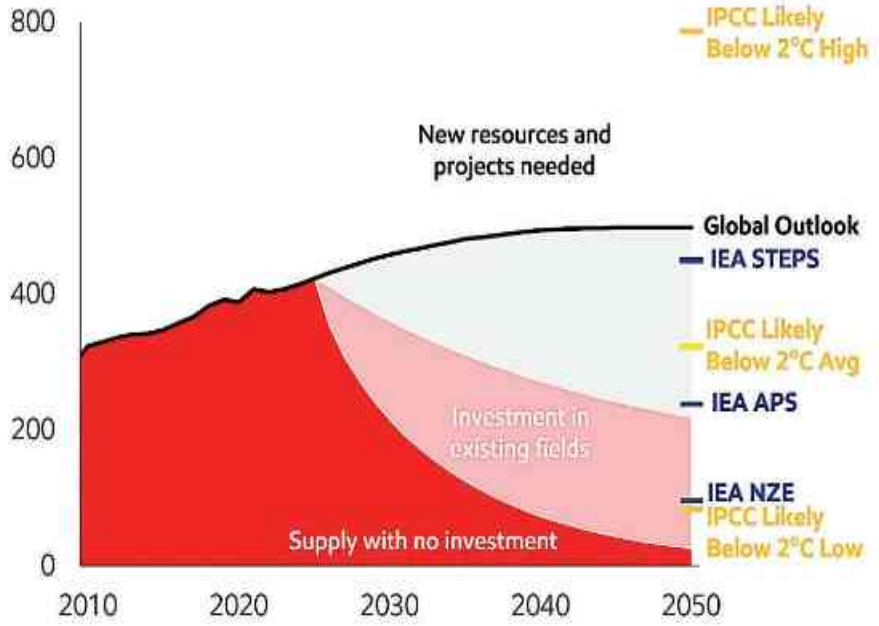
Million barrels per day



Excludes biofuels; IEA STEPS and IEA NZE Source: IEA WEO 2025; IEA APS Source: IEA WEO 2024; Global Outlook Source: ExxonMobil 2025 Global Outlook; IPCC Likely Below 2°C Average Source: IPCC AR6 Scenarios Database hosted by IIASA release 1.0 average IPCC C3:311 "Likely below 2°C" scenarios used; decline rates based on 10-yr Compound Annual Grown Rate (CAGR)

Projected global natural gas supply and demand

Billion cubic feet per day



Excludes flaring; IEA STEPS and IEA NZE Source: IEA WEO 2025; IEA APS Source: IEA WEO 2024; Global Outlook Source: ExxonMobil 2025 Global Outlook; IPCC Likely Below 2°C Average Source: IPCC AR6 Scenarios Database hosted by IIASA release 1.0 average IPCC C3: 311 "Likely below 2°C" scenarios used; decline rates based on 10-yr CAGR

Source: ExxonMobil Annual Report 2025

BP Scenarios

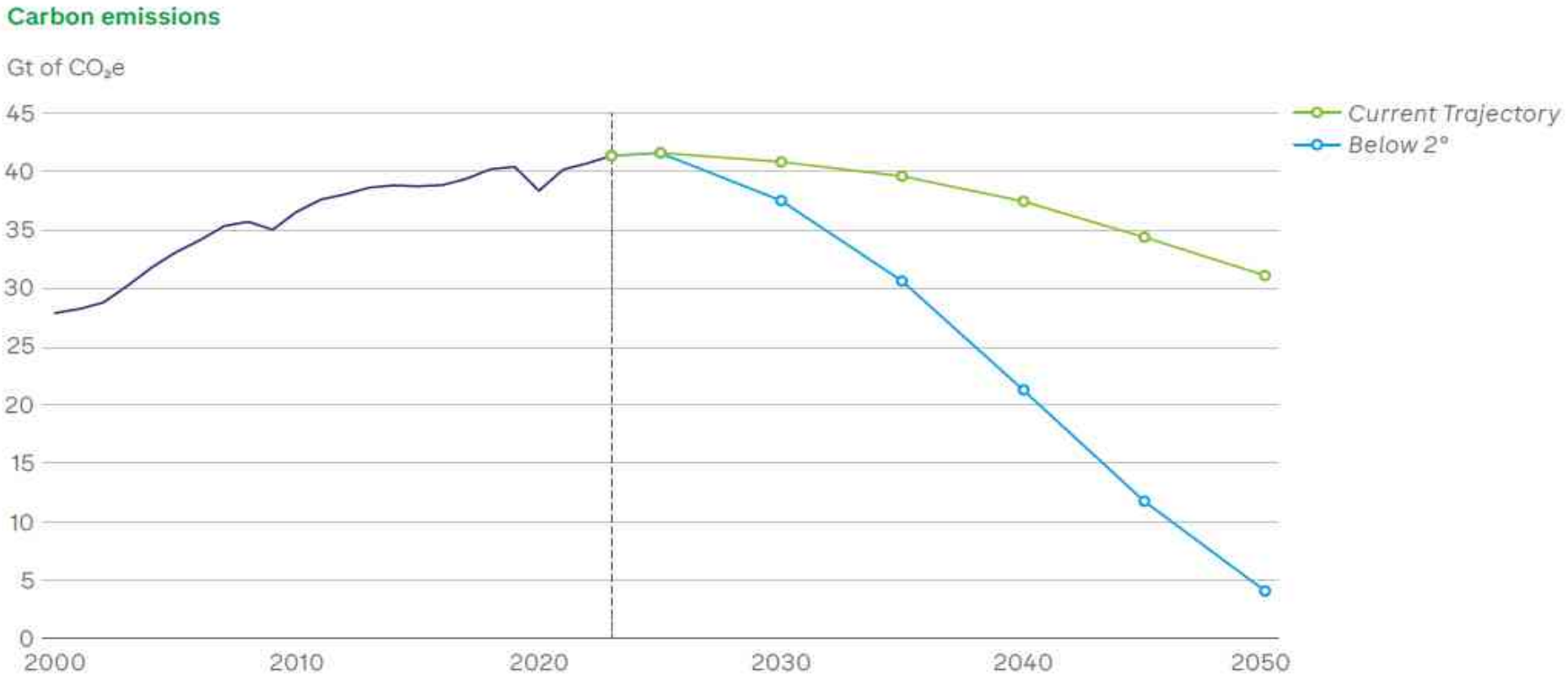
The BP Scenarios - BP Energy Outlook 2025

- This year's *Energy Outlook* is focused on two main scenarios: *Current Trajectory* and *Below 2°C*.
- These scenarios are not predictions of what is likely to happen or what BP would like to happen. Rather they explore the possible implications of different judgements and assumptions concerning the nature of the energy transition.
- The scenarios are based on existing technologies and do not consider the possible impact of entirely new or unknown technologies.

Source: BP Energy Outlook 2025

Carbon emissions in both scenarios
A vision by BP 2025 (1)

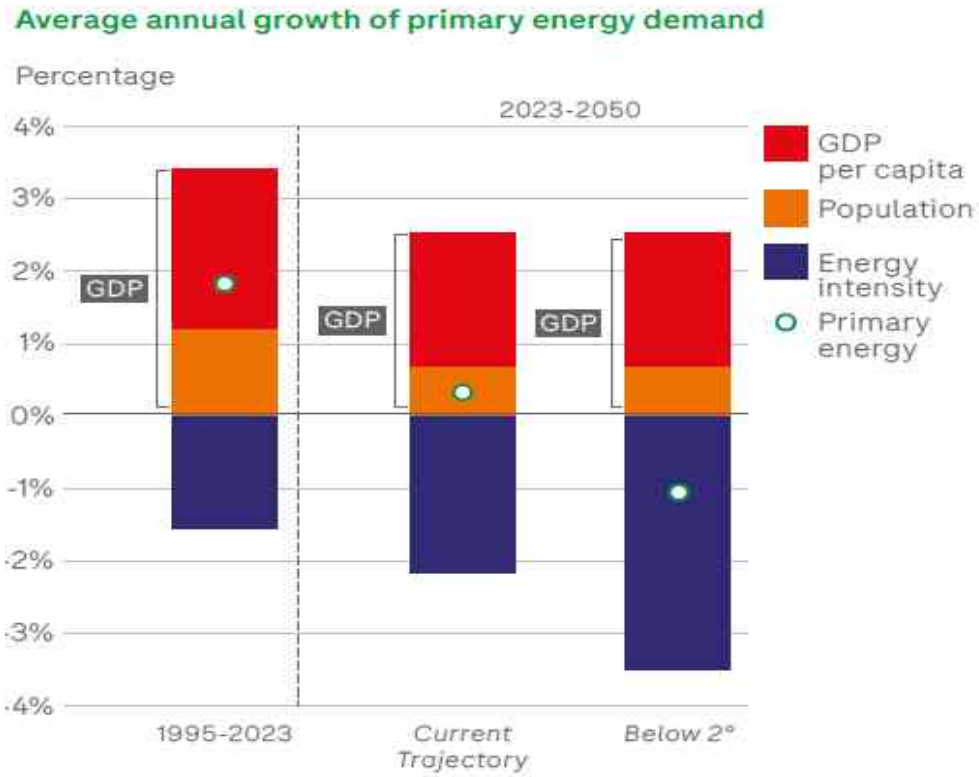
Two scenarios to explore the path of the energy transition out to 2050

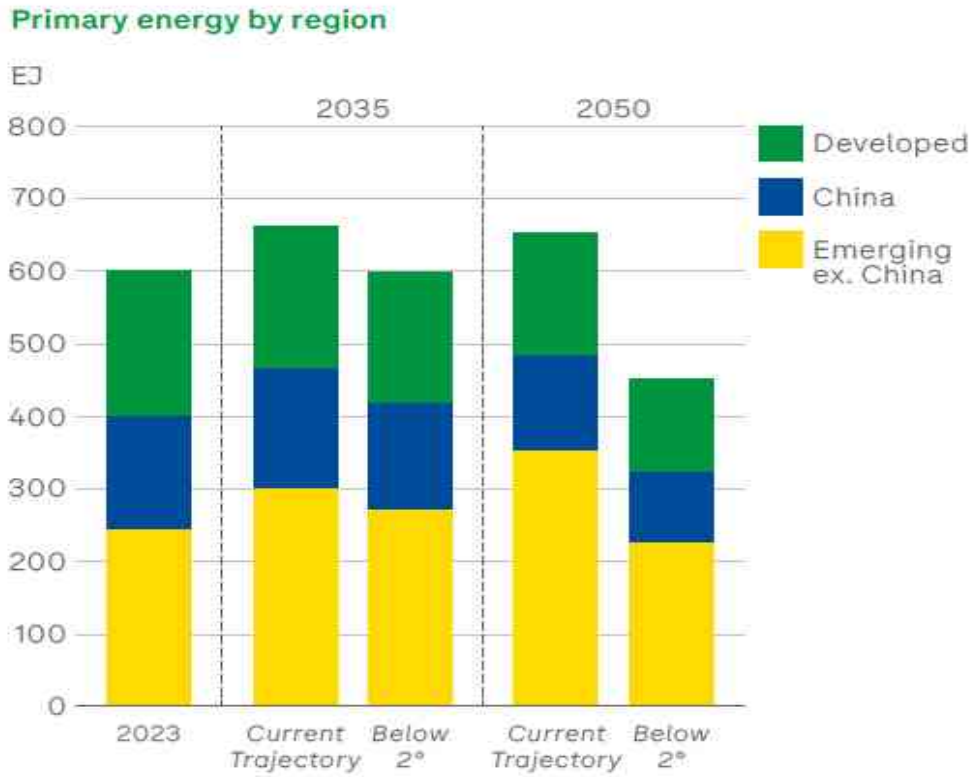


Source: BP Energy Outlook 2025

Primary Energy Demand
A vision by BP 2025 (2)

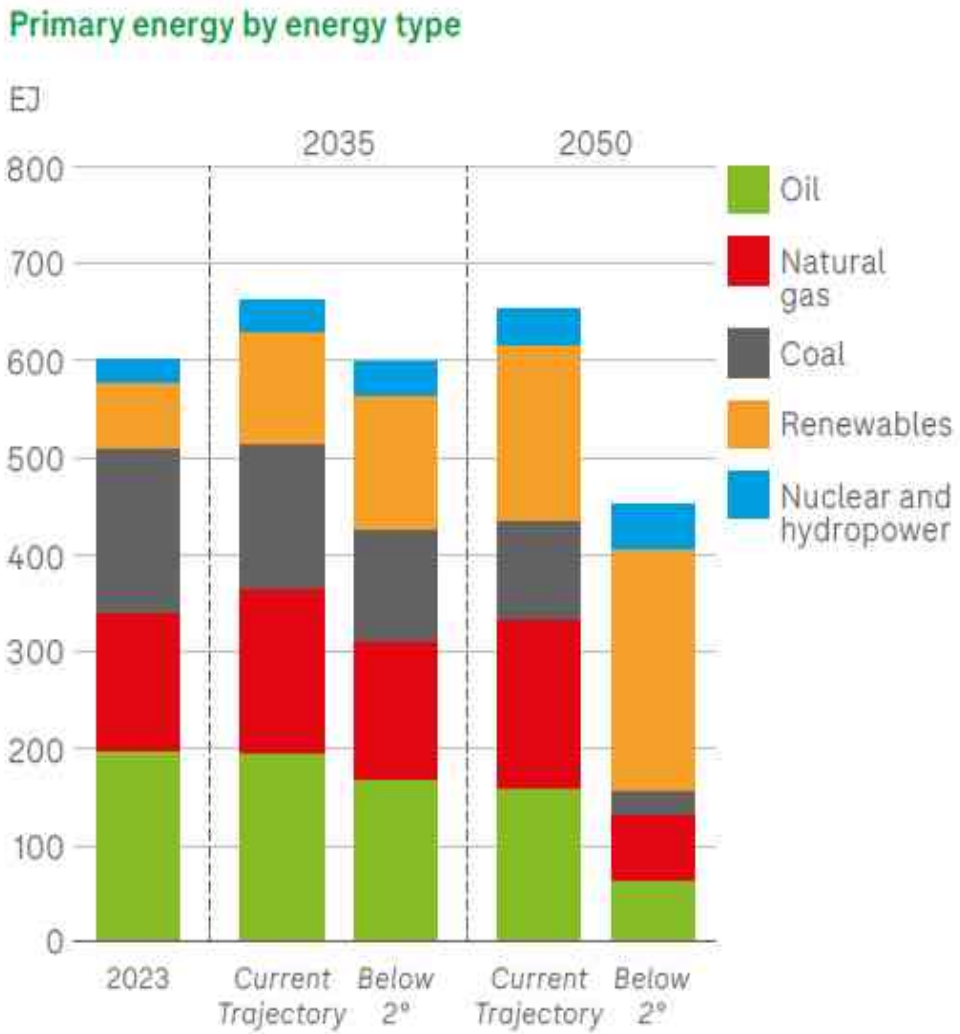
Growth in primary energy is driven by emerging economies, with its scale dependent on the path of energy efficiency

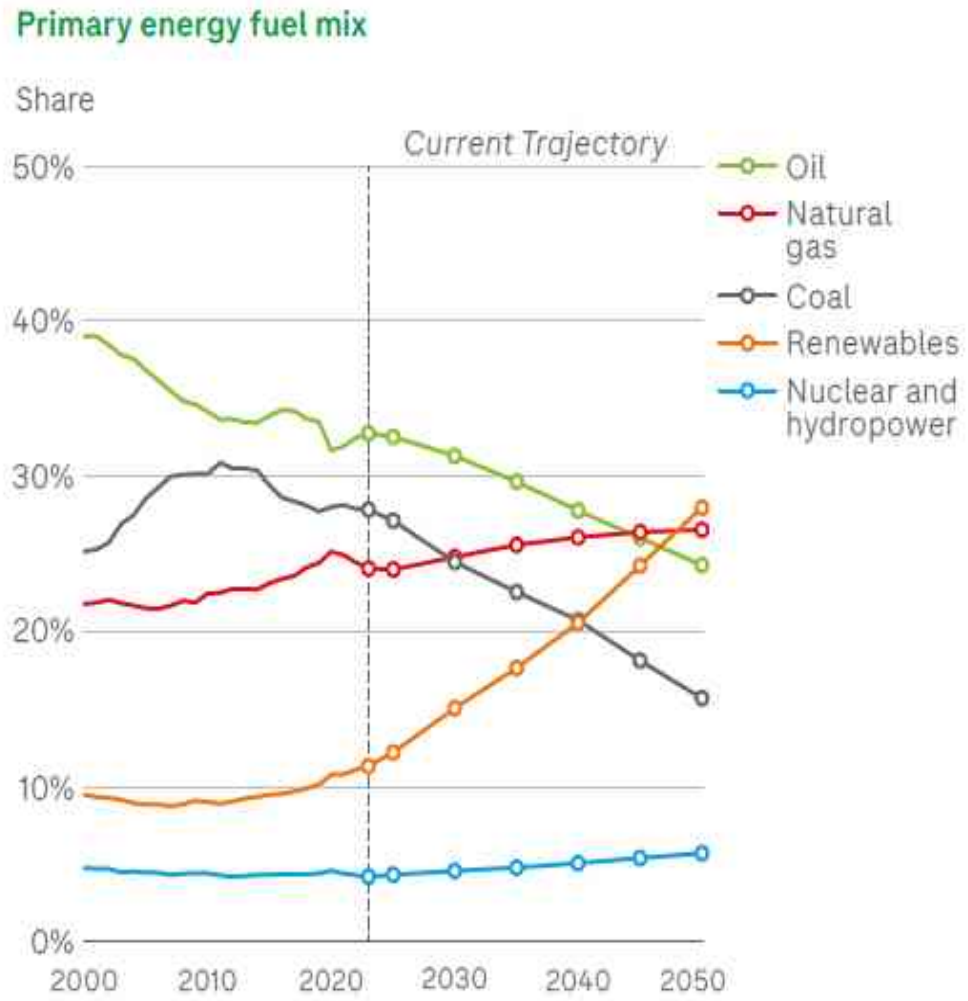




Source: BP Energy Outlook 2025

Primary Energy Demand
A vision by BP 2025 (3)

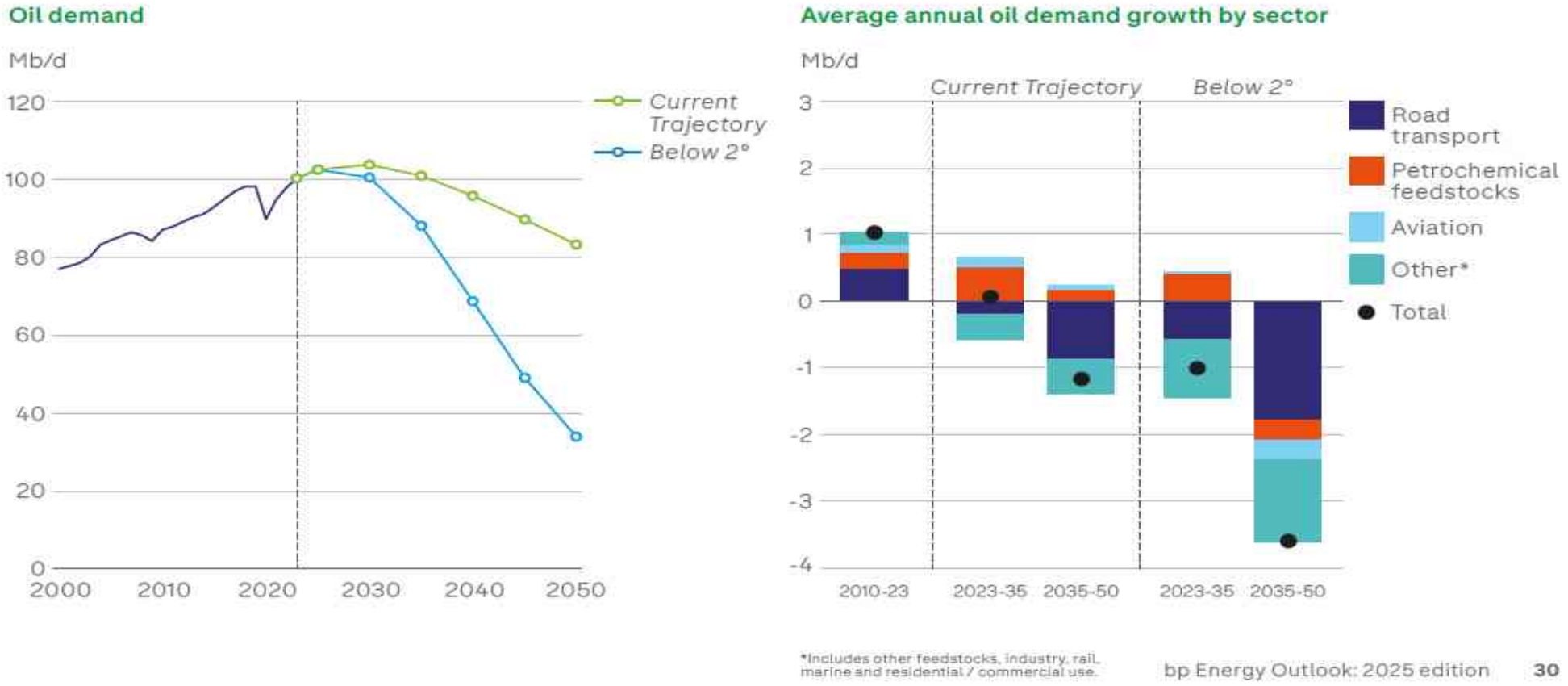




Source: BP Energy Outlook 2025

Oil Demand will continue to have a prominent effect
A vision by BP 2025 (4)

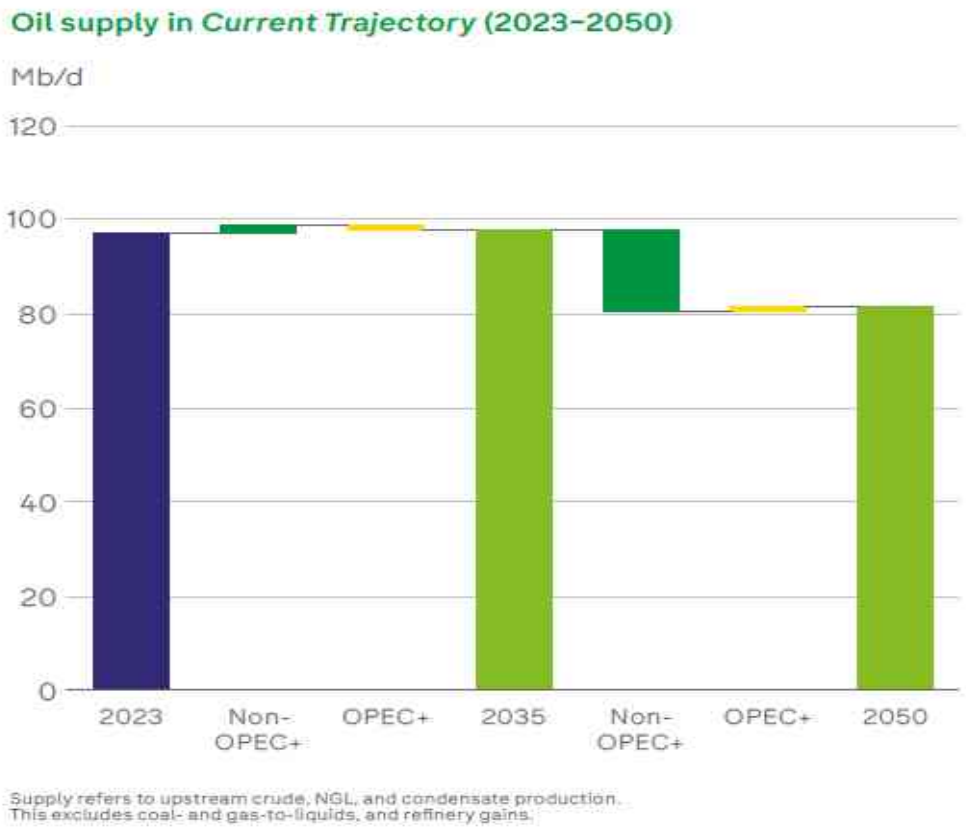
Oil continues to play a major role in the global economy

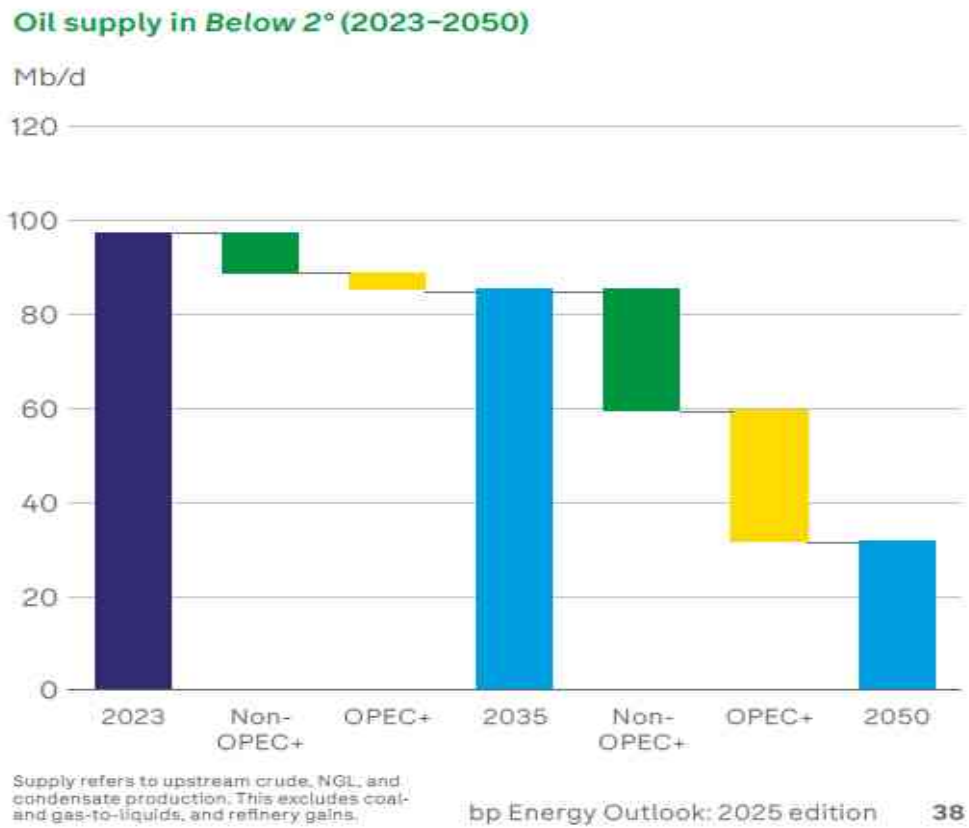


Source: BP Energy Outlook 2025

Oil Supply driven by US tight Oil evolution
A vision by BP 2025 (5)

The pattern of global oil supplies changes as US tight oil peaks and oil demand declines



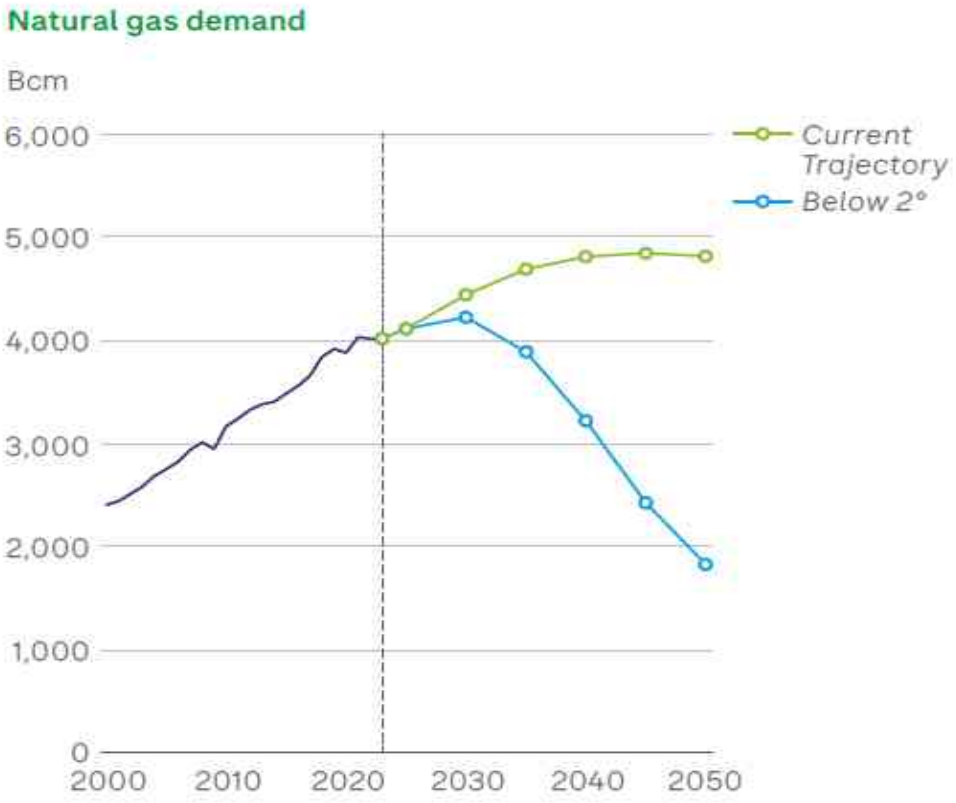


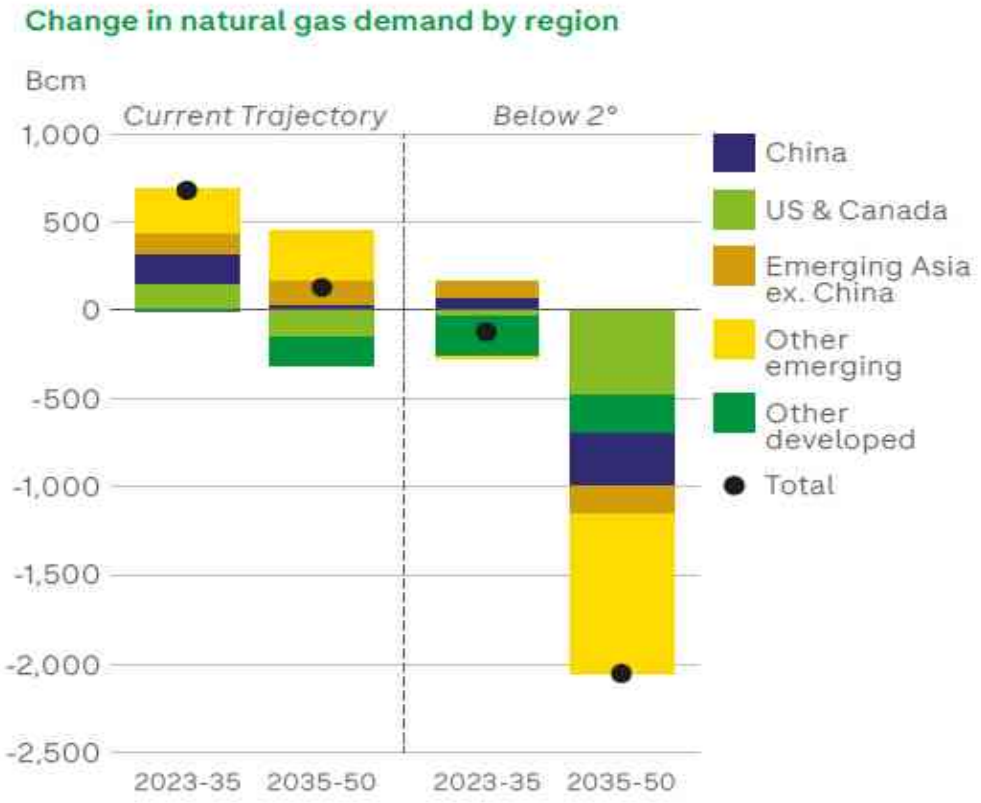
bp Energy Outlook: 2025 edition 38

Source: BP Energy Outlook 2025

Gas Demand
A vision by BP 2025 (5)

The outlook for gas demand depends on the speed of the energy transition

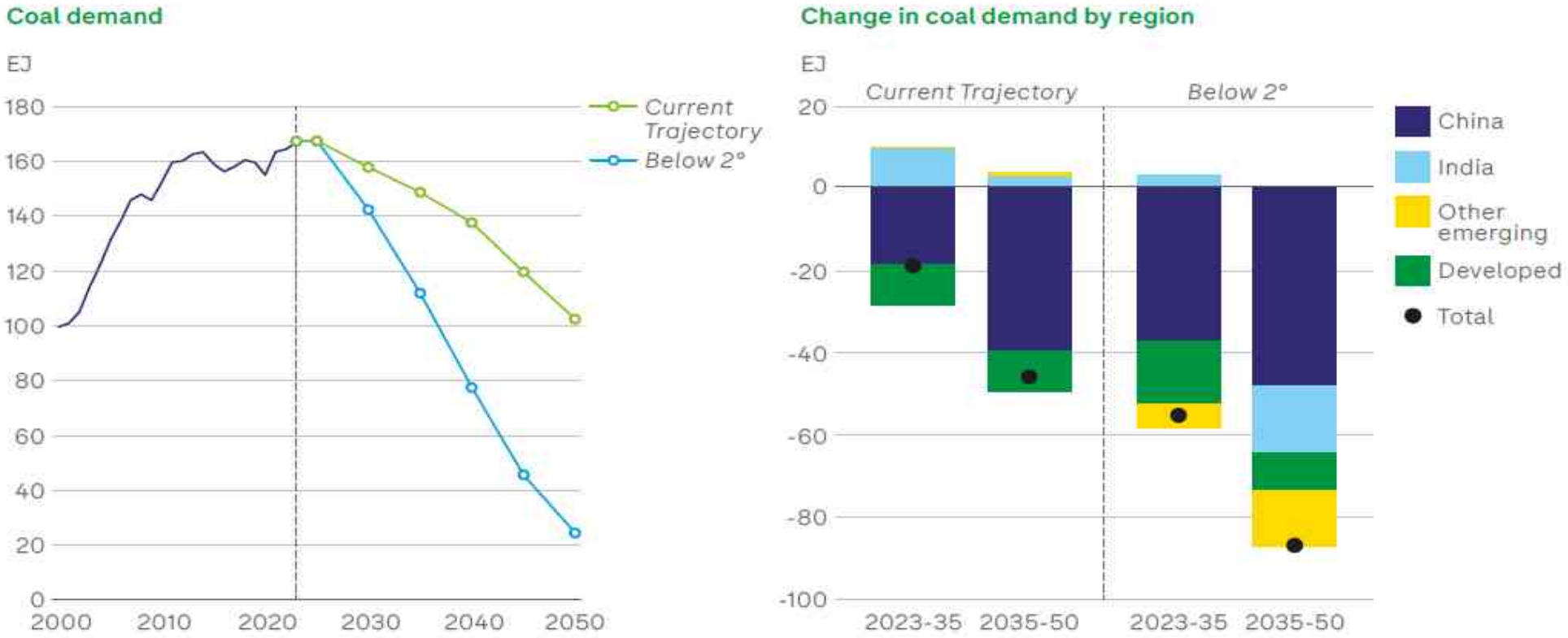




Source: BP Energy Outlook 2025

Coal Demand is declining sharply
A vision by BP 2025 (6)

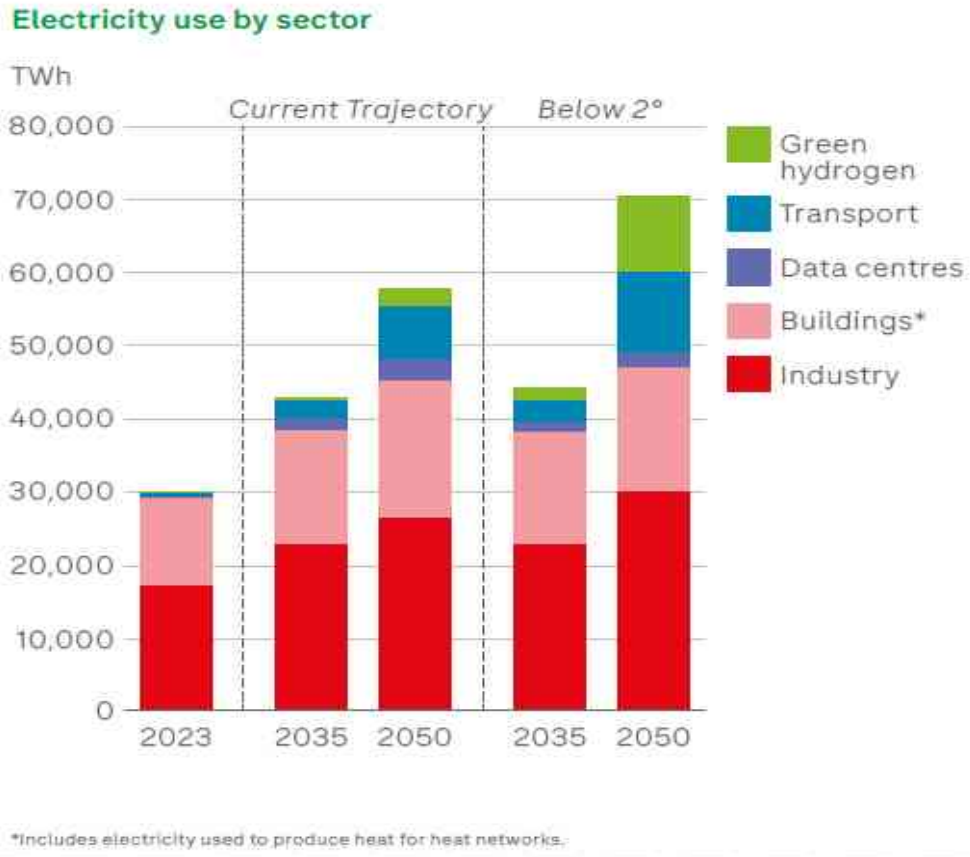
The role of coal in the global energy system declines, led by China

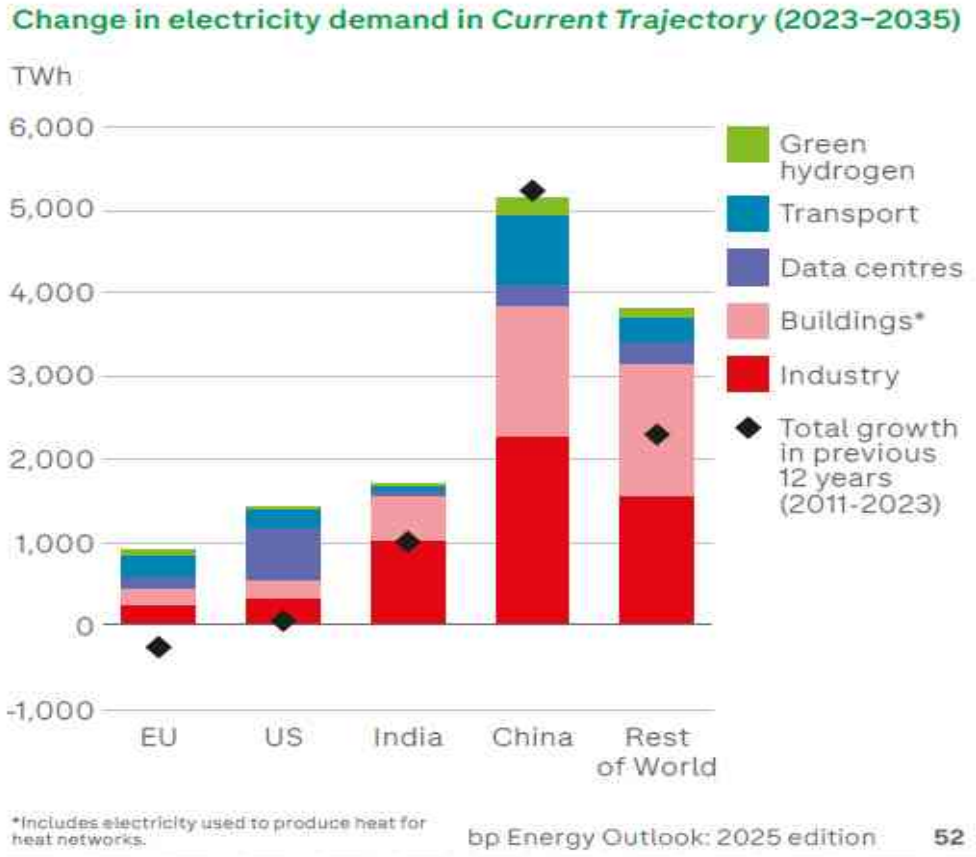


Source: BP Energy Outlook 2025

Electricity use is growing sharply
A vision by BP 2025 (7)

Electricity use grows rapidly, as emerging economies' demand rises and all sectors electrify

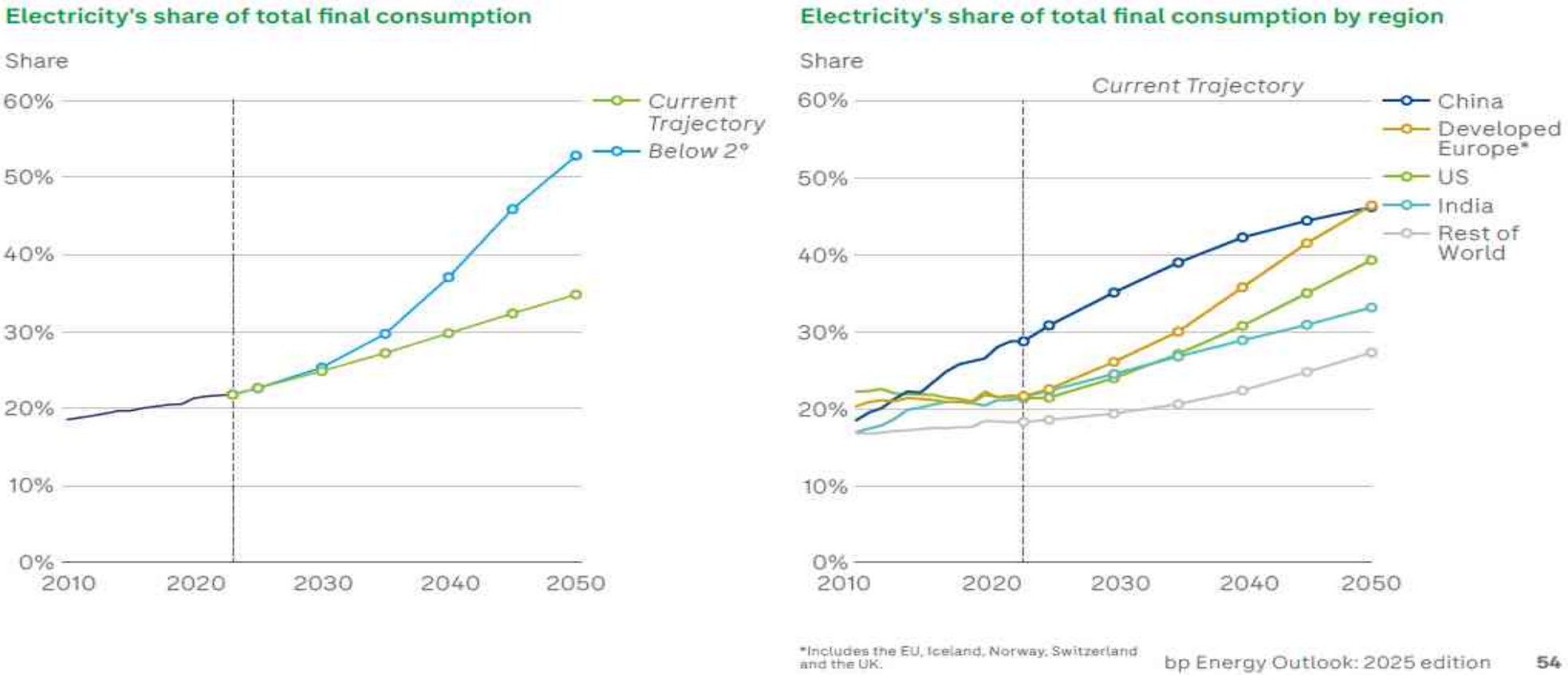




Source: BP Energy Outlook 2025

Electricity use is growing sharply
A vision by BP 2025 (8)

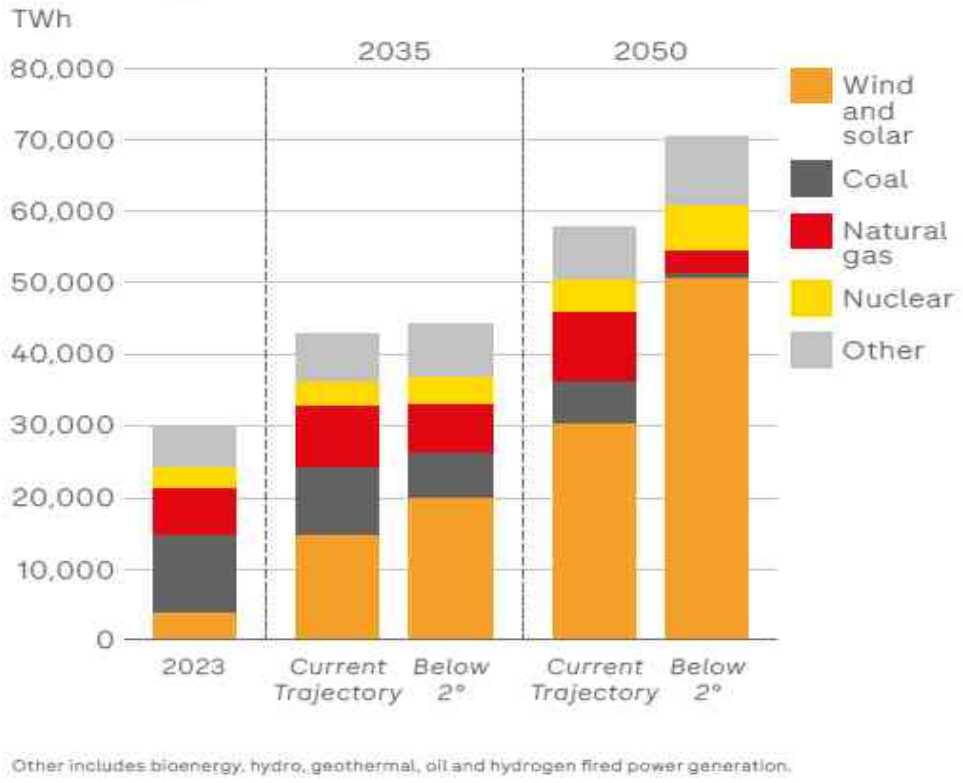
The global energy system continues to electrify

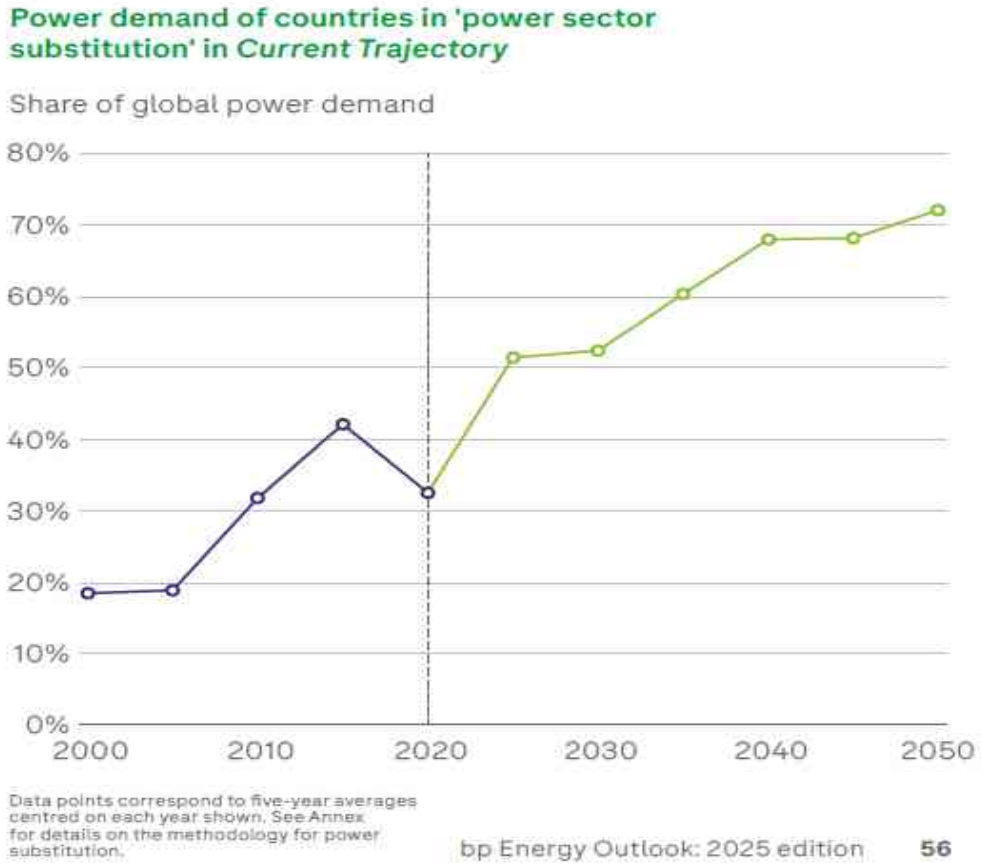


Source: BP Energy Outlook 2025

Electricity use is growing sharply mostly thanks to Wind & Solar
A vision by BP 2025 (9)

Growing electricity demand is mostly met by rapid increases in wind and solar power

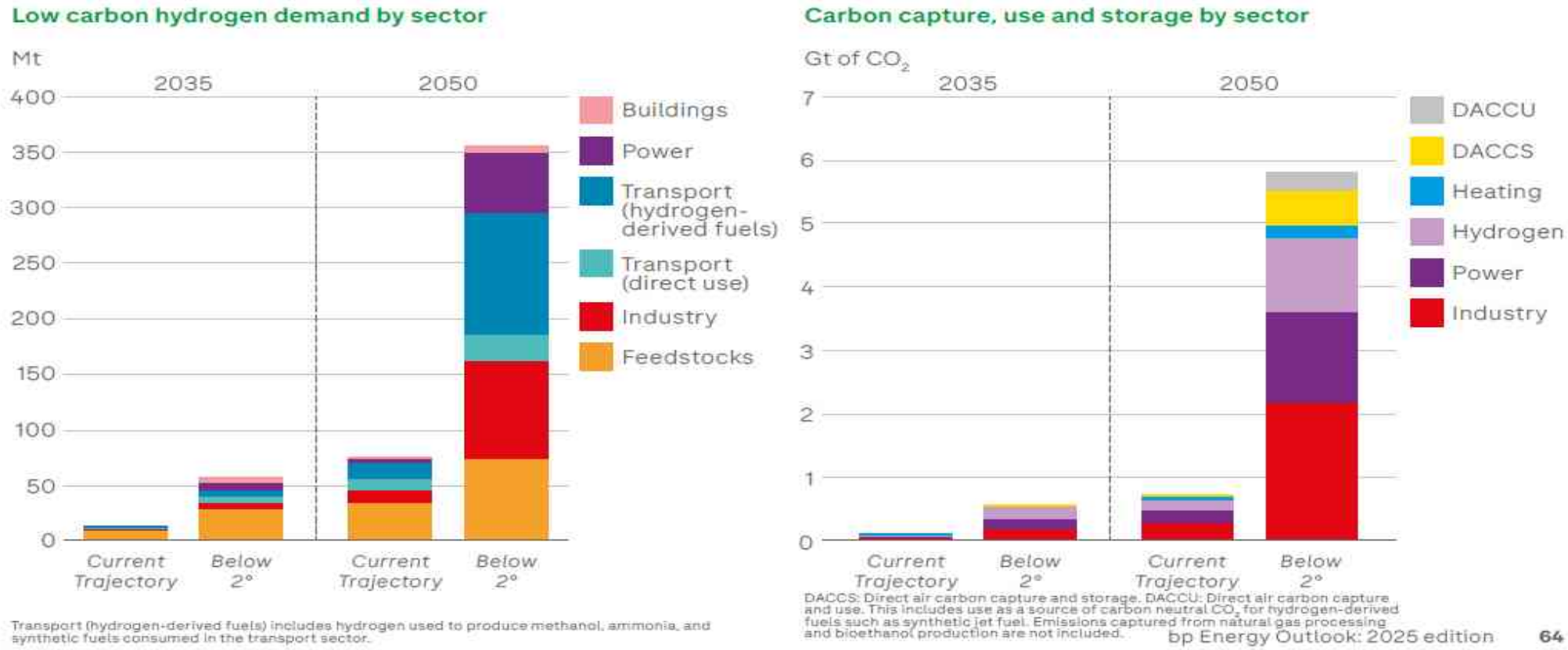




Source: BP Energy Outlook 2025

Low Carbon Hydrogen & CCUS: growing impact anticipated
A vision by BP 2025 (10)

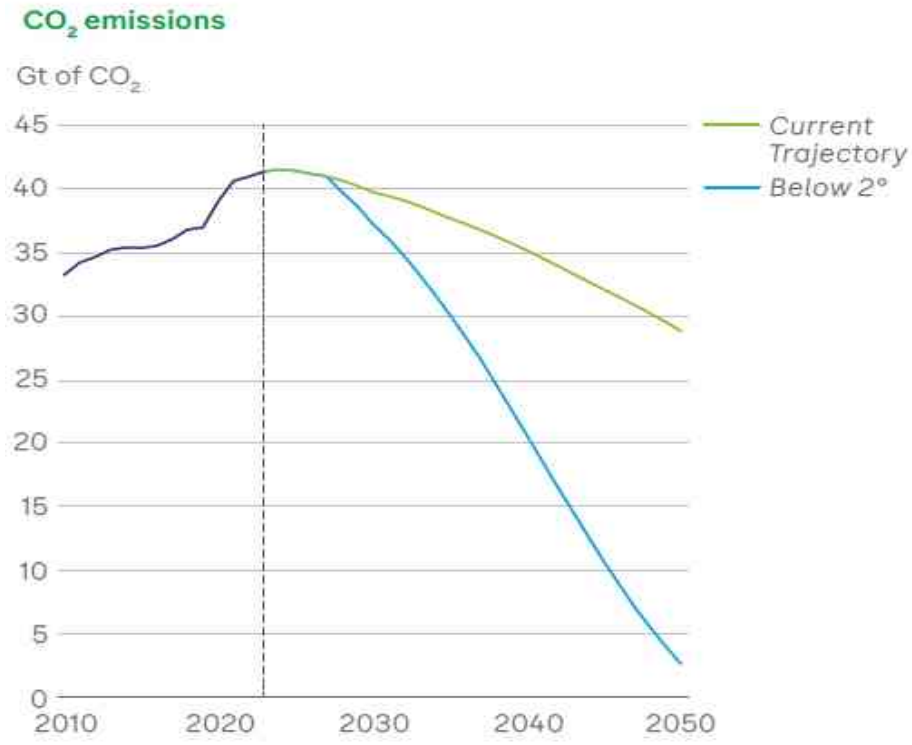
Low carbon hydrogen and CCUS play important roles supporting deep decarbonization pathways

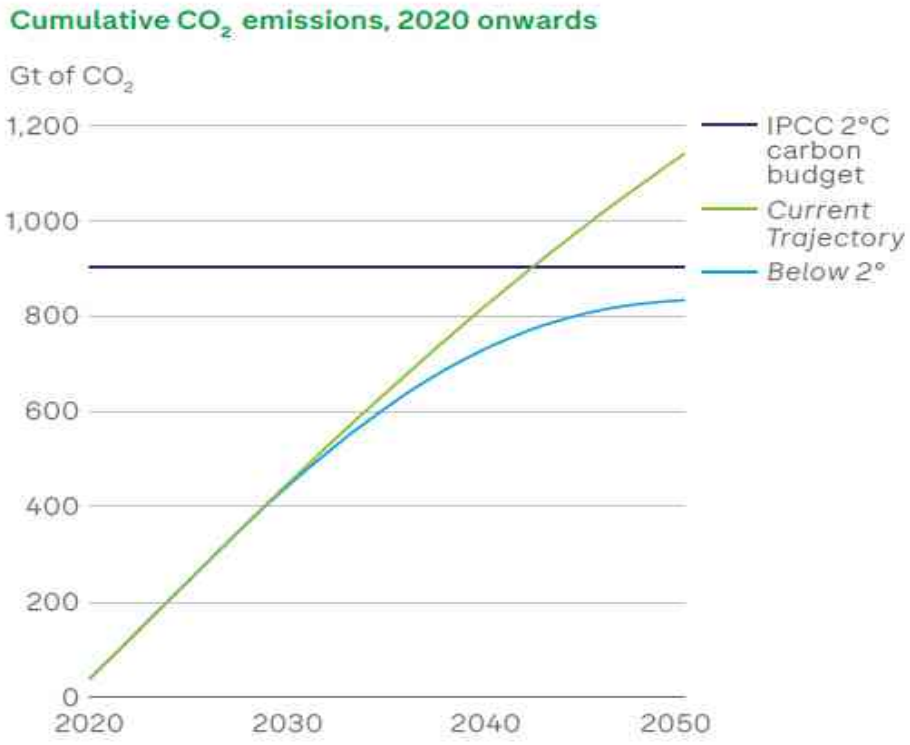


Source: BP Energy Outlook 2025

CO2 Emissions: the challenges
A vision by BP 2025 (11)

Challenges to remaining within a 2°C carbon budget





Includes emissions from AFOLU and excludes methane emissions from energy.

bp Energy Outlook: 2025 edition 82

Source: BP Energy Outlook 2025

US EIA International Energy Outlook (IEO)

US Energy Information Administration (EIA) no longer expects to publish one of its major energy reports this year after losing some of its staff through President Donald Trump's efforts to downsize the federal workforce.

The last EIA IEO (International Energy Outlook) report is dated 2023.

For Energy Scenarios in the US, see Book 6

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

The IEO2023 includes cases that vary technical and economic assumptions

- All cases reflect current laws and regulations as of March 2023, and the U.S. results come directly from the AEO2023, which assumes U.S. laws and regulations as of November 2022 remain unchanged.

Case	Assumptions
Reference	Global average annual GDP (purchasing power parity) percentage change (2022–2050): 2.6% Brent: $102 per barrel (2022$) in 2050 Zero-carbon technologies' 2022–2050 cost reductions: up to 20%
Economic Growth	Low: 1.8% average annual GDP percentage change (2022–2050) High: 3.4% average annual GDP percentage change (2022–2050)
Oil Price	Low: $48 per barrel (2022$) in 2050 High: $187 per barrel (2022$) in 2050
Zero-Carbon Technology Cost (electric power sector)	Low: 40% reduction in capital costs below Reference case by 2050 High: No reduction in costs

Note: Zero-carbon technologies include solar, wind, battery storage, and nuclear.

Source: EIA IEO 2023 – October 2023

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

IEO2023 Highlights

- Increasing population and income offset the effects of declining energy and carbon intensity on emissions.
- The shift to renewables to meet growing electricity demand is driven by regional resources, technology costs, and policy.
- Energy security concerns hasten a transition from fossil fuels in some countries, although they drive increased fossil fuel consumption in others.

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

Things to keep in mind

- Although we model a number of cases, we do not comprehensively address all issues that could drive significant change, like in a forecast.

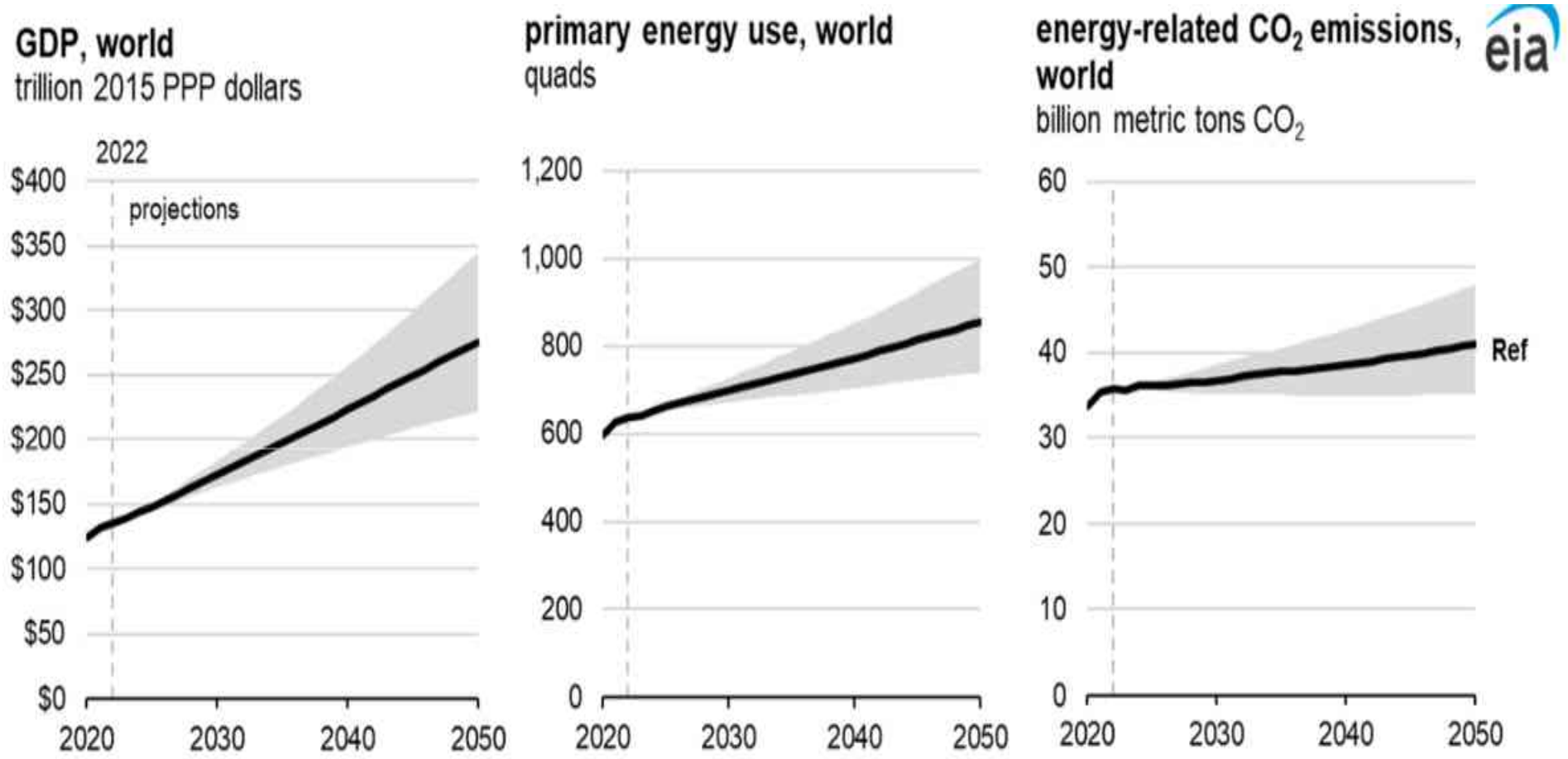
- New policies, geopolitical events, and technology breakthroughs will happen that shift the trajectory of the global energy system.

Therefore:

- IEO2023 is **not** a forecast.

- IEO2023 represents a set of policy-neutral baselines that focus on the current trajectory of the global energy system.

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

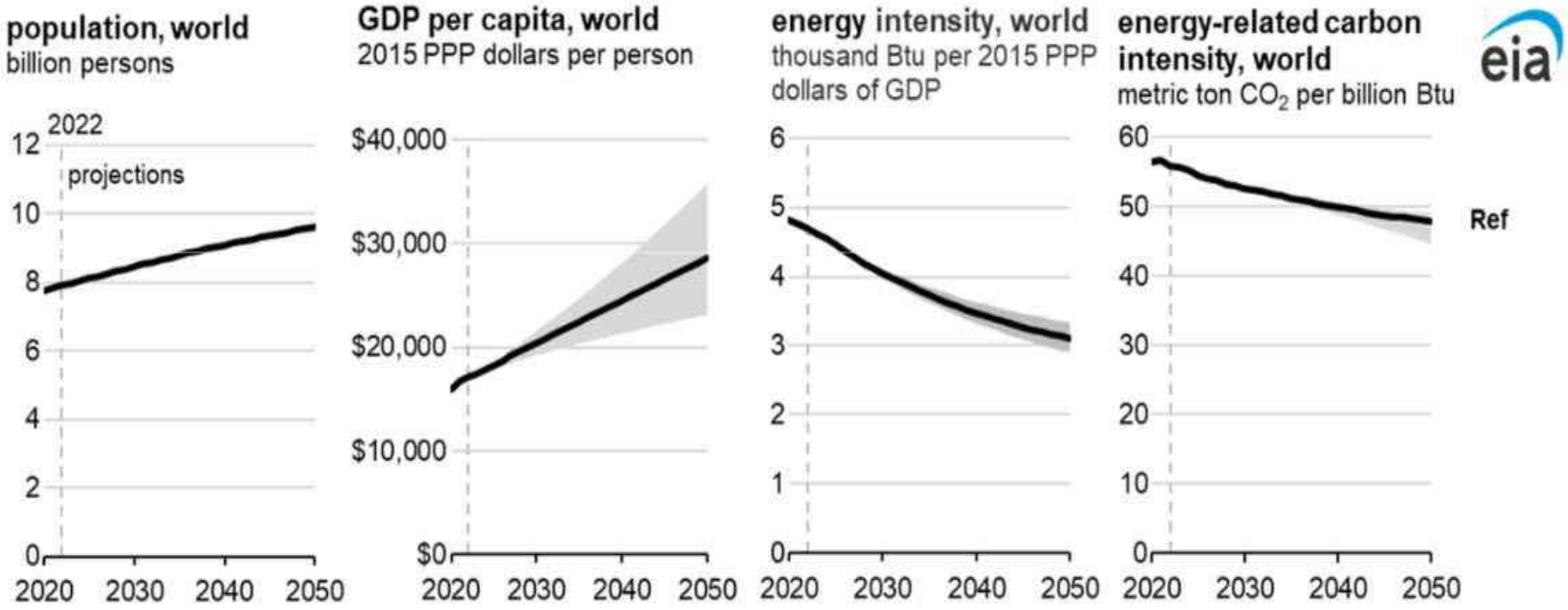


Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases. Ref=Reference case; GDP=gross domestic product; quads=quadrillion British thermal units; PPP=purchasing power parity.

Source: EIA IEO 2023 – October 2023

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

The upward pressures of population and GDP growth outweigh the downward pressures of energy and carbon intensity on emissions

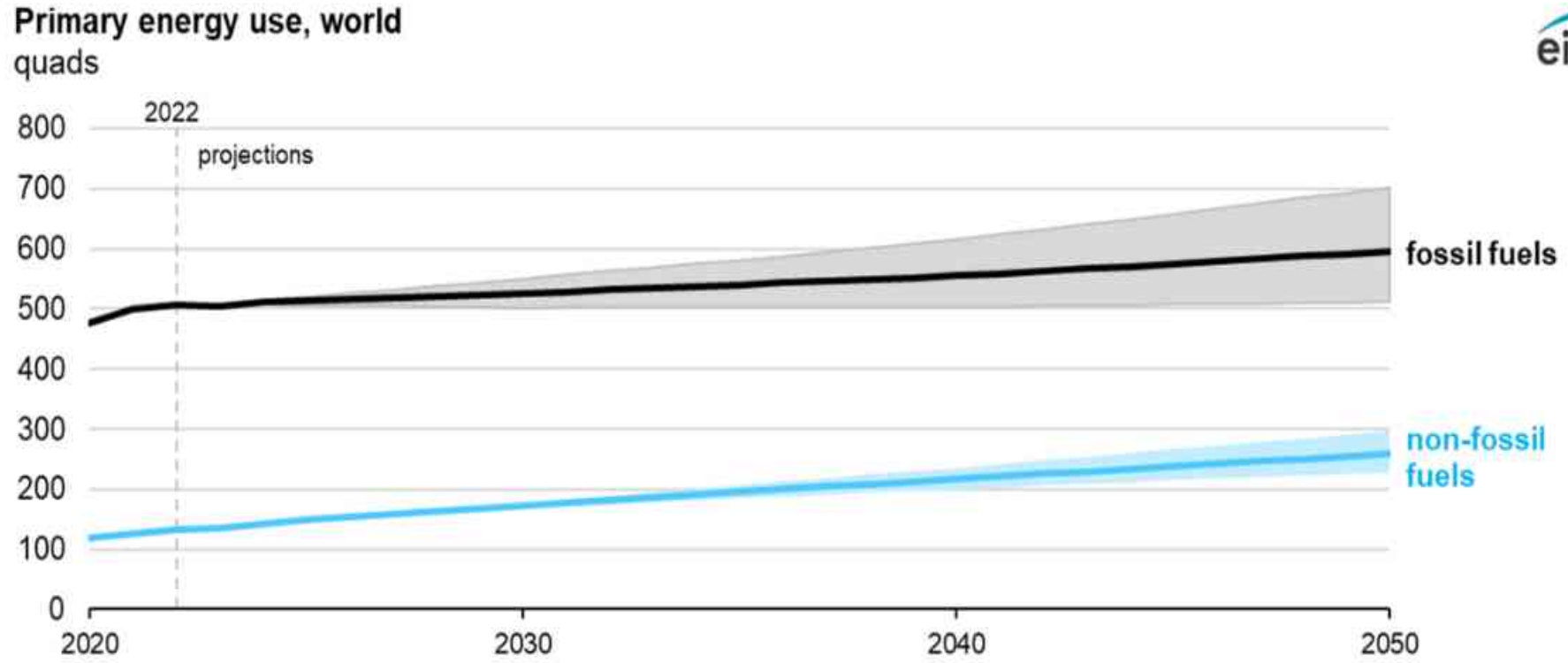


Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases. Our global population assumptions do not vary across side cases. GDP=gross domestic product; PPP=purchasing power parity; Btu=British thermal units; Ref=Reference case.

Source: EIA IEO 2023 – October 2023

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

Increasing demand and current policies drive steady growth in fossil fuel energy—and faster growth in non-fossil fuel sources

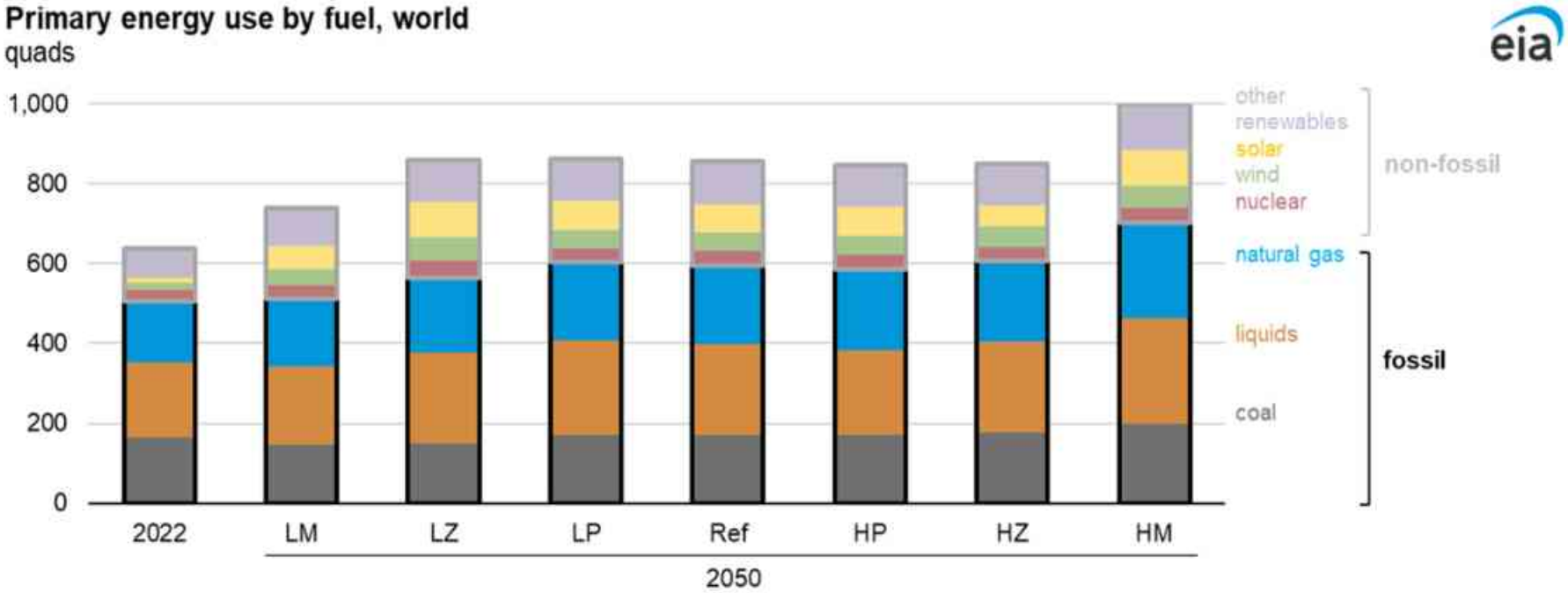


Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Each line represents IEO2023 Reference case projections. Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases. Quads=quadrillion British thermal units.

Source: EIA IEO 2023 – October 2023

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

Renewable energy grows the fastest as a share of primary energy consumption across all cases due to current policy and cost drivers

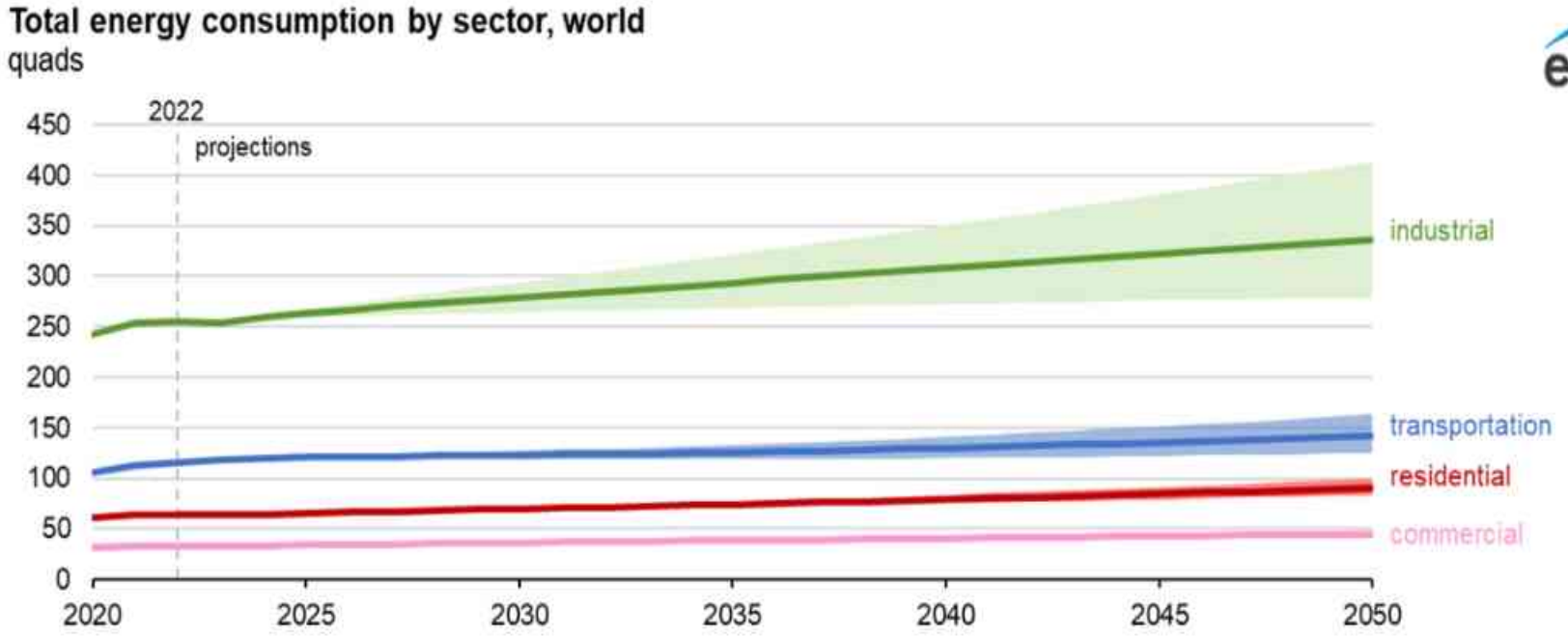


Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Biofuels are included in the "other renewables" category. Quads=quadrillion British thermal units; HZ=High Zero-Carbon Technology Cost case; LZ=Low Zero-Carbon Technology Cost case; HM=High Economic Growth case; LM=Low Economic Growth case; HP=High Oil Price case; LP=Low Oil Price case; Ref=Reference case.

Source: EIA IEO 2023 – October 2023

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

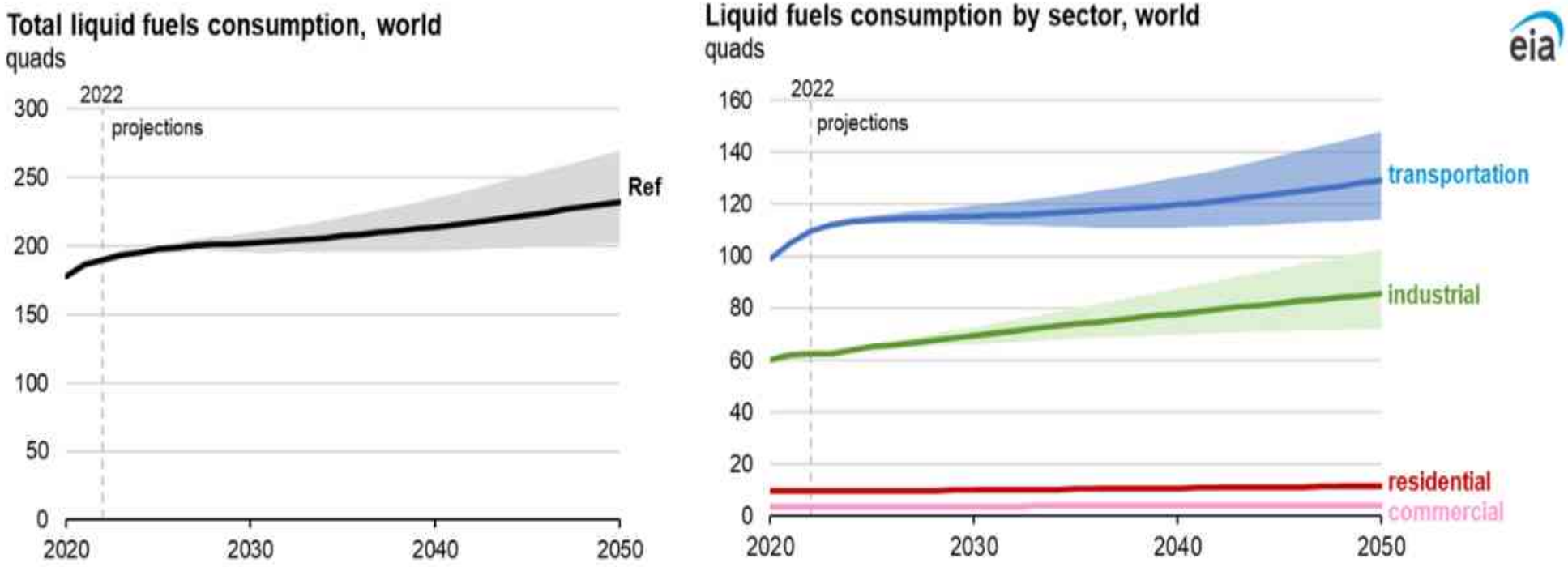
Across all IEO2023 cases, energy consumption increases, and global demand grows fastest in the industrial and residential sectors



Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Quads=quadrillion British thermal units. Each line represents IEO2023 Reference case projections. Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases.

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

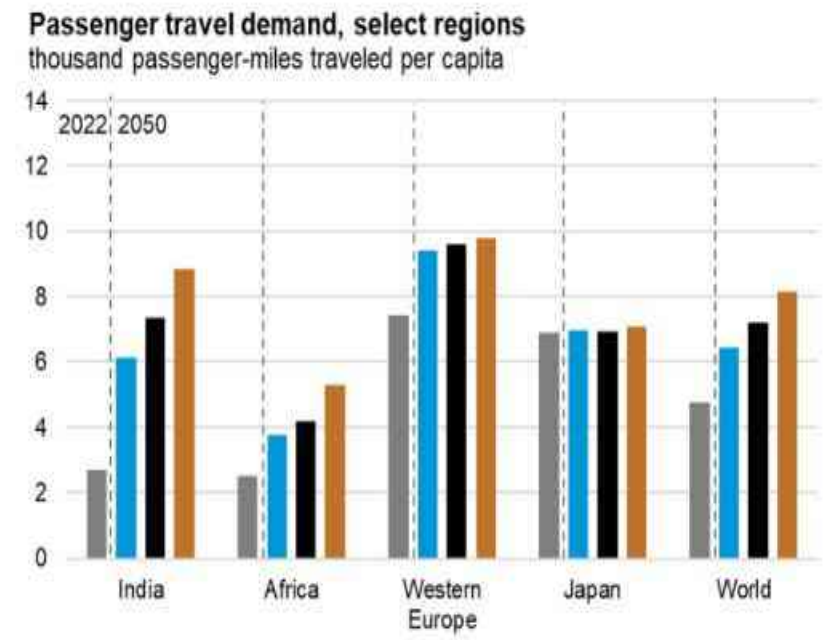
Under current laws, liquid fuels consumption increases through 2050 across all cases, driven by growth in the industrial sector



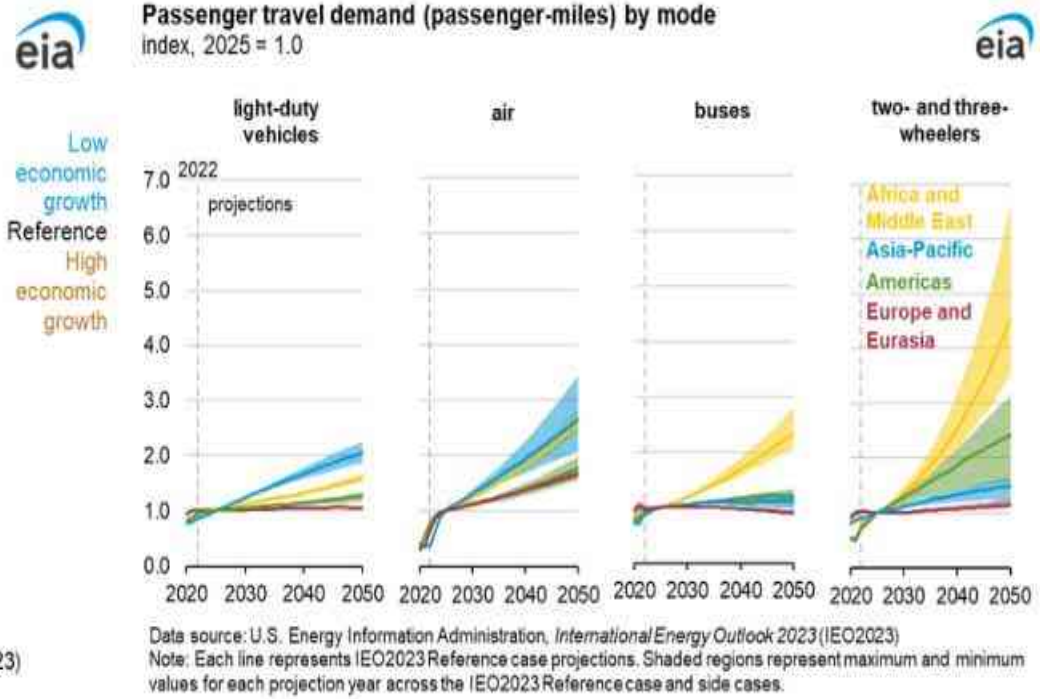
Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Each line represents IEO2023 Reference case projections. Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases. Quads=quadrillion British thermal units; Ref=Reference case.

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

Increasing passenger demand drives global transportation consumption; Rising income enables travelers to shift from inexpensive, more efficient modes to more convenient, less efficient modes



Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)

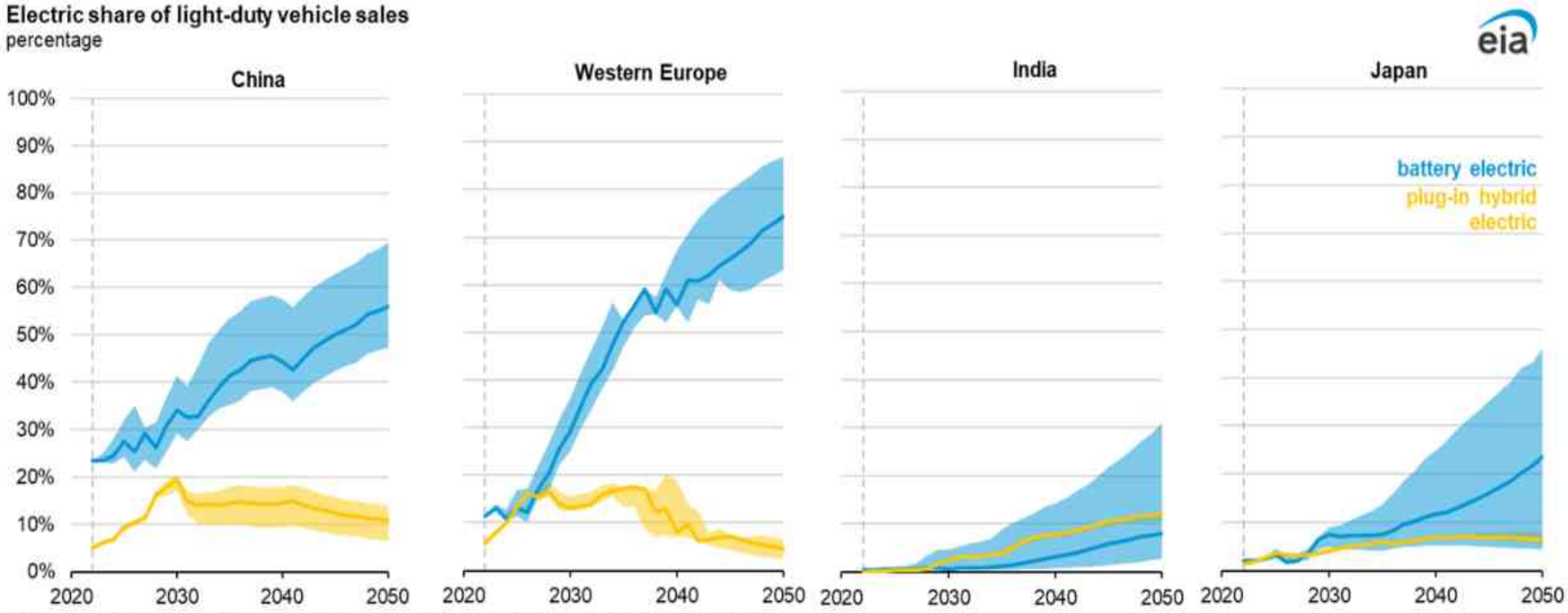


Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Each line represents IEO2023 Reference case projections. Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases.

Source: EIA IEO 2023 – October 2023

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

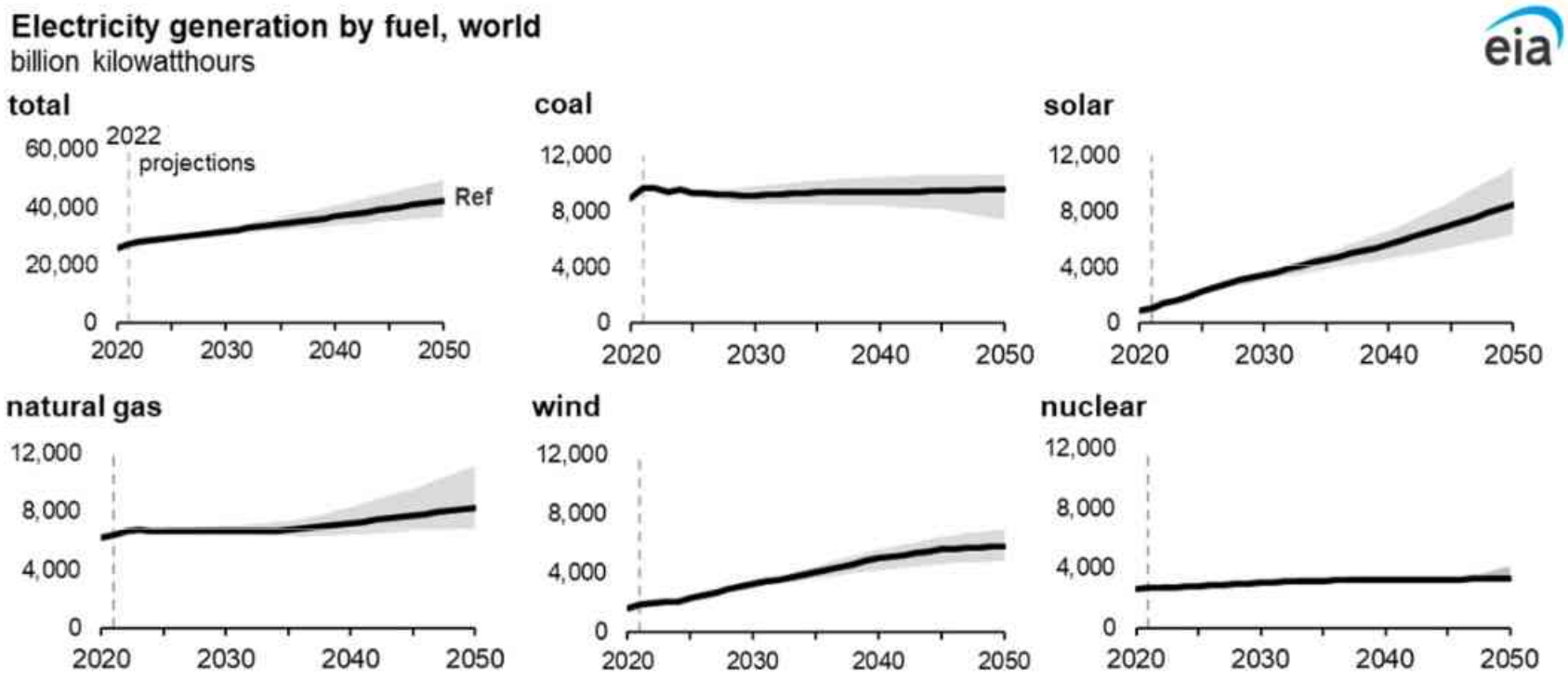
Electric vehicle sales grow due to policy incentives, battery costs, efficiency standards, and electricity prices



Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Each line represents IEO2023 Reference case projections. Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases.

EIA IEO 2023 Scenarios (No updates for 2024 & 2025)

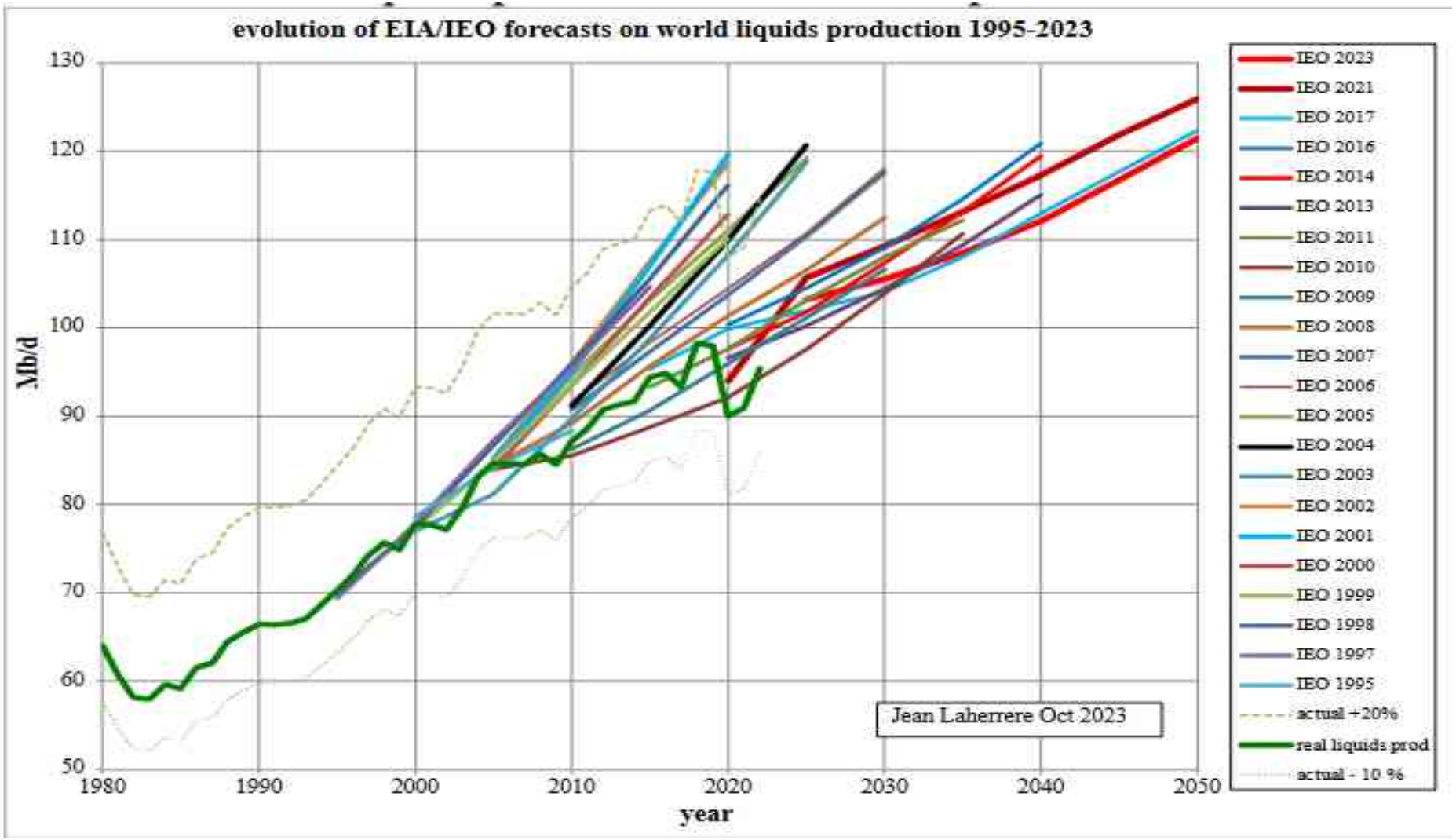
Total electricity generation worldwide increases 30% to 76% relative to 2022 across cases, and renewables and nuclear supply 54% to 67% of the total demand across cases in 2050



Data source: U.S. Energy Information Administration, *International Energy Outlook 2023* (IEO2023)
Note: Shaded regions represent maximum and minimum values for each projection year across the IEO2023 Reference case and side cases.
Ref=Reference case.

Source: EIA IEO 2023 – October 2023

World Liquids Production by EIA – IEO
Forecasting is a difficult exercise!

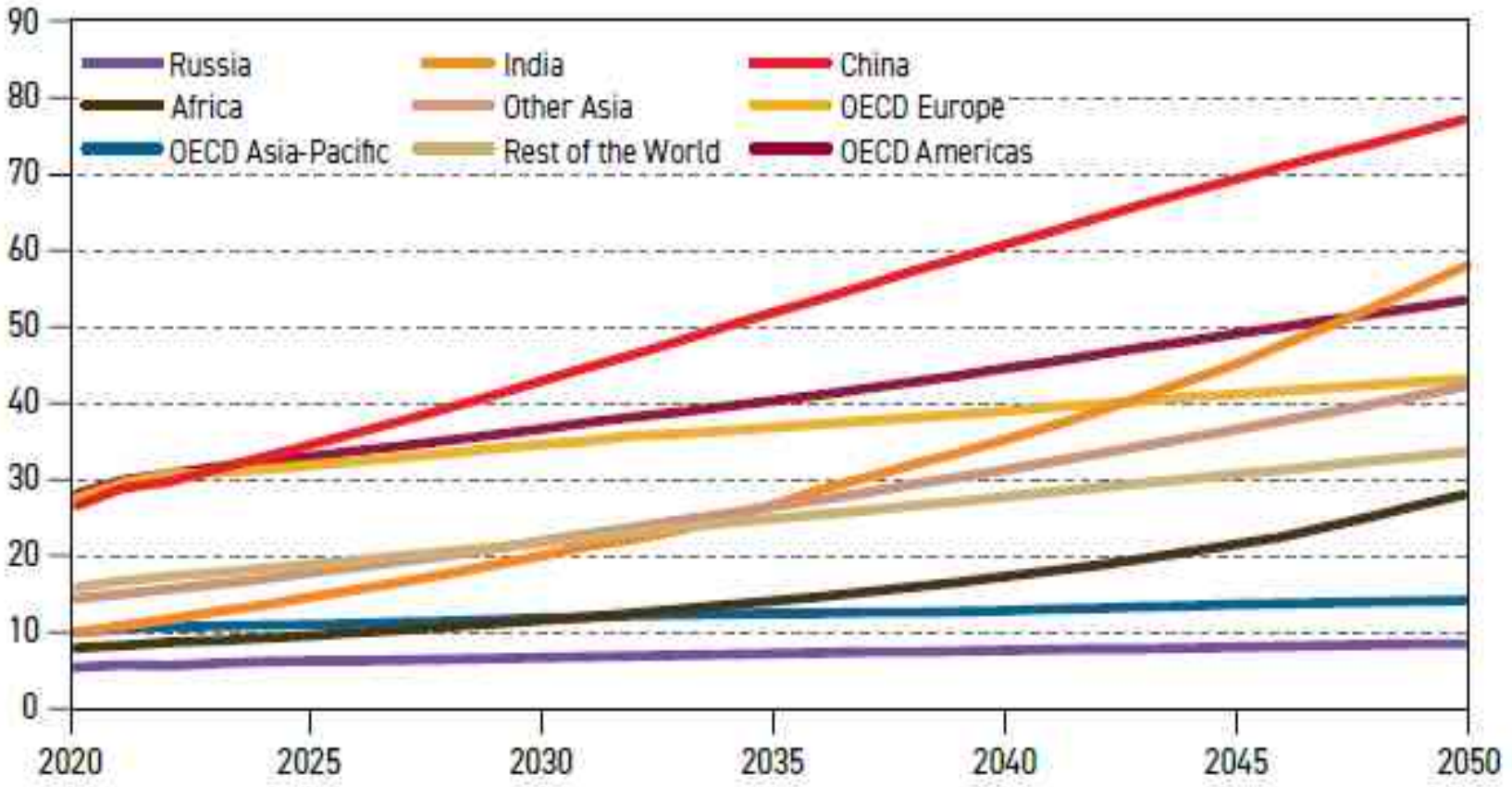


Source: Jean Laherrère – October 2023

OPEC Scenarios

GDP PPP of major Economies
A vision by OPEC 2026 (1)

GDP of major economies, 2020–2050, $(2021 PPP) trillion



Source: OPEC WOO 2026 – June 2026

World Economic Growth
A vision by OPEC 2026 (2)

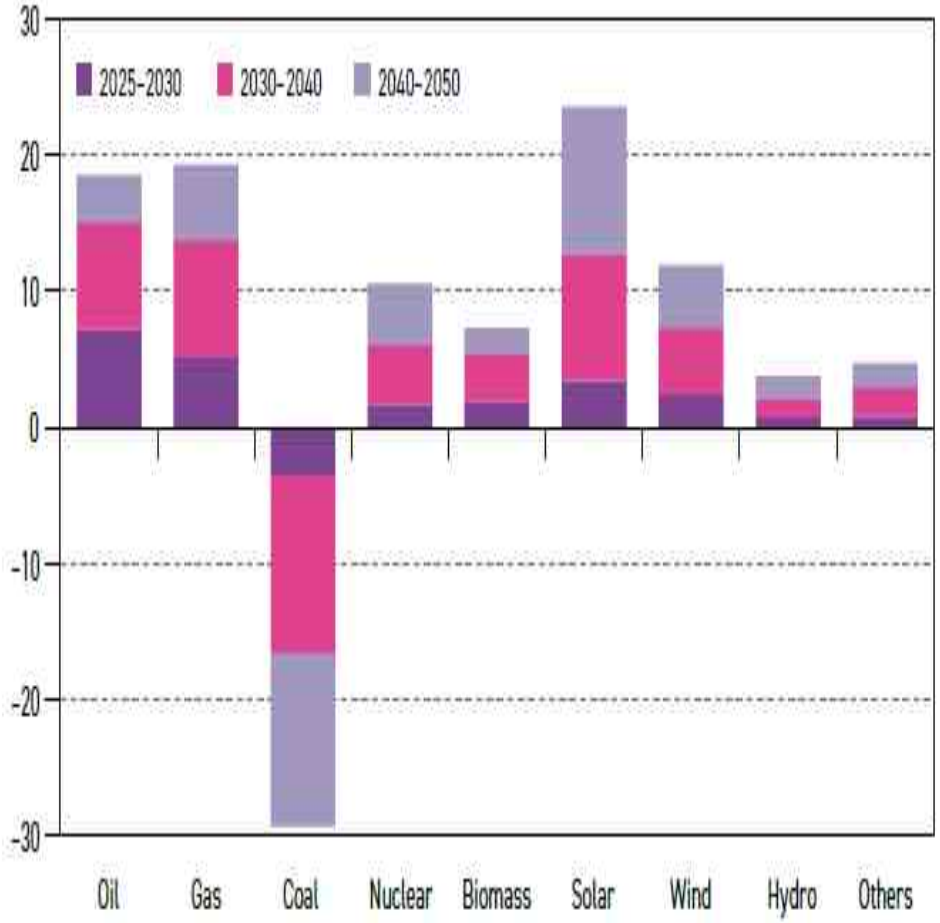
Long-term annual GDP growth rate (in real terms), % p.a.

	2025–2030	2030–2040	2040–2050	2025–2050
OECD Americas	2.1	2.0	1.9	1.9
OECD Europe	1.6	1.2	1.0	1.2
OECD Asia-Pacific	1.5	0.8	1.0	1.0
OECD	**1.8**	**1.5**	**1.4**	**1.5**
China	4.4	3.6	2.4	3.3
India	6.5	5.8	5.1	5.7
Other Asia	4.2	3.6	3.1	3.5
Latin America	2.5	2.2	1.7	2.1
Middle East	3.1	3.0	2.3	2.7
Africa	3.8	4.1	5.0	4.4
Russia	1.4	1.4	1.1	1.3
Other Eurasia	4.0	2.8	2.2	2.8
Other Europe	2.4	0.9	1.0	1.3
Non-OECD	**4.2**	**3.7**	**3.3**	**3.6**
World	**3.2**	**2.9**	**2.7**	**2.9**

Source: OPEC WOO 2026 – June 2026

Primary Energy Demand by Fuel types
OPEC 2026 Reference Scenario (Mboe/d) (3)

Growth in primary energy demand by fuel type, 2025-2050, mboe/d



World primary energy demand by fuel type, 2025-2050

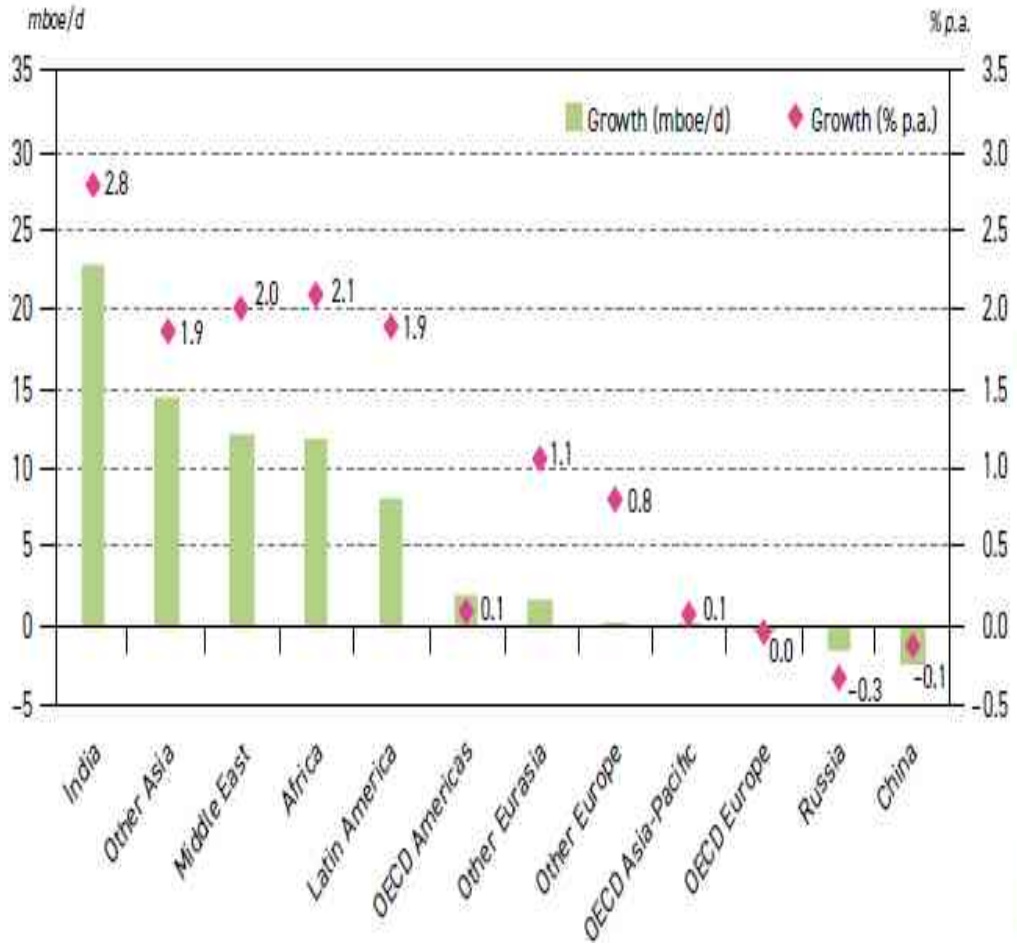
	Levels mboe/d						Growth mboe/d	Growth % p.a.	Fuel share %	
	2025	2030	2035	2040	2045	2050	2025-2050	2025-2050	2025	2050
Oil	94.9	102.2	107.4	110.0	111.9	113.5	18.6	0.7	30.4	29.7
Gas	72.0	77.1	81.9	85.7	88.9	91.3	19.3	1.0	23.0	23.8
Coal	82.6	79.1	72.9	66.1	59.5	53.3	-29.3	-1.7	26.4	13.9
Nuclear	15.0	16.7	18.8	21.0	23.3	25.5	10.5	2.2	4.8	6.7
Renewables	47.8	57.3	67.9	78.6	88.8	99.1	51.3	3.0	15.3	25.9
Biomass	*28.4*	*30.4*	*32.3*	*33.9*	*34.9*	*35.7*	*7.3*	*0.9*	*9.1*	*9.3*
Solar	*4.9*	*8.4*	*12.7*	*17.7*	*23.0*	*28.5*	*23.6*	*7.3*	*1.6*	*7.4*
Wind	*4.7*	*7.2*	*9.8*	*12.1*	*14.3*	*16.6*	*11.9*	*5.1*	*1.5*	*4.3*
Hydro	*7.7*	*8.4*	*9.1*	*9.8*	*10.6*	*11.5*	*3.8*	*1.6*	*2.5*	*3.0*
*Others**	*2.1*	*2.9*	*4.0*	*5.1*	*6.0*	*6.8*	*4.7*	*4.8*	*0.7*	*1.8*
Total	312.3	332.4	348.9	361.3	372.4	382.7	70.4	0.8	100	100

* *Includes geothermal, tidal and wave.*

Source: OPEC WOO 2026 – June 2026

Primary Energy Demand by Regions
OPEC 2026 Reference Scenario (Mboe/d) (4)

Growth in primary energy demand by region, 2025-2050

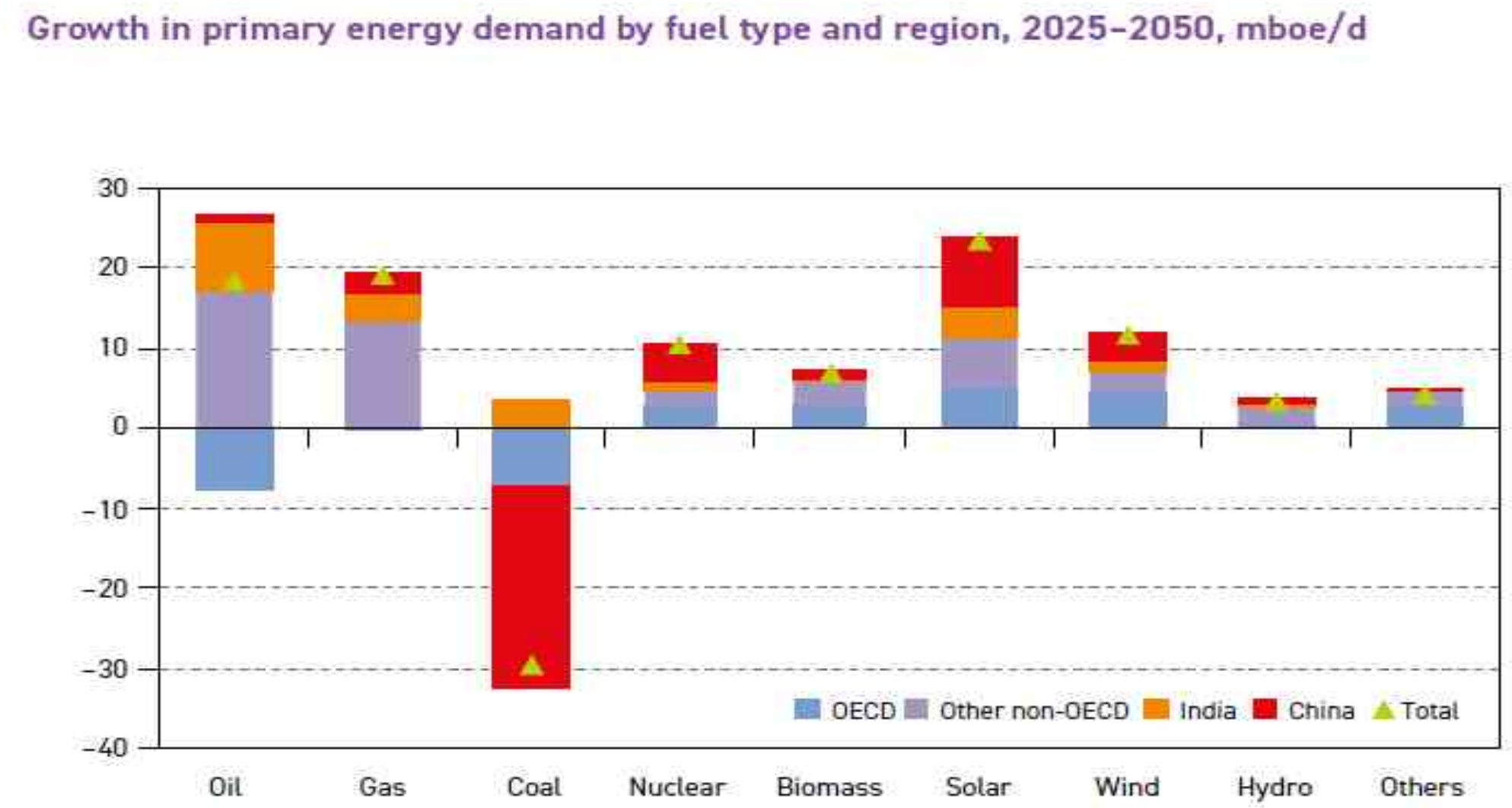


Total primary energy demand by region, 2025-2050

	Levels mboe/d						Growth mboe/d	Growth % p.a.	Share %	
	2025	2030	2035	2040	2045	2050	2025-2050	2025-2050	2025	2050
OECD Americas	56.9	58.6	59.3	59.7	59.8	59.1	2.2	0.1	18.2	15.4
OECD Europe	32.7	33.2	33.1	32.7	32.5	32.4	-0.3	0.0	10.5	8.5
OECD Asia-Pacific	17.5	18.0	18.3	18.3	18.2	18.0	0.5	0.1	5.6	4.7
OECD	107.1	109.8	110.7	110.8	110.5	109.5	2.3	0.1	34.3	28.6
China	82.3	85.0	85.5	83.9	81.9	80.0	-2.2	-0.1	26.3	20.9
India	22.9	27.1	31.4	35.8	40.6	45.6	22.7	2.8	7.3	11.9
Other Asia	24.8	28.2	31.6	34.6	37.2	39.4	14.5	1.9	8.0	10.3
Latin America	13.8	15.9	17.9	19.6	20.9	22.0	8.2	1.9	4.4	5.8
Middle East	18.9	21.6	24.5	26.8	29.1	31.1	12.2	2.0	6.1	8.1
Africa	17.5	19.5	21.8	24.2	26.6	29.3	11.8	2.1	5.6	7.7
Russia	17.1	16.9	16.6	16.3	16.0	15.7	-1.3	-0.3	5.5	4.1
Other Eurasia	5.8	6.2	6.7	7.1	7.4	7.6	1.8	1.1	1.9	2.0
Other Europe	2.0	2.1	2.2	2.3	2.3	2.4	0.4	0.8	0.6	0.6
Non-OECD	205.1	222.6	238.2	250.5	261.9	273.2	68.1	1.2	65.7	71.4
World	312.3	332.4	348.9	361.3	372.4	382.7	70.4	0.8	100	100

Source: OPEC WOO 2026 – June 2026

Primary Energy Demand Growth by Fuel types & Regions OPEC 2026 Reference Scenario (Mboe/d) (5)



Source: OPEC WOO 2026 – June 2026

Oil Demand by Regions - OPEC 2026 Reference Scenario (Mboe/d)
Oil up to > 110 Mb/d in 2050 (6)

Oil demand by region, 2025–2050

	Levels mboe/d						Growth mboe/d	Growth % p.a.	Share %	
	2025	2030	2035	2040	2045	2050	2025–2050	2025–2050	2025	2050
OECD Americas	21.2	21.4	21.2	20.3	19.1	18.0	–3.2	–0.7	22.4	15.9
OECD Europe	12.2	12.3	11.8	10.8	9.7	8.7	–3.4	–1.3	12.8	7.7
OECD Asia-Pacific	6.6	6.5	6.3	5.9	5.5	5.0	–1.5	–1.1	6.9	4.4
OECD	**39.9**	**40.3**	**39.3**	**36.9**	**34.3**	**31.8**	**–8.1**	**–0.9**	**42.1**	**28.0**
China	15.7	16.8	17.5	17.4	17.0	16.6	0.9	0.2	16.5	14.6
India	5.3	6.8	8.3	10.1	12.0	13.8	8.5	3.9	5.6	12.2
Other Asia	9.3	10.6	11.7	12.6	13.4	14.1	4.9	1.7	9.8	12.4
Latin America	6.3	7.1	7.9	8.4	8.8	9.1	2.8	1.5	6.6	8.0
Middle East	8.1	9.1	10.2	11.2	12.2	13.1	5.0	1.9	8.5	11.5
Africa	4.6	5.4	6.2	7.0	7.9	8.7	4.1	2.5	4.9	7.7
Russia	3.6	3.9	3.9	3.9	3.8	3.8	0.1	0.2	3.8	3.3
Other Eurasia	1.2	1.4	1.5	1.5	1.6	1.6	0.3	1.0	1.3	1.4
Other Europe	0.8	0.9	0.9	0.9	0.9	0.9	0.1	0.3	0.8	0.8
Non-OECD	**55.0**	**61.9**	**68.1**	**73.1**	**77.6**	**81.7**	**26.7**	**1.6**	**57.9**	**72.0**
World	**94.9**	**102.2**	**107.4**	**110.0**	**111.9**	**113.5**	**18.6**	**0.7**	**100**	**100**

Source: OPEC WOO 2026 – June 2026
Nota: Quantities in boe/d – Excludes biofuels, CtL, GtL

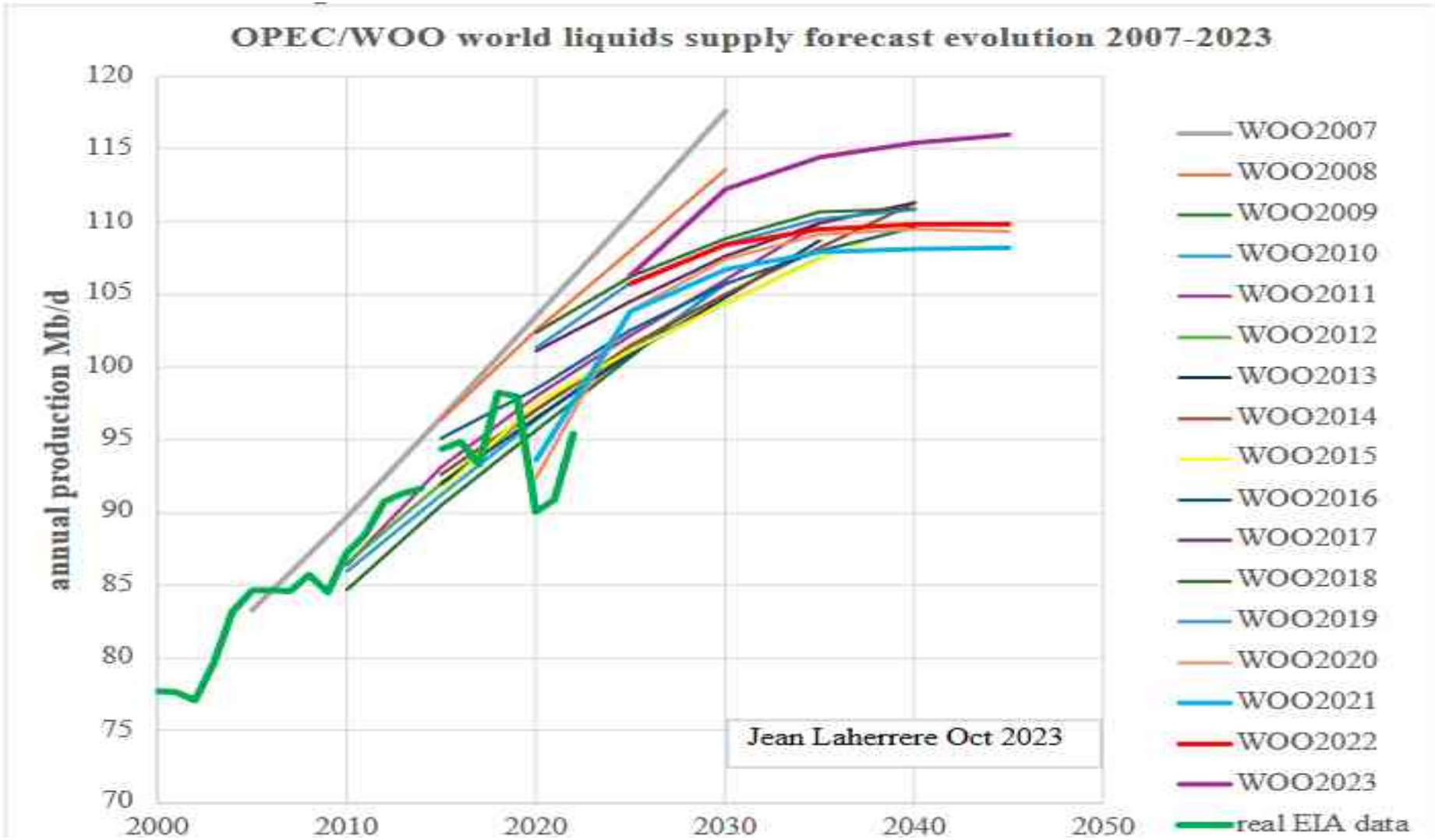
Long-term Oil Demand by Regions - OPEC 2026 Reference Scenario (Mboe/d) - Oil up to > 110 Mb/d in 2050 (7)

Long-term oil demand by region, mb/d

	2025	2030	2035	2040	2045	2050	Growth 2025–2050
OECD Americas	25.4	25.9	25.8	24.9	23.6	22.4	-3.0
OECD Europe	13.4	13.7	13.3	12.3	11.2	10.2	-3.3
OECD Asia-Pacific	7.1	7.1	6.8	6.4	5.9	5.5	-1.6
OECD	**45.9**	**46.7**	**45.9**	**43.6**	**40.8**	**38.0**	**-7.9**
China	16.9	18.1	18.9	18.8	18.4	18.0	1.1
India	5.6	7.1	8.8	10.4	12.1	13.8	8.1
Other Asia	9.8	11.3	12.5	13.4	14.3	15.1	5.3
Latin America	6.9	7.8	8.6	9.2	9.5	9.7	2.8
Middle East	8.9	9.9	11.0	12.0	12.9	13.6	4.7
Africa	4.9	5.7	6.5	7.4	8.3	9.2	4.3
Russia	4.0	4.3	4.4	4.3	4.3	4.2	0.2
Other Eurasia	1.3	1.5	1.6	1.6	1.7	1.7	0.4
Other Europe	0.8	0.9	1.0	1.0	0.9	0.9	0.1
Non-OECD	**59.2**	**66.6**	**73.1**	**78.1**	**82.3**	**86.1**	**26.9**
World	**105.1**	**113.3**	**119.0**	**121.7**	**123.1**	**124.1**	**19.0**

Source: OPEC WOO 2026 – June 2026
Nota: Quantities in boe/d – Includes biofuels, CtL, GtL

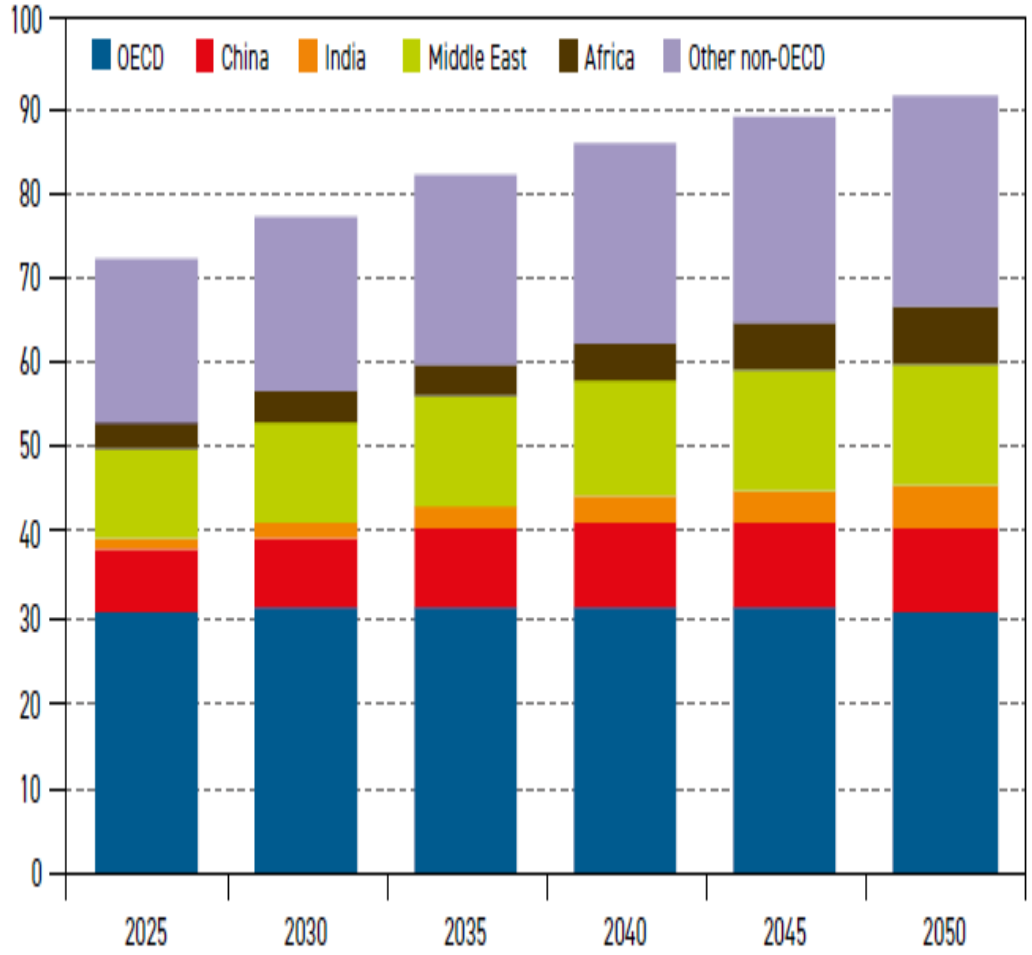
World Liquids Production by OPEC WOO (8)
Forecasting is a difficult exercise!



Source: Jean Laherrère – October 2023

Natural Gas Demand by Regions - OPEC 2026 Reference Case (Mboe/d) (9)

Natural gas demand by region, 2025-2050, mboe/d



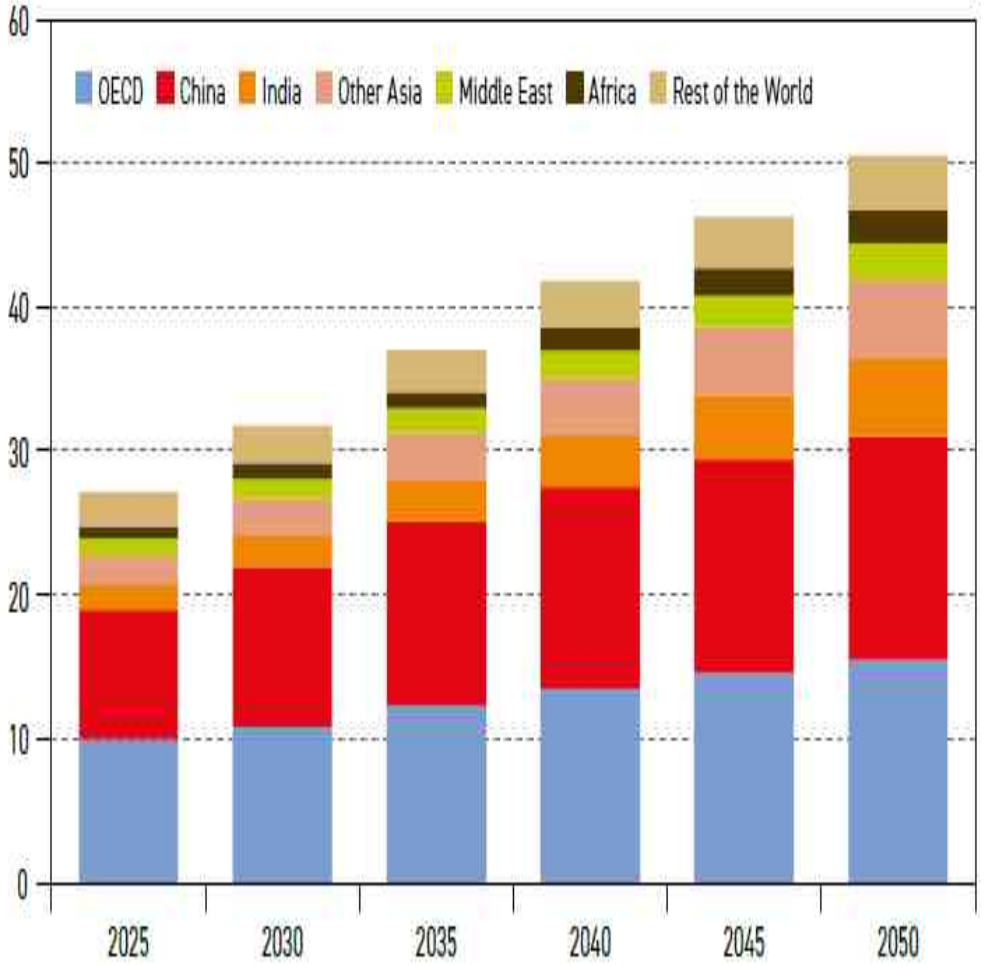
Natural gas demand by region, 2025-2050

	Levels mboe/d						Growth mboe/d	Growth % p.a.	Share %	
	2025	2030	2035	2040	2045	2050	2025-2050	2025-2050	2025	2050
OECD Americas	19.9	20.3	20.6	20.8	20.8	20.5	0.5	0.1	27.7	22.4
OECD Europe	7.3	7.2	7.0	6.9	6.7	6.4	-0.8	-0.5	10.1	7.1
OECD Asia-Pacific	3.7	3.7	3.7	3.8	3.8	3.8	0.1	0.1	5.1	4.2
OECD	30.9	31.2	31.4	31.4	31.2	30.7	-0.2	0.0	43.0	33.6
China	7.2	8.4	9.2	9.6	9.8	9.9	2.7	1.3	10.0	10.8
India	1.3	1.8	2.3	3.1	4.0	5.2	3.8	5.6	1.8	5.7
Other Asia	4.9	5.8	6.7	7.4	7.9	8.1	3.2	2.0	6.9	8.9
Latin America	2.5	3.0	3.5	4.0	4.6	5.1	2.7	3.0	3.4	5.6
Middle East	10.3	11.7	12.8	13.5	14.1	14.4	4.0	1.3	14.4	15.7
Africa	3.0	3.5	4.1	4.8	5.6	6.5	3.6	3.2	4.1	7.1
Russia	8.7	8.4	8.1	7.9	7.6	7.4	-1.3	-0.6	12.0	8.1
Other Eurasia	2.8	3.0	3.3	3.5	3.6	3.6	0.8	1.0	4.0	4.0
Other Europe	0.3	0.3	0.4	0.4	0.4	0.4	0.1	1.2	0.4	0.5
Non-OECD	41.0	45.9	50.6	54.2	57.6	60.6	19.5	1.6	57.0	66.4
World	**72.0**	**77.1**	**81.9**	**85.7**	**88.9**	**91.3**	**19.3**	**1.0**	**100**	**100**

Source: OPEC WOO 2026 – June 2026

Electricity Consumption by Regions - OPEC 2026 Reference Case (TWh) (10)

Global total final electricity consumption by region, 2025-2050, '000 TWh



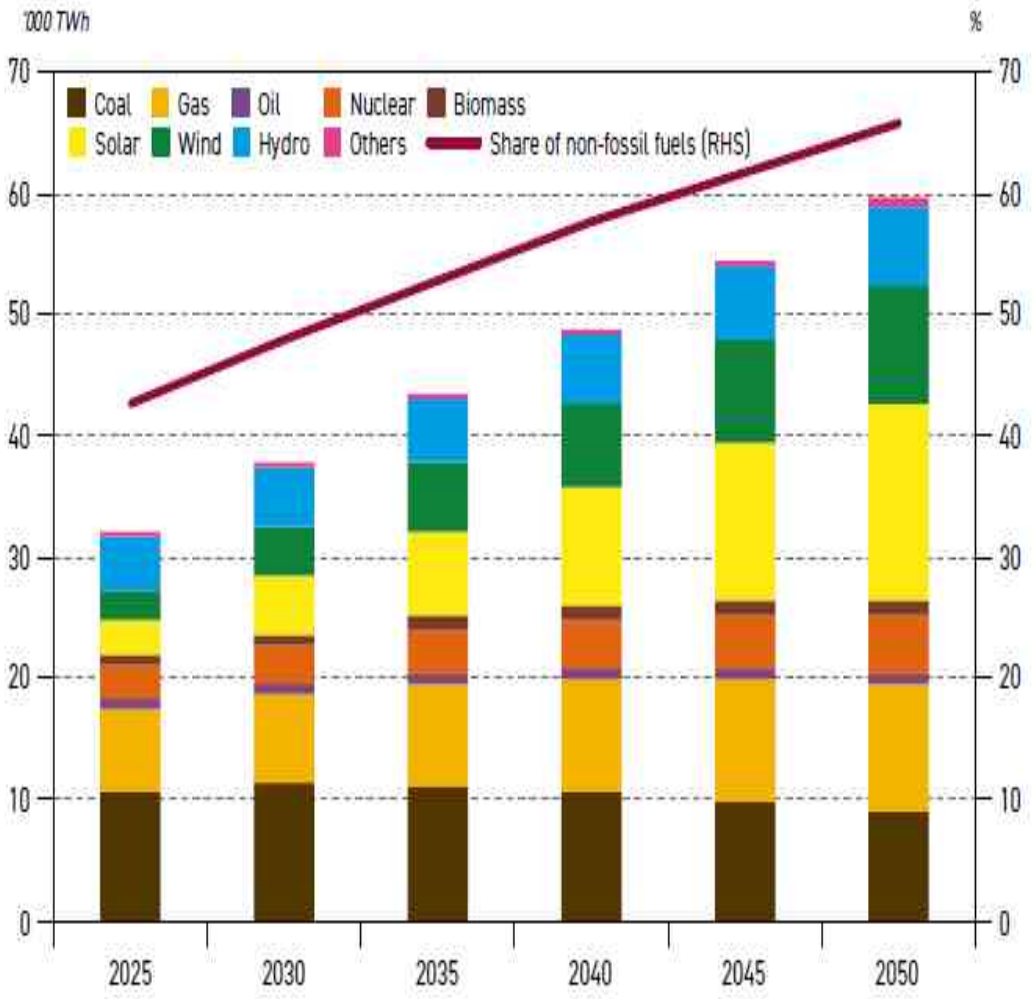
Global total final electricity consumption by region, 2025-2050

	Levels TWh						Growth TWh	Growth % p.a.	Share %	
	2025	2030	2035	2040	2045	2050	2025-2050	2025-2050	2025	2050
OECD Americas	5,147	5,637	6,377	6,960	7,427	7,815	2,669	1.7	18.9	15.5
OECD Europe	3,028	3,353	3,844	4,315	4,746	5,170	2,142	2.2	11.1	10.2
OECD Asia-Pacific	1,785	1,912	2,121	2,293	2,426	2,524	740	1.4	6.6	5.0
OECD	9,960	10,901	12,342	13,568	14,599	15,510	5,550	1.8	36.6	30.7
China	9,048	11,052	12,826	13,954	14,789	15,520	6,472	2.2	33.3	30.7
India	1,752	2,242	2,878	3,622	4,468	5,421	3,669	4.6	6.4	10.7
Other Asia	2,020	2,540	3,208	3,969	4,761	5,539	3,518	4.1	7.4	11.0
Latin America	1,038	1,214	1,457	1,725	1,988	2,225	1,186	3.1	3.8	4.4
Middle East	1,204	1,430	1,693	1,954	2,209	2,457	1,253	2.9	4.4	4.9
Africa	809	978	1,206	1,487	1,832	2,253	1,444	4.2	3.0	4.5
Russia	834	829	824	818	810	800	-34	-0.2	3.1	1.6
Other Eurasia	352	384	422	465	509	551	199	1.8	1.3	1.1
Other Europe	160	174	195	221	254	292	132	2.4	0.6	0.6
Non-OECD	17,218	20,841	24,710	28,216	31,620	35,057	17,840	2.9	63.4	69.3
World	27,177	31,743	37,052	41,784	46,219	50,567	23,390	2.5	100	100

Source: OPEC WOO 2026 – June 2026

Electricity Generation by Fuels - OPEC 2026 Reference Case (TWh) (11)

Global electricity generation by fuel, 2025-2050



Global electricity generation by fuel, 2025-2050

	Levels TWh						Growth TWh	Growth % p.a.	Fuel share %	
	2025	2030	2035	2040	2045	2050	2025-2050	2025-2050	2025	2050
Coal	10,758	11,221	10,946	10,469	9,873	8,904	-1,854	-0.8	33.6	15.0
Gas	6,782	7,616	8,694	9,479	10,200	10,728	3,946	1.9	21.2	18.0
Oil	781	792	776	739	685	620	-161	-0.9	2.4	1.0
Nuclear	2,860	3,194	3,588	4,016	4,461	4,875	2,015	2.2	8.9	8.2
Renewables	10,836	14,770	19,352	24,099	29,079	34,347	23,511	4.7	33.8	57.8
Biomass	*816*	*936*	*1,052*	*1,144*	*1,222*	*1,294*	*478*	*1.9*	*2.5*	*2.2*
Solar	*2,667*	*4,613*	*7,103*	*9,974*	*13,077*	*16,355*	*13,688*	*7.5*	*8.3*	*27.5*
Wind	*2,746*	*4,171*	*5,693*	*7,002*	*8,275*	*9,628*	*6,882*	*5.1*	*8.6*	*16.2*
Hydro	*4,458*	*4,855*	*5,251*	*5,662*	*6,128*	*6,644*	*2,186*	*1.6*	*13.9*	*11.2*
Others	*149*	*196*	*253*	*317*	*376*	*426*	*278*	*4.3*	*0.5*	*0.7*
World	32,017	37,593	43,356	48,803	54,298	59,474	27,457	2.5	100	100

Source: OPEC WOO 2026 – June 2026

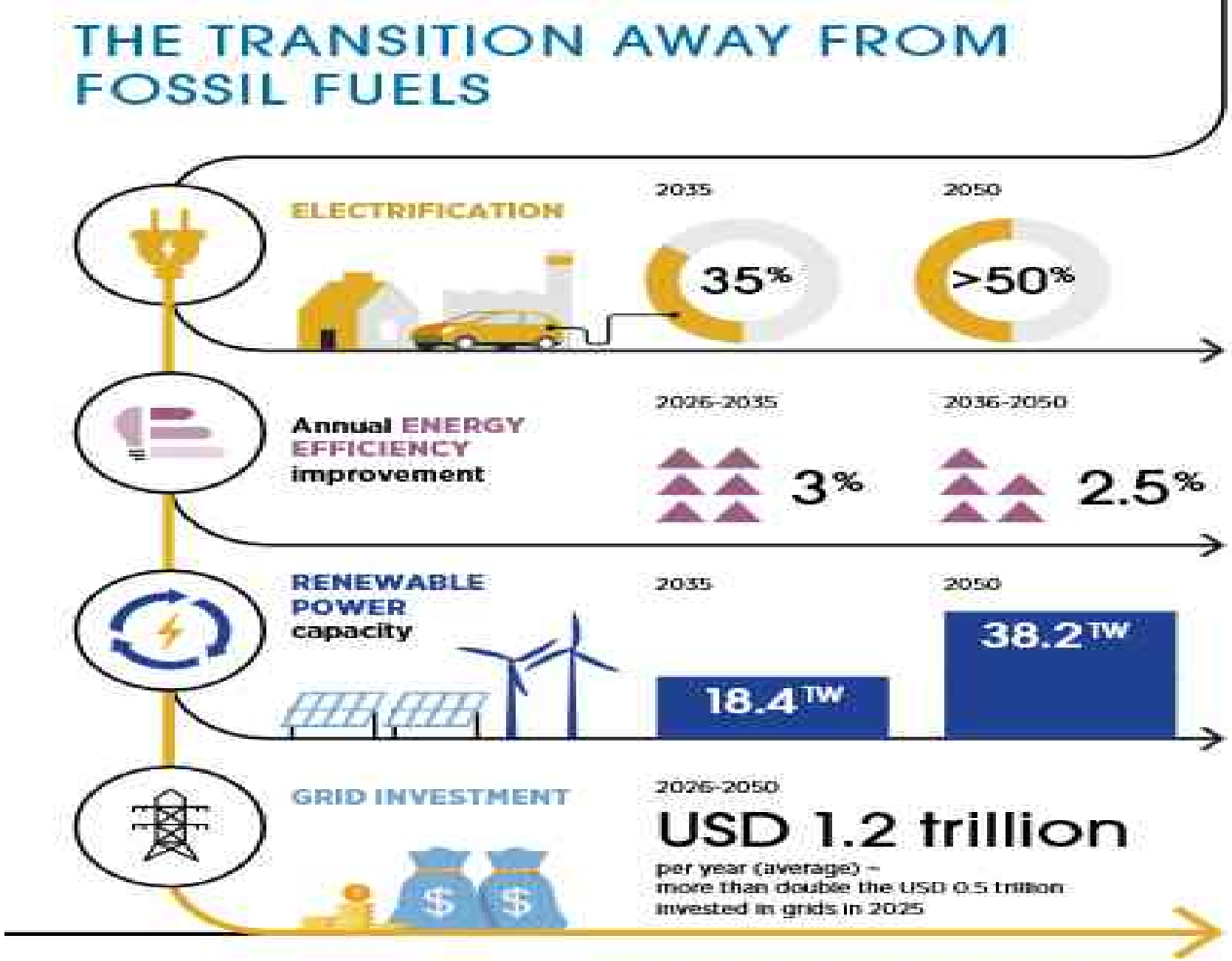
IRENA Scenarios

TRANSITIONING AWAY FROM FOSSIL FUELS

A roadmap powered by renewables, electrification and grid enhancement

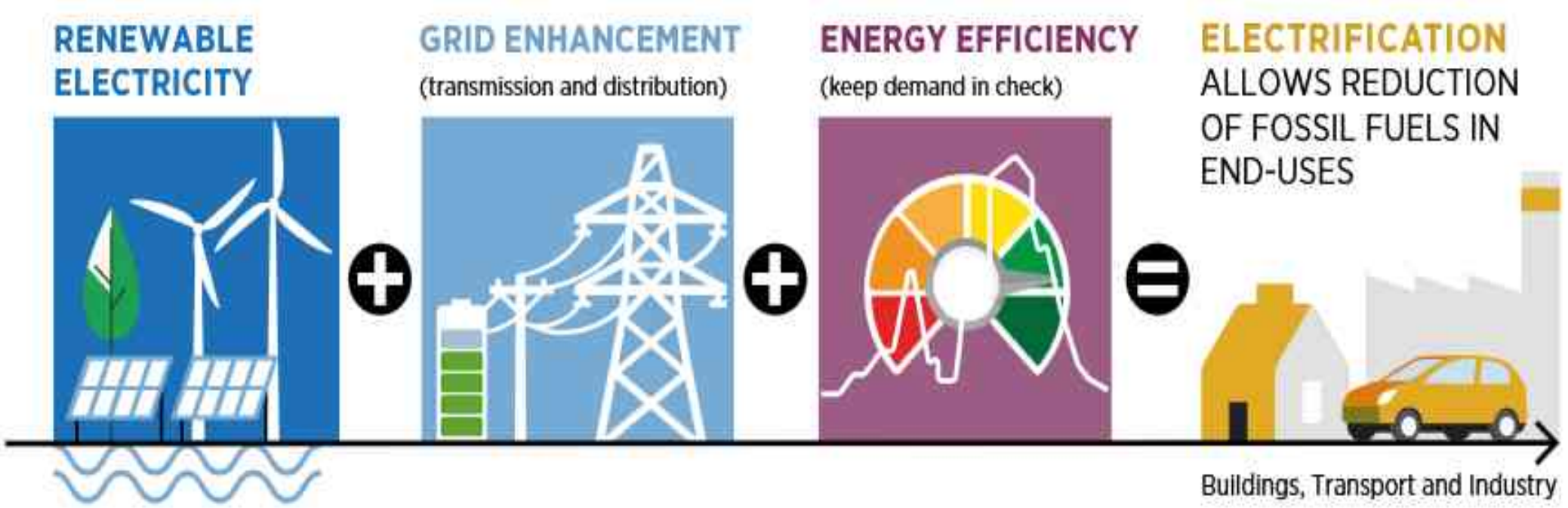


Source: IRENA Transitioning away from fossil fuels – 2026



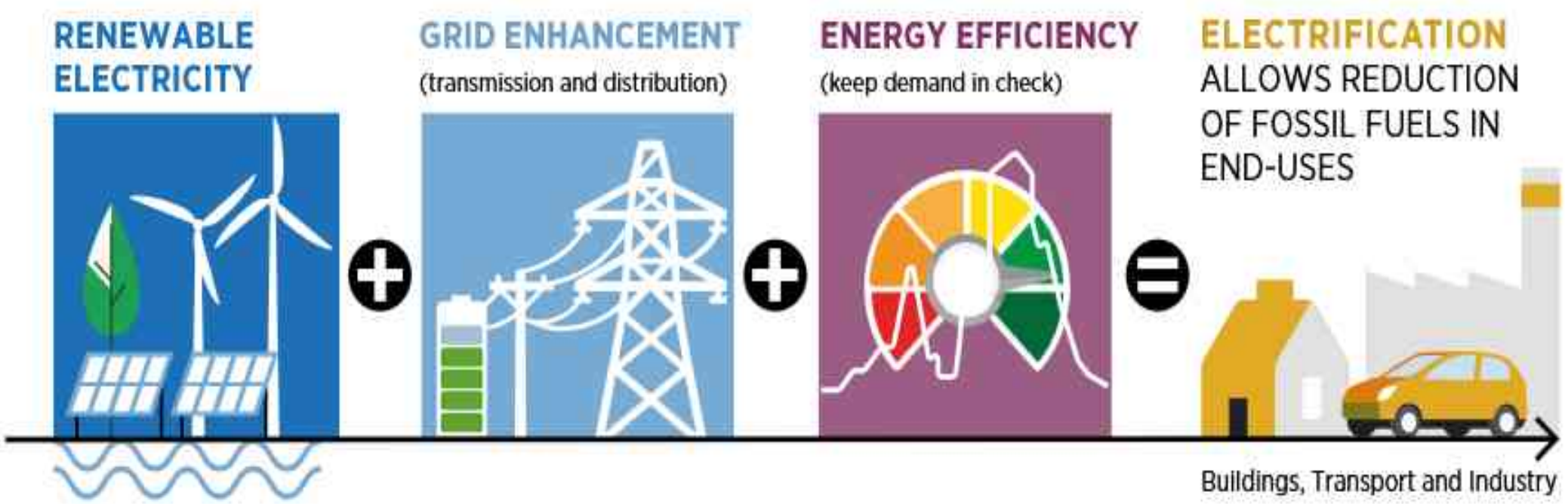
Source: IRENA Transitioning away from fossil fuels – 2026

THE TRANSITION AWAY FROM FOSSIL FUELS



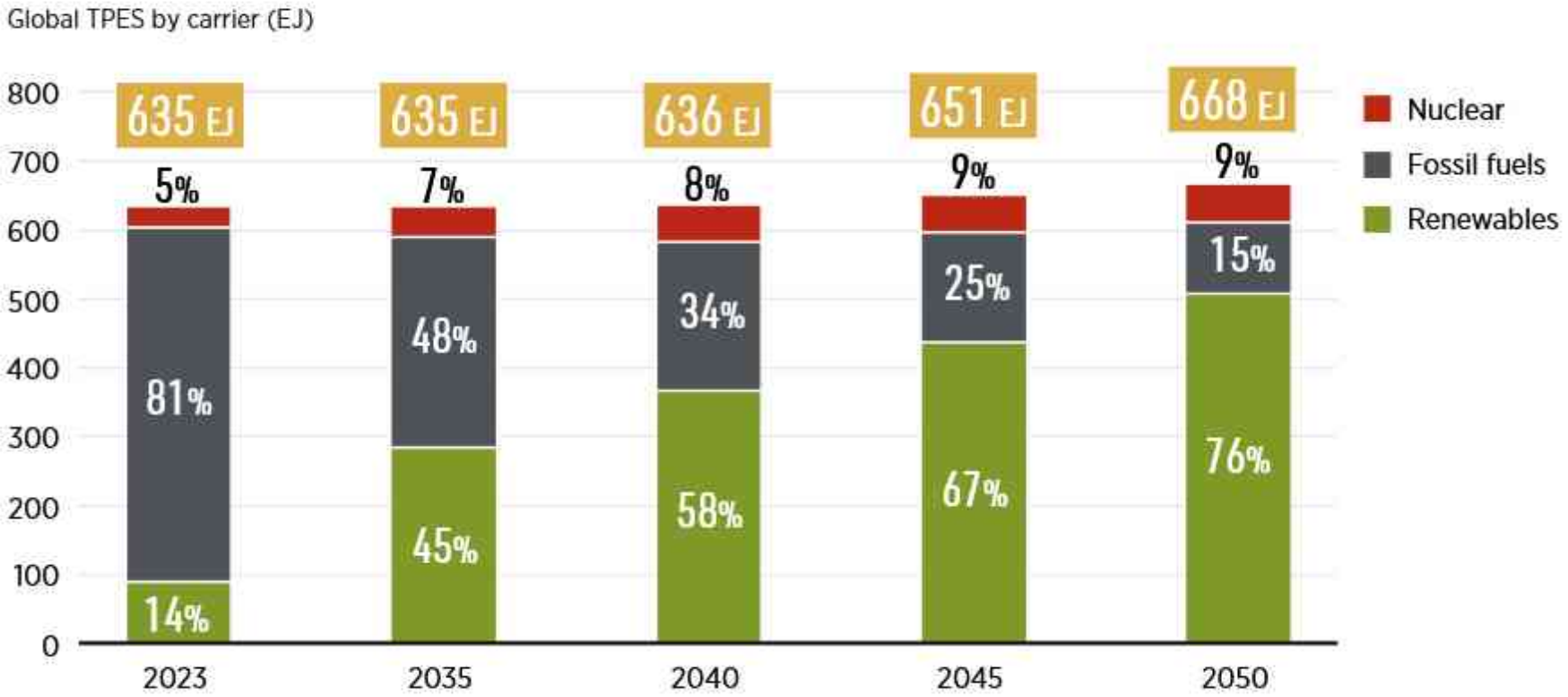
Source: IRENA Transitioning away from fossil fuels – 2026

THE TRANSITION AWAY FROM FOSSIL FUELS



Source: IRENA Transitioning away from fossil fuels – 2026

Total Primary Energy Consumption
The revised 1,5°C Scenario by IRENA



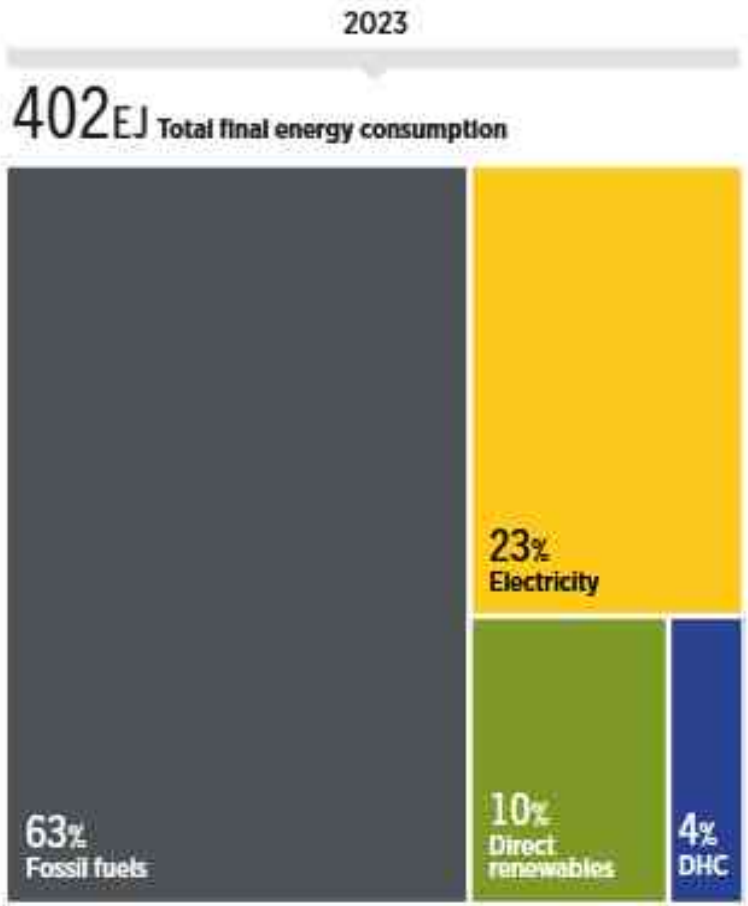
Source: (IRENA, Forthcoming a).

Notes: EJ = exajoules; TPES=Total primary energy supply; "renewables" include bioenergy, variable renewables (solar, wind) and others (hydro, geothermal, solar thermal); "fossil fuels" include oil derivatives, coal and natural gas; Maritime and aviation bunkers are included at the global level.

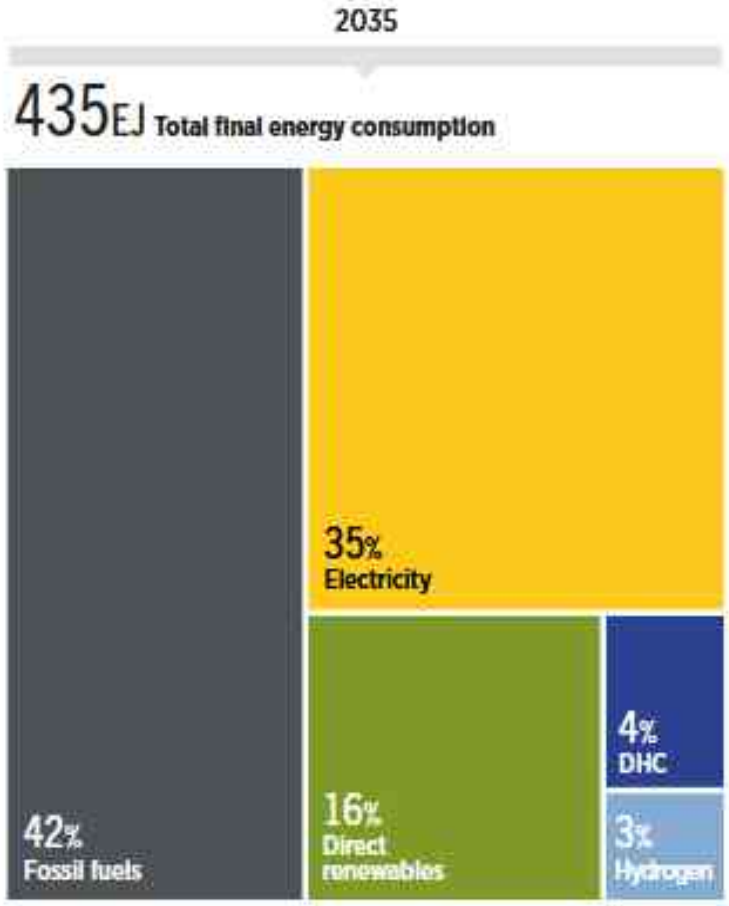
Source: IRENA Transitioning away from fossil fuels – 2026

Total Final Energy Consumption
The revised 1,5°C Scenario by IRENA

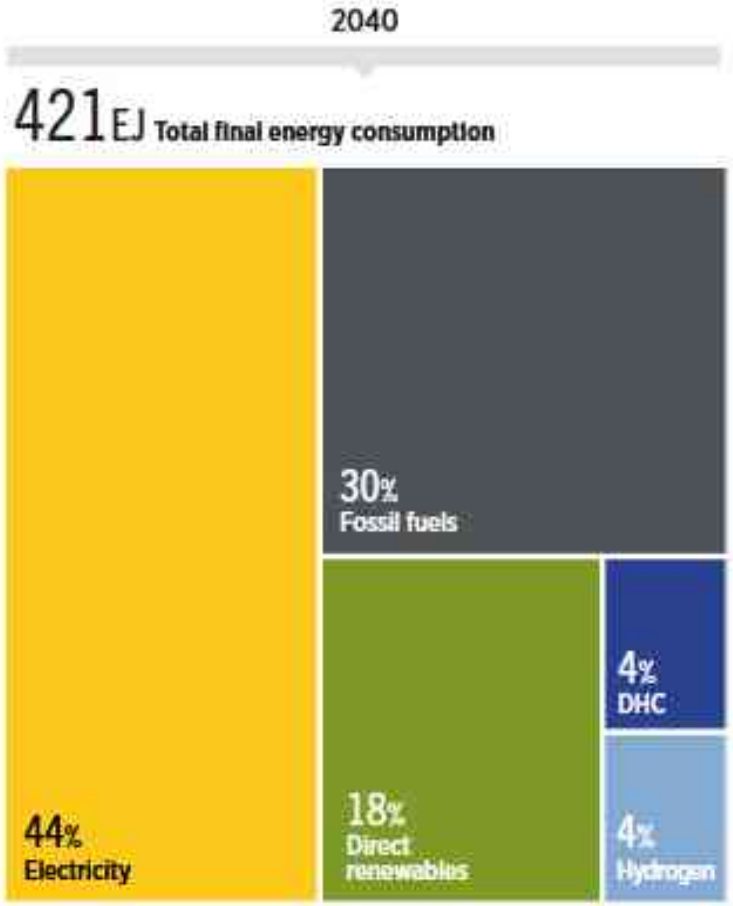
9,6 Gtoe



10,4 Gtoe



10,1 Gtoe

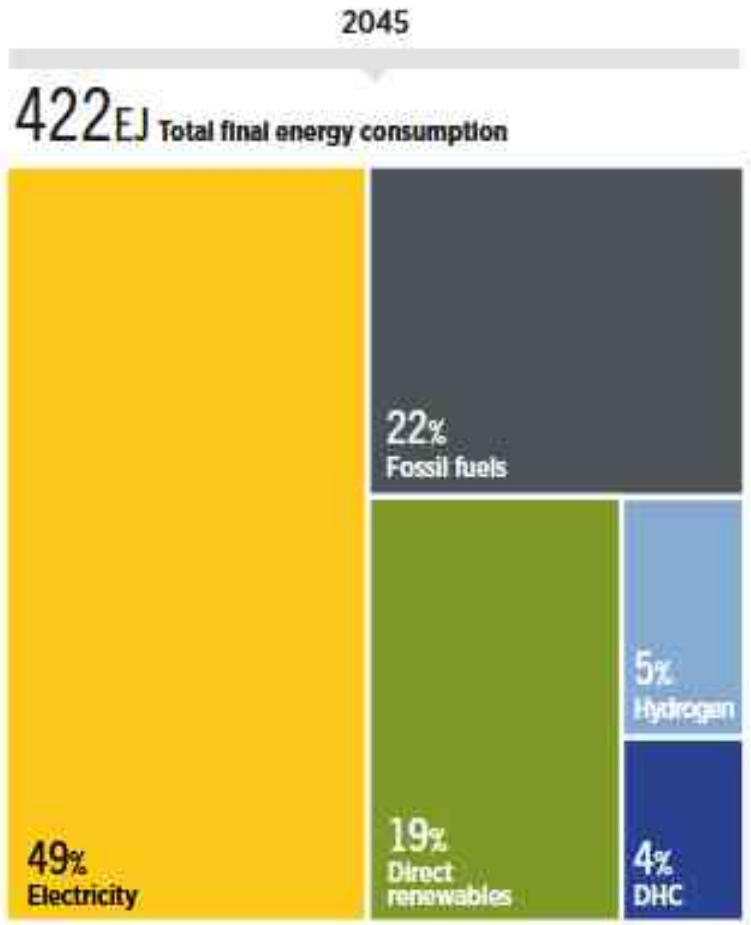


Source: IRENA Transitioning away from fossil fuels – 2026

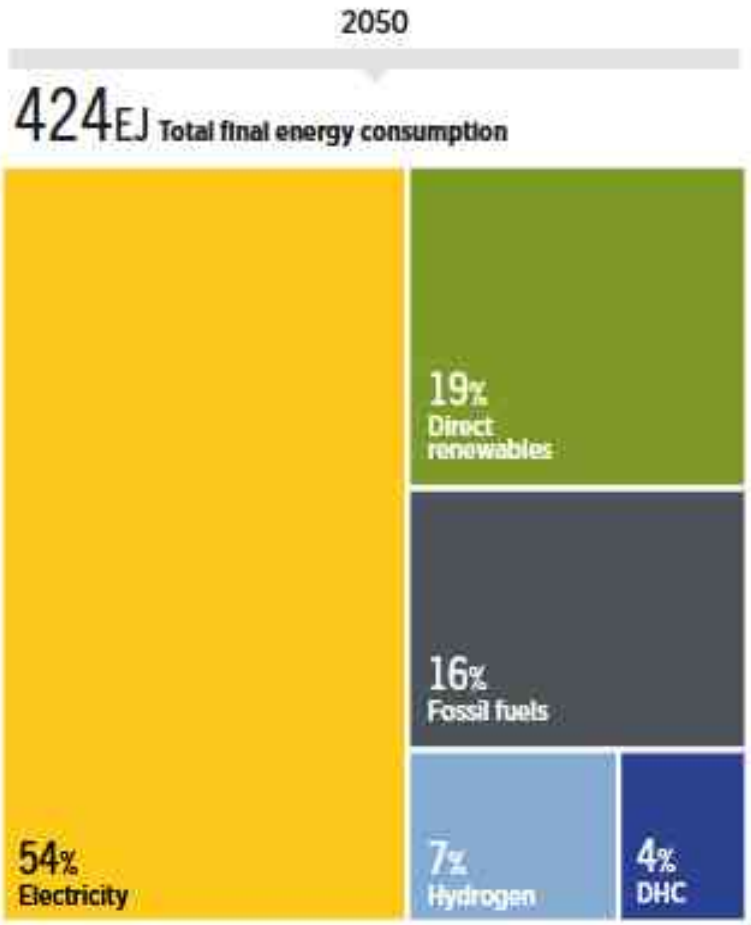
Total Final Energy Consumption
The revised 1,5°C Scenario by IRENA

Notes: EJ = exajoules; "fossil fuels" include oil derivatives, coal and natural gas; "direct renewables" = direct uses of renewable energy (solar thermal, geothermal); "DHC" = district heating and cooling; "hydrogen" refers to clean hydrogen (blue, green) and derivatives; Maritime and aviation bunkers are included at the global level; values of "non-energy" uses are not included.

10,1 Gtoe

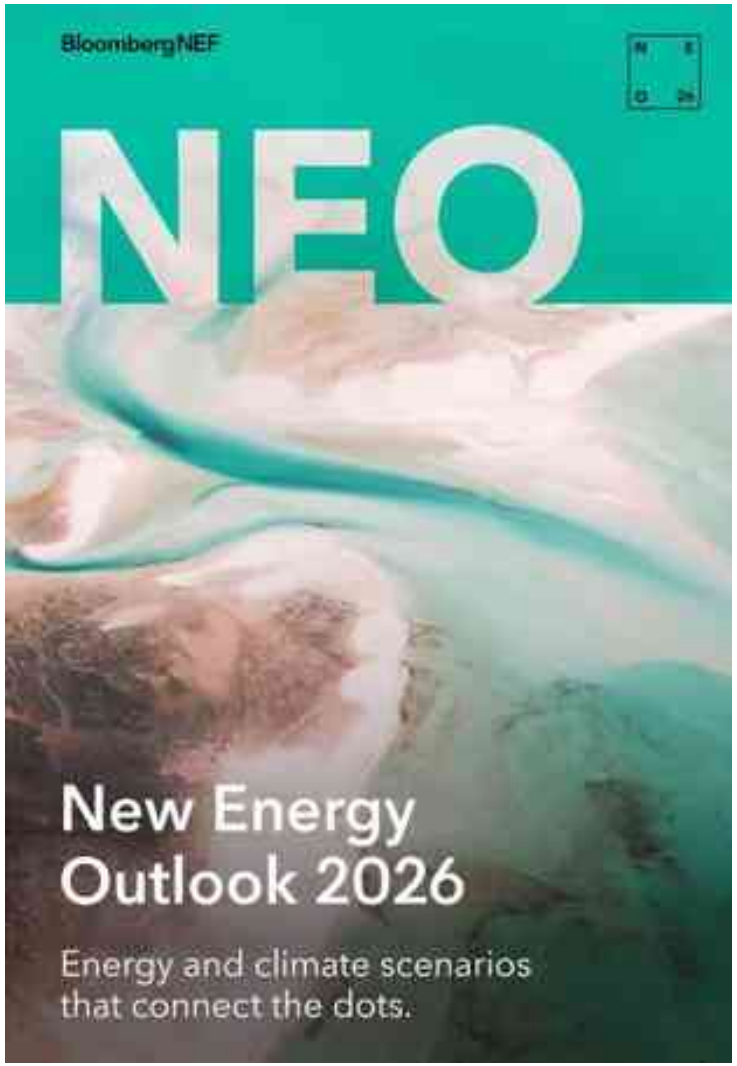


10,1 Gtoe



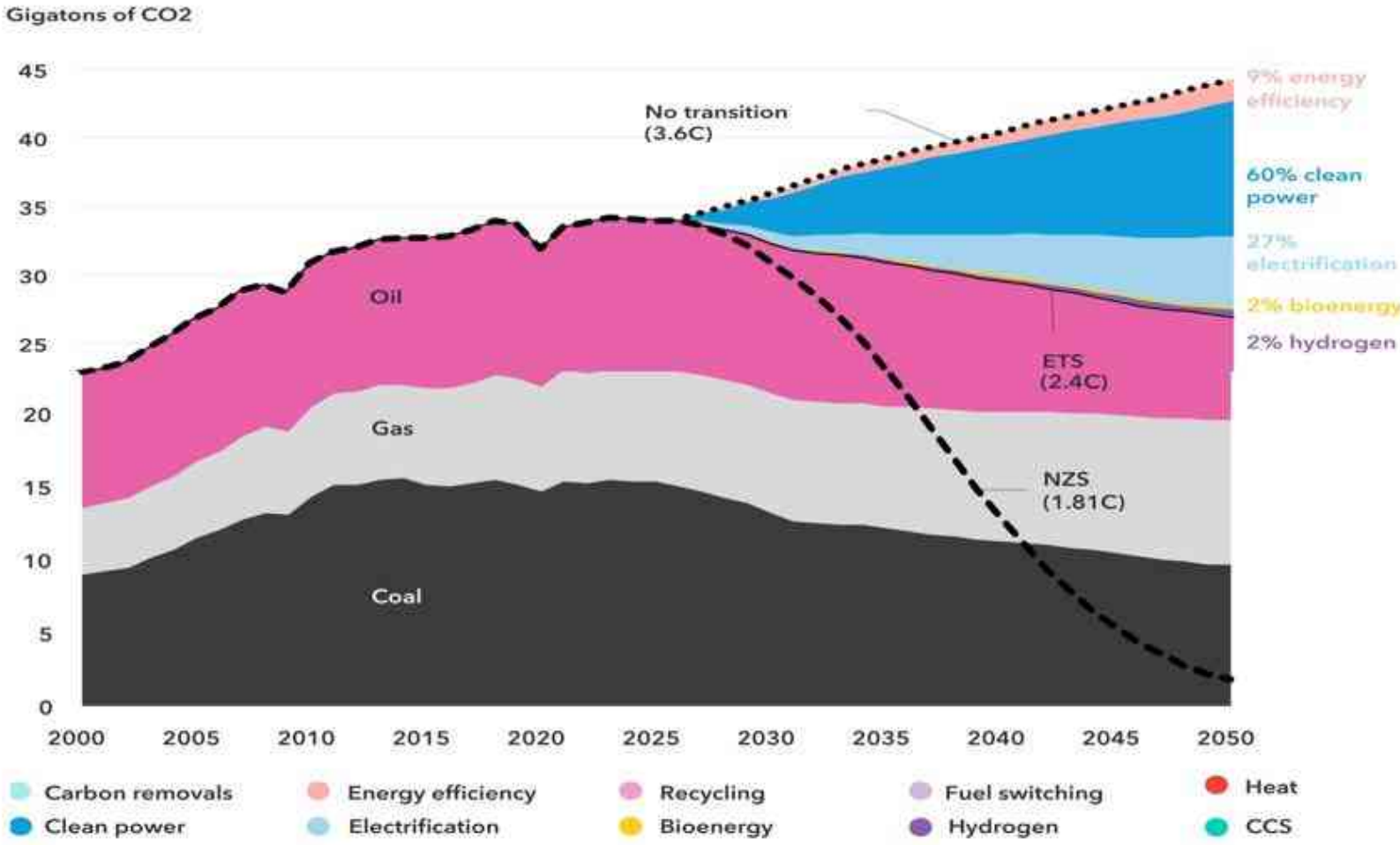
Source: IRENA Transitioning away from Fossil Fuels – 2026

BLOOMBERG NEF Scenarios



Bloomberg NEF Scenarios 2026

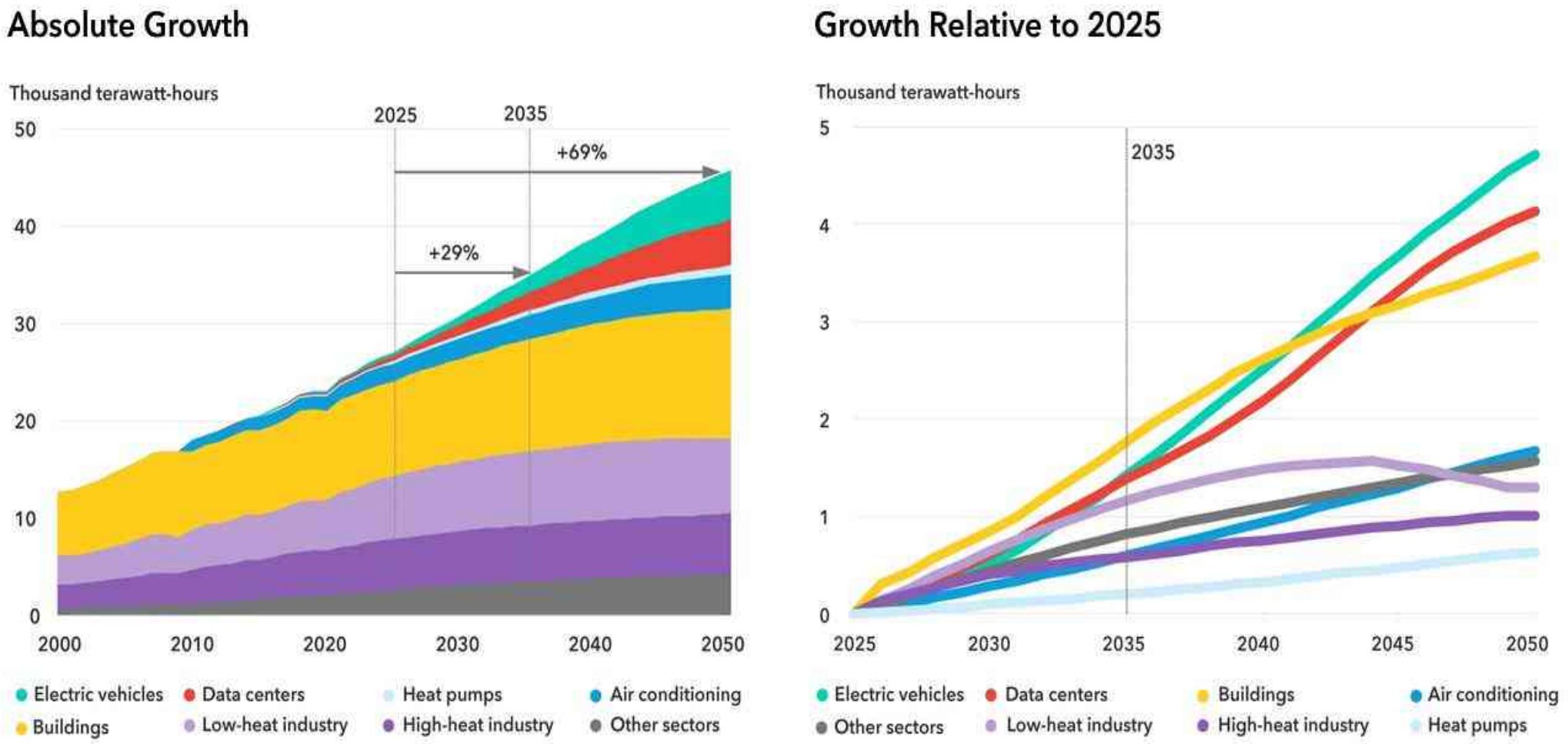
CO2 emissions reductions from fuel combustion by measures adopted, Economic Transition Scenario versus "no transition" scenario and Net Zero Scenario



Source: Bloomberg NEF New Energy Outlook 2026

Bloomberg NEF Scenarios 2026

Drivers of electricity demand growth, Economic Transition Scenario



Source: Bloomberg NEF New Energy Outlook 2026

Compilation of Scenarios from different sources
International Energy Forum/Outlooks Comparison



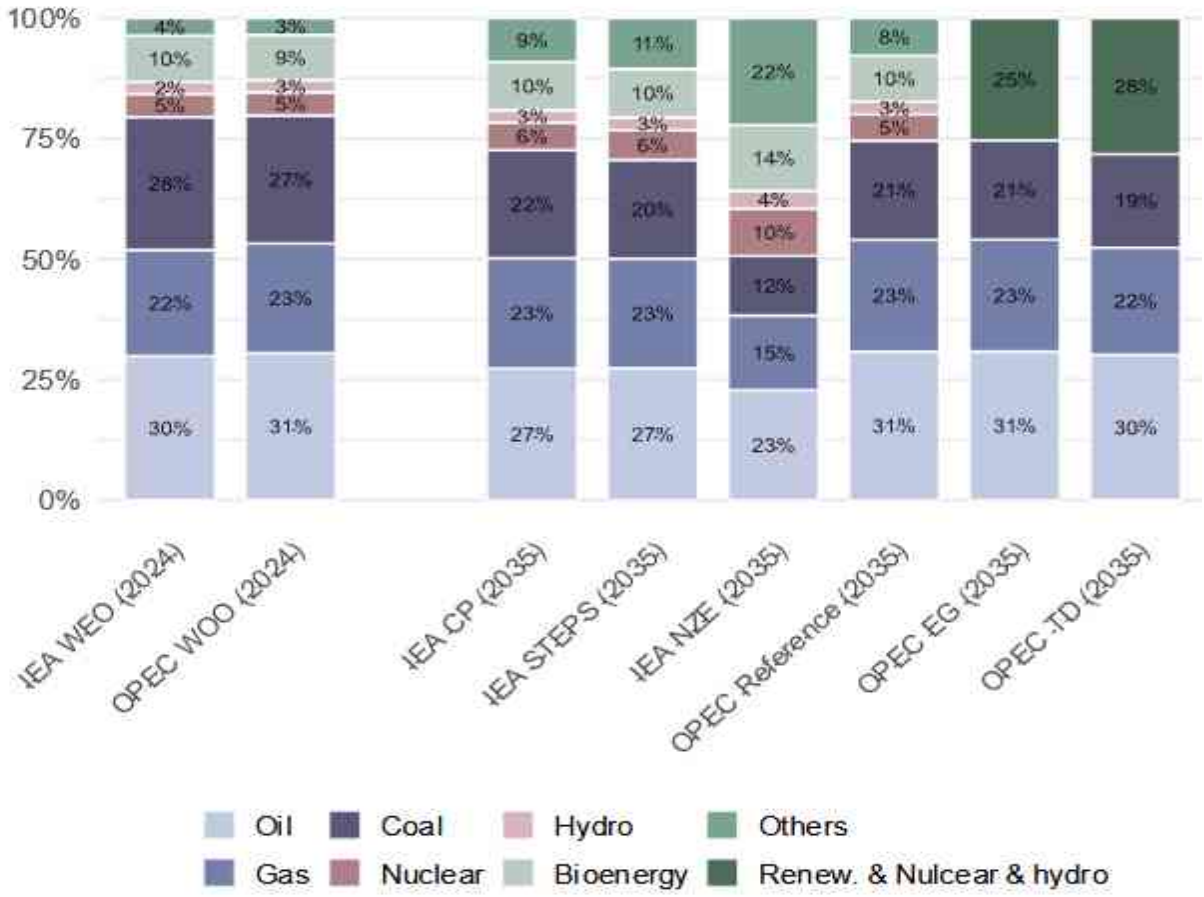
Source: IEF INTERNATIONAL ENERGY FORUM February 2026

2035 IEA & OPEC Outlook Highlights:

- Across all IEA and OPEC scenarios, hydrocarbons continue to account for more than two-thirds of total primary energy demand in 2035, with the highest shares in the IEA Current Policies and OPEC Equitable Growth scenarios.
- Low-carbon shares diverge sharply across outlooks, with the combined contribution of renewables, nuclear, and hydropower reaching around 50% in the IEA Net Zero scenario by 2035, compared with only about 25–30% in the Reference and Evolving Growth scenarios.
- Coal's share falls markedly in all scenarios, particularly under the IEA's Net Zero Emissions scenario, whereas oil and gas retain broadly stable shares through to 2035.
- All fuel-mix differences depend entirely on renewable deployment speed, not on hydrocarbons choices.
- Renewable percentage share of the energy mix becomes a measurable policy success indicator for emissions but not necessarily for energy security, affordability, and system resilience.

World Primary Energy Demand Fuel Share Outlook to2035

Percentage of total primary energy demand



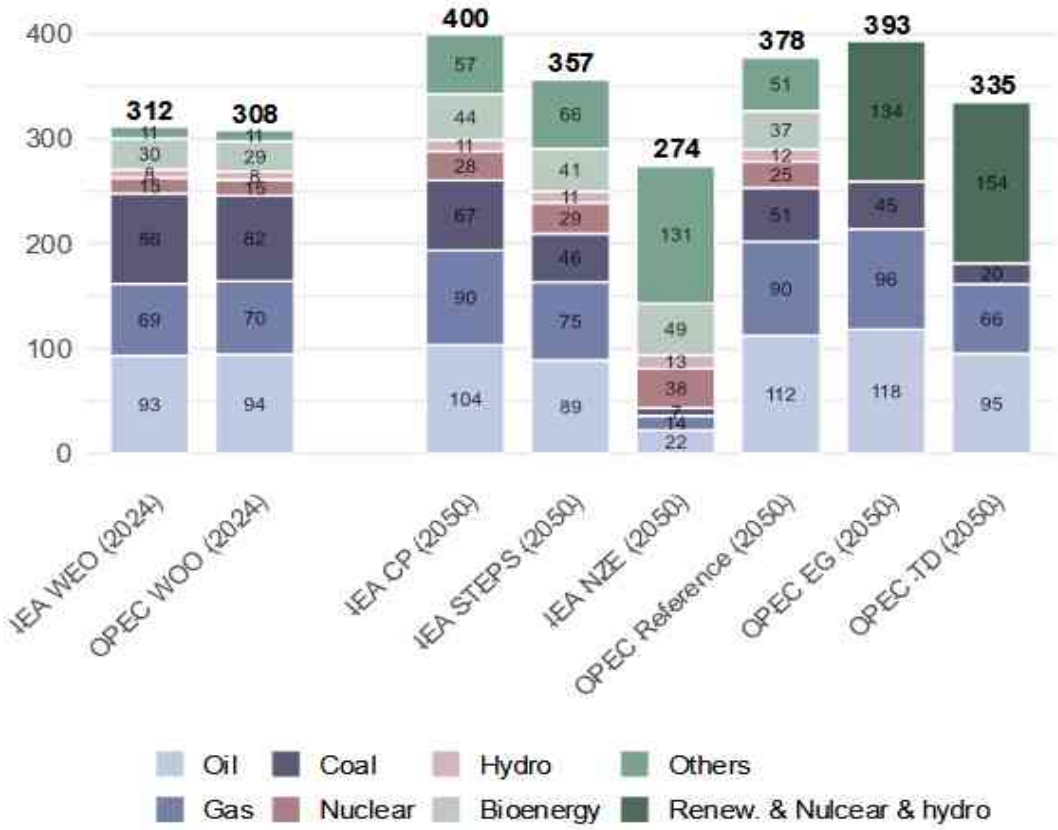
Source: IEF, IEA WEO 2025, and OPEC WOO 2025.

2050 IEA & OPEC Outlook Highlights:

- The 2050 energy outlook shows the largest scenario divergence of any time horizon, with total primary energy ranging from 274 Mboe/d (IEA NZE) to 400 Mboe/d (IEA CP), a difference of roughly 126 mboe/d, exceeding current global oil demand.
- High-growth scenarios cluster around annual energy demand growth of roughly 0.85–1.03% to 2050, moderate scenarios around 0.30–0.53%, while the IEA Net Zero case stands apart with an average decline of about 0.49% per year. The resulting 1.5-percentage-point spread in annual growth rates, between the IEA Current Policies trajectory (~+1%) and the IEA Net Zero pathway (~–0.5%), compounds into a gap of around 126 mboe/d by 2050, equivalent to a divergence of more than 40% from the 2024 baseline of ~310 mboe/d.
- This illustrates the high sensitivity of long-term energy outlooks to small differences in assumed energy demand growth. Relatively modest variations in policy, technology uptake, or behavioral change can translate into structurally different energy systems over a multi-decade horizon.
- Three fundamentally different demand trajectories emerge:
  - (1) high-growth pathways (IEA CP, OPEC Equitable Growth) project around a 28% increase in global energy demand to 2050, implying total demand approaching 400 mboe/d;
  - (2) moderate-growth pathways (OPEC Reference, OPEC TD) foresee demand rising by roughly 9–23%, with total supply in the range of 335–378 mboe/d; and
  - (3) a demand-reduction pathway (IEA Net Zero) projects an approximate 11% decline in global energy use to about 274 mboe/d by 2050, driven by efficiency gains and structural change despite continued economic growth.
- These outcomes correspond to three distinct energy systems: one requiring large-scale expansion of energy infrastructure, one broadly sustaining current growth patterns, and one characterized by policy driven contraction in total energy demand; "degrowth".

World Primary Energy Demand Outlook to 2050

Million barrels of oil equivalent per day



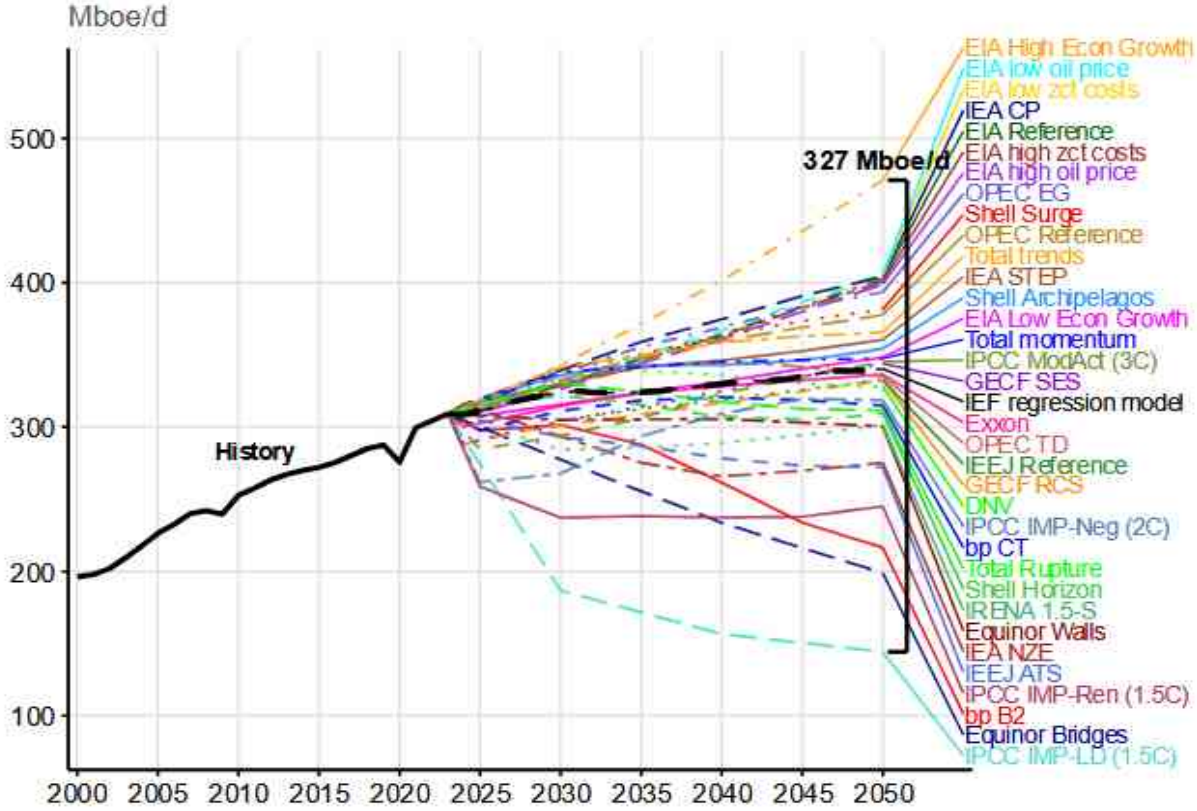
Source: IEF, IEA WEO 2025, and OPEC WOO 2025.

Source: IEF INTERNATIONAL ENERGY FORUM February 2026

IEA and OPEC Scenarios and Other Long-Term Energy Outlooks:

- This year's scenario set shows that the world's leading energy institutions are not converging on a single "most likely" future, but rather outlining a spectrum of energy system configurations, with total primary demand in 2050 ranging from roughly 150 to 470 mboe/d. This divergence reflects fundamentally different assumptions about economic growth, policy effectiveness, technology deployment, and the pace of energy-efficiency improvement.
- Across outlooks, projections remain closely aligned through the mid-2030s, indicating that near-term demand is largely shaped by pre-existing pathway dependencies on infrastructure, capital stock, and prevailing policy and market realities. Greater divergence emerges after 2035, underscoring that long-term outcomes in 2050 are driven primarily by choices made presently and in the current decade, rather than conditions in 2035.
- The "*IEF regression model*", defines a median trajectory across all published outlooks to capture the key trend emanating from the scenario ensemble. This gives a robust, data-driven benchmark that is less influenced by relative outliers.
- This median pathway follows a moderate expansion through the middle of the scenario range, with total primary energy demand increasing from around 310 mboe/d in 2020 to approximately 340 mboe/d by 2050, indicating a mid-range evolution of the global energy system under current expectations of policy and technology evolution.

Total Primary Energy Demand Scenarios Through 2050



Sources: IEF, IEA WEO 2025, OPEC WOO 2025, bp Energy Outlook 2025, TotalEnergies Energy Outlook 2025, IRENA World Energy Transition Outlook 2024, GECF Global Gas Outlook 2025, DNV's Energy Transition Outlook 2025, Equinor Energy Perspectives 2025, IEEJ Outlook 2024, EIA IEO 2023, Shell Energy Security Scenarios 2025, ExxonMobil Global Outlook 2025, and IPCC AR6. Note: Some scenarios start after the historical series ends ; their curves therefore begin at the first year each outlook reports projections .

Source: IEF INTERNATIONAL ENERGY FORUM **February 2026**

8

Global Energy Growth Mobility/Transport

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- 7. Global Energy Growth – Scenarios from various organizations
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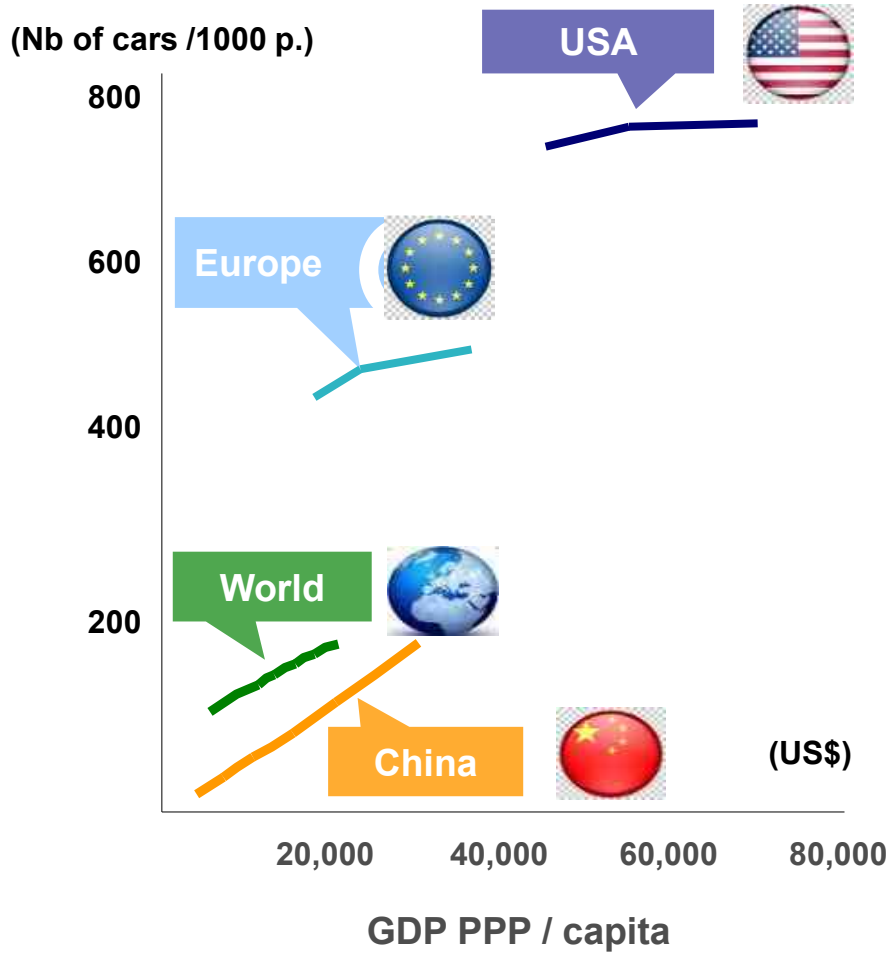
Transport - a key Economy Driver



The Emergence of Asian and Latin America Car Fleet

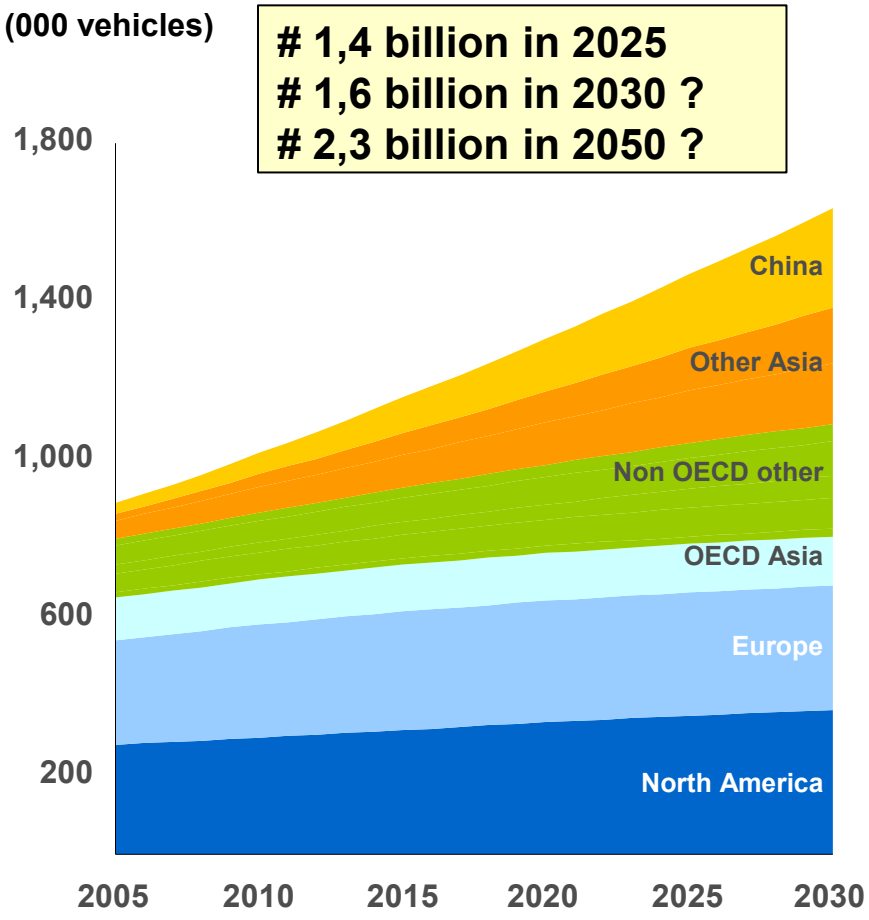
Light-duty Vehicles penetration - A 2010 Vision

Car equipment by GDP unit 2005 - 2030



Car fleet 2005 - 2030

1,4 billion in 2025
1,6 billion in 2030 ?
2,3 billion in 2050 ?



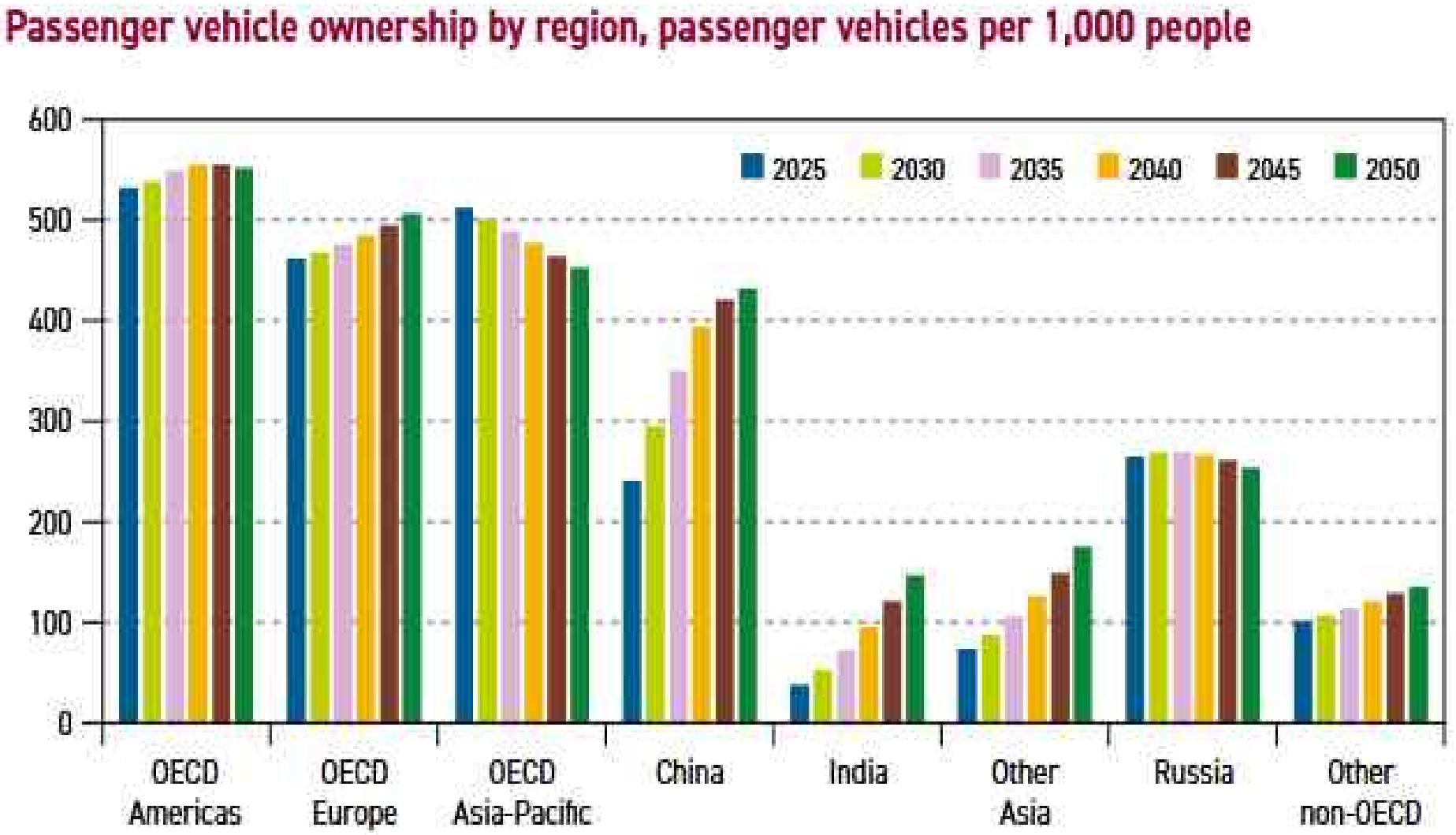
The Emergence of non - OECD Asian and Latin America Car Fleet
A scenario by OPEC 2026

Number of passenger cars by region, 2025–2050, millions

	2025	2030	2035	2040	2045	2050	Growth 2025–2050
OECD Americas	289	300	313	323	328	330	41
OECD Europe	273	277	281	284	288	292	19
OECD Asia-Pacific	111	107	104	99	95	91	-20
OECD	**673**	**684**	**698**	**707**	**712**	**714**	**41**
China	342	413	481	529	550	544	203
India	56	80	113	154	200	246	190
Other Asia	97	120	151	187	228	275	178
Russia	38	38	38	37	36	35	-4
Other non-OECD	260	297	340	388	440	494	233
Non-OECD	**793**	**948**	**1,123**	**1,294**	**1,454**	**1,594**	**801**
World	**1,466**	**1,632**	**1,821**	**2,002**	**2,166**	**2,307**	**841**

Source: OPEC WOO 2026

The Growth of Asian and Latin America Car Fleet
A scenario by OPEC 2026



Source: OPEC WOO 2026

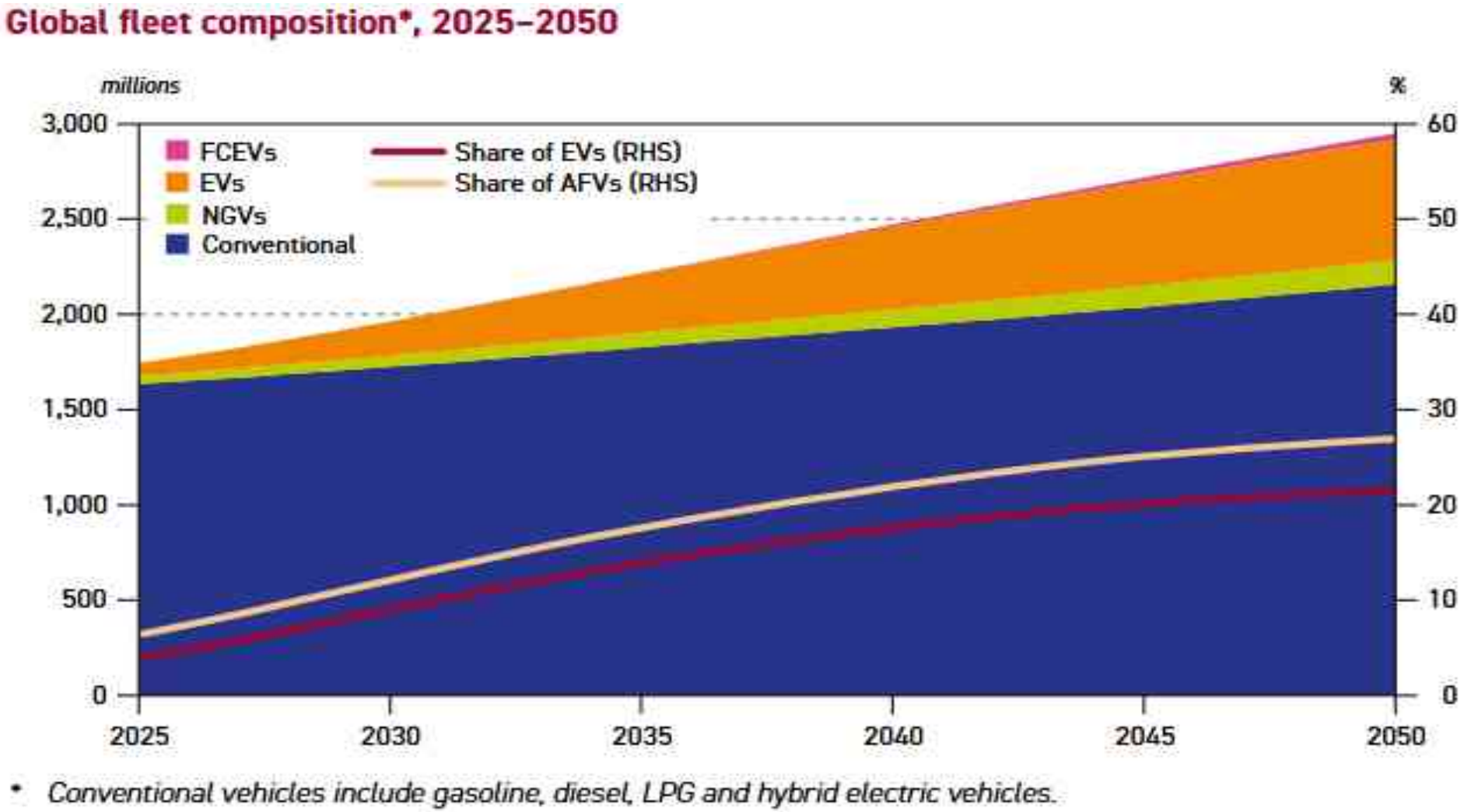
Number of commercial vehicles
A scenario by OPEC 2026

Number of commercial vehicles by region, 2025–2050, millions

	2025	2030	2035	2040	2045	2050	Growth 2025–2050
OECD Americas	43	47	53	60	68	77	33
OECD Europe	46	52	58	65	72	79	33
OECD Asia-Pacific	26	27	28	29	30	32	6
OECD	**115**	**126**	**139**	**154**	**170**	**187**	**72**
China	35	44	54	65	75	85	50
India	25	34	46	61	79	99	74
Other Asia	33	42	52	62	73	83	50
Russia	6	6	6	6	6	7	1
Other non-OECD	68	82	100	123	151	183	115
Non-OECD	**167**	**207**	**258**	**318**	**385**	**457**	**291**
World	**282**	**333**	**397**	**472**	**555**	**645**	**363**

Source: OPEC WOO 2026

Global Fleet composition (Passengers + commercial cars)
A scenario by OPEC 2026



Source: OPEC WOO 2026 (AFV: Alternative Fuel Vehicles, NGV: Natural Gas Vehicles, HEV: Hybrid Electric Vehicles, EV: Electric Vehicles, FCV: Fuel Cell Vehicles)

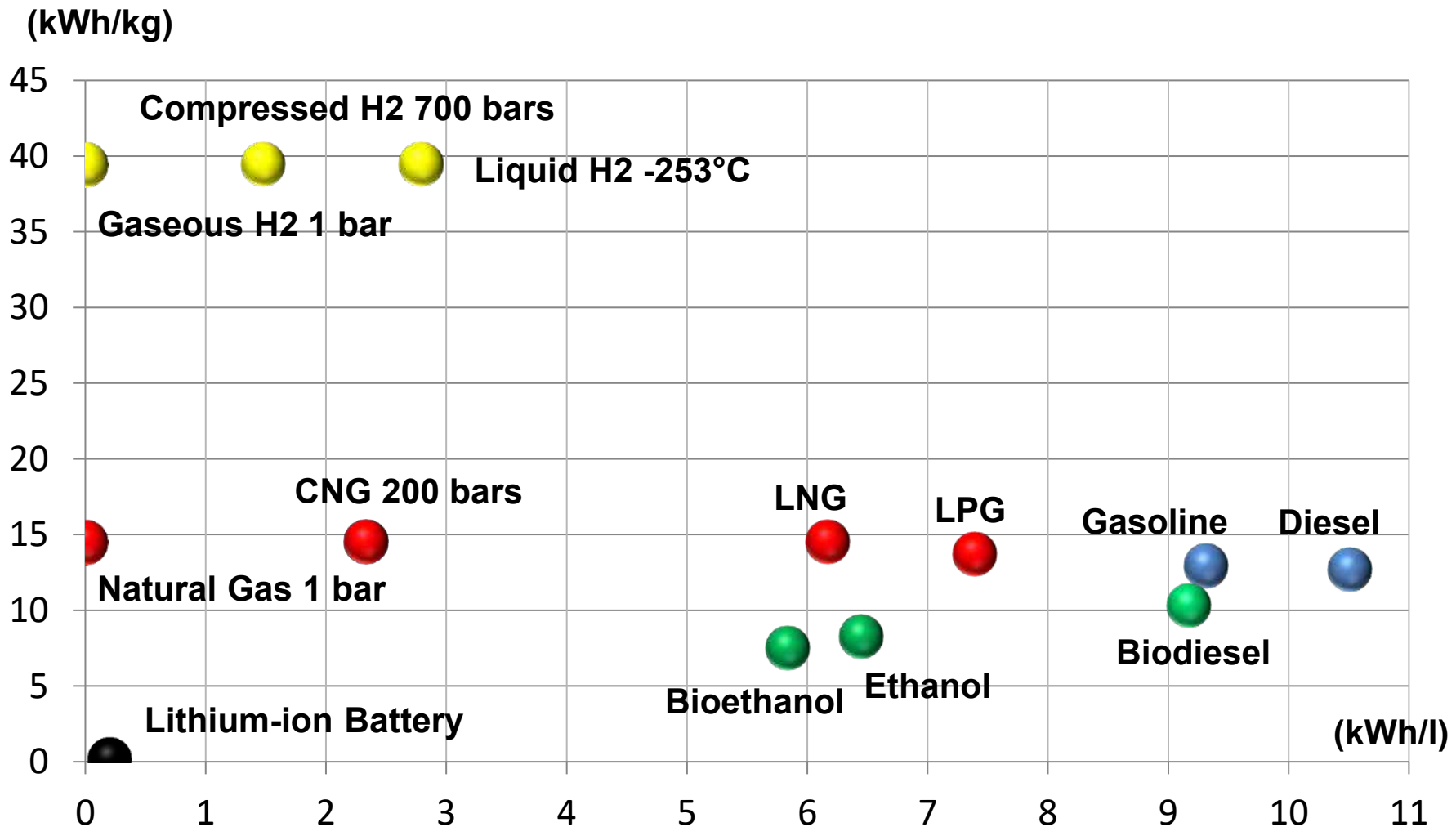
For the Transportation Sector, 2 factors of importance:
1) Fuel Energy Density (Volume & Mass)
2) Compactness of the Storage System

Reminder
Lower Heating Value (LHV) vs Higher Heating Value (HHV)

- The lower heating value (LHV also known as net calorific value) of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25°C) and returning the temperature of the combustion products to 150°C, which assumes the latent heat of vaporization of water in the reaction products is not recovered.
- The higher heating value (HHV known as gross calorific value or gross energy) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25°C) once it is combusted and the products have returned to a temperature of 25°C, which takes into account the latent heat of vaporization of water in the combustion products.

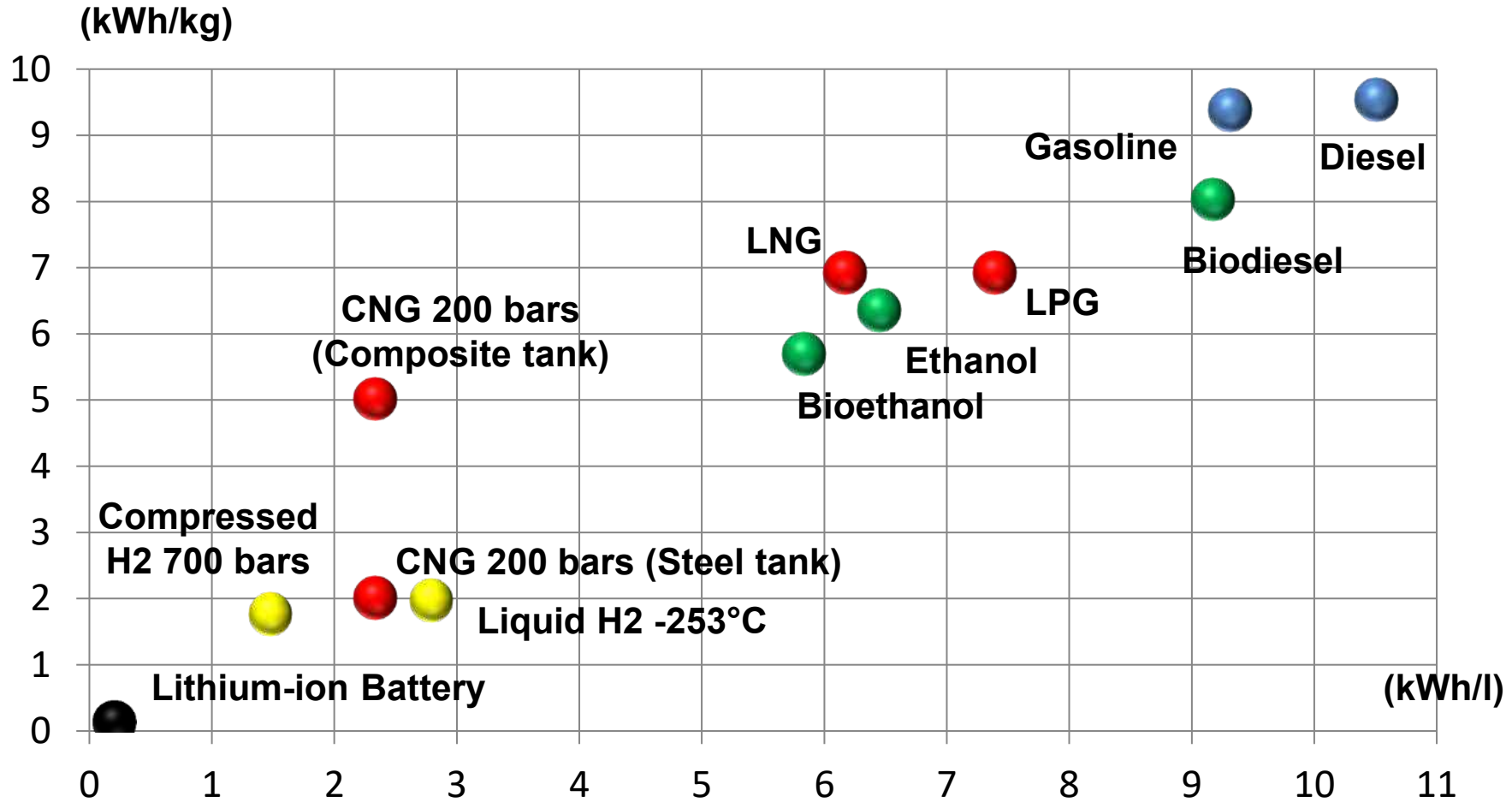
The total amount of heat liberated during the combustion of a unit of fuel, the HHV or HCV includes the latent heat stored in the vaporised water.

Fuels Gross Energy Density



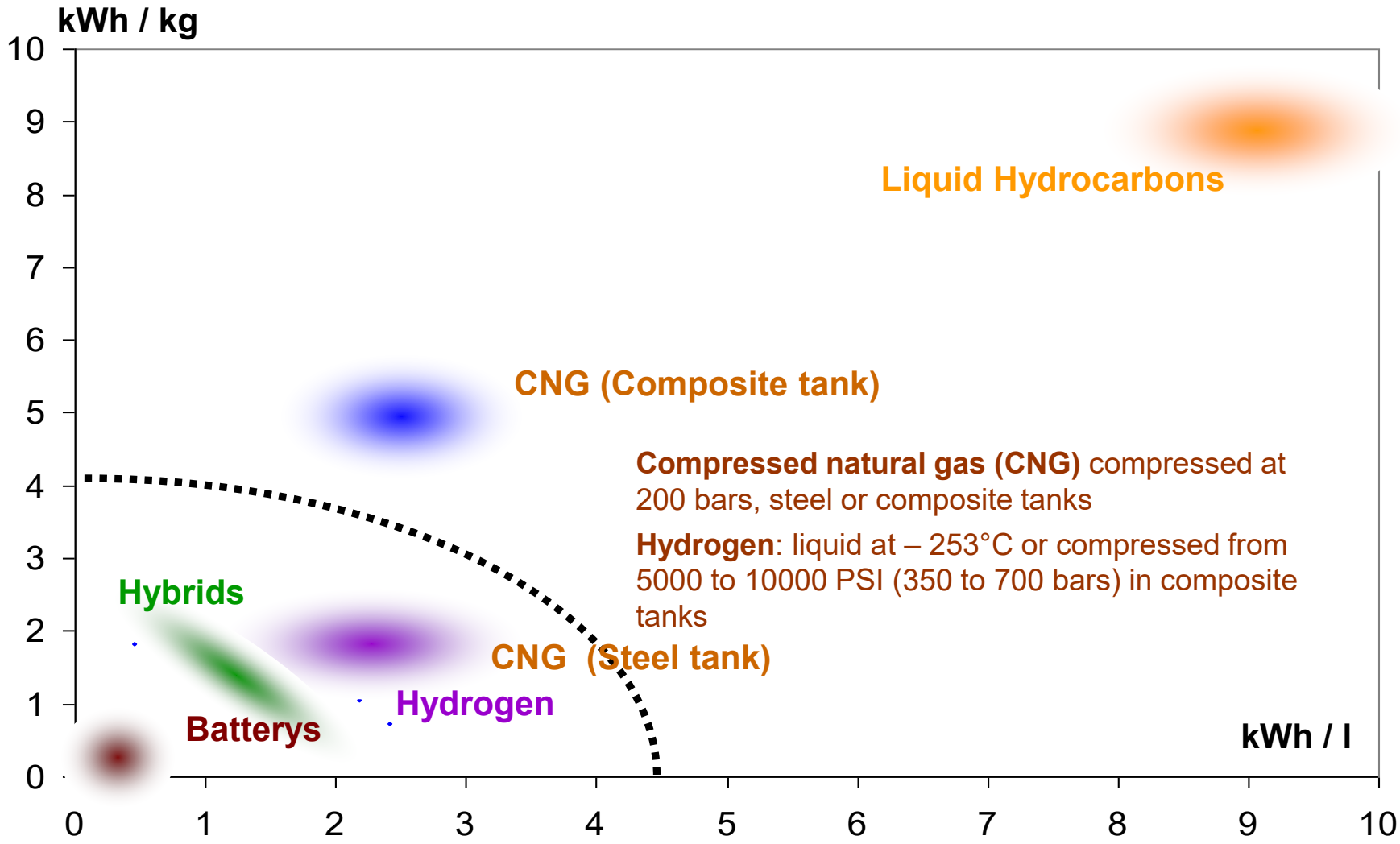
Source: Ch.Guéritte
Specific Energy: Energy/Mass (MJ or kWh/kg)
Energy Density: Energy/Volume (MJ or kWh/l)

Fuels Gross Energy Density
including Storage System Volume & Mass



Source: Ch.Guéritte
Specific Energy: Energy/Mass including Storage system (MJ or kWh/kg)
Energy Density: Energy/Volume (MJ or kWh/l)

Liquid Hydrocarbons: Unmatched Energy Compactness

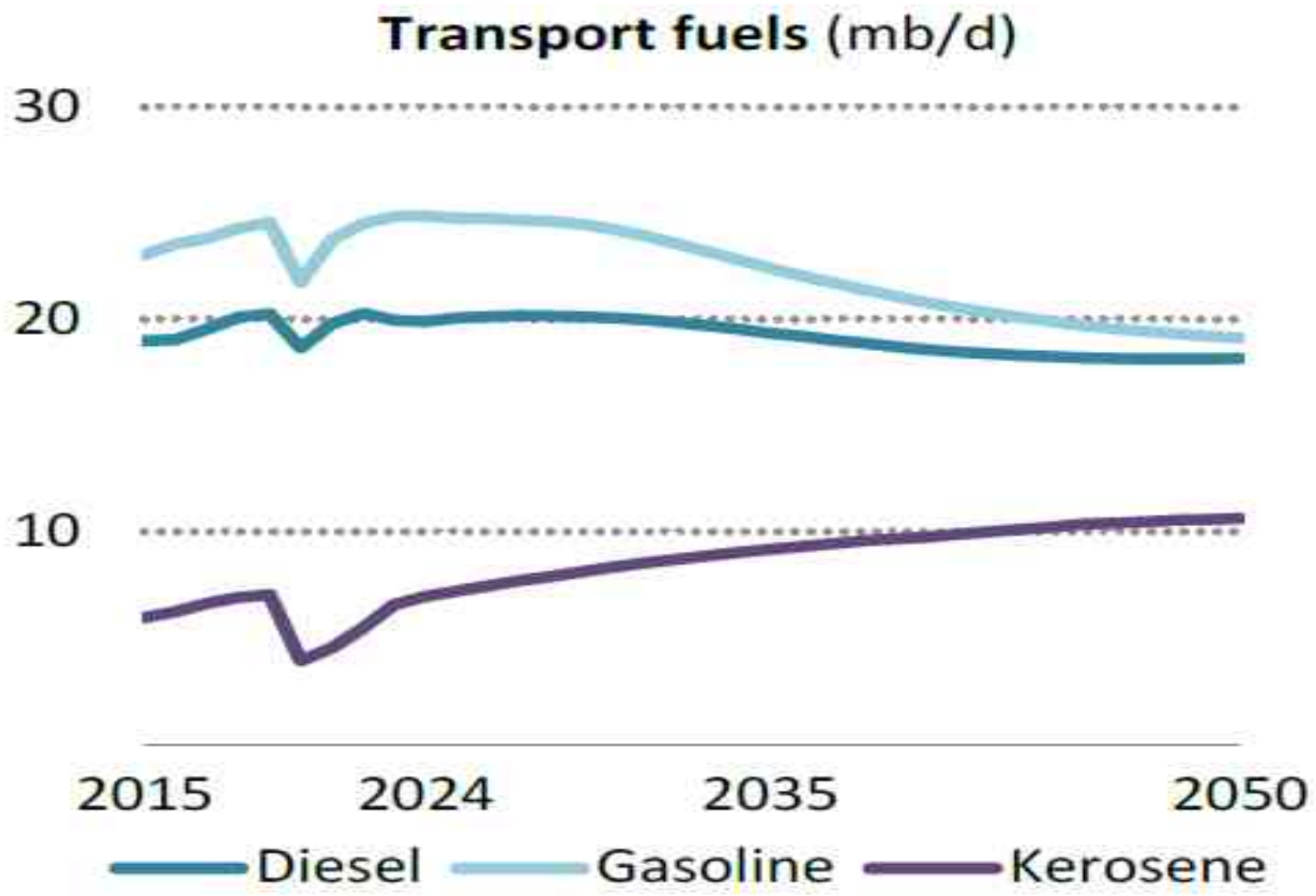


Average figures, numbers evaluated for HHV.
Energy density including Storage system.

Electric Vehicles & Hydrogen
The Challenges

- To Increase the Energy Density
- To Reduce Storage System Volume & Weight
- To Reduce the Costs
- To Expand massively Refuelling Stations & Network
- To Use Decarbonized Source of Electricity Production

Oil Demand in Transport - IEA 2025 STEPS Scenario



Source: IEA WEO 2025

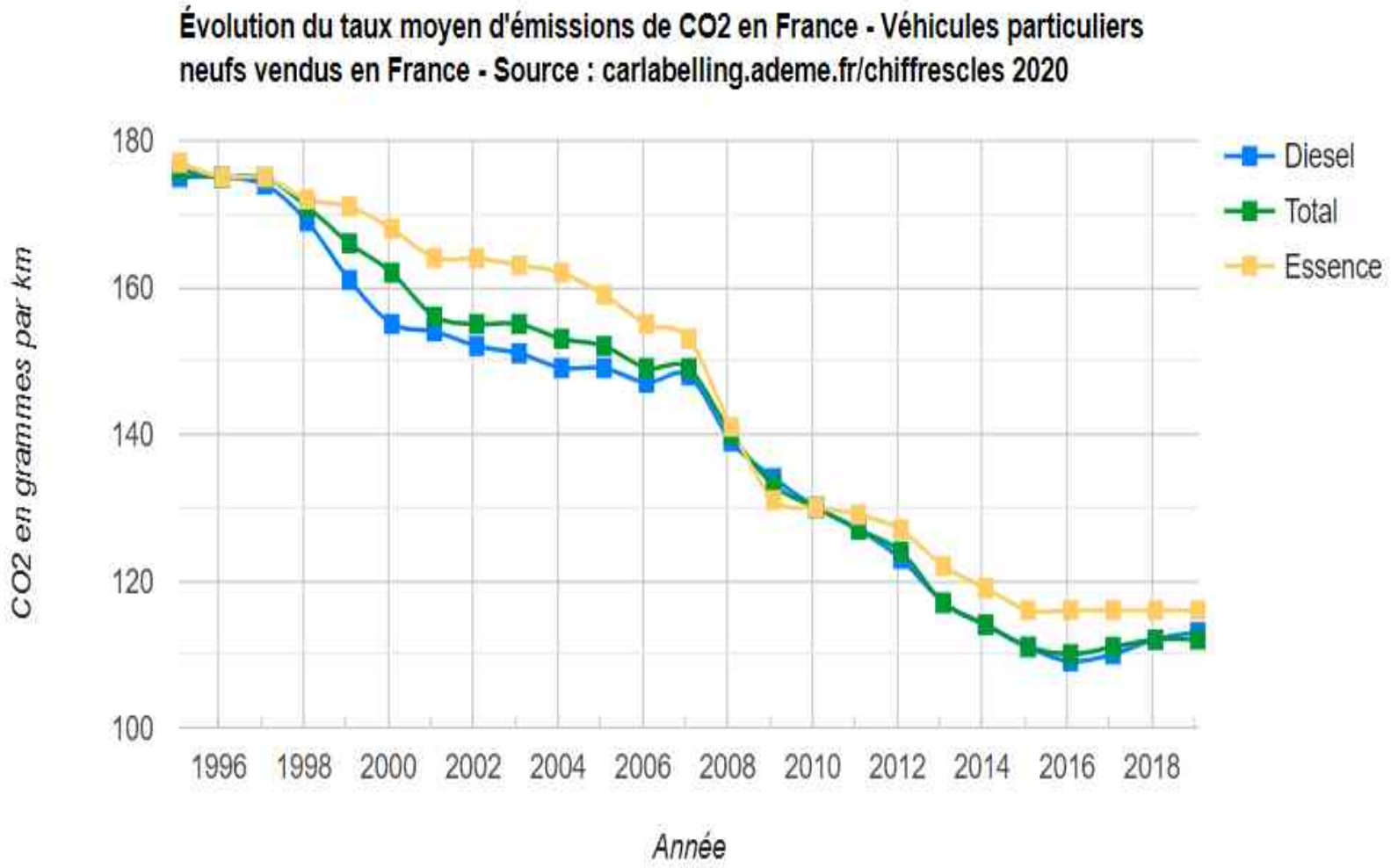
CO_2 Emissions in Transport - IEA 2025 STEPS Scenario

In 2024, Transport represents 24% of CO_2 emissions (Combustion activities)

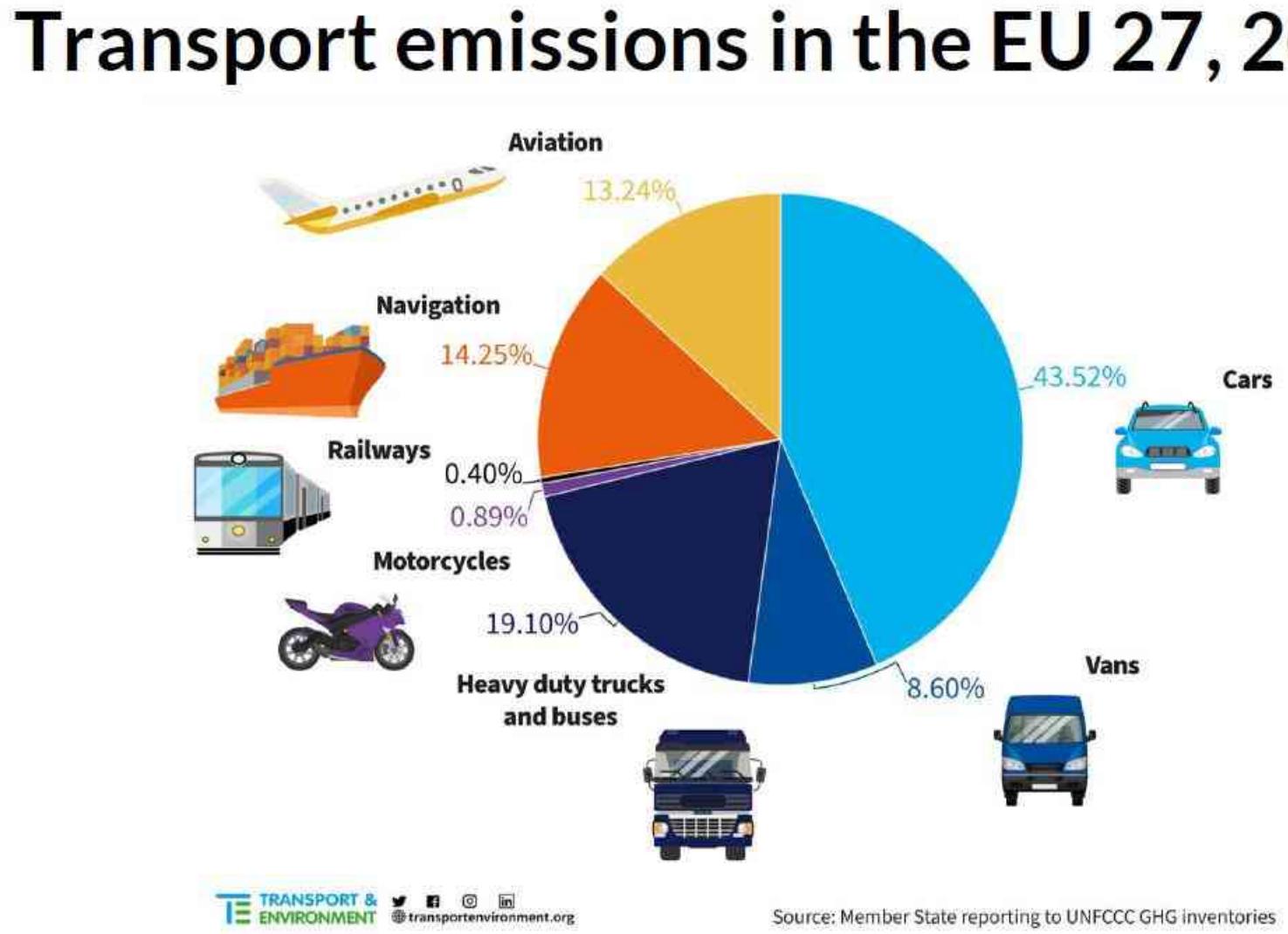
				Stated Policies (Mt CO_2)			CAAGR (%) 2024 to:	
	2010	2023	2024	2035	2040	2050	2035	2050
Transport	7 022	8 278	8 358	8 451	8 201	7 989	0.1	-0.2
Road	5 219	6 219	6 232	5 979	5 667	5 370	-0.4	-0.6
Passenger cars	2 634	3 193	3 208	2 828	2 617	2 409	-1.1	-1.1
Heavy-duty trucks	1 586	1 956	1 968	2 169	2 199	2 303	0.9	0.6
Aviation	758	957	1 018	1 334	1 422	1 551	2.5	1.6
Shipping	798	825	847	895	872	833	0.5	-0.1

Source: IEA WEO 2025

CO_2 Emissions for Light Vehicles - France



CO_2 Transport Emissions in EU 27



Transport Sector CO_2 Emissions in 2018:
1,1 $GtCO_2$ in EU 27
8,3 $GtCO_2$ Worldwide

Source: Transport & Environment 2024

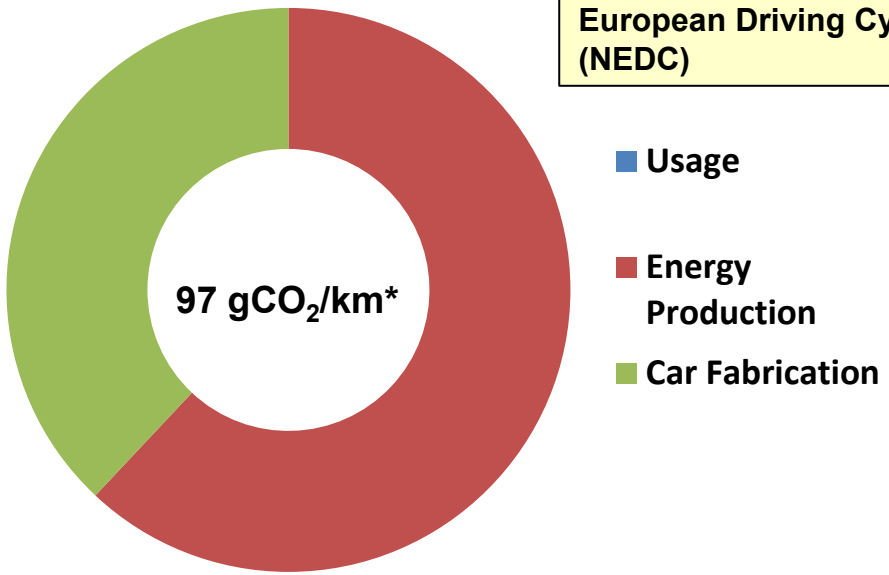
For Electric Vehicles, Decarbonized Electricity Production is a Must!



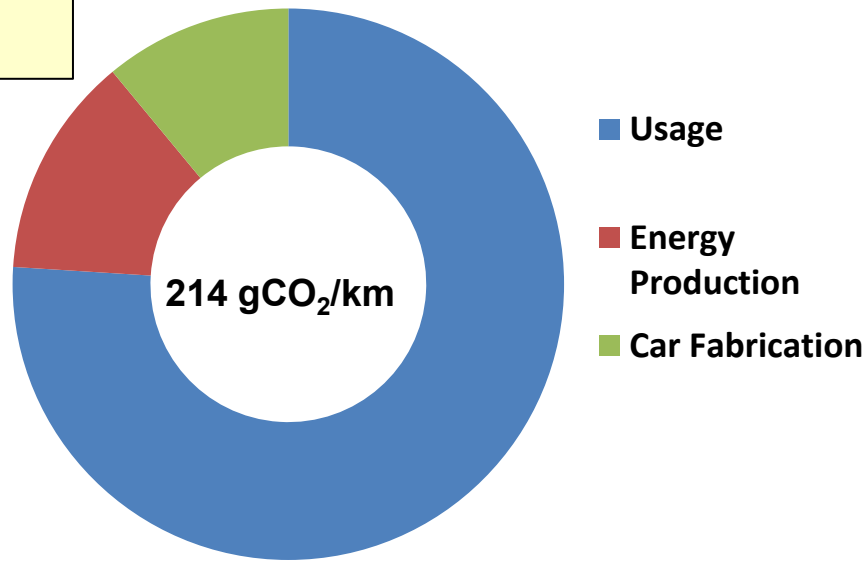
Which impact for CO_2 Emissions?
Full Life Cycle
All Electric vehicle vs Diesel – Average EU

New rules for car homologation: Worlwide Harmonized Light Vehicles Test Procedures (WLTP), replaces New European Driving Cycle (NEDC)

All Electric Vehicle



Diesel Vehicle



*Average for European Union

CO_2 Emissions related to Energy Production depend upon the source of Electricity Production (Nuclear, Gas fired, Coal fired, etc….)

In France, in 2020, Malus as from 138 gCO2 WLTP/km vs 145 gCO_2 WLTP /km in 2019. New limits: 2024: 118gCO_2/km, 2025: 113gCO_2/km

Source: Université de Bruxelles
Transport et Environnement/ Challenges/l'Argus

For Electric Vehicles, Decarbonized Electricity Production is a Must!

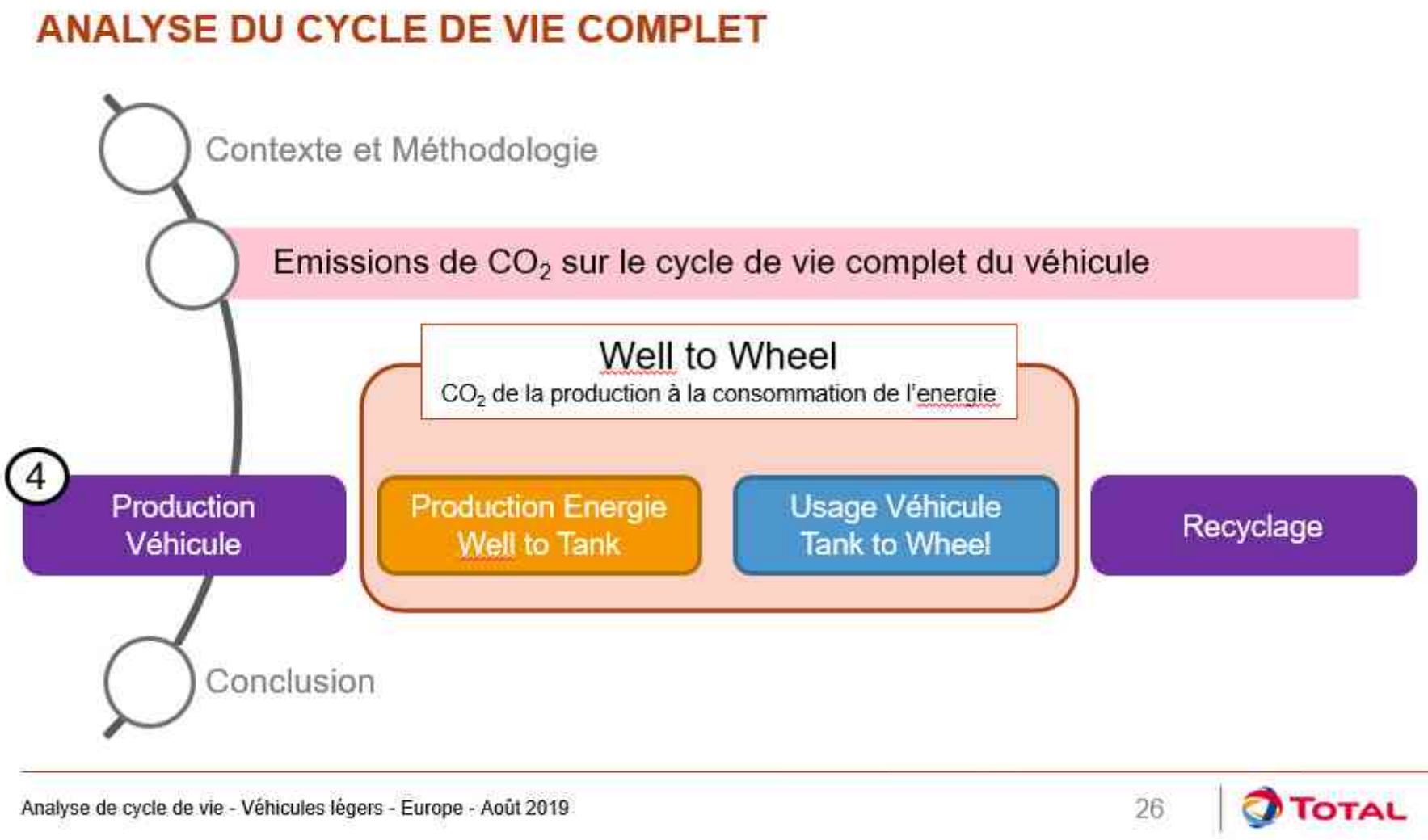


In Poland, an electric vehicle emits almost the same amount of CO_2 as a combustion-powered vehicle, during its life cycle:
48 tCO_2 vs 53 tCO_2……

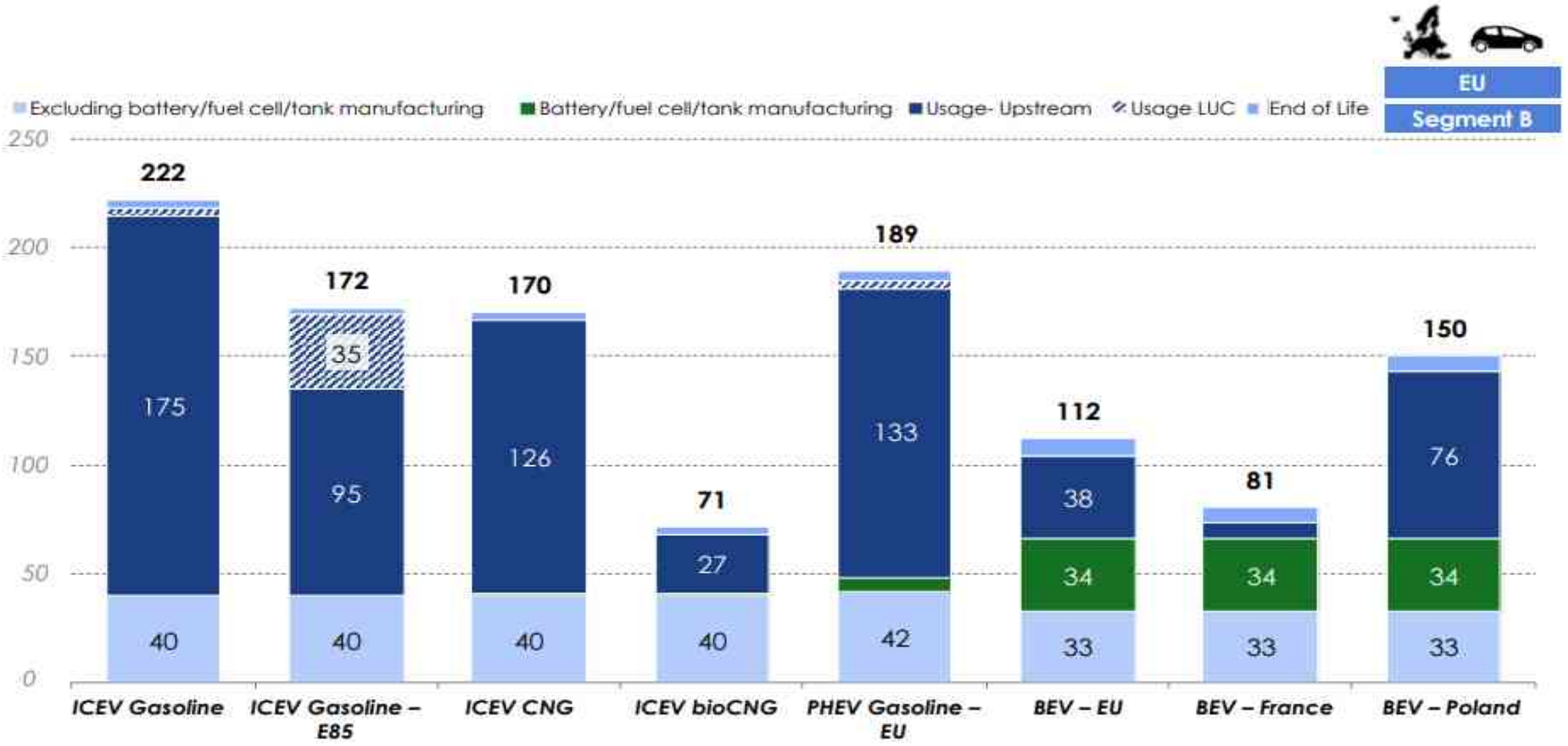
Because electricity is produced from coal-fired power plants…

Source: Courrier International

Transport Mobility - Light Vehicles
CO_2 Emissions – Full Life Cycle



CO_2 emissions on Life Cycle Analysis (gCO2e/km – small car - **EU**)

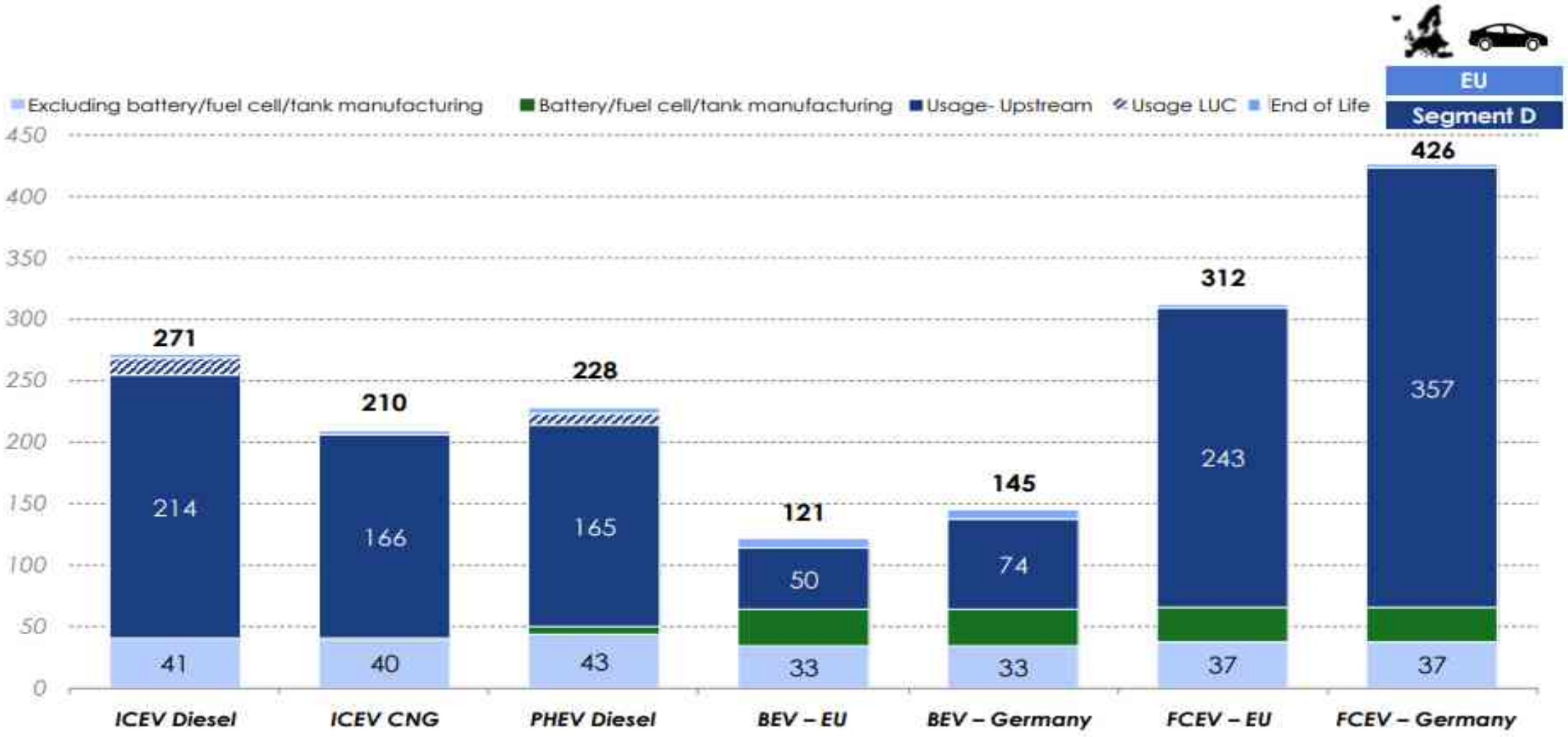


Sources: Carbon 4 Analysis

ICEV : Internal Combustion Engine Vehicle	PHEV : Electric Vehicle Plug-In Hybrid
BEV : Battery Electric Vehicle	FCEV: Fuel Cell Electric Vehicle
MHEV : Mild Hybrid Electric Vehicle	HVO : Hydrotreated Vegetable Oil
HEV : Hybrid Electic Vehicle	LUC: Land Use Change

carbone 4

CO_2 emissions on Life Cycle Analysis (gCO2e/km - medium car - **EU**)

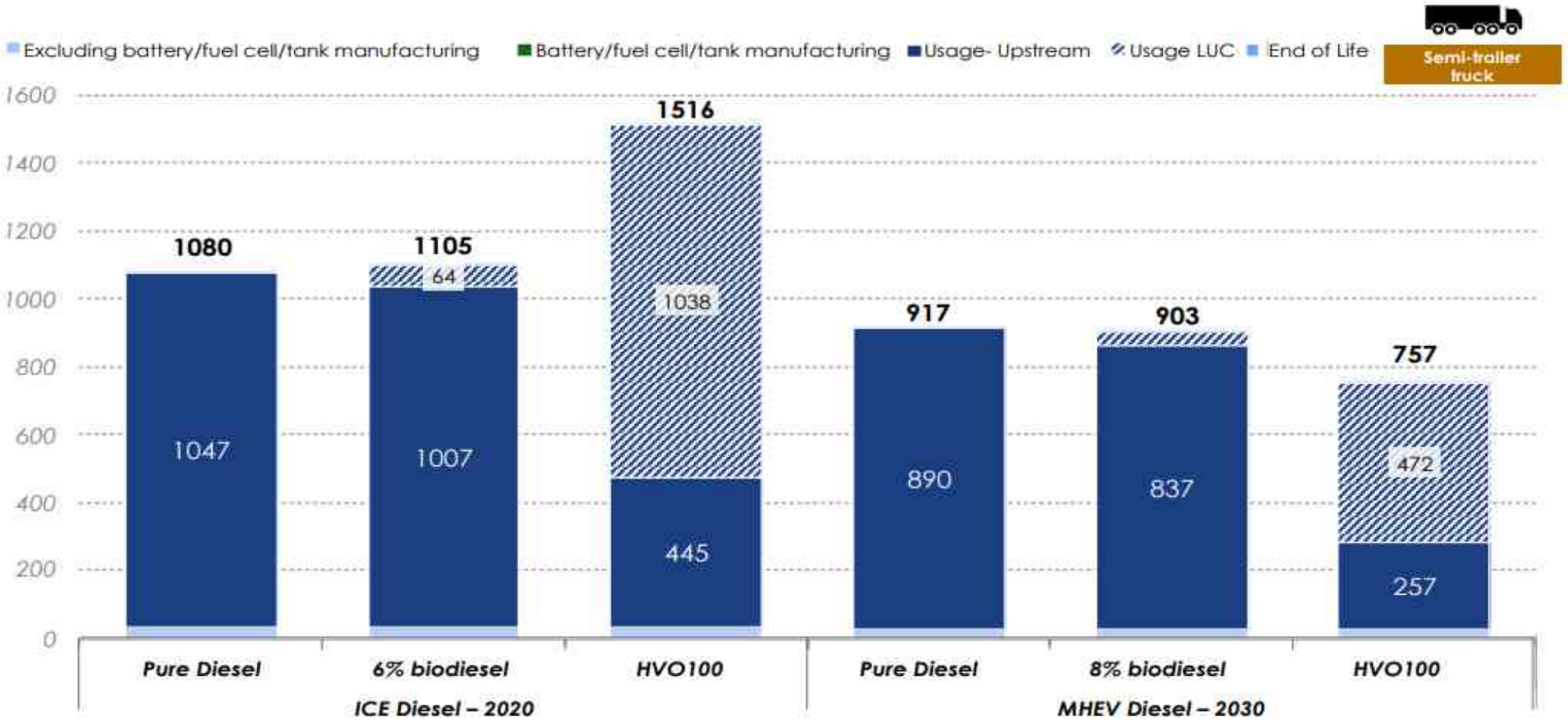


Sources: Carbon 4 Analysis

ICEV : Internal Combustion Engine Vehicle	PHEV : Electric Vehicle Plug-In Hybrid
BEV : Battery Electric Vehicle	FCEV: Fuel Cell Electric Vehicle
MHEV : Mild Hybrid Electric Vehicle	HVO : Hydrotreated Vegetable Oil
HEV : Hybrid Electic Vehicle	

carbone 4

Bios : impact of Land Change Use Assumptions (gCO2e/km – Truck)



Sources: Carbon 4 Analysis

ICEV : Internal Combustion Engine Vehicle	PHEV : Electric Vehicle Plug-In Hybrid
BEV : Battery Electric Vehicle	FCEV: Fuel Cell Electric Vehicle
MHEV : Mild Hybrid Electric Vehicle	HVO : Hydrotreated Vegetable Oil
HEV : Hybrid Electic Vehicle	

carbone 4

A Zoom on Electric Vehicles (EV)

A Zoom on Electric Vehicles (EV)



Electric Vehicles Initiative (EVI)

The Electric Vehicles Initiative (EVI) is a multi-governmental policy forum established in 2010 under the Clean Energy Ministerial (CEM). Recognising the opportunities offered by EVs, the EVI is dedicated to accelerating the adoption of EVs worldwide.



Source: IEA Global EV Outlook 2026 – May 2026

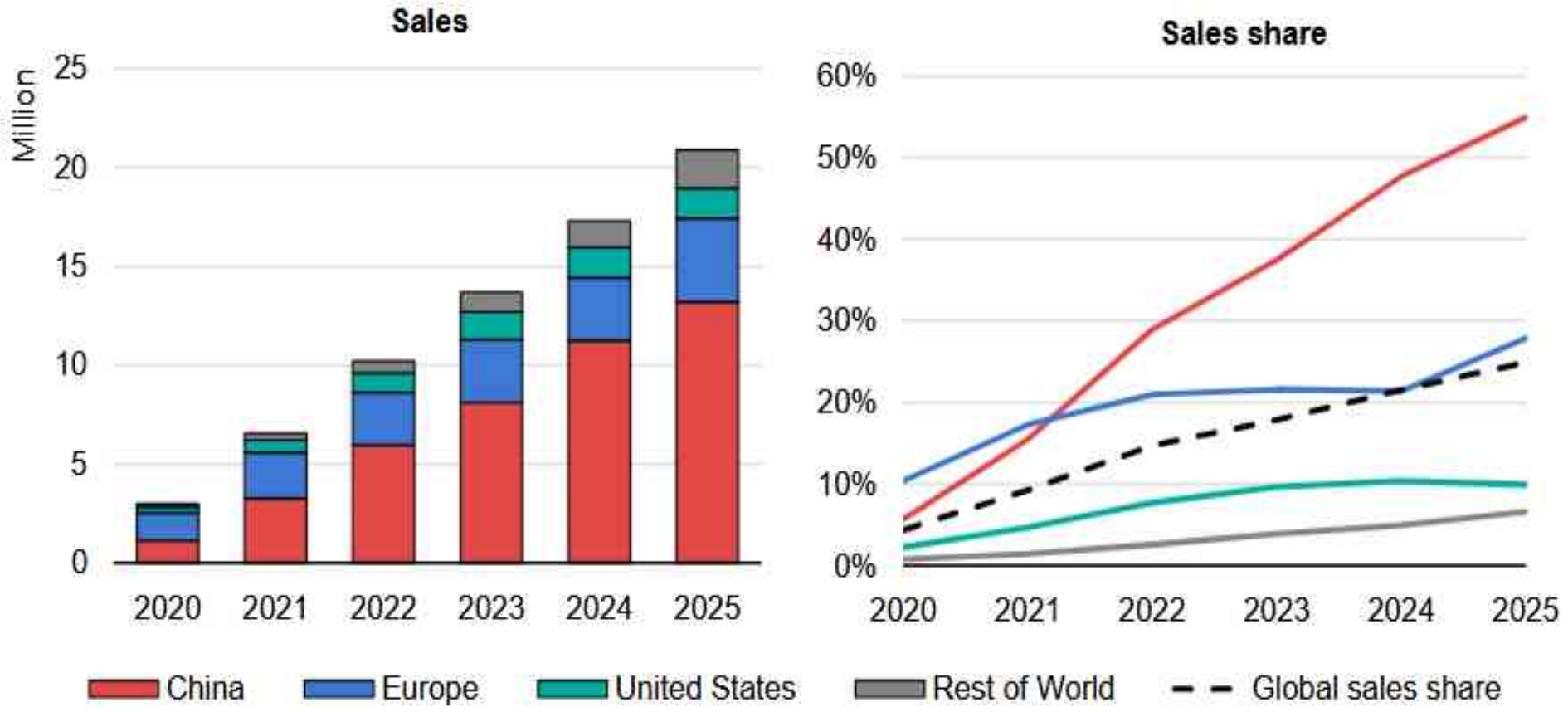
Vehicles typology & Mileages

Mileages

Vehicle type	Powertrain	Annual mileage (thousand km)
Passenger cars	Battery electric	12.5
Passenger cars	Plug-in hybrids	12.1
Passenger cars	Internal combustion engine	12.0
Passenger cars	Hybrid vehicles	12.8
Light-commercial vehicles	Battery electric	24.4
Light-commercial vehicles	Plug-in hybrids	23.3
Light-commercial vehicles	Internal combustion engine	16.2
Light-commercial vehicles	Hybrid vehicles	23.8
Buses	Battery electric	27.6
Buses	Plug-in hybrids	12.8
Buses	Internal combustion engine	19.9
Buses	Hybrid vehicles	36.4
Medium freight trucks	Battery electric	45.5
Medium freight trucks	Plug-in hybrids	26.9
Medium freight trucks	Internal combustion engine	22.7
Medium freight trucks	Hybrid vehicles	41.9
Heavy freight trucks	Battery electric	45.4
Heavy freight trucks	Plug-in hybrids	30.1
Heavy freight trucks	Internal combustion engine	37.2
Heavy freight trucks	Hybrid vehicles	28.2
Two- and three-wheelers	Battery electric	5.8
Two- and three-wheelers	Internal combustion engine	6.1

Source: IEA Global EV Outlook 2026 – May 2026

Electric Vehicles Sales 2020-2025 > 20 million in 2025



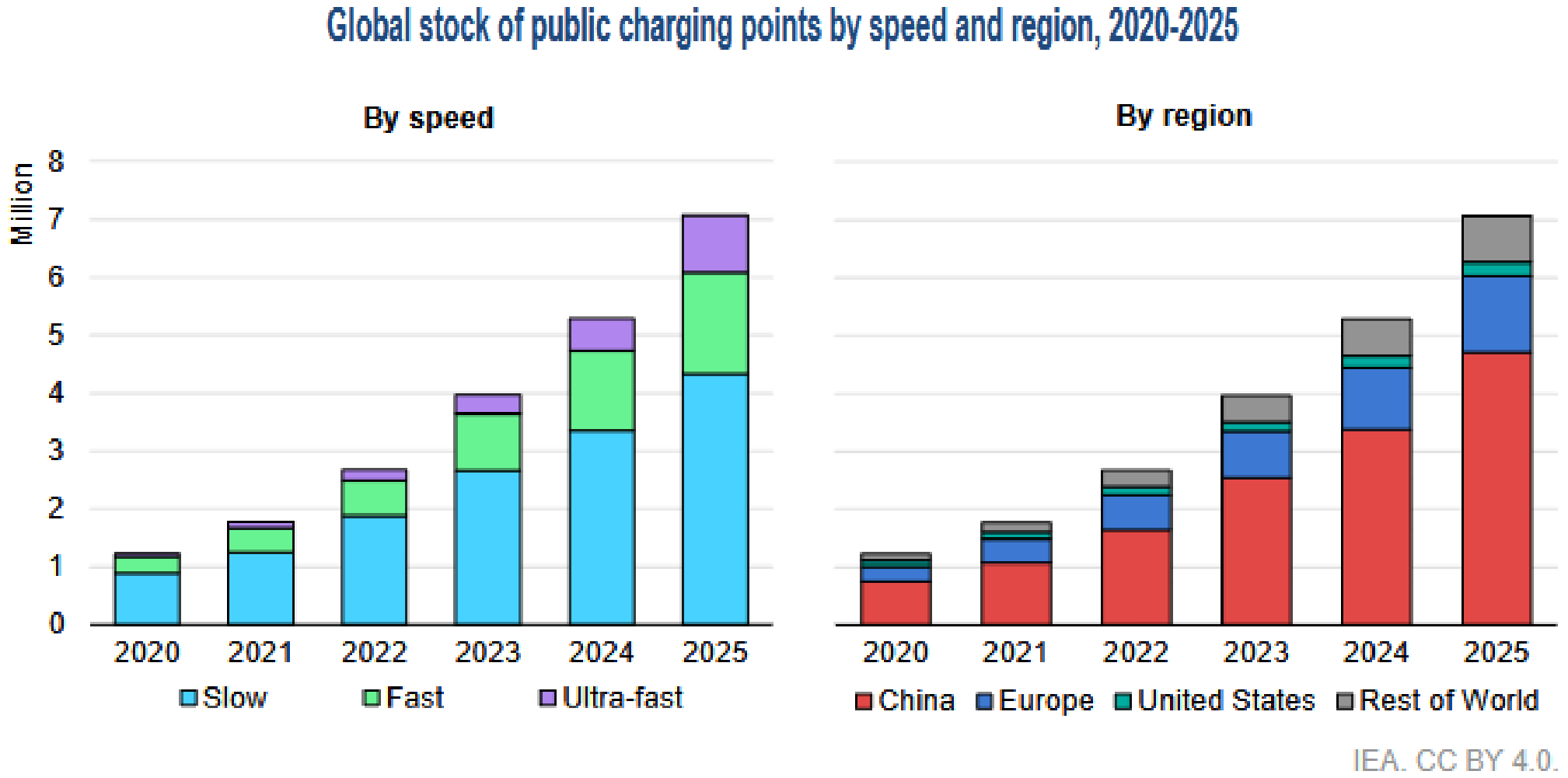
IEA. CC BY 4.0.

Note: Electric cars include battery electric and plug-in hybrid electric cars.

Sources: IEA analysis based on EV Volumes, ACEA, EAFO and country submissions.

Source: IEA Global EV Outlook 2026 – May 2026
Excludes Fuel Cell Vehicles

Global stock of Electric Vehicles public Charging Points 2020 - 2025

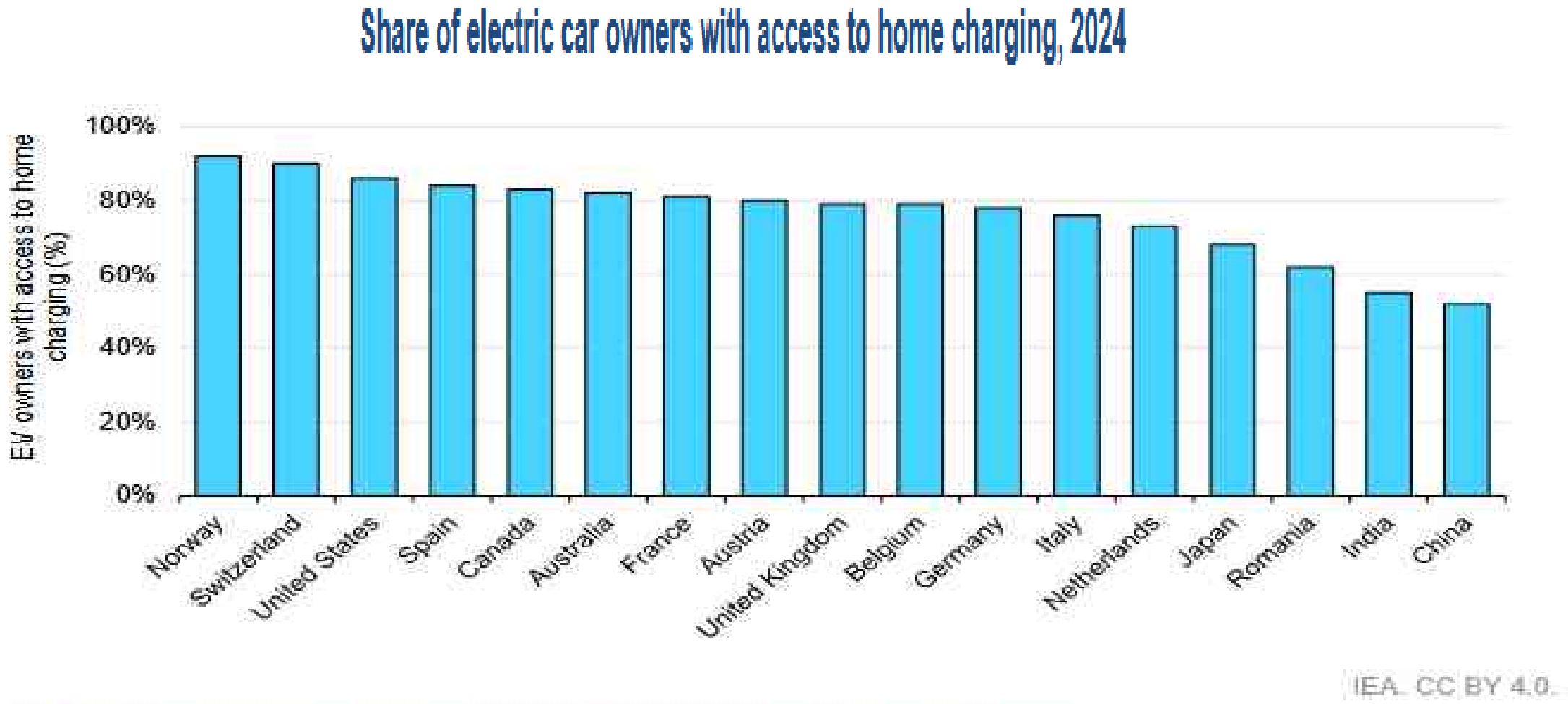


Note: Chargers less than or equal to 22 kW are classified as slow; chargers greater than 22 kW and up to 150 kW as fast; and 150 kW and above as ultra-fast.

Sources: IEA analysis based on EV Volumes, EAFO and BNEF.

Source: IEA Global EV Outlook 2026 – May 2026

Electric Vehicles owners with access to Home Charging Points 2024

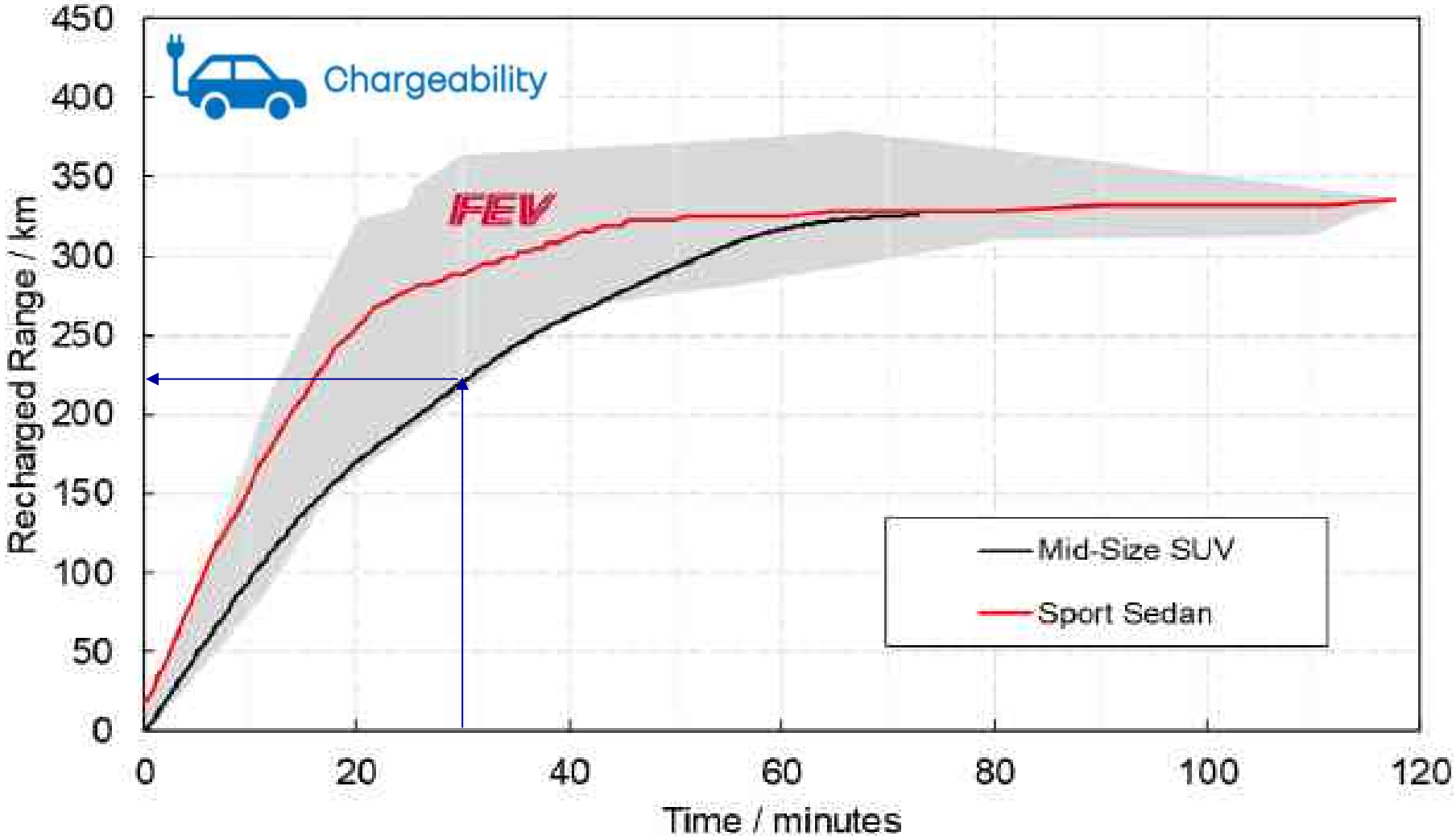


Note: EV owners with access to home charging excludes shared residential chargers.

Sources: IEA analysis based on: ChargeLab, eMobility Power, McKinsey, Mobilität in Deutschland 2023, Mobility Portal, Norwegian EV Association, Roland Berger, RVO, Government of Canada, Zapmap.

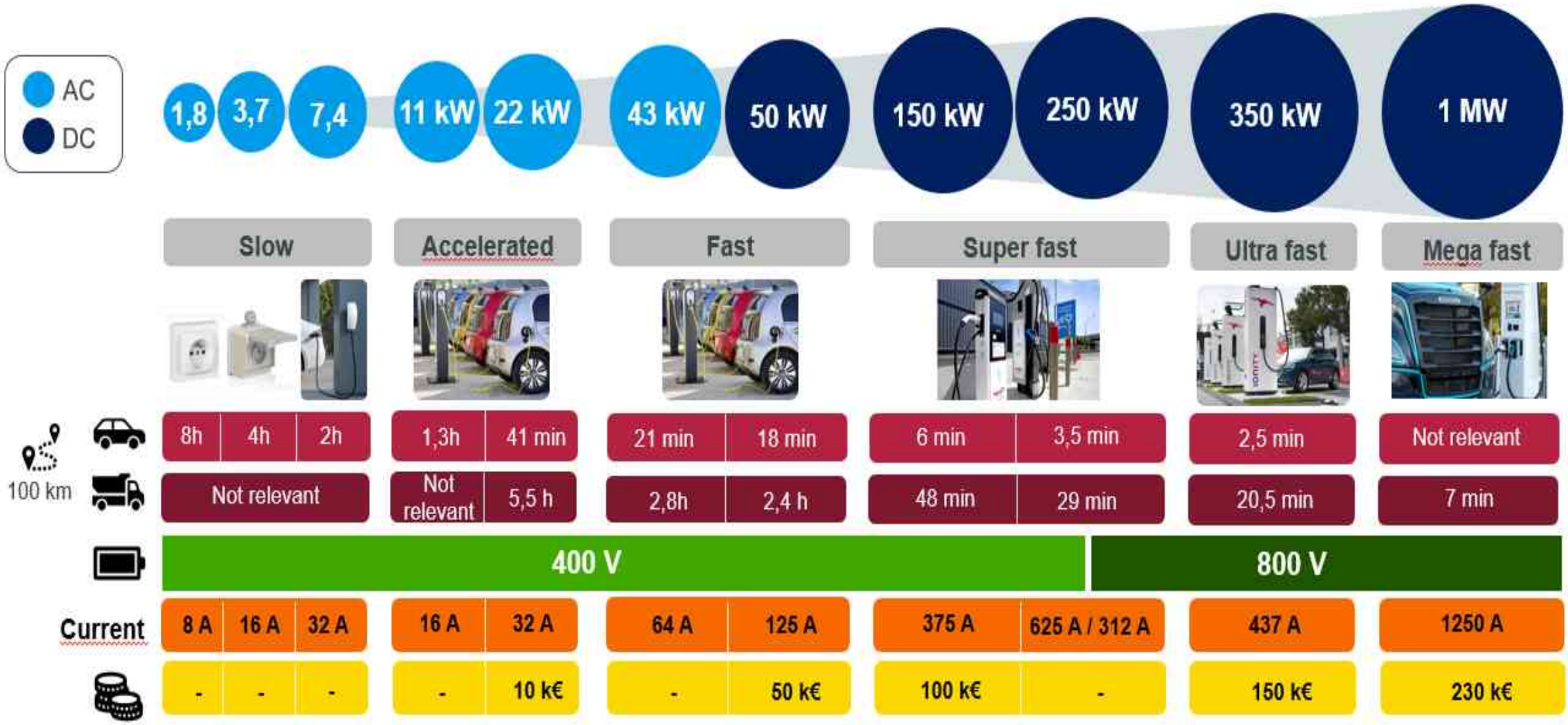
Source: IEA Global EV Outlook 2026 – May 2026

A Zoom on Electric Vehicles
Autonomy vs Chargeability



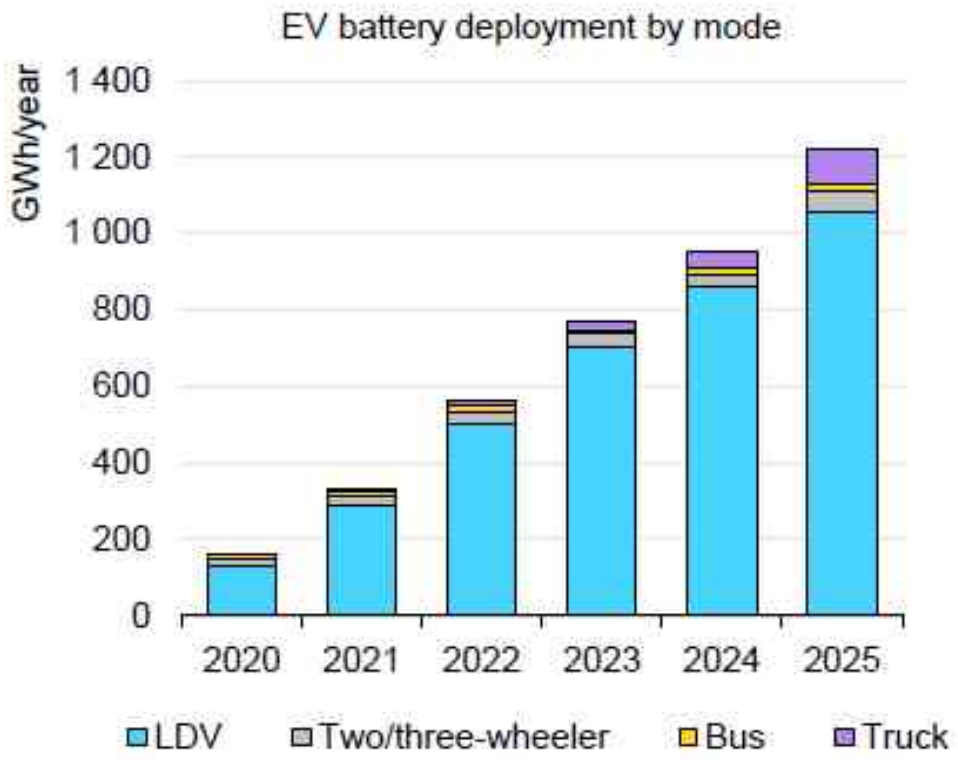
Source: TotalEnergies – Ph. China

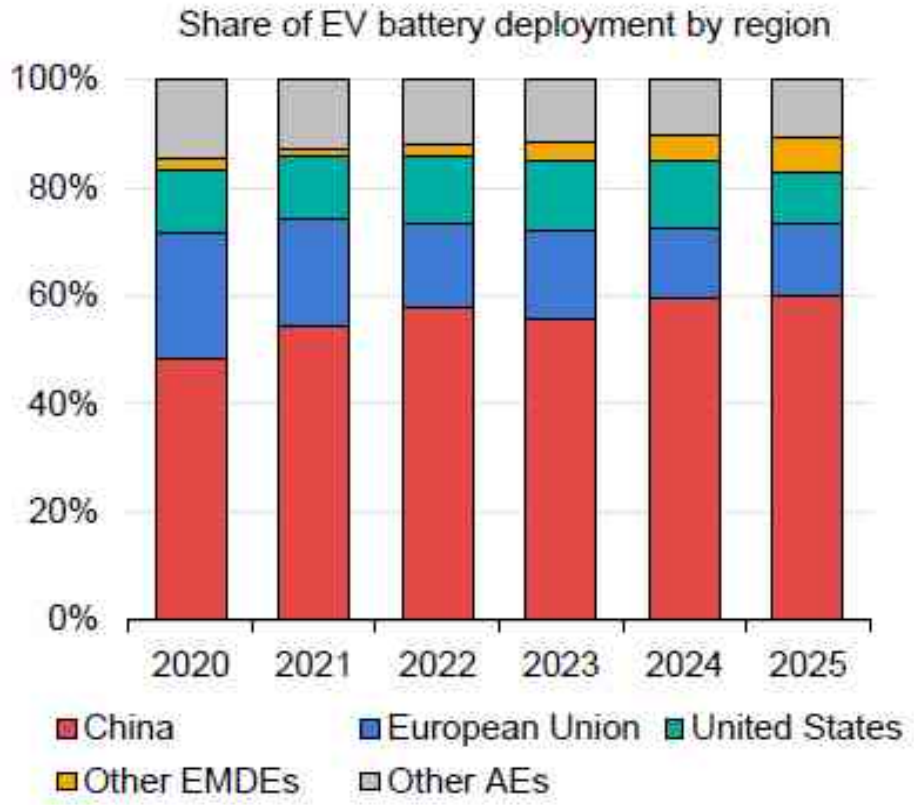
A Zoom on Electric Vehicles - Charging Technologies 2025+



Source: TotalEnergies – Ph. China

Electric Vehicles Battery Demand by Mode & Regions 2017 - 2023





IEA. CC BY 4.0.

Notes: LDV = light-duty vehicle, including cars and vans; EMDEs = emerging markets and developing economies; AEs = advanced economies. Battery deployment is defined as the volume-weighted average battery size multiplied by vehicle sales by mode and region.

Sources: IEA analysis based on country submissions and data from the European Automobile Manufacturers Association (ACEA), European Alternative Fuels Observatory (EAFO), Marklines and EV Volumes.

Source: IEA – Global EV Outlook 2026 – May 2026

Batteries for EV
Necessity to scaling up Batteries fabrication
Gigabatteries plants - A challenge?
Two european manufacturers: ACC (Automotive Cells Company & Northvolt
See Chapter 11

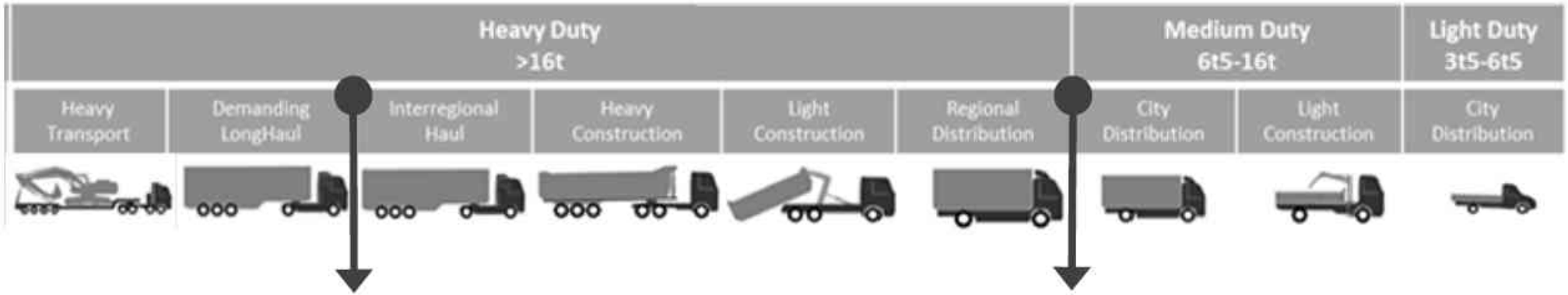
A Zoom on Trucks

European Trucks Market

Fleets: 291 millions of cars, 35 millions of LCV and 7.0 millions of trucks & buses (1)

Yearly new registrations: 320 000 trucks (2)

RENAULT TRUCKS VOLVO SCANIA MAN DAF IVECO



RENAULT TRUCKS



Long-Haul Truck

4 x 2 tractor with trailer

40 tons GCW

500 km / day - 118 500 km / year

460 ch - 30 l / 100 km



Urban Delivery Truck

4 x 2 rigid with dry body

16 tons GCW

170 km / day - 40 300 km / year

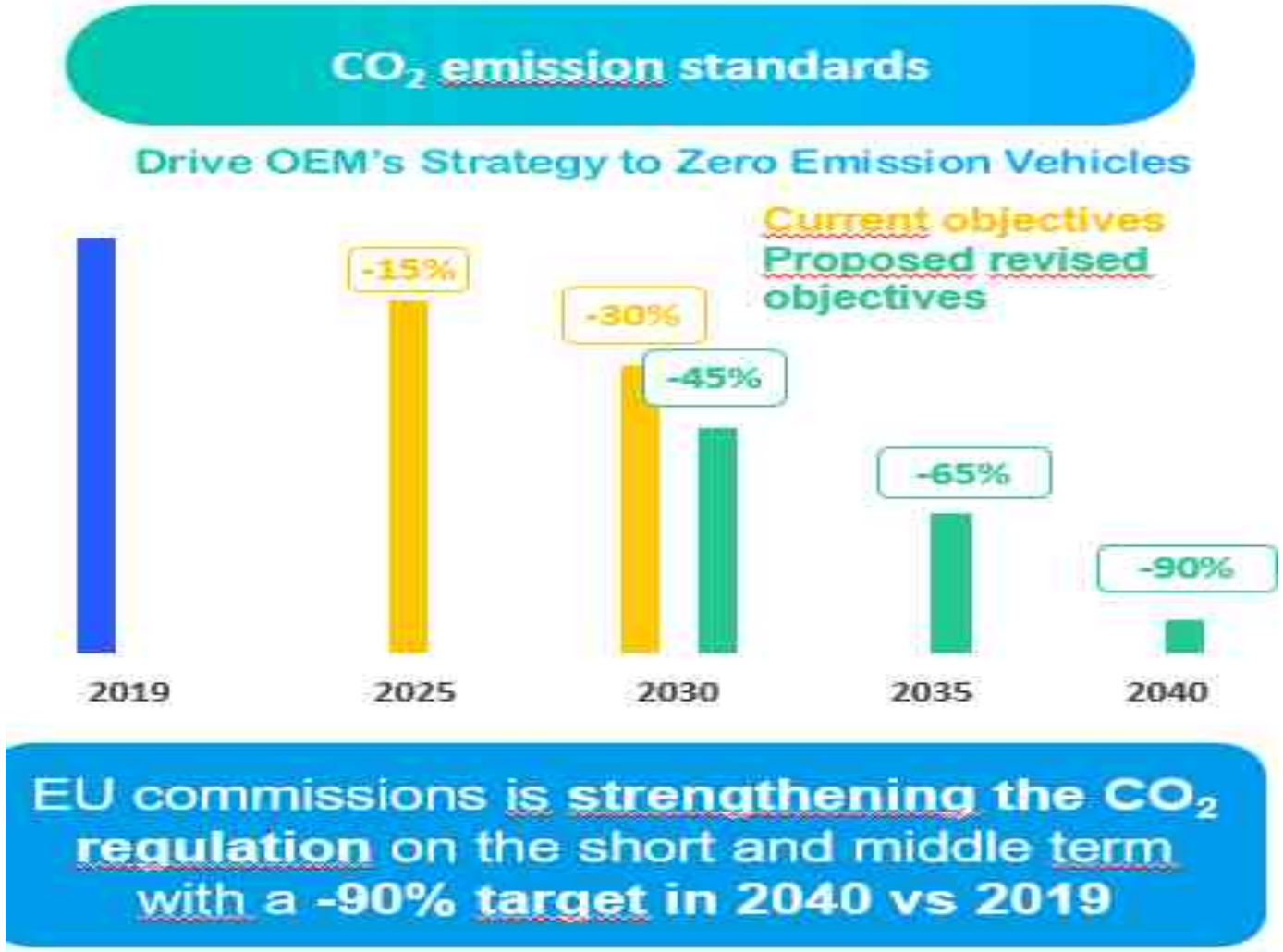
240 ch - 26 l / 100 km

(1) EU27+UK+NO+CH in 2020. Trucks and buses are vehicles above 3.5 tons. Source: ACEA, « Vehicle in Use in Europe », 2022

(2) EU27+UK+NO+CH in 2021. Trucks > 6.5 tons. Source: IHS Markit

Source: Renault Trucks

Trucks regulations in Europe



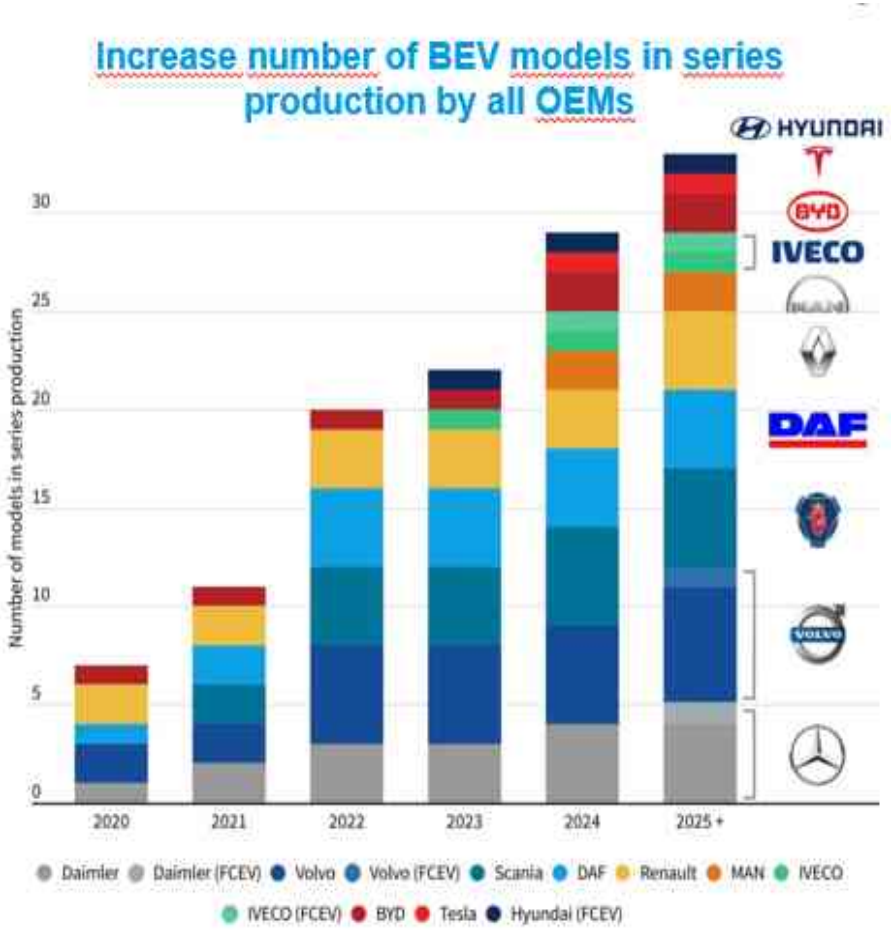
Source: TotalEnergies 2023

EV Trucks Sales by Original Equipment Manufacturer (OEM)



Sources: OEM announcements.

No other OEM annoucement for 2040



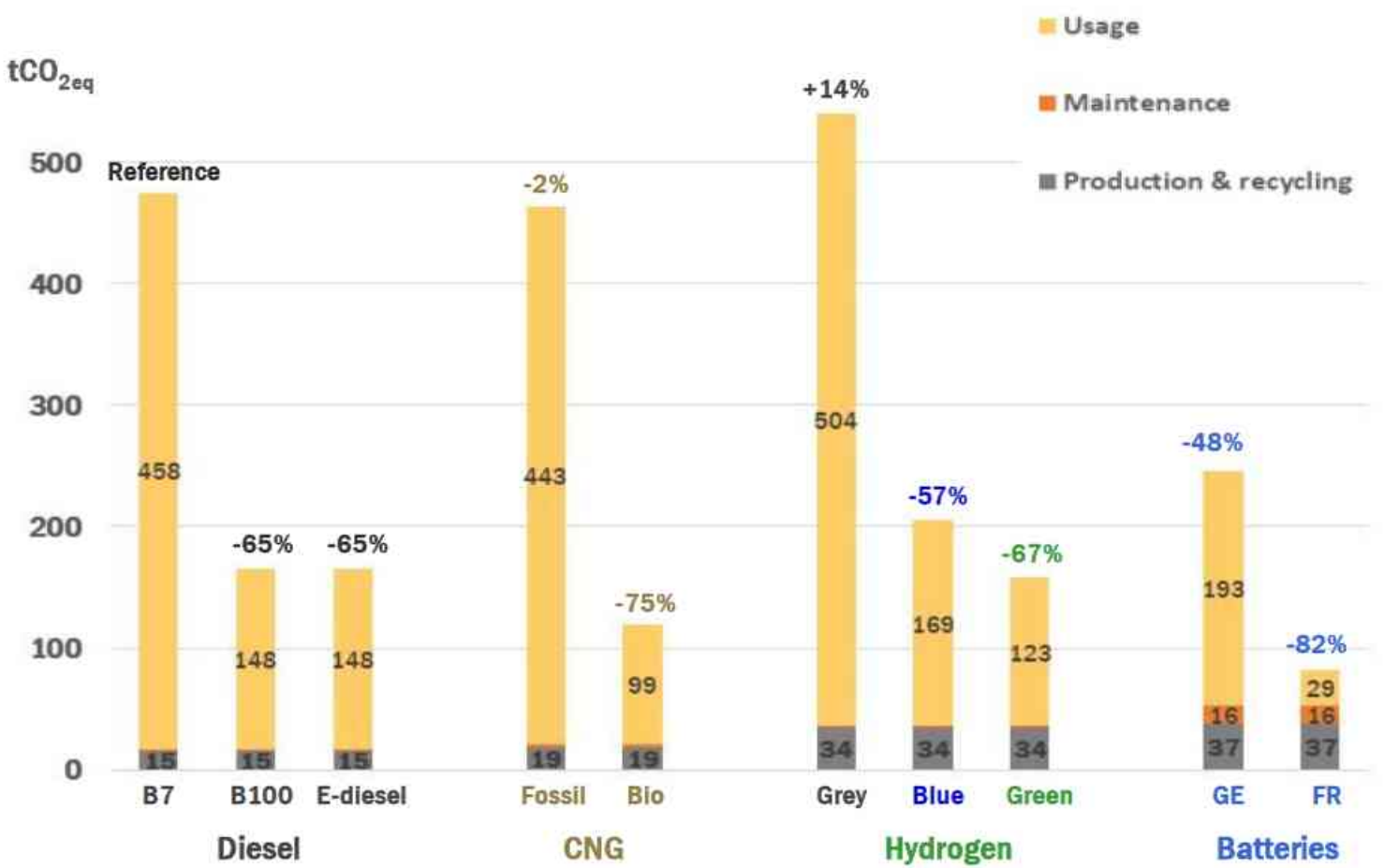
- Each OEM will increase the number of models in series production in the coming years to have an available portfolio for 2024-2025. They will have at least one BEV long haul offer before 2030.
- OEM are committed to ambitious ZEV sales share for 2030. Some pledges 100% zero emission vehicles sales in 2040

Source: TotalEnergies 2023

CO_2 Emissions by Technologies

GLOBAL WARMING POTENTIAL

For a 16-ton urban distribution truck



D 16-ton running 560 000 km over 14 years (2022-2036)

Production & recycling & maintenance : internal LCA for diesel and BEV in 2020, scaled for the other cases with Ricardo ED11344 report

CO_2 emission coefficients:

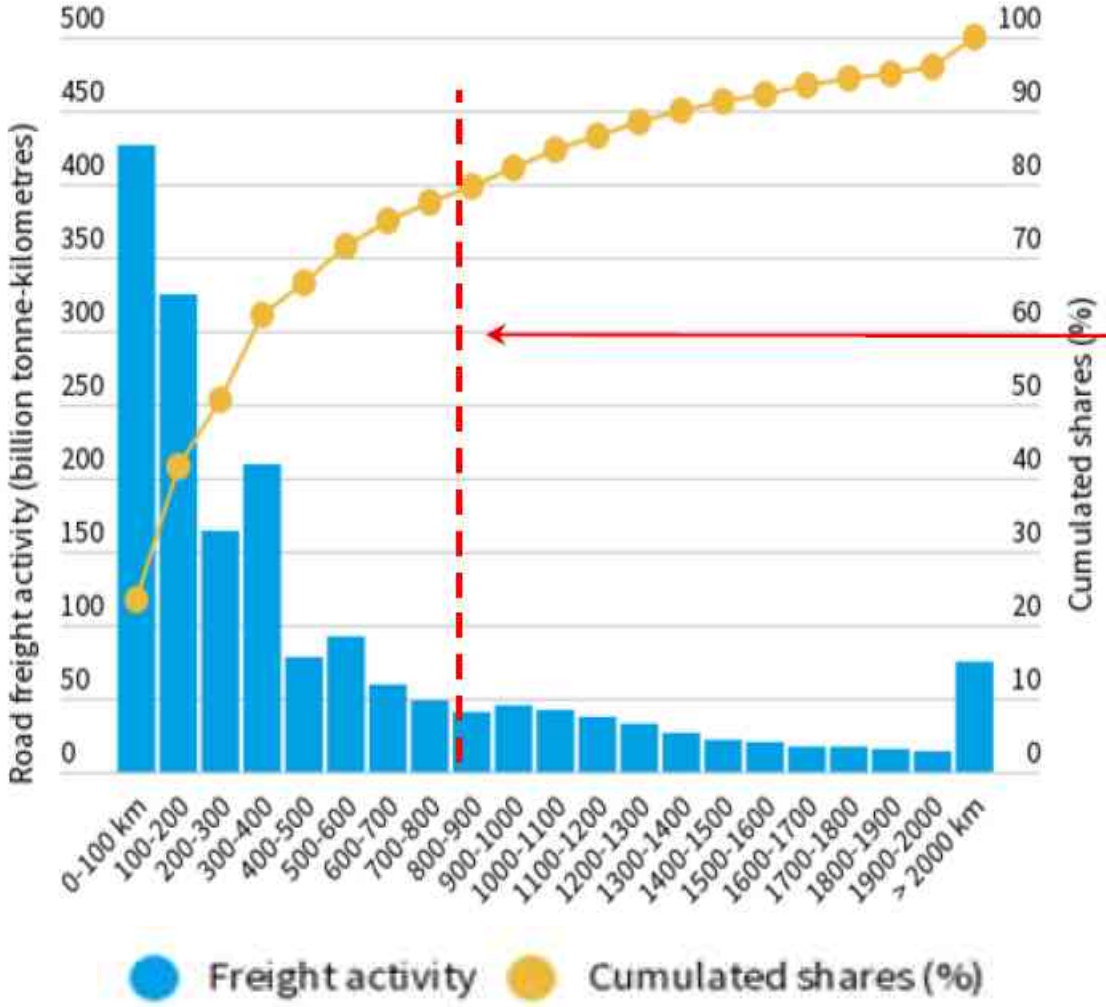
- **B100**: 31.6 gCO_2eq/MJ in 2020 (Avril), considered in 2050 at 50% of 2020 value
- **E-diesel**: own calculation using WNA emission coefficient report for solar and JEC in 2020, and 50% of its value in 2050
- **Bio-methane**: JEC (1/3 of OWCG1 and 2/3 of OWCG5) in 2020 (17 gCO_2eq/MJ), considered in 2050 at 50% of 2020 value
- **Hydrogen**: JEC GMCH1 (grey), GPCH2bC (blue), own calculation for green based on WNA and JEC, and 50% of its value in 2050
- **Grid electricity**: Germany (GE): 455 / 22 gCO_2eq/kWh cradle-to-tank in 2020 / 2050, France (FR): 69 / 17 gCO_2eq/kWh cradle-to-tank in 2020 / 2050

RENAULT TRUCKS

Source: Renault Trucks

Most Trucks activity is below 400 km

Truck activity across trip distance bands in the EU



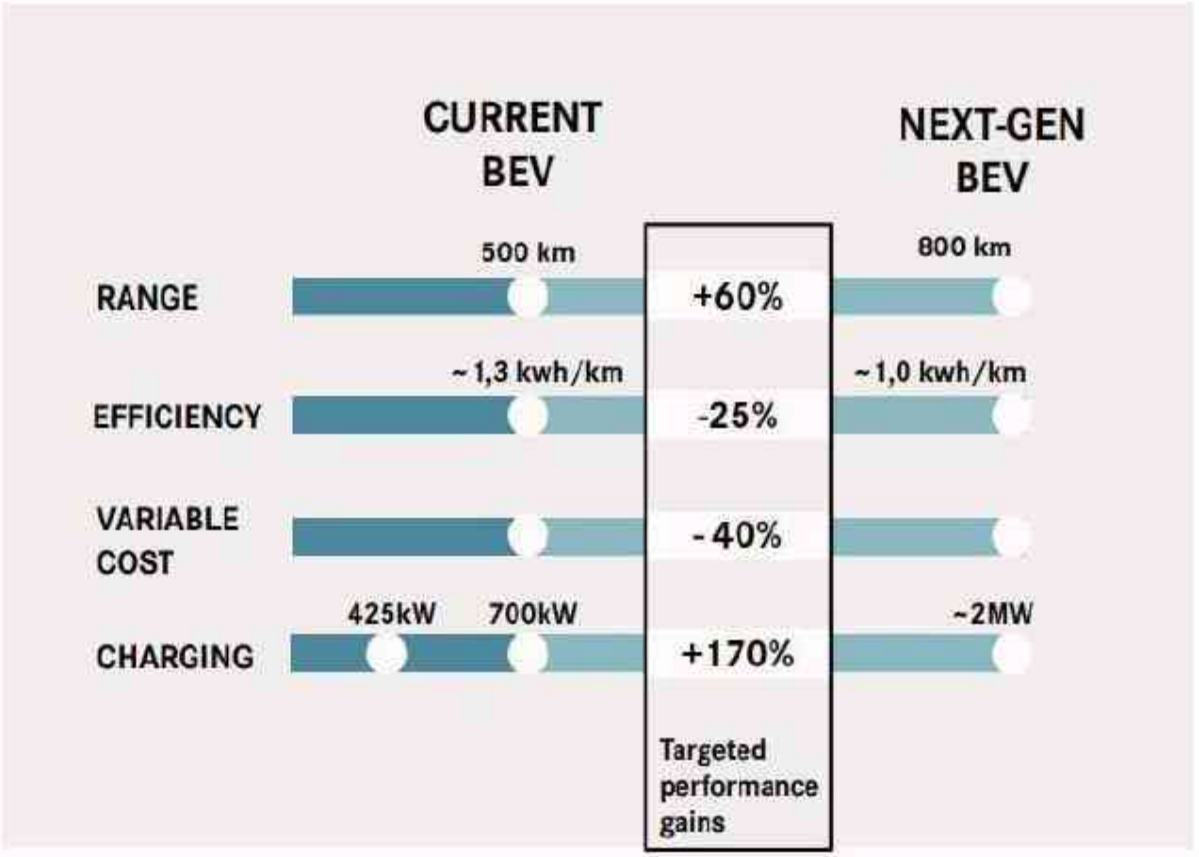
78% of truck activity on trips < 800 km

Source: Transport & Environment 2024

Better performances for next generation BEV Trucks

New BEV trucks about to hit the market; next-gen technology will leap further





Source: Transport & Environment 2024

E-Trucks charging infrastructure plans for Europe
Trans-European Transport Network (TEN-T)

Industry plans (by 2027)



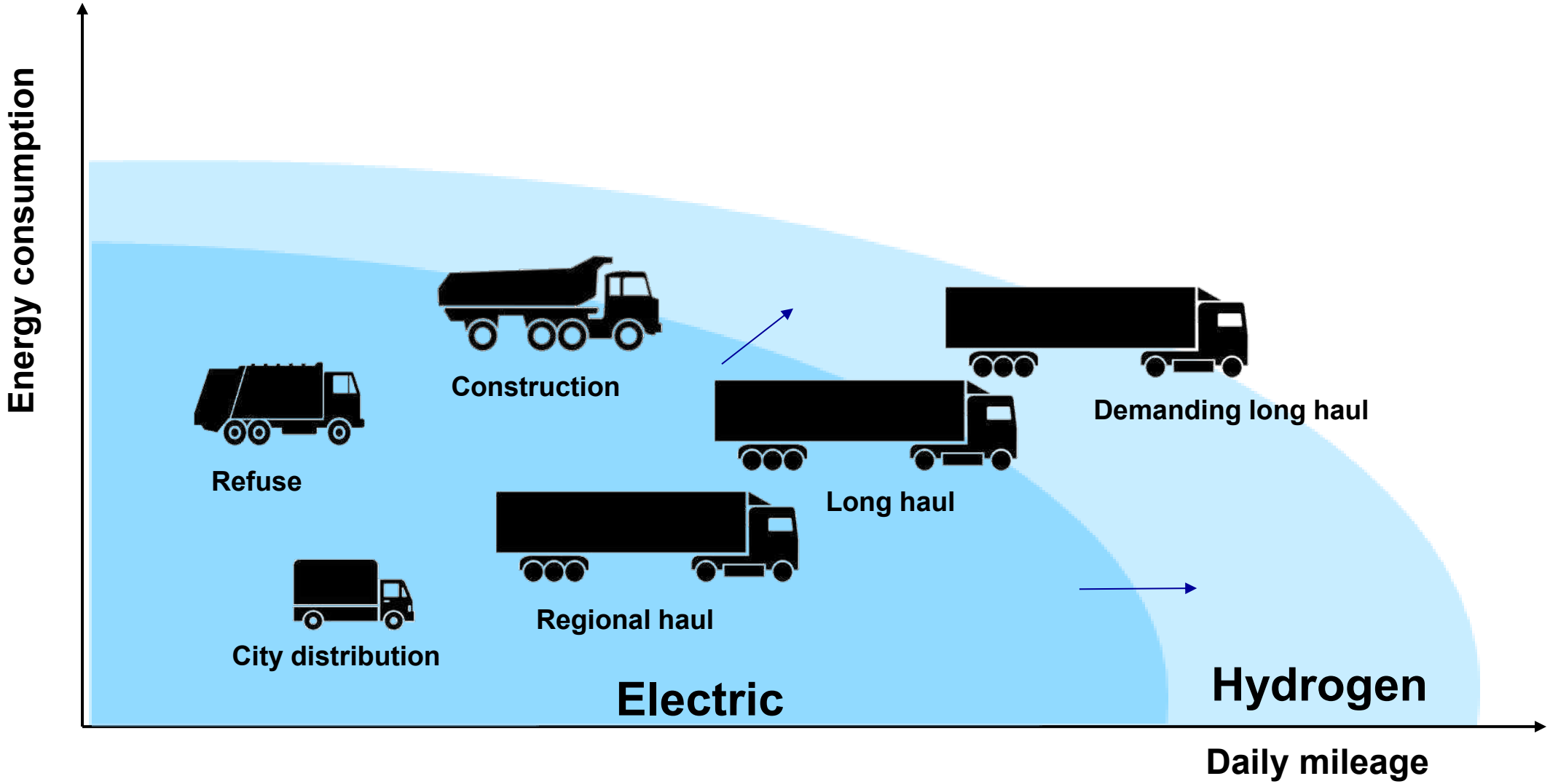
How it would look like



Notes: Total of 1,715 charge points under the scenario: 100km distance, 25% public charging, 5% BET, mean hour
Source: Fraunhofer ISI, 'A charging infrastructure network for battery electric trucks in Europe'

Source: Transport & Environment 2024

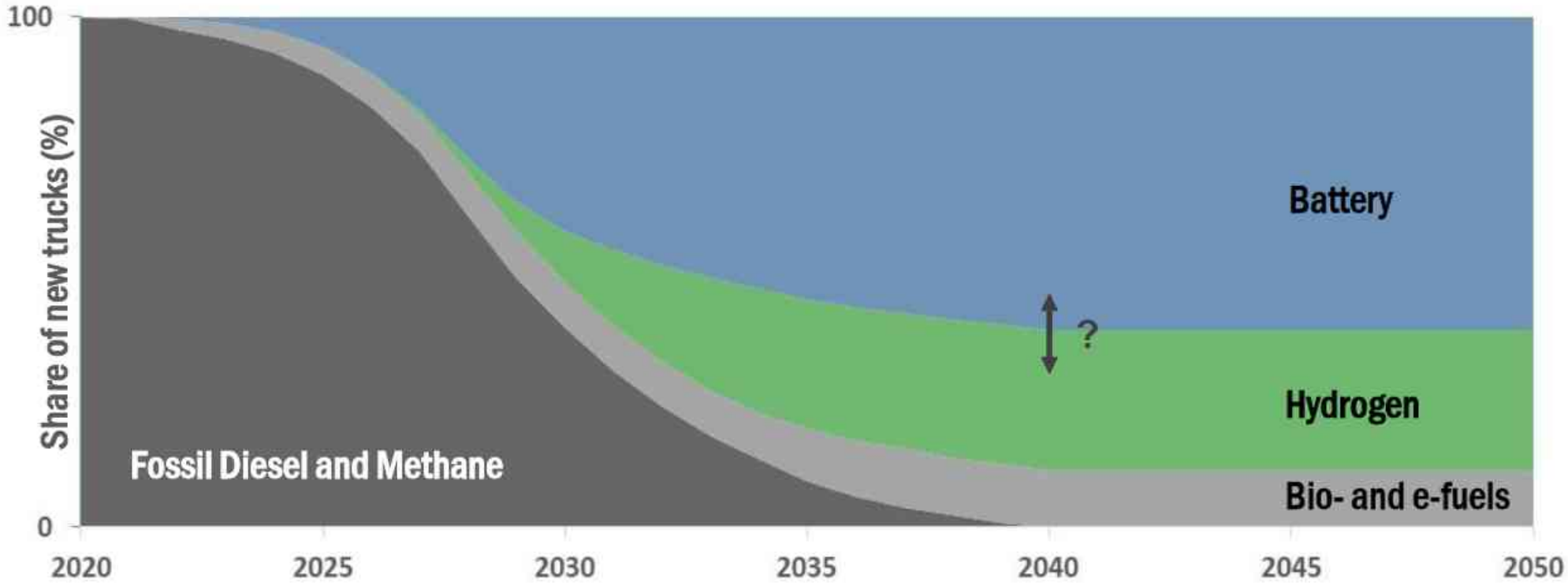
Electric vs Hydrogen for Trucks



Source: TotalEnergies – Ph. China

Road Map by Renault Trucks

- In all truck segments, we anticipate that **battery and fuel cell electric drivelines** will become the dominant powertrain before 2040. They will represent 50% of our sales in 2030.
- For long-range electric trucks, **hydrogen** fuel cell is an alternative to batteries
- Less internal combustion engines will be produced, and only for **biofuels or e-fuels**



RENAULT TRUCKS

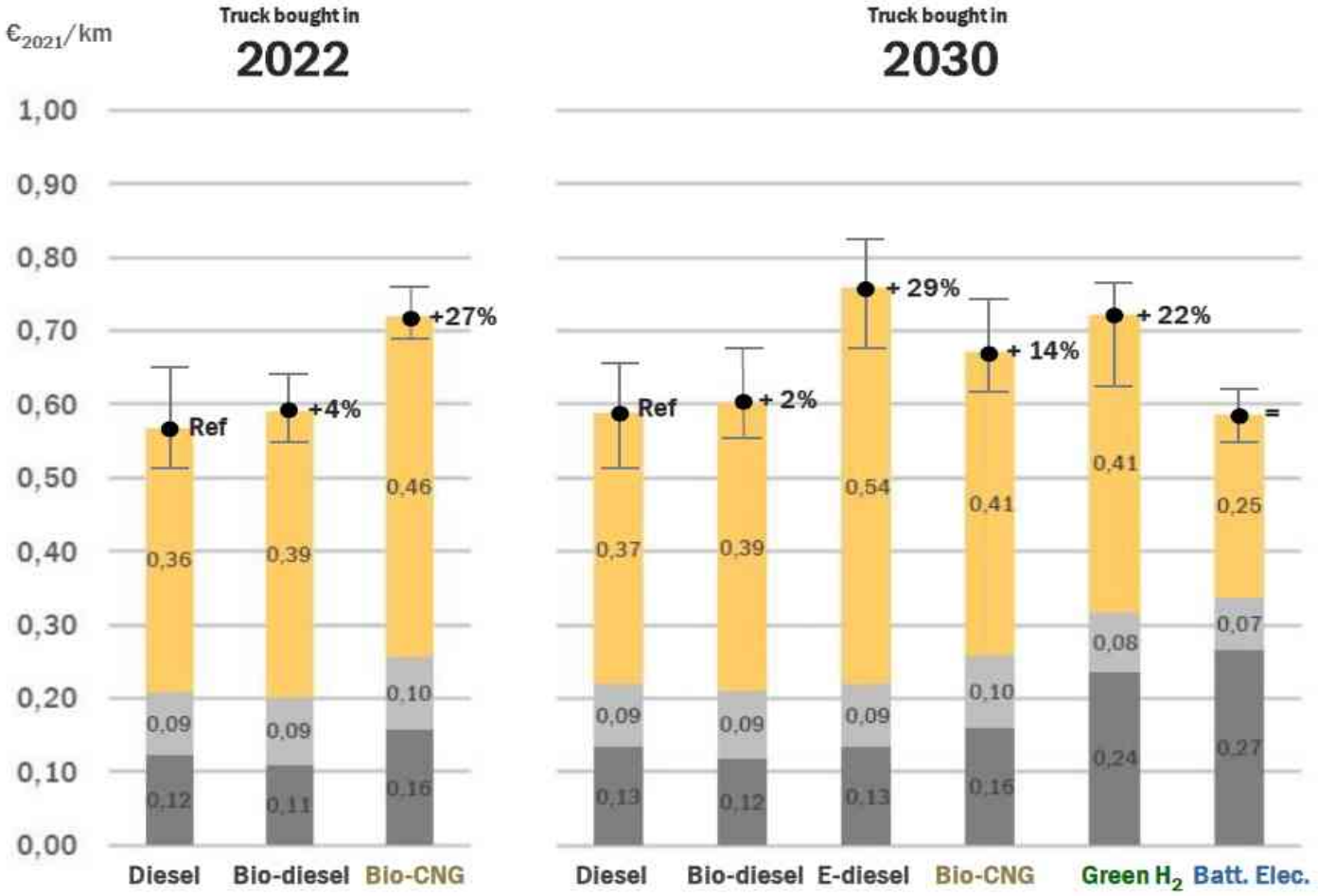
Source: Renault Trucks

Trucks – Total Cost of Ownership (TCO)

TOTAL COST OF OWNERSHIP

Example for a 40-ton long-haul truck running 829 000 km over 7 years in France





Energy cost (average over 7 years) is based on a forecast using financial market futures when available.

- Diesel: 1.35 €/l (22-29), 1.55 €/l (30-37). Includes tax (TICPE) reduction for transporters.
- Bio-diesel: 1.38 €/l (22-29), 1.51 €/l (30-37)
- E-diesel: 2.20 €/l (30-37).
- Bio-CNG: 1.85 €/kg (22-29), 1.80 €/l (30-37). Public subsidies for production not taken into account.
- Green hydrogen: 5.70 €/kg (30-37)
- Electricity: 0.224 €/kWh (30-37), with 80% at night (100 kW) and 20% at lunch (750 kW). Includes charger OPEX and CAPEX and initial connection cost amortization.

Tires, air drag improvements, and internal combustion engine (incl. Euro VII) improvements over time taken into account. Energy consumption increase of 2.4% per added ton of empty weight.

Maintenance cost includes predictive & corrective costs and tires (0.03 €/km for diesel, corrected proportionally to vehicle weight.).

Truck cost includes purchase, resale and capital cost.
All decided public subsidies and tax reduction taken into account.

- Battery pack: 100 €/kWh (2030), 80 €/kWh (2040) with 85% SOC use, and a residual value of 20% of a new battery for second life at 80% SOH.
- H_2 tank: 400 €/kg (2030, 2040)
- Fuel cell: 80 €/kW (2030), 50 €/kW (2040), average cycle efficiency of 52% (2030) and 54% (2040), efficiency decrease of 5% at mid-life.
- Initial low-volume production and extra warranty cost taken into account for FCEV and BEV.
- Internal combustion engines mild hybridized in 2027. +2%/year cost increase after 2027 due to the volume base and suppliers number reduction.

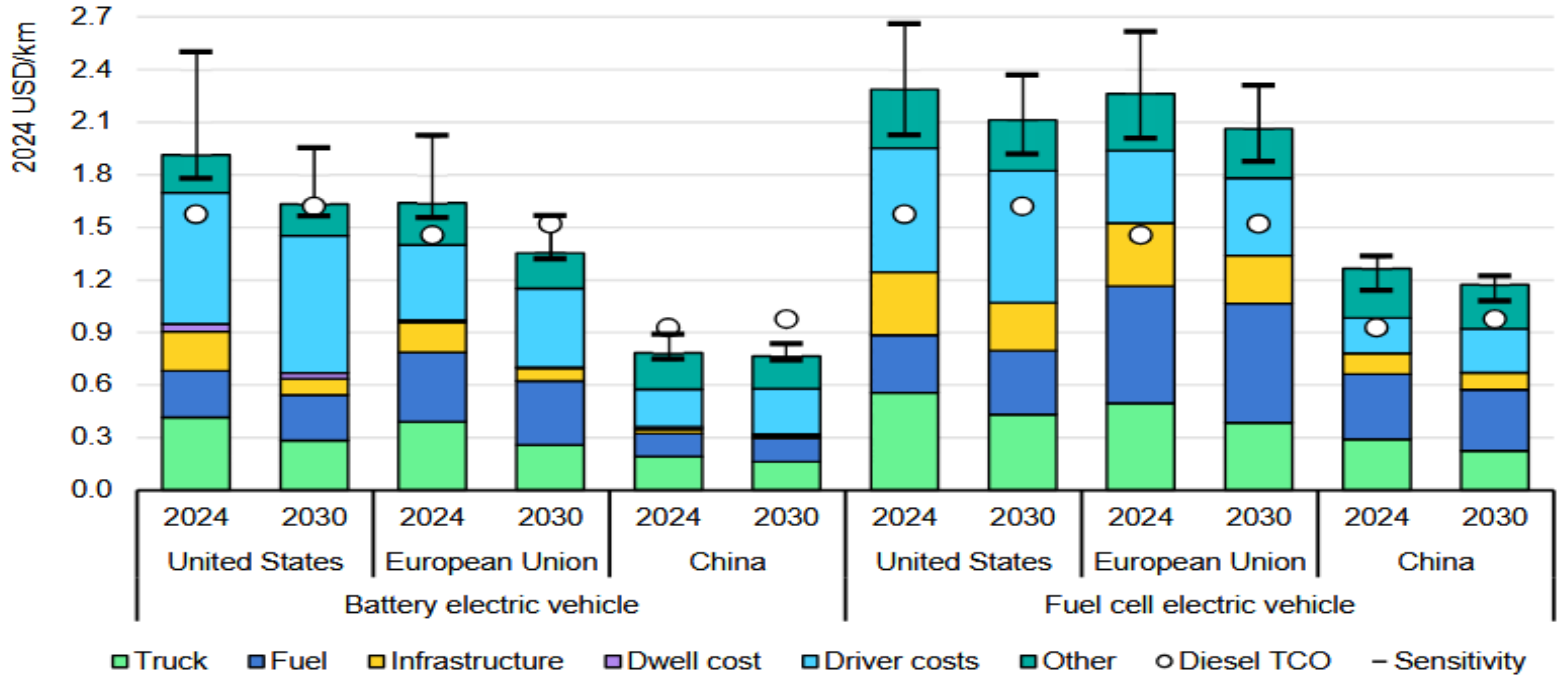
Uncertainty range on the graph relates only to energy cost.
All values in 2021 Euros (no inflation) without VAT.
Comparison exercise independent from Renault Trucks product plan.

RENAULT TRUCKS

Source: Renault Trucks

Trucks – Total Cost of Ownership (TCO)

Total cost of ownership for battery electric and hydrogen fuel cell heavy-duty trucks in 2024 and 2030



IEA. CC BY 4.0.

Notes: TCO = total cost of ownership. "Truck" refers to the cost of the truck including financing over 5 years at 5% interest and the residual value in year 5. "Infrastructure" is the levelised contribution to the cost of the EV charging or hydrogen refuelling station. "Driver costs" is the cost of employing a truck driver during normal working hours and does not include "dwell cost", which is the additional cost incurred when a driver must continue charging beyond their rest period. "Other" costs include insurance and maintenance. Cost projections are based on the 2024 Global Energy and Climate Model Stated Policies Scenario, as published in the World Energy Outlook 2024 report. Please see the Annex for a full list of sources, assumptions, and other inputs.

Sources: IEA analysis based on a studies from Ricardo, US Department of Energy, ICCT, the European Commission.

Source: IEA Global EV Outlook 2025 – May 2025

Low Carbon Fuels – Biofuels – E-Fuels

Low emission fuels : quid ? What is an e-fuel ?



- An emerging class of alternative fuels that are made by **using energy from renewable sources** in the chemical bonds of liquid or gas fuels
- No unified definition or terminology worldwide
- UE : e-fuel correspond to RFNBO as defined by RED II

Low Carbon Fuels (LCF)

Several production pathways for Low Carbon Fuels :



Biofuels

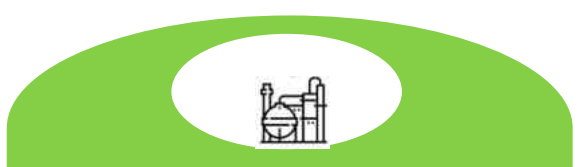
- Conventional
- Advanced



E-Fuels

- Water electrolysis (from renewable energy)

$H_2 + CO_2 \Rightarrow$ LCF



Other Low Carbon Fuels

- SMR NG + CCS
- SMR bio NG

$H_2 + CO_2 \Rightarrow$ LCF

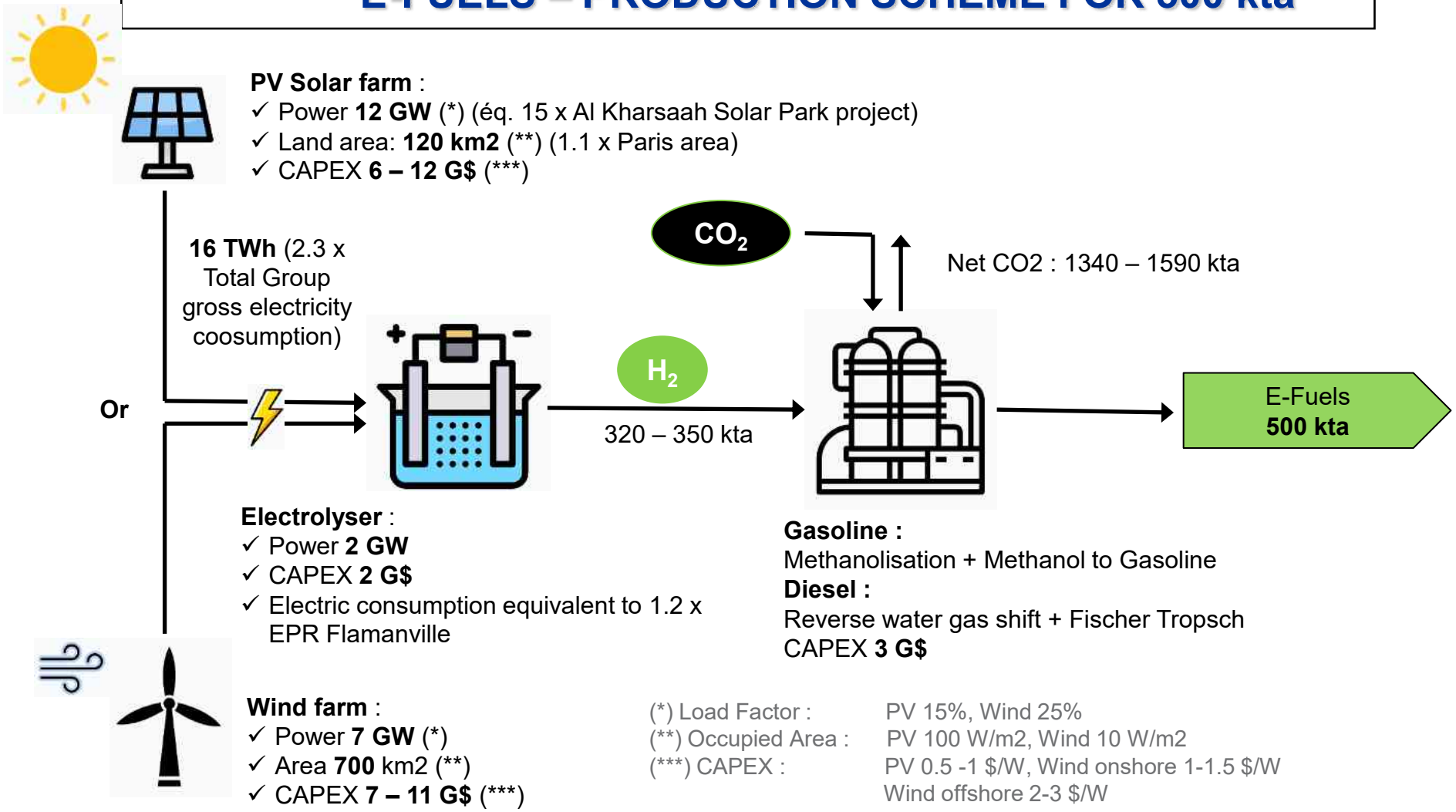
Conventional biofuel : Raw material based on « food & feed crops »
Advanced biofuel: **Raw material** essentially derived from products listed in annex IX A - REDII

Source: TotalEnergies

E-fuels: **Synthetic Fuels** resulting from the combination of **H_2** produced from electrolysis (with renewable energy) and **CO_2** (CO_2 being captured from air or concentrated source)

Other Low Carbon Fuels: Other **synthetic Fuels** produced from **H_2** derived from Steam Methane Reforming (SMR) and **CO_2** (CO_2 being captured from air or concentrated source)

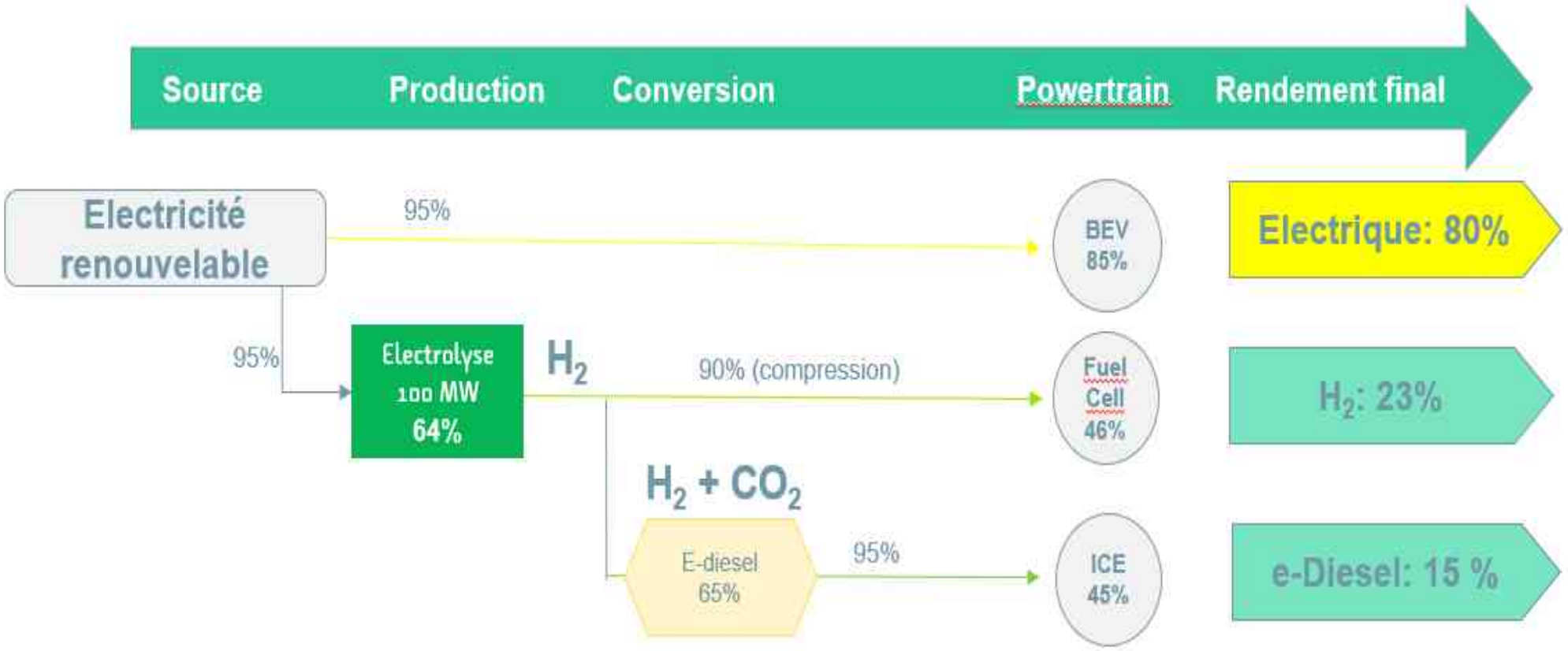
E-FUELS – PRODUCTION SCHEME FOR 500 kta



(*) Load Factor : PV 15%, Wind 25%
(**) Occupied Area : PV 100 W/m2, Wind 10 W/m2
(***) CAPEX : PV 0.5 -1 $/W, Wind onshore 1-1.5 $/W
Wind offshore 2-3 $/W

High CAPEX are necessary to finance the E-Fuels whole production chain

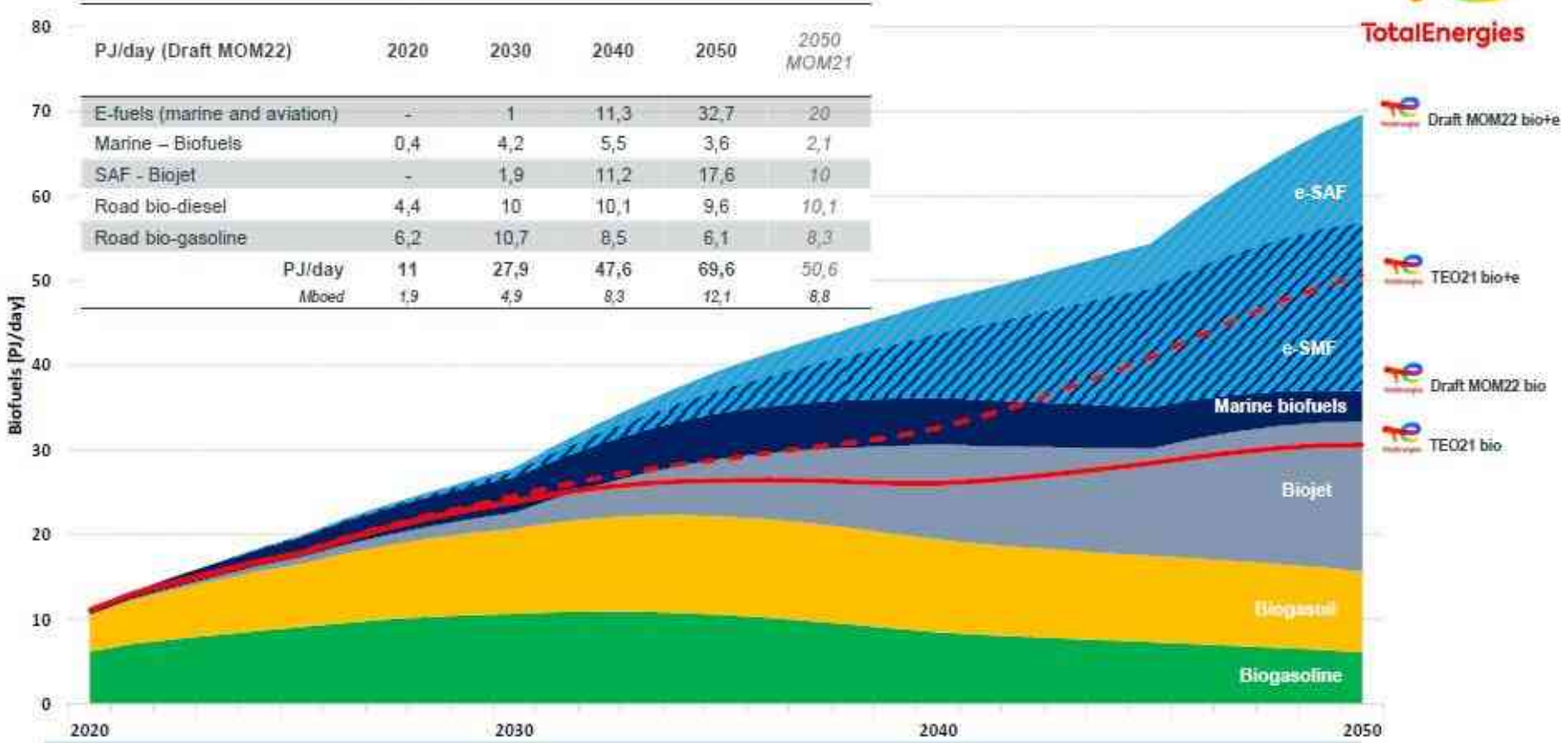
E-Fuels and H_2 : Yields remain low



Low Carbon Fuels – Biofuels – E-Fuels
TotalEnergies Scenario

Growth of low carbon fuels in the coming decades

PJ/day (Draft MOM22)	2020	2030	2040	2050	2050 MOM21
E-fuels (marine and aviation)	-	1	11,3	32,7	20
Marine – Biofuels	0,4	4,2	5,5	3,6	2,1
SAF - Biojet	-	1,9	11,2	17,6	10
Road bio-diesel	4,4	10	10,1	9,6	10,1
Road bio-gasoline	6,2	10,7	8,5	6,1	8,3
PJ/day	11	27,9	47,6	69,6	50,6
Mboed	*1,9*	*4,9*	*8,3*	*12,1*	*8,8*

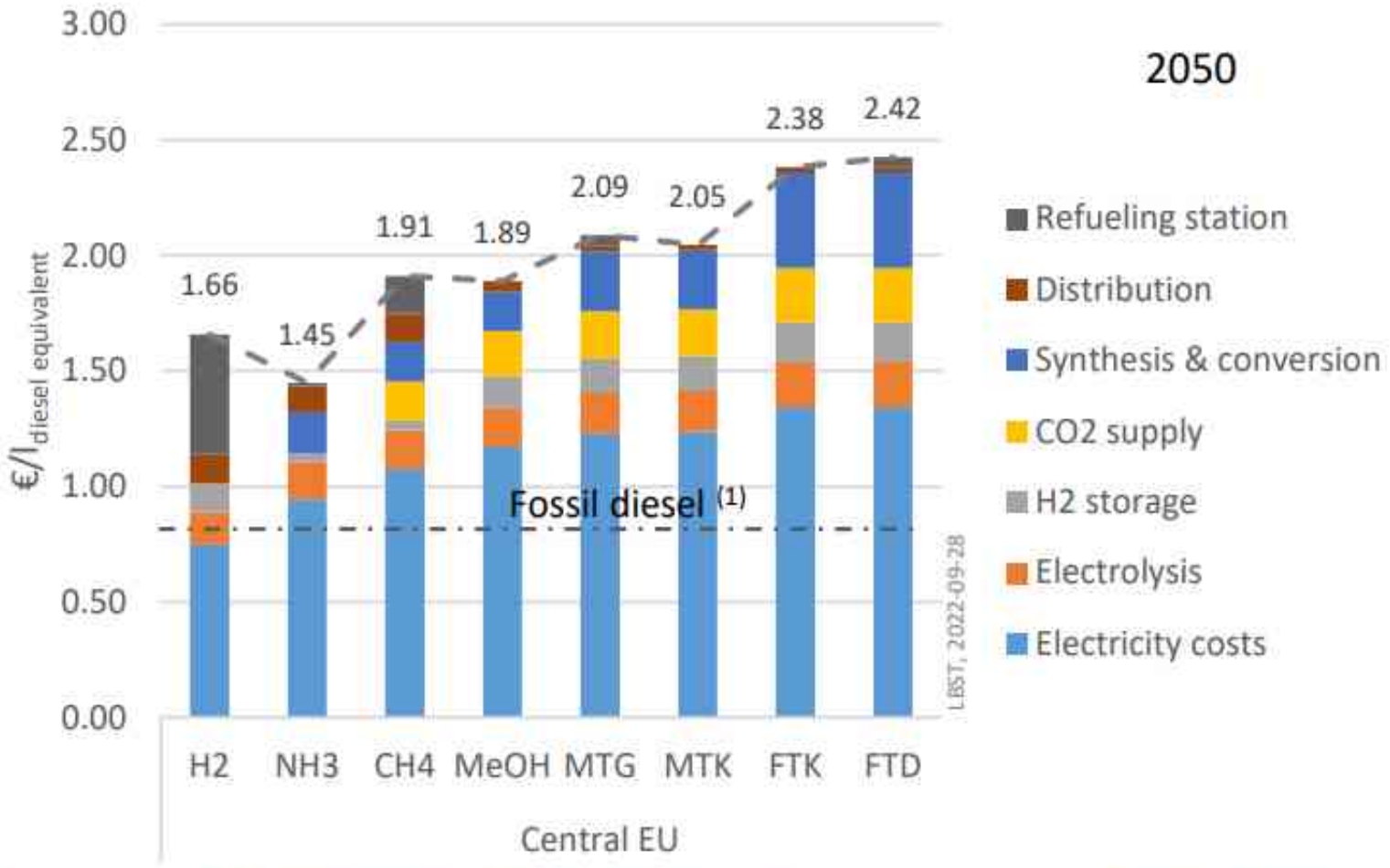


- Biofuels demand stable from 2035 as aviation compensates road decrease.
- Efuels demand driven by marine (methanol and ammonia) then by SAF.

Source: TotalEnergies

E-Fuels - Simulation of price in 2050

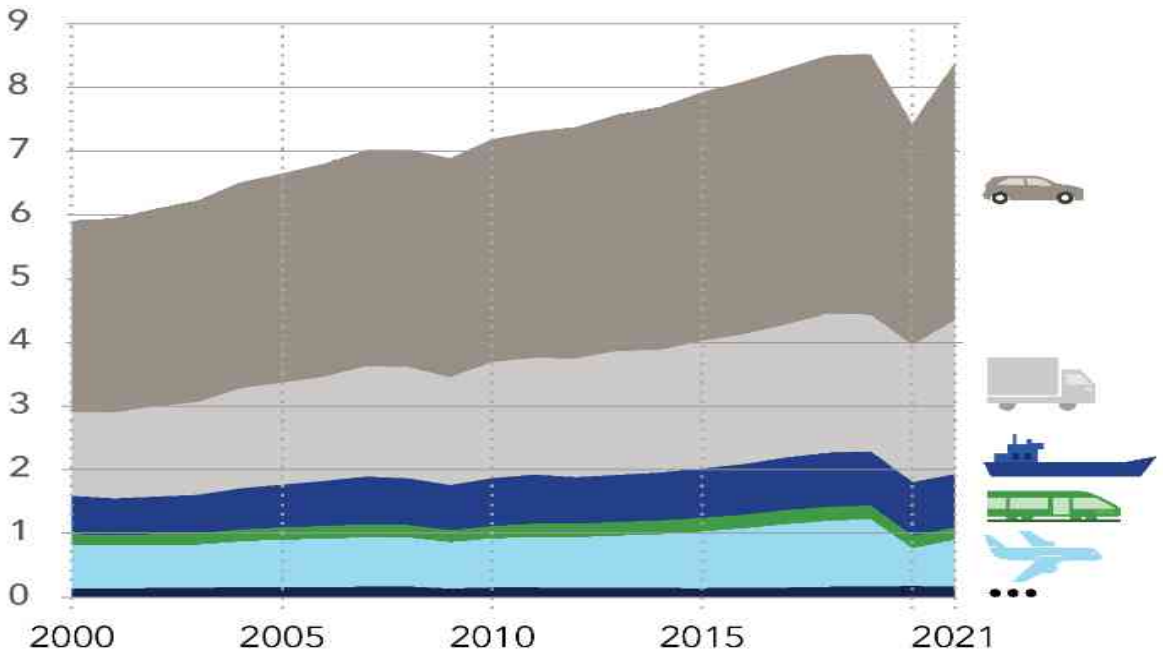
(Concawe source : M=Méthanol, FT=Fisher Tropsch, G= Gasoline, K=Kerosene, D=Diesel)



(1) Diesel price: 0.3 €/l (2020) - 0.8 €/l (2050), with crude-oil prices 40 €/bbl (2020) - 110 €/bbl (2050) taken from the EU Commission Impact Assessment [EU COM 2020]

CO_2 Emissions and fuel demand by transportation mode

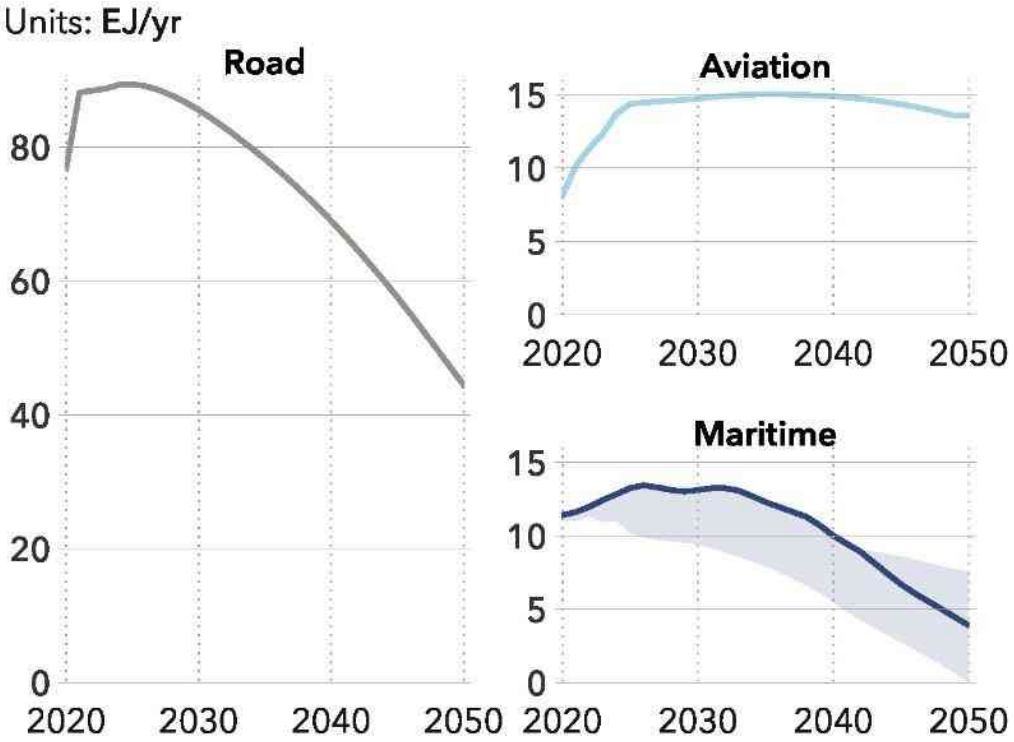
Global transport sector CO_2 emissions in the last two decades



Transport sector emissions have now rebounded to pre-pandemic levels, except in aviation, which is still lagging somewhat.

©DNV 2023

Fossil fuel demand in selected subsectors

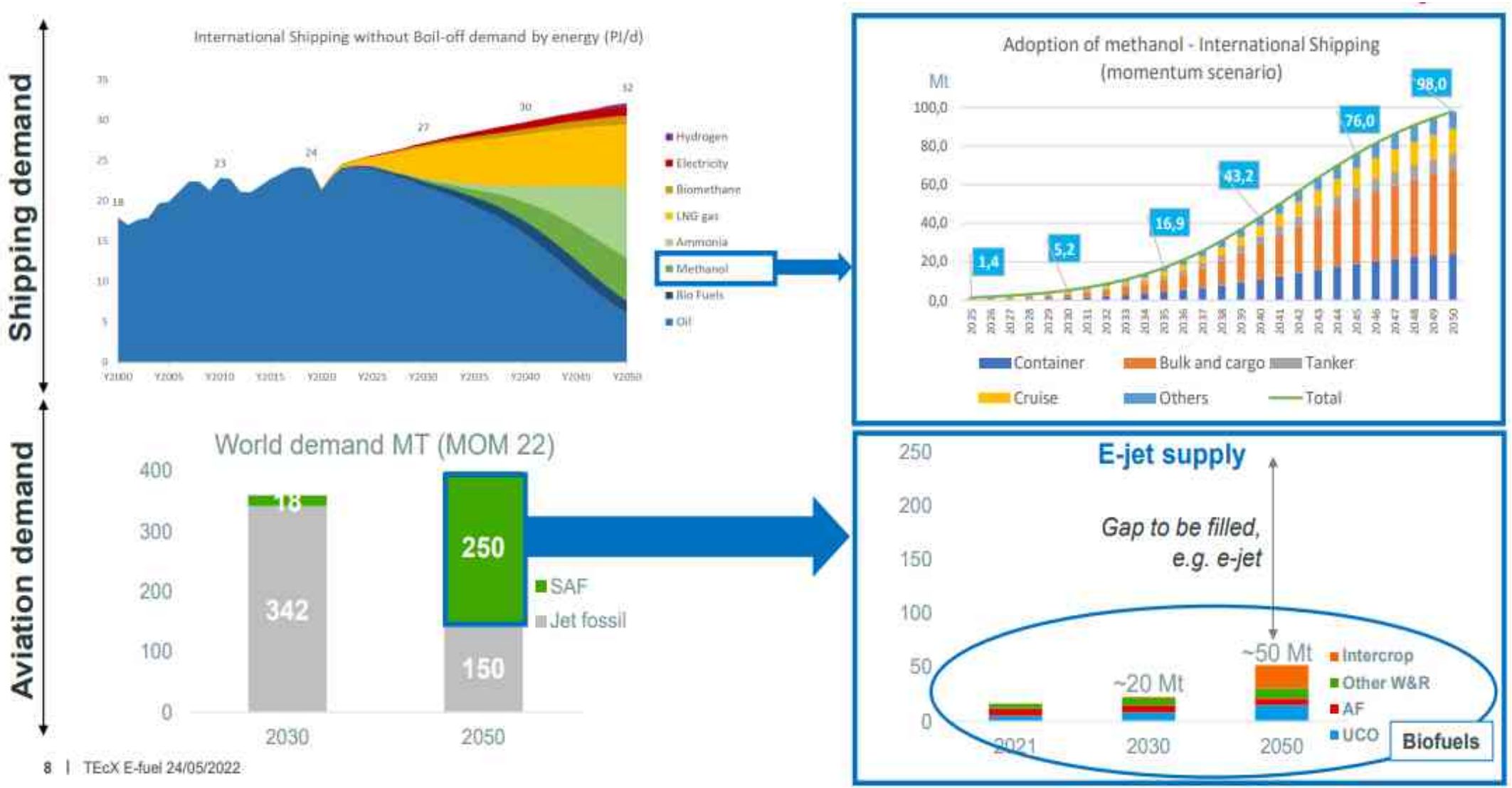


Shaded area represents the range of expected uptake as outlined in DNV's Maritime Forecast to 2050

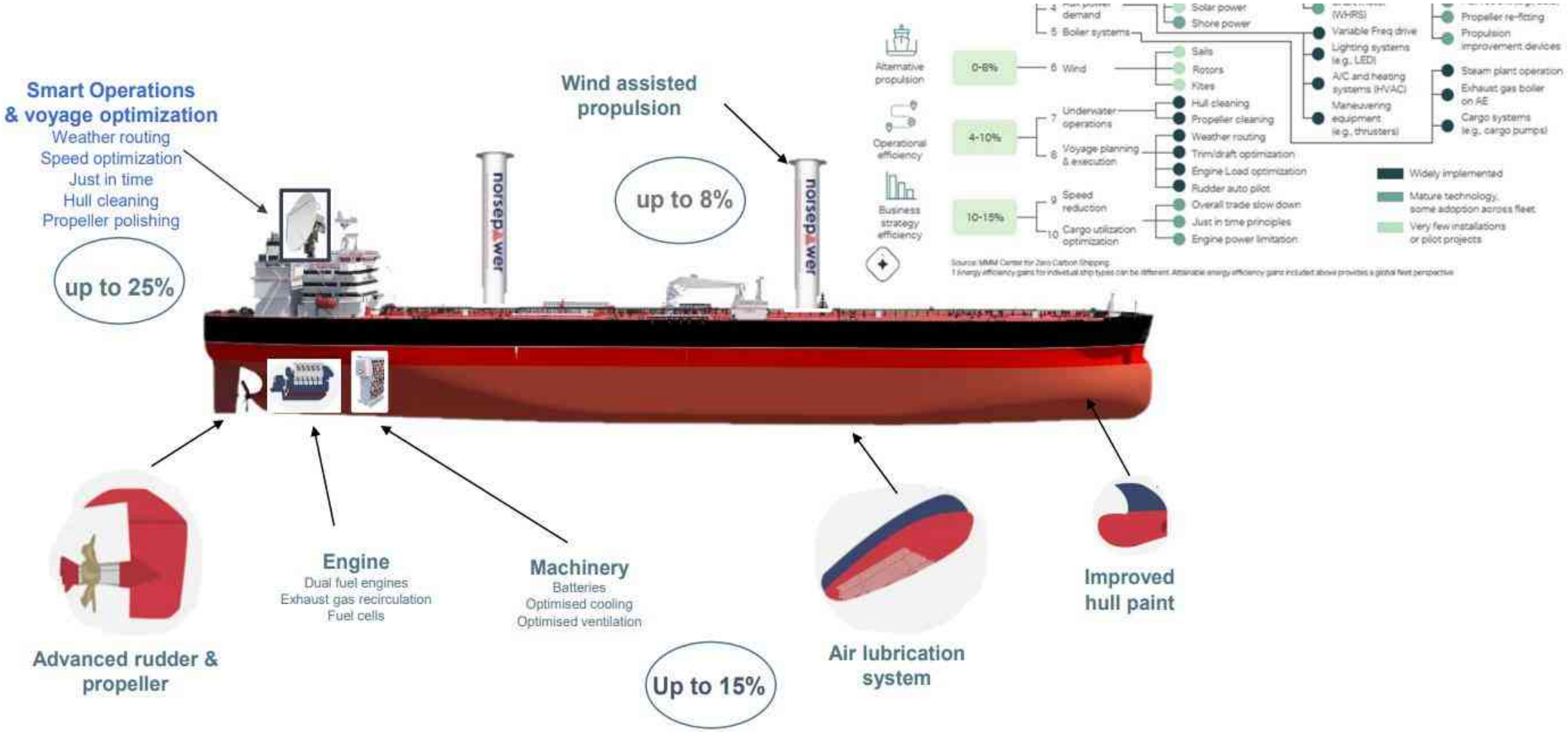
©DNV 2023

Source: DNV 2023

E-Fuels: Market simulation for Shipping and Aviation



Ways to optimize Ship emissions



Biofuels for Marine

Biodiesel

POSITIVE:

- **Carbon abatement as "Drop-in" fuel, can be immediately deployed by using the existing terminal infrastructure.**
- Biofuels are compatible with existing engines.
- Low SOx and PM (aromatics free).
- High energy density.

NEGATIVE:

- **Limited production.**
- **Competition with road and aviation transport (HVO).**
- Storage limitations for FAME due to ageing issue.



MSC, first major shipping line and largest taker of biofuels in Rotterdam (2019).

Biomethane (Liq)

POSITIVE:

- **Potential to reduce GHG emissions of LNG.**
- High potential of resources for production of biomethane.
- Low SOx and PM.
- Certificates (GoO) in some countries, avoid the need for a physical supply.

NEGATIVE:

- **Limited availability of liquefied biomethane for shipping.**
- **Methane slip (same as LNG).**
- Competition with local use of gas (energy, domestic transport).



Hurtigruten will retrofit 6 cruise vessels to run on liquified biomethane as from 2021.

Biomethanol

POSITIVE:

- **Liquid, easy to handle and deploy.**
- Neutral carbon fuel, low SOx and PM.
- Minor infrastructure adjustment is required (due to low flash point) to extend as fuel for bunkering.
- Combustion properties equivalent to conventional fuel.

NEGATIVE:

- **Limited production**
- Low energy density.



Maersk ordered in Feb 21 the 1st Methanol feeder vessel 2000 TEU to be operated on sustainable bio methanol or e-methanol

BioLPG

POSITIVE:

- **Good handling experience with fossil LPG in seaborne trade.**
- High energy density.
- Neutral carbon fuel. Low SOx.

NEGATIVE:

- **Lack of LPG experience as fuel.**
- **Limited production (by-product of HVO).**
- Competition with energy/ petrochemical applications.



E-Fuels for Marine

e-Ammonia

POSITIVE:

- **Zero carbon fuel, nearly net zero emission.**
- **no SOx and PM.**
- **Existing seaborne trade as cargo and availability of ammonia (from NG).**
- Not in competition with other transport modes.
- Can be used in combustion engine (ICE) or in fuel cell. **First engine (MAN) announced in 2023.**
- Excellent liquid hydrogen carrier.

NEGATIVE:

- **Acute toxicity per inhalation.**
- **Poor combustion properties**
- NOx emissions (can be addressed with SCR or other NOx abatement devices).
- Low energy density



Equinor Supply vessel project (SOFC)



Hyundai Mipo ammonia fuelled project

e-Hydrogen (liquid)

POSITIVE:

- **Zero carbon fuel, nearly net zero emission.**
- **no SOx and PM.**
- **No health and toxicity issues.**
- Excellent combustion properties.
- LH2 can be used in fuel cell or in combustion engine (ICE).

NEGATIVE:

- **Need to be liquified for shipping (-253°C).**
- **Very low energy density.**
- Handling risks (flammability).
- Cost of liquefication, transport and storage.
- Specific bunkering infrastructure to build.



1st Hydrogen fuelled tug ordered by The Port of Antwerp , to be delivered end of 2022 . 4000 KW



Jules Vernes 2, powered by hydrogen fuel cell (Nantes).

e-Methanol

POSITIVE:

- **Nearly net zero emission.**
- **no SOx and low PM.**
- **Liquid, easy to handle and deploy.**
- Technologically feasible as a shipping fuel and **few vessels are currently in operation (methanol).**
- Retrofitting or new build costs are considered low.
- Good combustion properties.

NEGATIVE:

- **Production scalability. Need CO2 source and capture for production of e-methanol.**
- Low energy density.

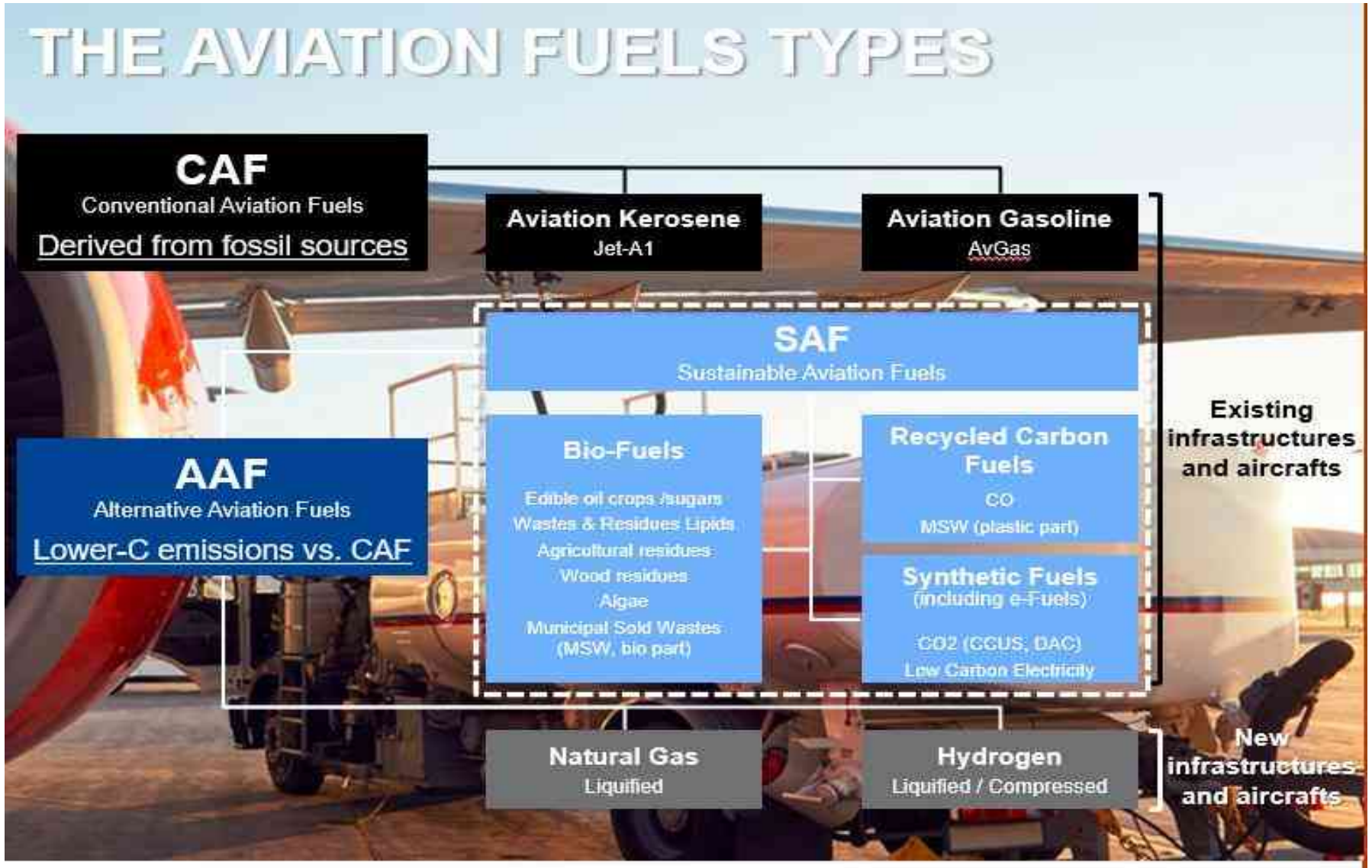


In 2015, StenaLine, retrofitted the Stena Germanica, a Ro-Pax ferry

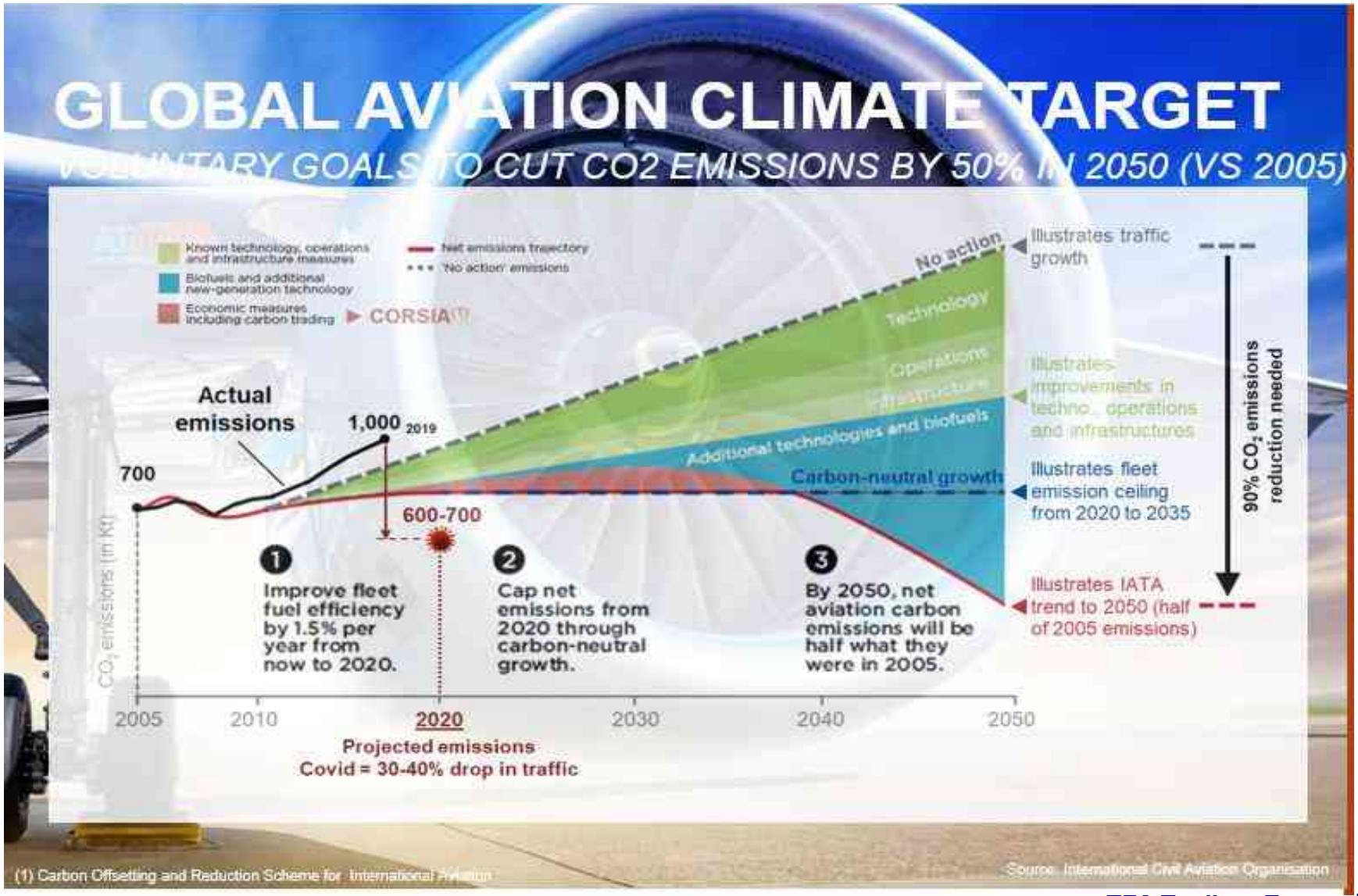


Pro Patria is a Methanol powered Product tanker owned by StenaBulk and Proman shipping

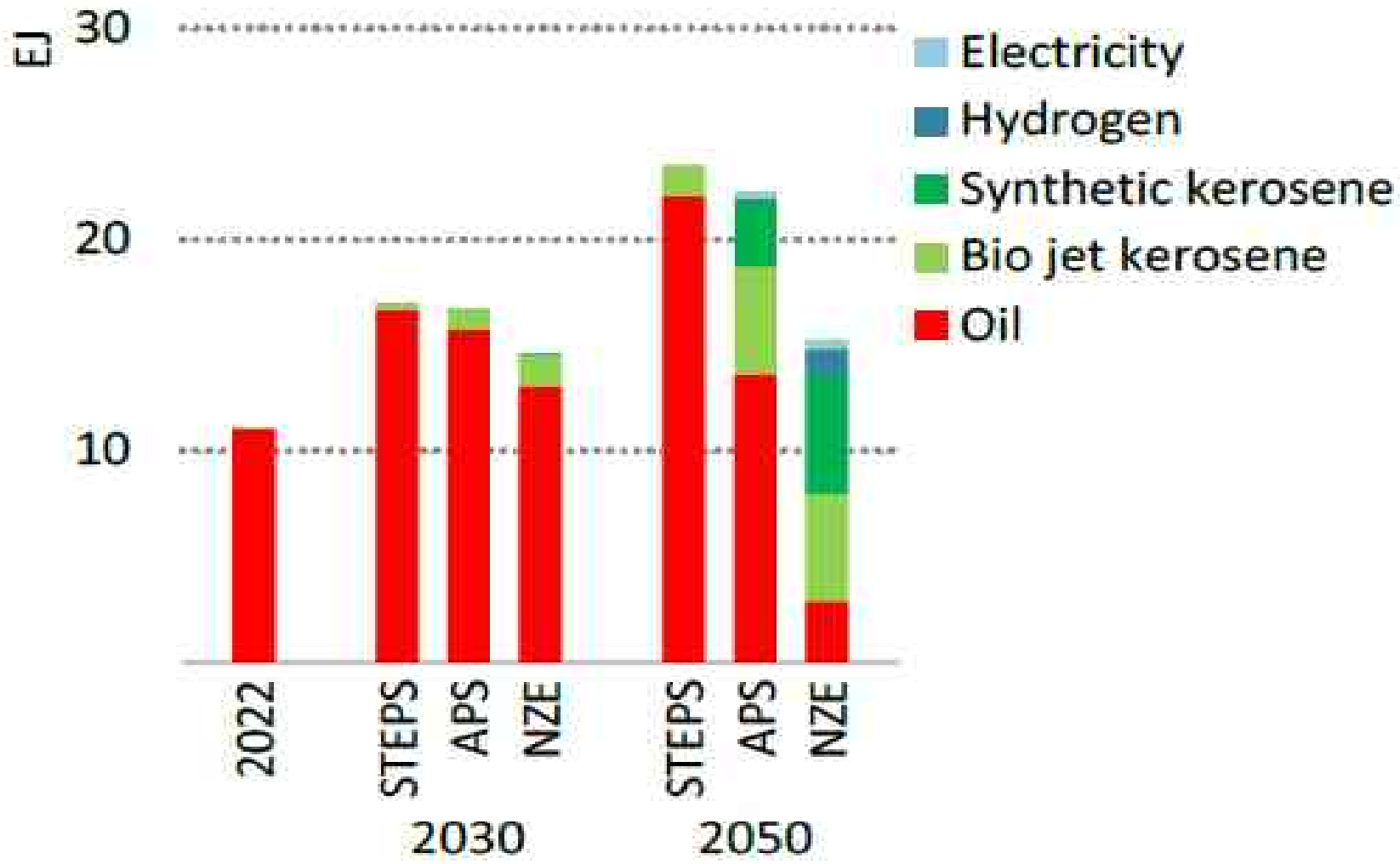
The Aviation Fuels Types



Global Aviation Climate Target



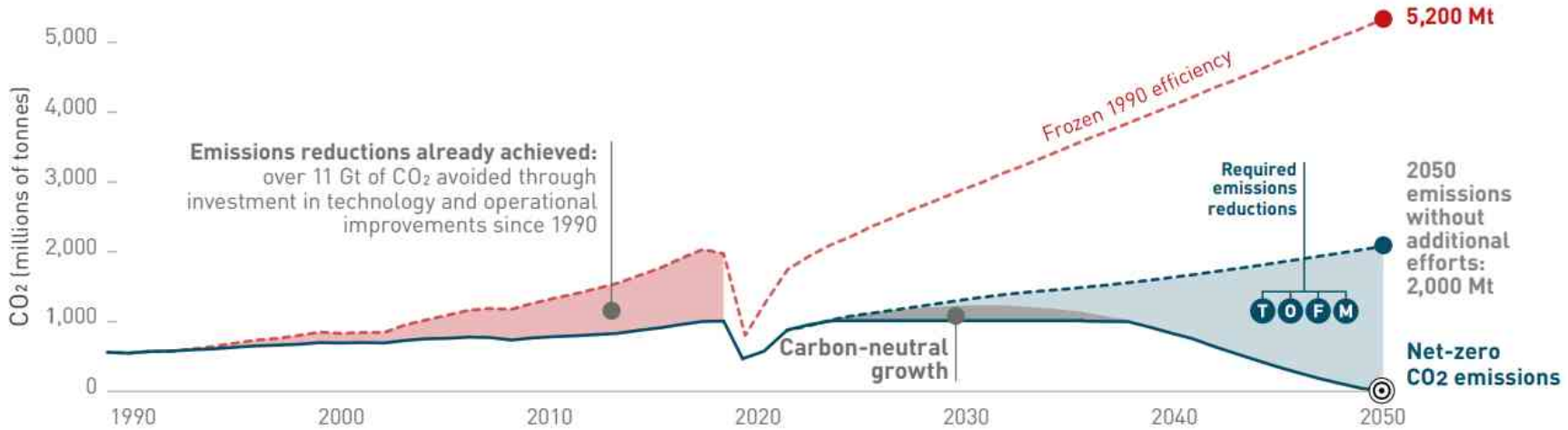
Global Aviation Energy Demand by IEA WEO 2023



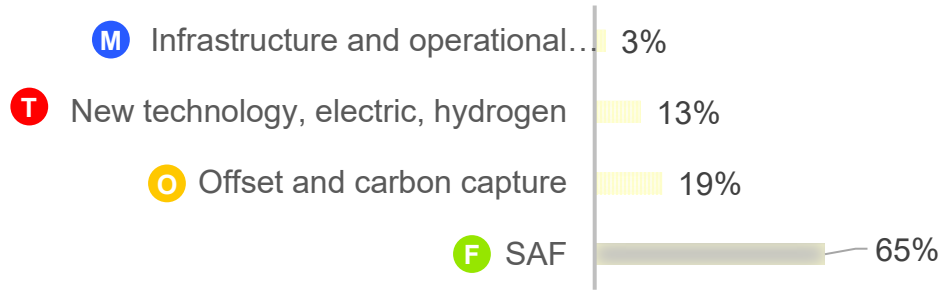
Source: IEA WEO 2023

Sector commitment to fly Net Zero by 2050

SAF is the aviation largest decarbonization contributor over the period 2021-2050

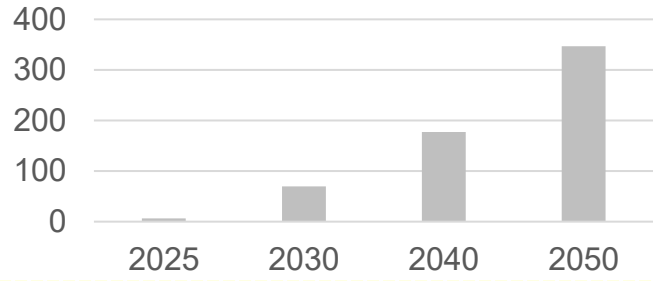


IATA Aviation decarbonization roadmap



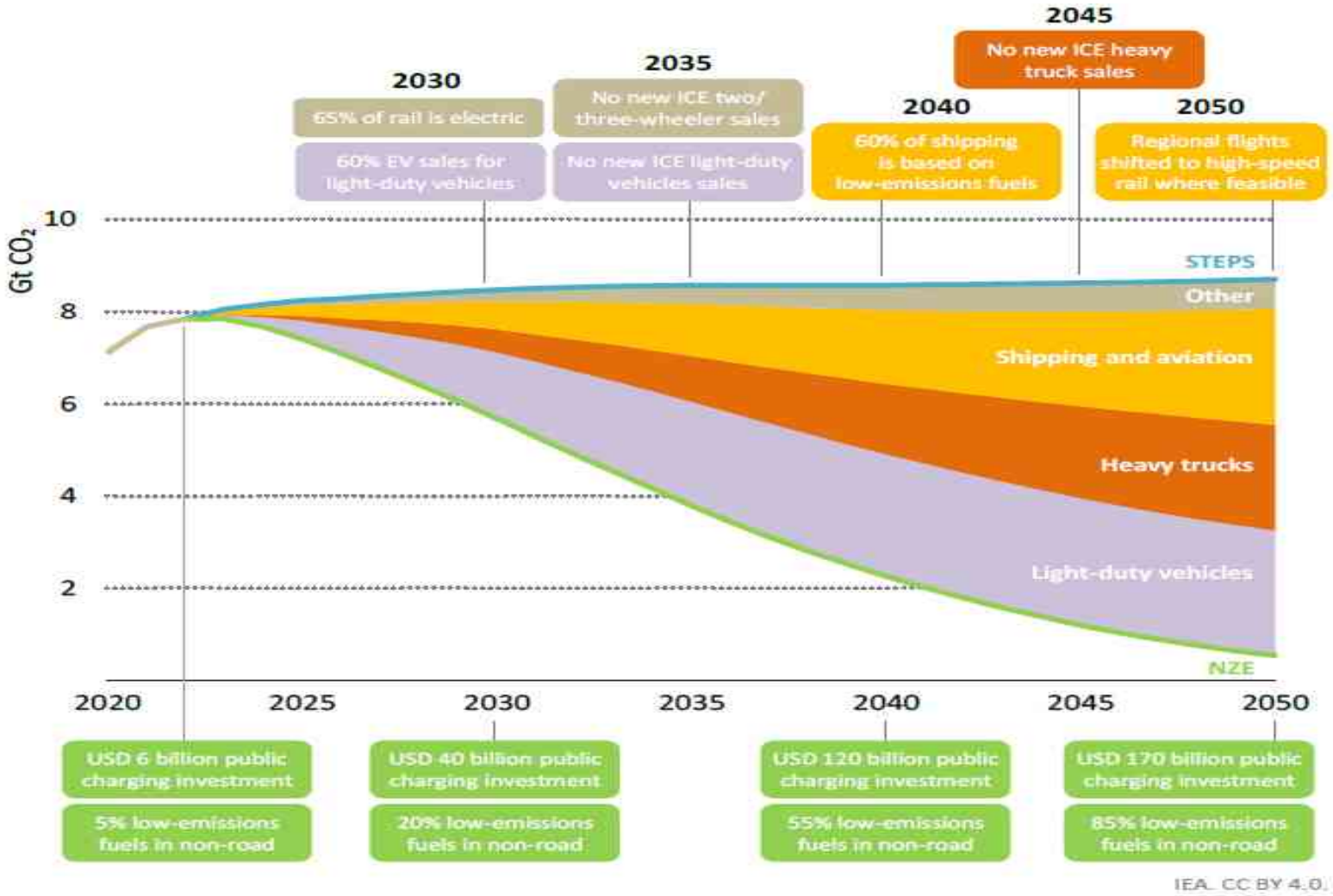
IATA expected SAF required to achieve net Zero in 2050

Incorporation of 350Mt in 2050



Source: IATA, Fly Net Zero, October 2021

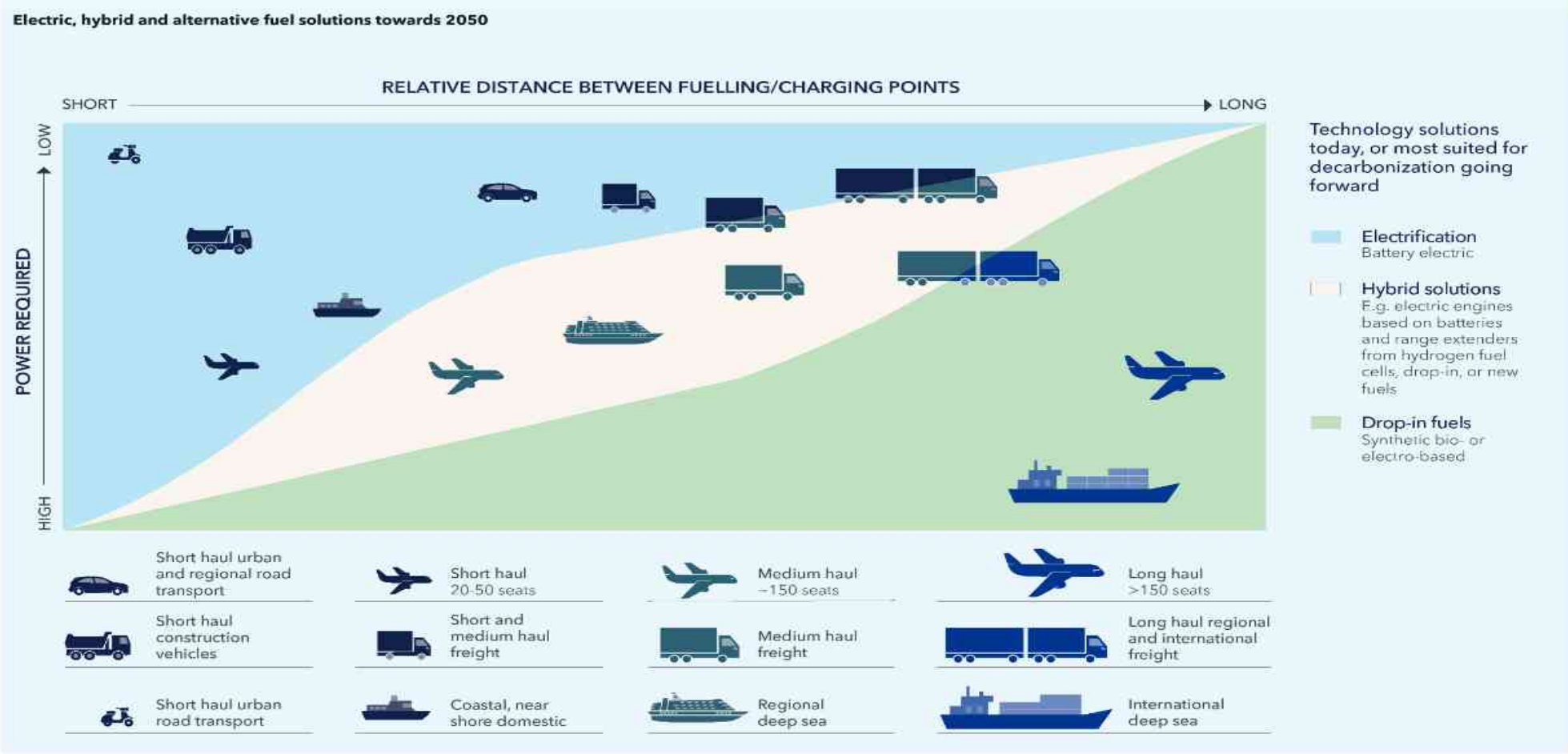
Reminder - Emissions reductions and key milestones in Transport in the NZE Scenario vs STEPS



Electrification of road transport and rail brings rapid and massive emissions reductions; behavioural changes and low-emissions fuels are key in aviation and shipping

Source: IEA WEO 2022

Alternatives Power per transportation mode



The easiest vehicles to electrify are those with shorter ranges and predictable routes. Heavy-duty trucks, ships, and planes require large amounts of energy to cover long distances, making electrification difficult with current battery technology. Therefore, a multifaceted approach that combines research, policy, and innovation should advance the technology and commercial readiness of feasible transition alternatives tailored to each transport segment.

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River navigation: Hydrogen barge - Demonstration Paris



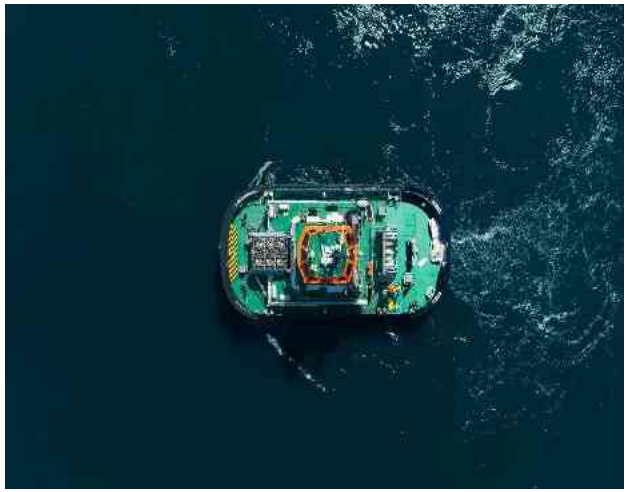
- April 2025
- Paris
- Demonstration of 18 months
- Sogestran Group
- 400 t payload
- Replaces 50 vans

- Conversion of an existing Zulu 06 boat
- Two 200 kWh fuel cells
- 20-foot removable container containing 300 kg of compressed hydrogen
- Container changed once a week
- Additional cost: Green H_2!
- Internal combustion engine maintained

River navigation: Hydrogen Tugboat - Demonstration Antwerp



- 2 Dual fuel engines
- Hydrogen & traditional
- V12 of 2 MW
- 415 kg of H_2
- 54 gas cylinders
- 24 hours of operations
- Pulling power 65t



- December 2023
- Port of Antwerp
- Test
- CMB.TECH





Source: port of Antwerp

River navigation: Electric Tugboat - Demonstration Antwerp



- Batteries: 2782 MWh
- Lithium-Titanium-Oxide
- 1,5 MW charging station
- 2 hours loading
- 12 hours sailing
- 12 knots
- Pulling power 70t





- May 2025
- Port of Antwerp
- Build in Vietnam
- Damen Shipyards Group

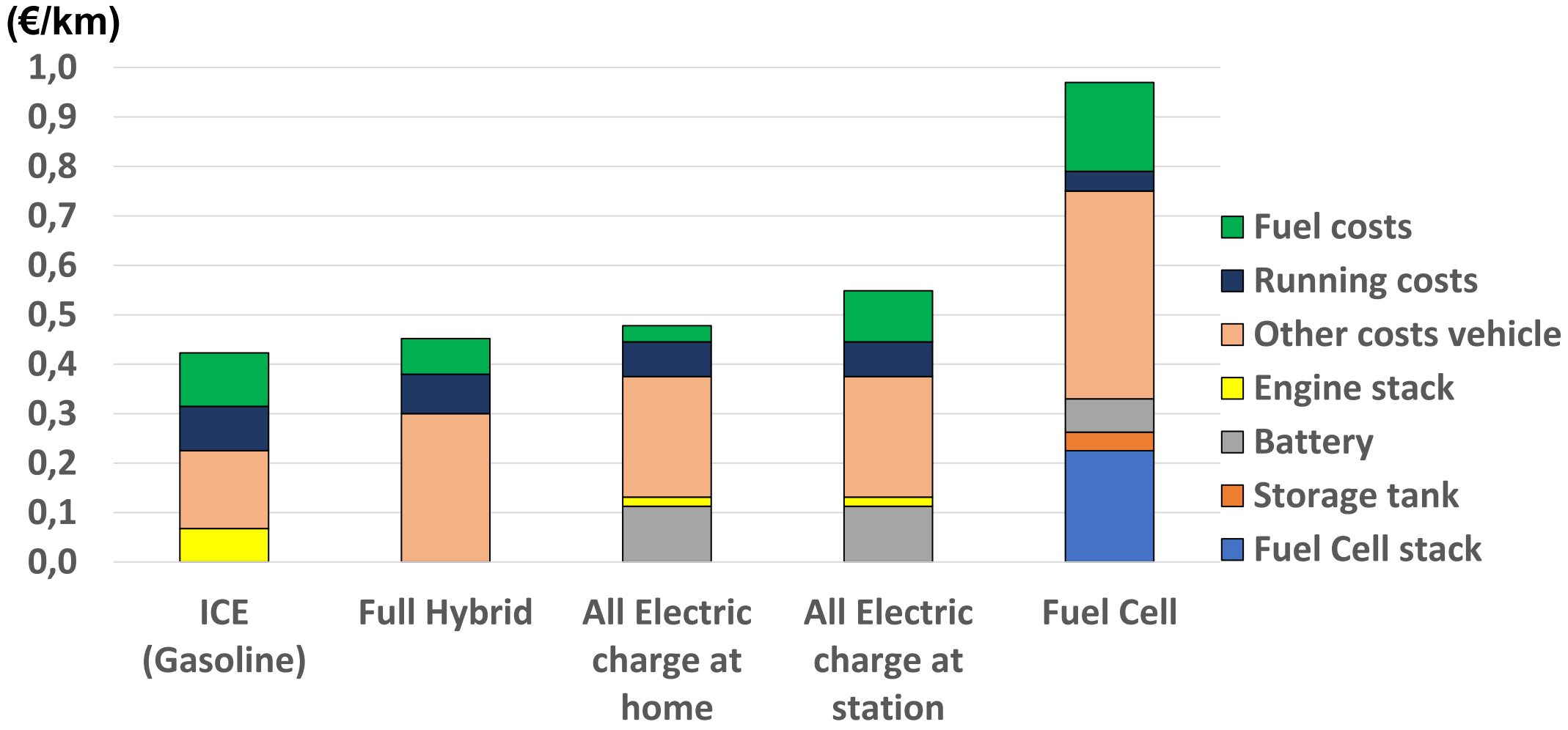
Source: port of Anwerp

Mobility
ICE vs Hybrid vs Electric vs Fuel Cell Vehicle



Source: Toyota

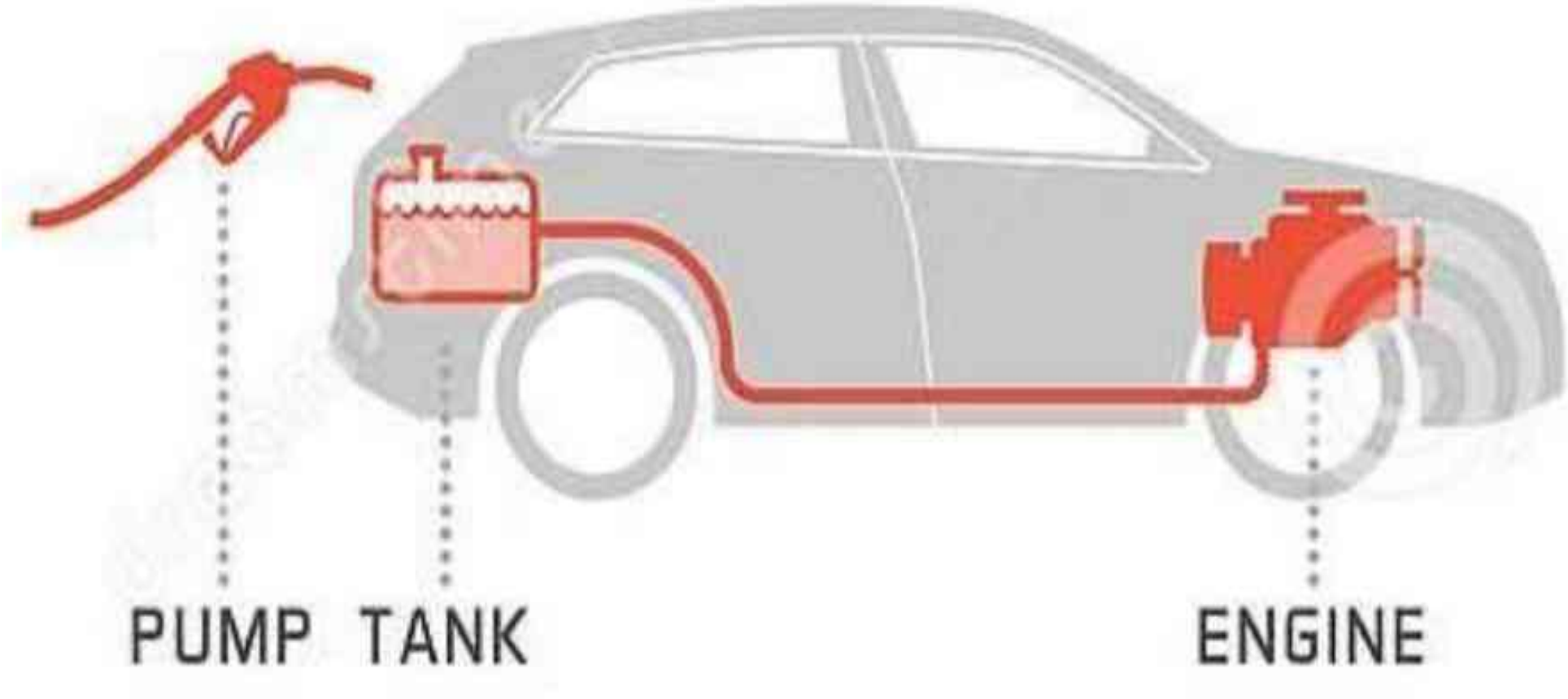
Synthesis of Costs split – Typical car - Average figures (€/km) ICE vs HEV vs BEV vs Fuel Cell vehicles



Source: Ch.Guéritte/Data from car manufacturers
ICE: Internal Combustion Engine
HEV: Full Hybrid Electric Vehicle
BEV: Battery Electric Vehicle/All Electric

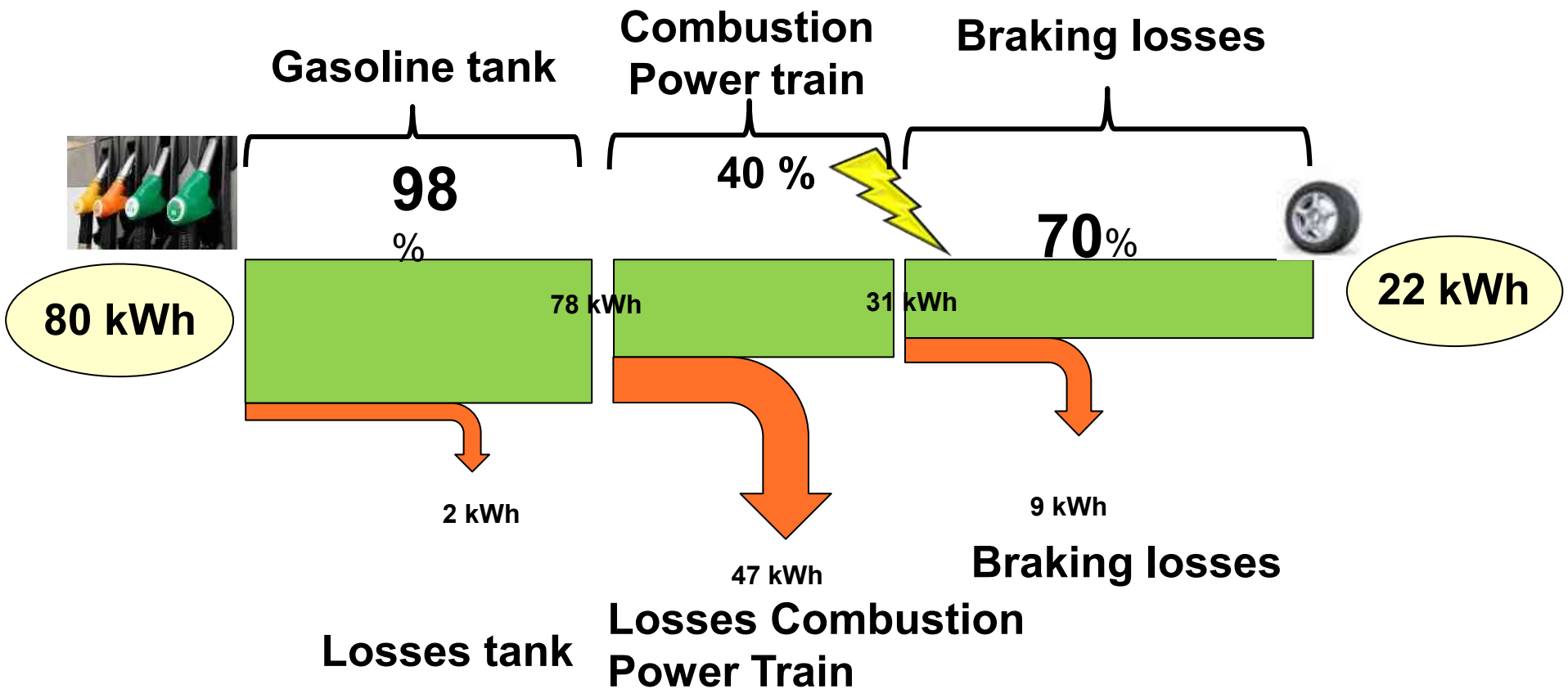
Mobility – Various types of Vehicles

ICE Vehicle



Source:
ResearhGate

Energy Efficiency of a ICE Vehicle (160 HP – 100 km)
Complete Cycle: Service station to Power

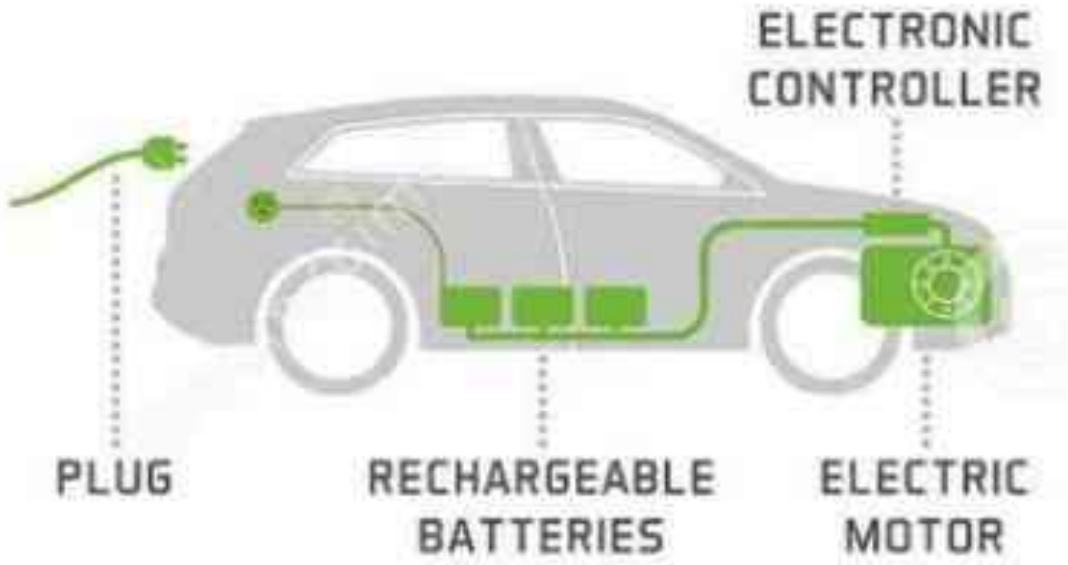


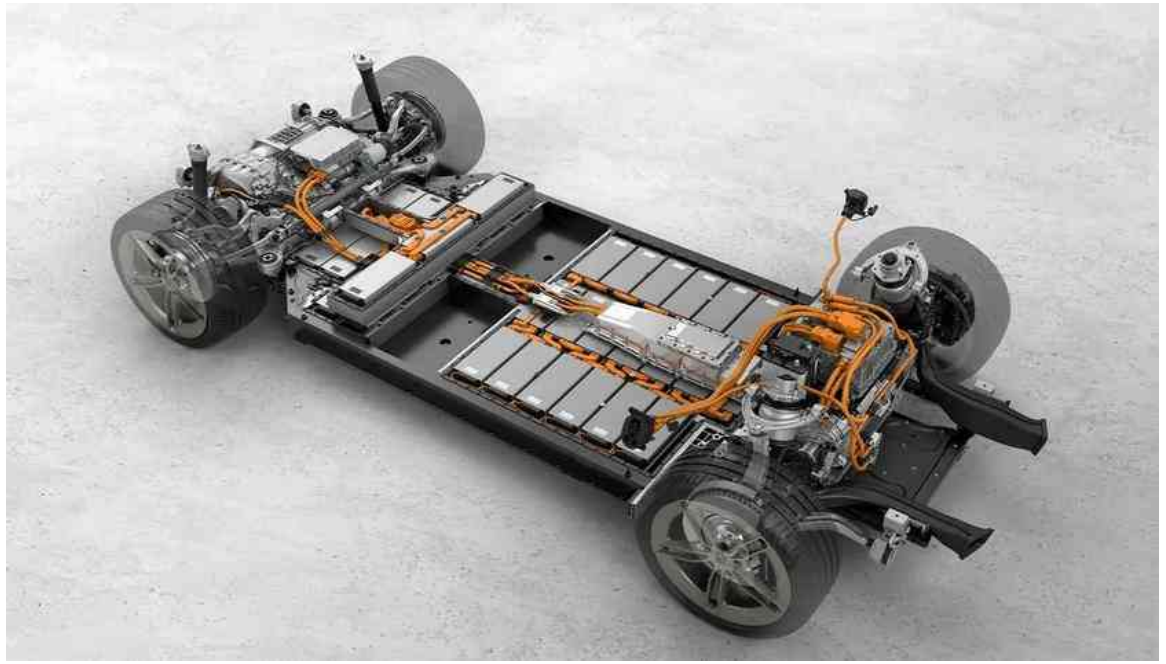
Energy Efficiency of the global chain # 28%

(Average and rounded figures according to present technology)

Nota: Basic data from car manufacturers

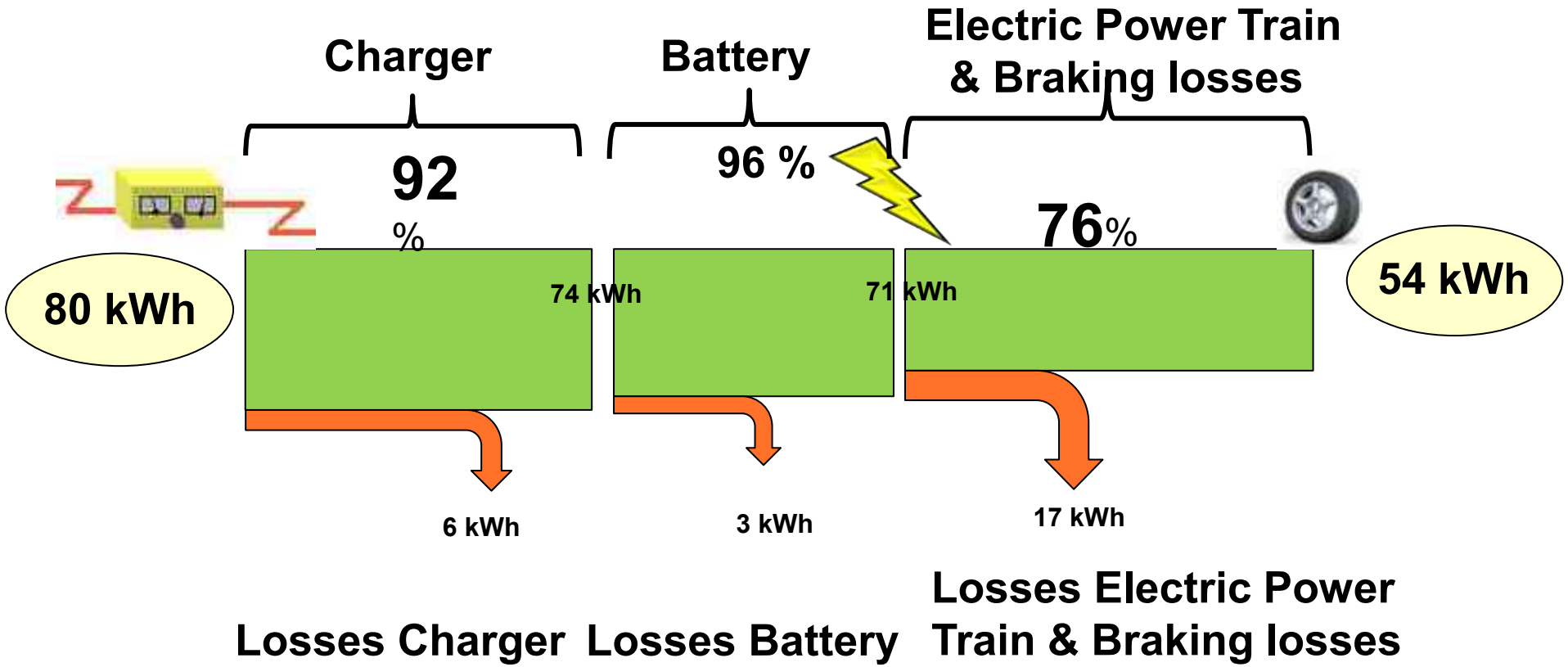
Battery Electric Vehicle





Source: ResearchGate/Green Cars

Energy Efficiency of an Electric Vehicle (160 HP – 100 km)
Complete Cycle: Power to Power

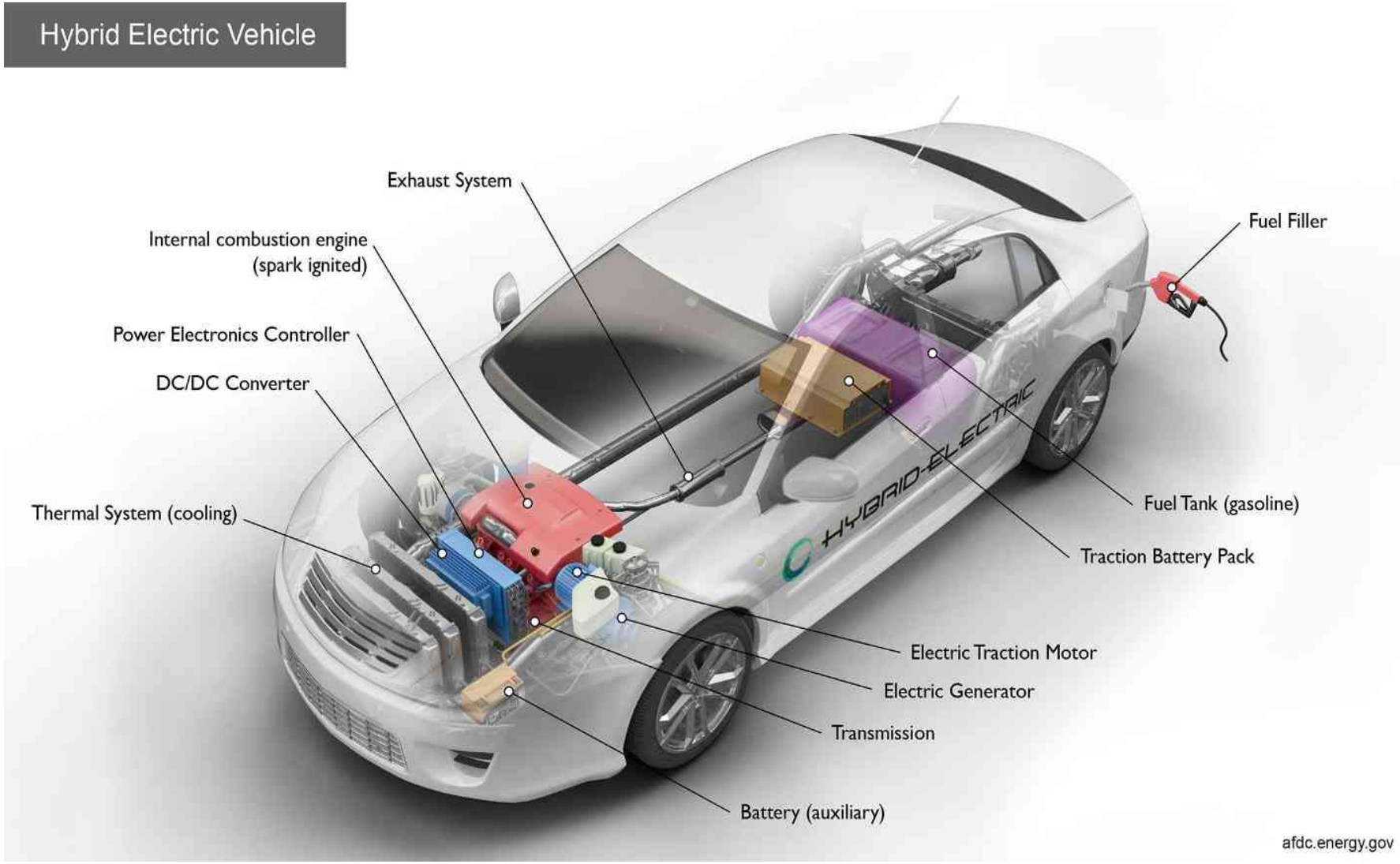


Energy Efficiency of the global chain # 68%

(Average and rounded figures according to present technology)

Nota: Basic data from car manufacturers

Full Hybrid Vehicle



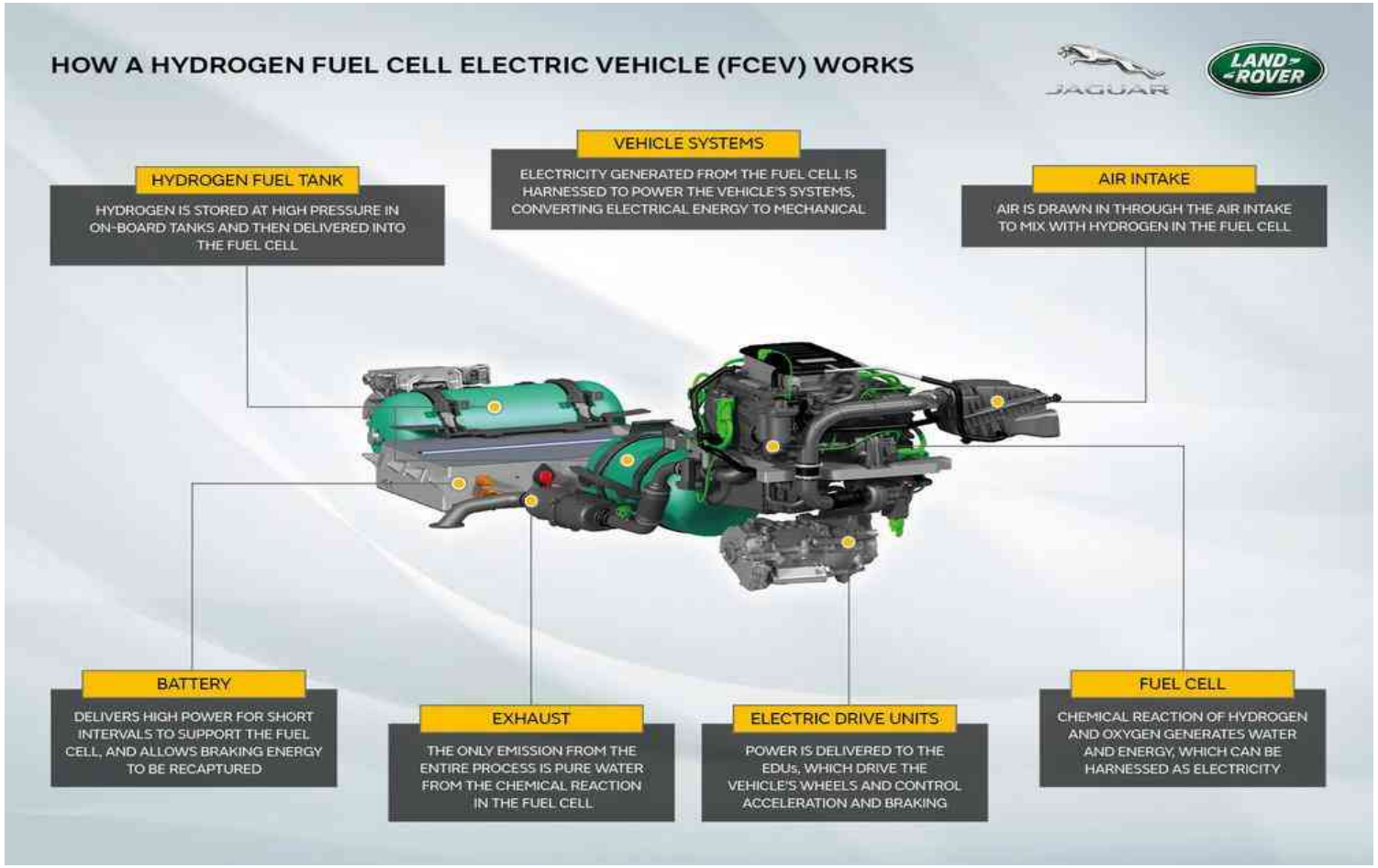
Source: US DOE – Alternative Fuels Data Center

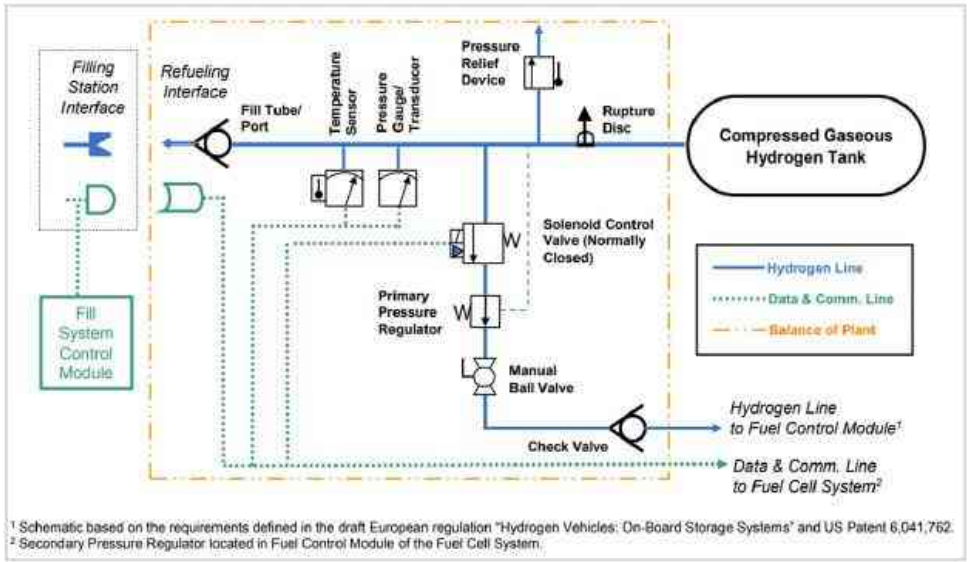
Full Hybrid Vehicle – Costs Split

Full hybrid vehicle		Hybrid
Gasoline Cost	€/l	**1,80**
Gasoline consumption	l/100 km	4,0
Gasoline Energy density (HCV)	kWh/l	9,3
Gasoline consumption	kWh/100 km	37,2
Gasoline Cost 100 km	€-100 km	**7,2**
Gasoline Cost 500 km	€-500 km	**36,0**
Gasoline Cost - 10000 km/year	€-10000 km	**720,0**
Vehicule purchase price	€	30000
Depreciation	Years	10
Vehicule Running costs	€/year	800
Total annual costs	€	**4520**
Total costs/km	€/km	**0,45**

Source: Car manufacturers/White paper International Council of Clean Transportation (ICTT)

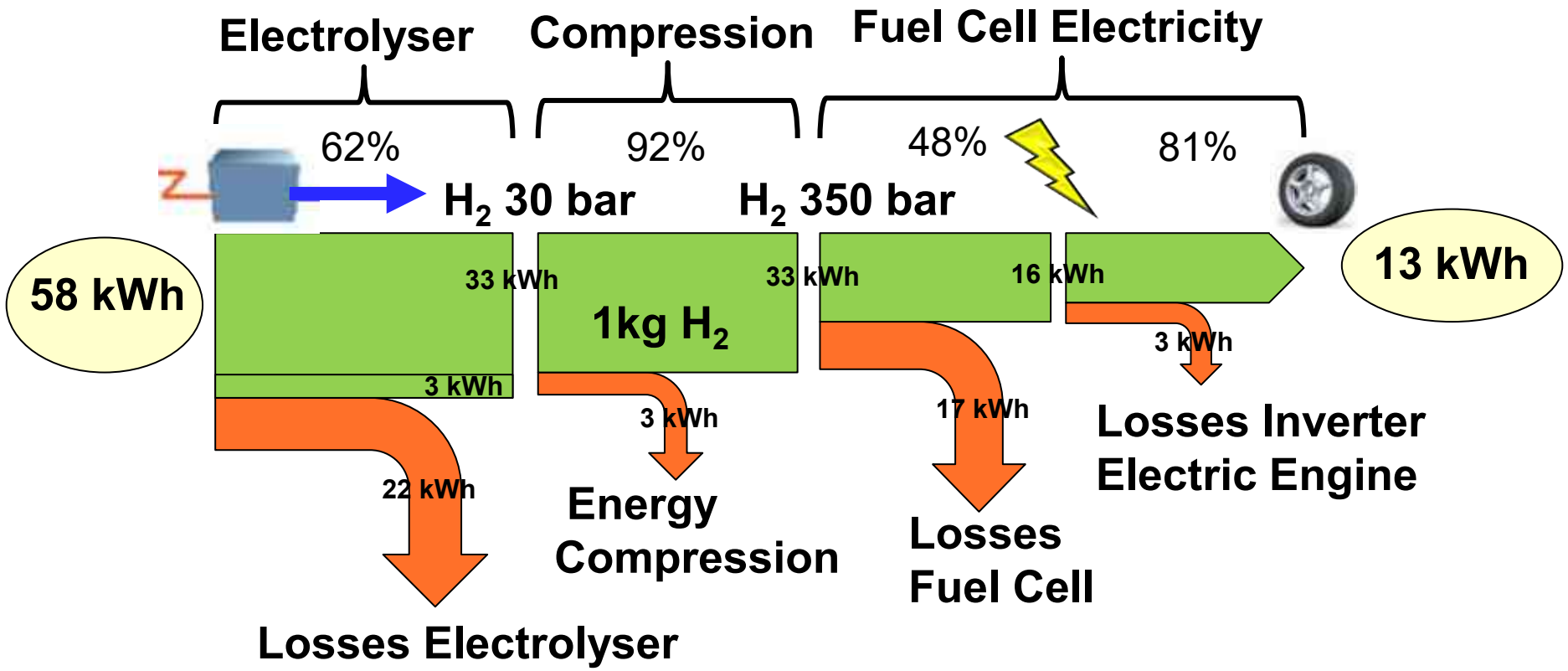
Operational Cycle for a Fuel Cell Electric Vehicule





Source: energies

Energy Efficiency of a Fuel Cell (using 1kg H_2)
Complete Cycle Power to H_2 to Power (See also chapter below: Hydrogen/A zoom on Fuel Cell)



Energy Efficiency of the global chain # 23%

(Average and rounded figures according to present technology)

Nota: Basic data from ADEME, car manufacturers

Fuel Cell Vehicle - Assumptions

FUEL CELL NEEDS		100 km	500 km
Vehicle Power	HP	160	160
Vehicle Power	kW	120	120
Needs of Hydrogen	kg H_2	1,2	6,0
Reservoir capacity	kgH2	6,0	6,0
Electricity Supply/kg Hydrogen	kWh/kg H_2	53,0	53,0
Electricity Supply	kWh	63,6	318,0
Price of Electricity Electrolyser	€/MWh	112,0	112,0
Price of Electricity Electrolyser	€/kWh	0,112	0,112

Source: Engie, Hyundai, Toyota

Fuel Cell Electric Vehicle (FCEV) – Cost split

Fuel Cell vehicle		H2
H2 Price	€/kgH2	15,0
Needs of Hydrogen 100 km	kgH2	1,2
H2 tank capacity	kgH2	6,0
Cost of H2 100 km	€-100 km	18,0
Cost of H2 500 km	€-500 km	90,0
Cost of H2 10000 km/year	€-10000 km	1800,0
Vehicle purchase price	€	75000
Fuel Cell cost	€/kW	185
Fuel Cell cost	€	22200
Fuel Cell cost	€	22500
Storage tank cost	€	3750
Battery cost	€	6750
Other costs vehicle	€	42000
Fuel Cell cost	%	30
Storage tank cost	%	5
Battery	%	9
Other costs vehicle	%	56
H2 Storage tank cost	€/kgH2	600
H2 Storage tank cost	€	3600
Depreciation	Years	10
Vehicule Running costs	€/year	400
Total annual technical costs	€	9700
Total annual costs/km	€/km	0,97

Source: Data from EdF/Bloomberg NEF/Mirova/Natixis/US DOE
Fuel Cell/Advanced Propulsion Center UK/Car manufacturers

9

Global Energy Growth
A zoom on Hydrogen

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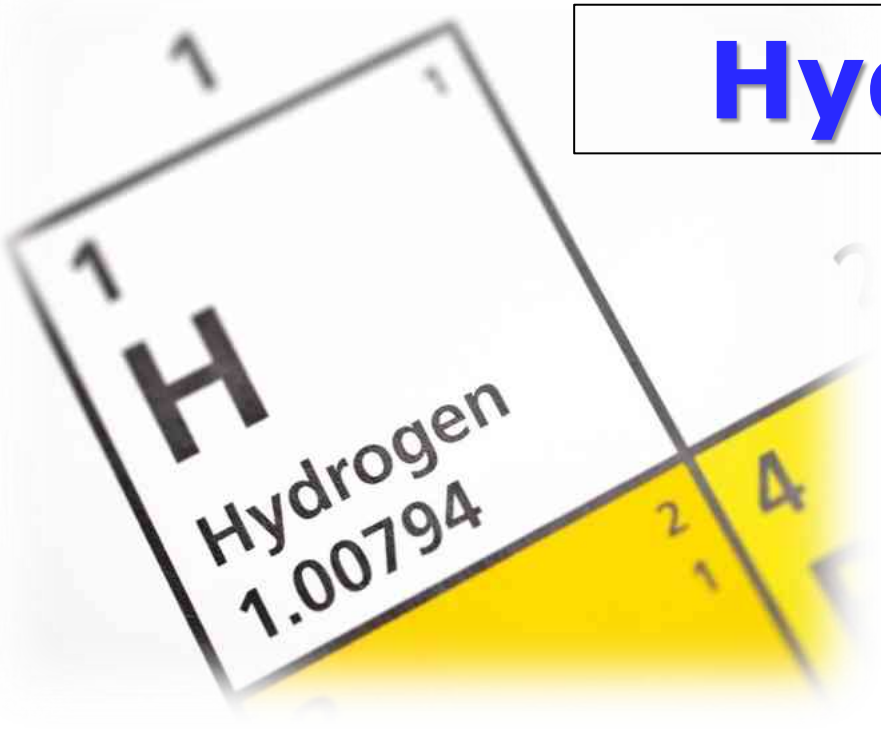
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- 6. Demography: A key element
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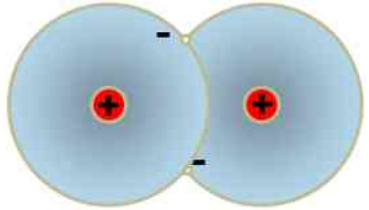

Specific Data
H2
HYDROGEN

Hydrogen some data

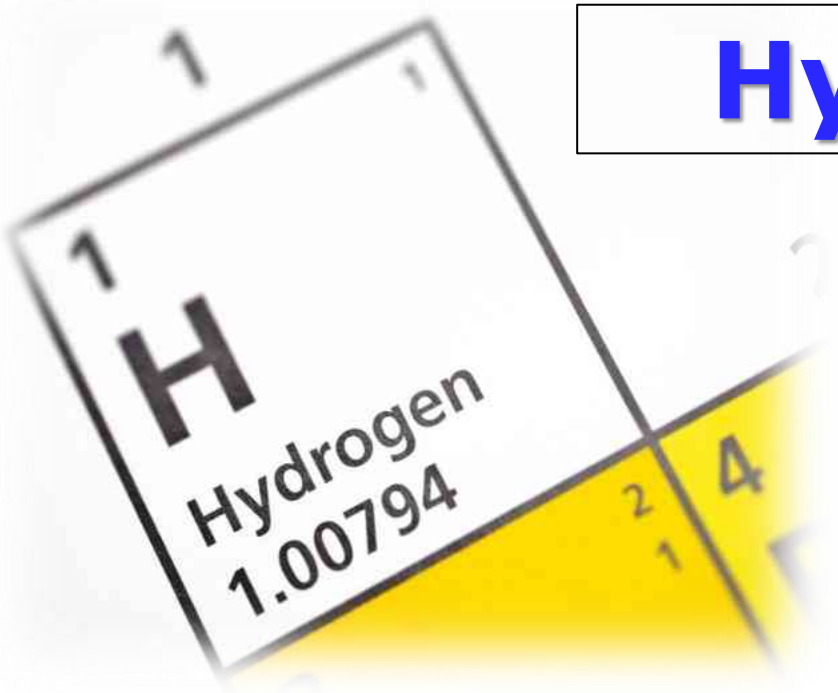


- First and lightest element of the periodic table :
  1 proton + 1 neutron
- The most present element in the universe: 75% by mass and 92% by number of atoms.
- Present in large quantities in stars, gaseous planets, nebulae and interstellar gas.
- Hydrogen clouds are the basis of the star formation process. It represents ¾ of the mass of the sun !

- Putting its electron in common with that of another atom to saturate its electron shell, it creates the dihydrogen molecule - H_2



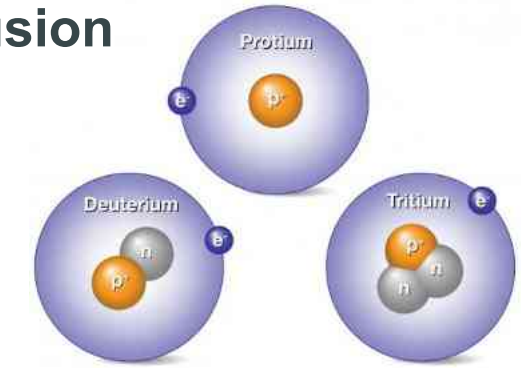
- A density of 0.090 g/l (gas at NCTP), and 0.071 kg/l (liquid, at -253°C and solid at -262°C)
- An explosive range between 4 and 75% in air, compared to 4 to 15% for methane
- At standard temperature and pressure, the molecule dihydrogen (H_2, Hydrogen) is a colorless, odorless, highly combustible gas.



Hydrogen some data

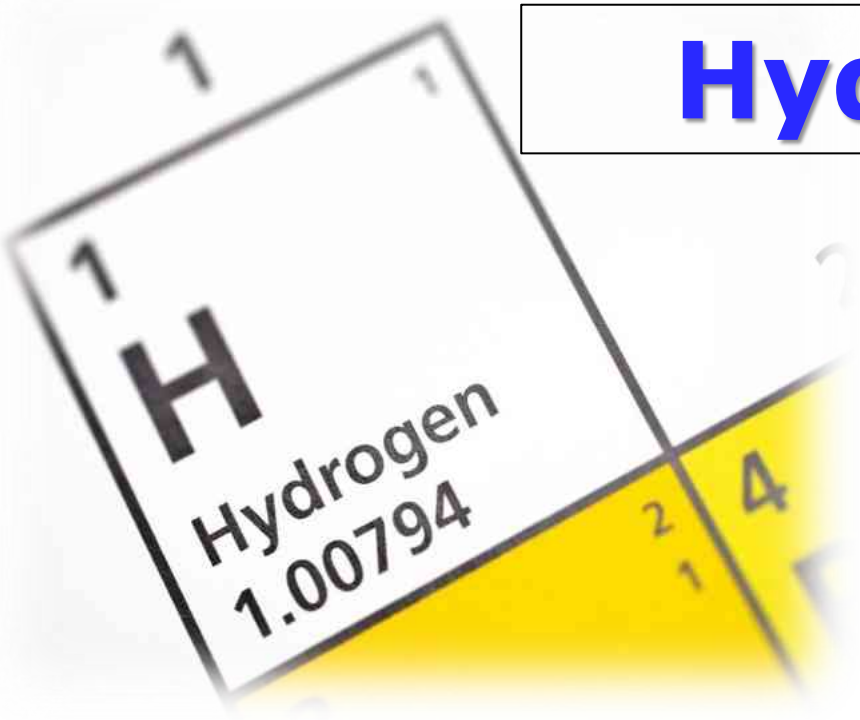
- There are three isotopes of Hydrogen :

- Hydrogen ^{1}H or protium (common) (1 proton and 0 neutron)
- Hydrogen ^{2}H or deuterium D (rare) (1 proton and 1 neutron)
- Hydrogen ^{3}H or tritium T (very rare) (1 proton and 2 neutrons)
- $D + T \Longrightarrow {}^{4}He + n + Energy$ = Nuclear fusion



- H_2 represents only 0.55 ppm of Earth's atmospheric gases.
- On Earth, water is the most common source of Hydrogen.
- Water covers 72% of the 509 million km² of the earth's surface. This is how we call the Earth the blue planet.
- The volume of the seas and oceans is estimated at around 1.4 trillion m³.

Hydrogen some data

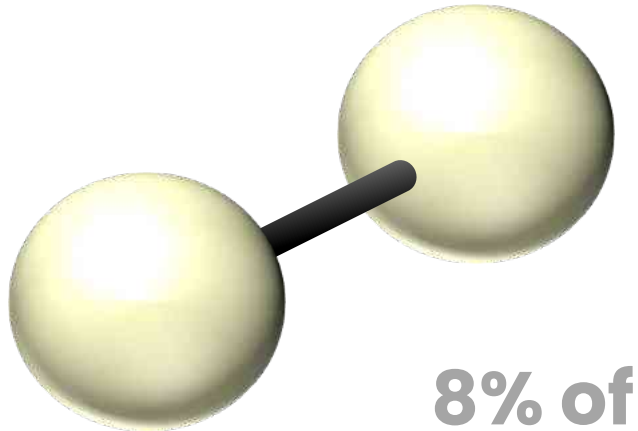


- Most of the Hydrogen on our planet exists in molecular forms such as organic compounds (methane, coal) or water (hence its name, Lavoisier 1783) .

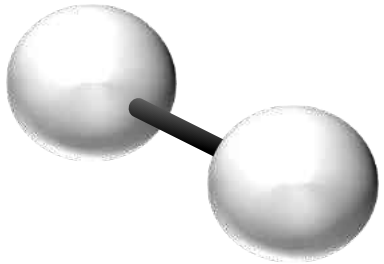
- It represents about 8% of the human weight.

- It is highly energetic:

High Heating Value (HHV) = 39,4 kWh/kg
Low Heating Value (LHV) = 33,3 kWh/kg

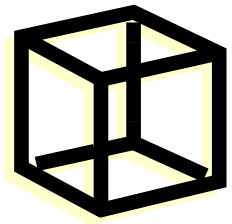


8% of the human weight



Hydrogen some data

Specific energy



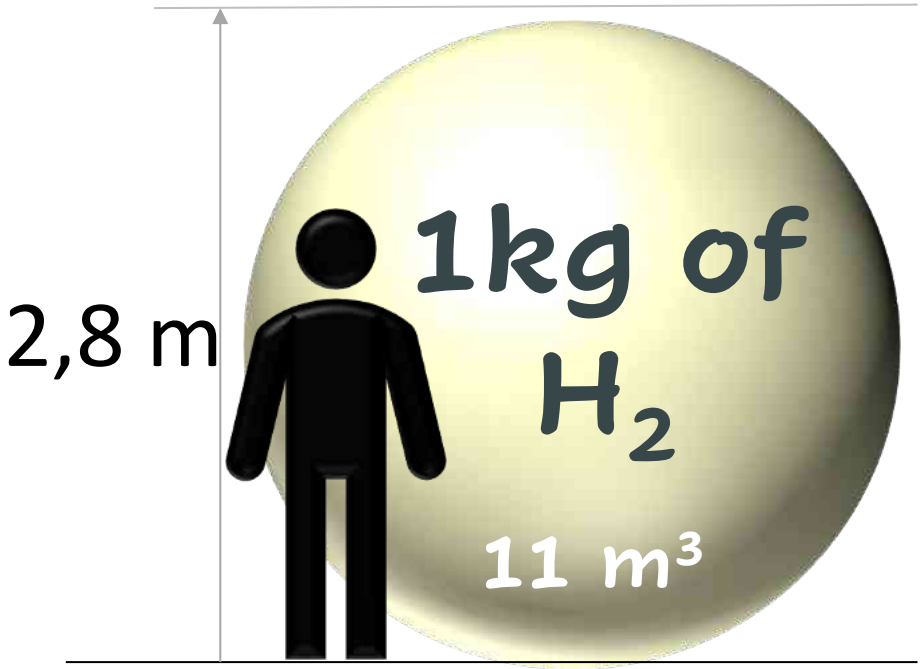
39,4 KWh/kg

(High Heating value)

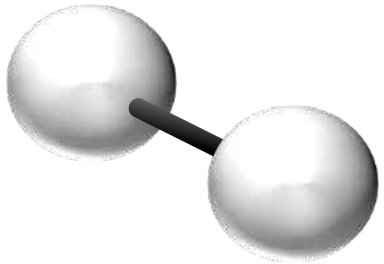
33,3 KWh/kg

(Low Heating value)

Density



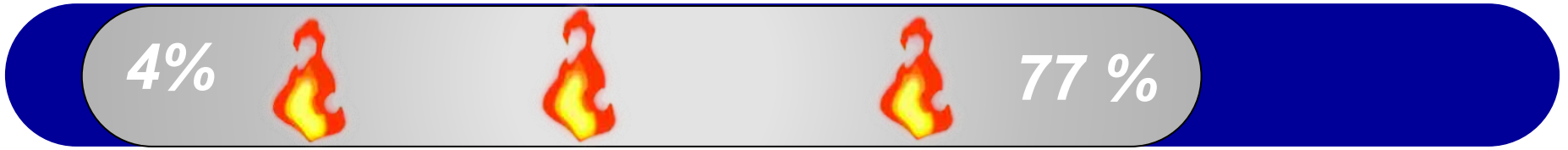
ρ_{H2} = 0,089 kg/m^3 (0°C, 1 bar)



Hydrogen Some Data

Air-Hydrogen mixture

Air



H_2

Lower flammable limit

Upper flammable limit

Air



CH_4

Air-methane mixture

Ignition range

Physical properties of Hydrogen

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Source: IEA 2019

Fundamentals of nuclear Hydrogen - 1

- **In Nature, two major sources of hydrogen exist:**
  - **Hydrocarbons** through Steam Reforming or other processes : $CH_4 + H_2O > CO + 3H_2$……. $CO + H_2O > CO2 + H_2$ at high temperature.
  - **Water** through electrolysis or thermochemical processes
- **Nuclear reactors can supply electricity and heat to produce Hydrogen.**
- **Hydrogen is a poor energy vector: its transportation costs are ten times those of liquid hydrocarbons per unit of energy.**
- **Hydrogen is a poor medium for storage in mobile systems, whatever technology is used (5% H_2 mass versus 95% for the containment system in the case of ground transportation).**

Fundamentals of nuclear Hydrogen - 2

- To produce hydrogen as an energy vector, the logic would be to attach carbon atoms to create hydrocarbon molecules: those molecules are efficient energy vectors and have excellent storage properties for mobile applications.
- The production of hydrogen can be made through electrolysis or from thermochemical processes. Terms of comparison between both possibilities will evolve with time. To cope with CO_2 emissions constraints, H_2 should be produced by decarbonized electricity.
- "Hydrogen mobility"? Rapid growth for Fuel Cell Electric Vehicles (FCEV):

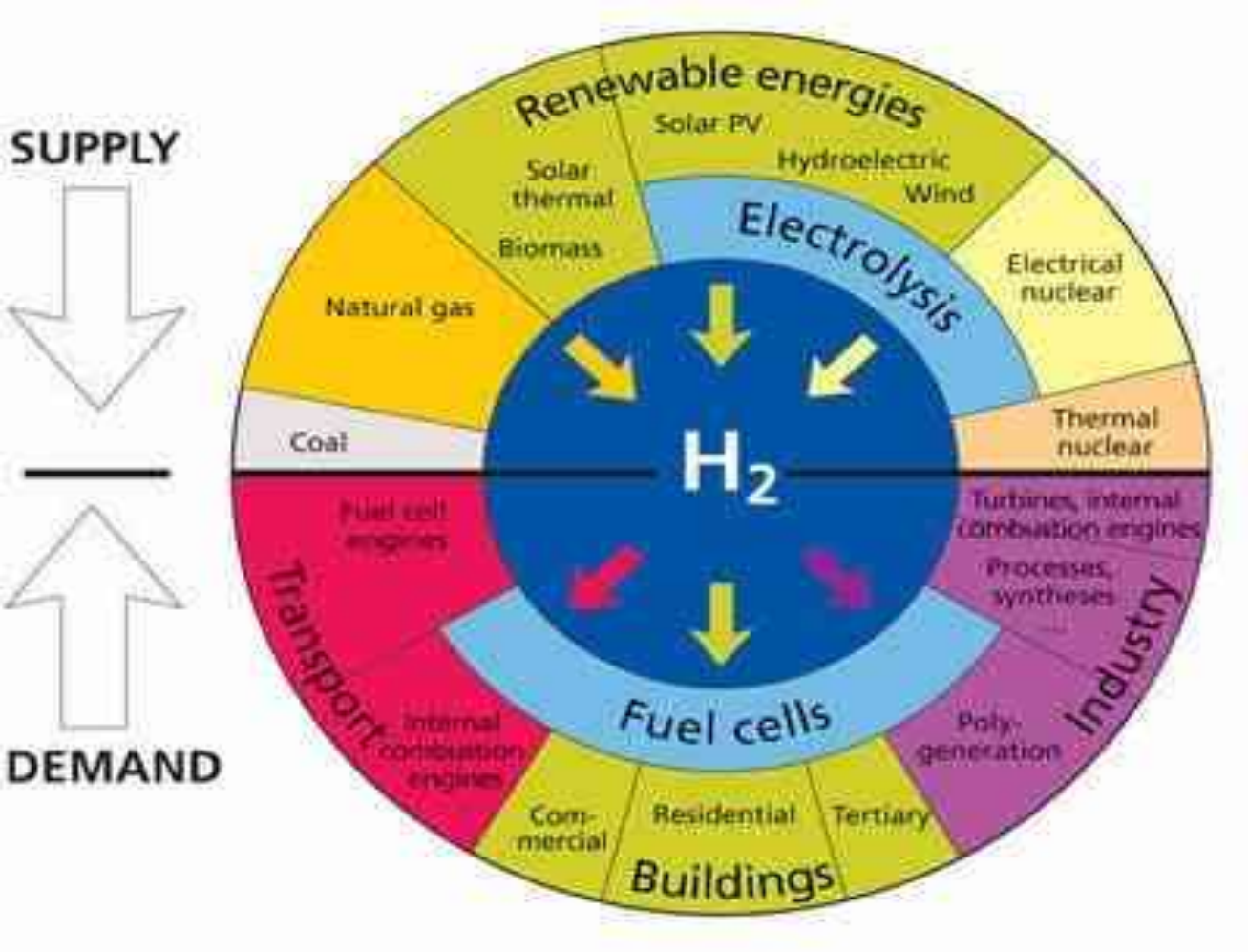
87 000 running FCEV worldwide in 2023, 11 000 in 2017 (vs 1,3 billion light vehicles worldwide in 2023)

1 100 existing hydrogen refueling stations (HRS) worldwide in 2023…..Additional sales of FCEV and construction of HRS are planned.

- "Hydrogen Council" established on 17 january 2017.
- Future deployment? Costs?


Industrial Use & Demand
H2
HYDROGEN

Hydrogen - Potentialities



Source: Horner.APG

Hydrogen – its industrial use today



Its use as **energy carrier** is limited today to aerospace domain (Rockets and satellites propulsion)

Chemical industry
Synthesis of plastic



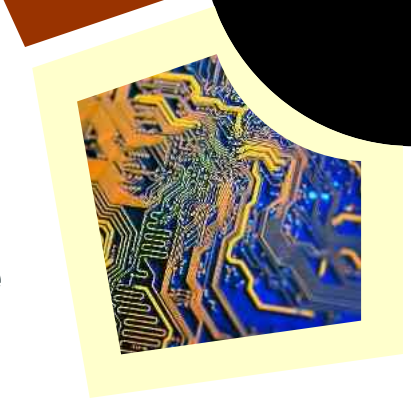


Refining industry
Fuel desulfurization

Industrial use of Hydrogen



Production of ammonia
Fertilizer industry

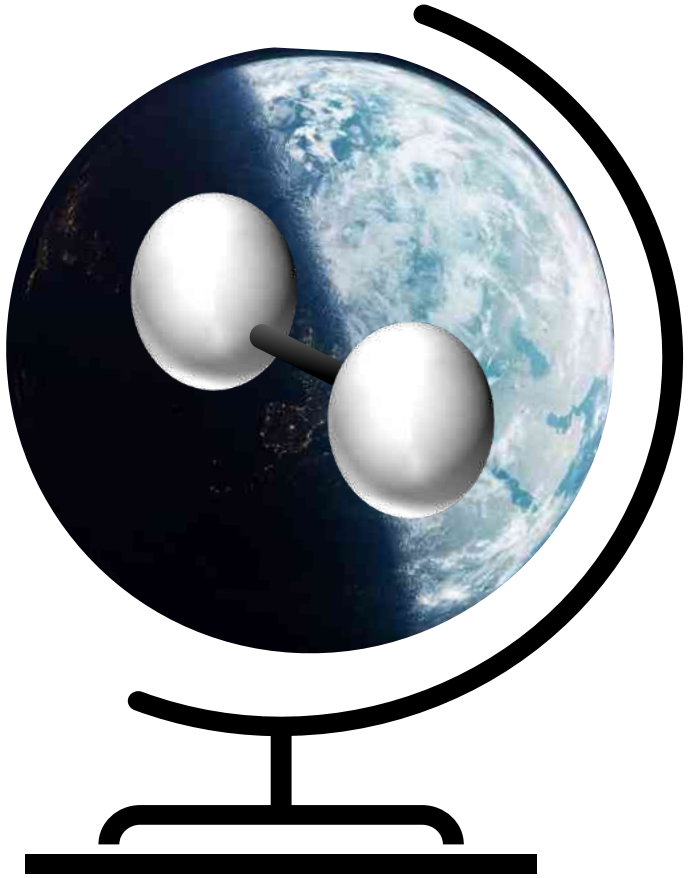


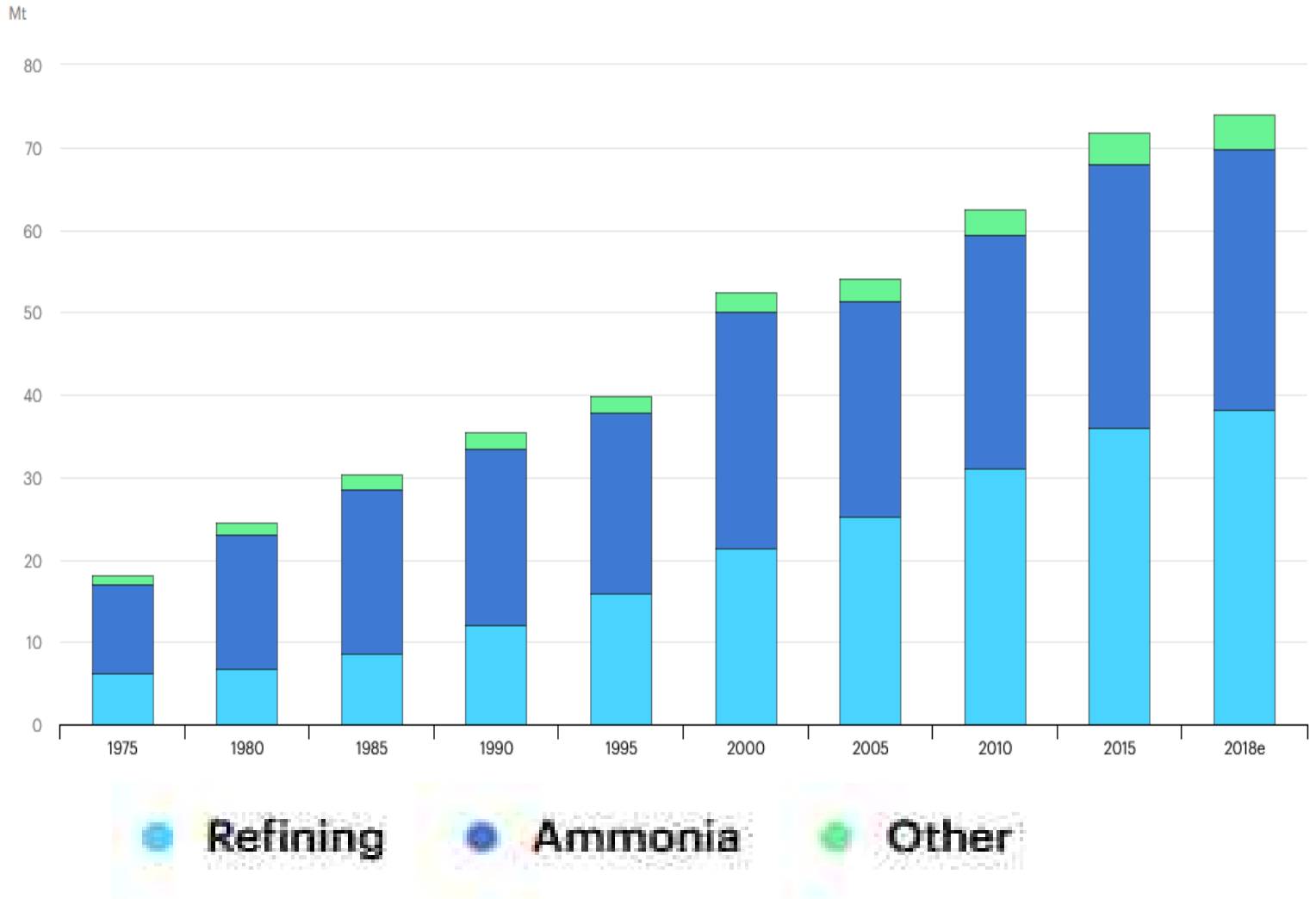
Printed circuit
Use of Hydrogen peroxide



Glass industry
as a heat source

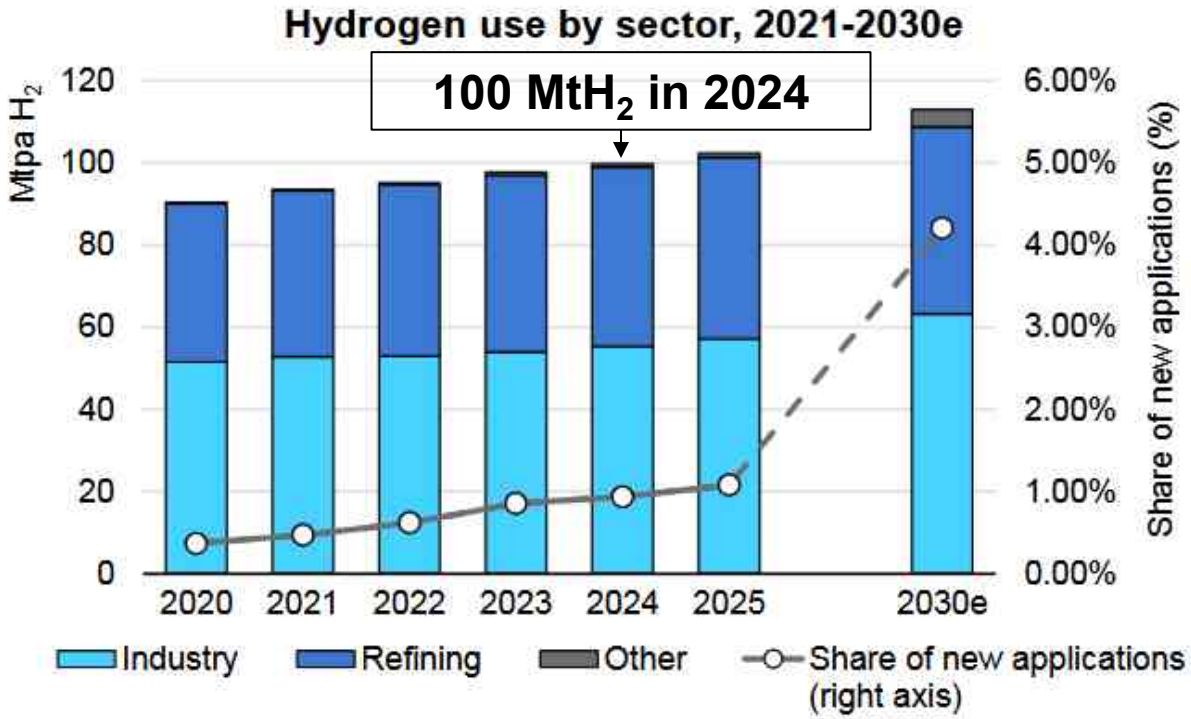
Past evolution Global Demand for Hydrogen: 1975 - 2018

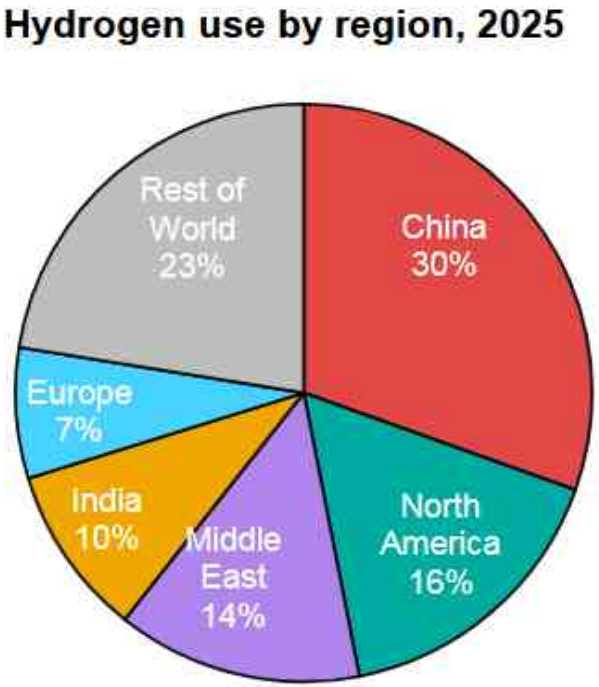




Source: IEA 2019

Hydrogen Demand by Sectors & Regions 2020 – 2030





IEA. CC BY 4.0

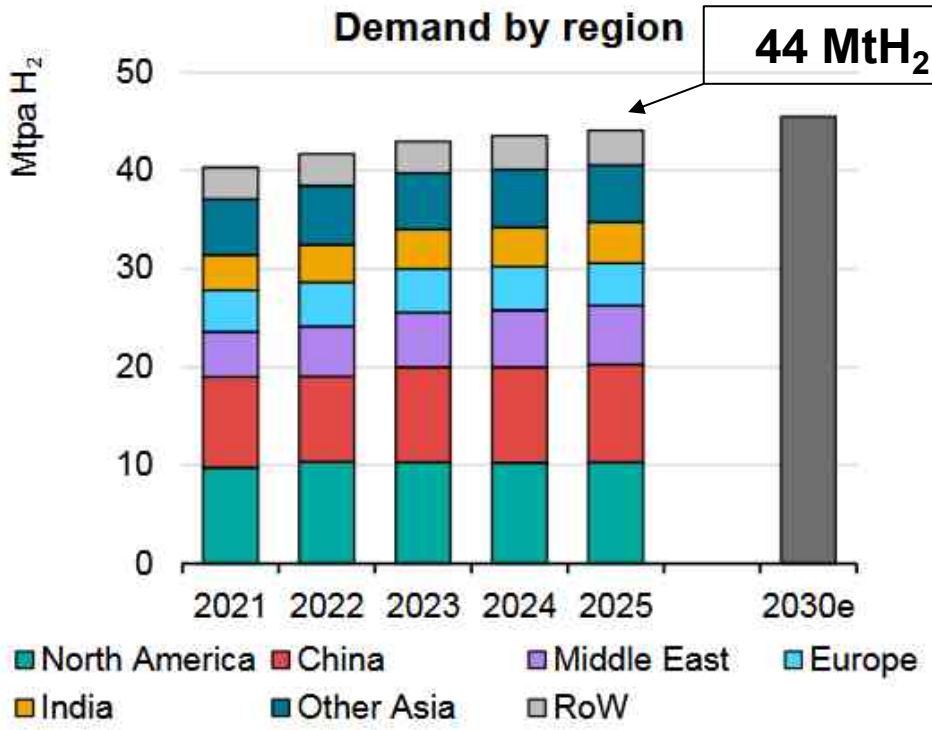
Note: "Other" includes transport, power generation, production of hydrogen-based fuels, buildings and biofuels upgrading.

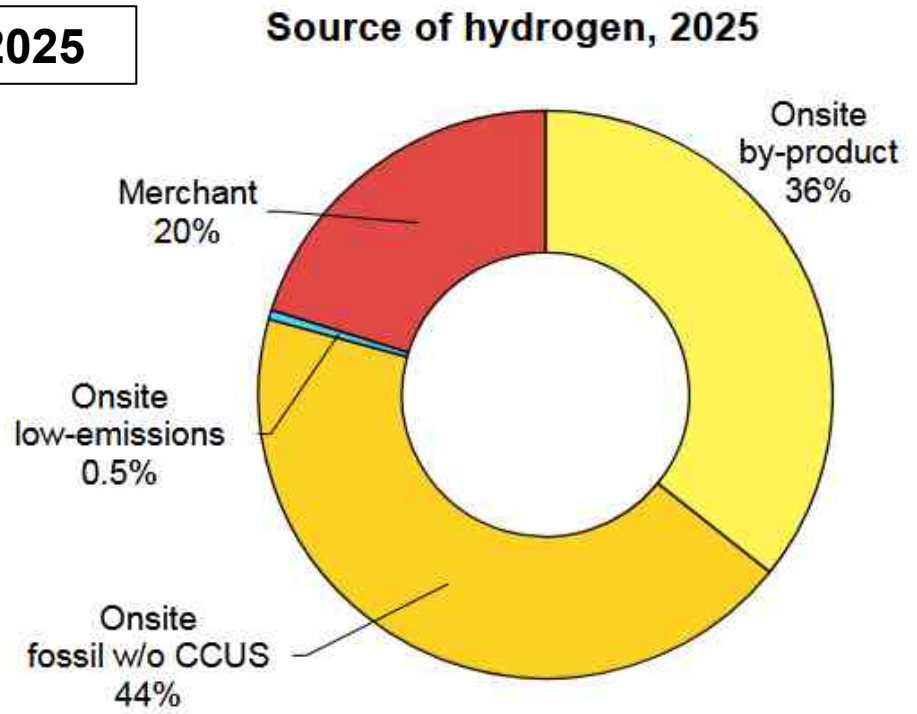
Sources: IEA analysis based on data from Argus Media Group, All rights reserved; International Fertilizer Association and World Steel Association.

Global hydrogen demand exceeded 100 Mt in 2025, concentrated in traditional applications in refining and industry.

Source: Global Hydrogen Review IEA July 2026

Hydrogen Demand & Source for Refineries 2021 - 2030





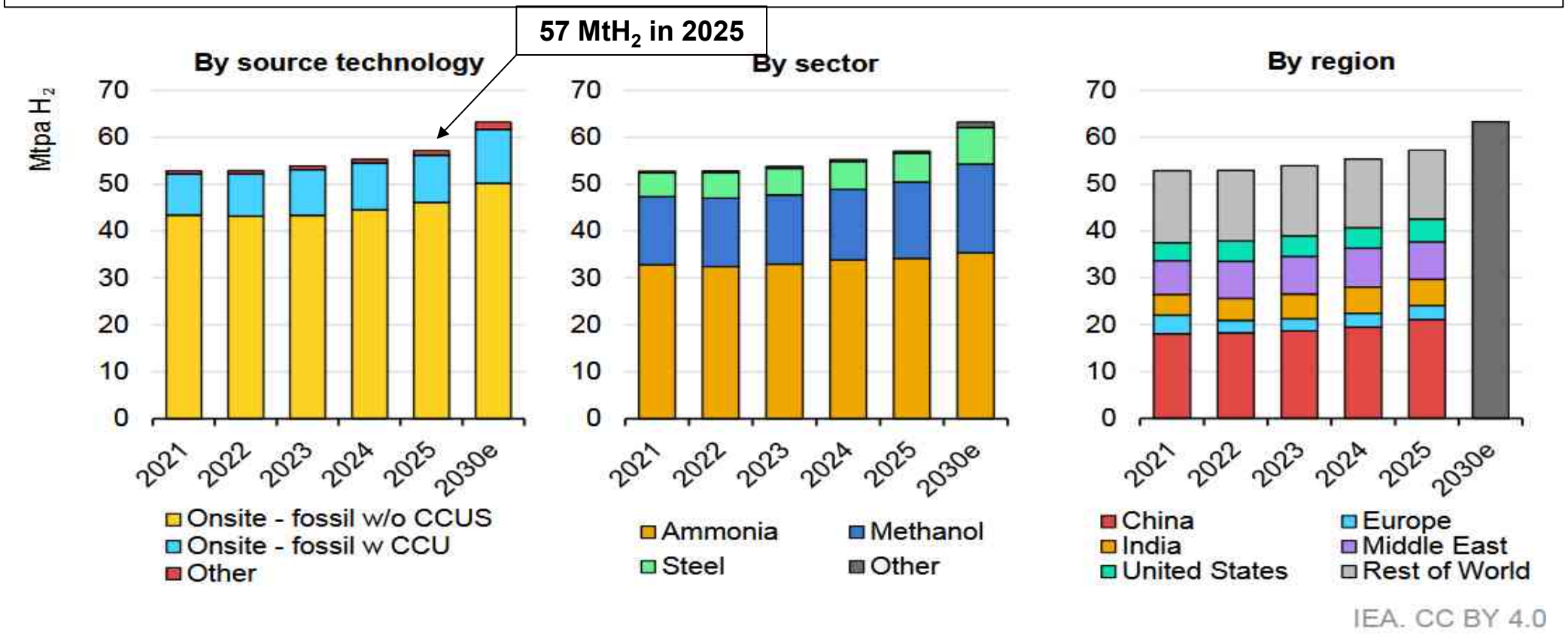
IEA. CC BY 4.0

Notes: fossil w/o CCUS = fossil fuels without carbon capture, utilisation and storage; RoW = Rest of World. "Onsite" refers to the production of hydrogen inside refineries, including dedicated captive production and as a by-product of catalytic reformers.

Hydrogen demand in refining increased in 2025 to reach 44 Mt, but short-term growth is uncertain due to the consequences of the conflict in the Middle East.

Source: Global Hydrogen Review IEA July 2026

Hydrogen Demand & Source for Industry 2021 – 2030



Notes: Fossil w/o CCUS = fossil fuels without carbon capture, utilisation and storage; Fossil w CCU = fossil fuels with carbon capture and use. In production by source technology, "Other" includes onsite production with bioenergy, carbon capture and storage or electricity, and merchant hydrogen. In demand by sector, "Other" includes dedicated hydrogen production for high-temperature heat applications.

Sources: IEA analysis based on data from Argus Media Group, All rights reserved; International Fertilizer Association and World Steel Association.

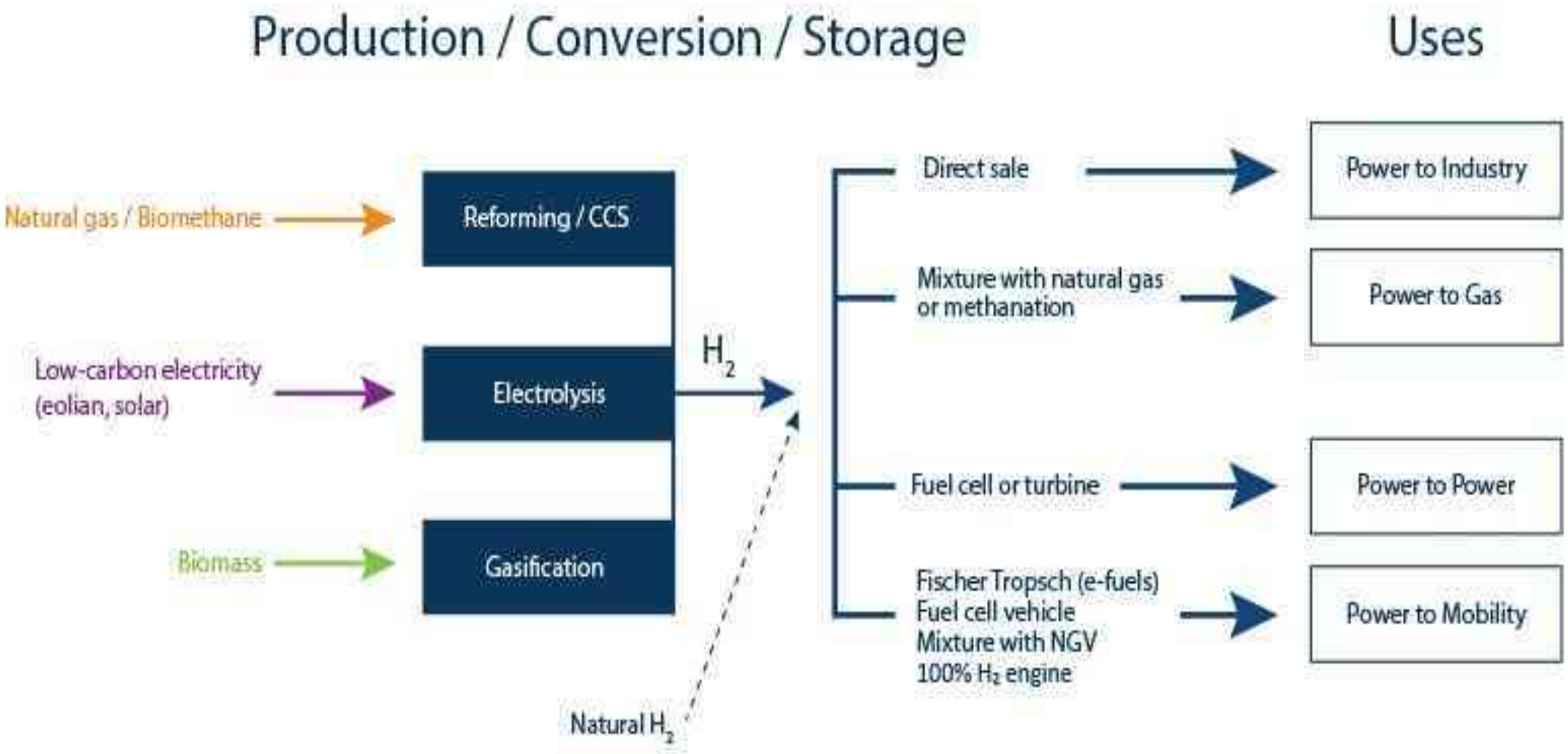
Industrial hydrogen demand grew 3% year-on-year, driven by methanol production.

Source: Global Hydrogen Review IEA July 2026

Hydrogen Production



Different Technologies to Produce Hydrogen

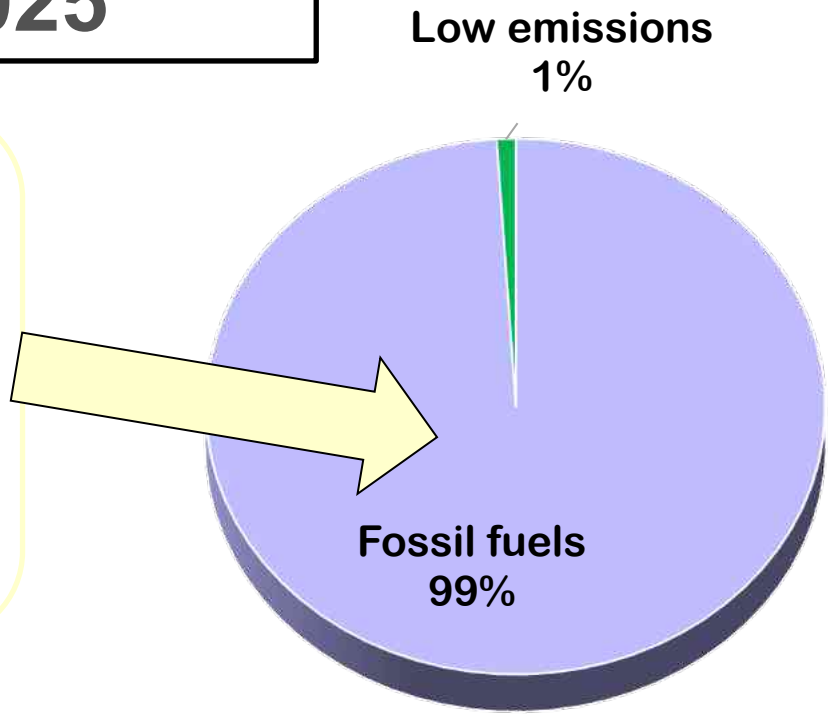


Source: IFP EN

*** For Fuel Cell, the right terminology should be: Power to H_2 to Power**

H_2 Production – Year 2025

61% of global natural gas and **22% of global coal**
are used for hydrogen production
99% of H_2 production come from unabated Fossil fuels
1% from Low emissions fuels, mainly Fossil with CCUS
Electrolysis: ε
CO_2 emissions of H_2 production highly depends on the fuel and technology used





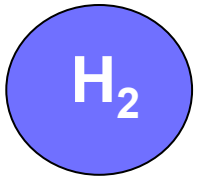
Global production of Hydrogen in 2025 (100 MtH_2) is responsible for emissions of around 1,0⁺ $GtCO_2eq$,
2/3 from unabated Natural Gas (10-14 kg $CO_2eq/kg\ H_2$)
20% from unabated Coal (22-26 kg $CO_2eq/kg\ H_2$)

Hydrogen – Production

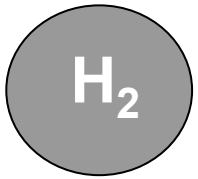
Hydrogen terminology (other colors exist!)



- Green Hydrogen: produced by electrolysis of water. Supply of Electricity must come from Renewable sources or Nuclear.



- Blue Hydrogen: produced from fossil fuels (typically Natural Gas), but emissions are dealt with using CCS technology.

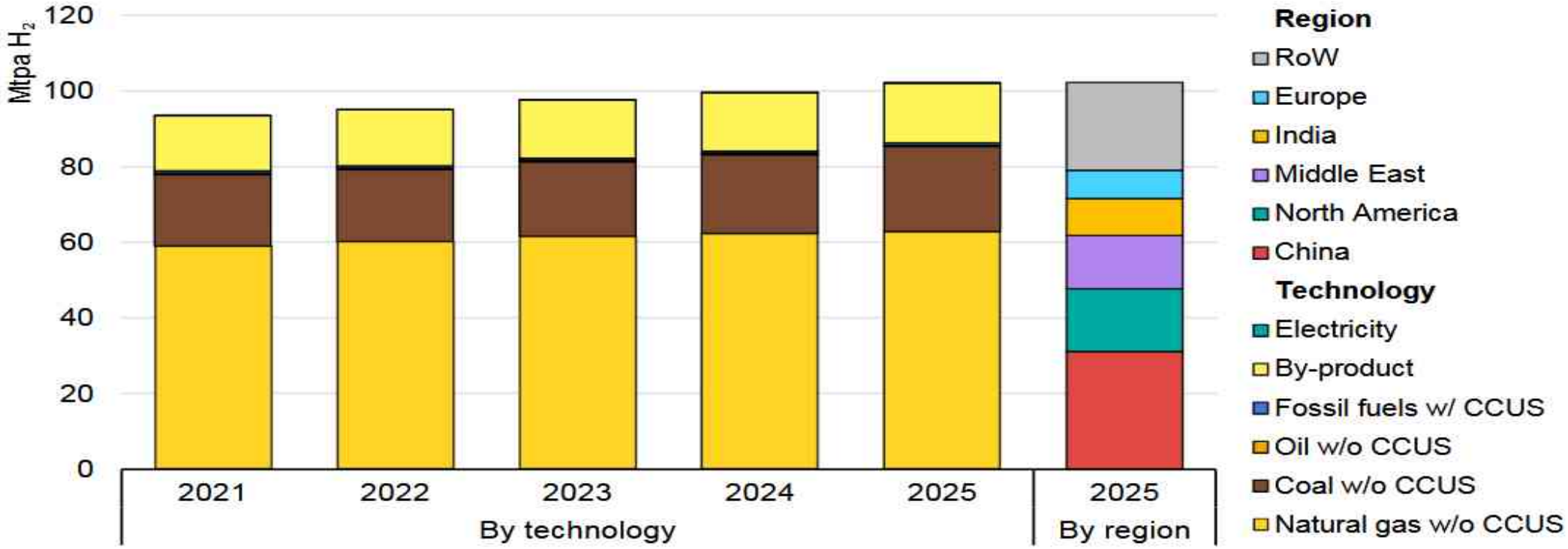


- Grey Hydrogen: produced from Natural Gas through steam reforming.



- Brown Hydrogen: produced from gasification of Coal.

Hydrogen Production by Technology & Region 2020 - 2025



Notes: CCUS = carbon capture, utilisation and storage; RoW = Rest of World. By-product hydrogen includes hydrogen production in catalytic naphtha crackers and steam crackers which is subsequently used in refining.

Hydrogen production remains dominated by unabated fossil fuels, leading to emissions of around 1 000 Mt of CO_2 in 2025.

Source: Global Hydrogen Review IEA July 2026
By-products originate from refineries and petrochemical industry from processes like naphte reforming

Steam-methane reforming (1)

Manufacturing H_2 from natural gas

Steam-methane reforming reaction
$CH_4 + H_2O$ (+ heat) → $CO + 3H_2$

Steam-methane reforming reaction
CH_4 + ***H_2O (+ heat/206kJ/mole)*** → ***CO*** + ***$3H_2$***



Natural gas

High-pressure steam
700°C–1,000°C



H_2

CO

HEAT (Endothermic reaction)

Steam-methane reforming (2)

Manufacturing H_2 from natural gas

Subsequently, in what is called the "water-gas shift reaction," the carbon monoxide and steam are reacting using a catalyst to produce carbon dioxide and more hydrogen.

Water-gas shift reaction

$CO + H_2O \rightarrow CO_2 + H_2$ (+ small amount of heat/41kJ/mole)



Carbon Oxyde

CO

High-pressure steam

700°C–1,000°C

3 to 25 bar



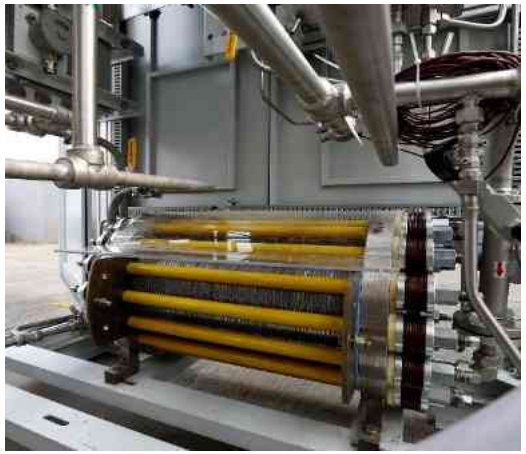
H_2

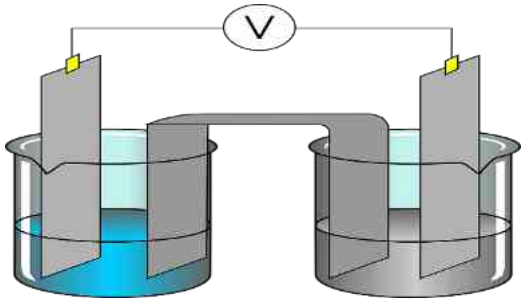
CO_2

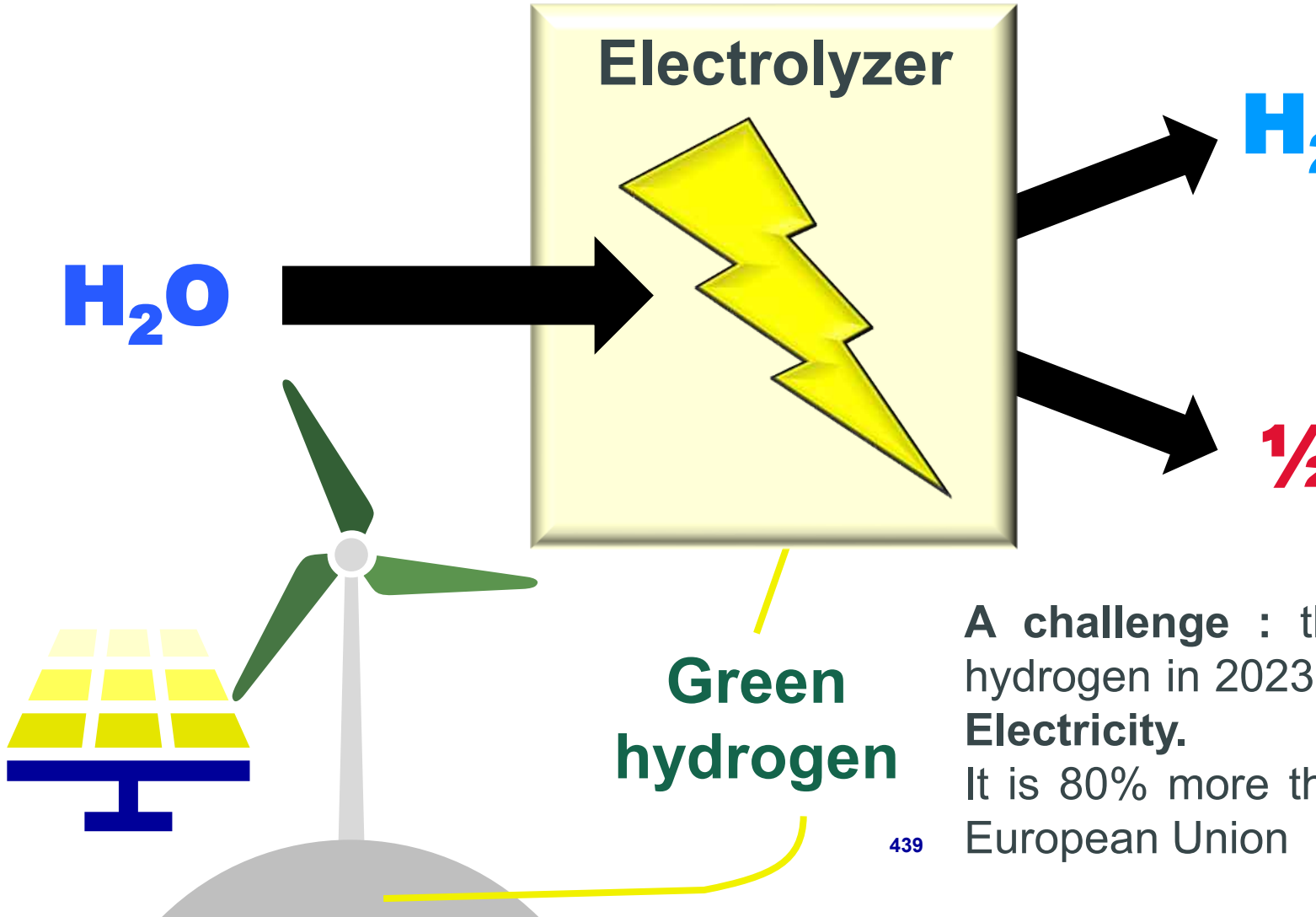
HEAT (Exothermic reaction)

Production of « clean » Hydrogen by electrolysis

Electrolysis is the process of using electricity to split water into Hydrogen and Oxygen. This process needs high quantity of Electricity







A challenge : the world global production of hydrogen in 2023 would **require # 5000 TWh of Electricity.**
It is 80% more than the electricity production of European Union

Natural Hydrogen



Naturally occuring Hydrogen

There are some scarce natural sources of hydrogen, offshore and onshore.

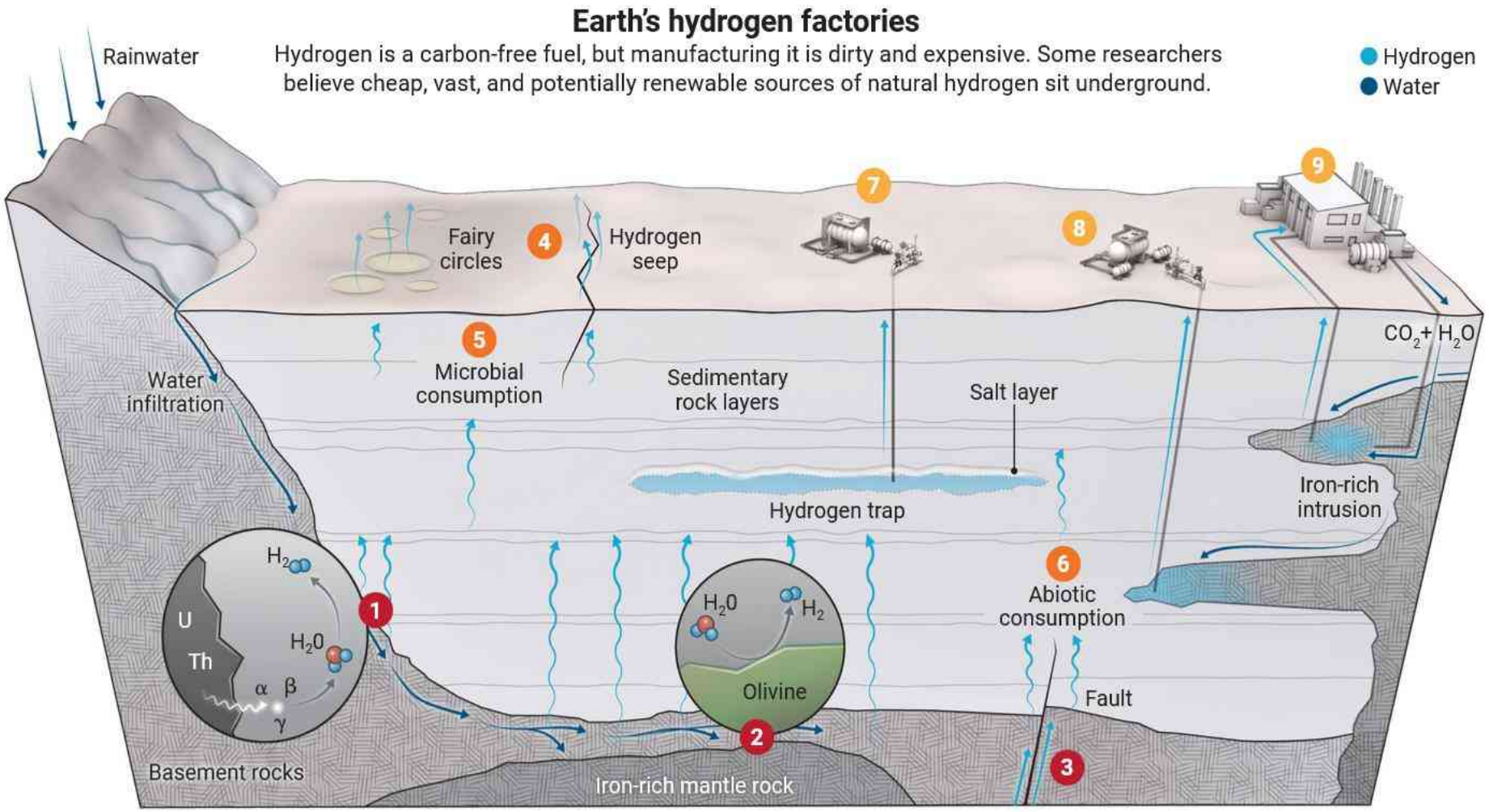
The mechanism of generation of this « natural » hydrogen is not yet fully understood (oxydation by water of reduced iron)

Offshore, the production of hydrogen from deep seabeds, far from the coast would not be economic.

Onshore, some deposits of hydrogen have been recently discovered in the middle of old tectonic plates (Mali, Russia, USA ..)

But « natural » hydrogen is today more a geological curiosity than an industrial resource.

Naturally occuring Hydrogen
How to exploit this operationally & economically?



(GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) GEOFFREY ELLIS/USGS

Naturally occuring Hydrogen

Generation

1 Radiolysis
Trace radioactive elements in rocks emit radiation that can split water. The process is slow, so ancient rocks are most likely to generate hydrogen.

2 Serpentinization
At high temperatures, water reacts with iron-rich rocks to make hydrogen. The fast and renewable reactions, called serpentinization, may drive most production.

3 Deep-seated
Streams of hydrogen from Earth's core or mantle may rise along tectonic plate boundaries and faults. But the theory of these vast, deep stores is controversial.

Loss mechanisms

4 Seeps
Hydrogen travels quickly through faults and fractures. It can also diffuse through rocks. Weak seeps might explain shallow depressions sometimes called fairy circles.

5 Microbes
In shallower layers of soil and rock, microbes consume hydrogen for energy, often producing methane.

6 Abiotic reactions
At deeper levels, hydrogen reacts withrocks and gases to form water, methane, and mineral compounds.

Extraction

7 Traps
Hydrogen might be tapped like oil and gas—by drilling into reservoirs trapped in porous rocks below salt deposits or other impermeable rock layers.

8 Direct
It might also be possible to tap the iron-rich source rocks directly, if they're shallow and fractured enough to allow hydrogen to be collected.

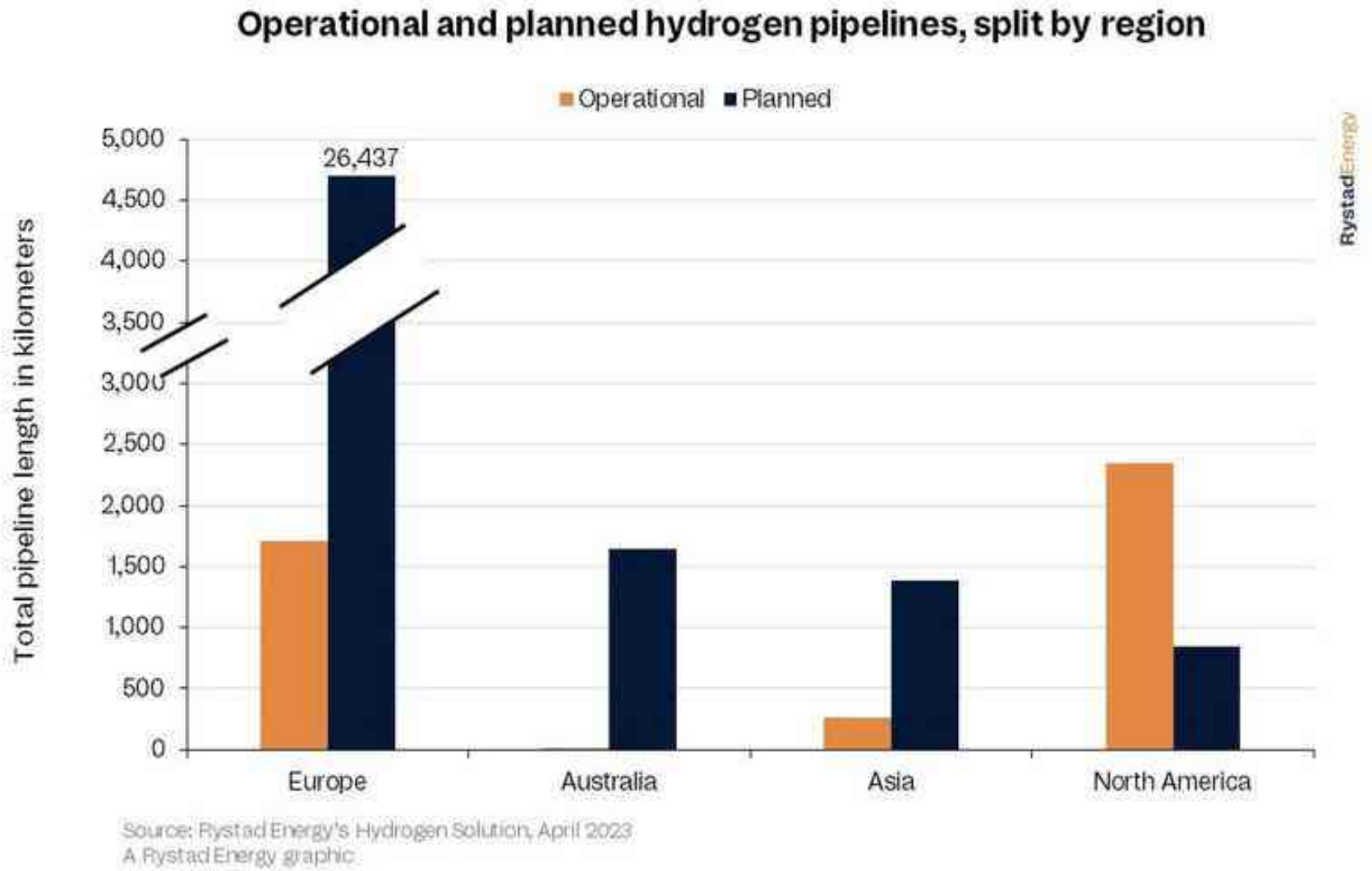
9 Enhanced
Hydrogen production might be stimulated by pumping water into iron-rich rocks. Adding carbon dioxide would sequester it from the atmosphere, slowing climate change.

(GRAPHIC) C. BICKEL/*SCIENCE*; (DATA) GEOFFREY ELLIS/USGS

Hydrogen transportation & trade

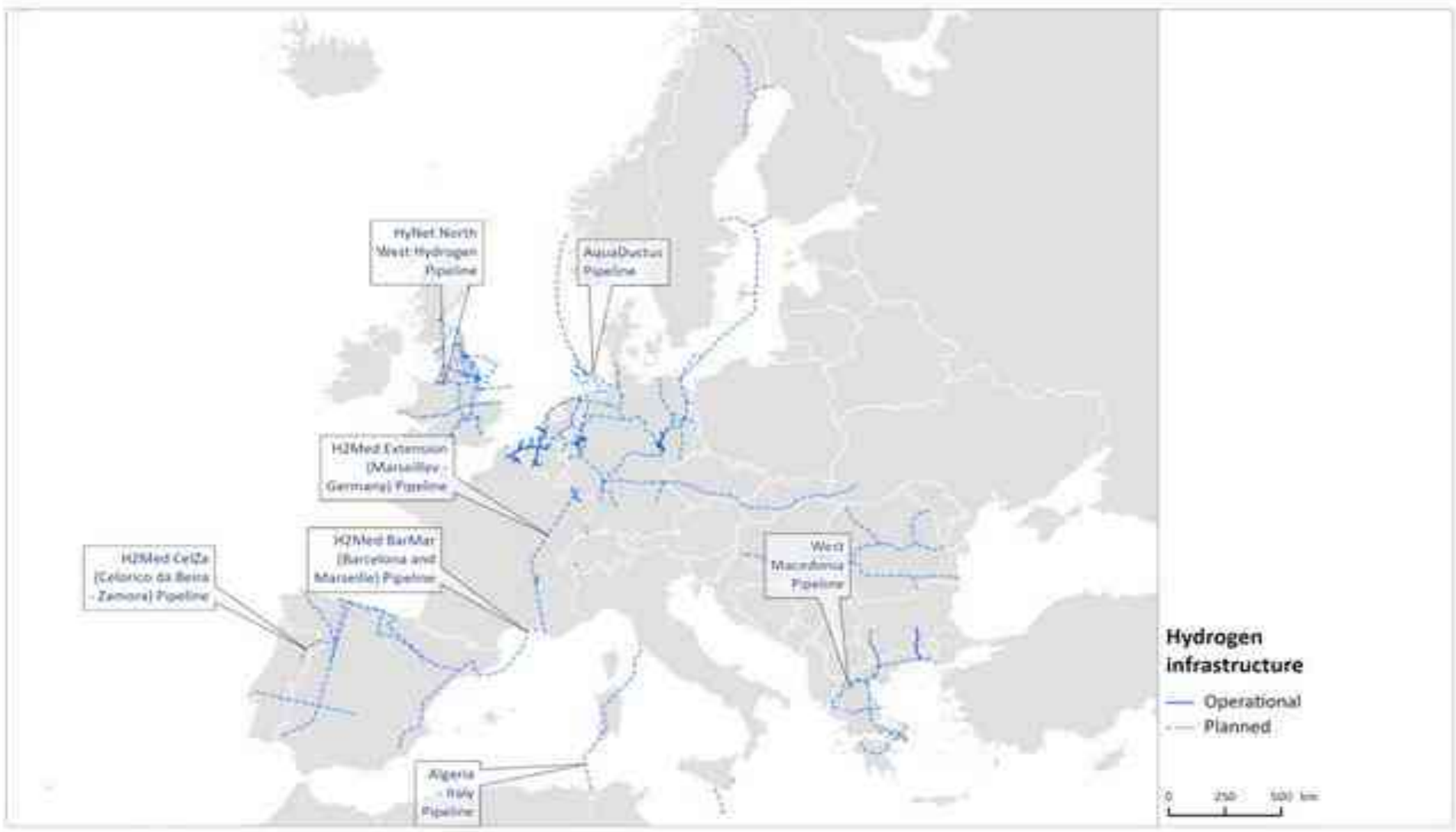


Hydrogen pipelines – Situation 2023



Source: RystadEnergy 2023

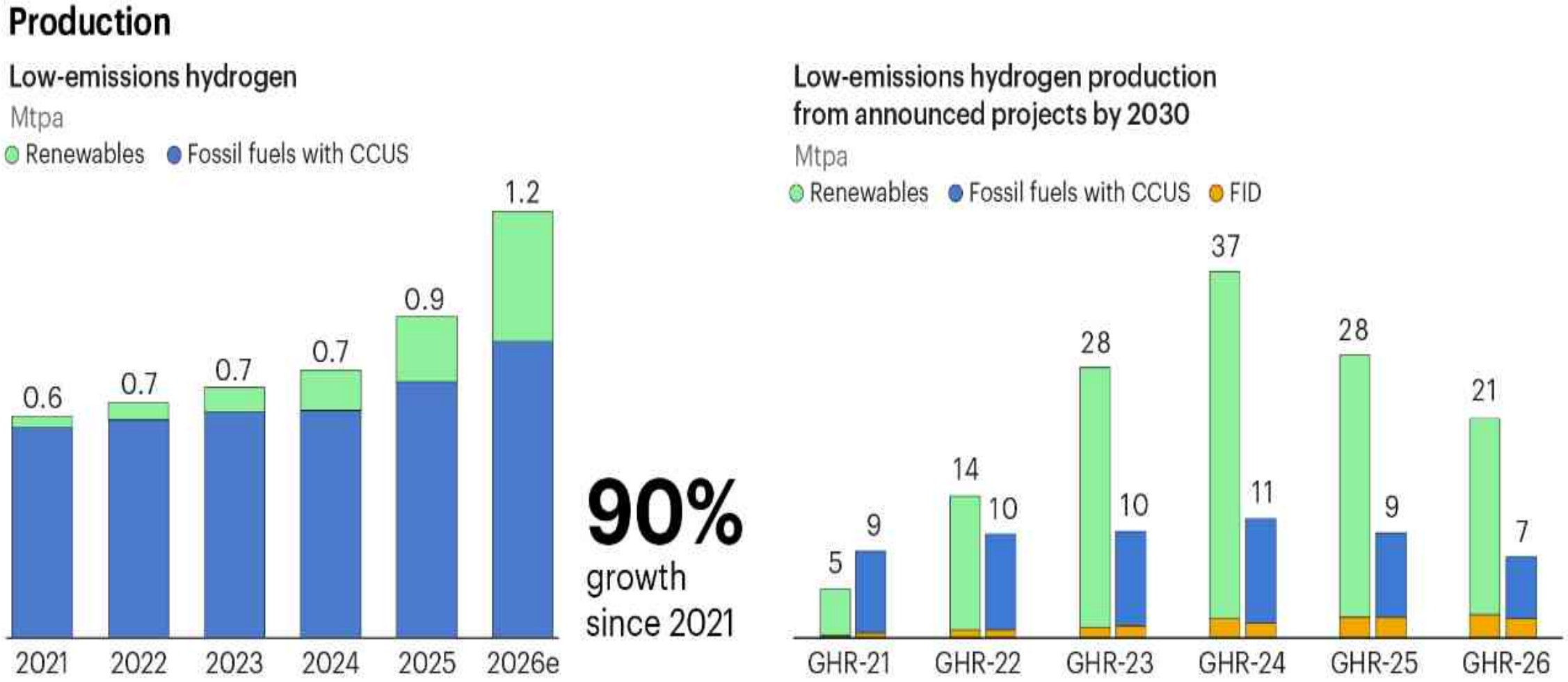
Hydrogen pipelines in Europe – Situation 2023



Source: RystadEnergy 2023

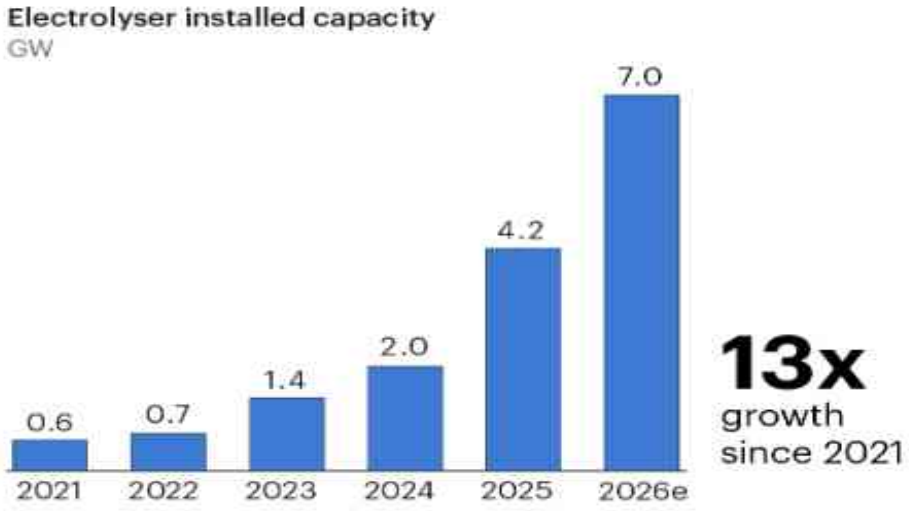

Clean Hydrogen &
Low –emissions Hydrogen
H2
HYDROGEN

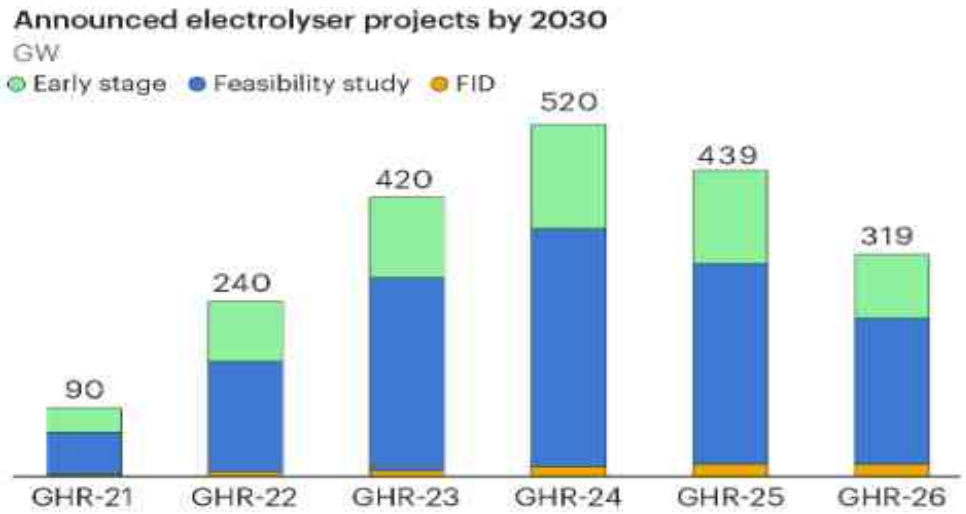
Low-emission Hydrogen Production Review
Low-emission Hydrogen # 1 MtH_2 in 2025 & 1,2 expected in 2026

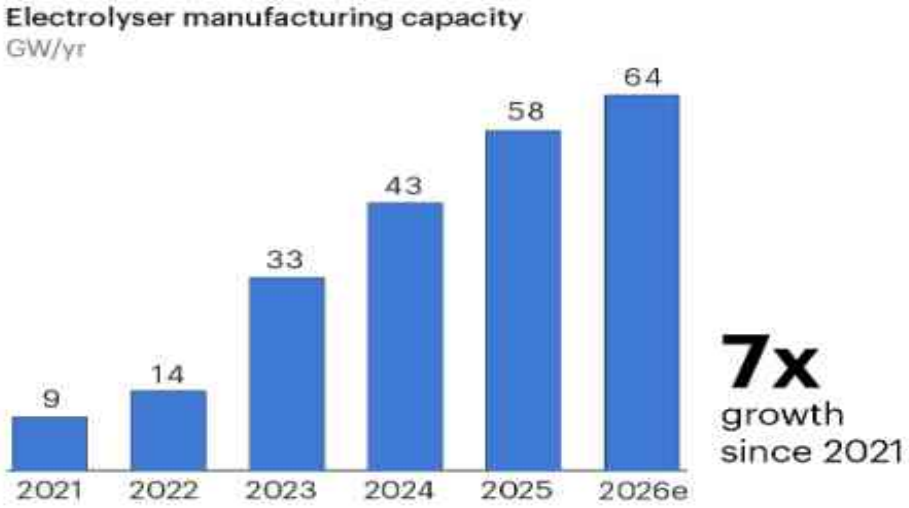


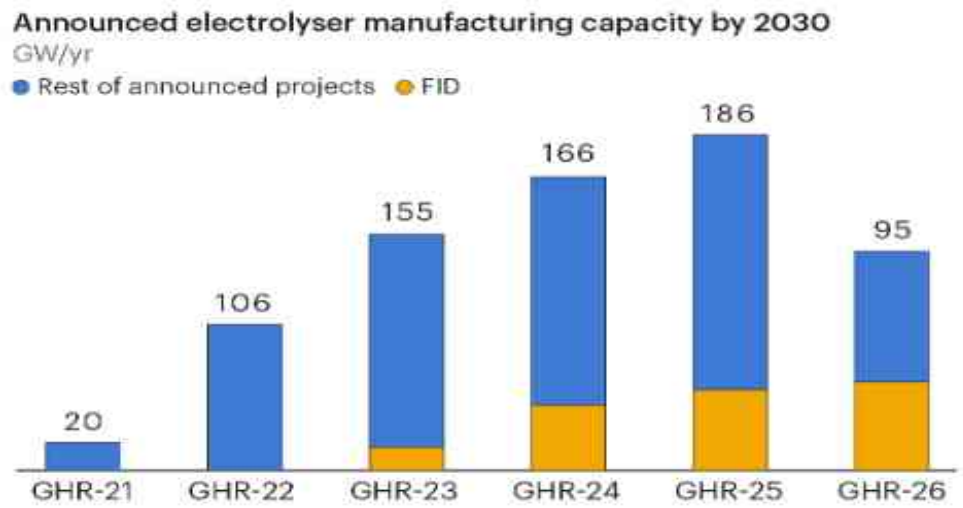
Source: Global Hydrogen Review IEA July 2026

Electrolyser Projects Review



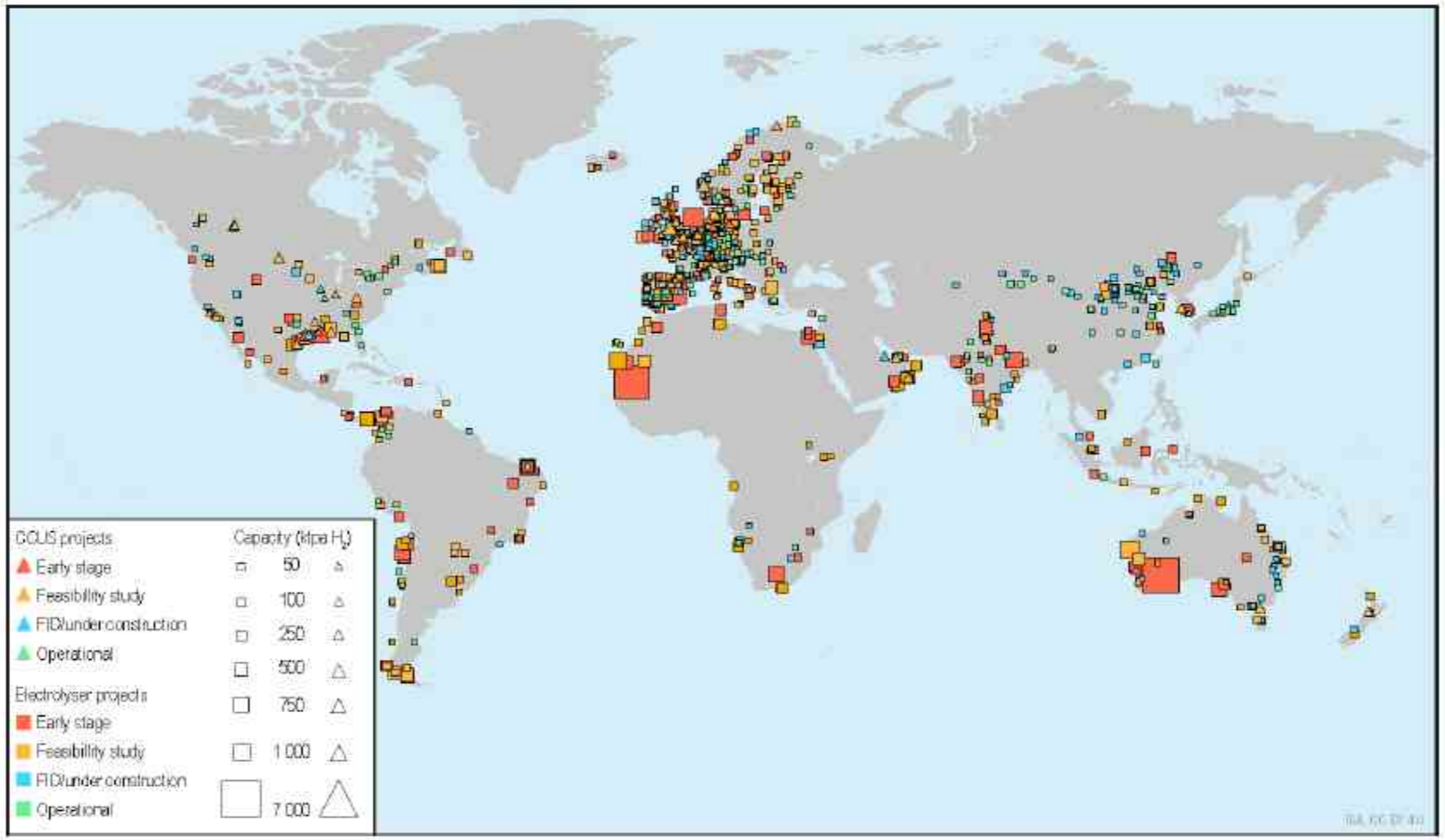






Source: Global Hydrogen Review IEA July 2026

Low-emission Hydrogen Production Review



Notes: CCUS = carbon capture, utilisation and storage; FID = final investment decision.

Source: IEA Hydrogen Production Projects Database (October 2024).

Source: Global Hydrogen Review IEA October 2024

Hydrogen Production by Electrolysis – Clean H_2

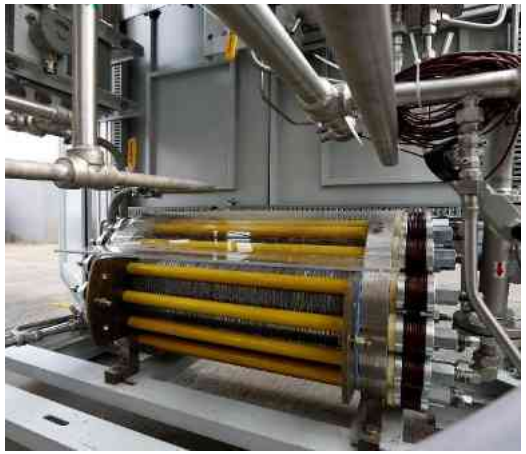
- Electrolysis is the process of using Electricity to split water into Hydrogen and Oxygen.

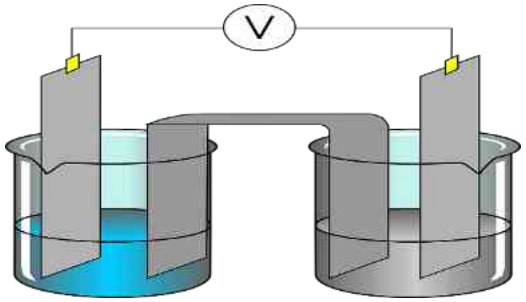
$$H_2O \longrightarrow H_2 + ½\ O_2$$

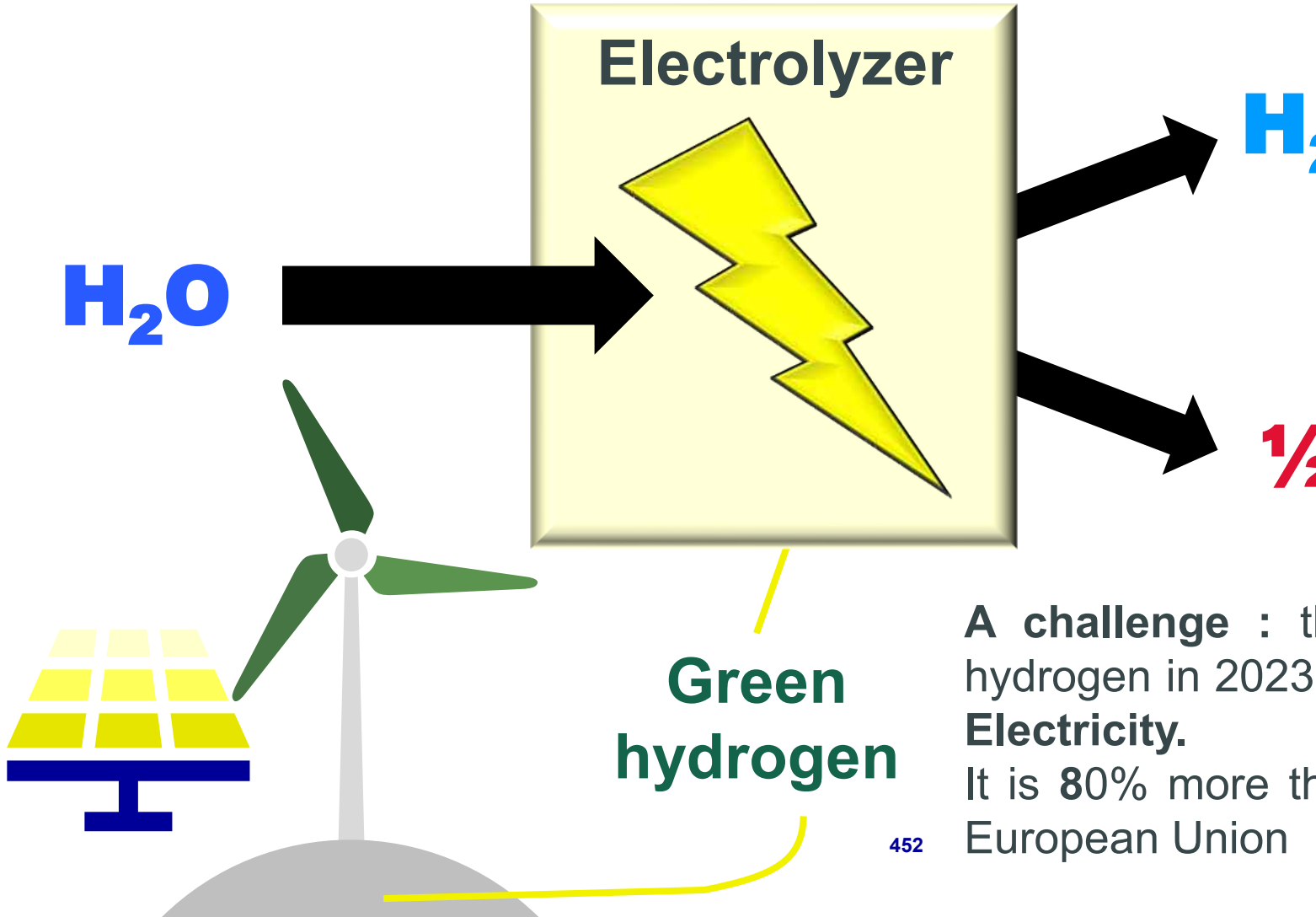
- This reaction takes place in an Electrolyser.
- Electrolysis process implies important needs for Electricity supply.
- **50/55 kWh are necessary to produce 1kg of H_2.** The production of all worldwide today's Hydrogen output (97 MtH_2) would require # 5000 TWh = 1,8 x Electricity production of European Union

Production of « clean » Hydrogen by electrolysis

Electrolysis is the process of using electricity to split water into Hydrogen and Oxygen. This process needs high quantity of Electricity







A challenge : the world global production of hydrogen in 2023 would **require # 5000 TWh of Electricity.**
It is 80% more than the electricity production of European Union

Hydrogen – Storage



Types of Hydrogen Storage Applications



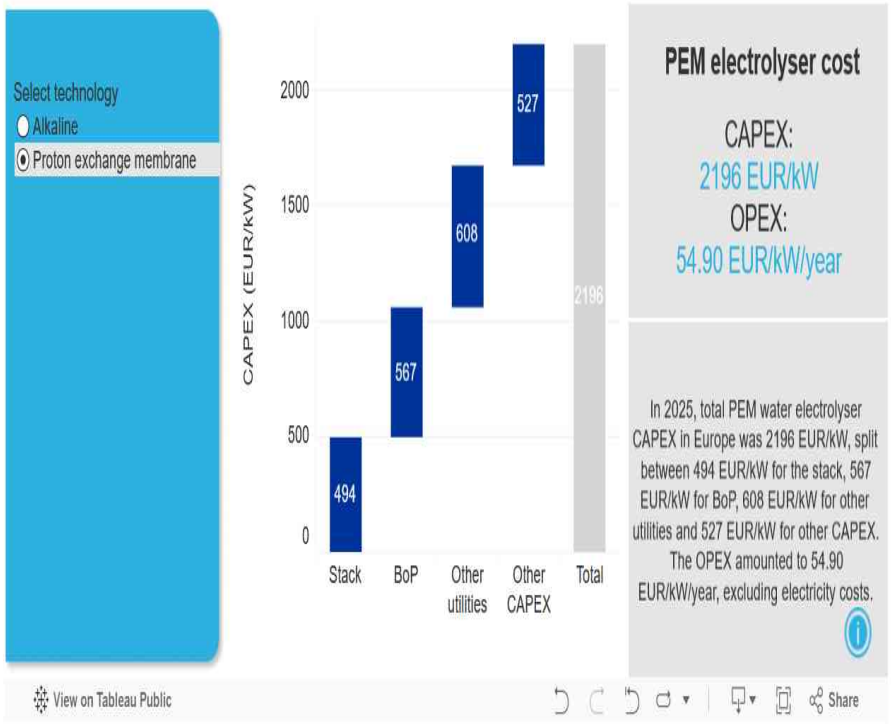
Source: energies MDPI 2023

Hydrogen – Mobility/transport Electrolyser



Electrolyser – High Power - Proton Exchange Membrane (PEM) Levelized Cost of Hydrogen (LCOH)

ELECTROLYSER high power - Power to H2 350 bar		
Capacity of Electrolyser	MW	**100**
Nb of working hours	hours/year	4000
Life time Electrolyser	years	**25,0**
Capacity factor	%	45,7
Electricity input/year	MWh/year	400000
Electricity input/day	MWh/day	1096
Electricity supply/kg H2	kWh/kg H_2	**53,0**
H2 production/day	kg H_2	20677
H2 production/year	kg H_2	7547170
H2 production total	kg H_2	188679245
Capex Electrolyser (France)	€/MW	2300000
Global capex	M€	230
Opex Electrolyser	€/MW/year	55000



Source:European Hydrogen Laboratory
Capex includes Stack + BoP (Balance of Plant) +other utilities + other Capex

Electrolyser – High Power - Proton Exchange Membrane (PEM) Levelized Cost of Hydrogen (LCOH)

GLOBAL COSTS		
Constant annuity Capex (@ 5%)		0,071
Constant annuity Capex/year	M€	16,32
Opex Electrolyser/year	M€	5,50
Electricity supply/year	M€	44,80
Total cost/year	M€	66,62
LCOH	€/kg H_2	**8,83**
GLOBAL COSTS/kgH2		
Constant annuity Capex/year	€/kg H_2	2,16
Opex Electrolyser/year	€/kg H_2	0,73
Electricity supply/year	€/kg H_2	5,94
LCOH discounted @ 5%	€/kg H_2	**8,83**
TOTAL COST NON DISCOUNTED		
Capex total	M€	230
Opex Electrolyser total	M€	138
Electricity supply total	M€	1120
Total cost	M€	1488
LCOH not discounted	€/kg H2	**7,88**



Source: Air Liquide

Source:European Hydrogen Laboratory
Capex includes Stack + BoP (Balance of Plant) +other utilities + other Capex

Hydrogen Refuelling Station



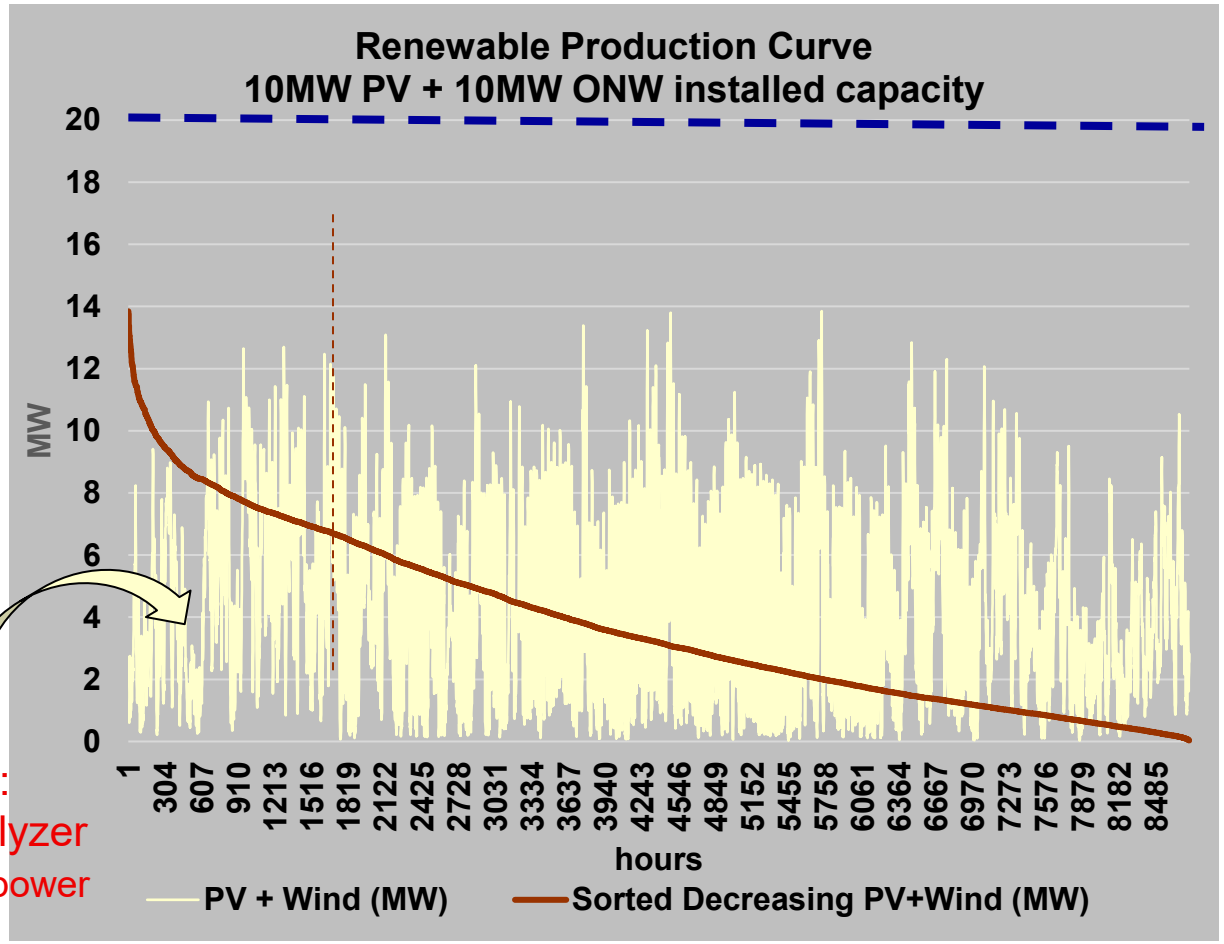
Feeding the Electrolyser: Nuclear or Renewables?
Efficiency of combined Renewables and Electrolyser



10 MW

+

10 MW





20 MW

Available energy :
~ **19%** load of electrolyzer
or **1660 h/y** equiv. full power

Full load (100%) : 20 MW x 8760 h
= 175.2 GWh

Matching the installed electrolyzer power with equivalent renewable power results in a **large under-utilisation** of the electrolyzer

H_2 Use for Transport



Hydrogen fuel cell powered bus



A Hyundai Xcient Fuel Cell truck



Alstom Coradia iLint train



Boeing Company Demonstrator hydrogen-powered



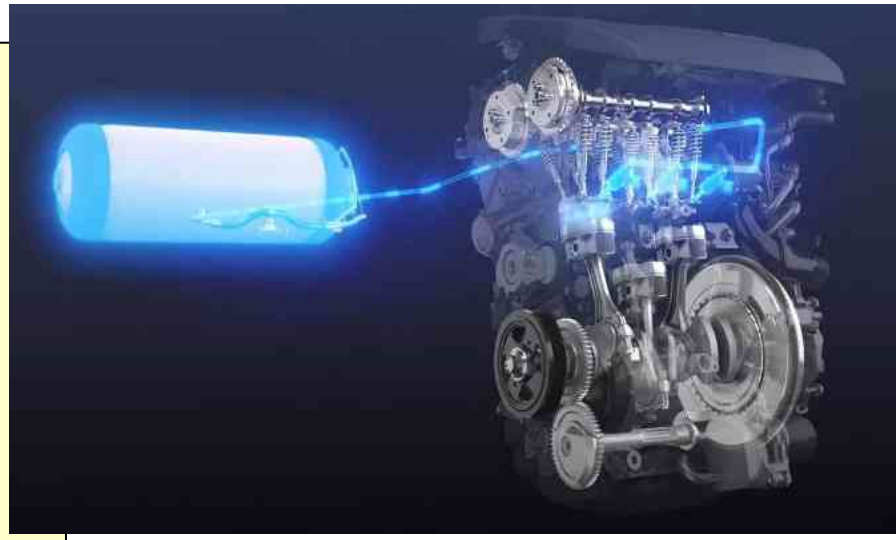
Denmark and Norway to build world's largest hydrogen ferry

Electric Vehicles & Hydrogen
The Challenges

- To Increase the Energy Density
- To Reduce Storage System Volume & Weight
- To Reduce the Costs
- To Expand massively Refuelling Stations & Network
- To Use Decarbonized Source of Electricity Production

Hydrogen for vehicles

Two main Technologies:



- **Hydrogen Internal Combustion Engine (HICE)**

Hydrogen combustion engines function similarly to traditional ICE. They use Hydrogen as fuel instead of gasoline of diesel.

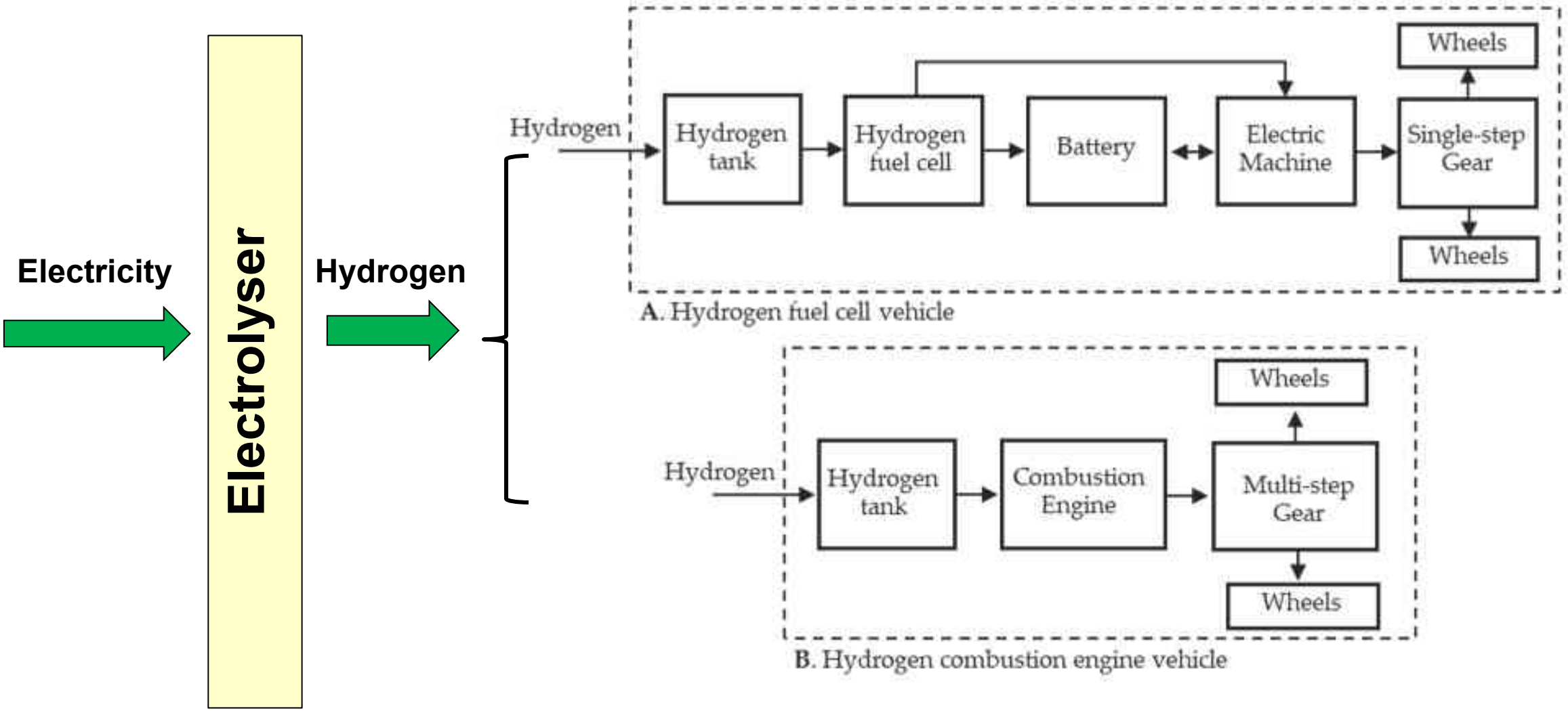


- **Fuel Cell Electric Vehicle(FCEV)**

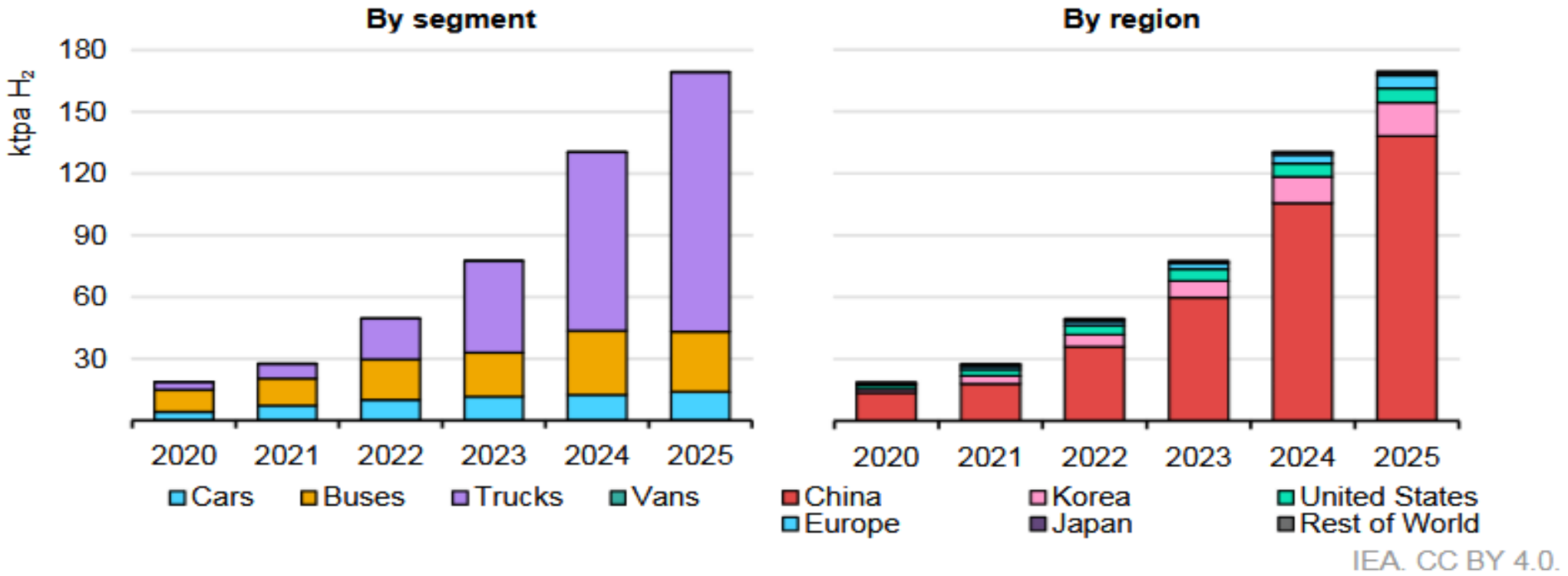
FCEVs convert Hydrogen into Electricity via an electrolysis process within a Fuel Cell which generates an electric propulsion.

TPA
Sharing Experience

Hydrogen Engine vs Fuel Cell



Hydrogen Use in Transport 2020 - 2025

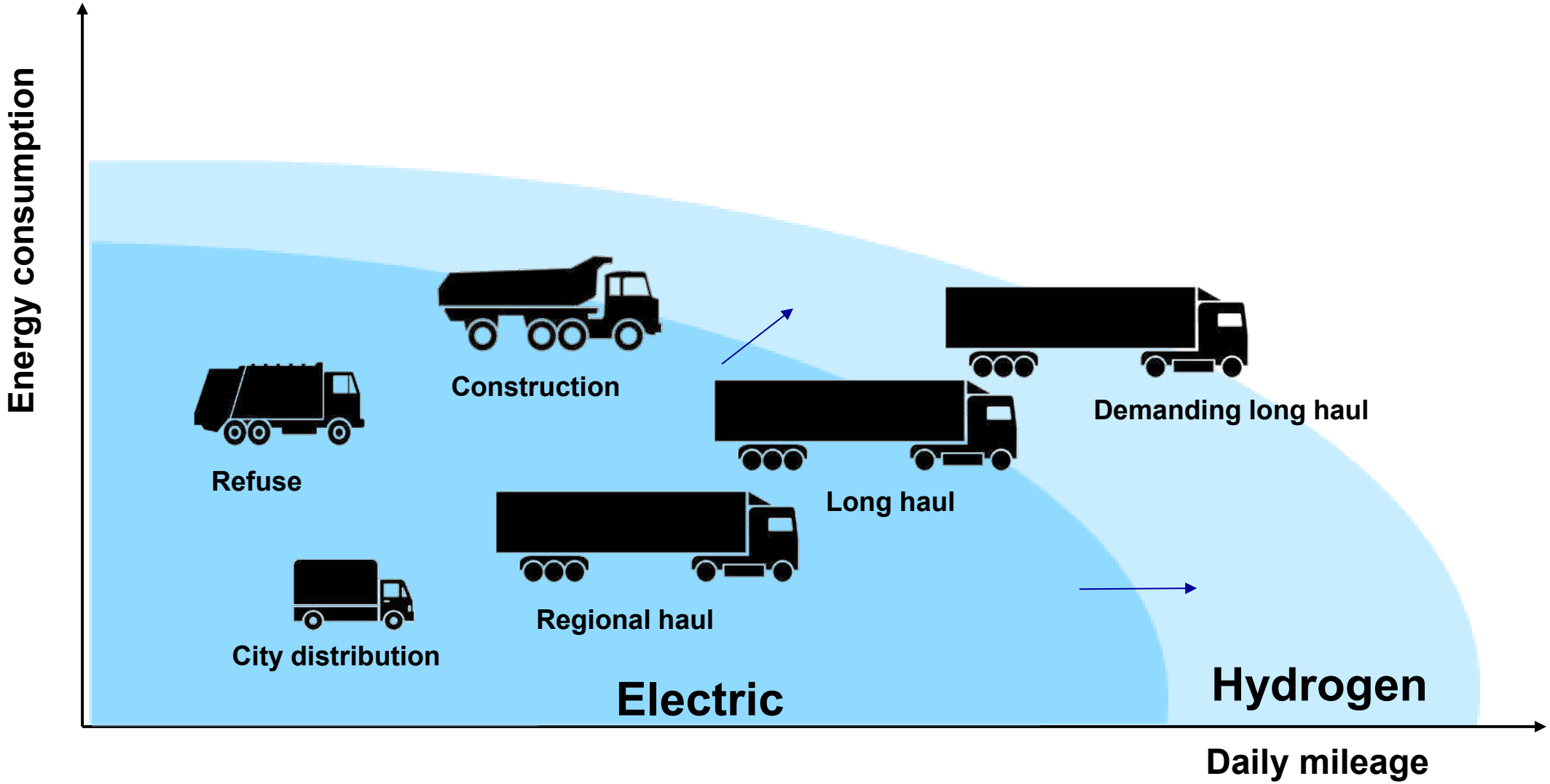


Notes: Total hydrogen consumption in road transport is calculated by multiplying vehicle stock, annual mileage and hydrogen consumption per kilometre for each vehicle segment and region. Annual mileage assumptions come from the IEA Global Energy and Climate modelling framework and fuel economy values are derived from a range of studies and research papers.

The large Chinese fleet and higher per-vehicle energy consumption of fuel cell trucks meant they accounted for 70% of the road sector's hydrogen demand globally in 2025.

Source: Global Hydrogen Review IEA July 2026

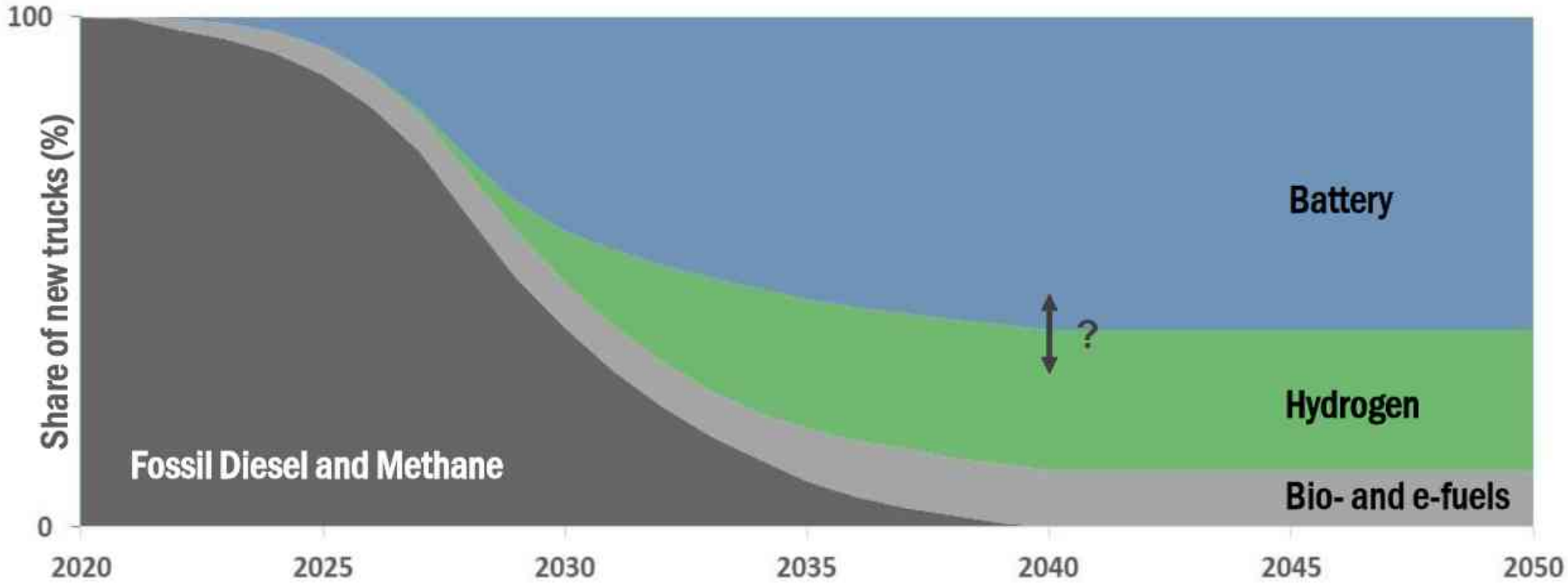
Electric vs Hydrogen for Trucks



Source: TotalEnergies – Ph. China

Road Map by Renault Trucks

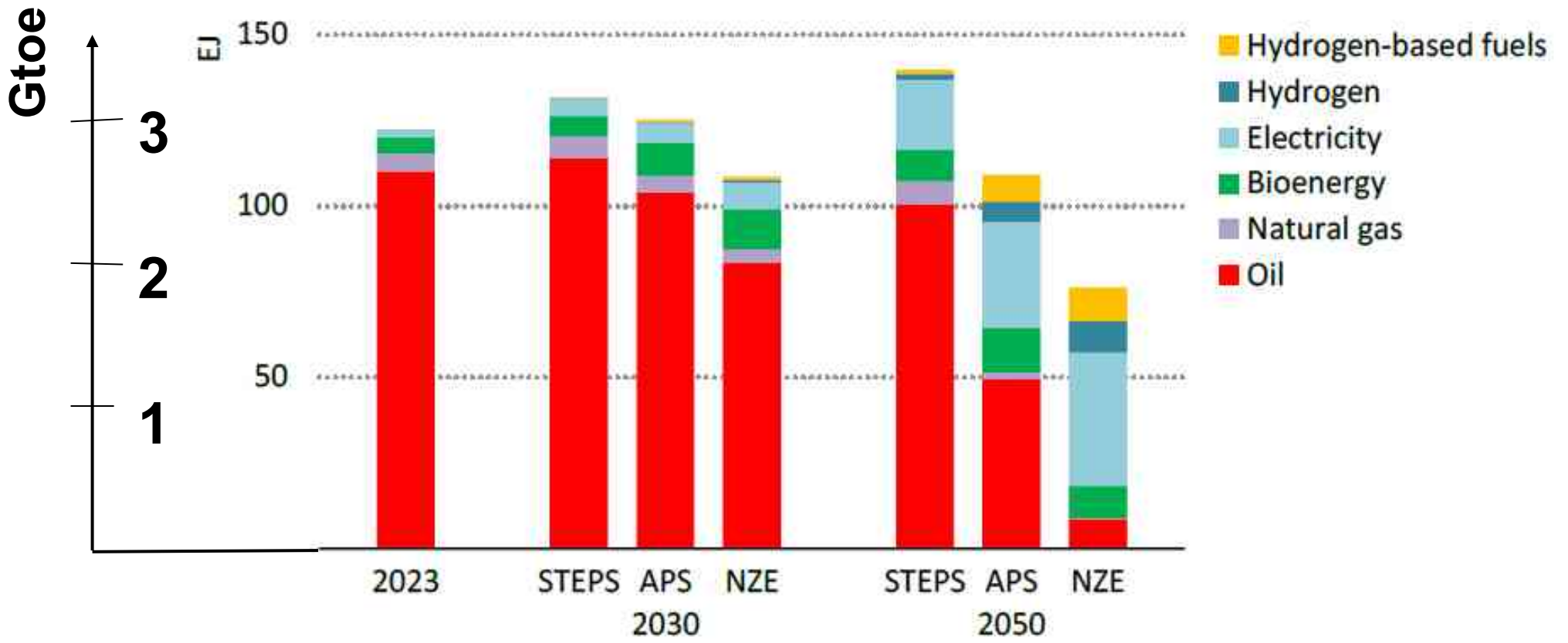
- In all truck segments, we anticipate that **battery and fuel cell electric drivelines** will become the dominant powertrain before 2040. They will represent 50% of our sales in 2030.
- For long-range electric trucks, **hydrogen** fuel cell is an alternative to batteries
- Less internal combustion engines will be produced, and only for **biofuels or e-fuels**



RENAULT TRUCKS

Source: Renault Trucks

Global Energy Demand for Transport by IEA WEO 2024



IEA. CC BY 4.0.

Electricity reduces the dominance of oil across scenarios, while hydrogen and hydrogen-based fuels contribute to aviation and shipping

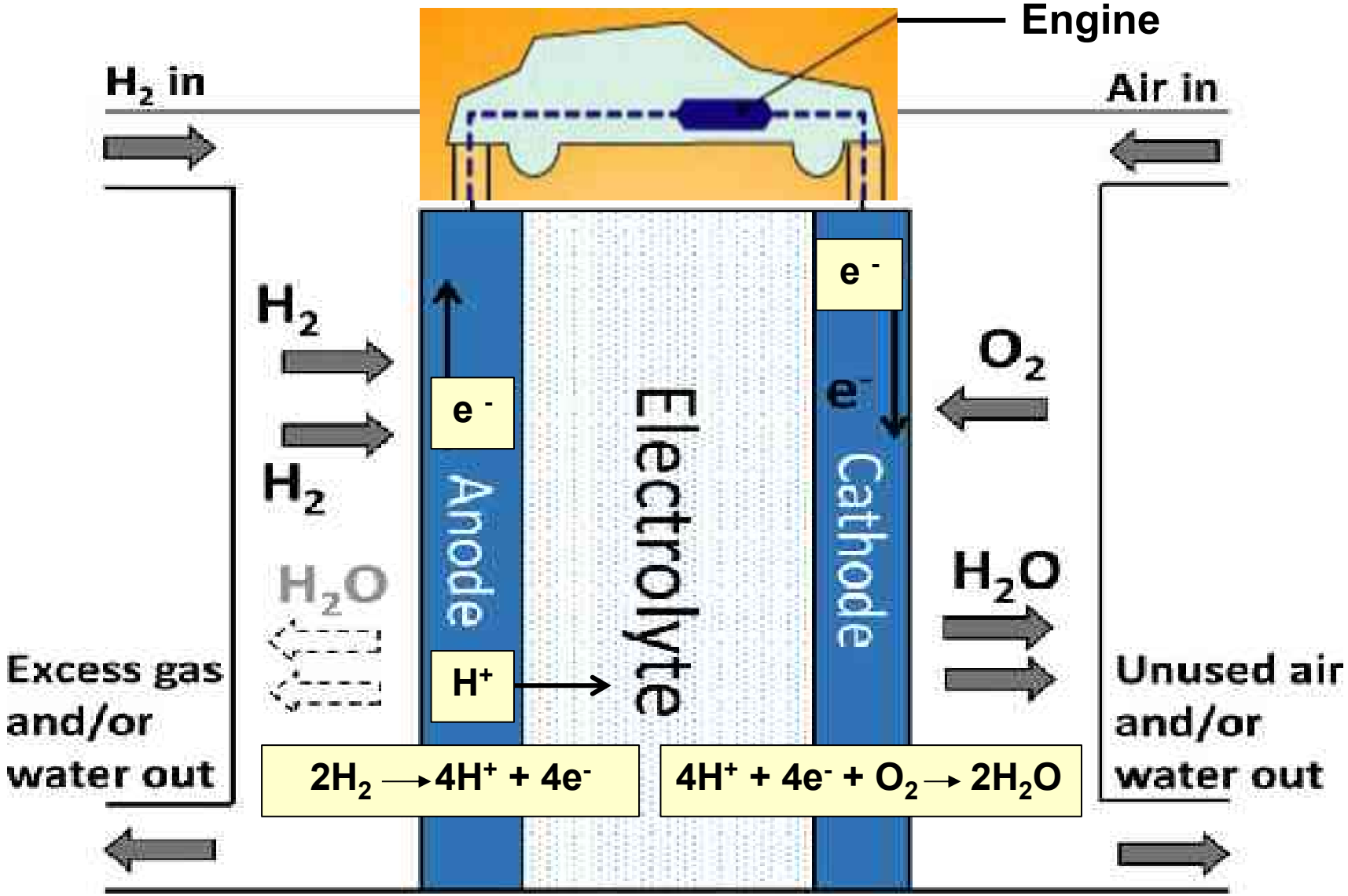
Source: IEA WEO 2024
1 EJ = 23,88 Mtoe



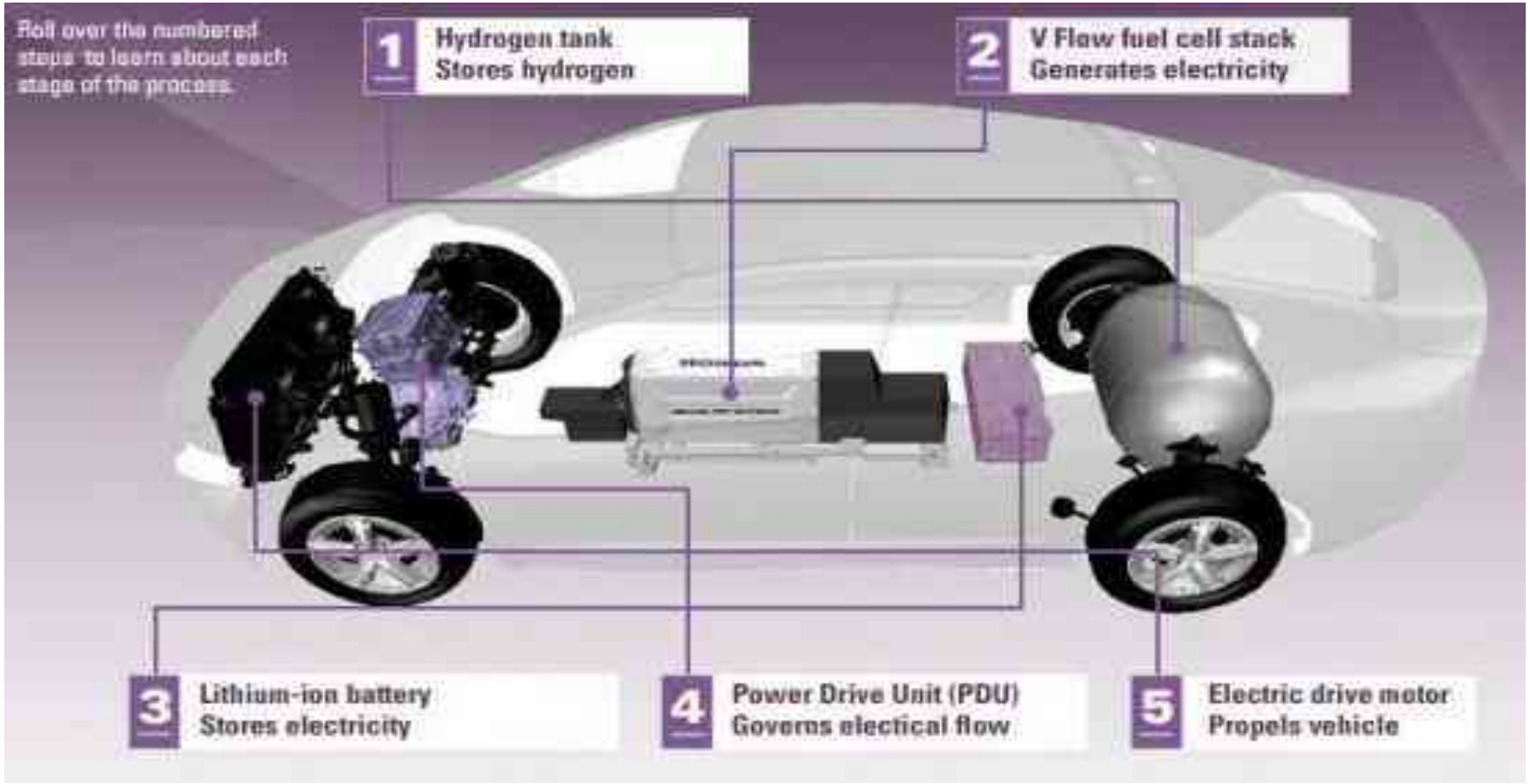
Hydrogen – A zoom on Fuel Cell

(See also Chapter 8 above)

Fuel Cell basic principle



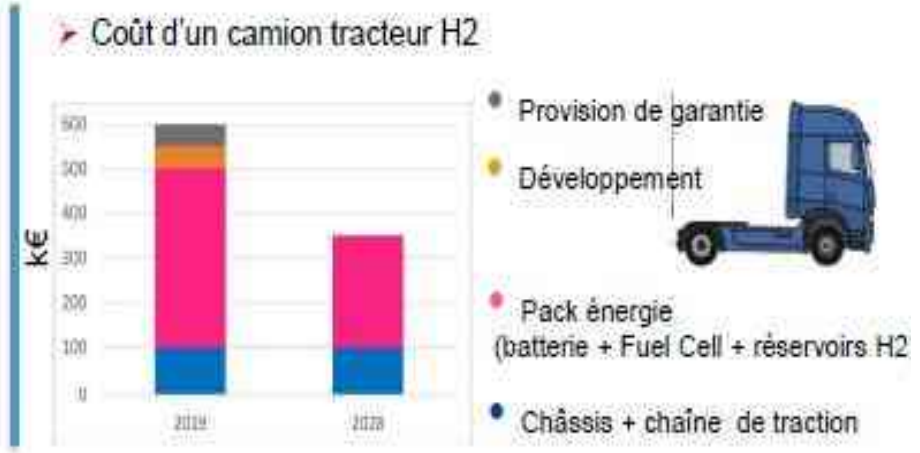
Principle of a Hydrogen Fuel Cell Vehicle



Operational Cycle for a Fuel Cell Electric Vehicule



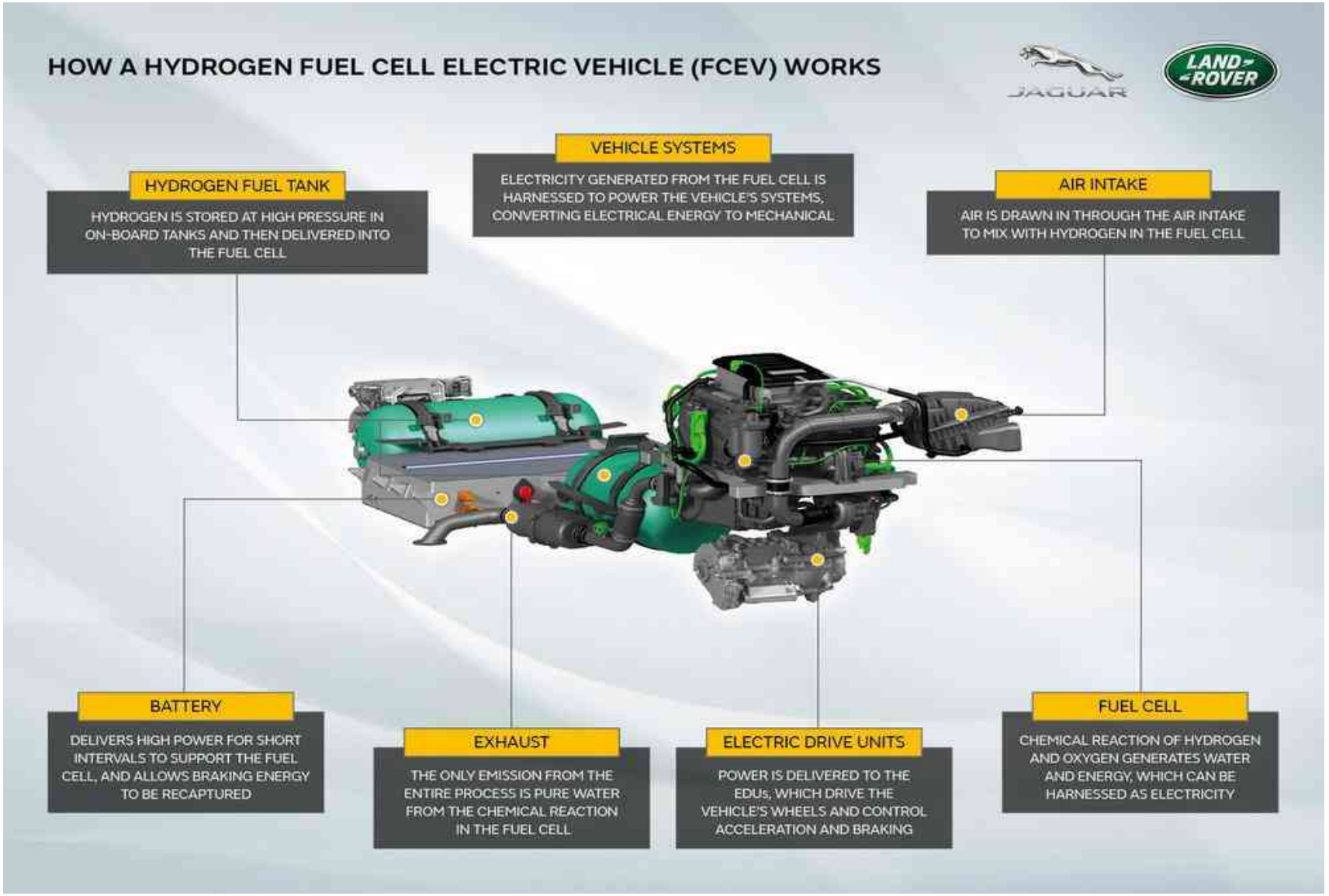




Source : PVI

- Un tracteur 44t consommerait 8 kg H2 /100km. Il faudrait 10 - 30 minutes pour avitailler 40 kg d'H2.
- L'intégration de tous les composants H2 reste un challenge important pour les constructeurs.

Operational Cycle for a Fuel Cell Electric Vehicule



Technological developments





Installed in a T-shape, the Mirai's tanks have 5.6 kg of H2, equivalent to 142.2 litres. They power a fuel cell totaling 182 HP of power.

With H_2 in the form of hydride we could board 2.5 times more H_2!
Ex: 100 discs = 4kg of H_2 = 470 km

Seven years after the first version, Toyota relaunches the Miraï, its hydrogen vehicle.
Announced range: 650 km. Target price 65 000 €. Fuel consumption: 0.84-0.89 kg/100km.

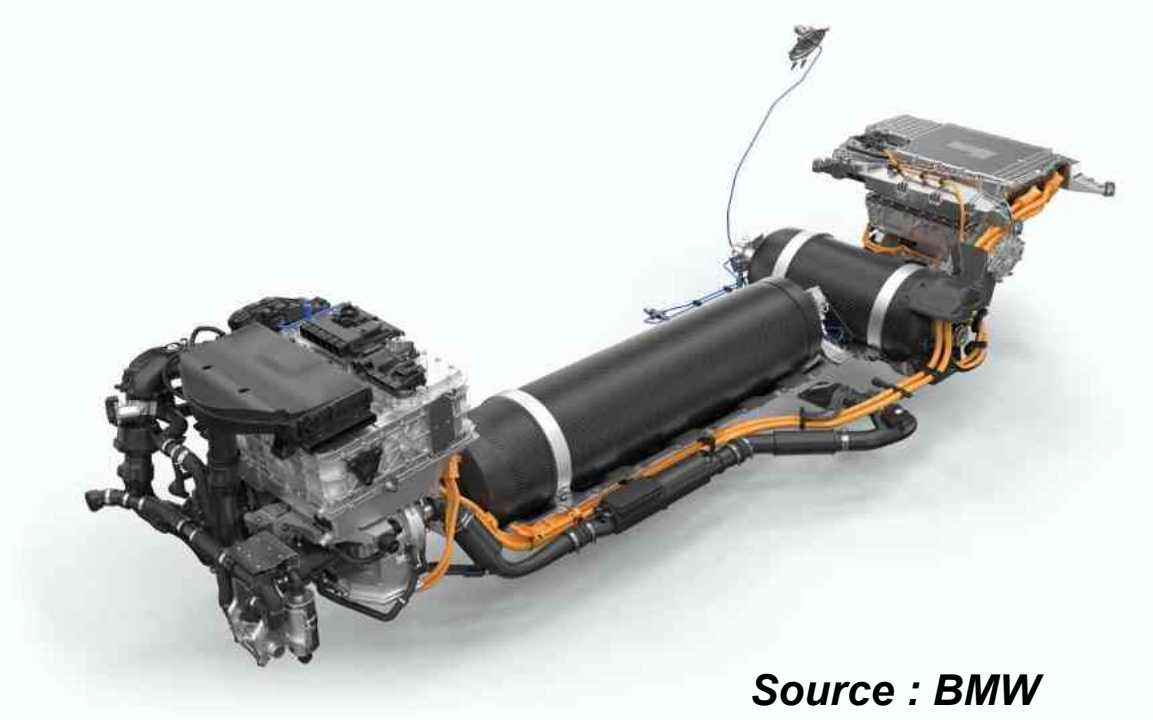
Technological developments



The Korean government's incentives for the purchase of a hydrogen car have halved the sales price of the Hyundai Nexo, at 30 000-35 000 €, but the price in Europe is 85.000 €.

Technological developments



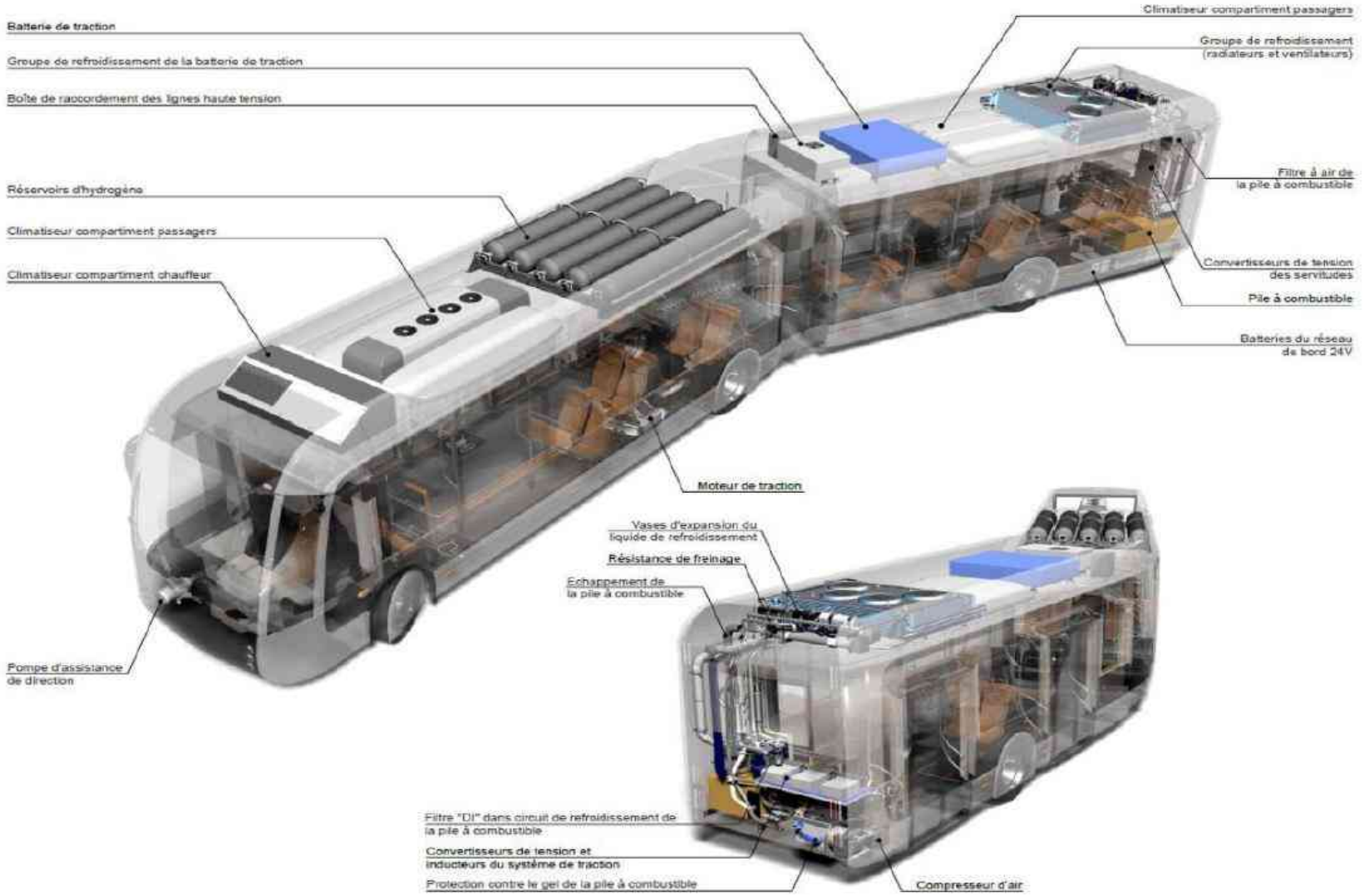


Source : BMW

Equipped with the fifth generation of the manufacturer's eDrive technology, the BMW iX5 Hydrogen receives a 374-horsepower engine. The electricity that powers the engine is produced by a 125 kW fuel cell designed in collaboration with Toyota. This is complemented by a battery that brings extra power during the phases of high loads.

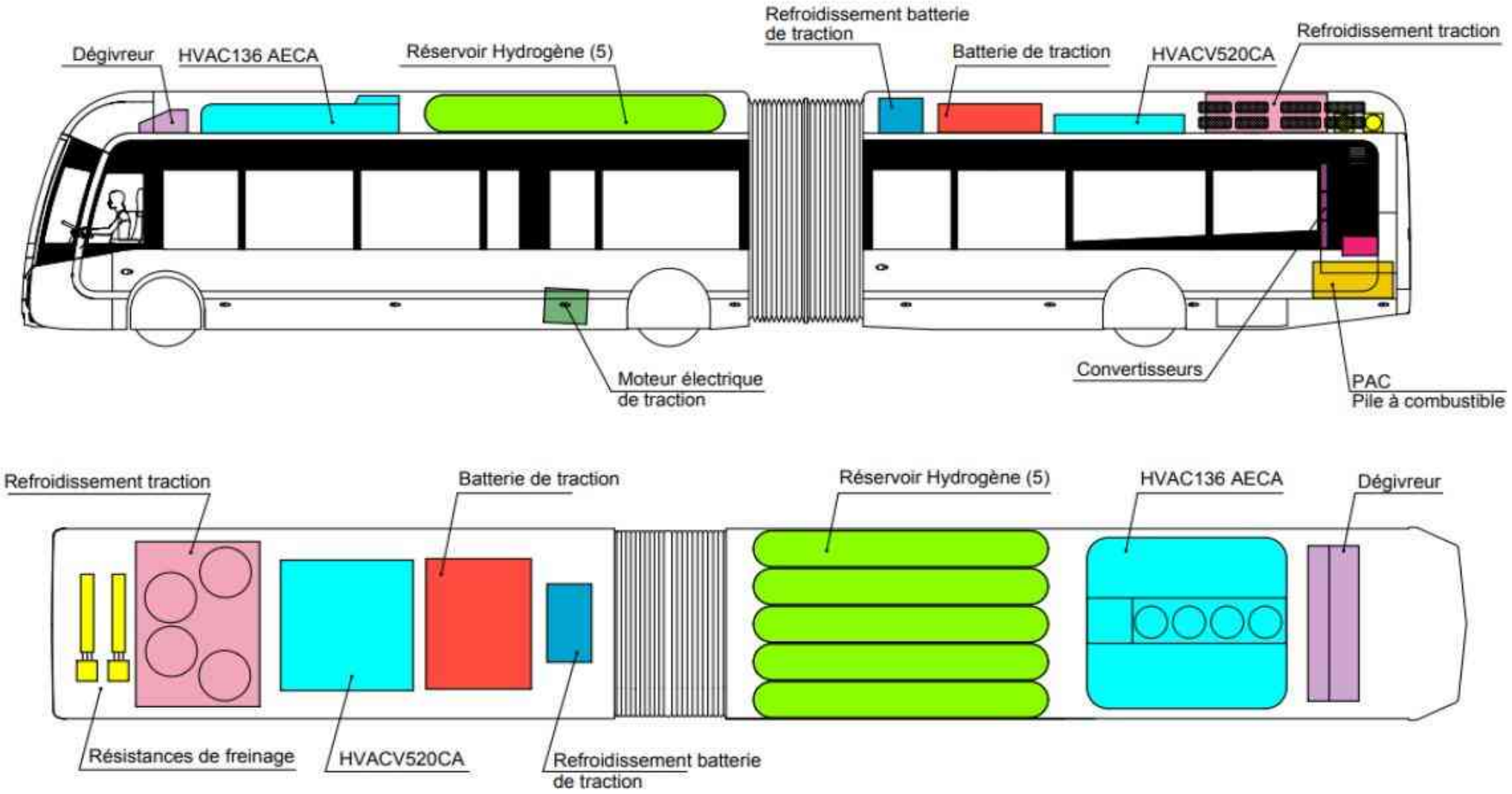
The hydrogen that powers the battery comes from two 700-bar tanks. The tanks carry up to 6 kilos of hydrogen. What to expect a range of about 500 km with a full tank. Price not communicated.

Hydrogen Bus – Pau/France
VanHool ExquiCity Fuel Cell 18 m



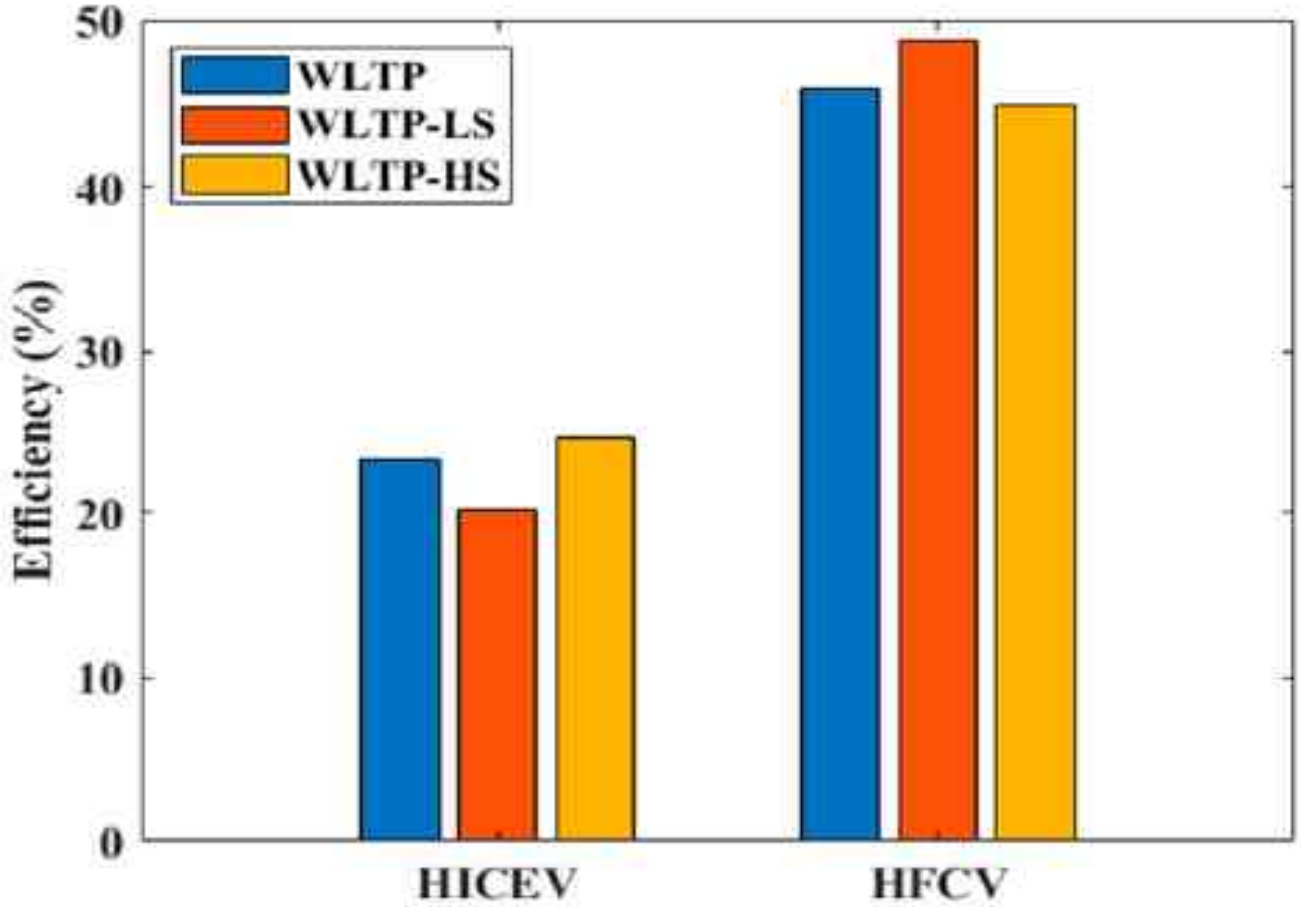
Source: SPL STAP Réseau Idelis

Hydrogen Bus – Pau/France
VanHool ExquiCity Fuel Cell 18 m



Source: SPL STAP Réseau Idelis

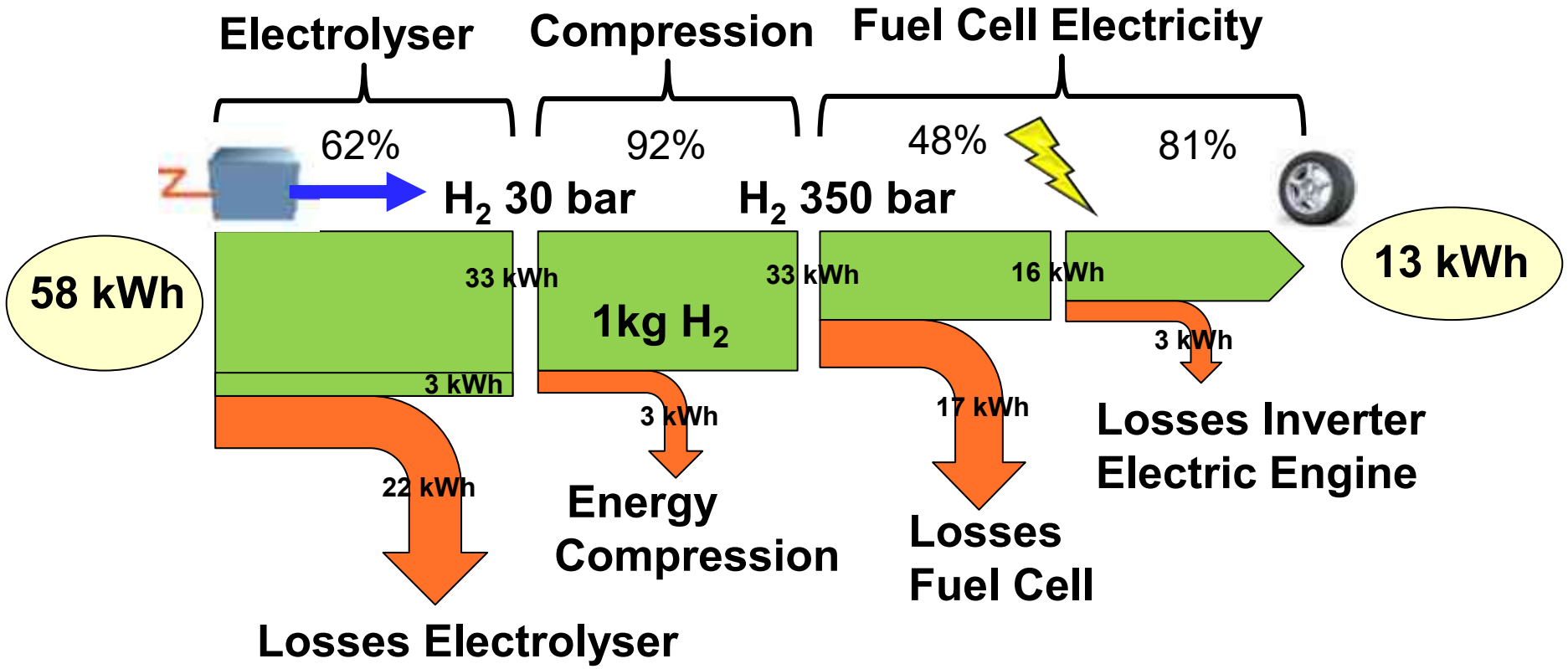
Efficiency Ratio Hydrogen Engine vs Fuel Cell Vehicle Cycle H_2 to Wheel (after Electrolyser and compression)



Source: energies MDPI 2024

Nota: HICEV: Hydrogen Internal Combustion Engine Vehicle
HFCV: Hydrogen Fuel Cell Vehicle
WLTP: Worldwide harmonized Light vehicle Test Procedure

Energy Efficiency of a Fuel Cell (using 1kg H_2)
Complete Cycle Power to H_2 to Power (Power to Wheel)

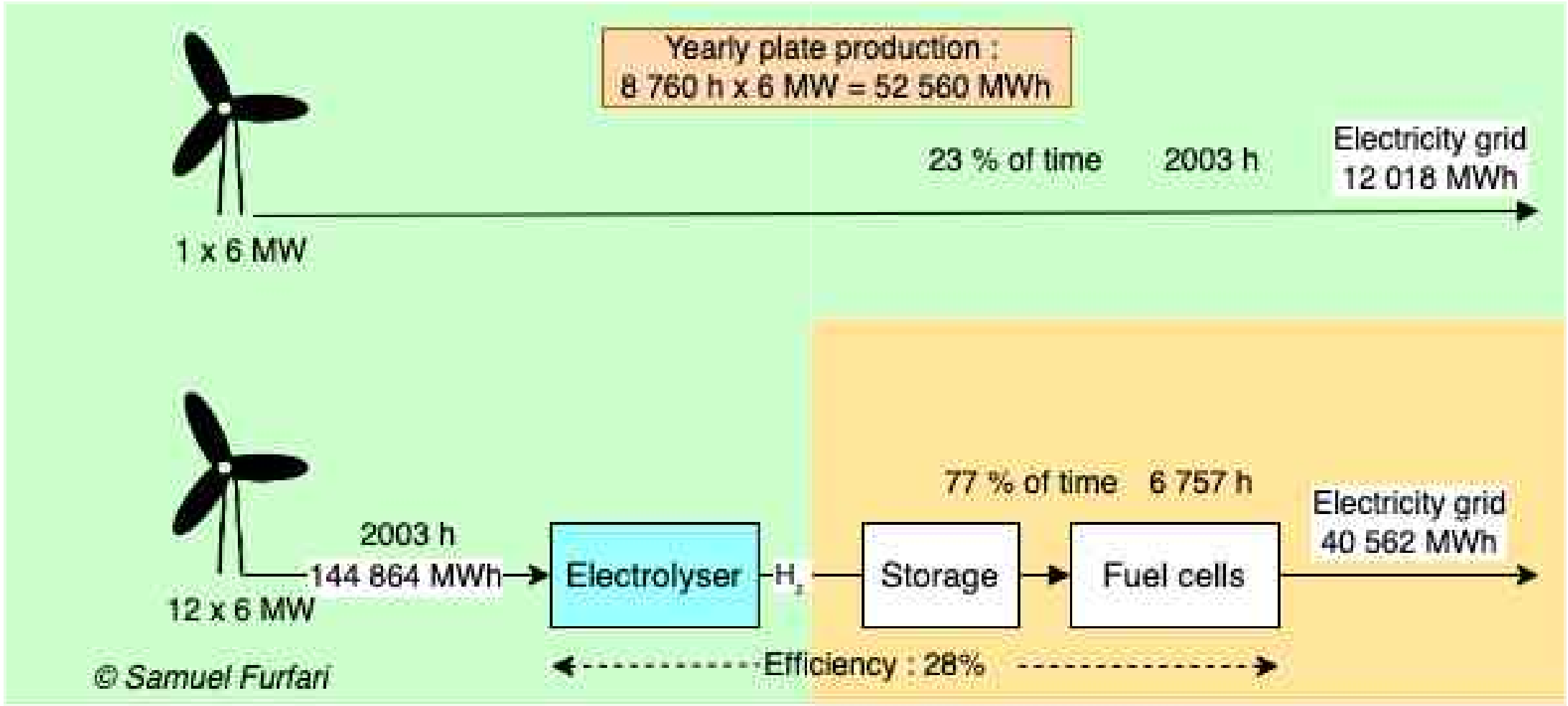


Energy Efficiency of the global chain # 23%

(Average and rounded figures according to present technology)

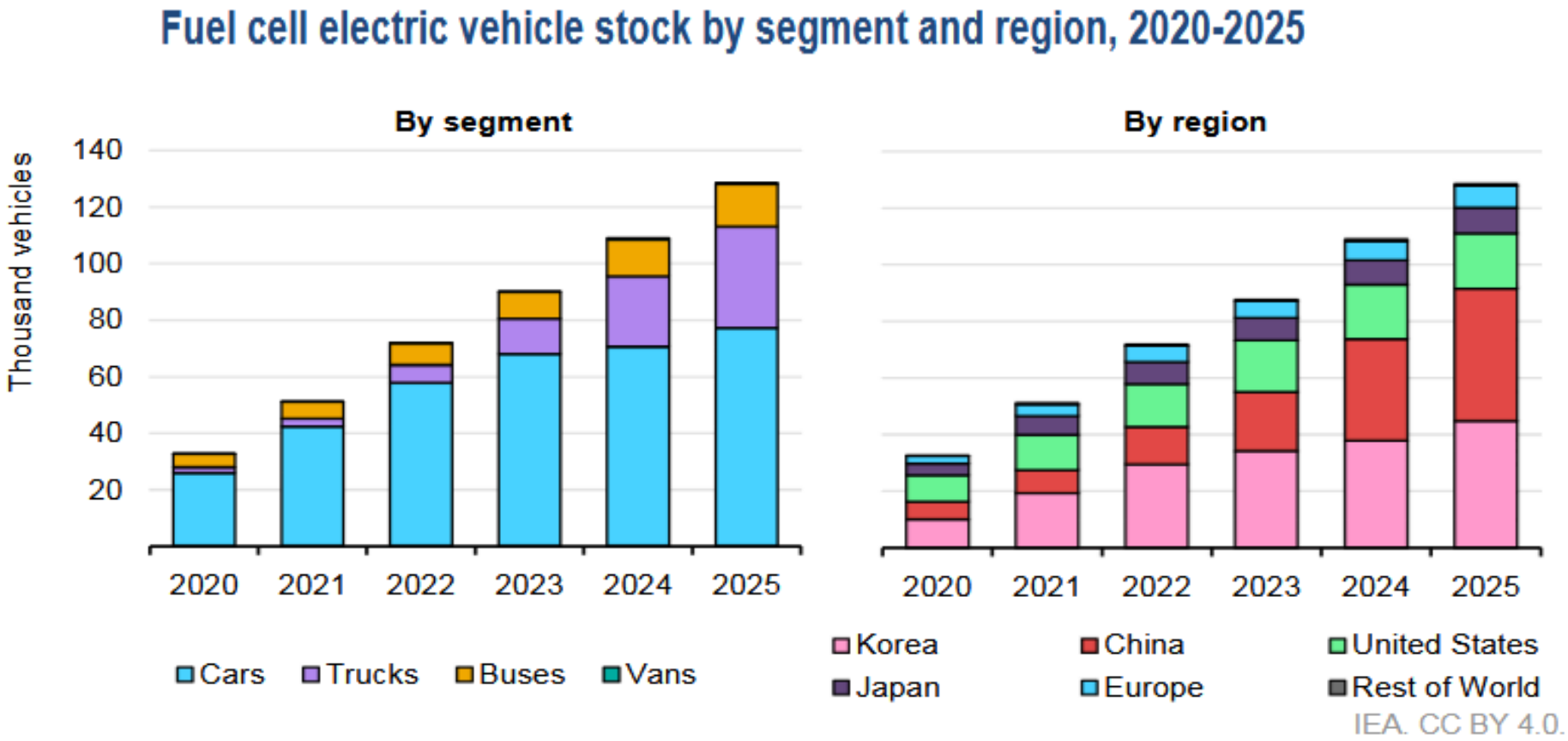
Nota: Basic data from ADEME

Energy Efficiency of a Fuel Cell
Power to H2 to Power



Source: Samuel Furfari

Fuel cell EV stock in Transport
130 000 FCEV worldwide in 2025



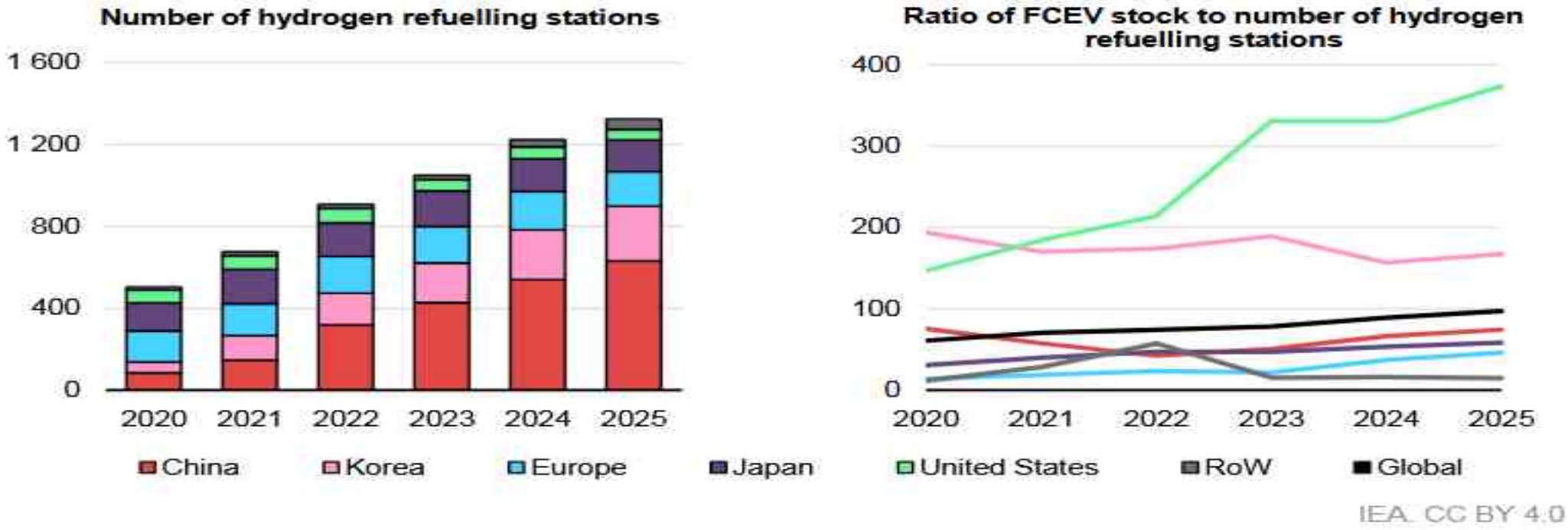
Sources: IEA analysis based on data from the Advanced Fuel Cells Technology Collaboration Programme, CATARC, AIRIA, EV Volumes, Toyota, California Fuel Cell Partnership.

Most early fuel cell vehicles were cars, but uptake is now shifting to trucks and buses.

Source: Global Hydrogen Review IEA July 2026

Hydrogen refuelling stations in Transport
1 300 refuelling stations worldwide in 2025

Number of hydrogen refuelling stations by region and ratio of fuel cell electric vehicle stock to number of stations, 2020-2025



Note: FCEV = fuel cell electric vehicle; RoW = Rest of World.

Sources: IEA analysis based on data from the Advanced Fuel Cells Technology Collaboration Programme; EAFO; US Alternative Fuels Data Center; Korea, Ministry of Climate, Energy and Environment

China leads the global roll-out of hydrogen refuelling stations, whereas station availability has declined in the United States, due to reliability and hydrogen supply issues.

Source: Global Hydrogen Review IEA July 2026


Ammonia & Hydrogen
H2
HYDROGEN

Ammonia & Hydrogen

- Ammonia (NH_3) is a carbon-free fuel and suitable for use in various sectors, in particular fertilizers.
- Ammonia serves as a Hydrogen carrier, is more energy-efficient to transport and store than Hydrogen and can contribute to accelerate the transition to a Hydrogen Economy.
- Existing Ammonia infrastructure is a important advantage for a Hydrogen Economy.
- To produce green Ammonia, Hydrogen is produced by electrolysis from 100% renewable sources and combined with Nitrogen extracted from ambient air using an air separator (Haber – Bosch process) This is a carbon-free process that produces a climate-neutral energy carrier.

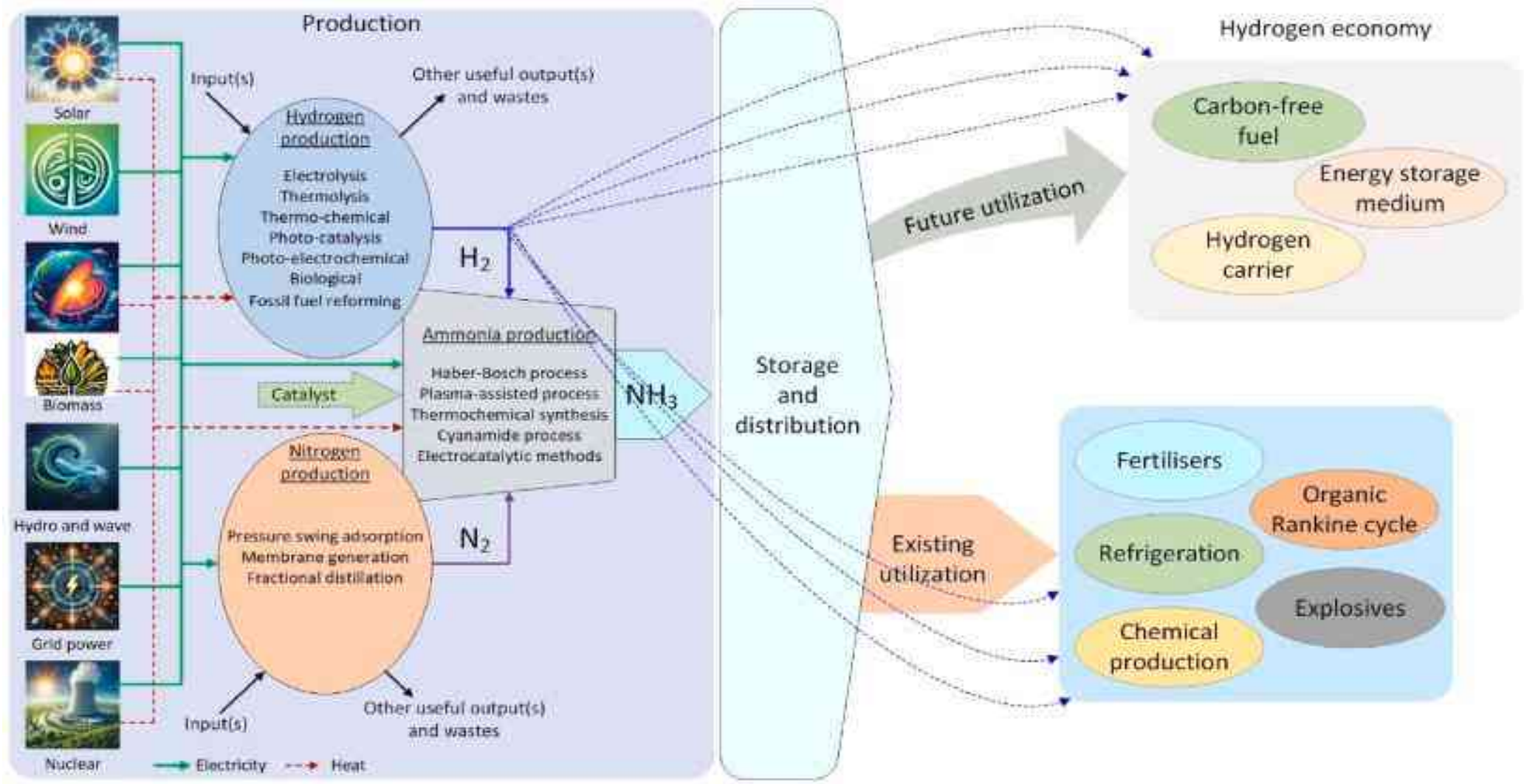
  $3/2\ H_2 + 1/2\ N_2 \Longrightarrow NH_3$ (Exothermic reaction)

- The green Ammonia produced can now be transported to its destination by ship. Ships and port terminals for this are already in place worldwide.
- After arrival at destination, Ammonia is split back into Hydrogen and Nitrogen using the Ammonia cracking process, using a catalytic cracking furnace at elevated temperatures.

  $NH_3 \Longrightarrow 3/2\ H_2 + 1/2\ N_2$ (Endothermic reaction)

- The Hydrogen can then be used in numerous industries as a climate-neutral energy carrier.

Value chain Ammonia & Hydrogen



Source: Science Direct

Ammonia & Hydrogen – Use in green Shipping sector



Source: Thysssenkrupp – Ammonia plant



Visualization of Air Liquide's industrial scale pilot plant for Ammonia Cracking



Source: Business Norway –
Solid oxyde Fuel Cell powered by Ammonia – Project in Norway



Source: Business Norway –
MH Hydra - Liquid H2 powered ferry in Norway

Ammonia & Hydrogen – TotalEnergies project in Morocco

TotalEnergies H_2 a company owned by TotalEnergies and eren

A·P·MØLLER CAPITAL

CIP Copenhagen Infrastructure Partners

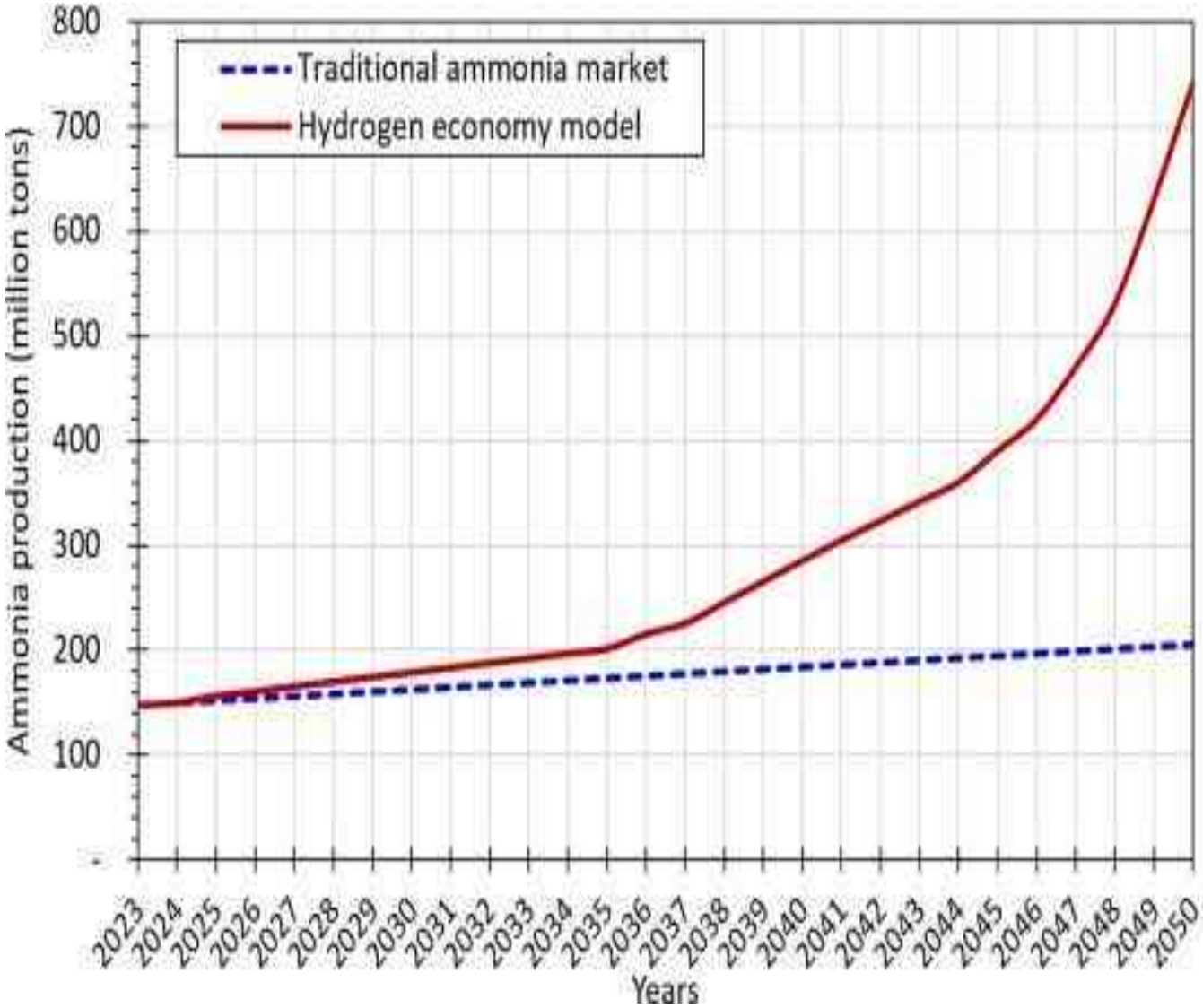
Paris/Rabat, October 28th, 2024 – Under the presidency of His Majesty King Mohammed VI of Morocco and His Excellency Emmanuel Macron, President of the French Republic, the government of the Kingdom of Morocco and TE H2, along with its partners, signed a Preliminary Contract for Land Reservation for the 'Chbika' project.

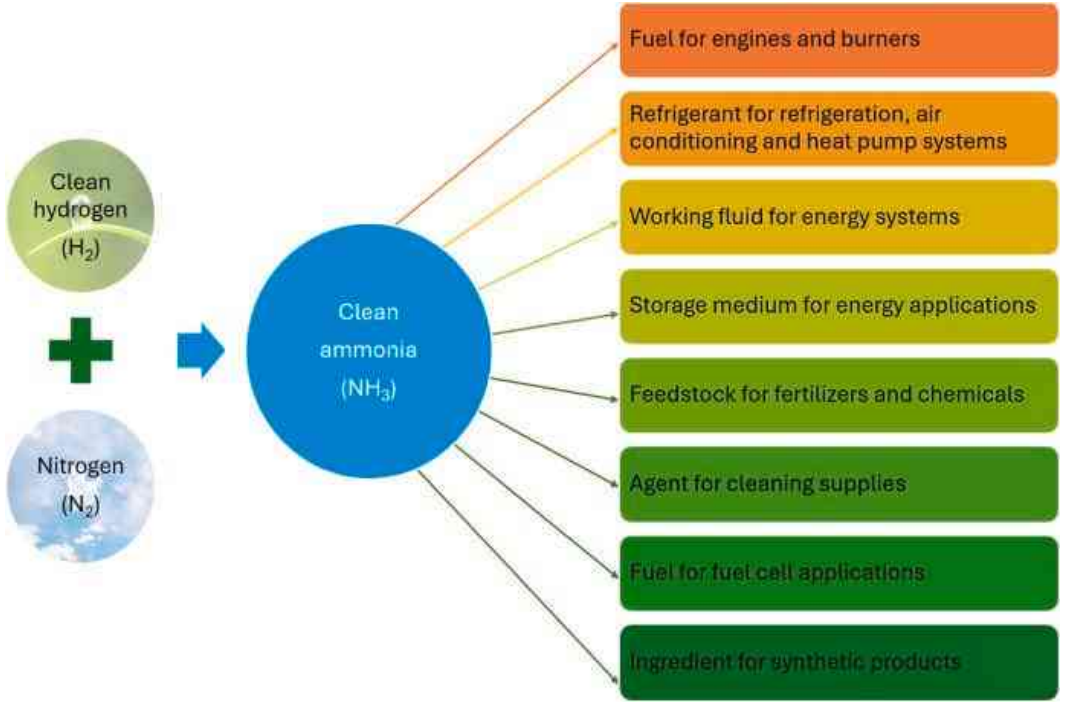
This agreement will allow TE H2, a joint venture between TotalEnergies and the EREN Group, together with the two Danish companies, Copenhagen Infrastructure Partners (CIP), through its Energy Transition Fund, and A.P. Møller Capital, through its Emerging Markets Infrastructure Fund, to launch the pre-FEED studies.

Located near the Atlantic coast in the Guelmim-Oued Noun region, the 'Chbika' project aims to build 1 GW of onshore solar and wind capacities that will power the production of green hydrogen through the electrolysis of desalinated seawater and its transformation into 200,000 tons per year of green ammonia for the European market. This project will constitute the first phase of a development program aimed at creating a world-scale green hydrogen production hub.

TE H2 and CIP will be responsible for the development of renewable energy production (solar, wind, green hydrogen, and its derivatives), while A.P. Møller Capital will develop the port and associated infrastructure. This contract, a first in Morocco, will highlight the country's exceptional renewable potential and contribute to the economic development of the Kingdom.

Value chain Ammonia & Hydrogen – A scenario by Science Direct





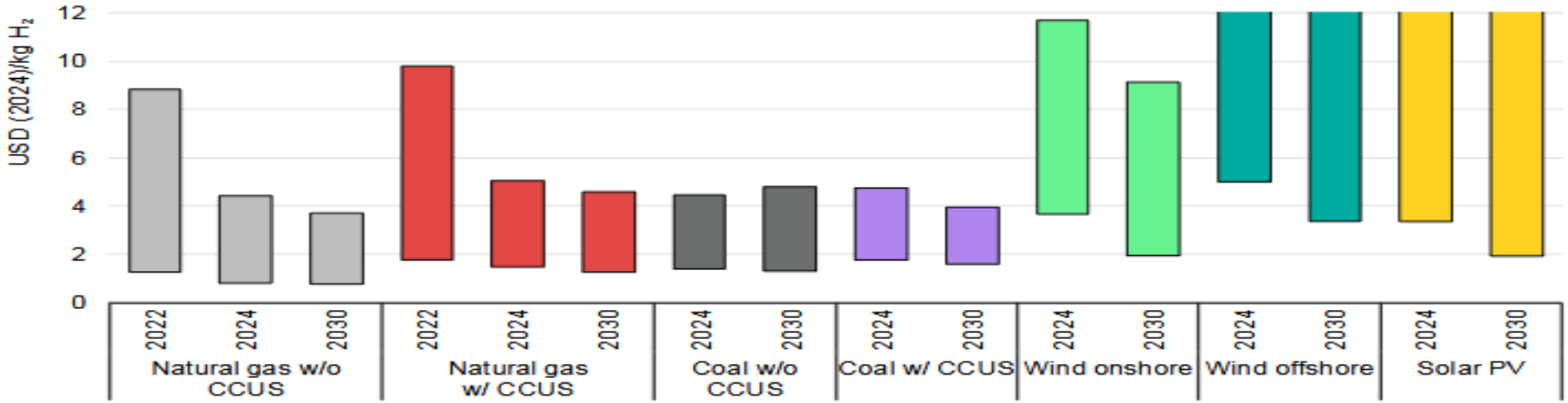
Source: Science Direct


Hydrogen – The Costs
H2
HYDROGEN

H_2 as a Fuel for Mobility - One example Economic Results for a Light vehicle with 500 kms autonomy

- Compressed gaseous H_2 at 700 bars
- H_2 consumption : 1,2 kg H_2 per 100 kms
- Consumption for 500 kms: 6 kg H_2
- Reservoir: 140 l, 120 kg
- Inherent cost of electricity to produce 1 kg H_2 (55 kWh/kg H_2 at consumer price): 10 €/kg
- H_2 price: 15 €/kg (France) (From 10 to 30+ depending upon the countries)
- Total cost H_2 for a full tank: 90 €

Hydrogen Production Costs vs Sources of Production



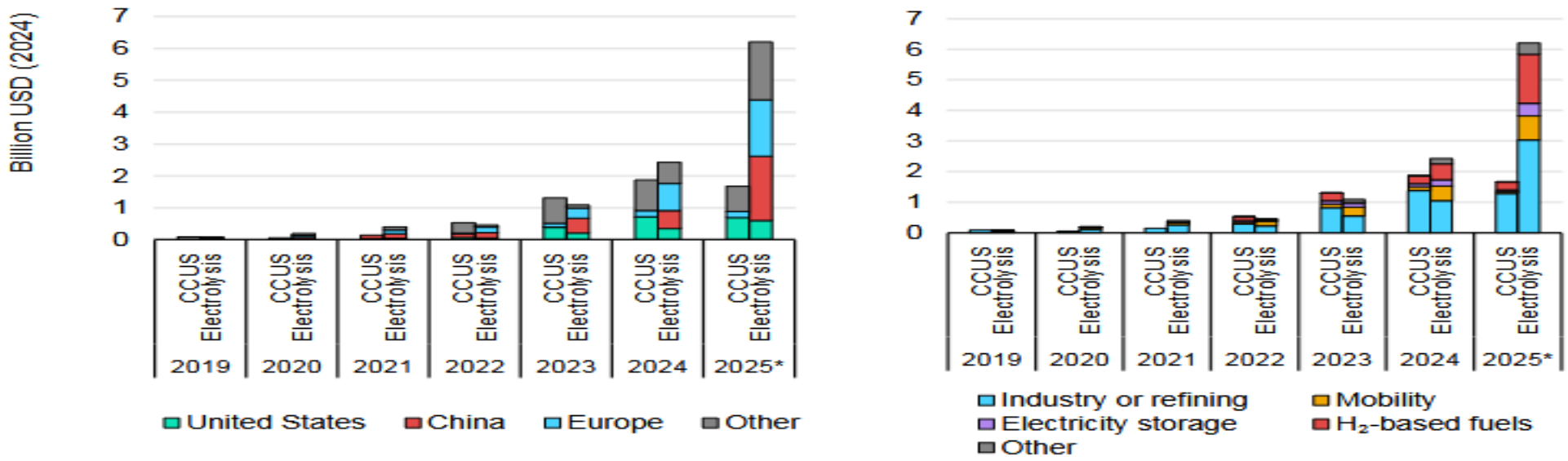
Notes: CCUS = carbon capture, utilisation and storage; w/ = with; w/o = without. Cost ranges reflect regional differences in fossil fuel prices, renewable costs, CO_2 prices, technology CAPEX and OPEX as well as cost of capital. Natural gas price is USD 5.7-50/MBtu for 2022, USD 1.7-25/MBtu for 2024 and USD 1.6-21/MBtu in the Stated Policies Scenario (STEPS) in 2030. Coal price is USD 21-260/t for 2024 and USD 22-200/t for the STEPS in 2030. CO_2 price is USD 0-90/t CO_2 for 2022, USD 0-70/t CO_2 for 2024 and USD 0-106/t CO_2 for the STEPS in 2030. The levelised production cost of solar PV electricity is USD 20-110/MWh for 2024 and USD 13-85/MWh for the STEPS in 2030, with a capacity factor of 12-35%. The levelised production cost of onshore wind electricity is USD 25-100/MWh for 2024, USD 23-90/MWh for the STEPS in 2030, with a capacity factor of 30-53%. The offshore wind electricity levelised production cost is USD 52-270/MWh for 2024, USD 40-165/MWh for the STEPS in 2030, with a capacity factor of 30-67%. For China, electrolyser CAPEX is USD 900/kW in 2024 and USD 675/kW for the STEPS in 2030, whereas for the rest of the world, it is USD 2 300/kW in 2024 and USD 1 600/kW for the STEPS in 2030. Electrolyser CAPEX includes the electrolyser system, balance of plant, engineering, procurement and construction (EPC) and contingencies; electrolyser capacity factor is assumed to be the same as the renewable power plant. The cost of capital is 6-20%. Figure capped at USD 12/kg H_2, although some production routes reach higher values. Water cost is not included. More details on the cost of producing low-emissions hydrogen using different technologies and in different regions can be found in the new Hydrogen Tracker available on the IEA website.

Sources: IEA analysis based on data collected through a survey to original equipment manufacturers, EPC companies and project developers, data from McKinsey & Company and the Hydrogen Council; BloombergNEF, Argus Media Group, All rights reserved, NETL (2022); IEA GHG (2017).

The recent drop in fossil fuel prices has increased the cost gap between low-emissions hydrogen production and unabated fossil-based routes.

Source: Global Hydrogen Review IEA October 2025

Investments in Low Emissions Installations by Countries and Sectors



Notes: CCUS = carbon capture, utilisation and storage; H_2 = hydrogen. "Other" intended uses include undisclosed end uses. Projects intended for export are classified under the relevant demand category, based on their intended use in the importing country (where known). 2025 values are estimated annualised spending on projects that had reached final investment decision (FID) by mid-2025, and are based on known project costs or capital cost assumptions and announced capacities. Only capital expenditures, including installation, on the hydrogen production facility are included and not any associated equipment for generating or supplying electricity or other fuel inputs, nor for the transport and storage of CO_2, nor for the conversion or end-use of the hydrogen output. The 2025* estimates assume that all projects with an announced FID have entered construction and will proceed according to their scheduled operational date. Delays in construction will lead to lower actual spending in 2025, as was the case for the estimates in GHR-24. Values for investment in new-build hydrogen production projects equipped with CCUS are inclusive of the costs of the base plant, such as the steam methane reformer, and not only the capital costs of CO_2 capture and any dedicated CO_2 transport and storage infrastructure. This is different from the approach taken in GHR-24, which did not include base plant costs. In addition, whenever it was publicly disclosed, specific project investment data was used instead of cost estimates.

Sources: IEA analysis based on data collected through a survey to OEMs, engineering, procurement and construction (EPC) companies and project developers, data from McKinsey & Company and the Hydrogen Council; BloombergNEF, Argus Media Group, All rights reserved, NETL (2022); IEA GHG (2017).

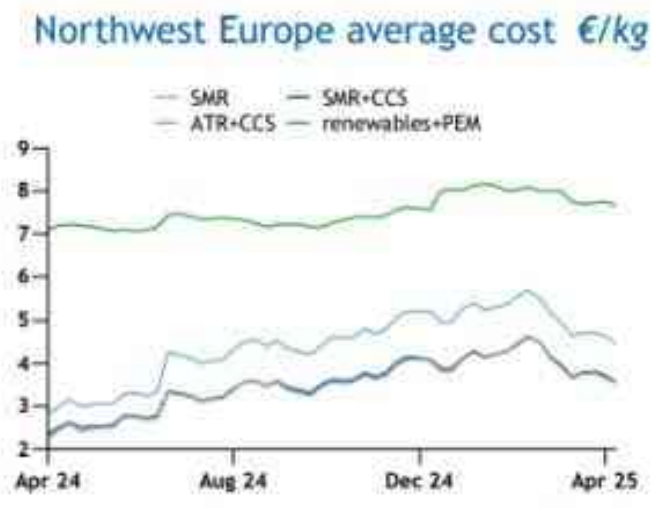
In 2025, investment in electrolysis-based production is set to reach more than triple that of CCUS-equipped production, with most of the spending for existing uses.

Source: Global Hydrogen Review IEA October 2025

Impact on Costs : Renewables + H_2 Electrolyser

		Σ = 7.1 €/kg H_2
Fixed OPEX	~ 2.5% of CAPEX / y	0.6
OPEX Bal.of Plant	~10% of process	0.4
OPEX (elec + grid + tax)	Electricity : 70 €/MWh Grids & Tax : 10 €/MWh x 55 MWh/tH2 = 4400 €/tH2 or 4.4 €/kgH2 (2)	4.4
CAPEX	PEM Electrolyzer : 2.5 M€/MW No return on invest. added	1.7

Comparison with other H_2 prod processes (1)



Source: (1) Argus Hydrogen
(2) In Europe: from 4 to 9 €/kgH2

Green Hydrogen – Difficulties for the French Sector

Main actors: HysetCo (TotalEnergies, Toyota, Air Liquide) & Hydrogen Refuelling Stations
Contracts cancelled with Taxi Hype (Taxis activities)



A zoom on Kenya H_2 strategy

In September 2023, Kenya launched its Green Hydrogen Strategy and Roamap

REPUBLIC OF KENYA

MINISTRY OF ENERGY AND PETROLEUM

POWERING FREEDOM

GREEN HYDROGEN STRATEGY AND ROADMAP FOR KENYA

Source: Ministry of Energy and Petroleum – Kenya

In September 2023, Kenya launched its Green Hydrogen Strategy and Roamap

Kenya: Good position for Renewable Energy.

Kenya Primary Energy Mix - 2023:
1 256 668 TJ = 30 Mboe

Sources Primary Energy	Contribution
Biomass & Waste	61,4 %
Solar, Wind, ….	18,0%
Hydro	0,8%
Oil	16,8%
Coal	3,0%

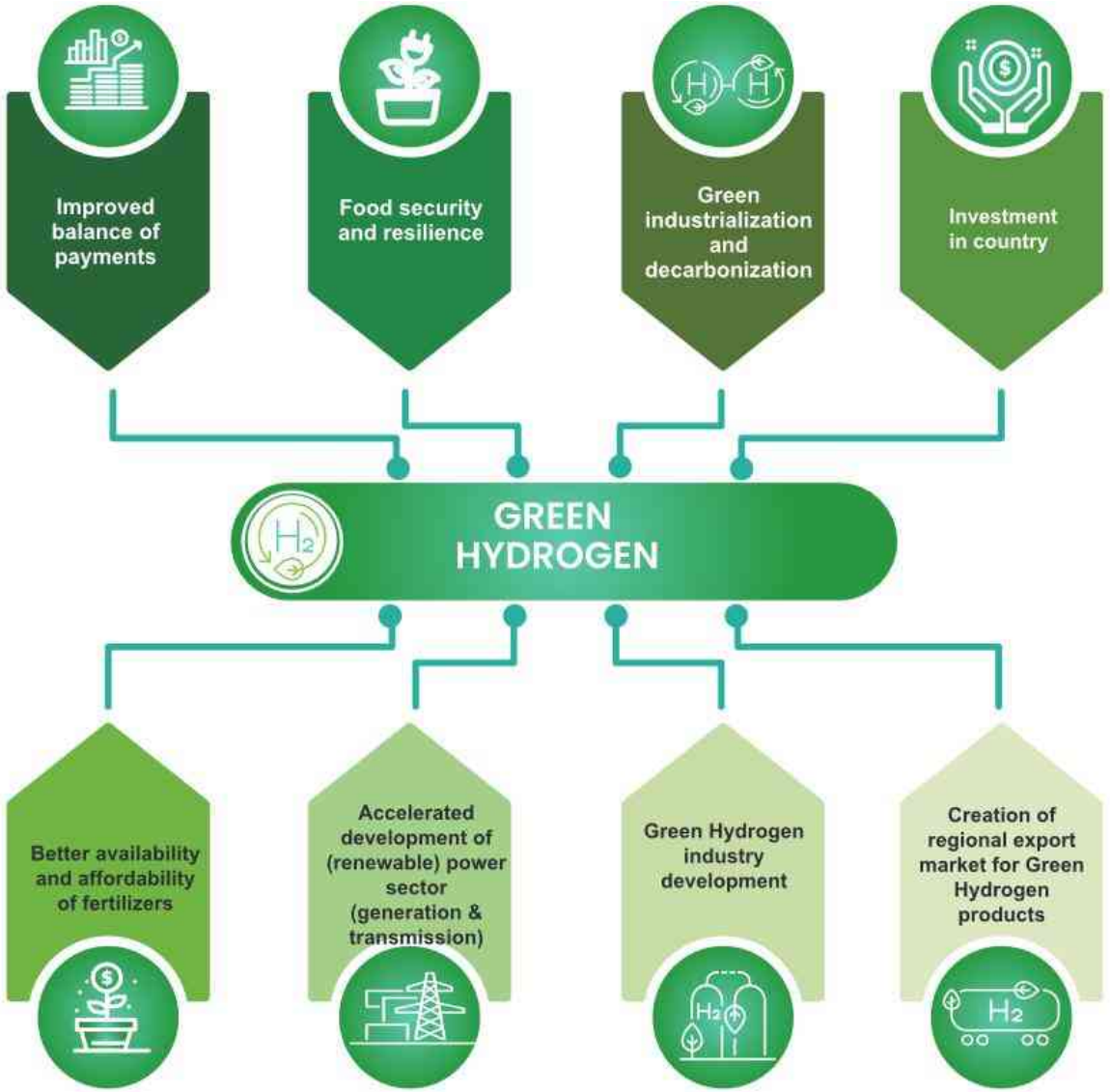
Electricity generation - 2023
12 701 GWh
Electricity represents 5% of final consumption

Source Electricity Generation	Contribution
Geothermal	47,5%
Solar PV	3,9%
Wind	15,8%
Biofuels	1,6%
Hydro	21,0%
Oil	10,3%



Source: Ministry of Energy and Petroleum - Kenya

In September 2023, Kenya launched its Green Hydrogen Strategy and Roamap



Source: Ministry of Energy and Petroleum - Kenya

Hydrogen - Conclusions



Launching of « Hydrogen Council » Davos - 17 january 2017



13 Founding Members: Air Liquide, Alstom, Anglo American, BMW Group, Daimler, Engie, Honda, Hyundai, Kawasaki, Shell, Linde Group, TotalEnergies, Toyota

The Hydrogen Council

The Hydrogen Council is a global CEO-led initiative with a united vision and long-term ambition for hydrogen to foster the clean energy transition



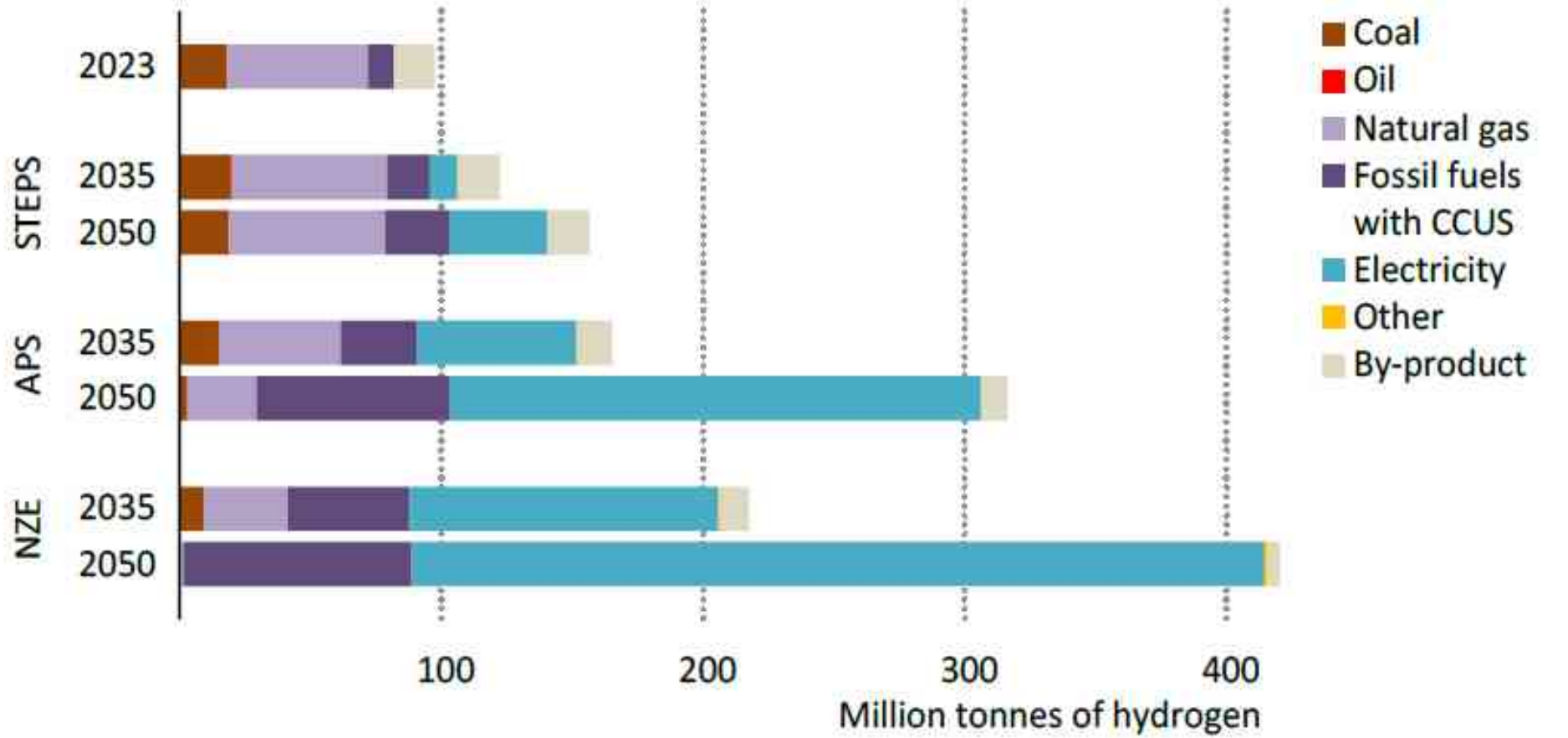
Specialized international forum for the promotion of Clean Energy and Hydrogen (29 countries members incl. EU, 21 countries participants)



Potential future utilization of Hydrogen

- Hydrogen has today a much higher economic value in its chemical utilizations (refining, petrochemicals, chemicals. But hydrocarbons productions are going to decrease in the next decades to come.
- Transportation utilization of Hydrogen, whether gaseous or in a liquid form, should remain "marginal“ - at least for ground transport.
- R&D is progressing fast in the car industry and Hydrogen vehicles are being developed at a small scale at the present time with important growth perspectives.
- The aviation (and shipping) market could develop after 2050: liquid (cryo) Hydrogen could become the future "Jet Fuel" … even if synthetic Kerosene appears today as a more likely solution for the second half of the 21st century.
- Energy sources to feed these projects must be decarbonized (Nuclear, Renewables)

For the Energy transition, growth of Hydrogen Production is needed



IEA. CC BY 4.0.

Low-emissions hydrogen production increases rapidly in the APS, more than tripling from 2035 to 2050, but it remains two-thirds of the level required in the NZE Scenario by 2050

Source: IEA WEO 2024

Which fuel for vehicles in the future?

Which fuel for vehicles in the future? (See also chapter 8)

➢ All Electric vehicles

Good energy efficiency ratio, 0 carbon emissions if non-carbonated source of electricity. Autonomy rather limited. 100% dependant on electricity supply.
The greater autonomy, the higher battery density.
Refuelling time for a Tesla vehicle: 40 minutes for a refuelling at 90%.
Tesla (Elon Musk) car prices (Models S & X): 80 000/130 000 $. Battery weight: 600 kg. Autonomy: 560/630 km. Tesla Model 3 promoted at 35 000 $, Autonomy: 560 km.
Electrical vehicle market: either a small urban car with limited autonomy, or high-end vehicle, 400 km autonomy, heavier and more costly.
Battery represents 30 to 50% of the cost of the car (2019)
World electrical vehicles sales in 2017:
China: 470 000, 412 000 1st half 2018 (+111% vs last year)
Norway: 34 000
France: 31 000 (Ademe forecast: 22% of the french market in 2035)
Germany: 29 000
UK: 15 000

➢ Hybrid vehicles (petroleum + electricity)

Two axis: Mild Hybrid (advanced functions, engine energy recovery, etc) and Plug-In Hybrid. Much more autonomy and flexibility. Technical progress on petroleum fuel consumption per 100 km should reduce CO_2 emissions.
Probably the best option efficiency/economics for the near term future.
Ademe forecast: 62% of the french market in 2035.

Which fuel for vehicles in the future?

➢ **LPG (Liquid Petroleum Gas)**

In the world, 25 million vehicles are fuelled with LPG, 14 million in Europe. More than 30 000 service stations. Less CO_2 emissions than using traditional gasoline or diesel.

➢ **Other possible fuels under study/development**

CNG (Compressed Natural Gas), Bio CNG, LNG (Liquefied Natural Gas). Less CO_2 emissions than using traditional gasoline or diesel. Market: Commercial, public vehicles, trucks.

➢ **Hydrogen**

Which fuel for vehicles in the future?

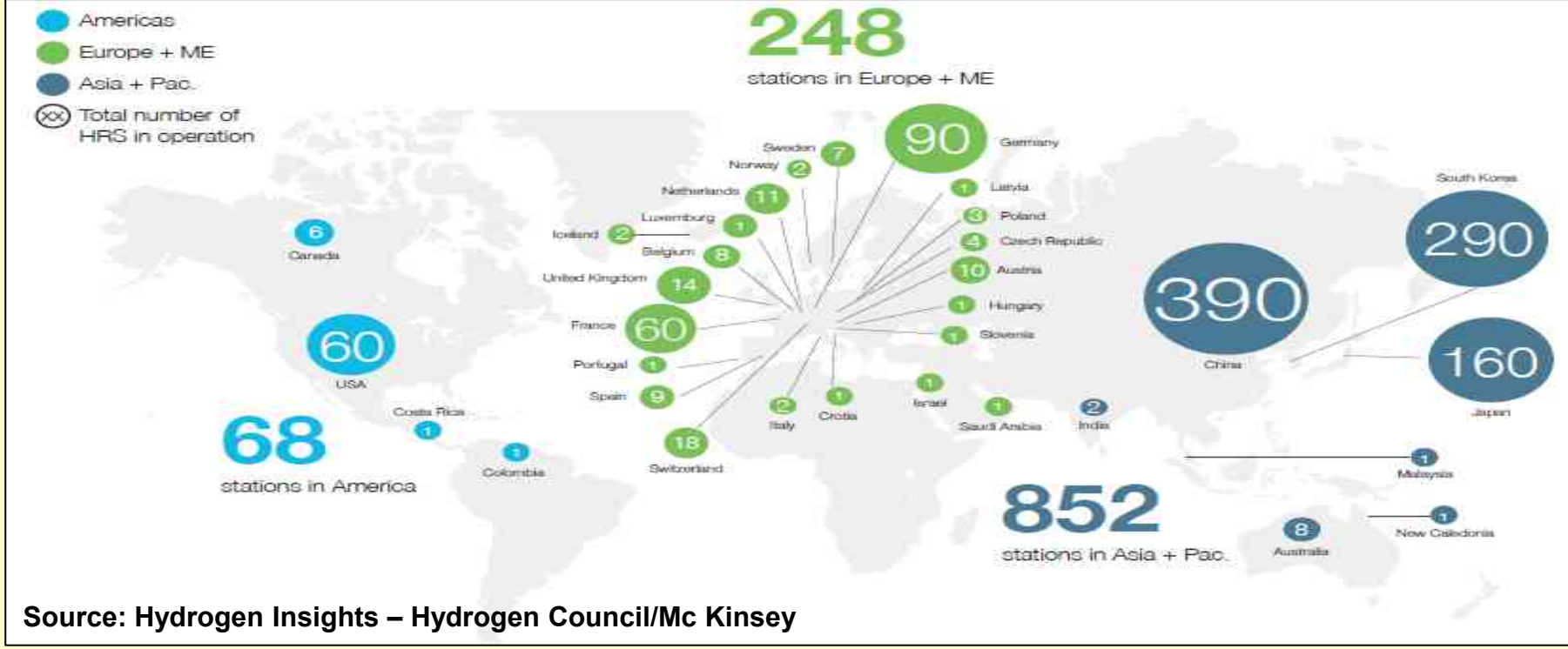
➢ Hydrogen/Fuel cells (1)

- ❑ Hydrogen produced from steam reforming in not suitable for Fuel Cells (limited costs: 1 to 3 €/kg, depending upon the gas price, but bad quality).
- ❑ Hydrogen produced by electrolysis is pure, but expensive to produce: 4 to 7 €/kg using grid electricity, for operating hours from 2000 to 8000 hours. The hydrogen production costs from electrolysis include the capital cost of the electrolyser, its utilization and the electricity purchase price.
- ❑ Fuel Cells need important quantity of platinium. Other technologies are under study.
- ❑ For Fuel Cell Electric Vehicles (FCEV), Hydrogen is expensive to transport, to store in vehicles, to convert into electricity.
- ❑ At 700 bars, the weight of the reservoir is 20 times the weight of the fuel.
- ❑ To produce Hydrogen by electrolysis needs huge quantity of energy: 55 kWh of electricity to produce 1kg H_2.
- ❑ Hydrogen raises important safety questions, either in liquid state (-253°C) or in hyperbar gaseous state (350 or 700 bars).
- ❑ Energy efficiency ratio is 2/3 times less than the one of electric vehicle.
- ❑ The weight and size of the storage tank is a challenge.
- ❑ Fuel cells costs have been divided by 10 in 15 years. Need to divide again the cost by 2 to get this technology economically viable.
- ❑ Costs could be reduced on the long term when considering access to direct sources like solar PV or Wind in specific regions.

Which fuel for vehicles in the future?

➢ Hydrogen/Fuel cells (2)

- ❑ Top manufacturers: Hyundai (South Korea),Toyota and Honda (Japan)
- ❑ At end 2023, 87 000 Fuel Cell Electric Vehicles (FCEV) worldwide.
- ❑ At end 2023, # 1100 Hydrogen refuelling stations (HRS) worldwide (x2,4 vs 2019). Cost of a service station = 1 to 2 M€ = x10 vs refuelling electric plug = x3 vs petroleum service station.



Source: Hydrogen Insights – Hydrogen Council/Mc Kinsey

Which fuel for vehicles in the future?

➢ Hydrogen/Fuel cells (3)

- Price of H_2: 10 to 30$^+$ €/kg/100 km (depends upon the country)
- To produce Hydrogen by electrolyis needs huge quantity of energy: 55 kWh of electricity to produce 1kg H_2 or 5kWh to produce 1 Nm3 H_2 (22,4 l H_2 = 2g)
- The 2023 world H_2 production is 97 Mt. 99% originates from steam reforming. Low carbon H_2 production amounts to 0,7 Mt in 2023.
- If the totality of this production was generated from electrolysis, the quantity of electricity needed would be > 5000 TWh, equivalent to more than the US consumption of electricity.
- If the totality of the world car fleet was driven by H_2 (1,3 billion vehicles, 1,2 kg H_2/100km, H_2 # 160 Mt), the quantity of electricity needed would be 8800 TWh, equivalent more than to the China consumption of electricity.
- In order to avoid considerable CO_2 emissions, the source of electricity must be decarbonized (nuclear, renewables, or fossile with CCS or CCUS)
- The overall cost involved for vehicles (1,2 kg H_2/100km) looks high.
- These considerations mean that a potential massive extension of H_2 utilization for transport mobility still needs important technological progress to be put in place and represent an outstanding challenge.

Which fuel for vehicles in the future?

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10

Global Energy Growth
Electricity Demand & Generation

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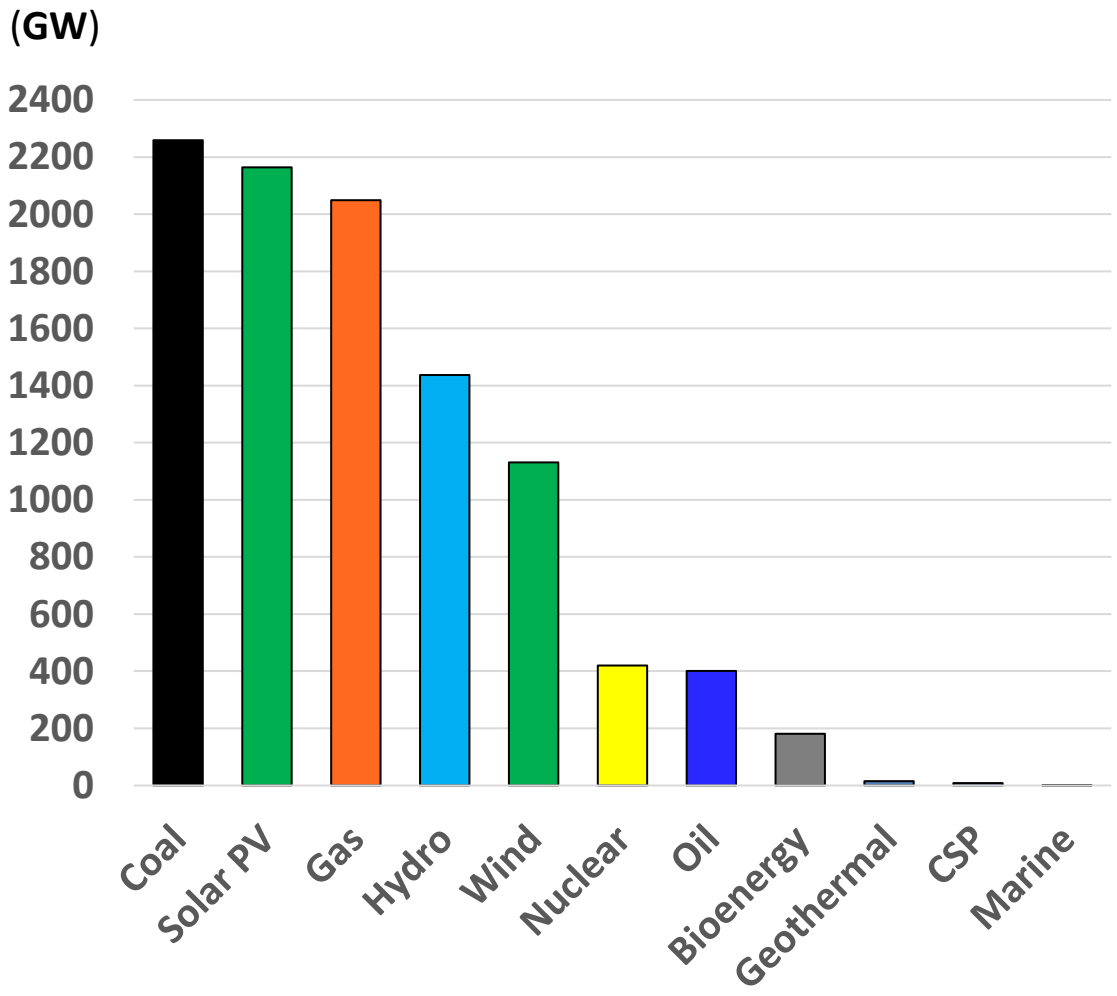


A bright Future for Electricity

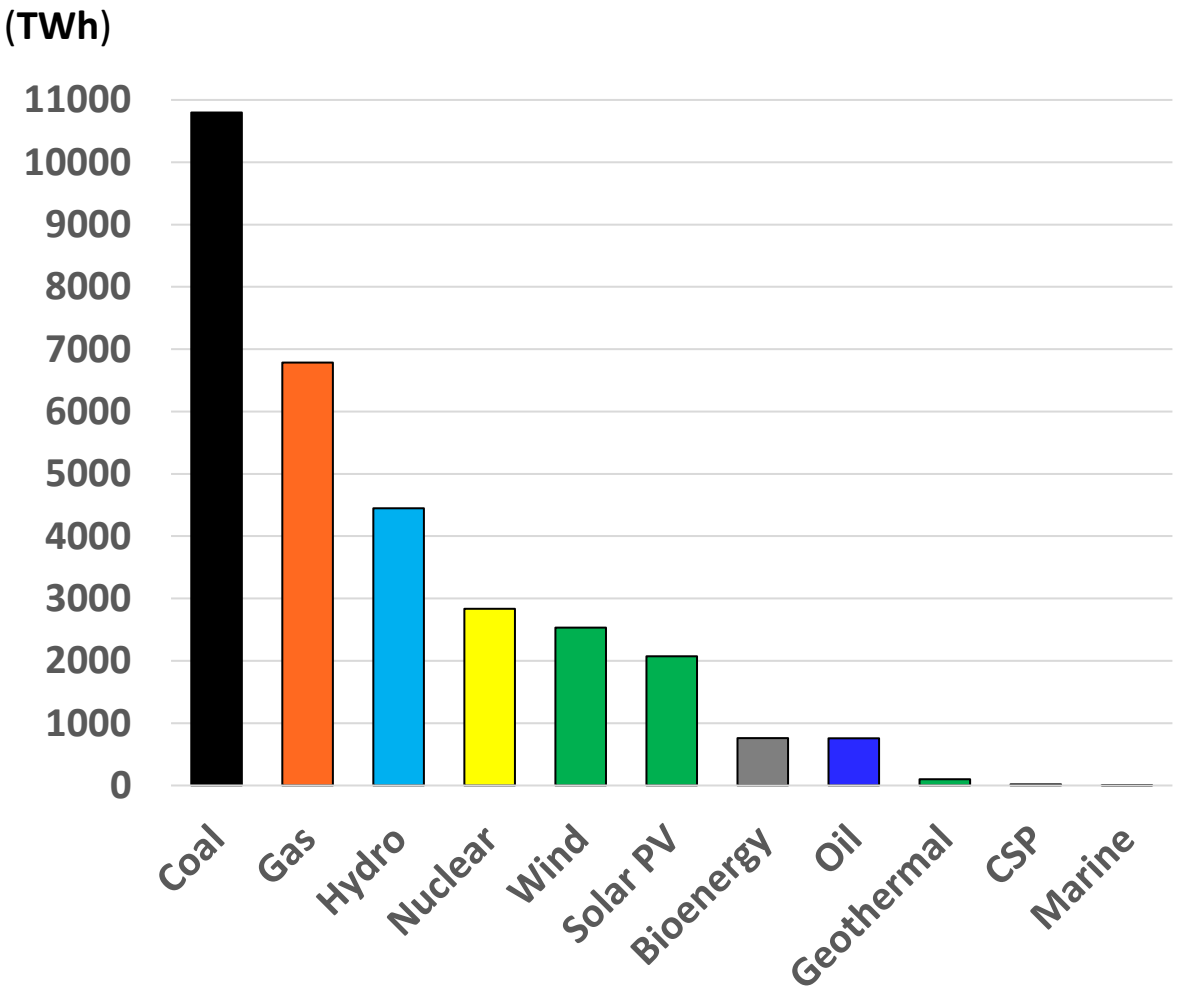
Electricity Demand
=
Gross Electricity Generation
-
Own Use in Production Plants
+
Net Trade (Imports – Exports)
-
Transmission and Distribution Losses

Electricity - World Installed Capacities and Generation (2024)

World Installed Capacities # 10 100 GW (+8% vs 2023)



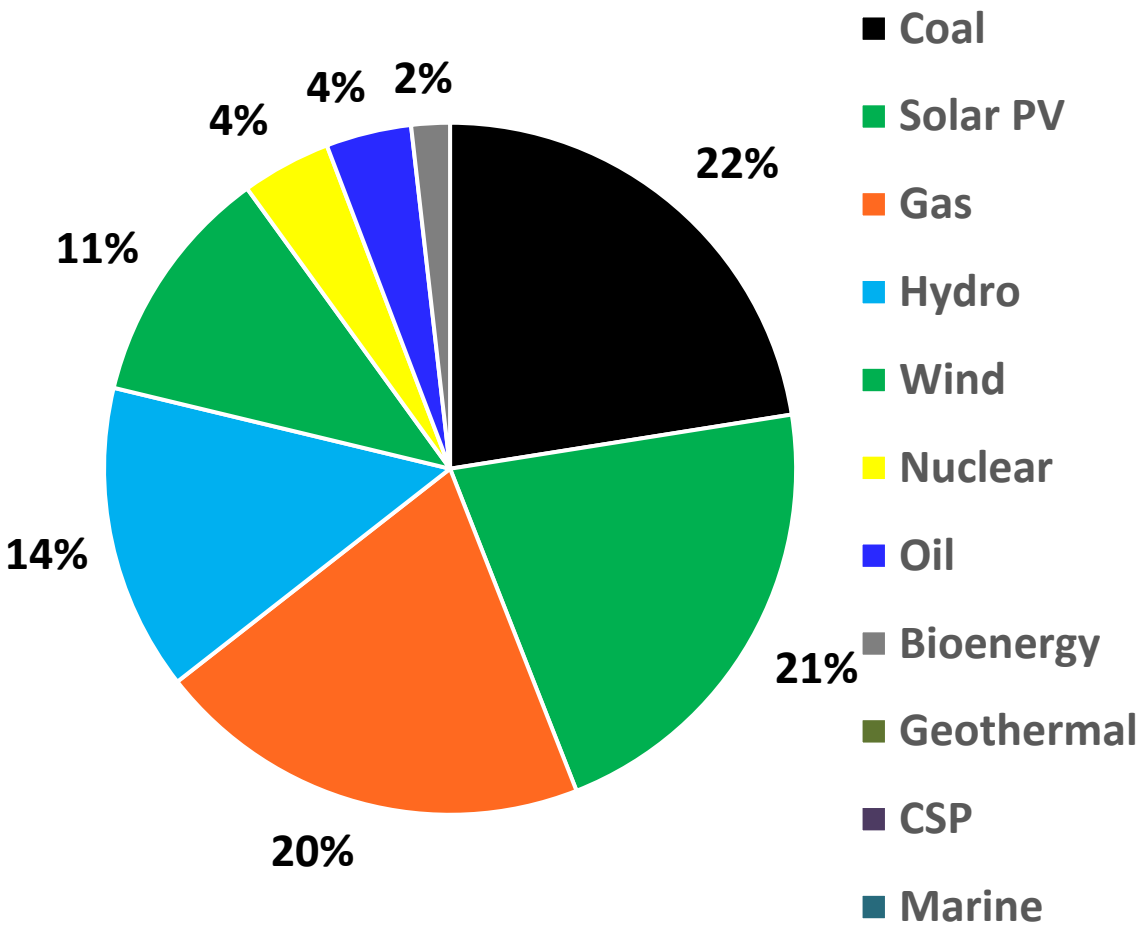
World Electricity Generation # 31 100 TWh (+5% vs 2023)



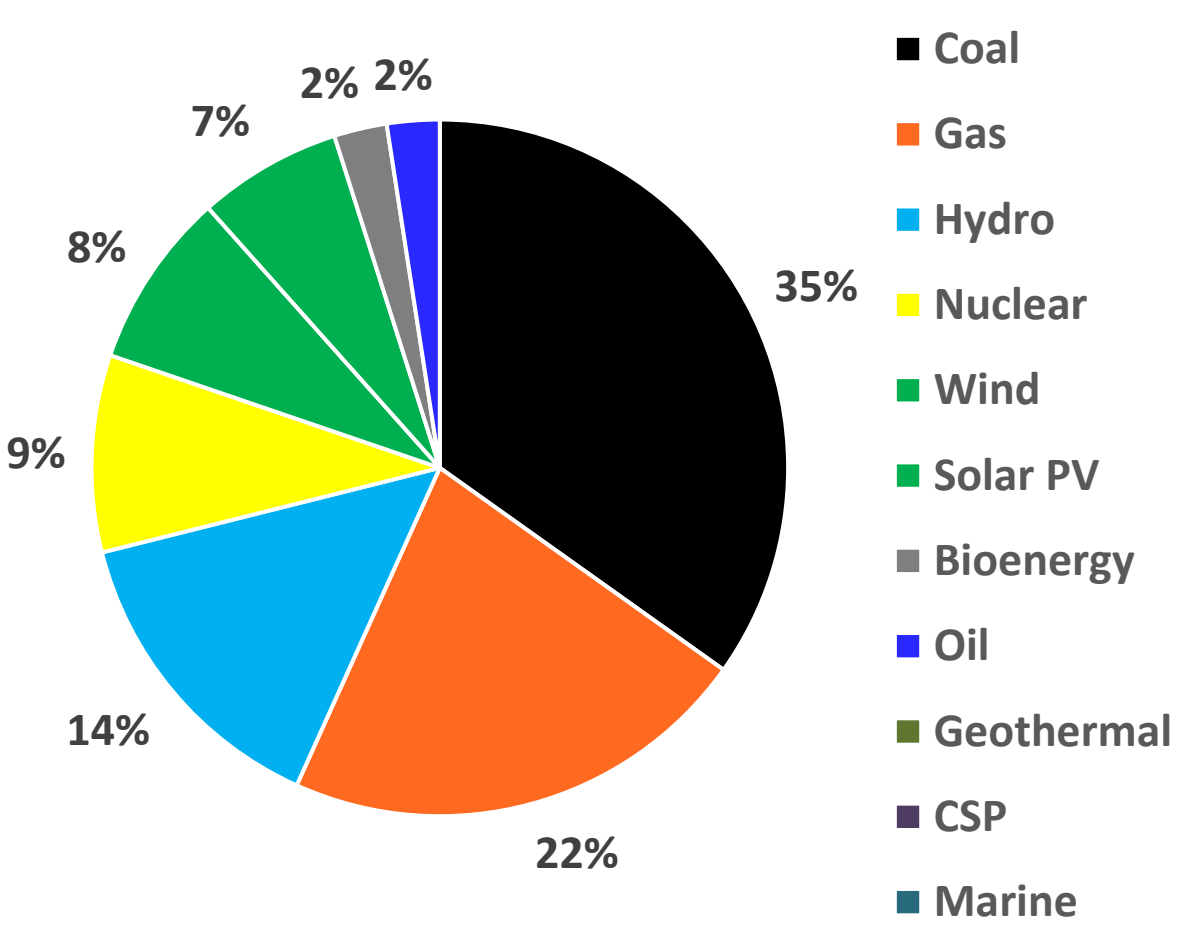
Source: Data from IEA WEO 2025 (Excl. Battery storage)

Electricity - World Installed Capacities and Generation (2024)

World Installed Capacities # 10 100 GW

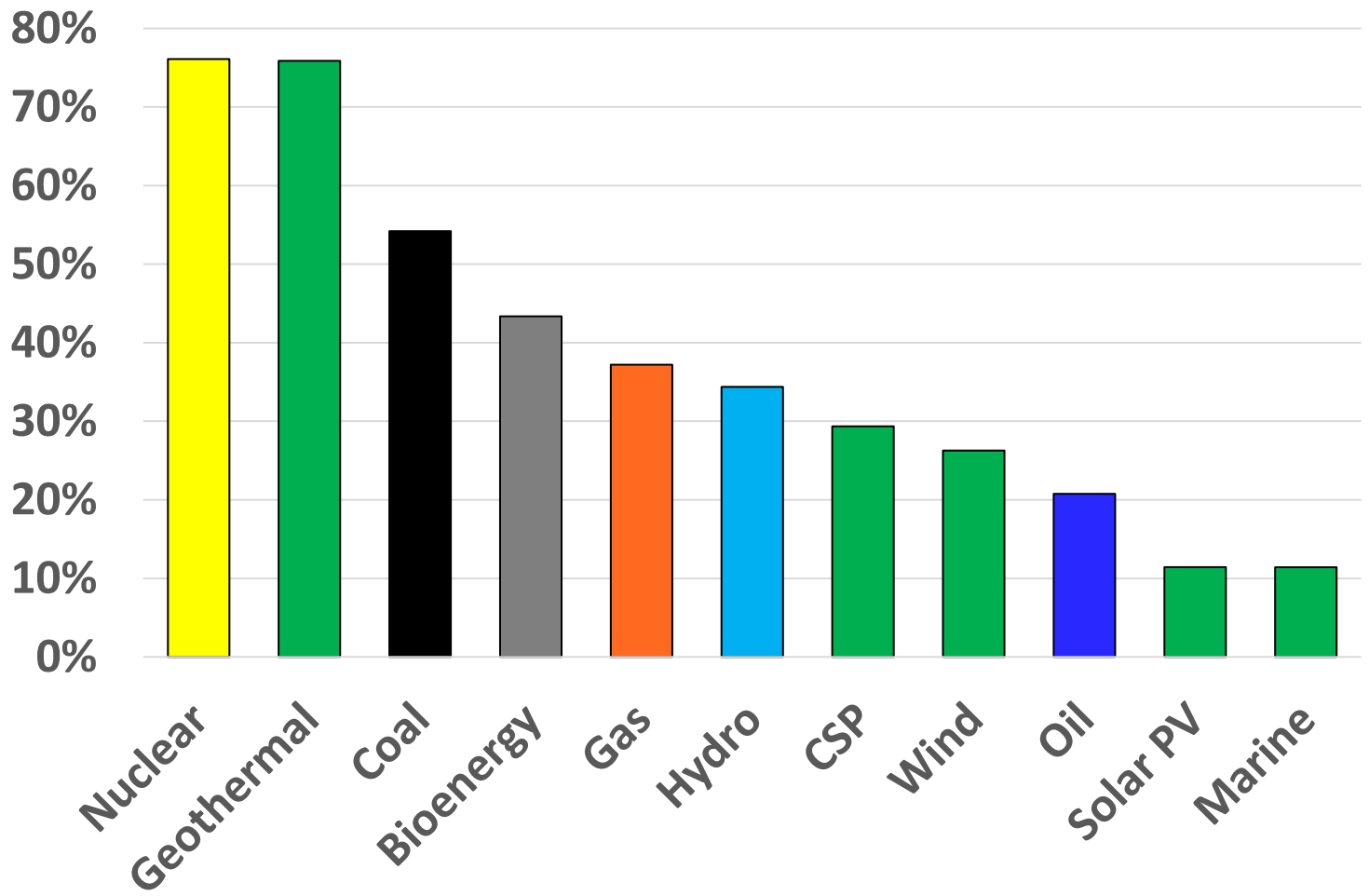


World Electricity Generation # 31 100 TWh



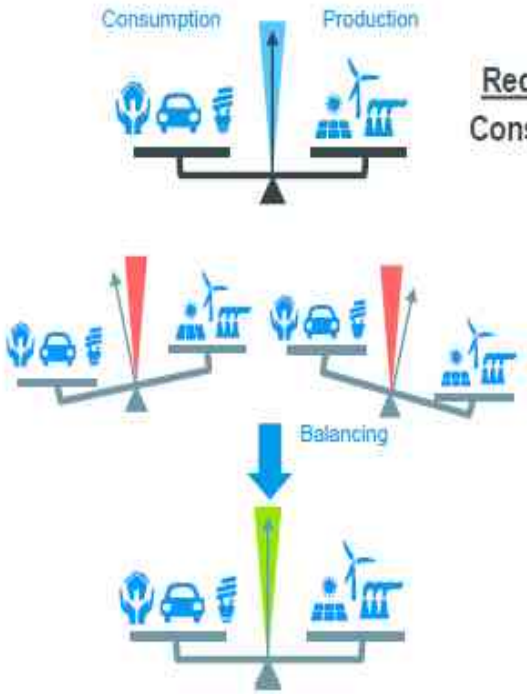
Source: Data from IEA WEO 2025

Electricity – Capacity factors Year 2024
World average



Source: Data from IEA WEO 2025

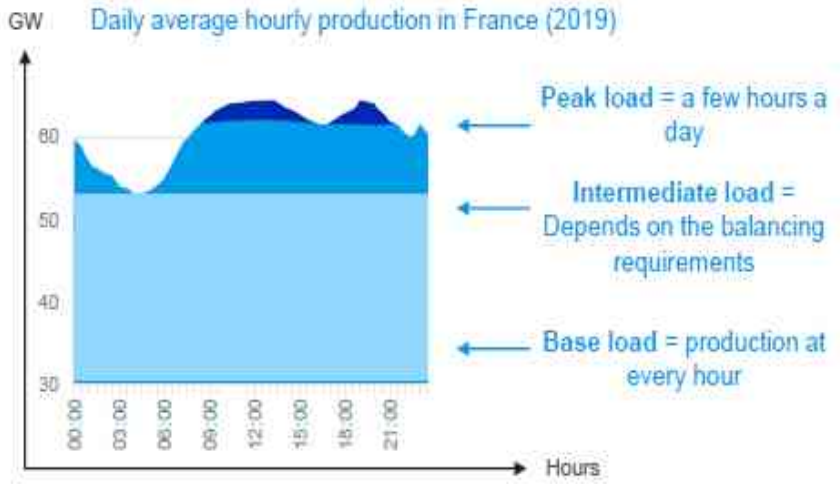
Power Systems must adapt to intermittent Renewables



Requirement: at any time
Consumption = Production

- **Unbalancing**: weather, intermittency (wind, solar, etc.), demand.
- **Balancing by**: peak load solutions, storage, etc.

Means of production and role in the electrical system

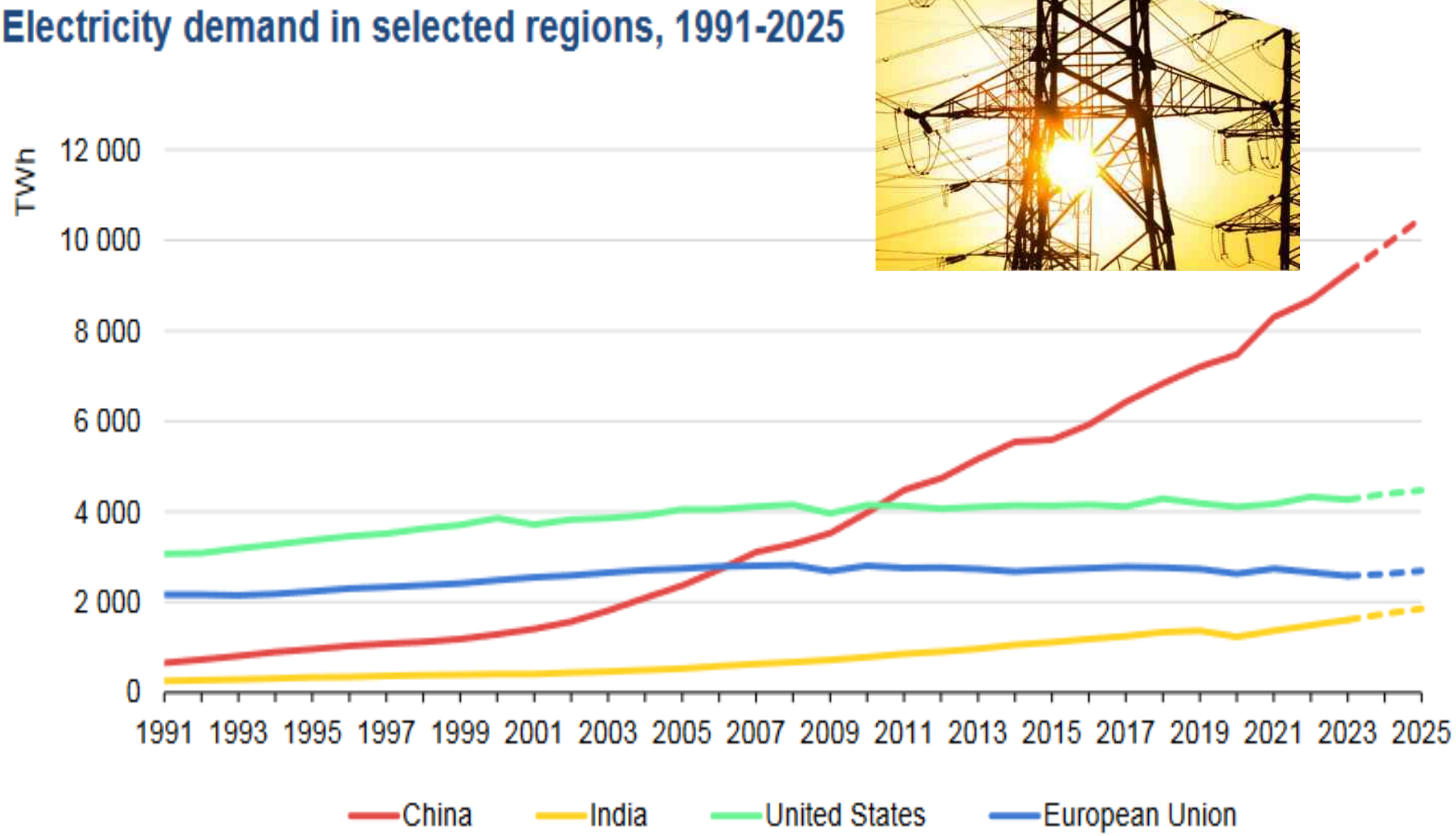


- Electrical generation is composed of multiple means of production with different roles

The massive introduction of intermittent renewable energy has a systemic impact on electric network balance
Their intermittency needs mitigation : storage, intermediate load and peak load power plants & clients demand response

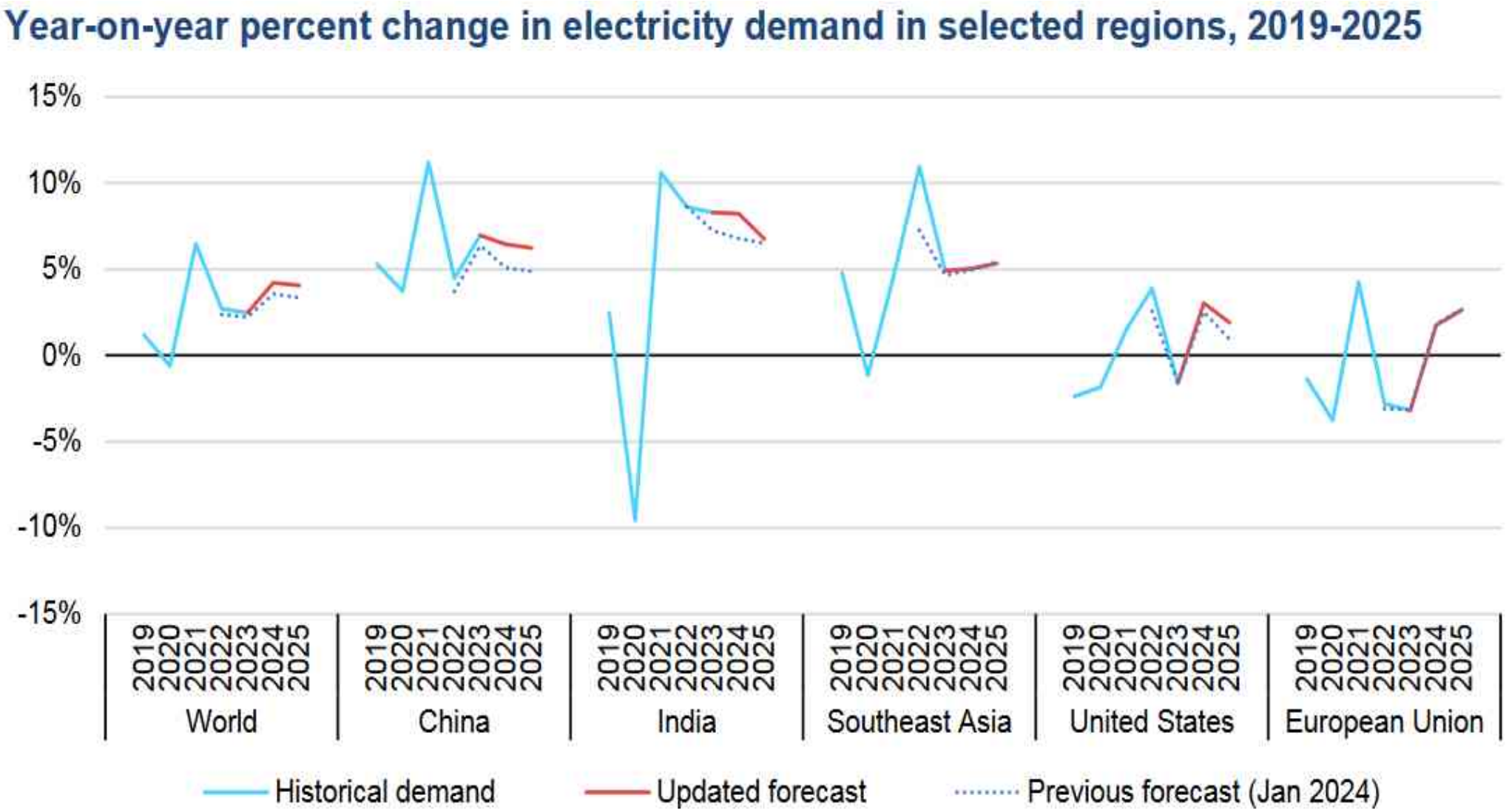
Source: TotalEnergies-Cap Gemini/Energy Landscape September 2021

Electricity Demand in selected Regions IEA 2024



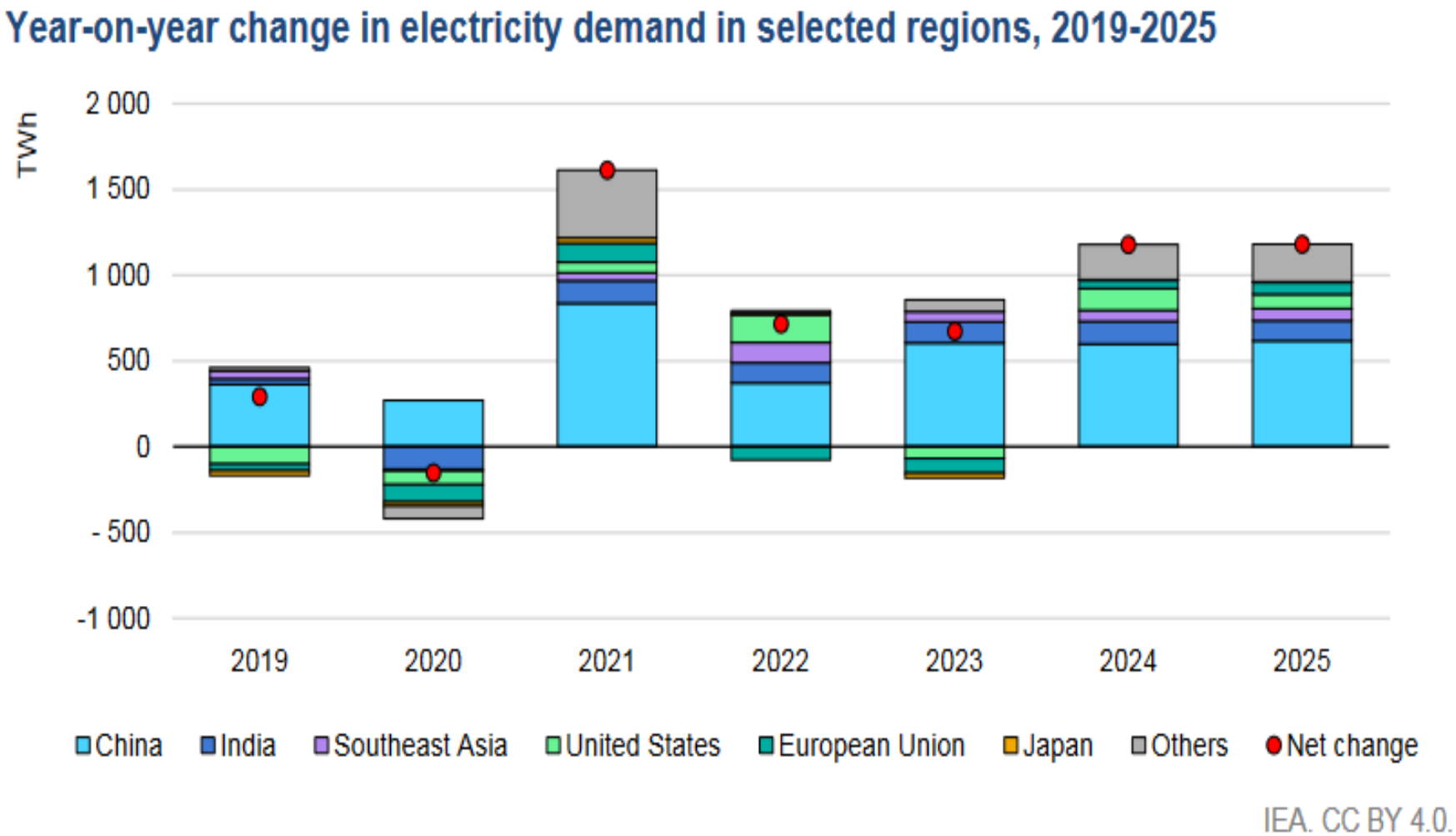
Source: IEA Electricity Mid-year Update 2024

World Electricity Demand IEA 2024



Source: IEA Electricity Mid-year Update 2024

World Electricity Demand IEA 2024

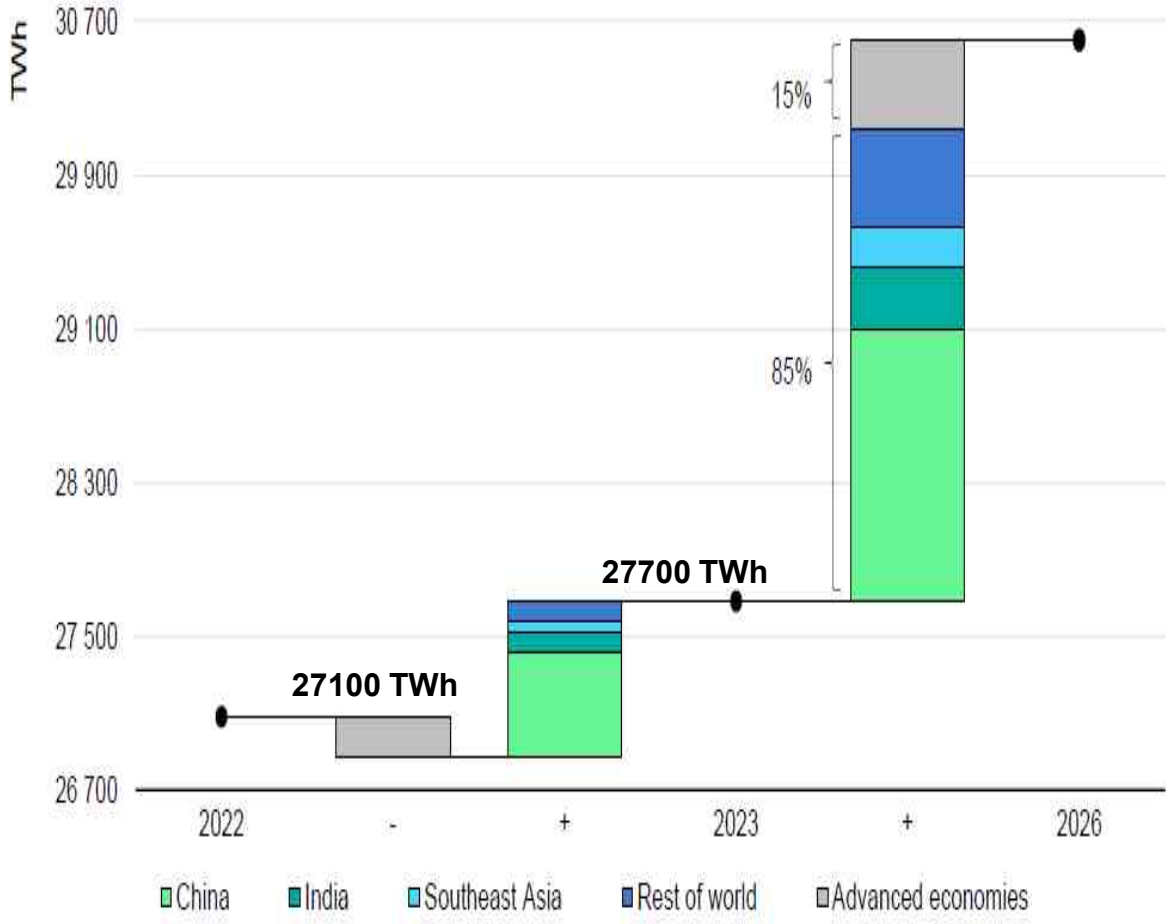


Note: The figures for 2024 and 2025 are forecast values.

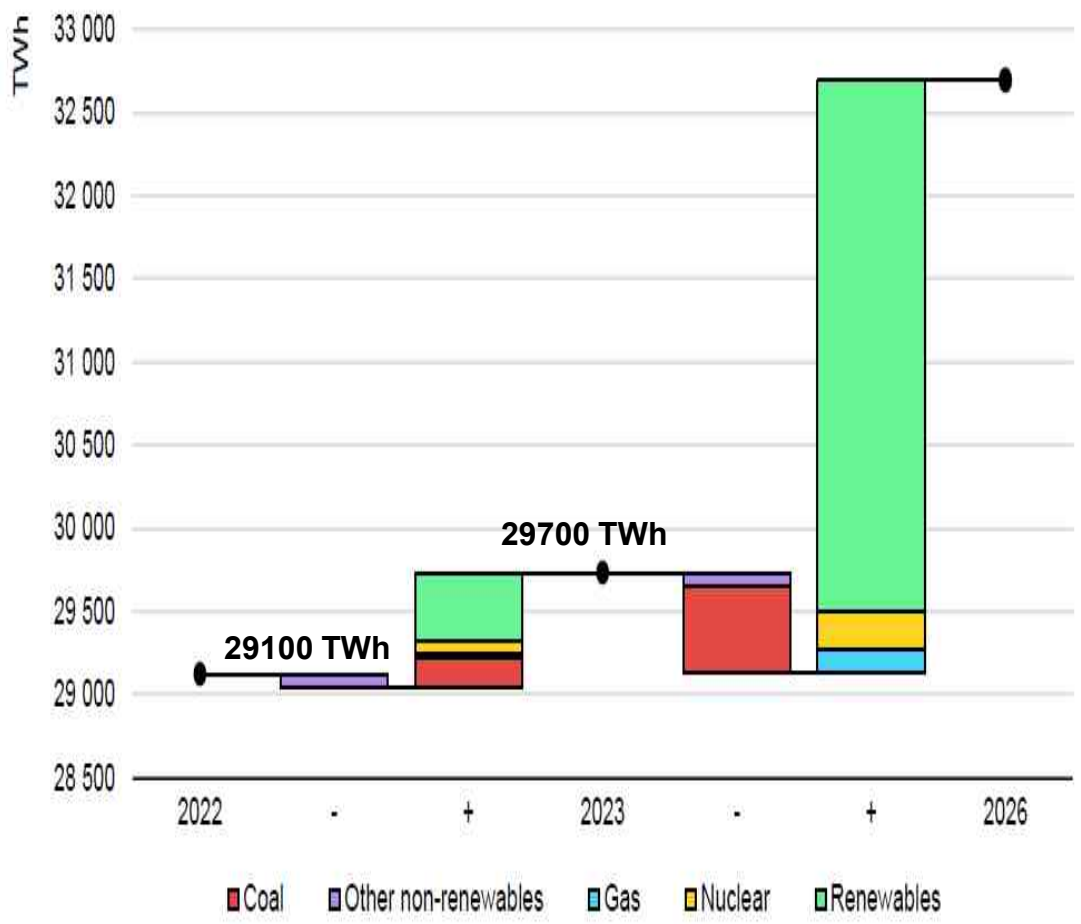
Source: IEA Electricity Mid-year Update 2024

Electricity Demand & Generation 2022 – 2026 by IEA 2024

Year-on-year change in electricity demand by region, 2022-2026



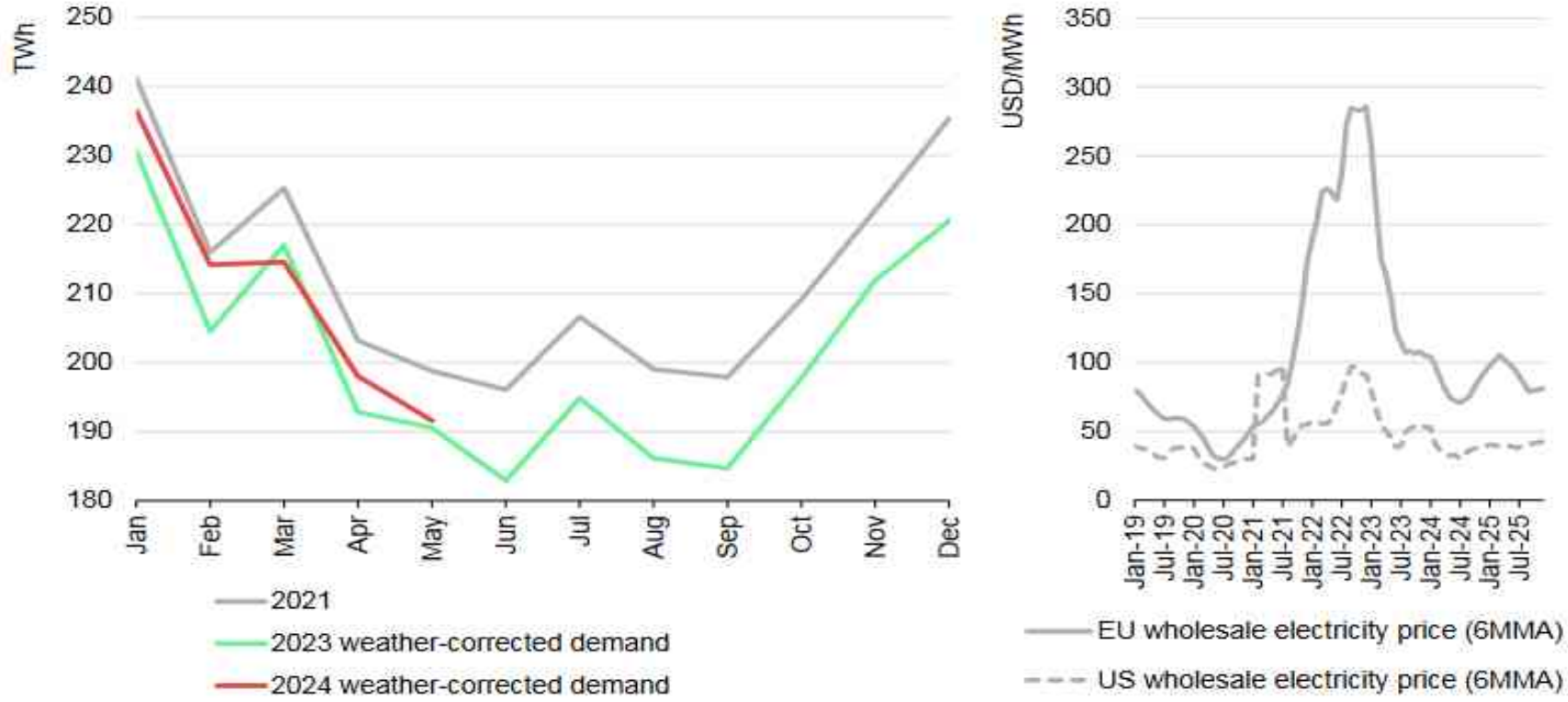
Changes in global electricity generation, 2022-2026



Source: IEA Electricity 2024

A Zoom on EU Electricity Demand IEA 2024

Monthly EU electricity demand, 2021-2024 (left), and average wholesale electricity prices in the European Union and the United States, 2019-2024 (right)



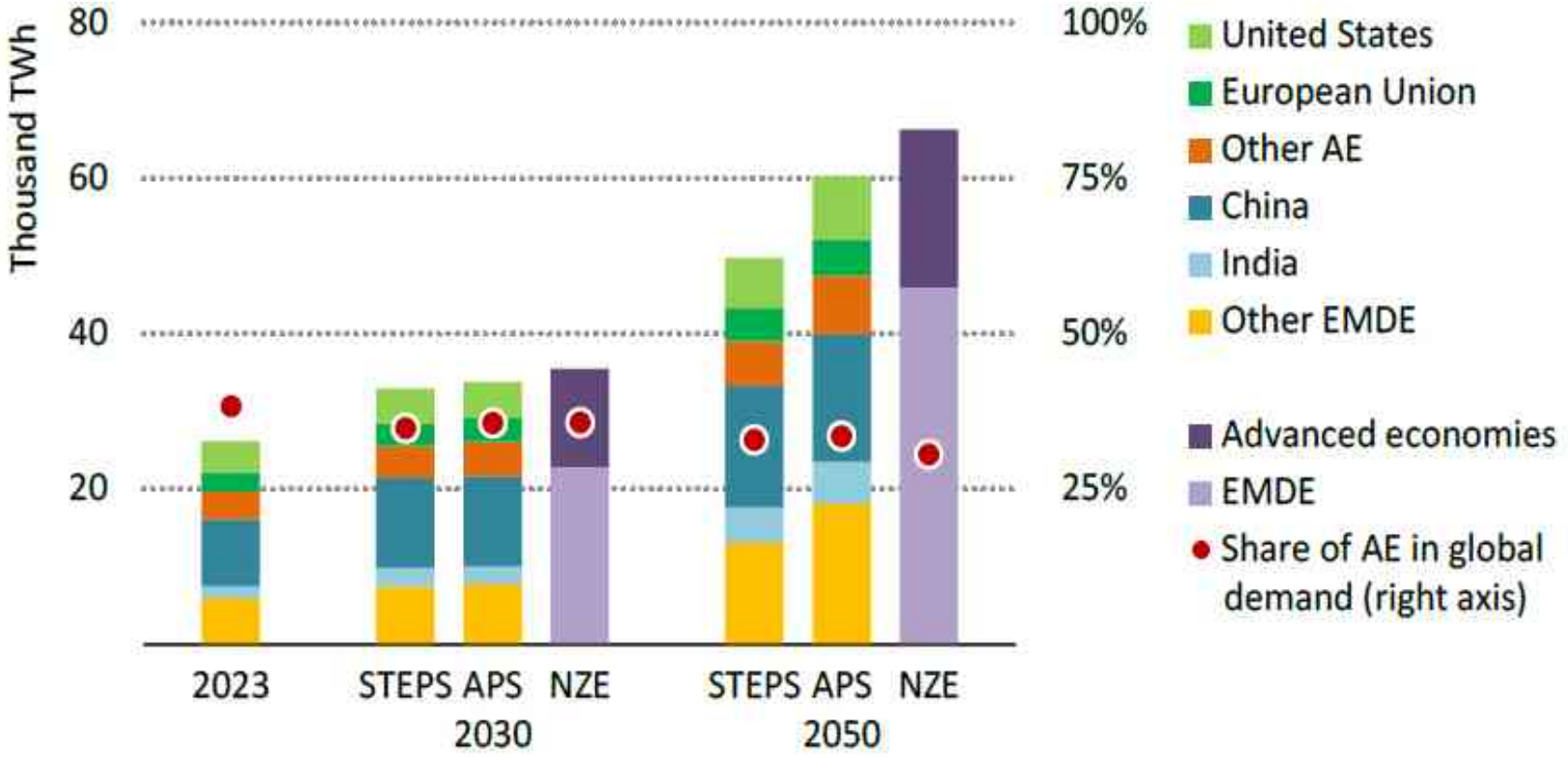
IEA. CC BY 4.0.

Notes: In the chart on the left, 2023 and 2024 demand is weather-corrected to the base year of 2021 for comparison purposes. The 2021 demand profile corresponds to the realised net demand. In the chart on the right, the plotted average wholesale prices are 6-month moving averages (6MMA).

Source: IEA analysis based on data from Eurostat (2024) and EIA (2024).

Source: IEA Electricity Mid-year Update 2024

World Electricity Demand scenarios - IEA WEO 2024



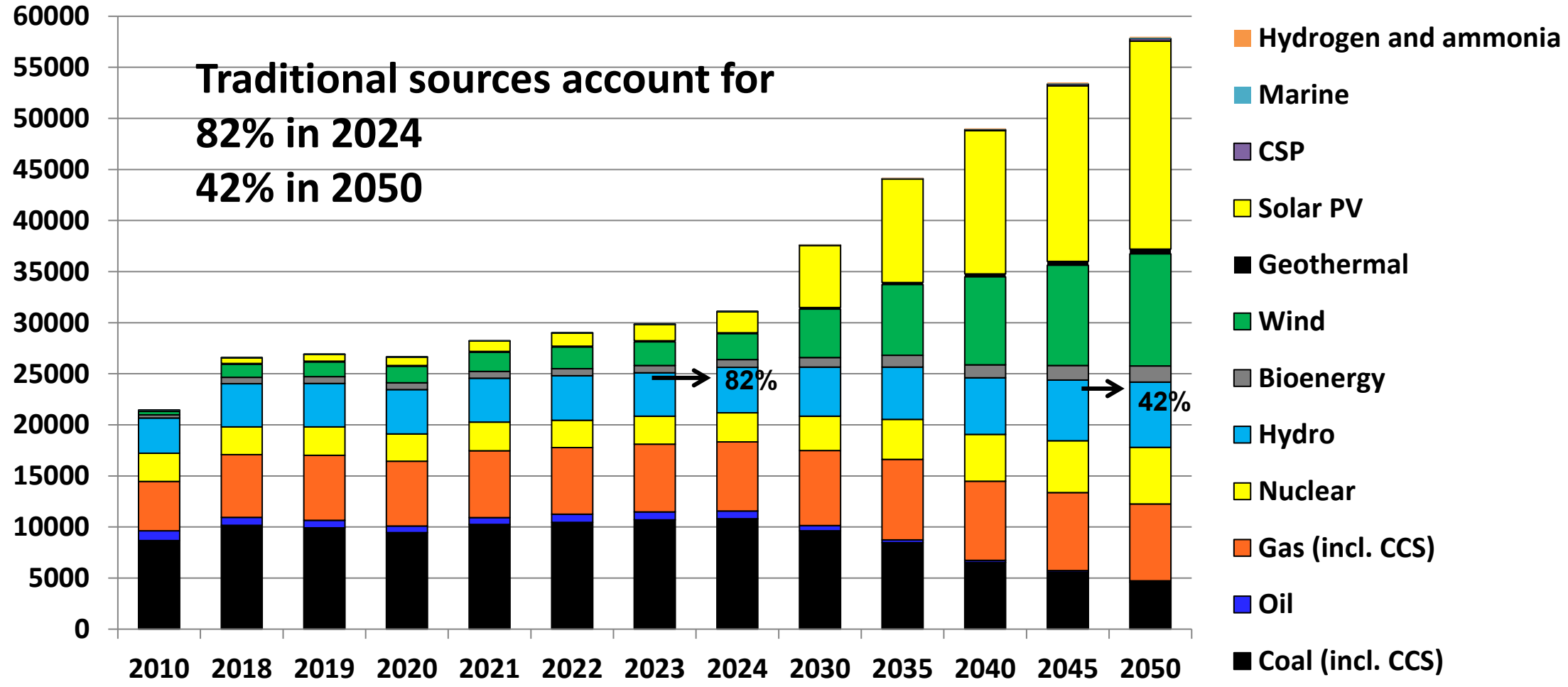
Advanced economies currently account for nearly 40% of global electricity demand, but their share decreases over time across scenarios

Note: TWh = terawatt-hours; AE = advanced economies; EMDE = emerging market and developing economies.

Source: IEA WEO 2024

World Electricity Generation by Source
IEA WEO 2025 STEPS

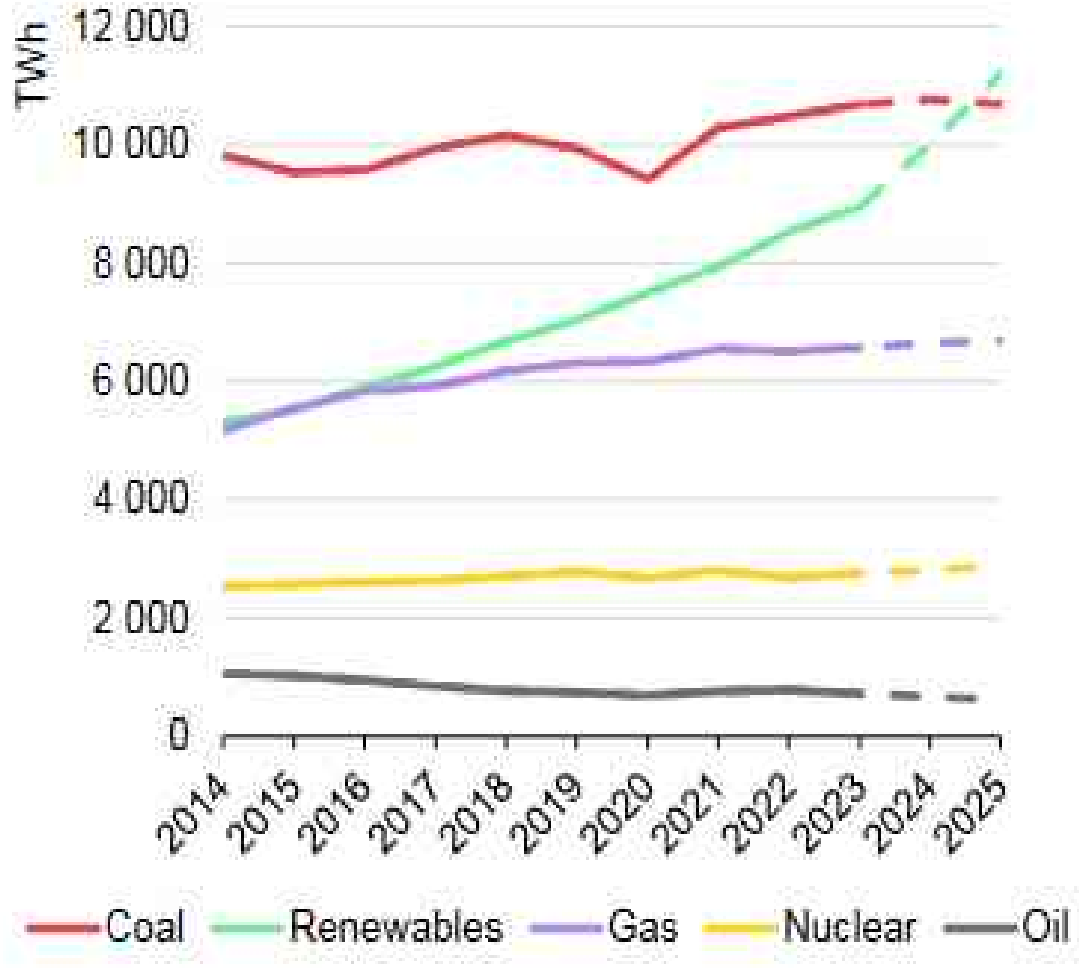
Electricity Generation grows substantially, « traditional » Energy sources are drastically reduced. Wind and Solar PV take the lead

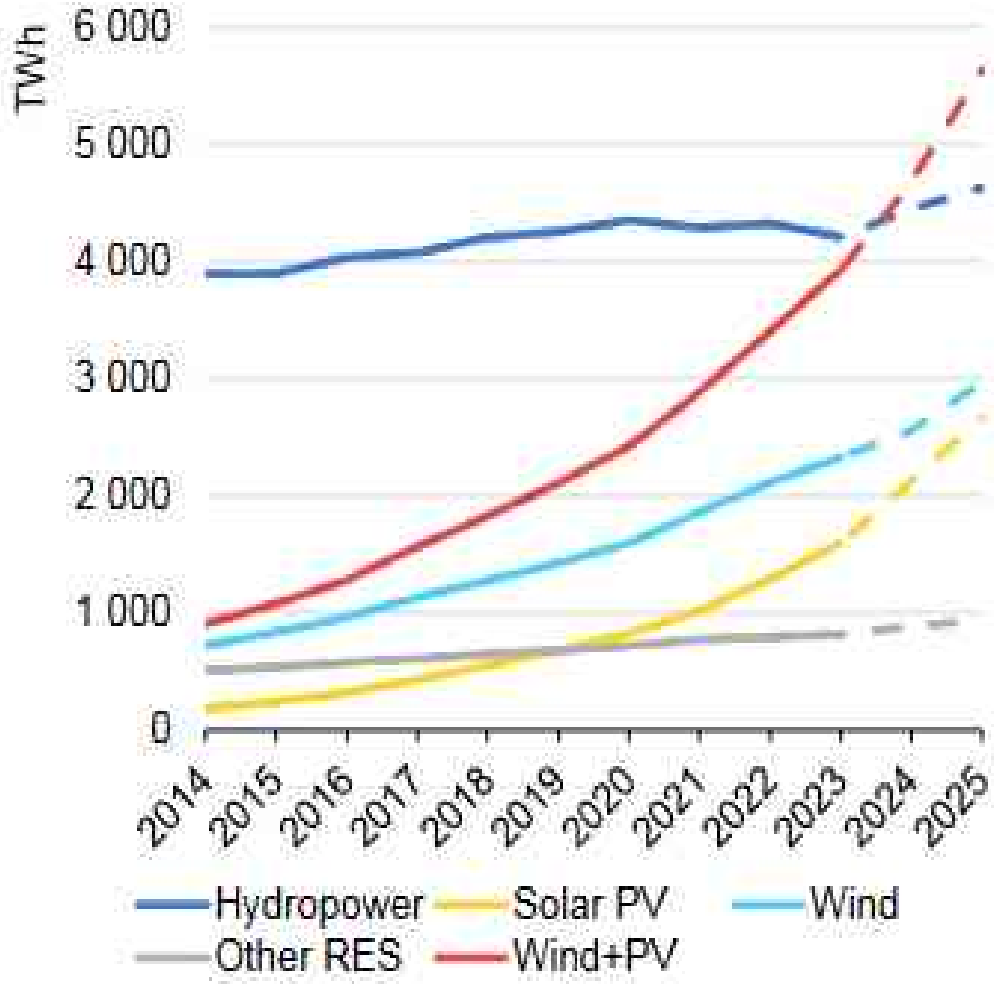


Source: Data from IEA WEO 2025

World Electricity Generation by sources – IEA 2024

Global electricity generation by source, 2014-2025

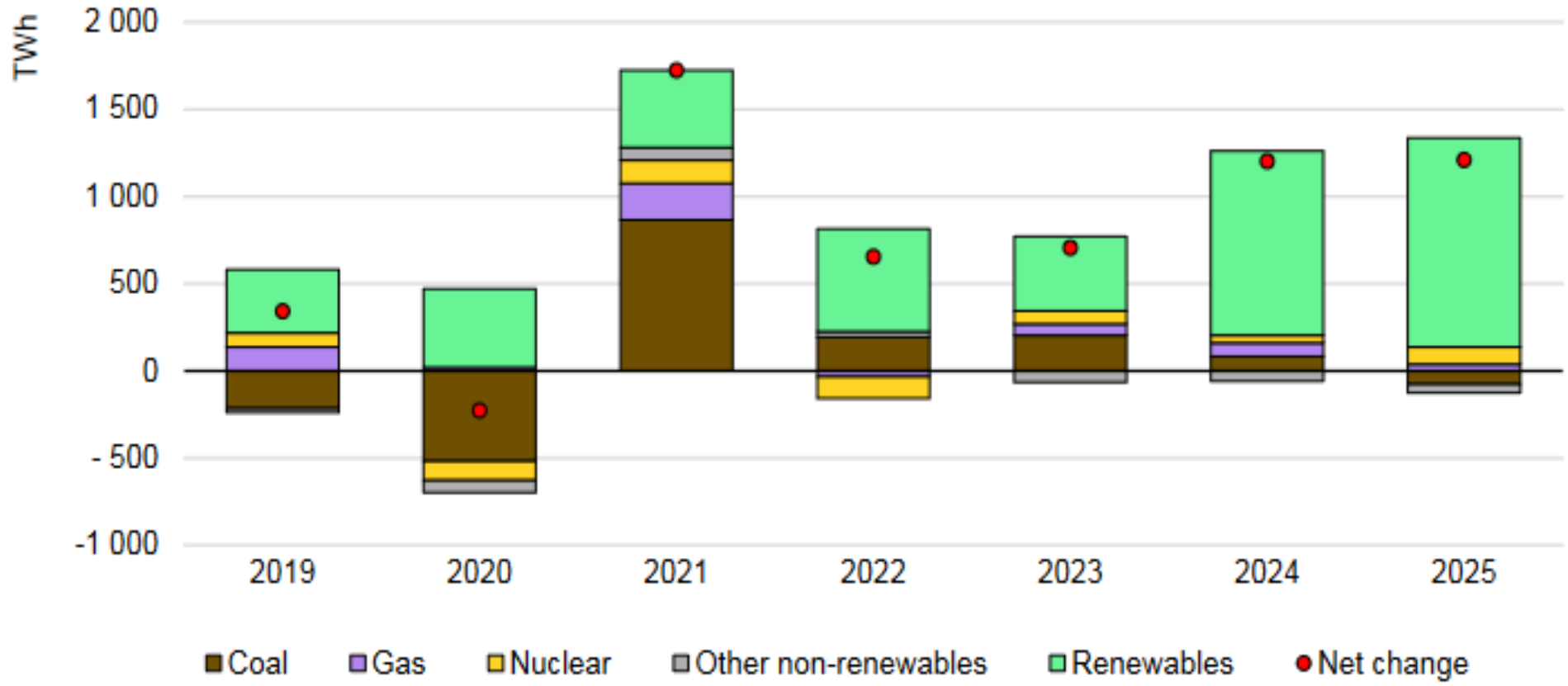




Source: IEA Electricity Mid-year Update 2024

World Electricity Generation by sources – IEA 2024

Year-on-year global change in electricity generation by source, 2019-2025



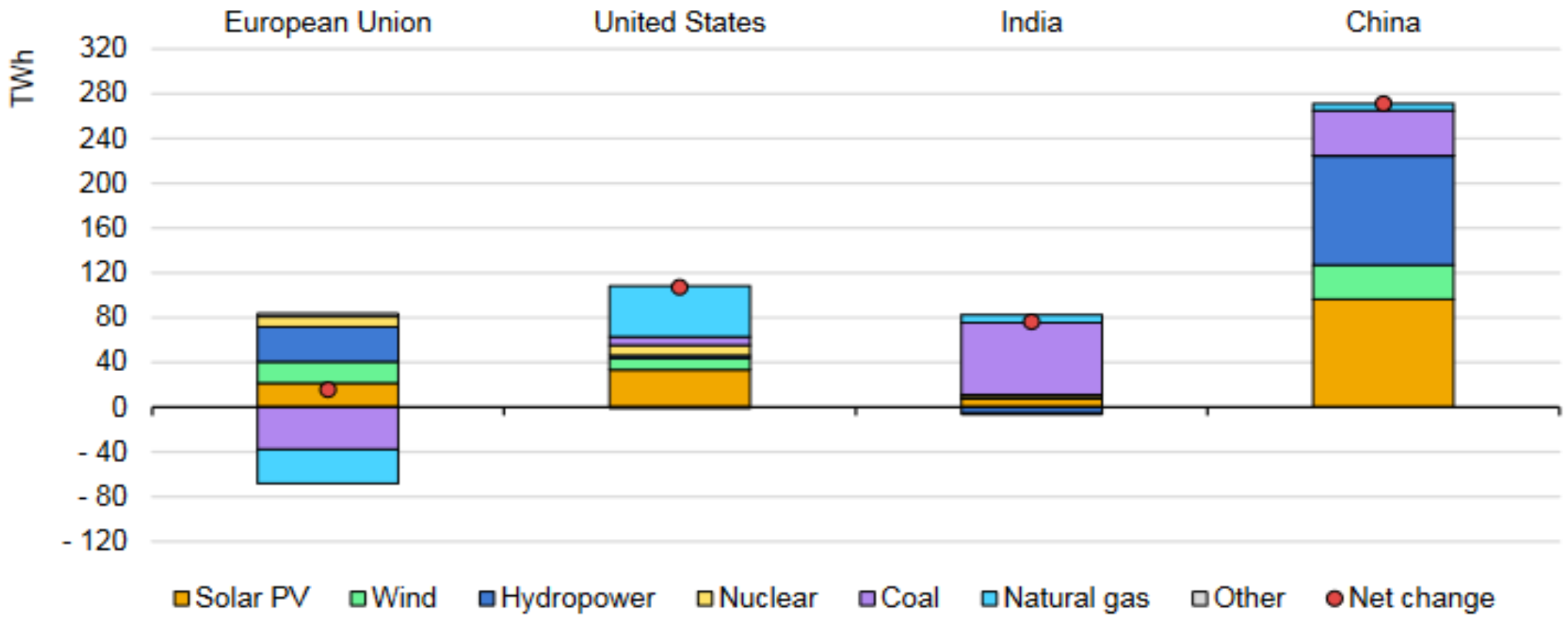
IEA. CC BY 4.0.

Notes: *Other non-renewables* includes oil, waste and other non-renewable energy sources. The figures for 2024 and 2025 are forecast values.

Source: IEA Electricity Mid-year Update 2024

World Electricity Generation by sources – IEA 2024

Year-on-year change in electricity generation by source in selected regions in H1 2024



IEA. CC BY 4.0.

Notes: Net electricity generation is shown.

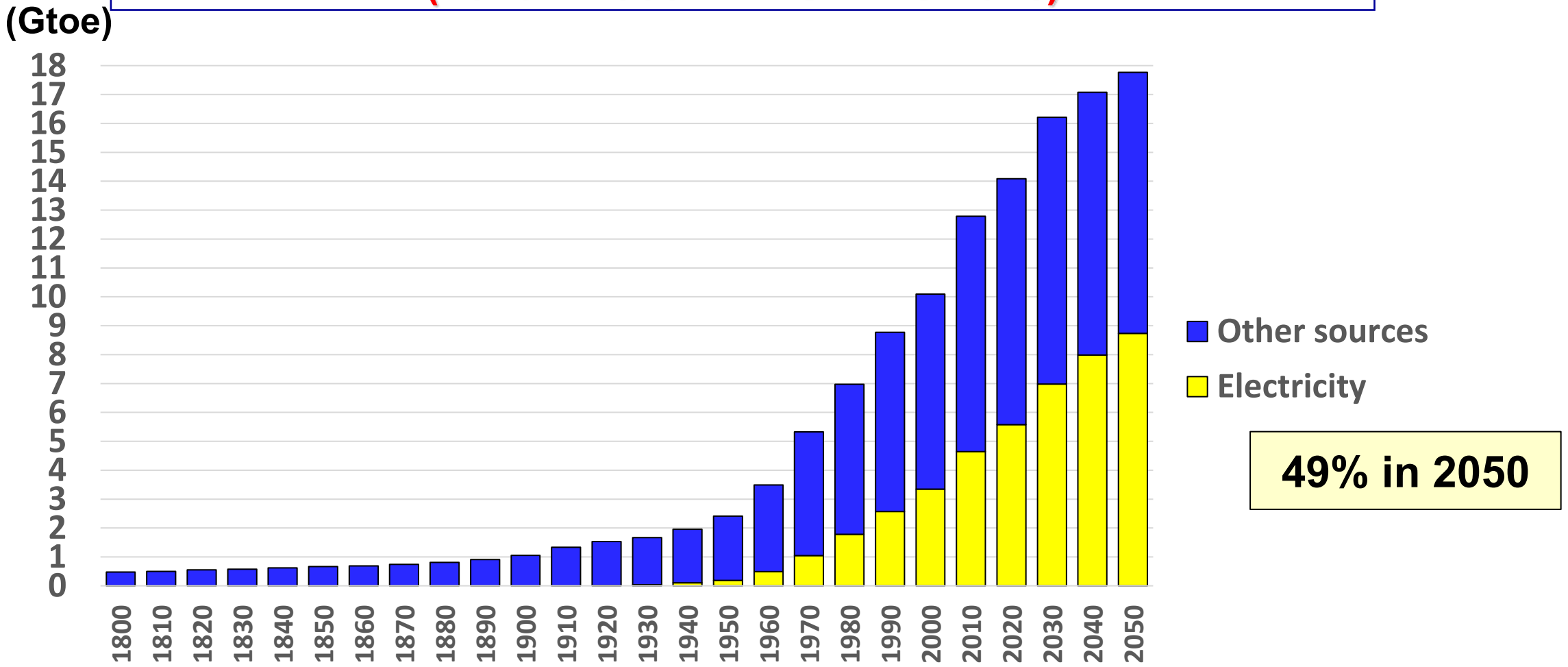
Source: IEA Electricity Mid-year Update 2024

World Electricity Generation by Regions & Scenarios - IEA WEO 2025

				Current Policies		Stated Policies	
	2010	2023	2024	2035	2050	2035	2050
World	21 519	29 975	31 229	45 109	59 426	44 274	58 081
North America	5 233	5 444	5 581	6 683	7 742	6 623	7 763
United States	4 354	4 430	4 564	5 480	6 179	5 420	6 237
Central and South America	1 129	1 416	1 462	1 949	2 832	1 911	2 723
Brazil	516	708	748	970	1 362	925	1 240
Europe	4 119	3 896	3 971	5 335	6 740	5 412	6 764
European Union	2 955	2 718	2 772	3 797	4 792	3 847	4 816
Africa	687	912	939	1 446	2 562	1 449	2 560
Middle East	829	1 426	1 461	2 140	3 323	2 122	3 245
Eurasia	1 251	1 468	1 511	1 712	2 001	1 701	1 967
Russia	1 036	1 159	1 188	1 297	1 431	1 279	1 374
Asia Pacific	8 270	15 414	16 304	25 844	34 227	25 055	33 058
China	4 236	9 530	10 170	16 791	20 583	15 854	19 696
India	972	1 987	2 090	3 597	6 022	3 687	5 805
Japan	1 164	993	1 009	1 106	1 156	1 082	1 105
Southeast Asia	692	1 365	1 457	2 329	3 618	2 334	3 525

Source: IEA WEO 2025

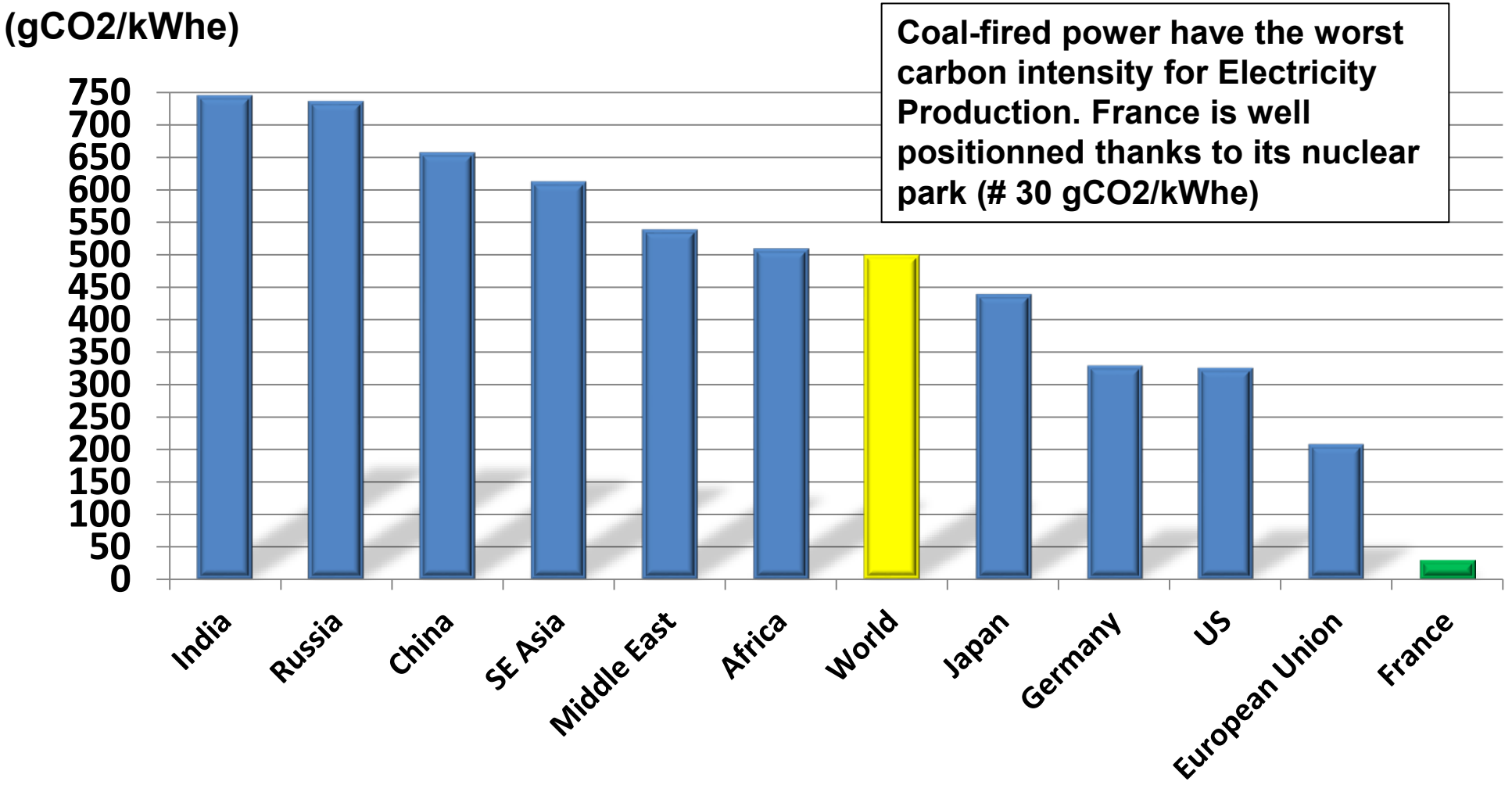
In terms of Primary Energy equivalent demand, electricity is taking more and more importance in the Energy mix (2020 – 2050: IEA STEPS 2025)



Source; Ch.Guéritte Nota: 1 Mtoe = 11632 Gwhe. Data from IEA WEO 2025

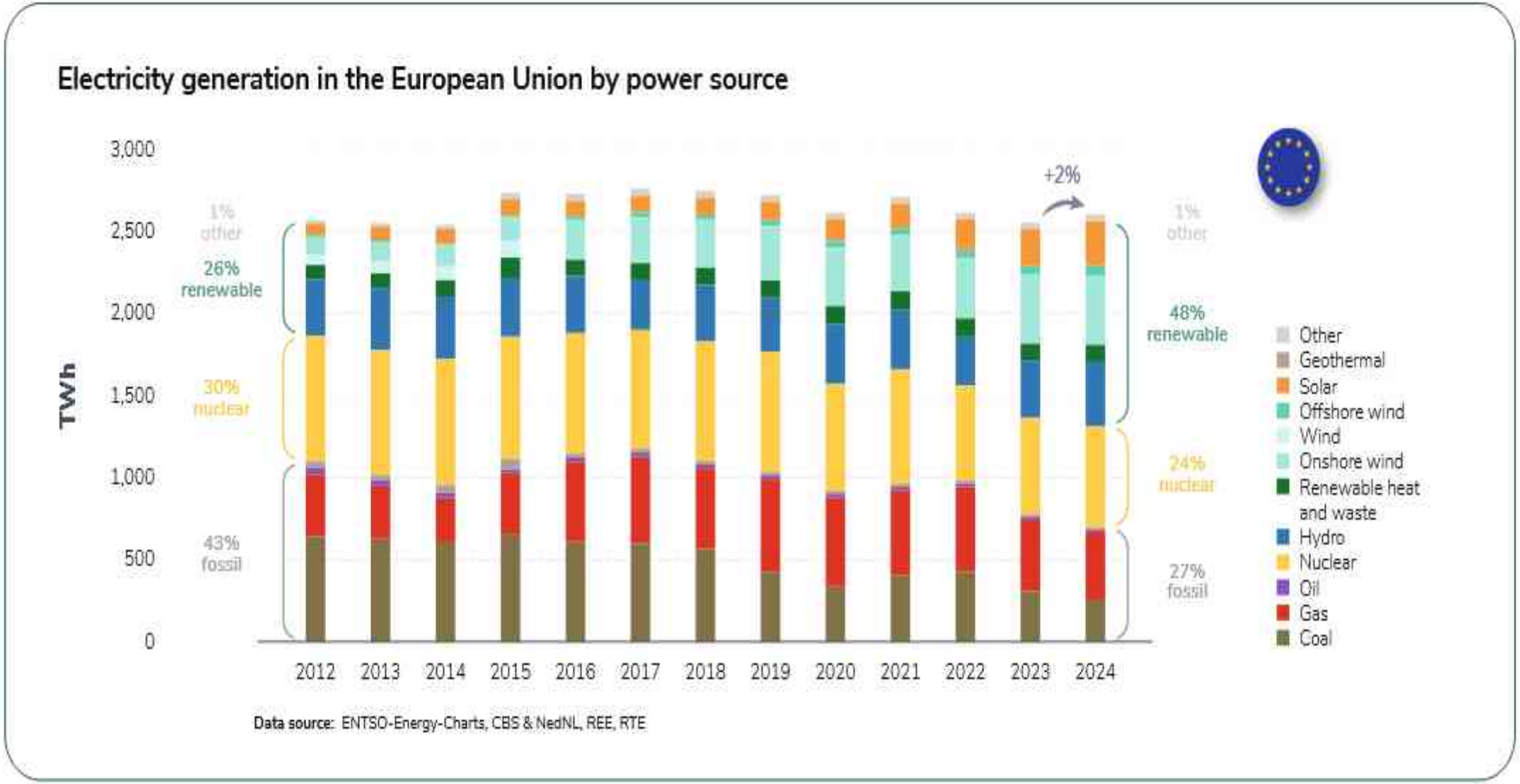
1 Gwhe # 2,6 GWh eq. Primary Energy in 2010
2,4 GWh eq. Primary Energy in 2020
1,9 GWh eq. Primary Energy in 2040
1,7 GWh eq. Primary Energy in 2050

Carbon Intensity of Electricity Production in selected Regions/Countries - Year 2024
Most of the countries have seen their Carbon Intensity of Electricity Production decreasing in 2024 vs 2023 except India & Russia



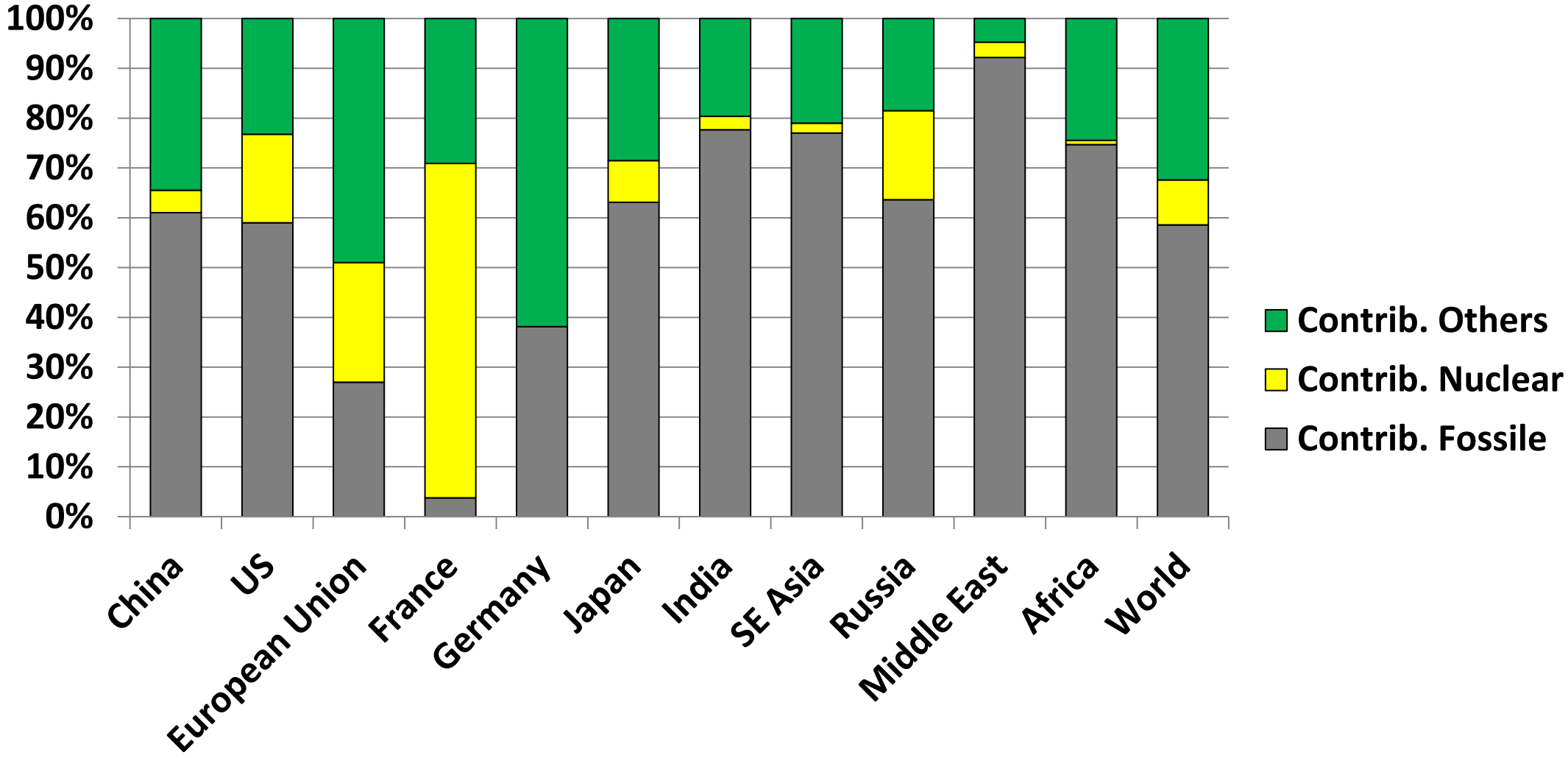
Source: Data from IEA WEO 2025
EI Stat. Review 2025 – ENTSO - EMBER – RTE - Energiewende

Electricity Generation in European Union - Year 2024



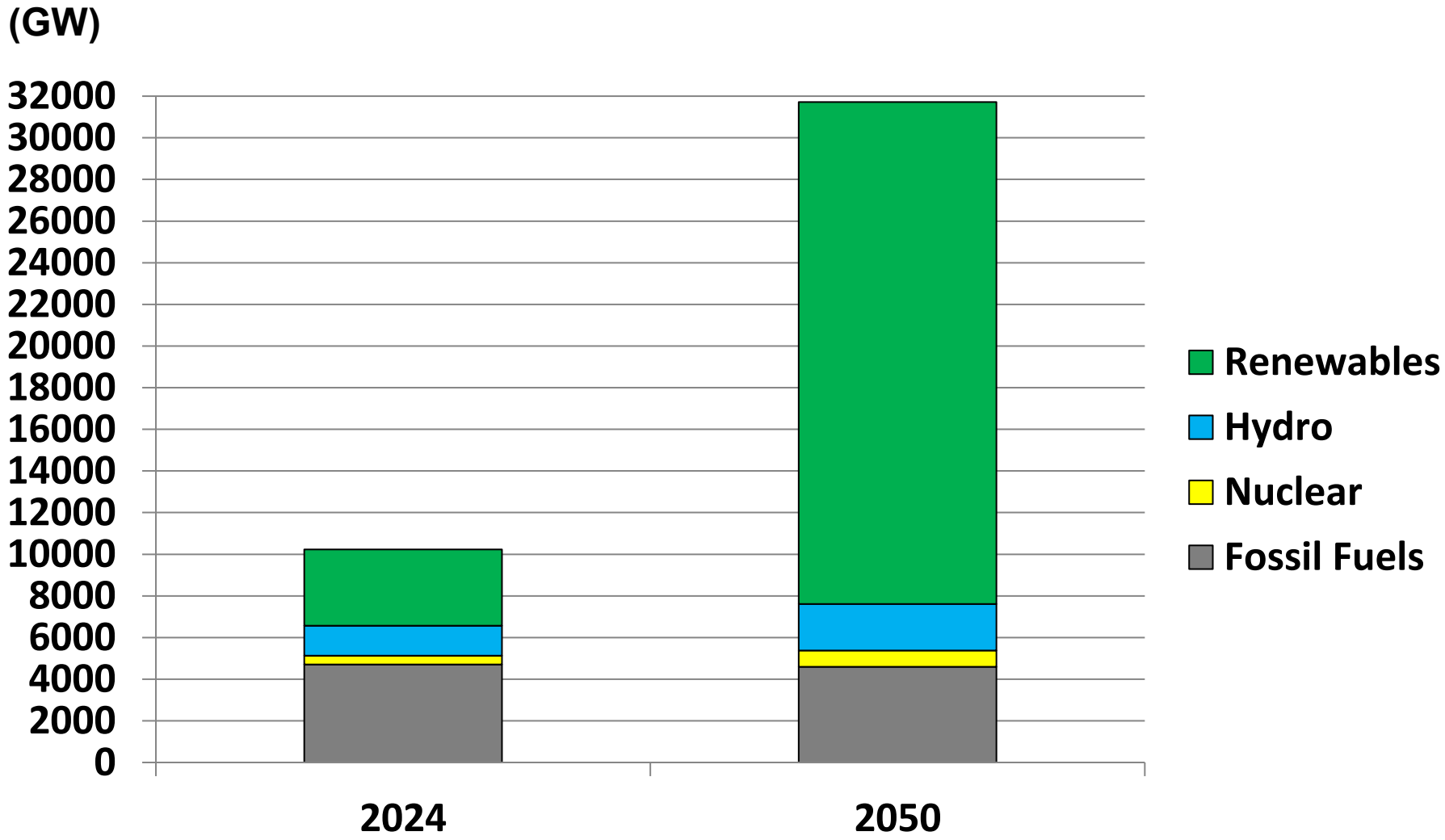
Source: RTE 2024 Electricity Review

Contribution of Fuels in Electricity Production in selected Regions/Countries Year 2024 - Fossile: Coal, Gas & Oil



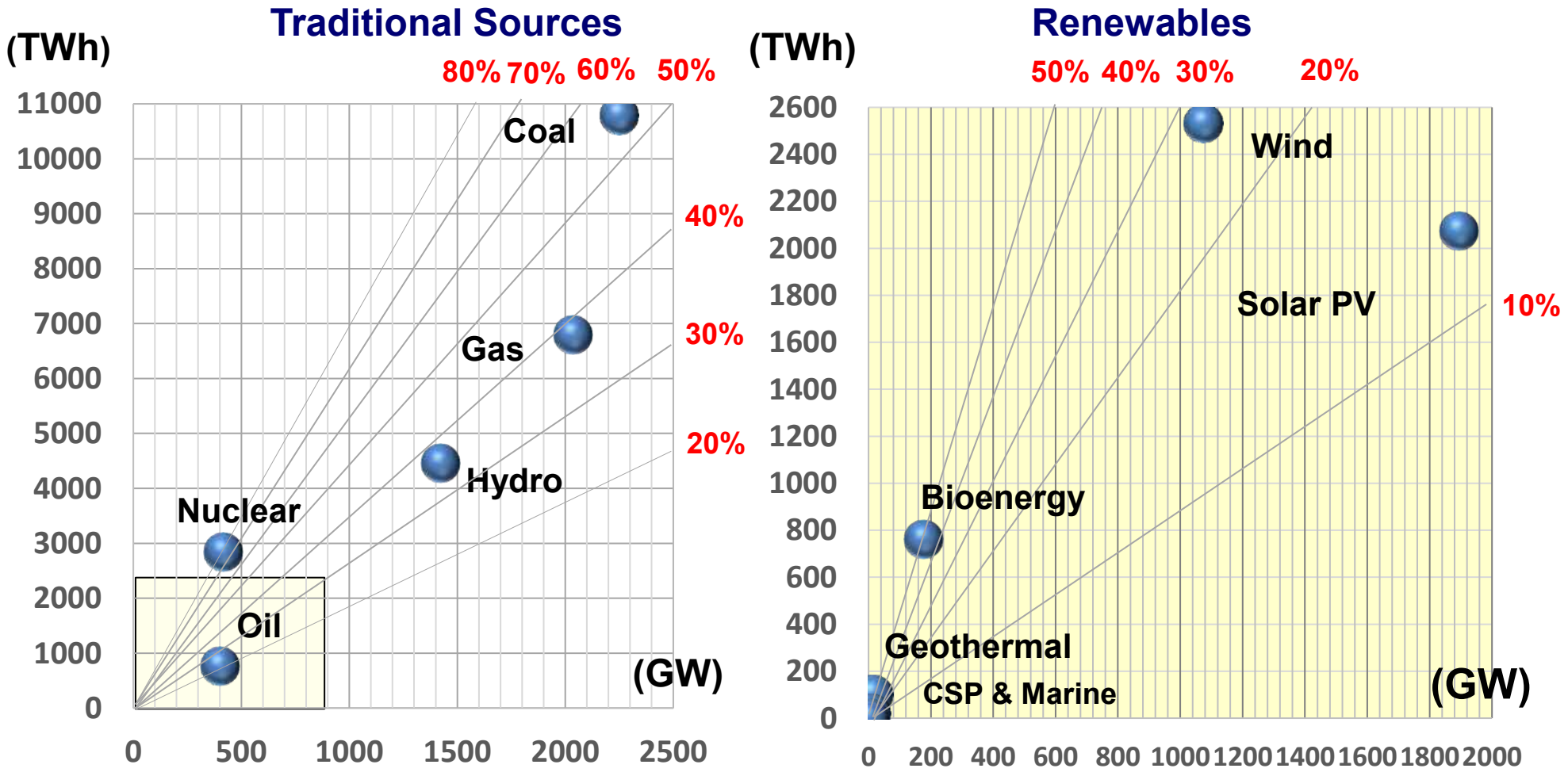
Source: Data from IEA WEO 2025 & EI Stat. Review 2025

World Electricity Generation Capacity (IEA WEO 2025 STEPS) x 3 from 2024 to 2050



Source: Data from IEA WEO 2025
Capacity includes Battery storage

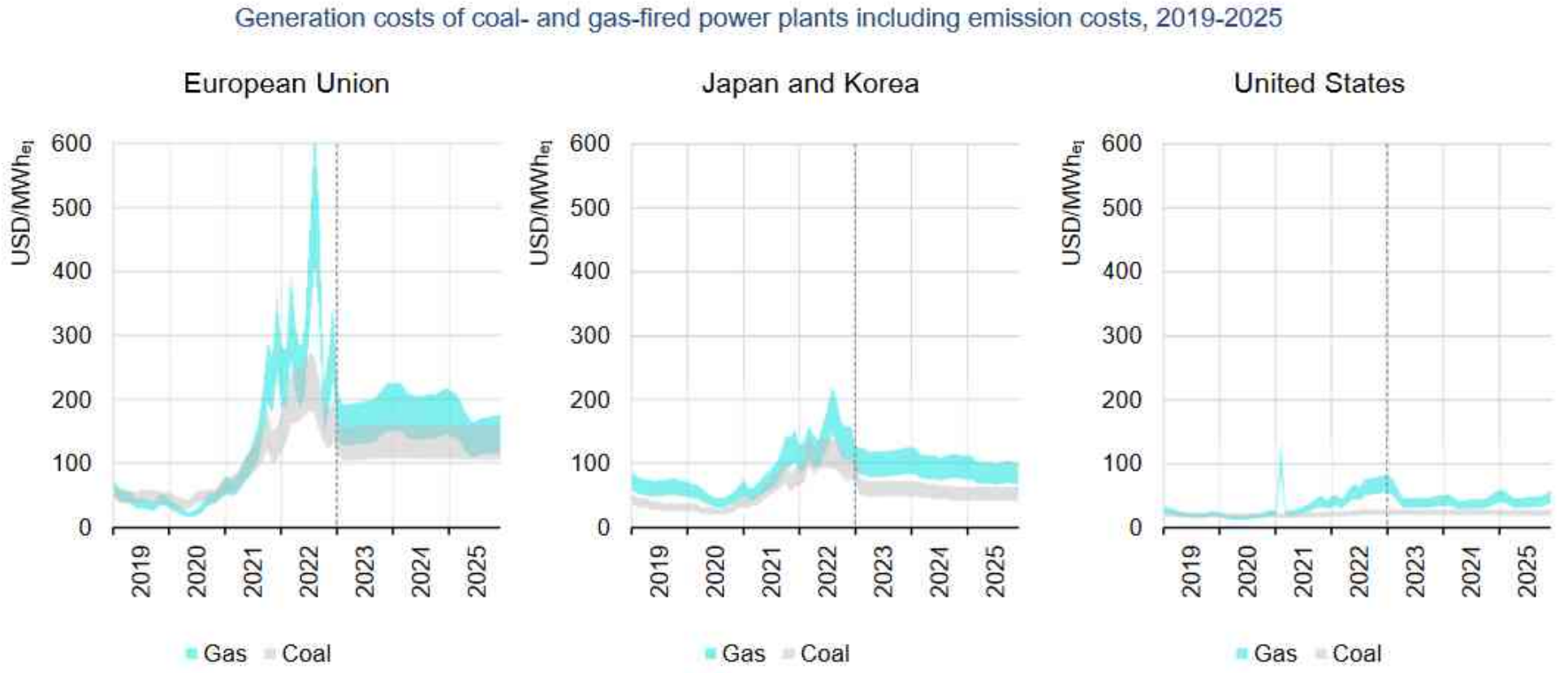
Capacity Factors(CF)* for Electricity Generation according to Technologies – World/Year 2024



Source: Ch.Guéritte/Data from IEA WEO 2025

- CF = Production/Average Capacity 2022-2023x24 hoursx365 days
  = Production/Average Capacity 2022-2023x8760 hours

World Electricity Generation Costs for Gas & Coal by Regions IEA 2023



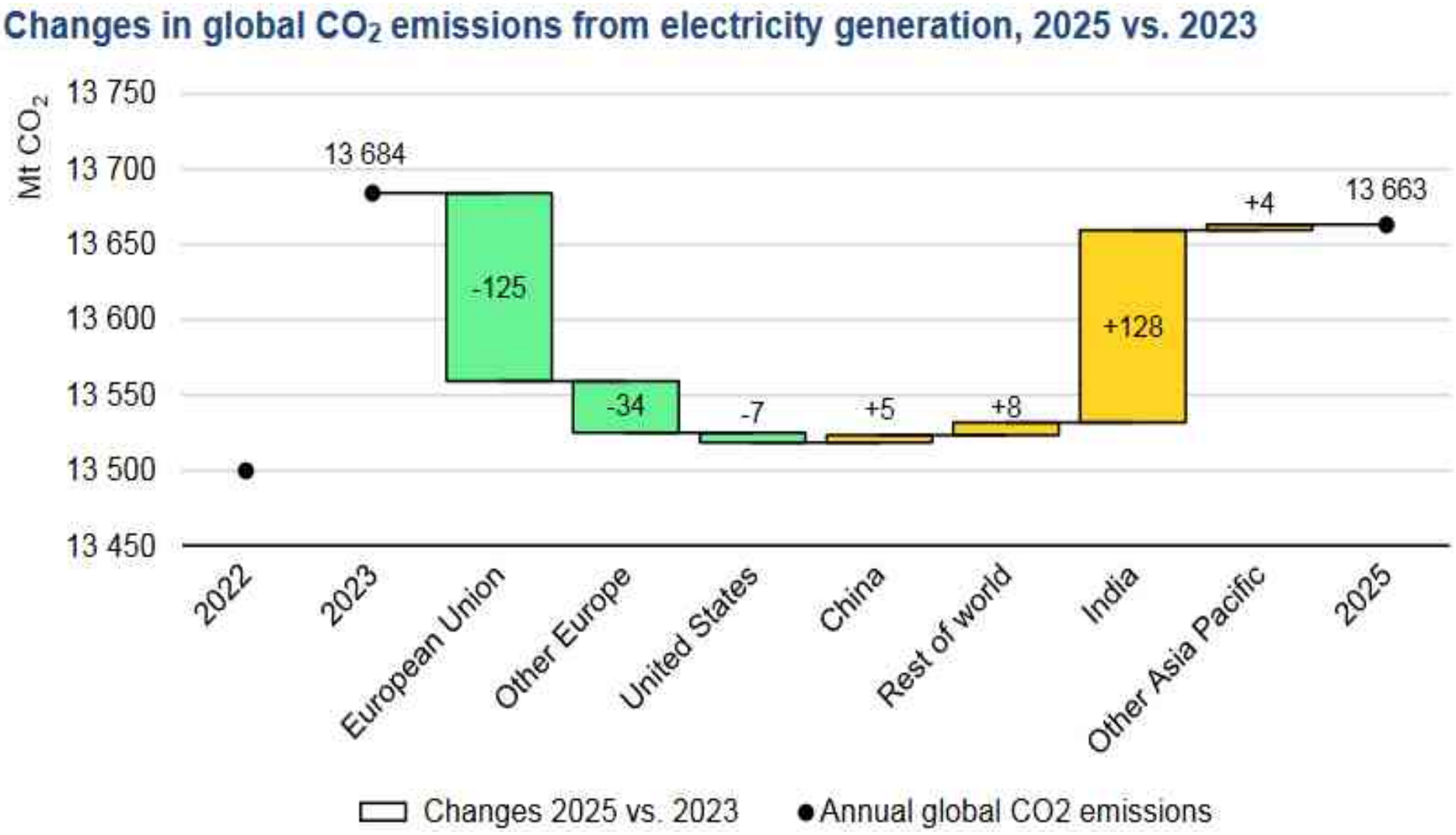
IEA. All rights reserved.

Notes: Coal range reflects 33-45% efficiency; gas range reflects 43-55% efficiency. Due to the large geographic areas covered in each region, costs can differ between and within countries and should therefore be interpreted as general trends. In the United States, natural gas prices increased significantly (exceeding USD 15/MBtu) in February 2021 due to supply constraints. 2023-2025 costs for the regions are based on forward prices of fuels as of end of January 2023 and should not be interpreted as forecasts, rather as costs reflecting the current market expectations. Fuel price assumptions for the model forecasts presented in this report are based on average forward prices.

Sources: United States: based on EIA (2023), STEO January 2023. European Union: natural gas prices TTF; coal prices CIF ARA; emission costs EU ETS. Japan and Korea: natural gas prices reflect estimated LNG import prices, including via oil-indexed LNG contracts and spot procurements; coal prices are Japan marker prices. Latest update: 31 January 2023.

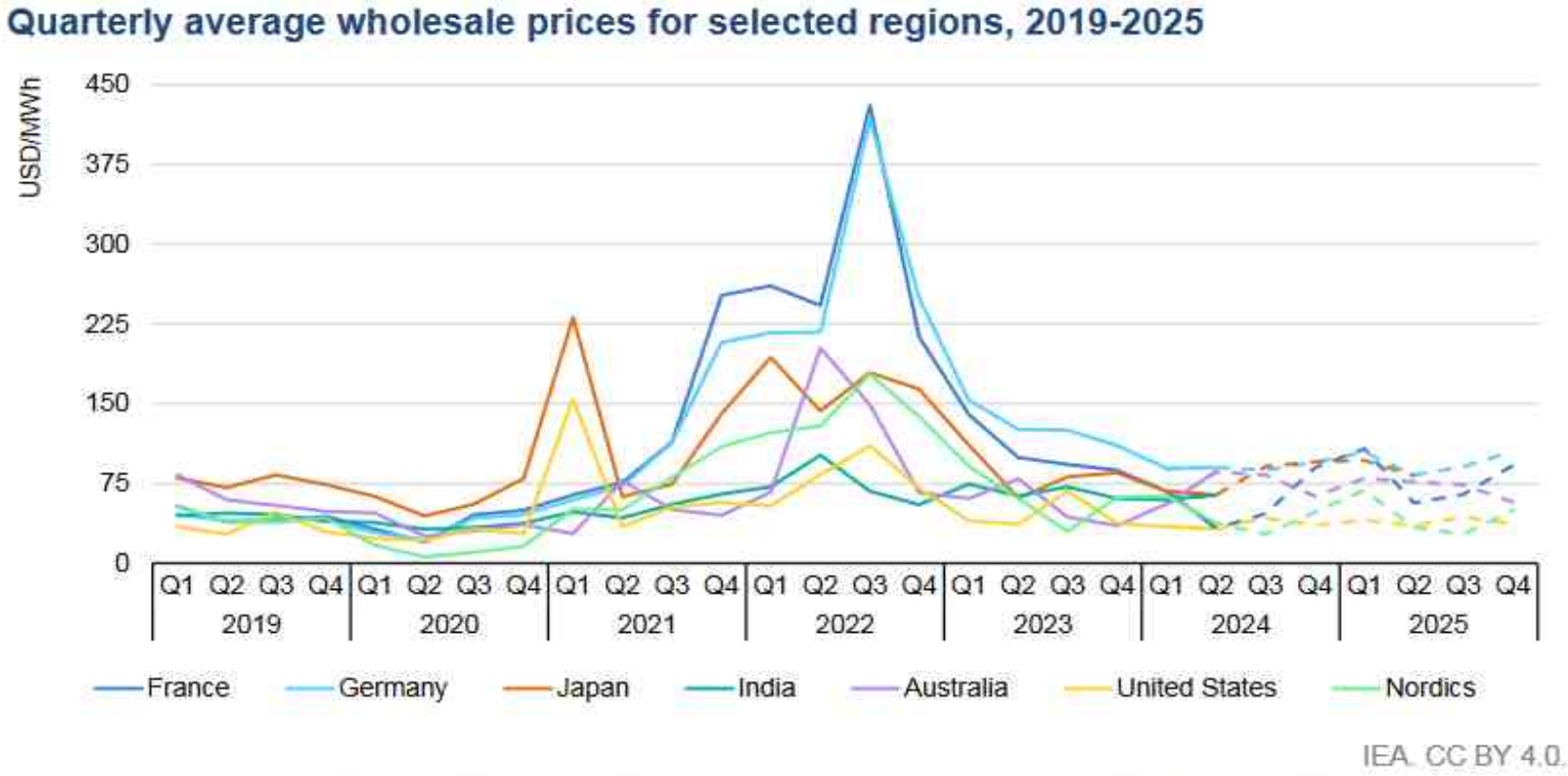
Source: IEA Electricity Market Report 2023

World Electricity Generation CO_2 emissions by Regions IEA 2024



Source: IEA Electricity Mid-year Update 2024

World Electricity Price evolution by Regions
IEA 2024



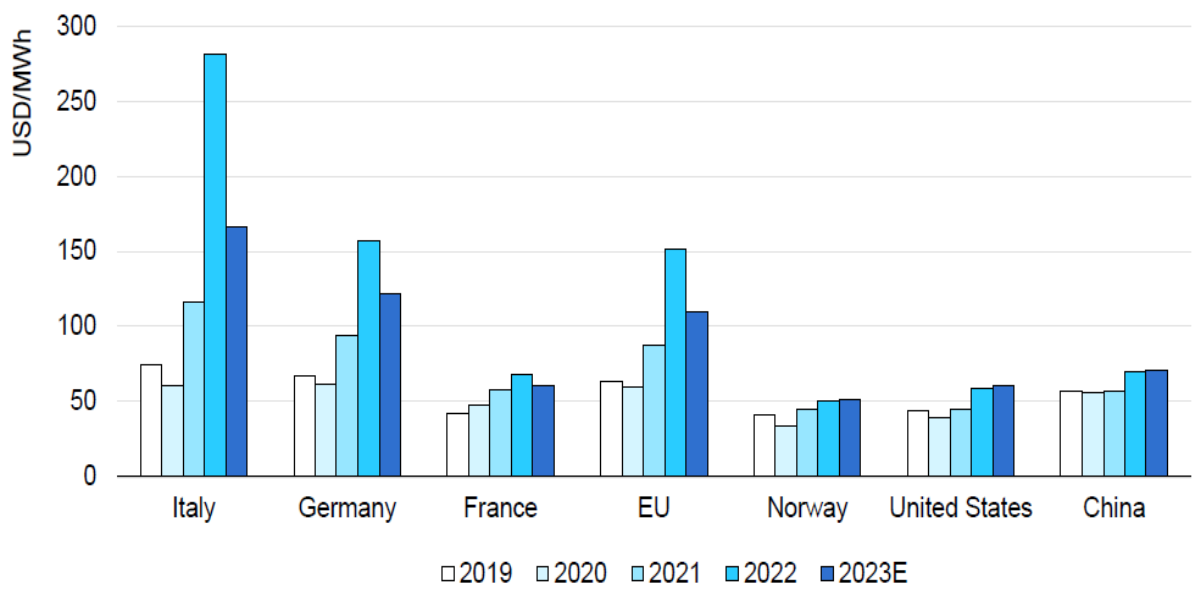
Notes: The prices for Australia and the United States are calculated as the demand-weighted average of the available prices of their regional markets. Continuous lines show historical data and dashed lines refer to forward prices.

Sources: IEA analysis based on data from RTE (France) – accessed via the ENTSO-E Transparency Platform; Bundesnetzagentur (2024), SMARD.de; AEMO (2024), Aggregated price and demand data; EIA (2024), Short-Term Energy Outlook, July 2024; IEX (2023), Area Prices; EEX (2024), Power Futures; ASX (2024), Electricity Futures © ASX Limited ABN 98 008 624 691 (ASX) 2020. All rights reserved. This material is reproduced with the permission of ASX. This material should not be reproduced, stored in a retrieval system or transmitted in any form whether in whole or in part without the prior written permission of ASX. Latest update: 11 July 2024.

Source: IEA Electricity Mid-year Update 2024

World Electricity Price evolution by Regions
IEA 2024

Estimated final electricity price for large industrial customers in energy-intensive industries, 2019-2023

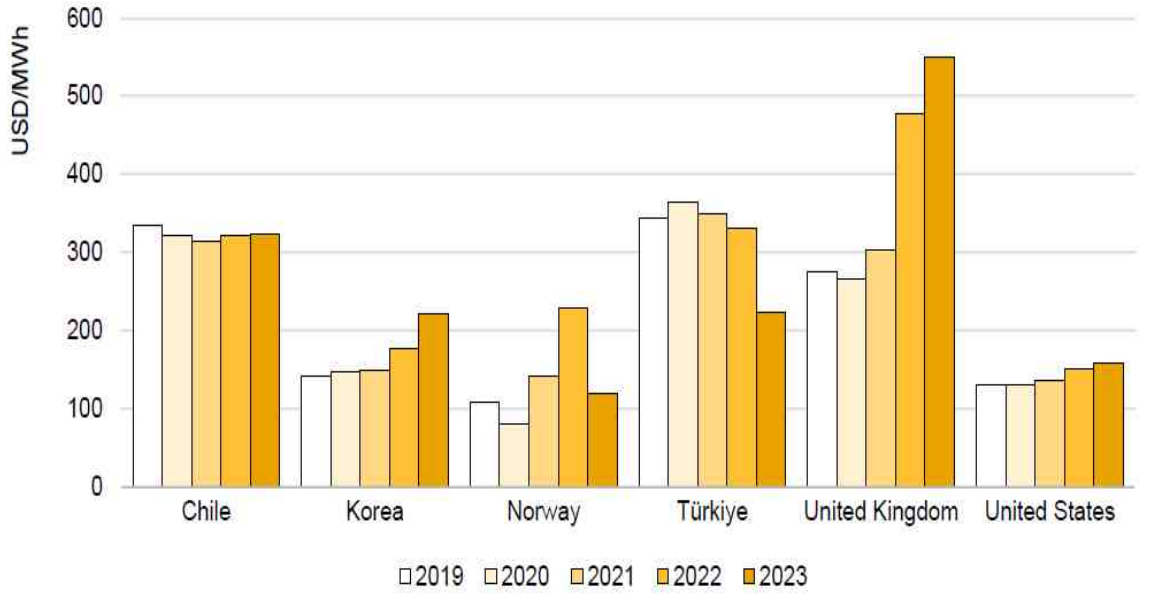


IEA. CC BY 4.0.

Notes: The analysis considers electricity costs of industries with greater than 150 GWh of annual electricity consumption for the European countries, based on Eurostat data. Electricity price compensation included for countries that participate in EU-ETS. For the calculation of the maximum possible state aid for electricity price compensation in European countries, the analysis assumes that the specific product has an electricity consumption benchmark of 0.8 and that the company in question receives the maximum possible state aid once this benchmark is incorporated into the maximum aid calculation. The prices for the US and China are indicative of the average reported prices; individual industries depending on their energy consumption levels and where they are located can face different prices.

Sources: IEA analysis based on IEA end-use prices database; data from Eurostat (2023); Official Journal of the European Union (2021), Southeastern U.S. Industrial Rate Survey; Brubaker & Associates (2023); Shanghai Metals Market (2023); Intercontinental Exchange (2023), EUA Futures (Accessed November 2023).

Average household electricity prices in USD/MWh in purchasing power parity (PPP), 2019-2023



IEA. CC BY 4.0.

Note: Residential electricity prices include taxes and have been converted from local currencies to USD/MWh (PPP) using PPP conversion rates provided by the IMF PPP database. 2023 value is the average of Q1-Q3 2023 for all the countries except Chile, which is based on Q1-Q2 2023 average. The countries shown here are chosen due to data availability for 2023 as the time of publication of this report.

Sources: IEA electricity prices database, IMF, PPP database.

Source: IEA Electricity 2024

Electricity Price – Specificities in the French Energy system

Electricity Prices depend upon several factors:
- Production, storage, transport, marketing costs.
- Production costs depend upon availability of nuclear park, wind and solar capacity factors from time to time.
- Taxes (CTA, TVA, TCFE, CSPE)
- Price of Gas for Electricity imports.
- CO_2 price, depending of quotas and resulting from the European ETS (Emission Trading System).

Prices are particularly connected with the trends of the European Wholesale market.
Before being proposed to the final consumers (households & enterprises) through the Retail market, Electricity is purchased and sold to Electricity producers operating power plants on the European Wholesale market (on the spot or future markets)
At any time, production must be adapted to the demand. On the European Union market, the Wholesale price of Electricity is determined by the marginal cost of the last Gas power plant which balances supply and demand.

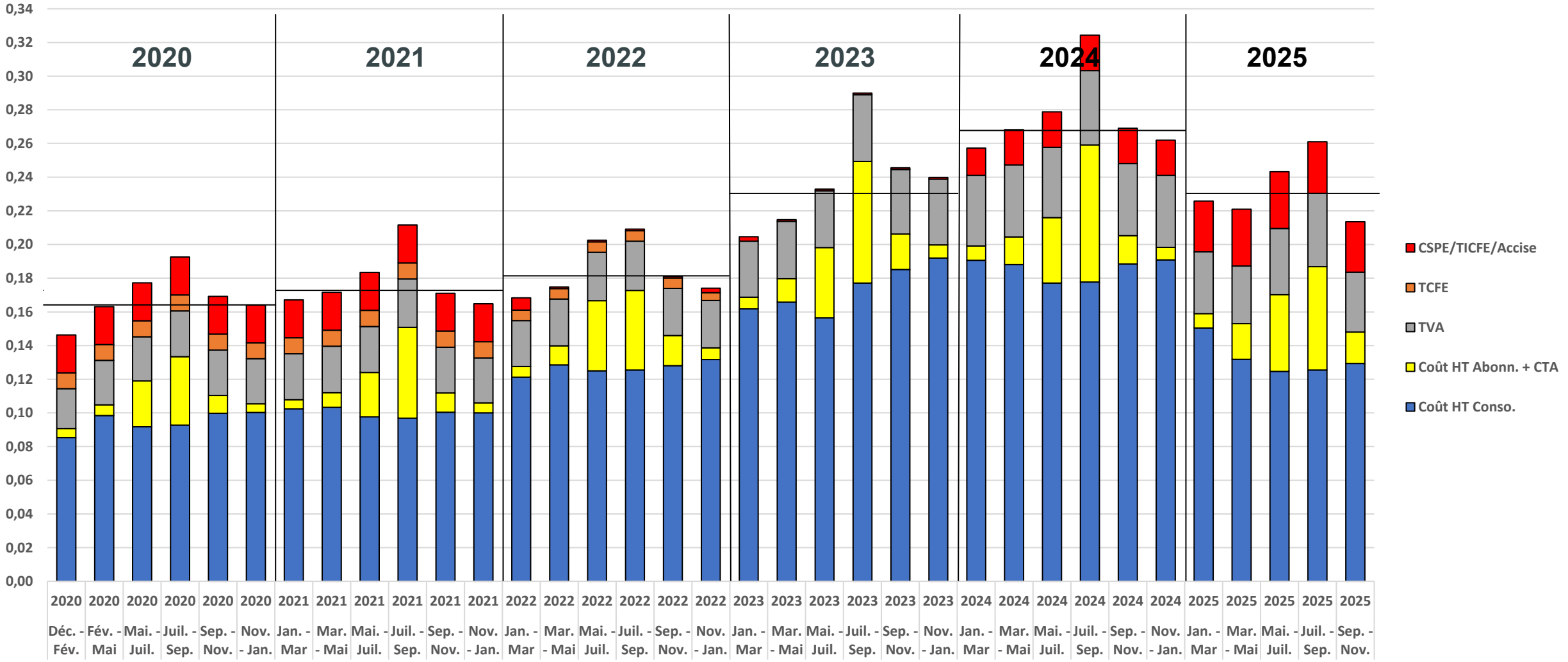
Then, the historical supplier (EDF) or alternative suppliers propose a contract to the final consumer, through regulated, fixed tariffs, market prices, etc.

Since 1996, the french Gas and Electricity market has been open to competition, 1999 for enterprises, 2007 for households. Any Electricity producer can sell to any consumer and use the network managed by RTE.
Since 2010, the NOME law (Nouvelle Organisation du Marché de l'Electricité) obliges EDF to sell ¼ and more of its electricity at a price of 42 €/MWh to alternative producers (Law ARENH, Accès Régulé à l'Energie Nucléaire Historique) The NOME law ends in 2025.

Source: IEA Electricity 2024

Electricity invoice – One example for a french consumer (€/kWh) – Le bouclier tarifaire, Quid?

TCFE & CSPE have disappeared in 2023…but are coming back as from 2024…..while market price has decreased in 2025

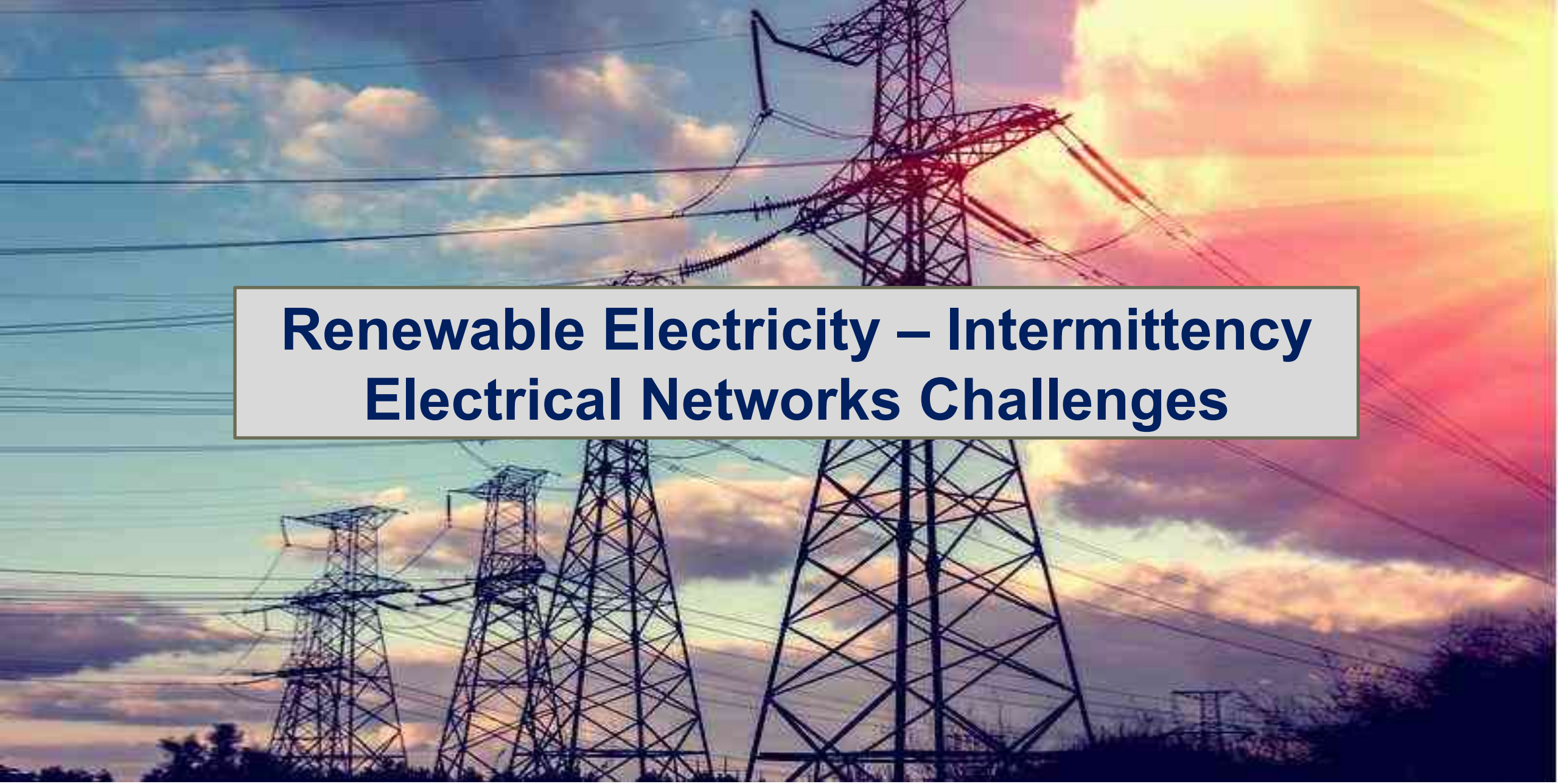


Source: Ch.Guéritte - CTA: Coût Tarifaire d'Approvisionnement - TVA: Taxe à la Valeur Ajoutée - TCFE: Taxe sur la Consommation Finale d'Électricité
CSPE: Contribution au Service Public de l'Électricité. Nouvelle appellation a/c 2016: TICFE et Accise a/c 2022.

Electricity Price – Specificities in French Energy system IEA 2024

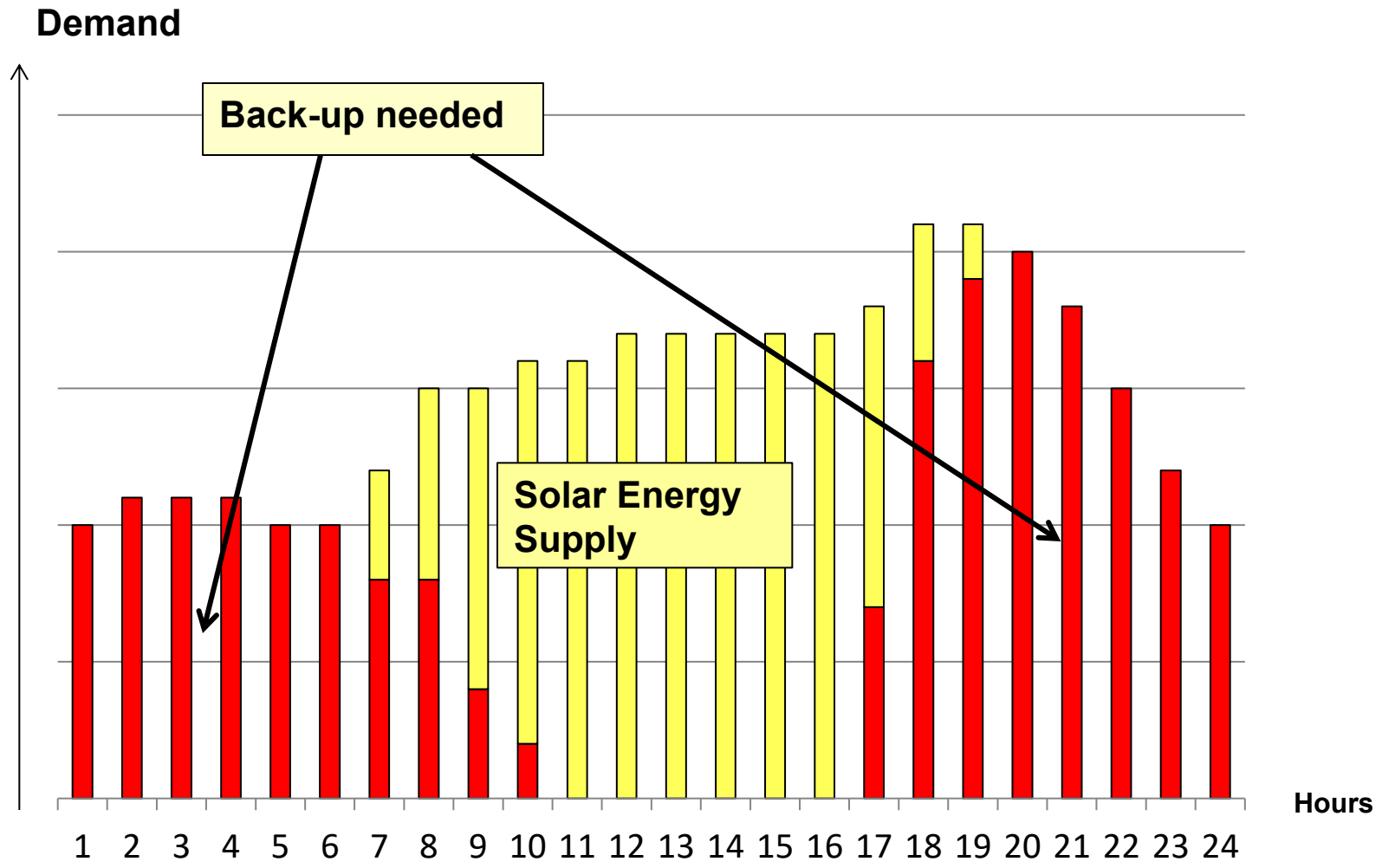
In France, the amount of nuclear power sold by French state-owned utility EDF to alternative suppliers at the regulated price of EUR 42/MWh under the ARENH law decreased from 120 TWh in 2022 to 100 TWh in 2023, which added upward pressure on prices. Expiring at the end of 2025, the ARENH scheme will be succeeded by a new agreement between EDF and the French government. It stipulates that all of EDF's nuclear generation is targeted towards an intended average price of EUR 70/MWh. The agreement aims to achieve this with a mechanism to redistribute excess profits of EDF back to consumers, where 50% of any additional revenue generated above EUR 78-80/MWh (with the exact price still to be determined at the time of writing of this report) would be redistributed, and 90% of all revenues exceeding a price of EUR 110/MWh. These thresholds are regularly renegotiated. The agreement remains subject to approval by the European Commission.

Source: IEA Electricity 2024



Renewable Electricity – Intermittency Electrical Networks Challenges

Illustration: Typical winter daily Demand for Electricity (Example: Europe)



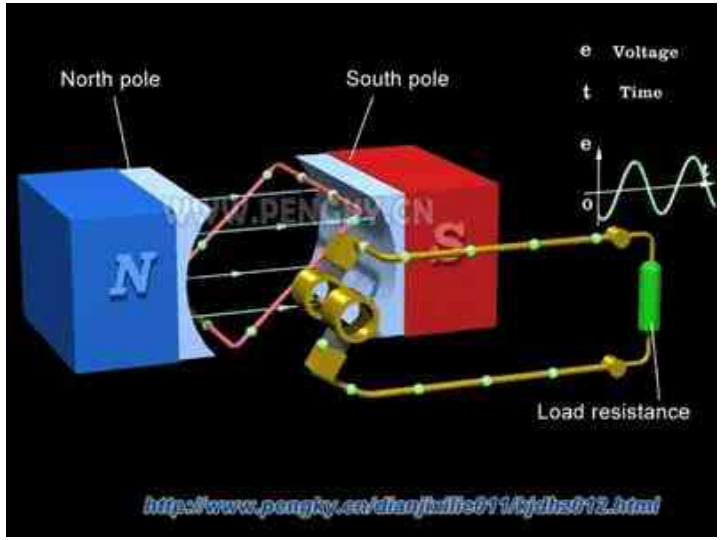
Basic reminders on Electricity Markets

The Electricity Market evolution

- **Electricity Market: a system which organizes the exchange of Electricity - related goods and services.**
- **During the last few years, a restructuring, deregulation of Electric Power Industry took place in many countries.**
- **The vertically integrated and regulated traditional Electricity Market → Multiple competitive markets for Electricity generation, transmission, distribution, and retailing.**
- **Electricity: A public service → A tradable good (like crude oil)**
- **As of 2020s, traditional markets are still common in some regions, including large parts of the United States and Canada.**
- **In Europe most countries secure the electricity supply via a national grid.**
- **Off-grid solutions exist in many developing countries, particularly to provide cost-effective access to electricity in rural and sparsely populated areas.**

Electricity: the physical constraints

- Electricity: **difficult to store, has to be available on demand.**
- **The supply shall match the demand very closely at any time** despite the continuous variations of both.
- The **safety margins are provided by the kinetic energy of the rotating machinery** (turbines and synchronous generators delivering alternative current) which produce Electricity in traditional power plants.
- If there is a **mismatch at any time between supply and demand, 2 cases**:
  - Demand exceeds Supply: generators slow down causing the utility frequency to decrease. Generation is increased by conventional energy (Hydro, CCGT, ..)
  - Supply exceeds Demand: generators speed up causing the frequency to increase. Generation is reduced by putting power plants off the grid.
- Frequency: **50 Hertz** in European countries, **60 hertz** in North America) In case of out-of-bounds frequency, generators automatically disconnect from the grid to protect themselves, leading to a **potential blackout.**
- The Electricity storage issue is essential. The **intermittency of Renewable Energy** (Solar and Wind) is creating more challenges on the storage issue. The Industry is currently developing new technologies to build-up **large electricity storage facilities**.

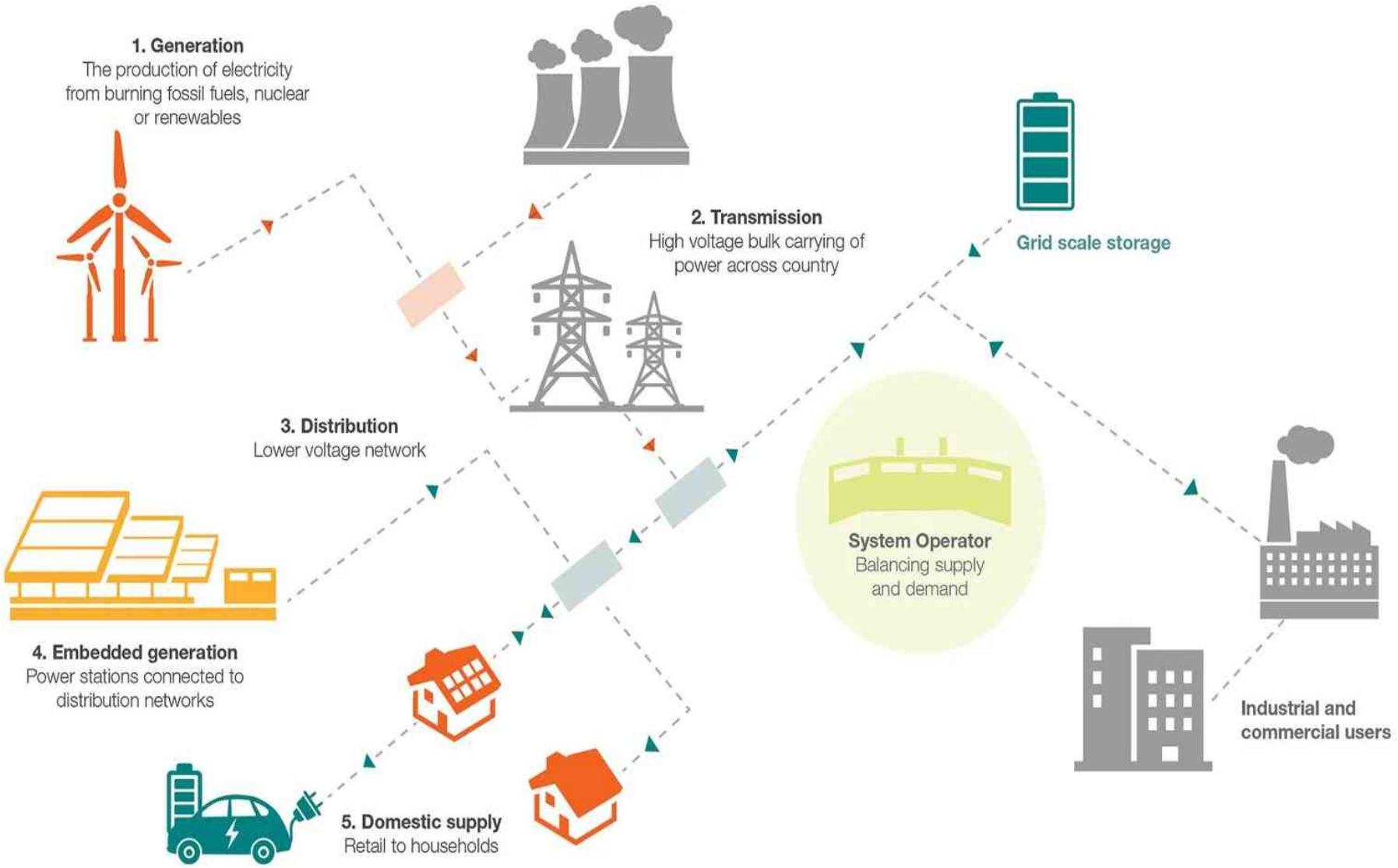






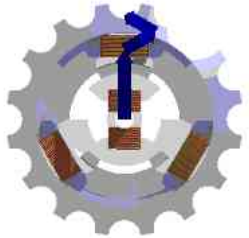
Example: 2 magnetic poles, 1 North & 1 South
Number of pair of poles: n = 1
Rotation speed: Ω = 3000 rotations/mn
Frequency: f = nxΩ/60 = 50 Hz

Electricity Market: How does it work?

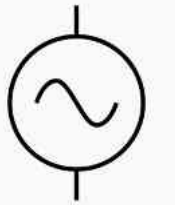












Electricity Market: How does it work?

➢ A basic tool: the Wholesale electricity market

The **wholesale market** is where electricity is traded (bought and sold) before being delivered to end consumers (individuals, households or businesses) via the grid.





➢ Balancing supply and demand

In physical terms, the wholesale electricity market plays a central role in the operation of the power system, by allowing the supply of electricity to be balanced with demand through the **Balancing Mechanism**.



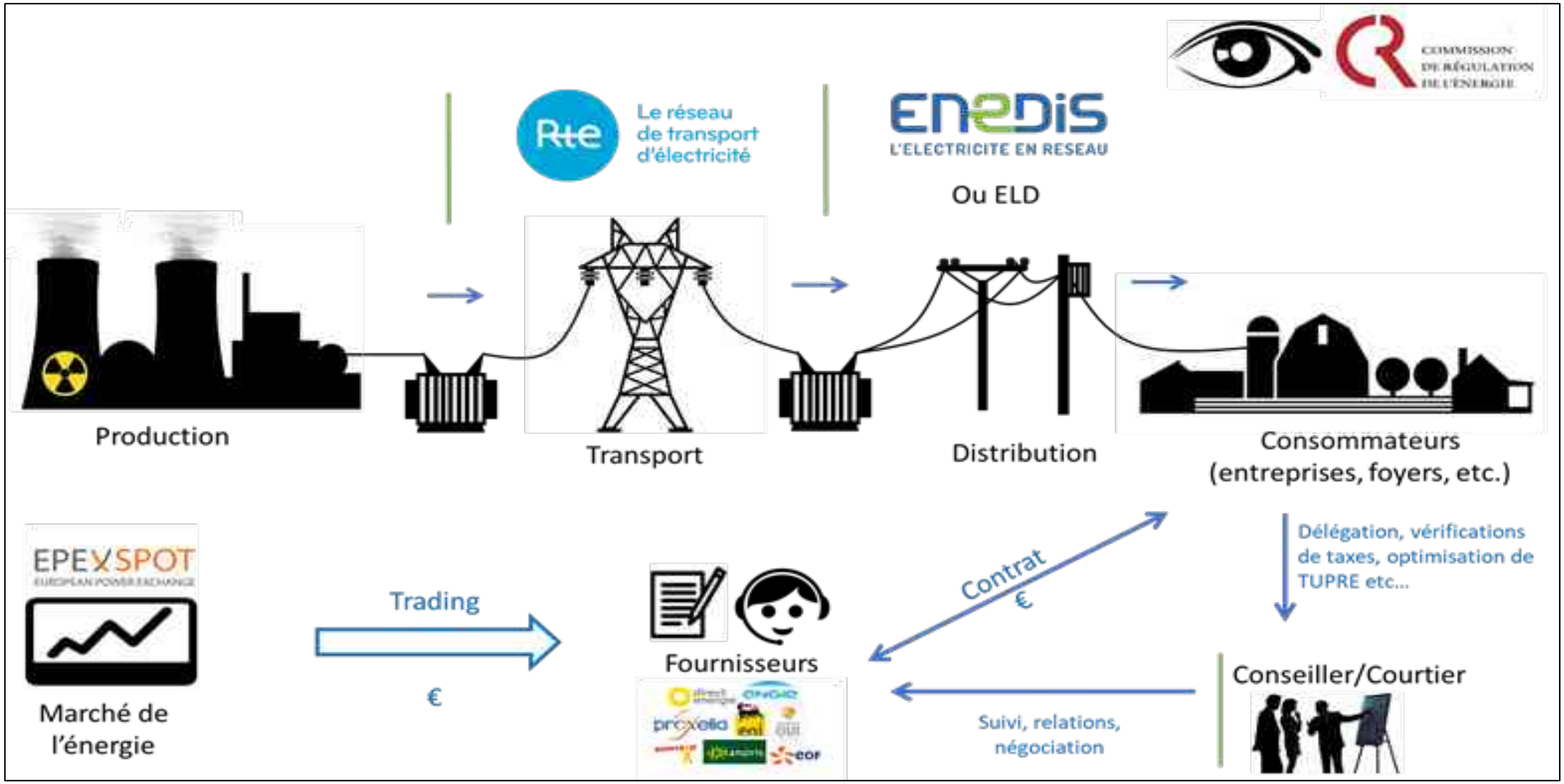
At the top of the chain, Electricity injected into the network comes from the following sources:
generating facilities (nuclear power plants, thermal power plants, solar farms, wind farms and others) plus imports from other countries.



At the end of the chain, Electricity is extracted from the network to satisfy end consumption and export to other countries.

An illustrative Business Case - France

The Electricity Market in France



Average daily Electricity Consumption - France

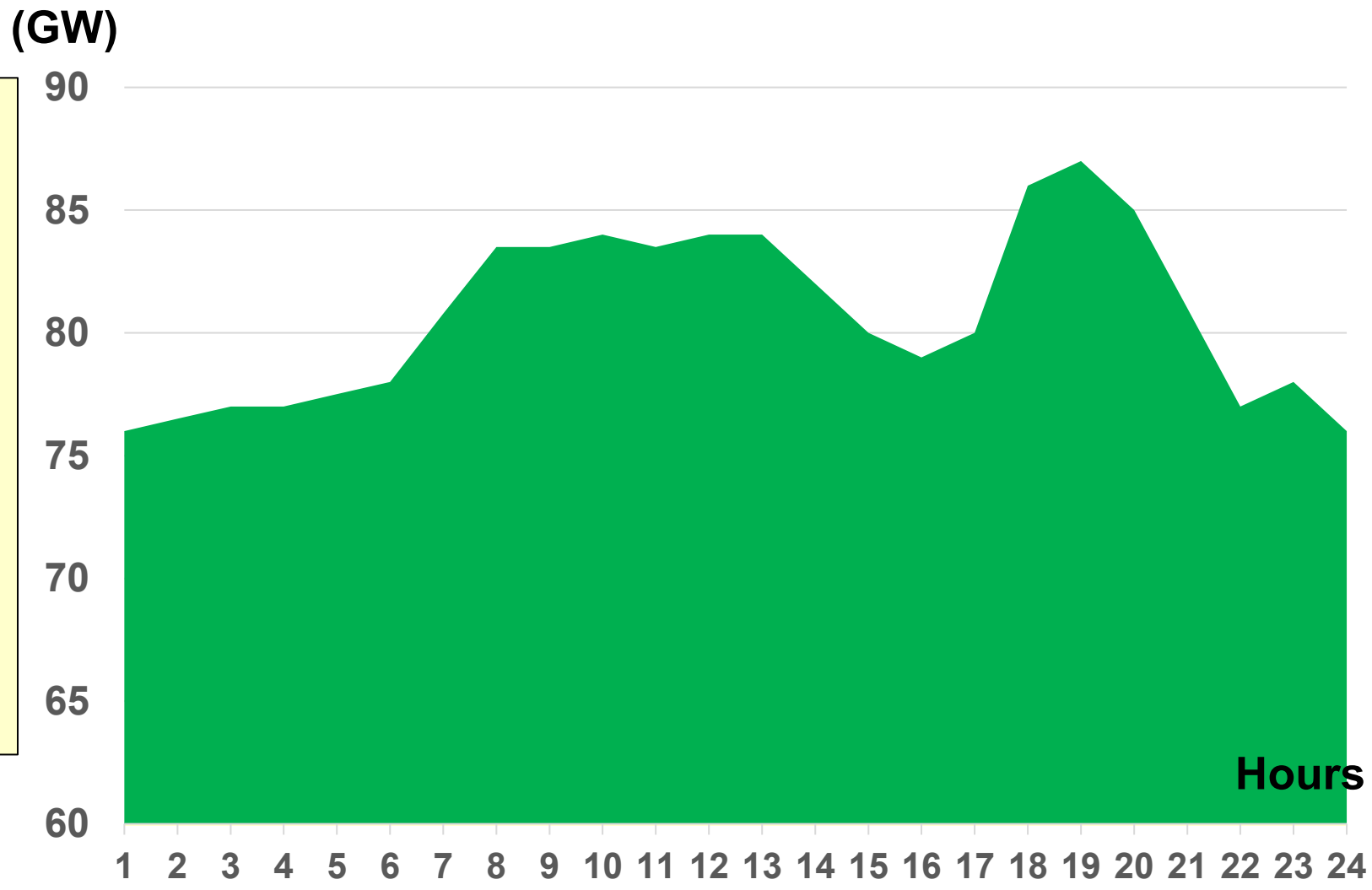
Year 2024

Maximum Winter Demand:
87 GW

Gross Electricity Consumption 2024:
449 TWh

Gross Electricity Consumption per capita (Industry & Residential):
6700 kWh

Household Electricity Consumption per capita:
2220 kWh



Source: ChG/Data from RTE/Hello watt
RTE: Réseau de Transport d'Électricité

Illustration of Electricity Demand & Supply

Let's consider a city of 100000 inhabitants, whose Electricity Consumption is homothetical to the standard average Demand curve.

Electrical Power needed: 50 MW.

Electricity is supplied by priority by a Wind onshore farm and a Solar farm. The remaining need/Back-up is supplied by a CCGT Power Plant or a Nuclear Plant

Solar and Wind Supplies follow the typical Production curve homothetical to the standards curves given by RTE (See next slide)

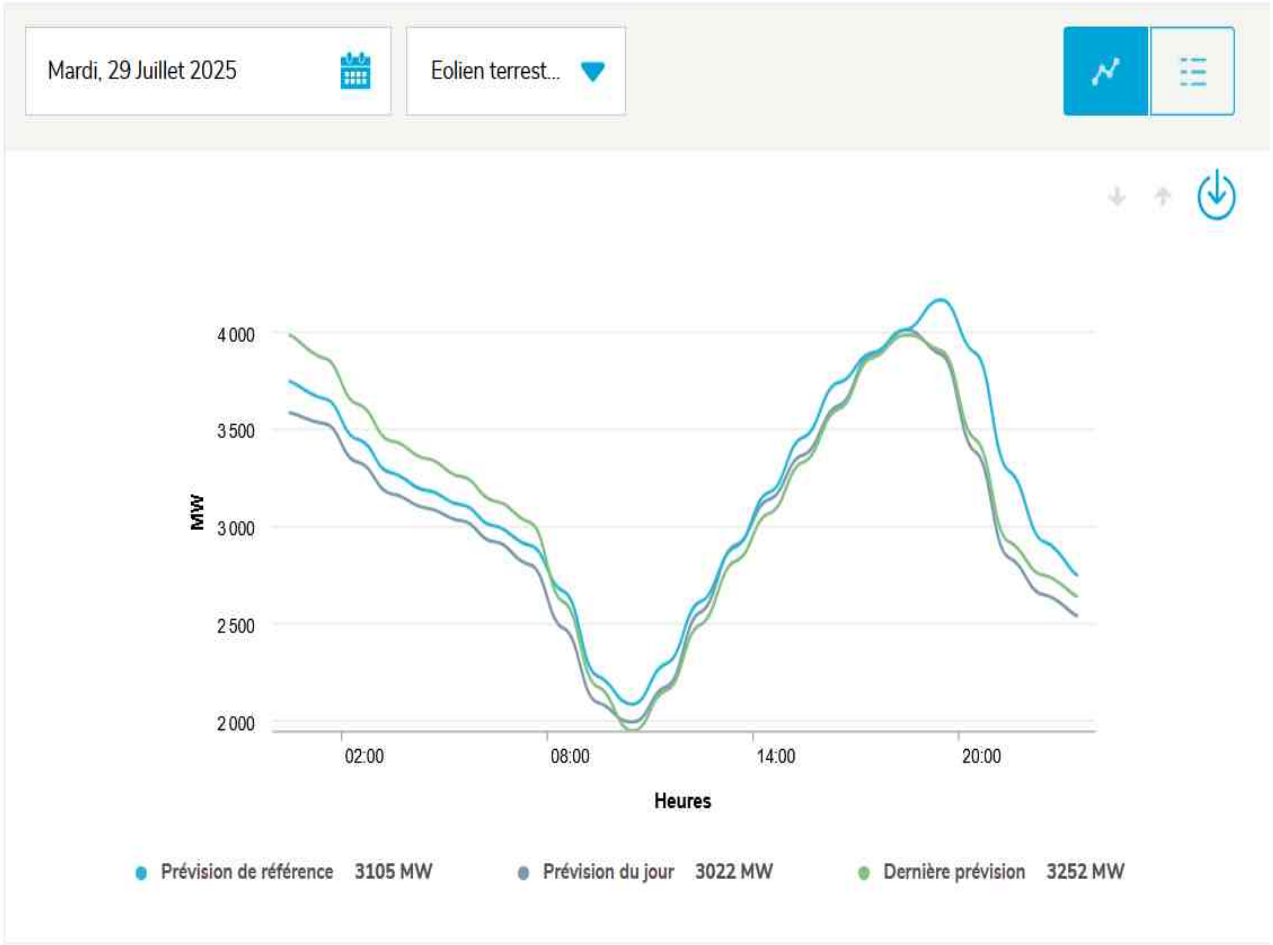
Solar Energy Supply: 30 MWp

Wind Energy Supply: 8 Wind turbines, 5 MW each = 40 MW

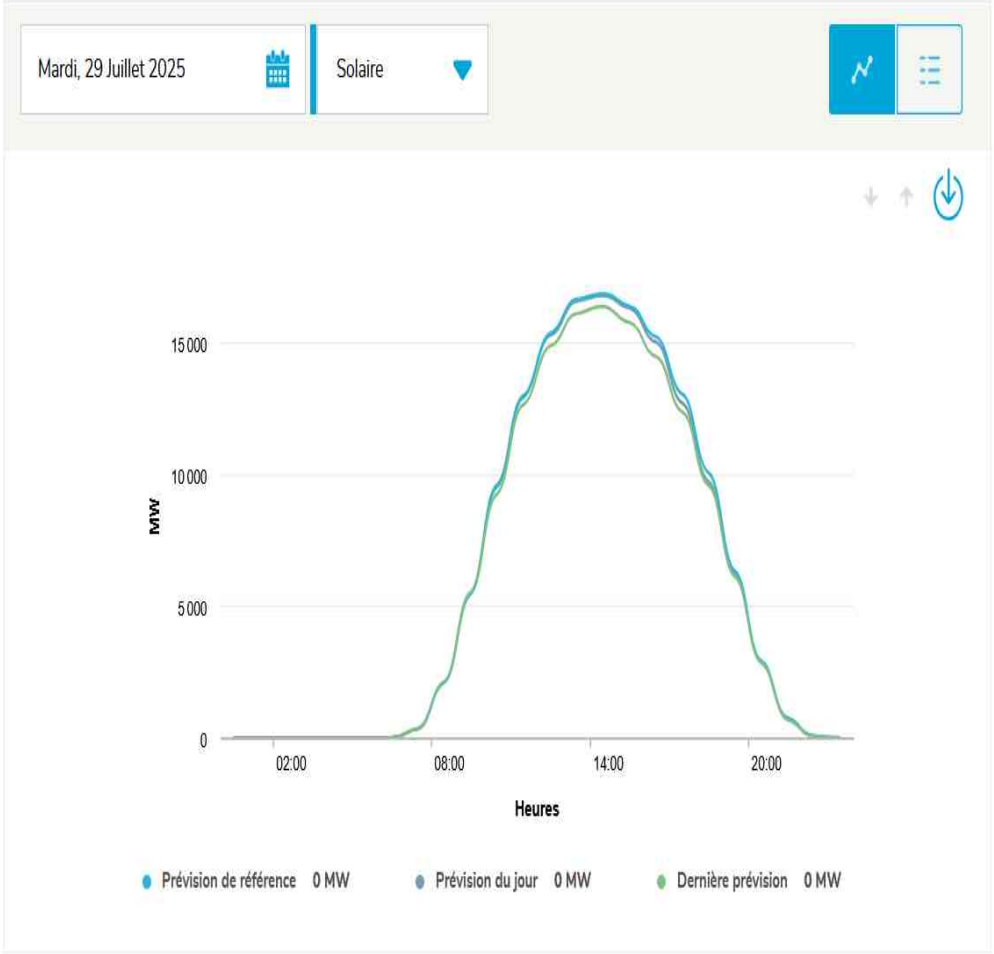
CCGT (Combined Cycle Gas Turbine): 600 MW. This Power Plant feeds other facilities.

Illustration of Electricity Demand & Supply

Wind onshore Production

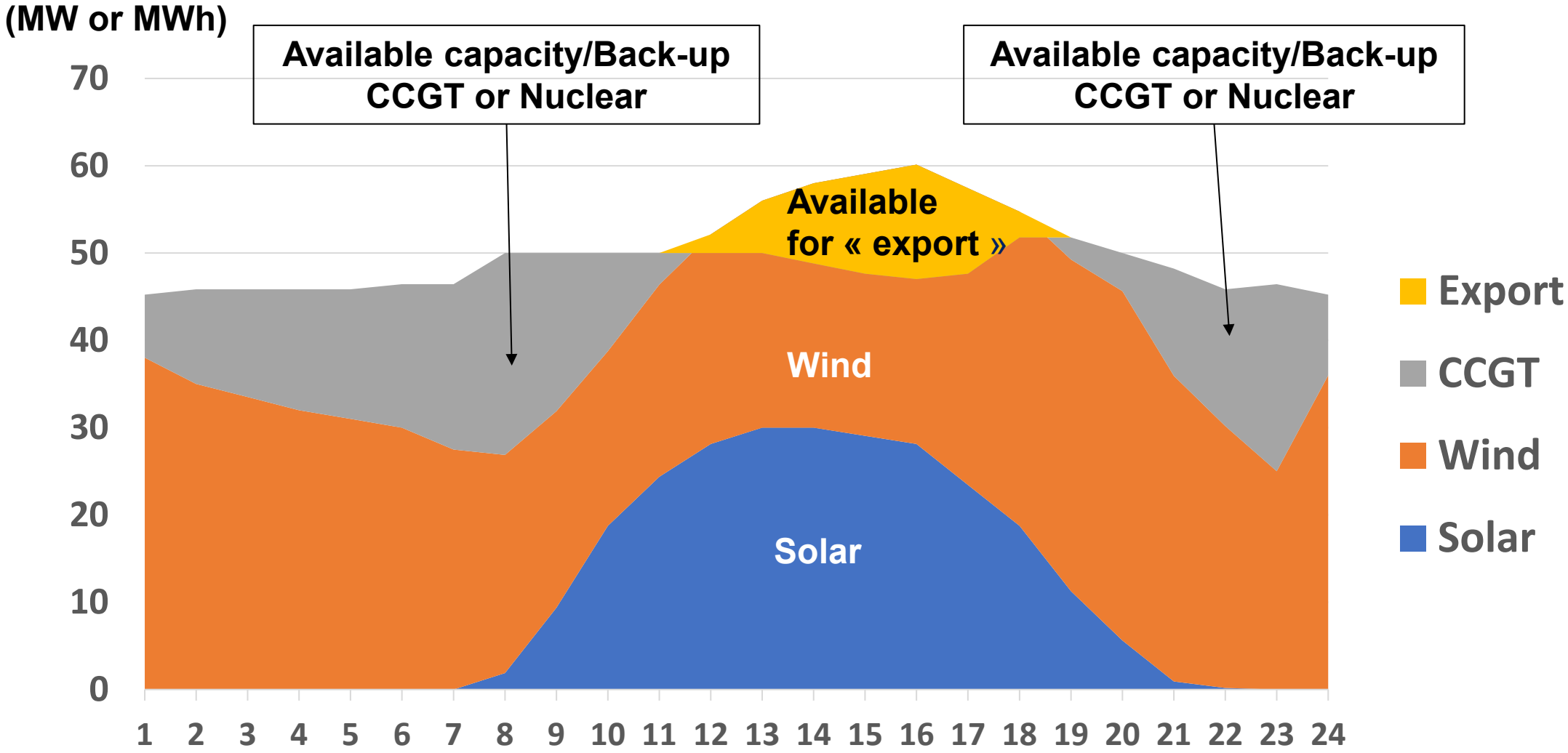


Solar Production



Source: RTE 2025

Illustration of Electricity Demand & Supply



Source: ChG/Data from RTE. Nota: 1 MWh corresponds to 1 MW produced within 1 hour

The Challenges to get the benefits of Energy Transition through Renewable Energy

Intermittency of Wind and Solar Energy has an important impact on the management of the global Electricity Supply.

The Demand for Electricity is going to grow for the next decades.

Back-up solutions (Nuclear, Hydro, Gas turbines, ….) must be available in all circumstances.

Energy Storage capacities must be developped.

The extensive development of Wind and Solar Energy could lead to an overcapacity of Electricity Supply which could be wasted if no outlet.

Grid interconnections between electrical networks must be massively developped also taking into account the obsolescence of a number of existing networks.

The relevant costs & investments are great.

The Challenges to get the benefits of Energy Transition through Renewable Energy – Some difficulties

The ENERGYMIX
Climate news that makes a difference

May 2025

A lack of transmission capacity has left 1,700 gigawatts of renewable energy projects waiting to be connected to the grid in Europe alone, depriving the continent of more than three times the new renewable capacity it would need to meet its 2030 energy and climate targets, concludes a report released last week.

In the United States, the grid interconnection queue reached 2,600 GW in 2023, the Lawrence Berkeley National Laboratory reported last April.

Contrepoints
édité par l'IREF

Juillet 2025

Un article du *Financial Times* du 13 juillet nous apprend que la situation du réseau électrique néerlandais est critique : 11 900 entreprises (y compris médicales ou de lutte contre l'incendie) et des milliers de maisons neuves sont en attente de connexion au réseau. Ces files d'attente ont doublé depuis 2023.
En effet, les opérateurs de réseaux de transport et de distribution électriques du pays n'arrivent pas à tenir le rythme du développement des ENRi décentralisées, dont la Hollande s'est voulue une championne. Les ménages bataves sont 31% à disposer de panneaux photovoltaïques sur leur logement contre moins de 2% en France, et la puissance éolienne installée par habitant est le double de celle de notre pays.

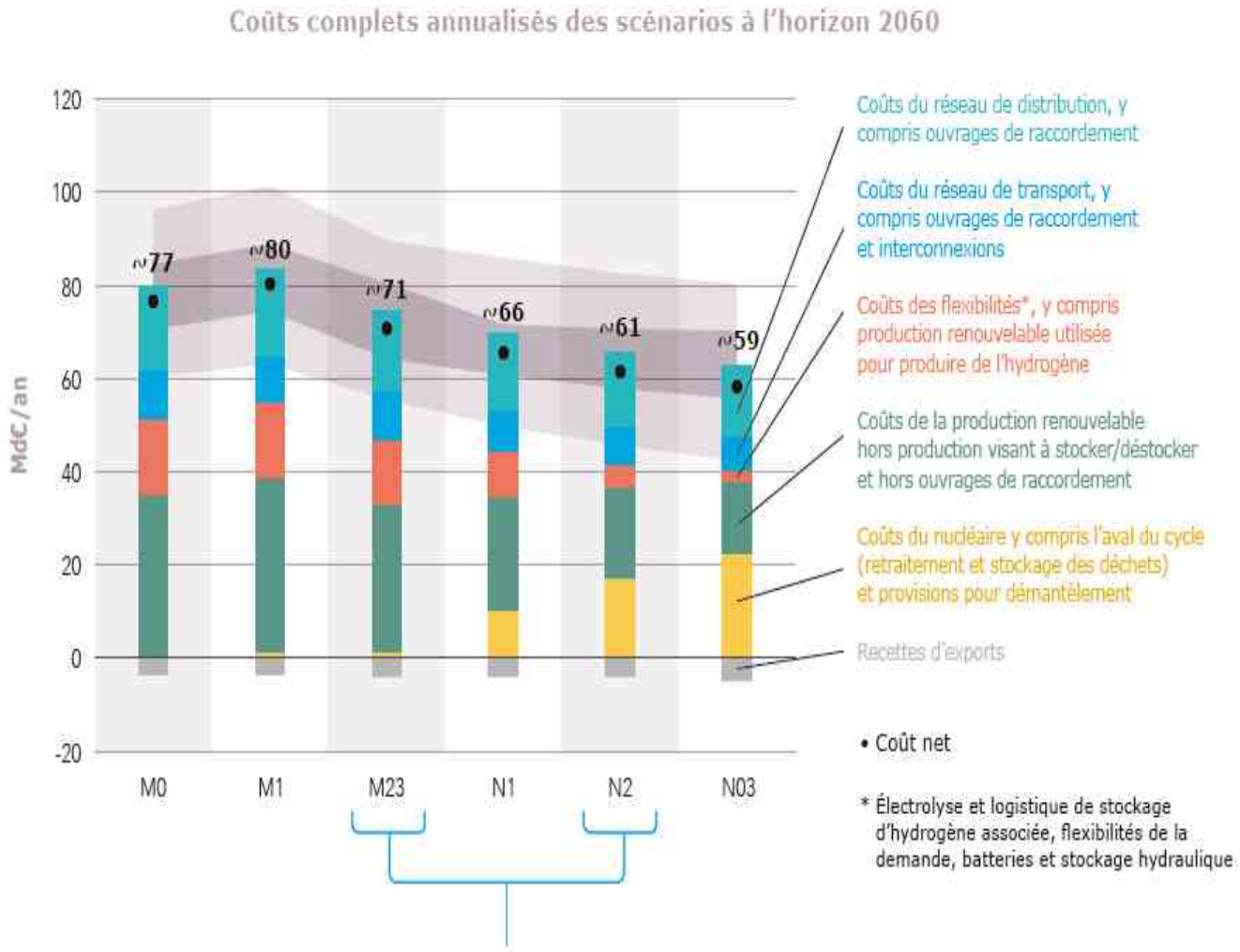
The Costs – Scenarios RTE 2060 (October 2021)

Scenario M0: 100% in 2050 (Feasible ??)

Yearly net Costs	# 77 G€
Nuclear	# 0 G€
Renewables Production	# 35 G€
Flexibility	# 15 G€
Transport & Distribution	# 30 G€
Exports	# -3 G€

Scenario N2: Renewables + existing Nuclear + new Nuclear in 2050

Yearly net Costs	# 61 G€
Nuclear	# 17 G€
Renewables Production	# 19 G€
Flexibility	# 4 G€
Transport & Distribution	# 25 G€
Exports	# - 4 G€

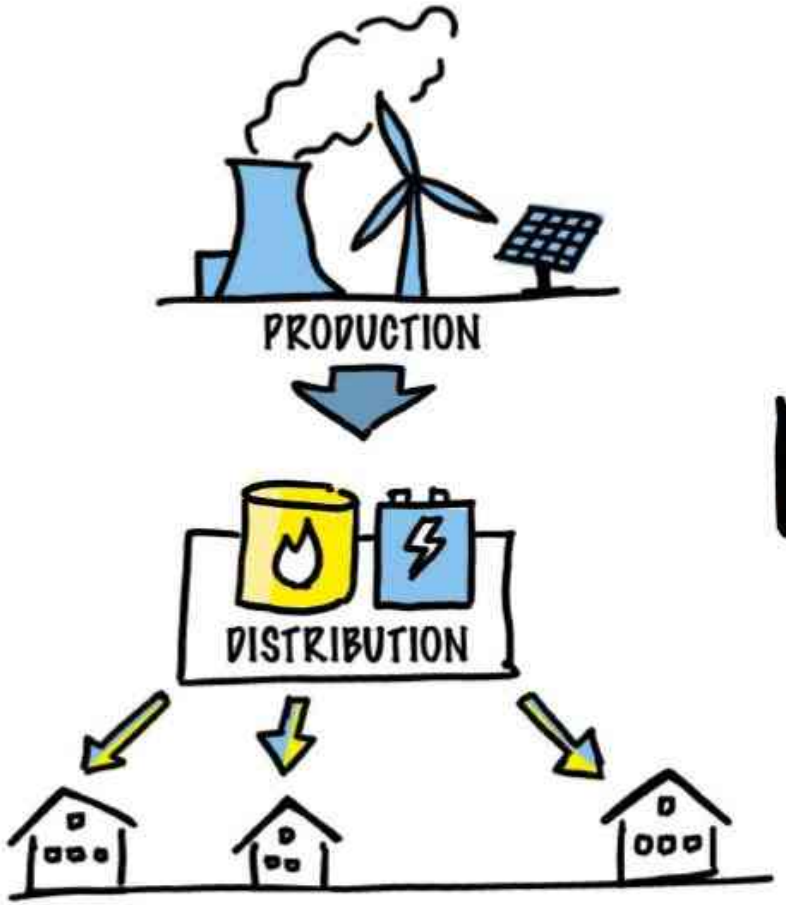


Source: RTE October 2021 – Futurs énergétiques 2050
Stratégie Nationale Bas Carbone (SNBC)

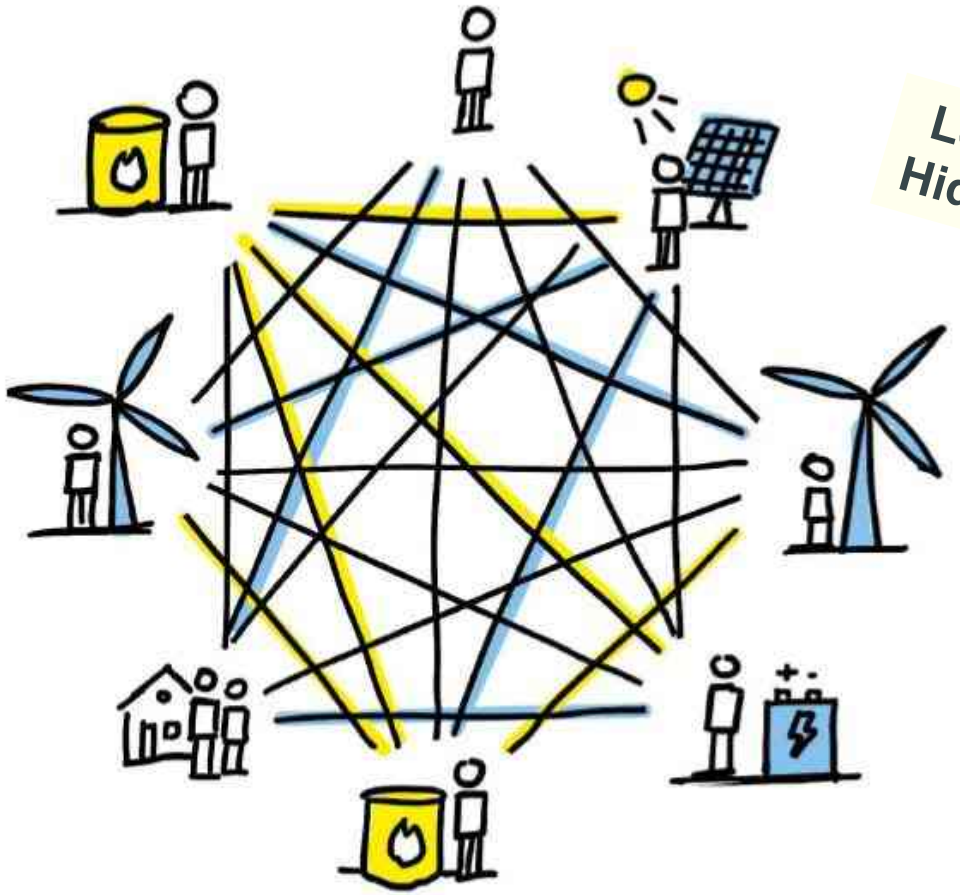
The case of Belgium

Need to reinforce the existing grid : national

Classical : Centralized production



New : De-Centralized production



Lesson #9: Hidden Cost

Source: Synergrid

Need to reinforce the existing grid : international



Need for cross-border electricity transmission, storage and peaking capacity in Europe 2040 (ENTSOE)

- To compensate intermittency (partially)
  - Not windy everywhere
  - Not sunny everywhere
- To support each other's networks
  - Ex. Spanish shut-down (spring 2025)

Lesson #9: Hidden Cost

Impact of offshore wind development (Belgium 1)

Existing 380 V infrastructure with two locations for nuclear power plants



Nuclear power plants

Source: Elia

Impact of offshore wind development (Belgium 2)

<u>North Sea</u>:

- Offshore wind
- Energy Island
- Interconnexions : UK, Denmark

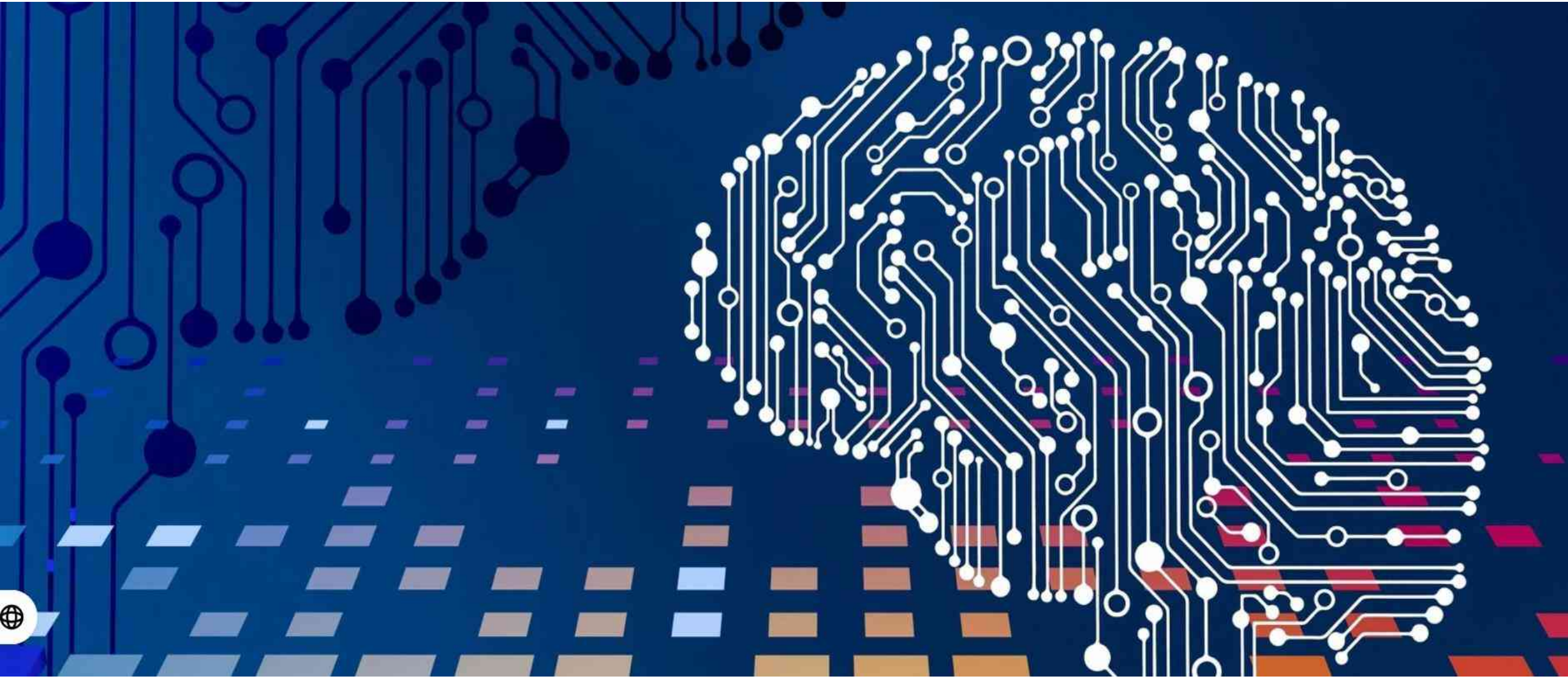


Source: Elia

The impact of Artificial Intelligence (AI) on Electricity Demand will be great

AI is not a new technology (Physical AI = Industrial robots)
Generative AI is a new business.
Let's recall that Generative AI is basically characterized by a very simple process.
In the current digital world, one can have access through the net to an exponential increase of billions of data related to any kind of subjects, the deep learning built-up in the machines.
It is therefore possible to respond to any kind of question by using specific stochastic algorithms and models which can be optimized and get all the information needed in a minimum period of time by searching in powerfull data centers.
These processes needs huge quantity of Electricity.

A Zoom on Energy Use of Artificial Intelligence

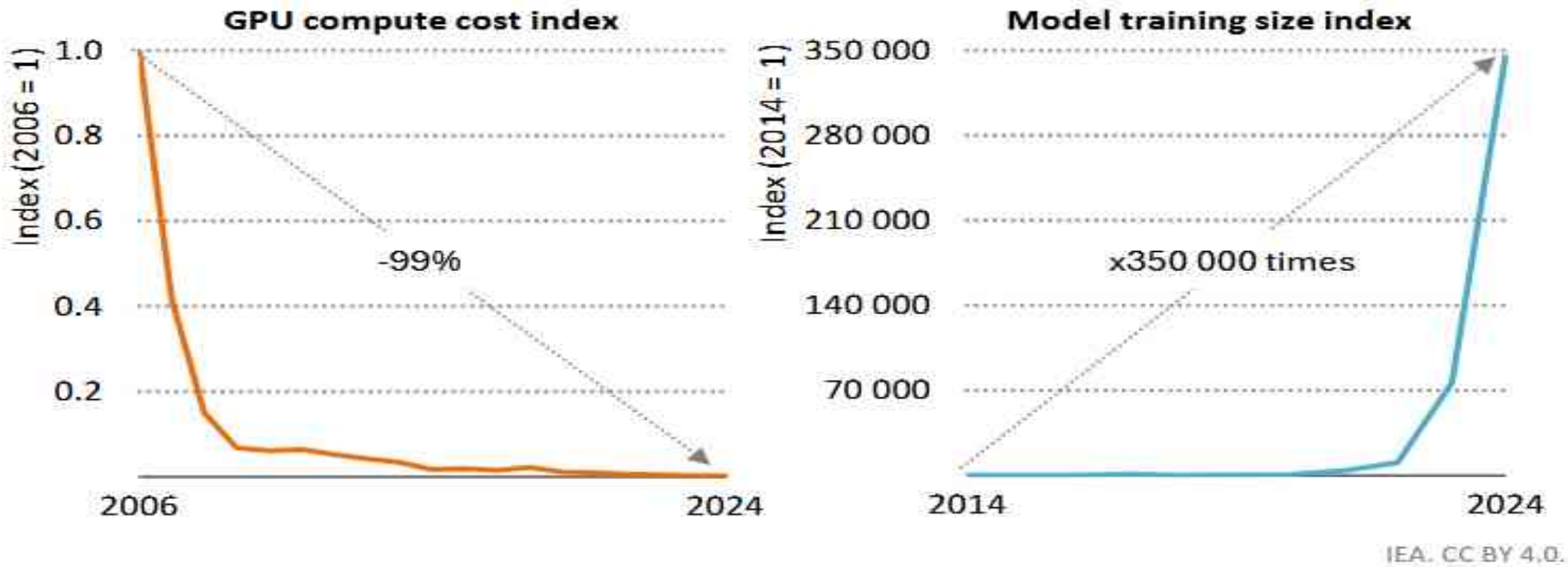


Source: World Economic Forum 2024 - Center for Energy & Marerials

Massive increase in computing power and decline in cost

Huge decrease of Graphics Processing Unit (GPU) cost per unit of computation

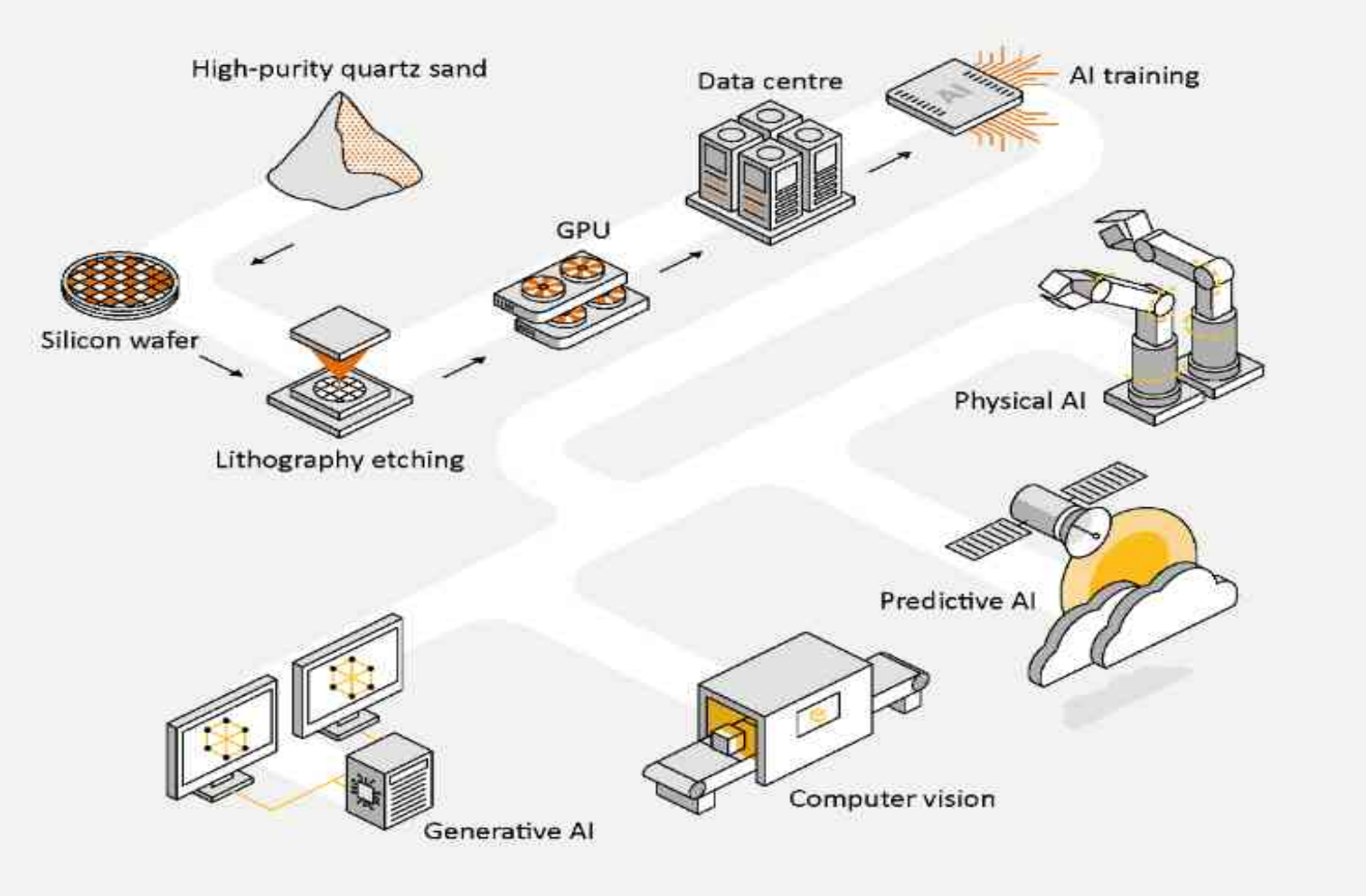
Huge increase of availability and quality of data to train AI models



In the past decade, cheaper computing, exponentially more data and research breakthroughs in model design have turbocharged AI model capabilities

Sources: IEA analysis based on data from EpochAI (2024), and Coyle and Hampton (2024).

AI infrastructure and types of application

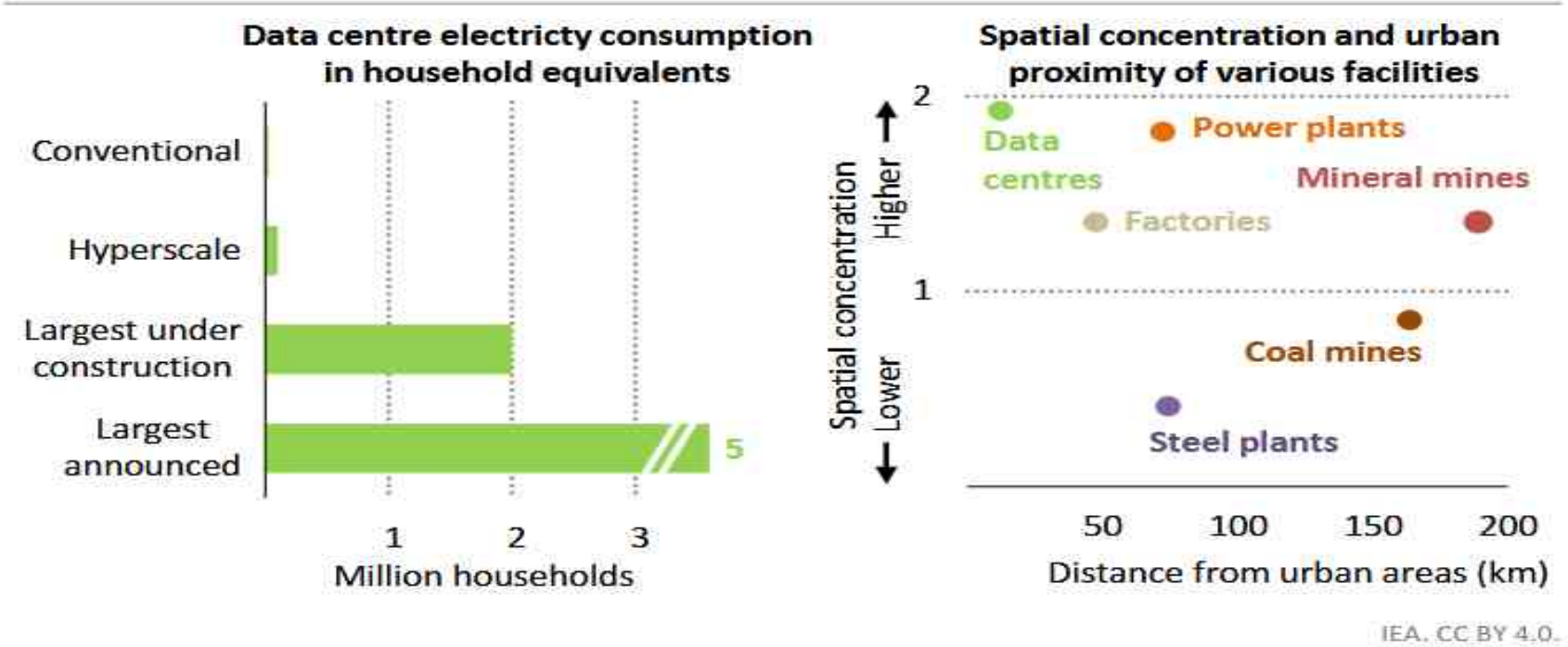


IEA. CC BY 4.0.

AI is supported by a highly complex global supply chain

Source: IEA Energy and AI Report – April 2025

Data centers Electricity consumption is huge
Data centers are concentrated and located around cities



Data centres tend to be geographically concentrated and located around cities; a 100 MW data centre can consume as much electricity as 100 000 households

Notes: km = kilometre. The conventional data centre capacity considered is 25 MW. The hyperscale data centre capacity considered is 100 MW. The largest under-construction data centre capacity considered is around 2 000 MW. The largest planned data centre capacity considered is 5 000 MW. The spatial concentration is calculated as the inverse of the linearised Nearest Neighbour Index, which is a mathematical representation of how clustered or dispersed each category is, calculated via the ratio of the observed mean distance to the expected mean distance.

Source: IEA Energy and AI Report – April 2025

Large Data centers locations

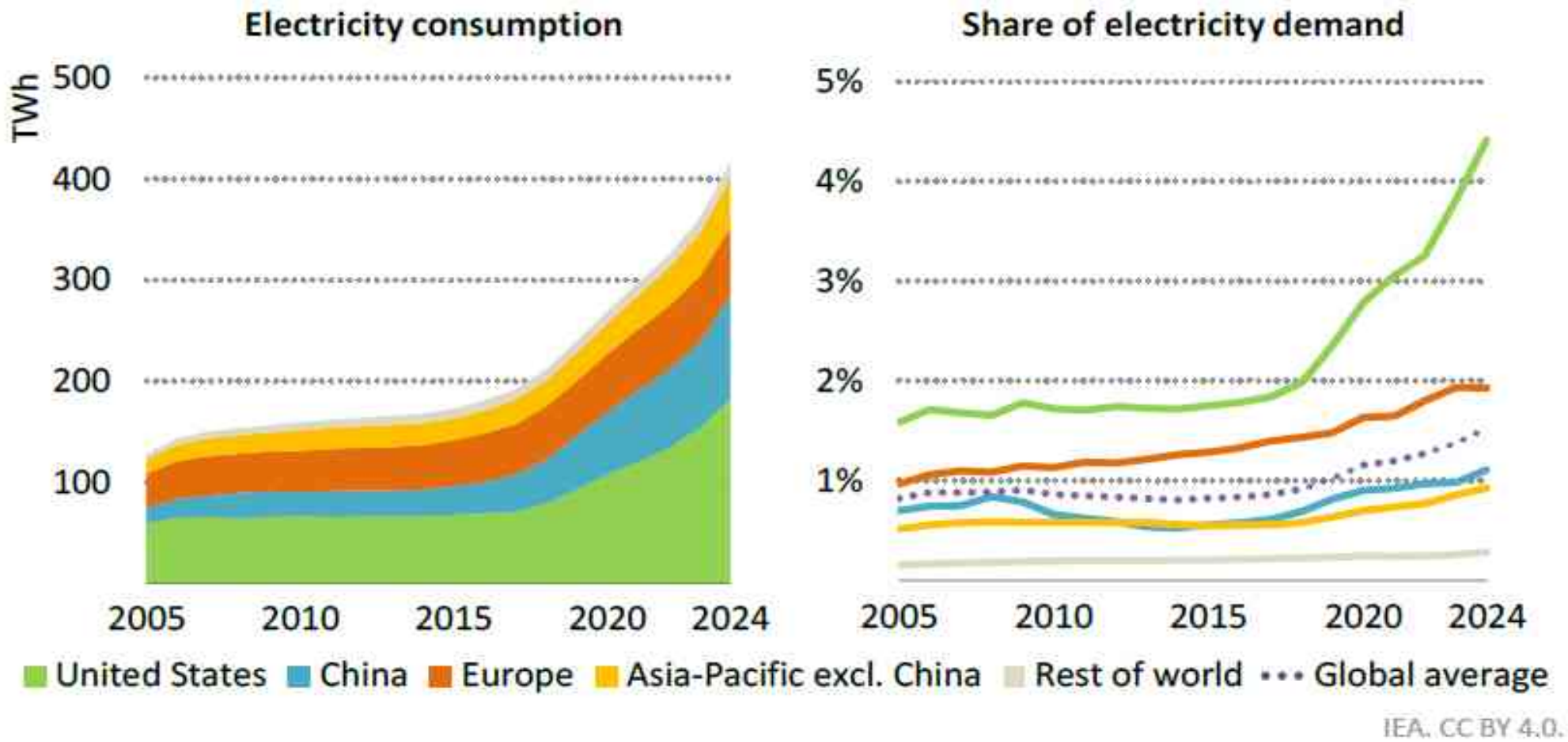


Data centres are often located in large clusters, potentially creating challenges for local electricity systems

Notes: GW = gigawatt. We define a data centre cluster as a group of data centres located within 100 km of each other. The ten largest clusters have been named. The Pearl River Delta encompasses the combined capacity of Guangzhou, Shenzhen and Hong Kong (China).

Source: IEA analysis based on data from OMDIA (2025).

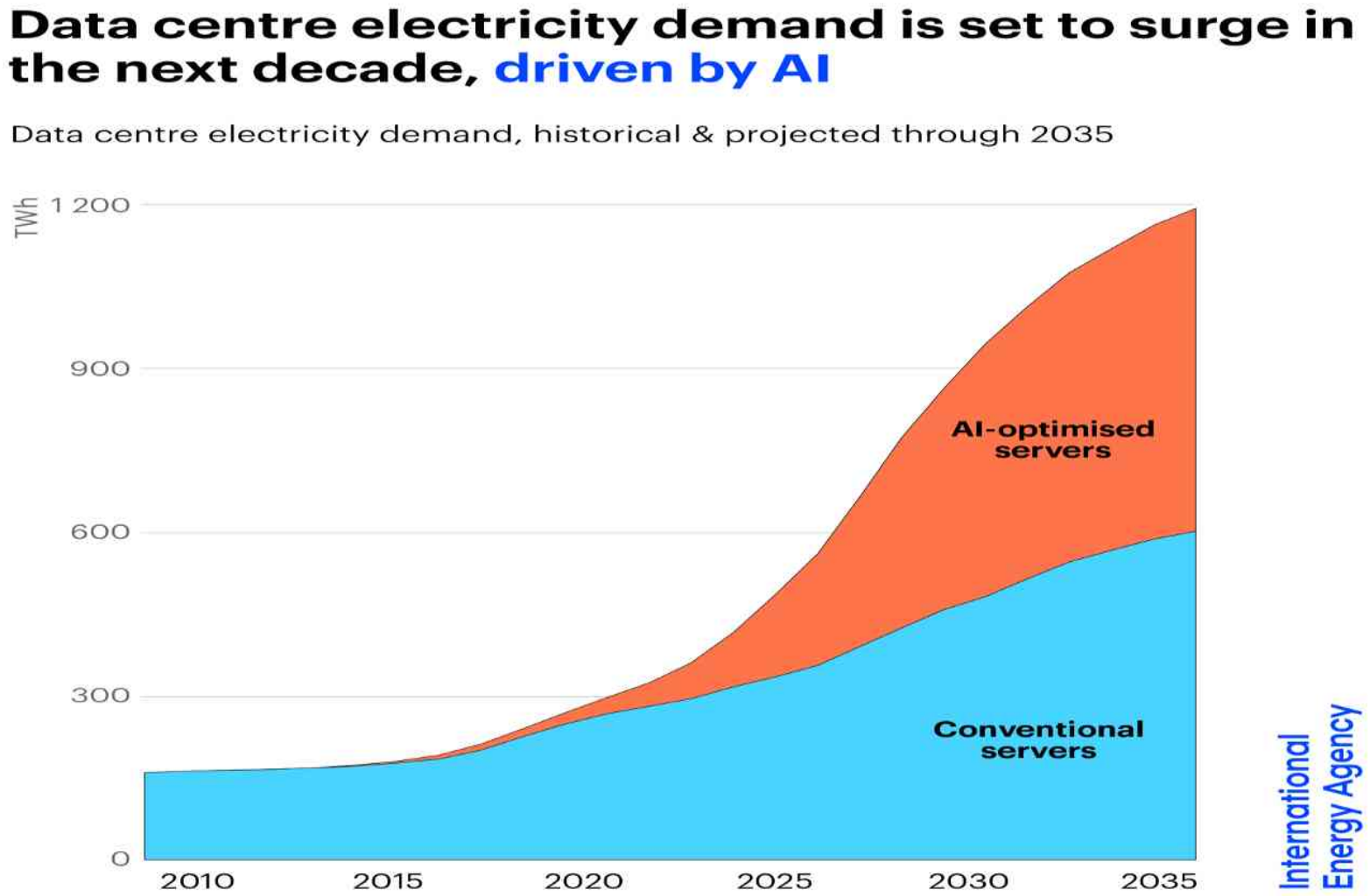
Electricity Consumption by Data Centers – 2005 - 2024



The acceleration in data centre electricity consumption observed in 2017 was mainly driven by the United States and, to a lesser extent, by China

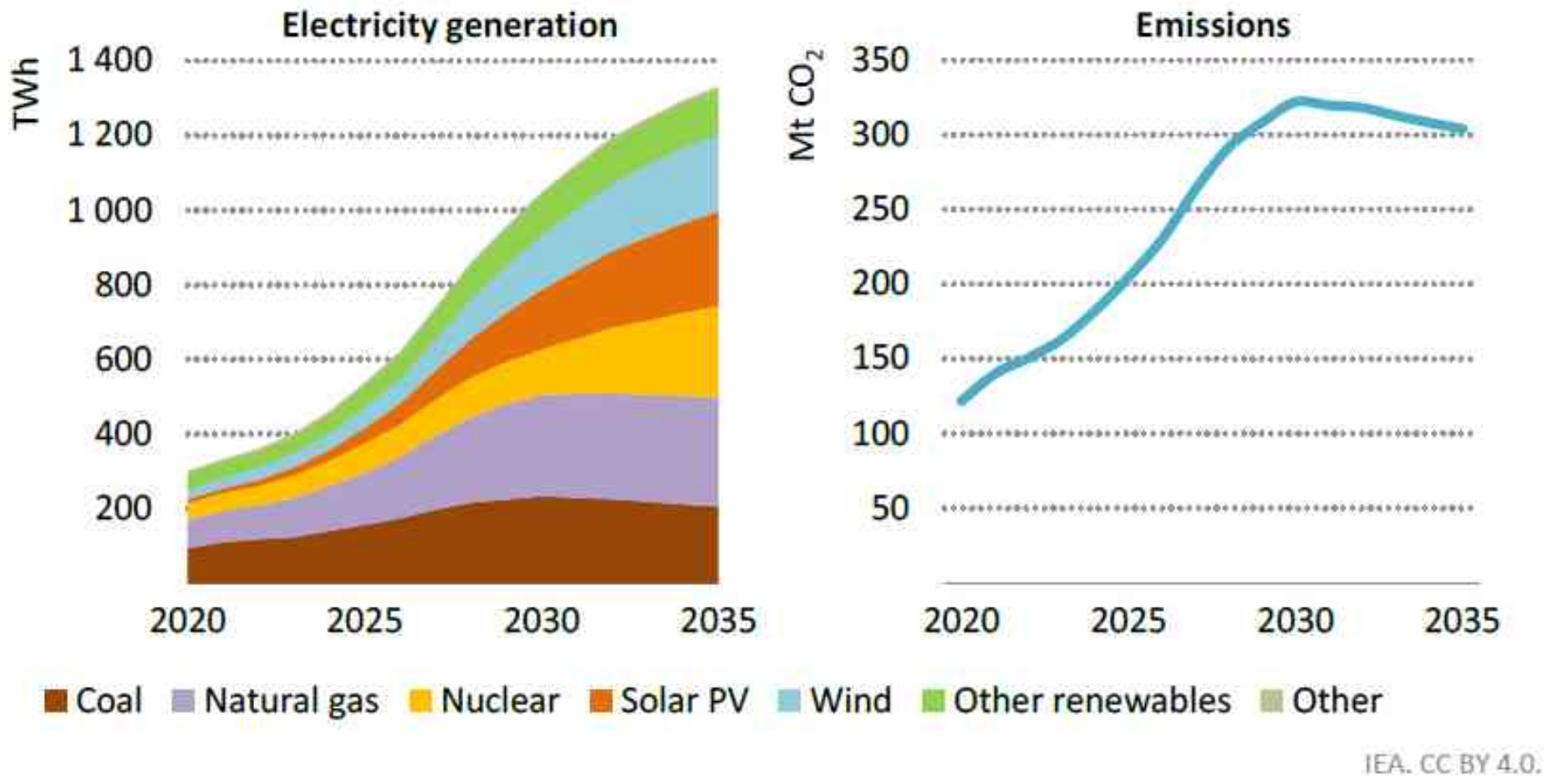
Source: IEA Energy and AI Report – April 2025

Perspectives of Electricity Demand by Data for AI development 2010 – 2035 by IEA



Source: IEA Energy and AI Report – April 2025

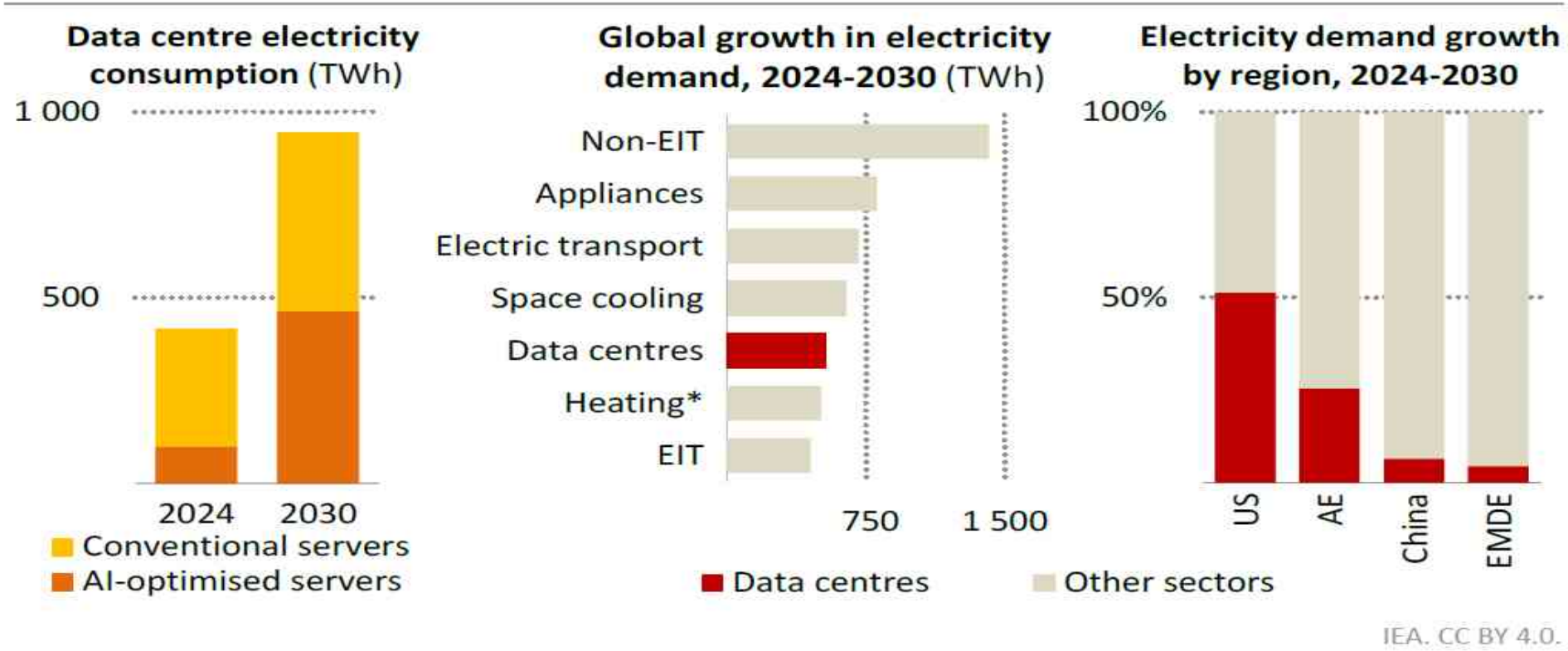
Perspectives of Electricity Generation called by by Data Centers and CO_2 Emissions 2020 – 2035 by IEA



Between now and 2030, renewables meet nearly half of the increase in global data centre electricity demand, followed closely by natural gas and coal-fired electricity generation

Source: IEA Energy and AI Report – April 2025

Perspectives of Electricity Consumption called by by Data Centers 2024 - 2030



Even as electricity consumption from AI-optimised servers surges, data centres remain just one of the many sources of electricity demand growth in most economies

*Space and water heating in buildings.

Note: TWh = terawatt-hour; AI = artificial intelligence; EIT = energy-intensive industry; US = United States; AE = advanced economies; EMDE = emerging market and developing economies.

Source: IEA WEO 2025

Energy Use of Artificial Intelligence

How much energy does AI use? Ask ChatGPT and this is what it says:

"AI systems vary widely in energy consumption depending on their complexity and usage, but they generally require significant amounts of electricity to process and analyse data efficiently."

That response required around ten times the electricity of a Google search, by some estimates. And with 100 million users of ChatGPT every week, the extra energy demand starts to add up. And that's just users on one platform.

Across the industry, the increasing energy demand, primarily from building and running the data centres used to train and operate AI models, is contributing to global greenhouse gas (GHG) emissions.

Microsoft, which has invested in ChatGPT maker OpenAI and has positioned generative AI tools at the heart of its product offering, recently announced its CO2 emissions had risen nearly 30% since 2020 due to data centre expansion. Google's GHG emissions in 2023 were almost 50% higher than in 2019, largely due to the energy demand tied to data centres.

So while AI tools promise to help the energy transition, they also require significant computing power.

Source: World Economic Forum 2024 - Center for Energy & Materials

Energy Use of Artificial Intelligence

Huge quantities of Electricity needed to run Data Centers:

Microsoft: Since 2020, Electricity consumption from 11 to 24 TWh. Every 6 months, calculation capacities x 2.

One question to Chat GPT needs 10 times more Energy than a research on Google.

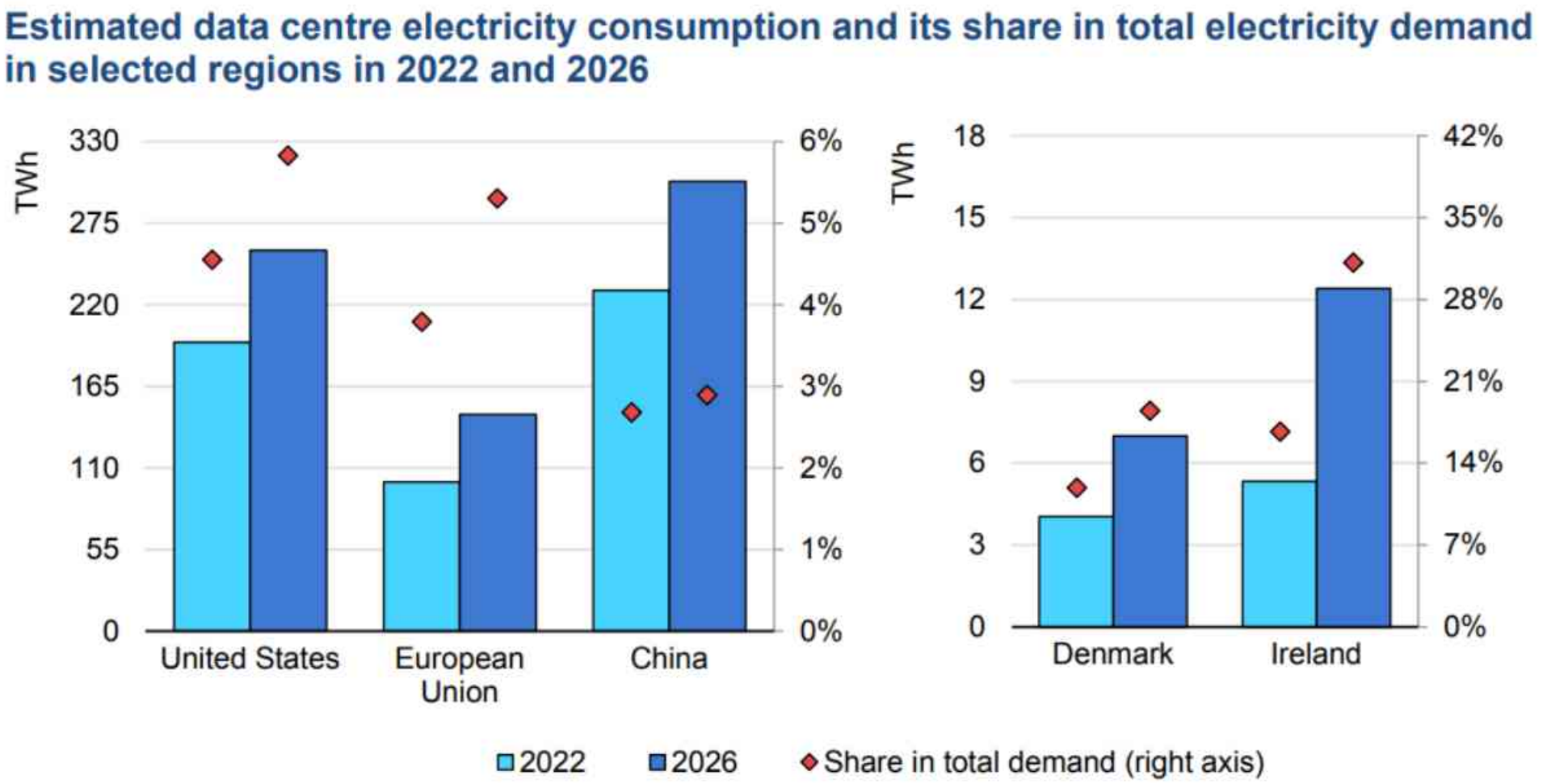
To train GPT-3, OpenAI would need 1290 MWh over 15 days.

Also, need for high quantities of water to cool the Data Centers and produce Electricity.

Amazon, Microsoft & Google are going to supply the increased need for Electricity with nuclear plants and are planning to invest massively for that purpose (Microsoft thinks to reactivate Three Mile Island reactor (Pennsylvania)

Source: Challenges – November 2024

A Zoom on Energy Use of Artificial Intelligence

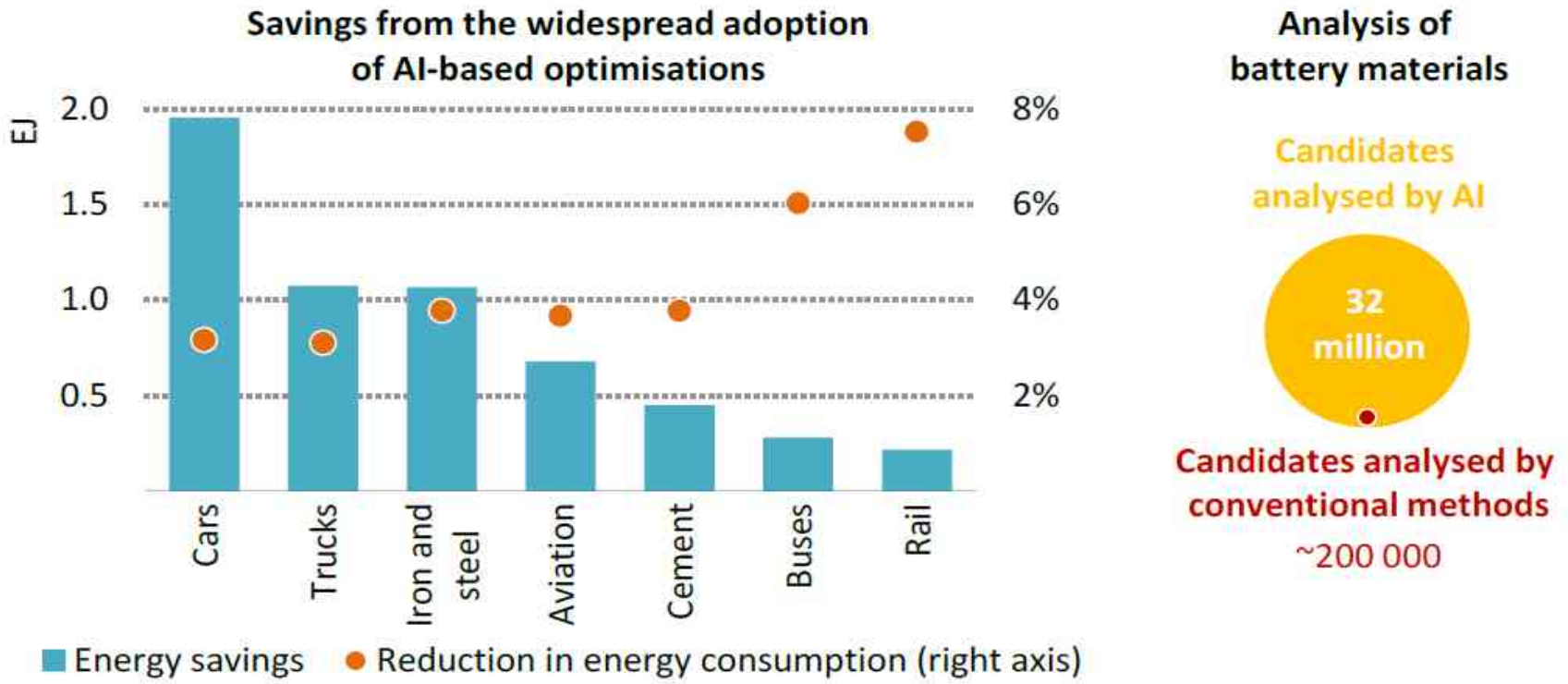


Data centre electricity consumption around the world.

Image: IEA

Source: World Economic Forum 2024 - Center for Energy & Marerials

Can Artificial Intelligence bring Energy savings from several uses?



IEA. CC BY 4.0.

Widespread adoption of known AI applications has the potential to save 13.5 EJ in 2035, which is larger than the total energy consumption in Indonesia today

Notes: EJ = exajoule. Materials research related to batteries considers historical global research and development for screening potential candidates. Conventional methods include both physical experiments and detailed mechanistic computer simulations.

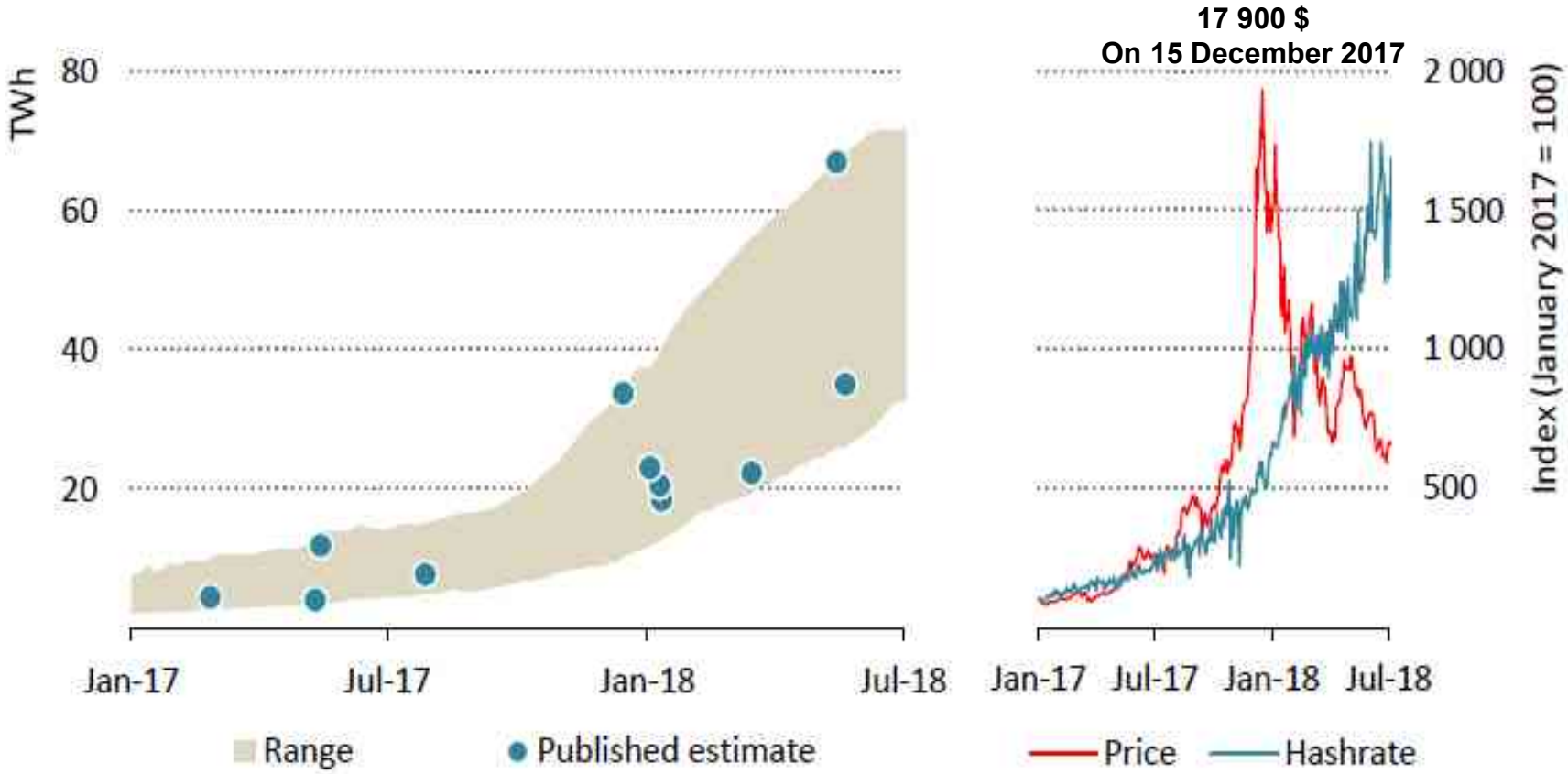
Source: IEA WEO 2025

High increase of Energy Use for Blockchain, Crypto-currencies and Artificial Intelligence

A Zoom on Energy Use of Blockchain and Crypto-currencies

- In a traditional business environment, central authorities, banks, etc., verify and log transactions.
- Blockchain underlying technology proposes a new way to conduct and record transactions. Blockchain removes the need for a central authority, bank or payment gateway. Instead, the ledger is held, shared, and validated across a distributed network of computers running a free particular software. The system is created , held electonically and decentralized.
- The bitcoin Blockchain is a public ledger that records bitcoin transactions.
- The lack of central, trusted authority means that the Blockchain needs a « consensus mechanism » to ensure trust across the network. In the case of bitcoin, consensus is achieved by a method called « Proof of Work » (PoW), where computers on the networks (« Miners ») compete whith each other to solve a complex algorithmic puzzle. Once the puzzle is solved, the latest block of transactions is approved and added to the chain of transactions. The first Miner to solve the puzzle is rewarded with new bitcoins and network transactions fees.
- Supply is limited up to 21 million bitcoins. Transactions cannot be reversed.
- These mechanisms need a huge quantity of energy. (50+TWh/year = Portugal consumption)

A Zoom on Energy Use of Blockchain and Crypto-currencies



Estimates of bitcoin energy use vary considerably based on the price of bitcoin, hashrates and other assumptions, as well as differences in methodology

Source: IEA WEO 2018
Hashrate: nb of Thashes/second the bitcoin network is performing
Hash: complex operations by a computer

11

Global Energy Growth
Electricity Storage

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The Need for Electricity Storage

Renewable Energy
The question of Intermittency

- Intermittency: In the absence of energy storage system, solar doesn't produce power at night or in bad weather. Electricity produced at any given point in time by a given wind turbine depends upon wind speed, air density…. When no wind, no power.

- 100% Renewable Energy consisting of solar and wind is not foreseeable in the absence of Back-up with dispatchable « traditional » energy sources.

- For solar and wind energy, a Back-up system is necessary. This has a cost which must be added to the cost of producing each MWh. What is this cost?

Renewable Energy
The question of Intermittency

- If we assume that every solar or wind energy farm should have a dedicated Back-up system (as a gas power plant), the additional cost can be huge.

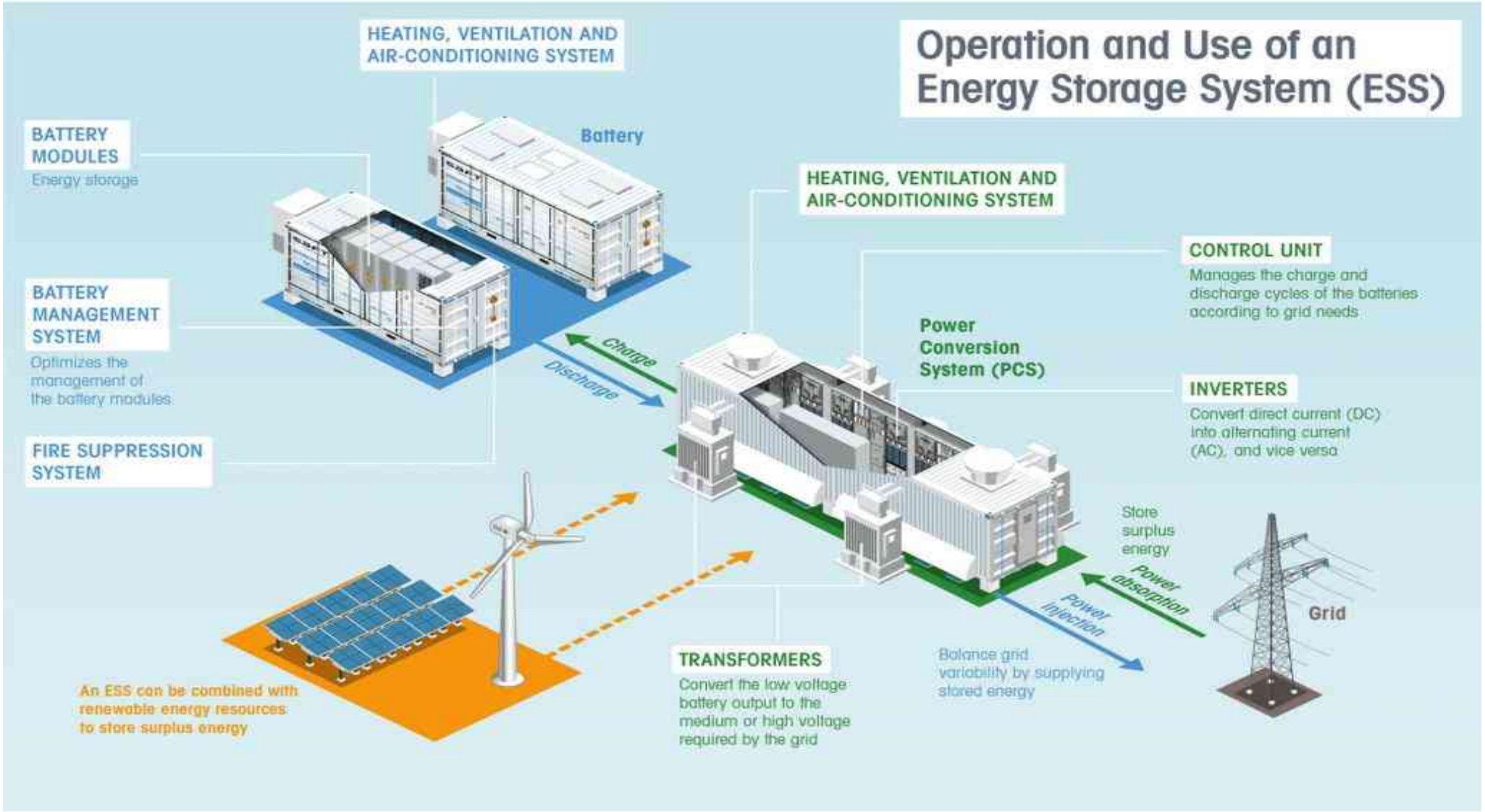
- Grids have existing and operational and spinning reserves to compensate for existing uncertainties on the power network. The addition of intermittent sources such as wind and solar doesn't not require 100% Back-up because operating reserves and balancing requirements are calculated on a system-wide basis, with large interconnections and not dedicated to a specific generating plant.

- The additional cost for Back-up can therefore be limited.

- Based upon the degree of penetration of renewables (10%, 15%, etc….) and local environment, this cost can vary between ε and up to 100 €/MWh.

- ……. And Renewable Energy Storage is of prime importance.

Necessity to develop Energy Storage System



Source: TotalEnergies 2023

Necessity to develop Energy Storage System



Source: ENGIE

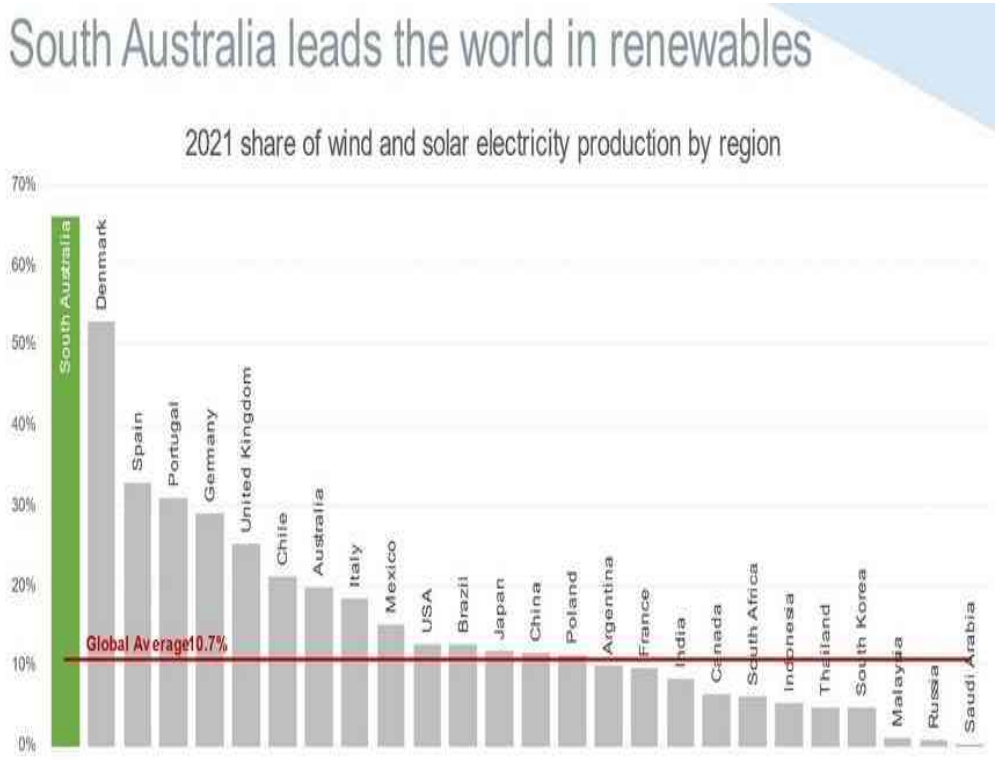
Necessity to develop Energy Storage System



Source: TotalEnergies 2023

A crucial question: Energy Storage

- Due to the intermittency of solar and wind energy, back-up solutions have to be found.
- Projects are developped to build-up new electricity storage capacities.
- One recent example in Southern Australia (in Australia, in 2021, 51% of electricity generation is coming from coal-fired power plants). In South Australia, the last coal-fired power plant was closed in 2016.



- Tesla won a contract to construct originally the biggest lithium-ion battery in the world (Hornsdale Power Reserve), with a capacity of 100 MW & delivered energy of 129 MWh (Capex = 90 MA$) connected to a Neoen wind farm (Hornsdale Wind Farm, 315 MW, 99 Wind turbines).
- These facilities (completed end 2017) could feed 30 000 households during peak-hours. Subsidies ? In 2016/2017, Renewables accounted for 49% in the electricity production. They reach 66% in 2021.
- South Australia's goal is to achieve 100% in 2030.

South Australia – Tesla/Neoen project
The biggest lithium - ion battery



Source: Australian Wind Alliance

The Hornsdale Power Reserve has been expanded by 50% (50 MW/64,5 MWh – 71 M$) Operational in September 2020



Source: Neoen

Finland – Saft/TuuliWatti project - Lithium - ion battery to store # 7 MWh (Power: # 6 MW) fed by a Wind Farm Production (21 MW)

Paris, le 20 novembre 2019 – Saft, filiale à 100% de Total vient de remporter un contrat pour la fourniture de trois conteneurs **Intensium Max 20 High Energy** auprès de TuuliWatti, le développeur et opérateur éolien finlandais. Ce système de stockage d'énergie lithium-ion assurera des services de réglage de fréquence pour améliorer l'intégration au réseau électrique de l'énergie renouvelable produite par un parc éolien de 21 mégawatt (MW) situé à Viinamäki, dans le nord-ouest de la Finlande. Il permettra ainsi d'optimiser l'énergie éolienne tout en offrant la puissance nécessaire à une alimentation de secours et à un démarrage à froid.

Ce système de stockage lithium-ion, le plus grand des pays nordiques, dispose d'une capacité de stockage de 6,6 MWh et d'une puissance de 5,6 MW pour assurer le réglage de fréquence tout au long de sa durée de vie de 15 ans. Il se compose de trois conteneurs intégrés, de 2,2 MWh chacun, conçus et fabriqués sur le site de production de Saft à Bordeaux.

Selon Tommi Riski, gestionnaire de portefeuille Électricité de TuuliWatti : *« TuuliWatti entend devenir le premier développeur et producteur d'énergie éolienne de la région arctique. Les conteneurs haute énergie de Saft nous aideront à atteindre cet objectif, en améliorant la compétitivité de l'énergie éolienne sur le site de Viinamäki. Ils fournissent une solution rapide dans des conditions environnementales difficiles, ainsi*



France - Germany – Saft/PSA project - Year 2020
A new Joint-Venture: Automative Cell Company

30/01/2020 News

Paris – During French President Emmanuel Macron's visit to the Saft Nersac plant near Angoulême, in the Nouvelle-Aquitaine region, Total, through its affiliate Saft, and PSA with Opel, are announcing their plan to combine their know-how to develop EV battery manufacturing activity in Europe. To that end, the partners intend to establish a joint venture named Automotive Cell Company (ACC).

The project will leverage cutting-edge R&D, notably provided by Saft, in order to produce EV batteries starting in 2023. The technology used will offer the highest level of energy performance, both in terms of range and charging time, and a lower carbon footprint than that of the competition, setting a new standard in Europe.

The first phase of the project focuses on R&D, including building a pilot plant on the land of Saft's Nersac facility. The plant is scheduled to start up in mid-2021 and represents an investment of 200 million euros. The project will generate around 200 high-skilled jobs in France's Nouvelle-Aquitaine region to develop, qualify and commercially scale up new, high-performance lithium-ion batteries.

This first phase will trigger the investment decision for a large-scale production plant (8 GWh initially, rising to 24 GWh later on) in the northern Hauts-de-France region, followed by a second one of equal capacity in Germany, in order to reach 48 GWh of combined capacity by 2030. That would represent production of one million batteries a year, or around 10-15% of the European market. Ultimately, nearly €5 billion will be required to complete this ambitious program.

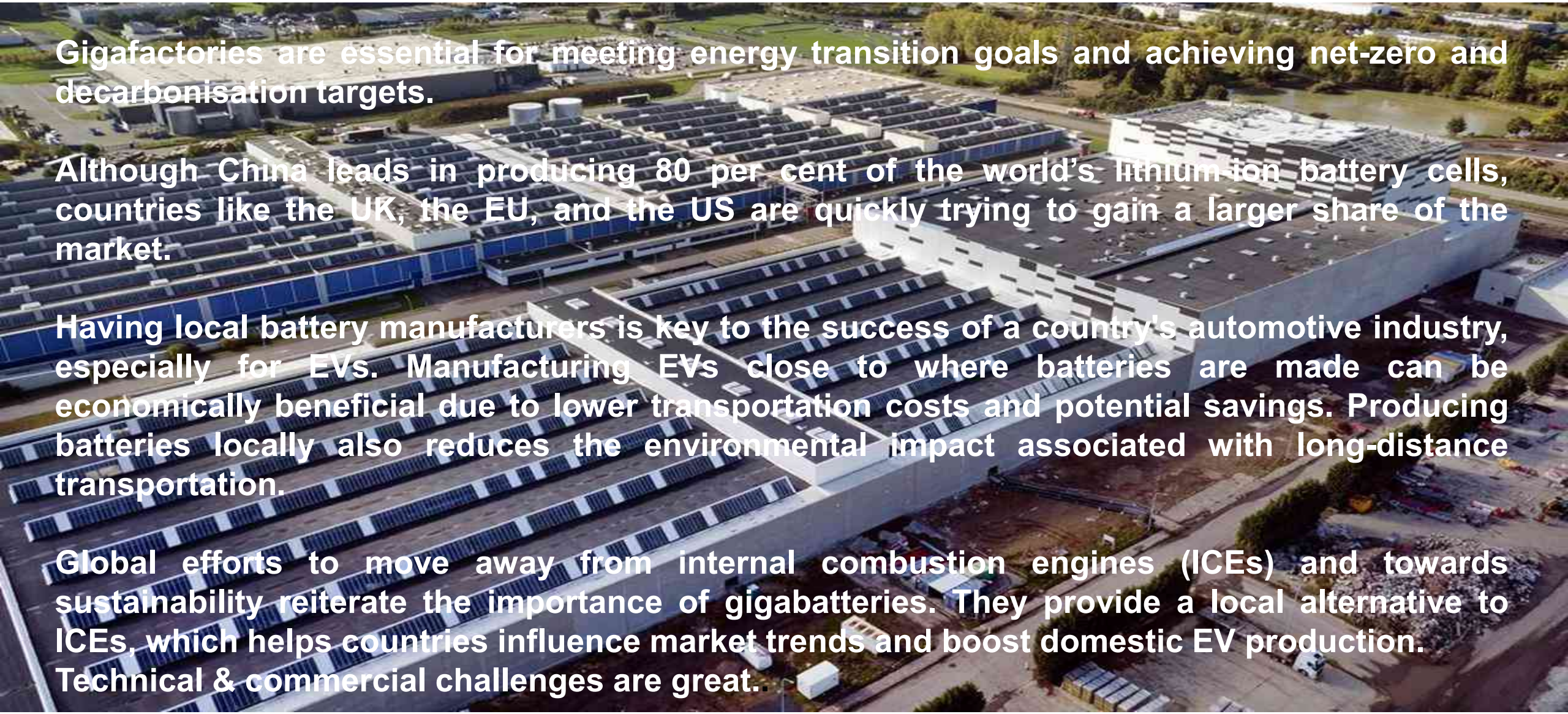
Total and Groupe PSA acknowledge the support of French, German and European Union authorities for the project, expected to receive nearly €1.3 billion in public funding during its development in the frame of the Important Projects of Common European Interest (IPCEI) initiative authorized by the European Commission.



Source: TotalEnergies

Batteries for EV
Necessity to scaling up Batteries fabrication
Gigabatteries plants - A challenge?
Two european manufacturers:
ACC (Automotive Cells Company) & Northvolt

Why Gigafactories?



Gigafactories are essential for meeting energy transition goals and achieving net-zero and decarbonisation targets.

Although China leads in producing 80 per cent of the world's lithium-ion battery cells, countries like the UK, the EU, and the US are quickly trying to gain a larger share of the market.

Having local battery manufacturers is key to the success of a country's automotive industry, especially for EVs. Manufacturing EVs close to where batteries are made can be economically beneficial due to lower transportation costs and potential savings. Producing batteries locally also reduces the environmental impact associated with long-distance transportation.

Global efforts to move away from internal combustion engines (ICEs) and towards sustainability reiterate the importance of gigabatteries. They provide a local alternative to ICEs, which helps countries influence market trends and boost domestic EV production. Technical & commercial challenges are great..

Several Gigafactories projects in France

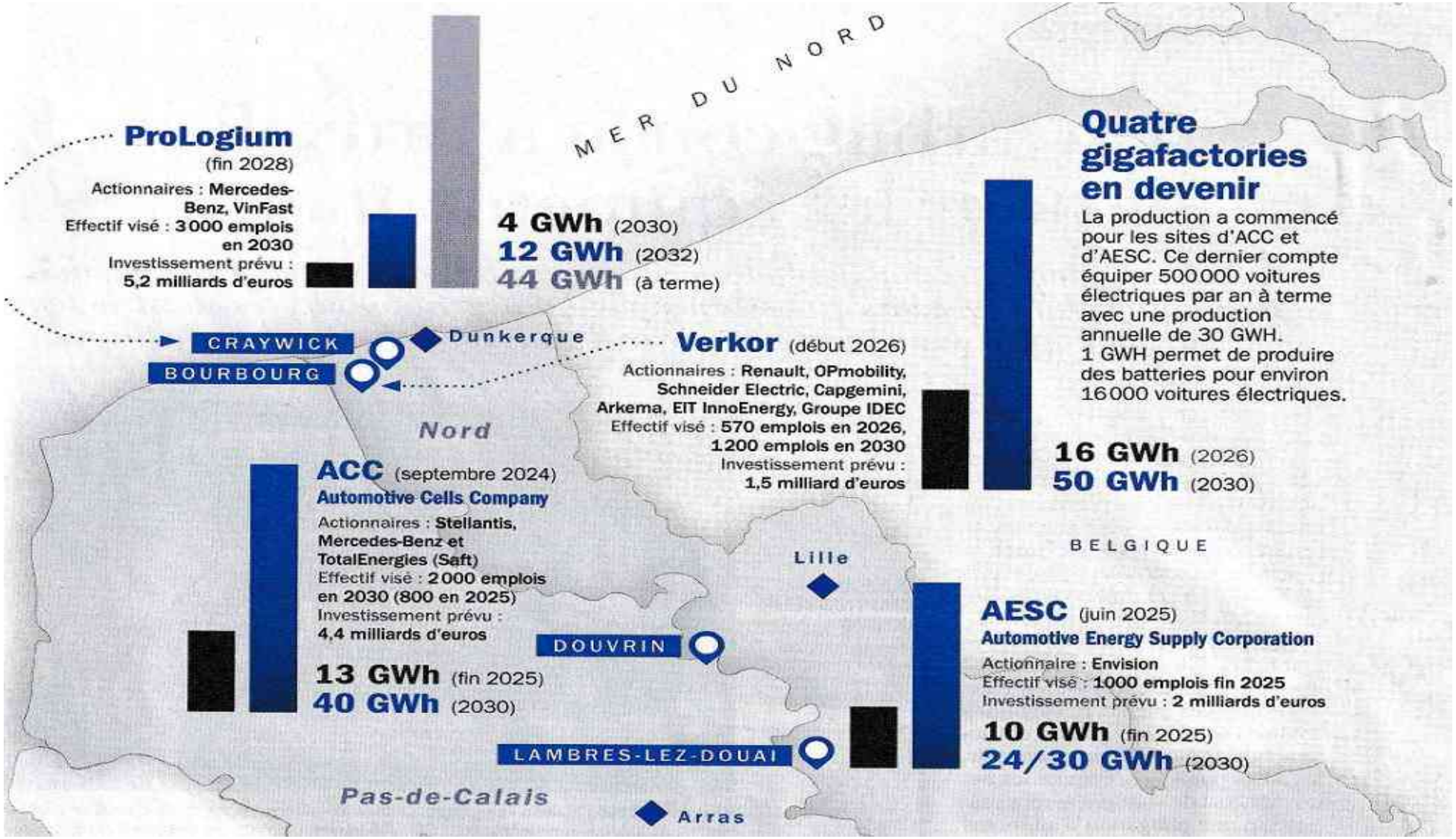
GIGAFACTORIES: POWERING THE ECONOMY AND THE ENVIRONMENT

What is a gigafactory? It is a massive industrial facility dedicated to the production or recycling of batteries for electric vehicles. Here are some of the main gigafactories in Hauts-de-France:

- Automotive Cells Company (ACC) Gigafactory in Billy-Berclau/Douvrin: A joint venture between Stellantis, TotalEnergies, and Mercedes-Benz, inaugurated in May 2024. Projected production: 200,000 to 300,000 batteries per year by 2030.
- Envision AESC Gigafactory in Douaisis: Production capacity of 9 GWh in 2024, increasing to 24 GWh by 2030. Will supply batteries to Renault's electric vehicle plant.
- Verkor Gigafactory in Dunkirk: Operational by 2025 with an initial capacity of 16 GWh per year. Produces high-performance, low-carbon European batteries.
- Prologium Gigafactory in Dunkirk: Uses solid-state battery technology, which is safer and has a higher energy density than traditional lithium-ion batteries. Production expected to start in 2026.

Source: VIA MICHELIN Magazine

Several Gigafactories projects in France



Source: Challenges 12 mars 2026

Automative Cell Company (ACC) New Developments as of 2021



Usine pilote d'ACC à Nersac (Charente). Cette ligne fabriquera des prototypes en vue de leur production à grande échelle dans les futures gigafactories du groupe.

Source: Challenges November 2021

Automative Cell Company (ACC)
Some technical challenges for a rapid growth!

- ACC: A New Venture comprising Saft (TotalEnergies affiliate), Stellantis (ex PSA), Mercedes.
- Cost of Batteries represents 1/3 of the cost of a electric vehicle. Today, 90% of Batteries production comes from asian companies. Batteries are also essential to back-up Renewable Energy's intermittency.
- ACC is the only car batteries manufacturor in Europe with Northvolt (Sweden) which is in great financial difficulties. Northvolt went bankrupt beginning 2025.
- ACC initial objective: to build gigafactories in Europe producing 2,5 million Lithium-ion batteries by end 2030. Capex: 7 G€. Capex mobilized today: # 2,4 G€.
- First gigafactory operational in 2023 in France, Douvrin (Pas-de-Calais) Fabrication process very complex. Challenges for the production build-up. 2024 production will equip 2000/2500 vehicles, less than expected. Today, fabrication of « classical » NMC batteries (Nickel, manganese, cobalt) Other technology less expensive: LFP (Lithium, Iron, phosphate)
- Competition is severe: Korean, Chinese (CATL) companies are also present in Europe.

Difficulties for Northvolt (Sweden)
Some technical challenges for a rapid growth!



VERKOR: A new player in Dunkirk - France



VERKOR: A new player in Dunkirk – France
Opening ceremony - 11 December 2025



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Global Energy Growth Petrochemicals

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Reminder - TotalEnergies Vision 2021 - Petrochemicals

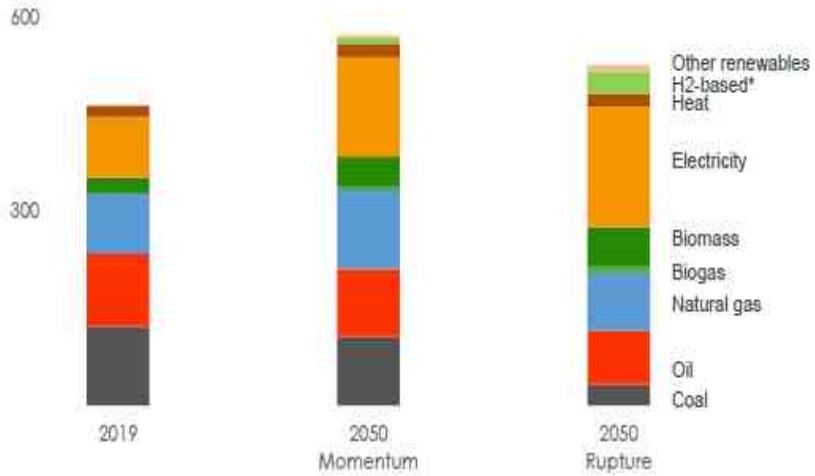
Rupture: World demand in Industry

Mobilizing all levers to decarbonize industry

TotalEnergies

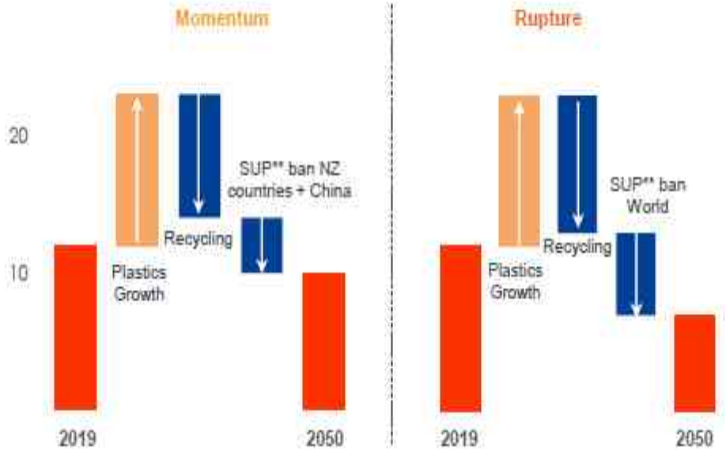
Industry total final consumption

PJ/d



Oil demand for petrochemicals

Mb/d



- Industry faces a major decarbonization challenge, which will require:
  - Coal-to-gas substitution wherever possible, then gas-to-electricity
  - Switching to H2 whenever the technology is available (ex: DRI)
  - Massive CCS deployment (~2 Gt)
  - Recycling raw materials ("scrap steel"...)

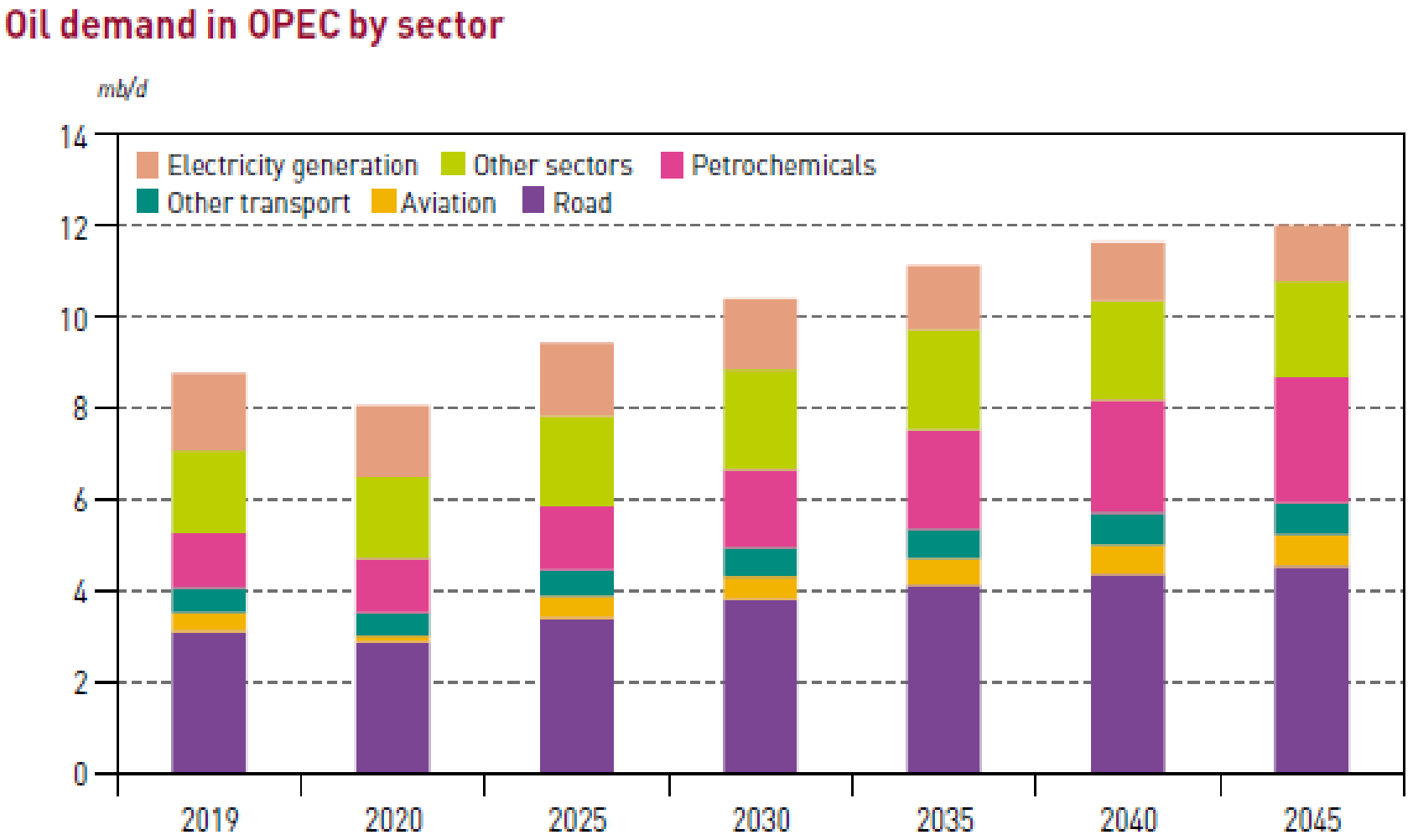
- In Momentum, recycling offsets ~80% of plastics demand growth by 2050. Together with SUP** ban in NZ 2050 countries and China, it lowers oil demand for petrochemicals by ~15%
- In Rupture, combined effects of worldwide SUP** ban and higher recycling rate (~50%) in 2050 drive down oil demand for petrochemicals by 40%

* *Includes H2, e-fuels (H2 + CO2), methanol, ammonia...*

** *Single-Use Plastic*

Source: TotalEnergies Strategy & Outlook 2021 September 2021

Increased Demand for Petrochemicals
Reminder: A vision by OPEC Reference Case 2021



Source: OPEC WOO 2021

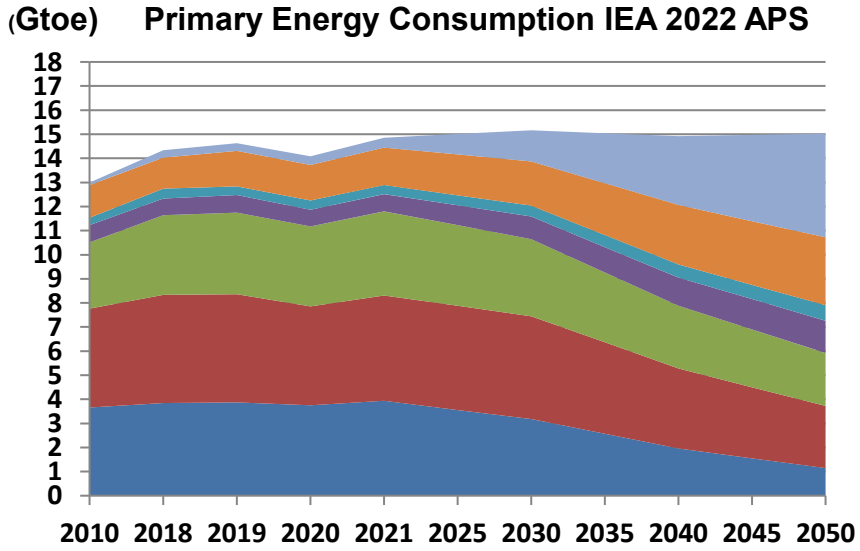
The combination of Energy Demand Growth and the increase of GHG in the atmosphere needs a new balance in the Energy Mix where Traditional Sources of Energy will continue to play a role while Renewable Energy will be extensively developed

Due to the Inertia of the Energy World, Traditional Sources of Energy will continue to be necessary for the Society for the next two decades, despite some inherent geopolitical, environmental and social debates









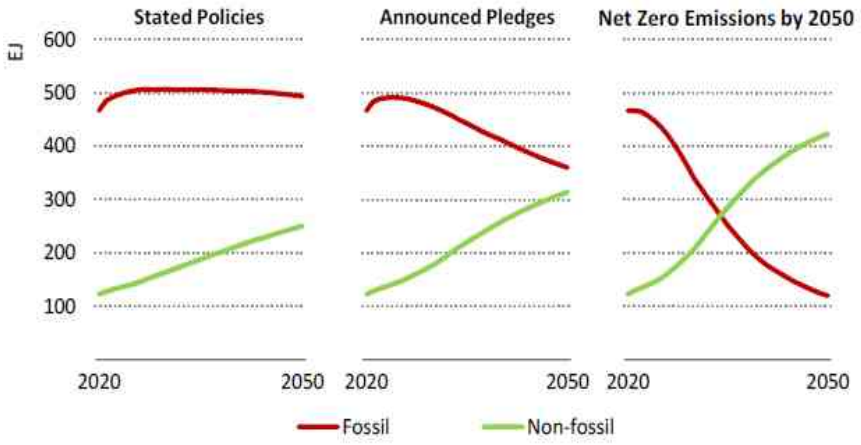
And New Renewable Sources of Energy must be extensively developed in order to mitigate the CO2 emissions and temperature increase







Projected Non Fossil Sources of Energy (IEA 3 scenarios)



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The Kaya equation

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The Dilemma
Carbon Emissions
vs Chemical and Thermodynamical effects &
Global Economy Growth & Demography

The Kaya* Equation
(One tool among others)

*Yoichi Kaya is a japanese energy economist



THE DILEMMA

Demography

Carbon emissions



Global Economy

Chemical and thermo-dynamical effects

The Kaya* Equation

(One tool among others)

*Yoichi Kaya is a japanese energy economist

The Kaya Equation

$$CO_2 = \frac{CO_2}{Energy} * \frac{Energy}{GDP} * \frac{GDP}{Pop} * Pop$$

$$tCO_2 = \frac{tCO_2}{toe} * \frac{toe}{k\$} * \frac{k\$}{Pop} * Pop$$

CO_2 = Carbon Intensity x Energy Intensity x Purchasing Power x Population

Nota: GDP is expressed in constant money

Kaya Equation
The situation in 2024 – World average

Carbon Intensity (CI) # 53,80 tCO_2/TJ = 2,25 tCO_2/toe
Energy Intensity (EI) # 3,31 GJ/k$ = 0,079 toe/k$
Purchasing Power* (PPP) # 24,2 k$ per capita
Population (POP) # 8,15 billion

CO_2 Emissions # 35,2 $GtCO_2$
(= CI*EI*PP*POP)

Nota: Energy data from IEA are expressed in Joule as from 2021
1 TJ = 10^{12} J = 23,88 toe

Nota: Figures are based on 2024 situation and are rounded.
GJ: Gigajoule = 10^9 Joule, TJ: Terajoule = 10^{12} Joule, PT: Petajoule = 10^{15} Joule, EJ: Exajoule = 10^{18} Joule
CO_2 emissions are related to combustion activities, include industrial process & flaring
$ are based on constant money 2024
World GDP (PPP) # 197,4 T$ 2024 *PPP: Purchasing Power Parity
Source: WB 2024, IEA WEO 2024

More Energy, less Carbon!

More people

World population

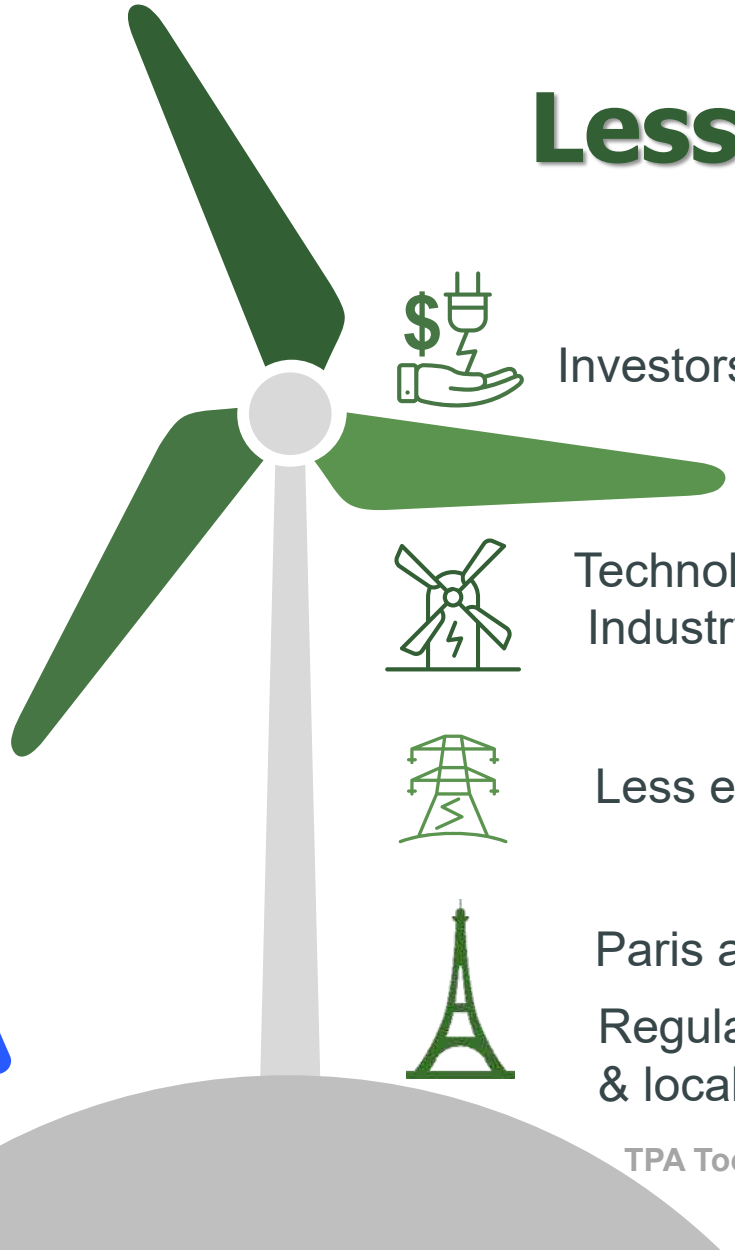
From 8,0 to 9,7 billion hab. in 2050

Better living standards

World GDP PPP to grow by

+ 2,8%/yr (Average 2024 – 2050)

(IEA assumption for the 3 scenarios?)



Less carbon

- Investors push/ access to finance
- Technology & Innovation
  Industry mobilization
- Less energy consumption
- Paris agreement
- Regulations & mandates at state & local level

The Kaya Equation
The Challenge to reach 2°C/1,5°C

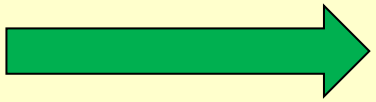
$$CO_2 = \frac{tCO_2}{toe} * \frac{toe}{k\$} * \frac{k\$}{Pop} * Pop$$



Considering Population growth and World Economy growth, reaching the 2°C/1,5°C 2050 objective, (ie. reducing CO2 emissions by a factor 3) means drastic efforts to reduce both Carbon Intensity and Energy Intensity.

The Kaya Equation

$$CO_2 = CI * EI * PP * POP$$



Per period of time:

$$\frac{CO_2\ t}{CO_2\ t_0} = \frac{CI\ t}{CI\ t_0} * \frac{EI\ t}{EI\ t_0} * \frac{PP\ t}{PP\ t_0} * \frac{POP\ t}{POP\ t_0}$$

Historical Evolution
One scenario for 2050 – Achievable??

		1970-1980	1980-1990	1990-2000	2000-2010	2010-2050
ΔCI/CI (%/year)	Carbon Intensity	*-0,1%*	*-0,4%*	*-0,2%*	*+0,2%*	*-3,5%*
$CI_{end}/CI_{begin.}$		**0,99**	**0,96**	**0,98**	**1,02**	**X1/4**
ΔEI/EI (%/year)	Energy Intensity	*-0,9%*	*-0,8%*	*-1,4%*	*-1,0%*	*-1,8%*
$EI_{end}/EI_{begin.}$		**0,92**	**0,93**	**0,88**	**0,91**	**X1/2**
ΔPP/PP (%/year)	Purchasing Power	*+1,8%*	*+1,0%*	*+1,3%*	*+2,1%*	*+1,6%*
$PP_{end}/PP_{begin.}$		**1,17**	**1,09**	**1,12**	**1,21**	**X1,9**
ΔPOP/POP(%/year)	Population	*+1,5%*	*+1,6%*	*+1,3%*	*+1,1%*	*+0,9%*
$POP_{end}/POP_{begin.}$		**1,14**	**1,15**	**1,12**	**1,10**	**X1,4**
$\Delta CO_2/CO_2$ (%/year)	CO_2 Emissions	*+2,3%*	*+1,4%*	*+1,1%*	*+2,4%*	*-2,8%*
$CO_{2\ end}/CO_{2\ begin.}$		**1,22**	**1,13**	**1,10**	**1,24**	**X1/3**

Source past data: Various, IPCC

Historical Evolution
One scenario for 2050 – Achievable??

In order to satisfy the 2°C objective on the long term, CO_2 emissions must be divided by 3 in 2050 compared to 2010.

The factor Carbon Intensity x Energy Intensity must be divided by 8.

For example, Carbon intensity (t CO_2/toe) must be divided by 4, meaning a reduction of 3,5% per year and Energy intensity (toe/k$GDP) must be divided by 2, meaning a reduction of 1,8% per year.

Achievable??

Historical Evolution
One scenario for 2050 – Achievable??

Oil, Gas and Coal are limited and finite resources.
One day will arrive when, physically and technically, these resources will not longer exist.

CO_2 emissions deriving from fossil energy will then disappear, on a long term stand-point.

It is a matter of period of time.
It also concerns the issue of reversibility for the long term effects deriving from the persistance of CO_2 content in the atmosphere.

For the next decades to come, the objective of 2°C represent outstanding challenges and put the emphasis on energy savings, energy efficiency, and decarbonized fuels: nuclear energy and renewables, also taking into consideration the economic aspects of these technologies.

How to combat climate change?
knowing that world population is growing……
and
knowing that the world of Energy
has a great inertia vs changes

Considerations for long term perspectives

- Oil and gas will still be produced beyond the end of the 21st century in a specific environment for the industry (fluctuating prices, instability, ….)
- During the next decades, oil and gas prices will evolve with up's and down's, with shocks and counter shocks, impacted by geopolitical aspects, like the recent experiences, as well as unexpected events (like the Covid-19 pandemia and its consequences, like the russian invasion of Ukraine in 2022)
- Nuclear industry will also prevail all along the 21st century. Nuclear energy, a non-carbonated source of large quantities of energy can contribute to drastic reduction in CO_2 emissions. However, public criticism with regards to the use of nuclear energy may refrain such development and the cost evolution of new nuclear (like EPR) is a challenge. Future of Small Modular Reactors (SMR)?
- This will be combined with the growth of renewable energy, in particular solar energy, which essentially derives from an unlimited nuclear power.
- Due to the intermittency of renewable energy (Solar and wind), the question of electricity storage is crucial.
- All types of energy sources will contribute to the energy mix.
- Energy Transition will need a considerable access to mineral materials. This will be an important challenge.
- In the end, the economic viability together with the less possible impact to the environment will be the keys to select the best technologies, combined with the efforts on R&D and technological progress.
- As part of this, the challenges to combat GHG emissions and increase of earth temperature are enormous.

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The Energy Sector
The Needs for Raw and Mineral Materials

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The Criticality of Mineral Materials & Rare Earth Elements



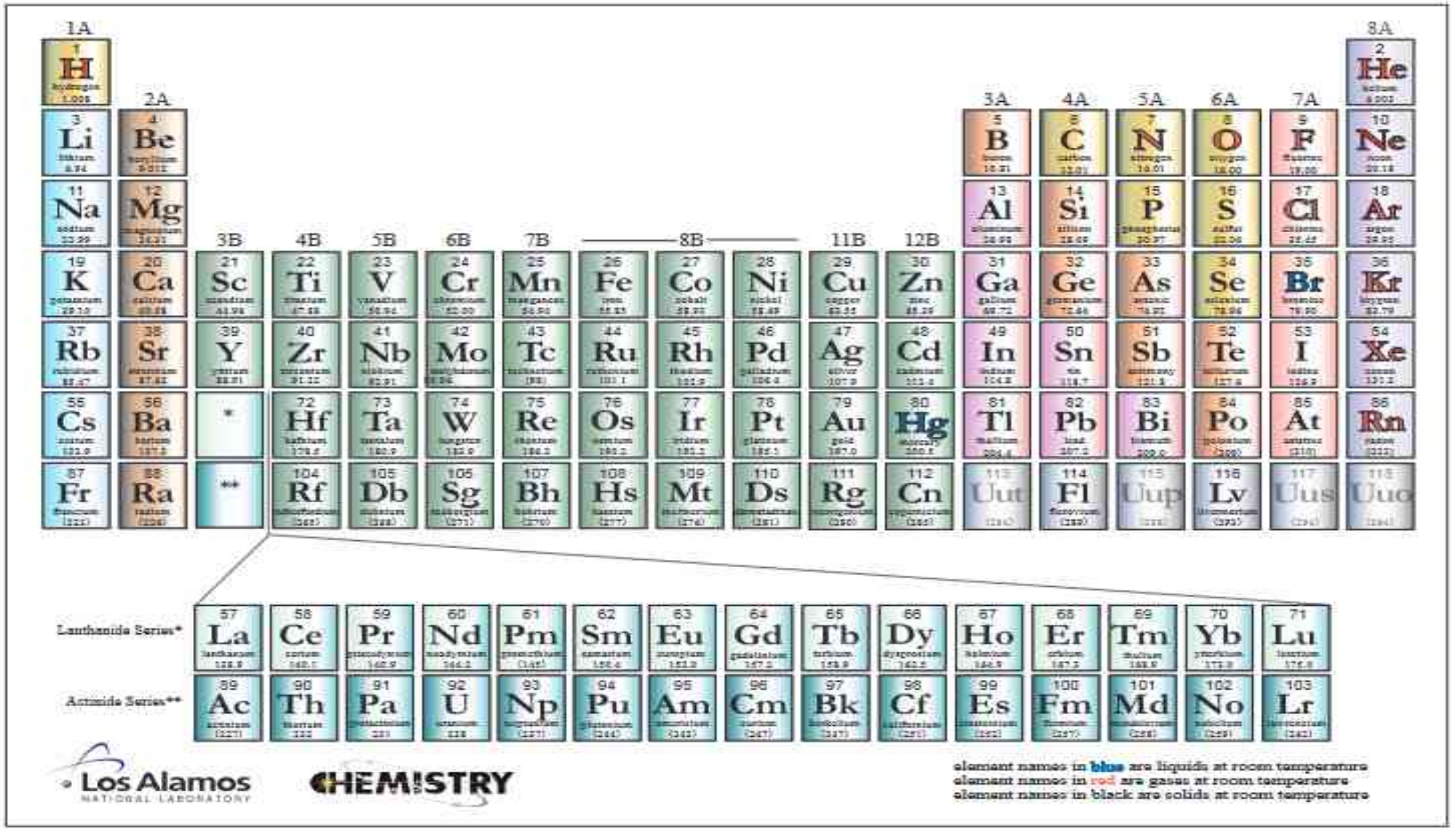






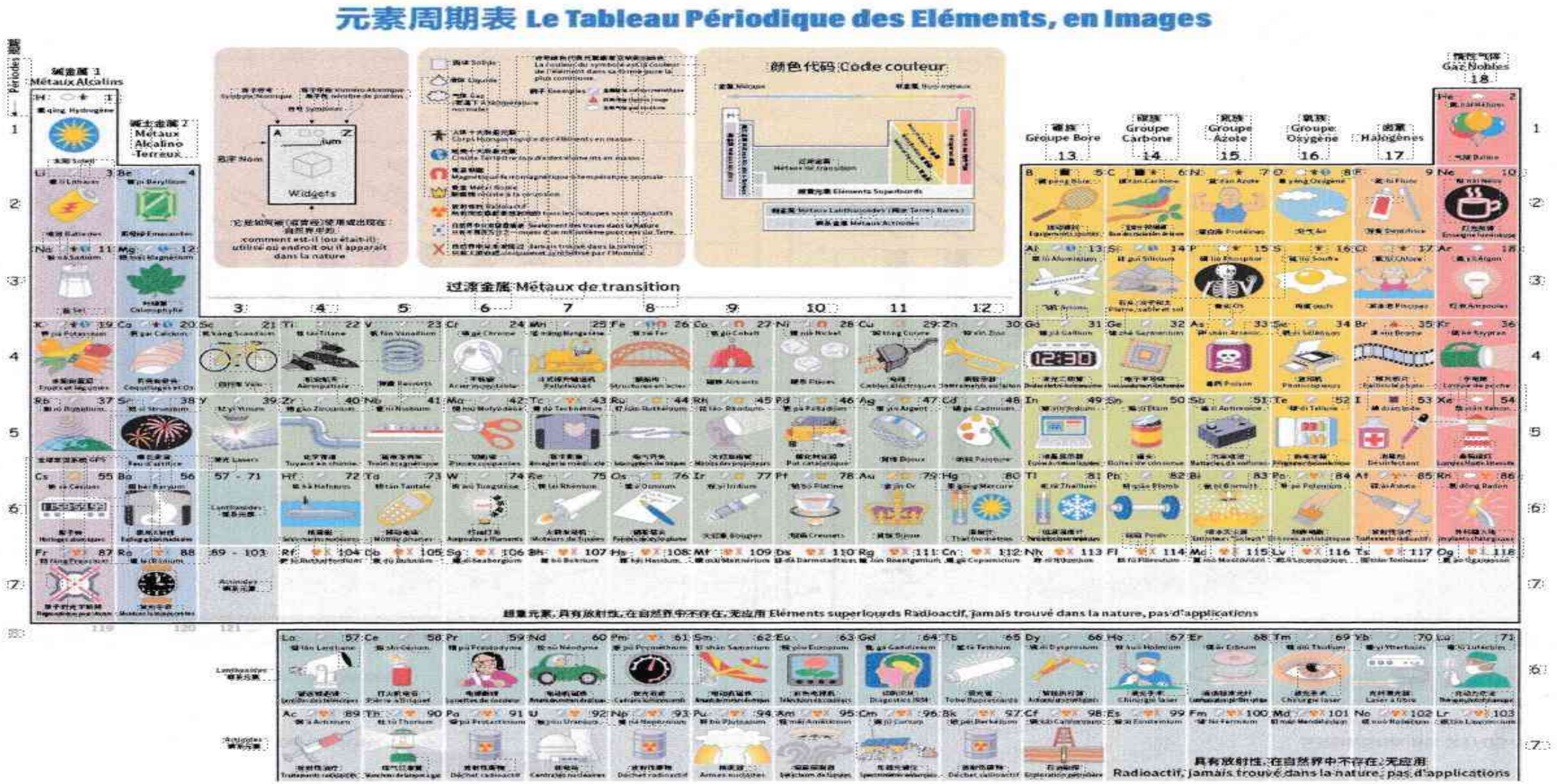


Periodic Table of Elements



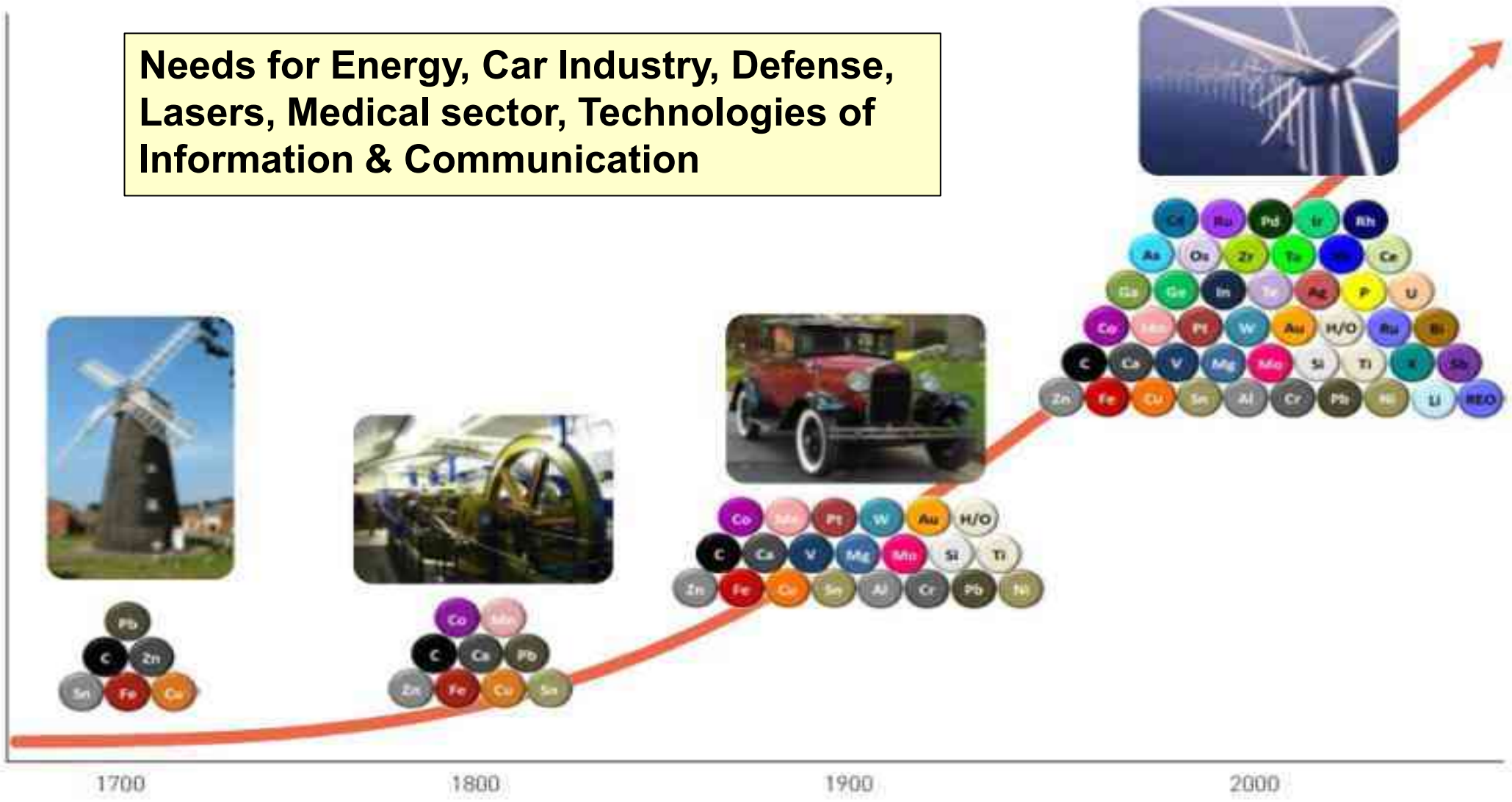
Source: US Department of Interior/USGS 2021

Periodic Table of Elements, a franco-chinese illustration



More and more Materials are needed for Industry

Needs for Energy, Car Industry, Defense, Lasers, Medical sector, Technologies of Information & Communication



Source: Ademe /Geldron

More and more Materials are needed
2025 Production

COBALT
310 kt



LITHIUM
290 kt

SILICIUM
9,6 Mt



TELLURE
960 t

GRAPHITE
1,8 Mt

GALIUM
900 t

ARGENT
26 kt

PLATINOIDES
360 kt

INDIUM
1100 t



CIMENT
4,0 Gt

Terres Rares
390 kt



ACIER
1,9 Gt

TANTALE
2,5 kt





CUIVRE
23 Mt

Photo : Frédéric Bisson via Flickr

Source: Ademe /Geldron/ update USGS March 2026
Tellure: World Mining Data 2026
Platinoides: Platinium + Paladium

Categories of Minerals in the World Industry

Federal Ministry
Finance
Republic of Austria

International Organizing Committee for the World Mining Congresses



- Iron and Ferro-Alloy Metals
- Non-Ferrous Metals
- Precious Metals
- Industrial Minerals
- Mineral Fuels

Iron and Ferro-Alloy Metals:

Iron, Chromium, Cobalt, Manganese, Molybdenum, Nickel, Niobium, Tantalum, Titanium, Tungsten, Vanadium

Non-Ferrous Metals:

Aluminium, Antimony, Arsenic, Bauxite, Beryllium, Bismuth, Cadmium, Copper, Gallium, Germanium, Indium, Lead, Lithium, Mercury, Rare Earth Minerals, Rhenium, Selenium, Tellurium, Tin, Zinc

Precious Metals:

Gold, Platinum-Group Metals (Palladium, Platinum, Rhodium), Silver

Industrial Minerals:

Asbestos, Baryte, Bentonite, Boron Minerals, Diamond (Gem/Industrial), Diatomite, Feldspar, Fluorspar, Graphite, Gypsum and Anhydrite, Kaolin (China-Clay), Magnesite, Perlite, Phosphates (incl. Guano), Potash, Salt, Sulfur, Talc (incl. Steatite and Pyrophyllite), Vermiculite, Zircon

Mineral Fuels:

Steam Coal (incl. Anthracite and Sub-Bituminous Coal), Coking Coal, Lignite, Natural Gas, Petroleum (incl. Condensate), Oil Sands, Oil Shales, Uranium

Minerals are essential for the Global Economy

Minerals – Backbone of the economy

Major developments in global mining production based on World Mining Data 2026

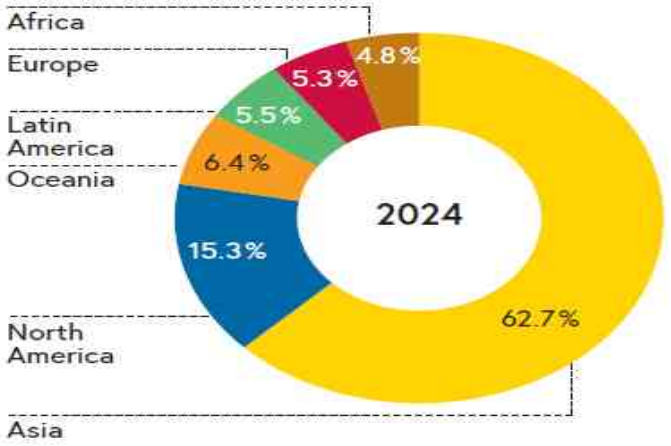
World mining production

2024
19.4 Billion metric tons

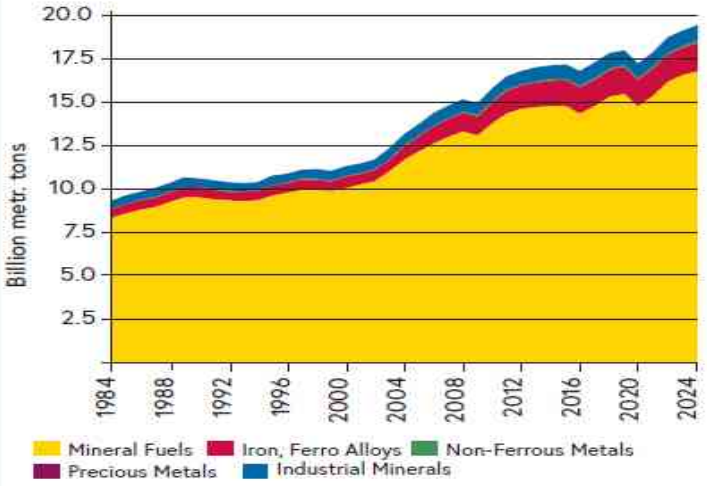
2000
11.3 Billion metric tons

1985
9.6 Billion metric tons

Share of total mining production 2024 by continents

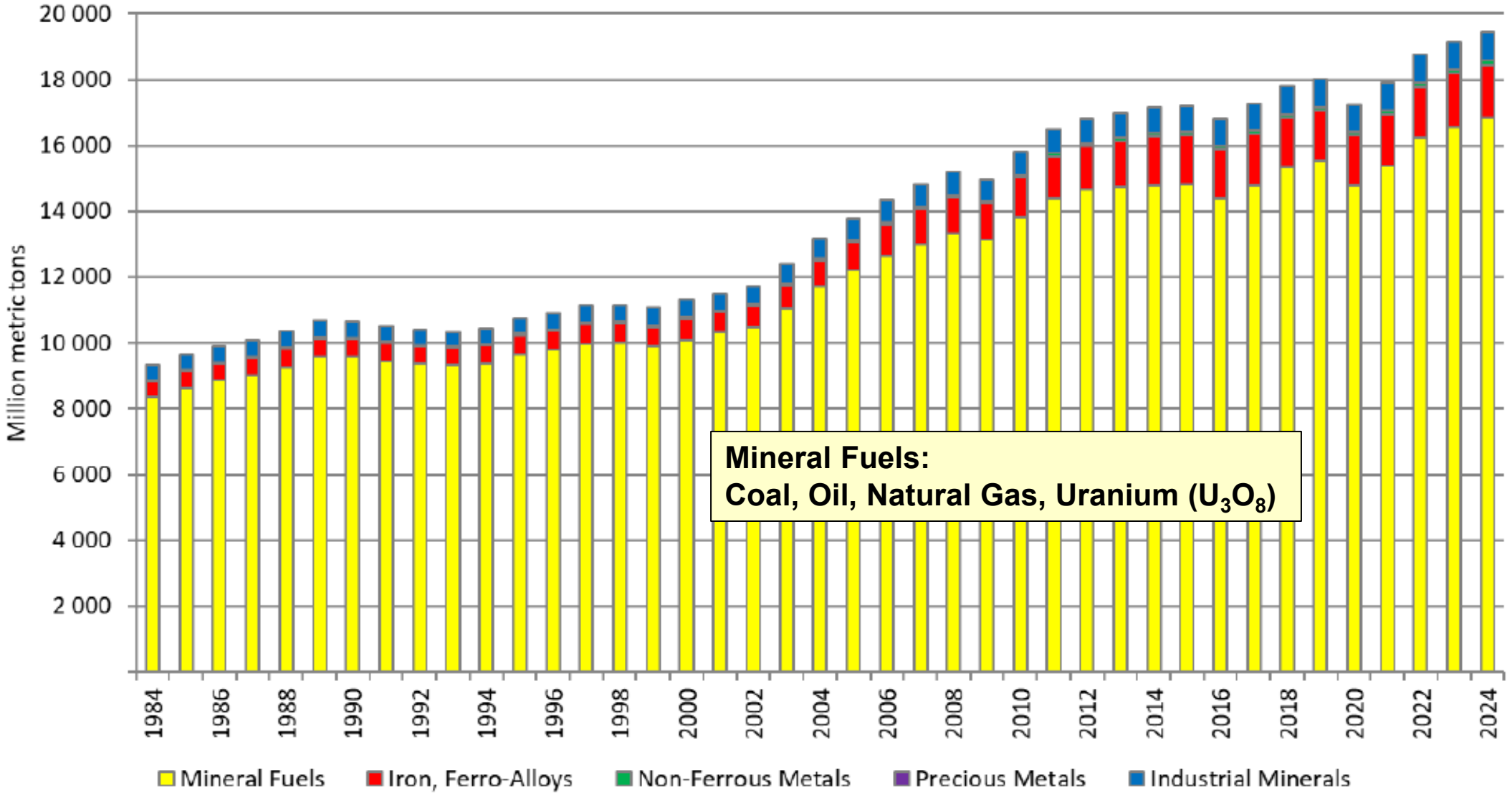


Total mining production 1984–2024



Source: World Mining Data April 2026

World Mining Production 1984 – 2024 by Minerals (Mt)

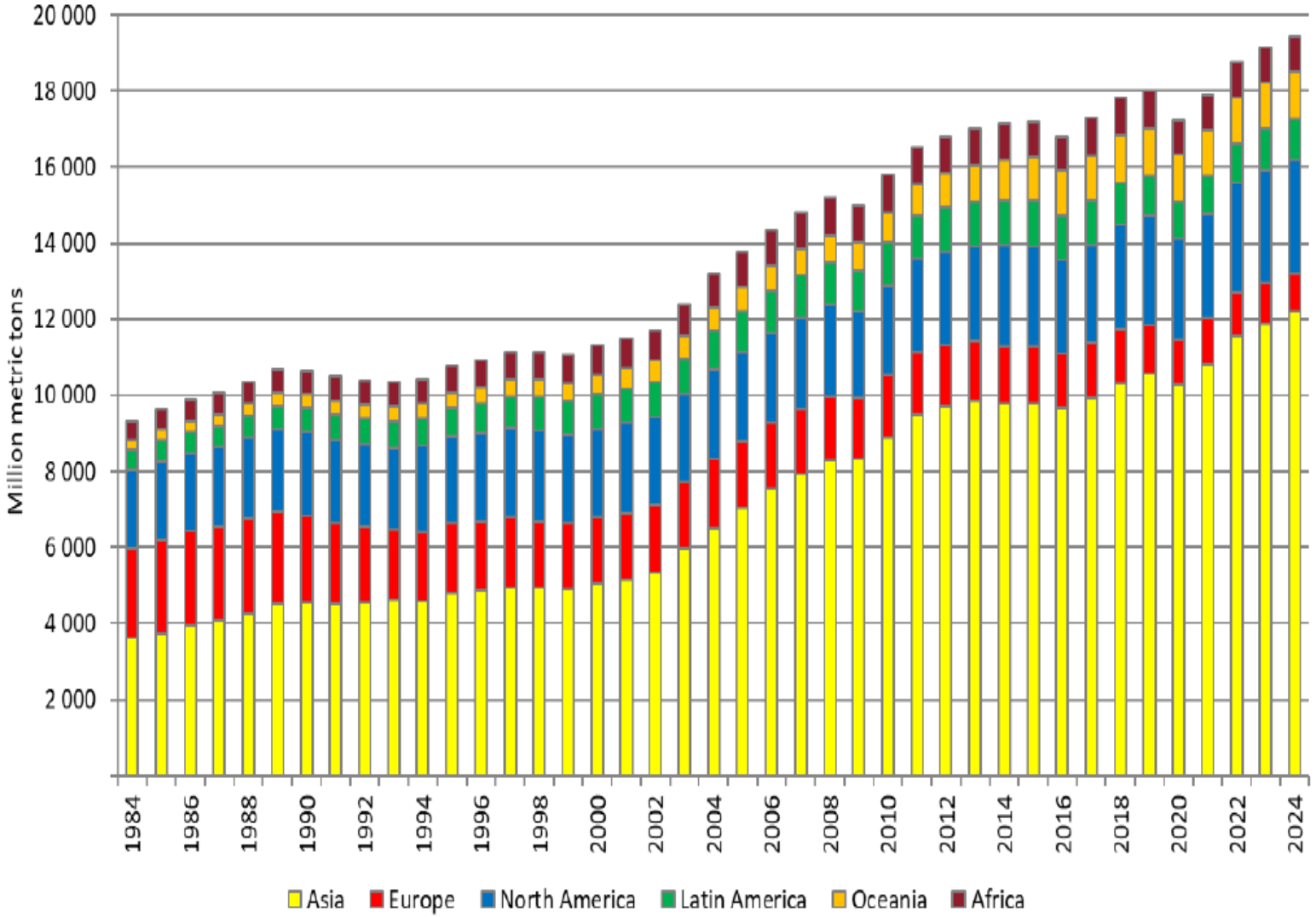


Source: World Mining Data April 2026

World Mining Production 1984 – 2024 by Continents (Mt)

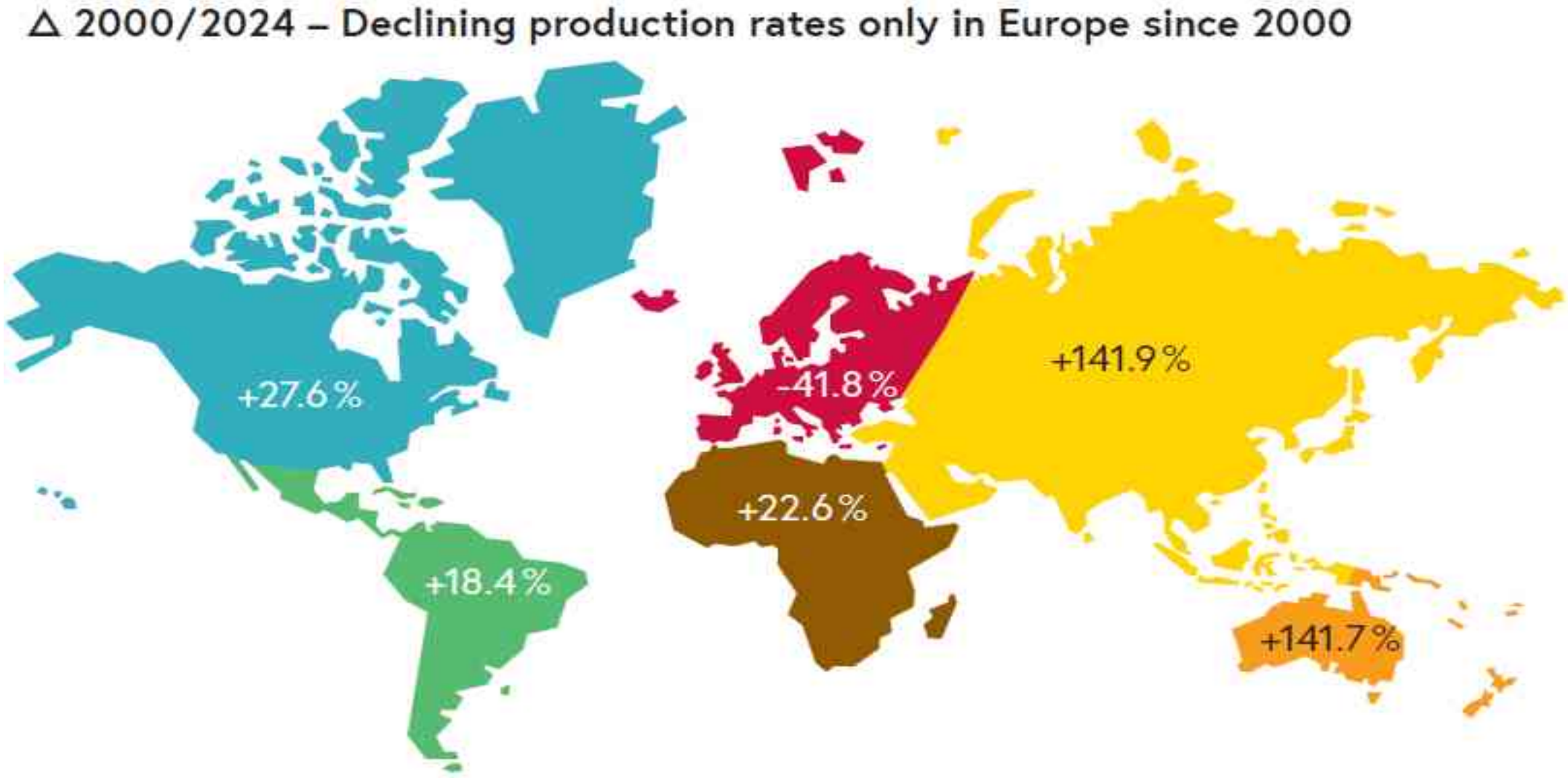
China is world's largest producer of 31 different commodities:

- 4 Iron and Ferro–Alloy Metals: Mo, Ti, W, V
- 14 Non-Ferrous Metals: Al, Sb, Bi, Cd, Ga, Ge, In, Pb, Hg, REE, Se, Te, Sn, Zn
- 1 Precious Metal: Au
- 10 Industrial Minerals: Baryte, Fluorspar, Graphite, Gypsum, Kaolin, Magnesite, Perlite, Phosphate Rock, Salt, Sulfur
- 2 Mineral Fuels: Steam Coal, Coking Coal



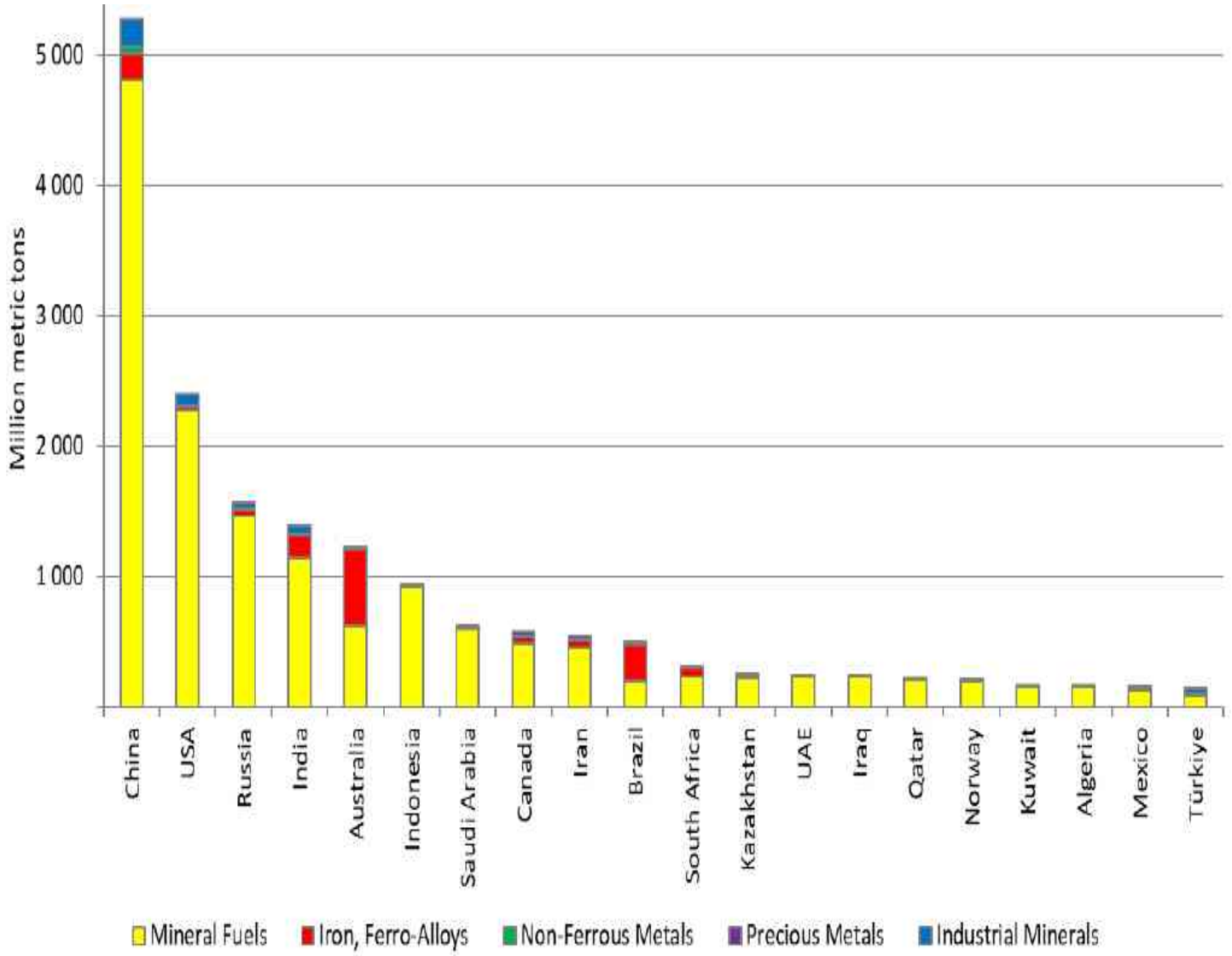
Source: World Mining Data April 2026

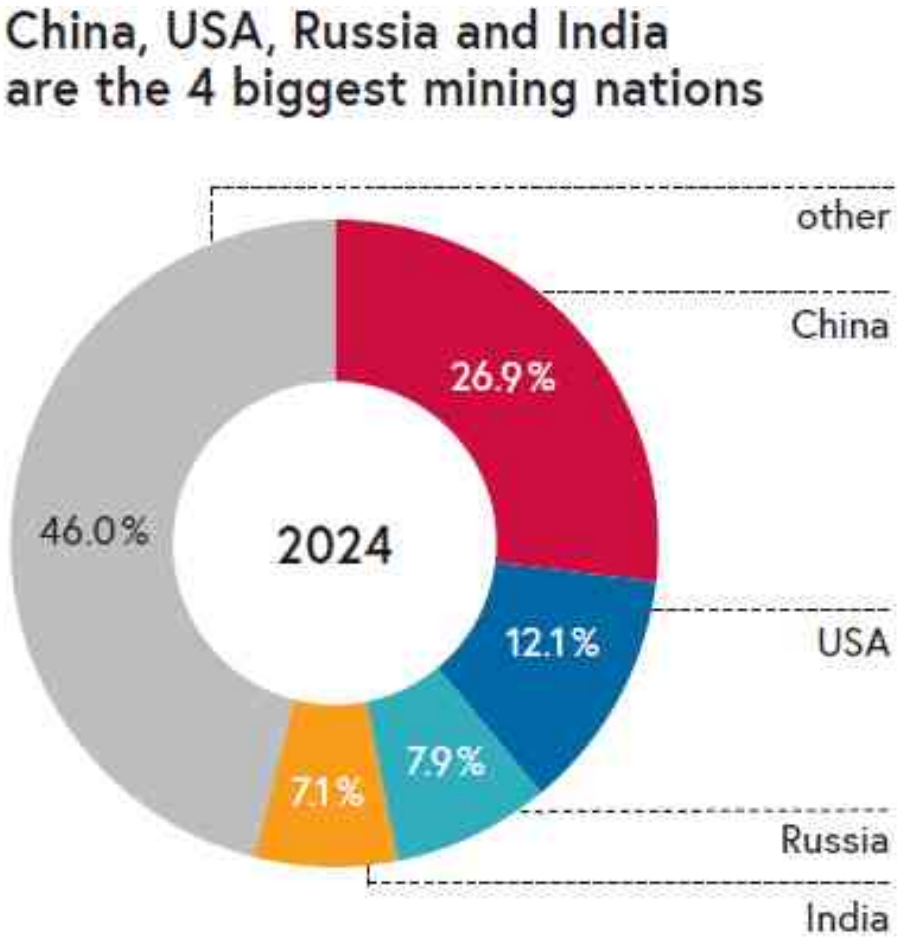
Mining Activity in the World Industry – 2024 vs 2000



Source: World Mining Data April 2026

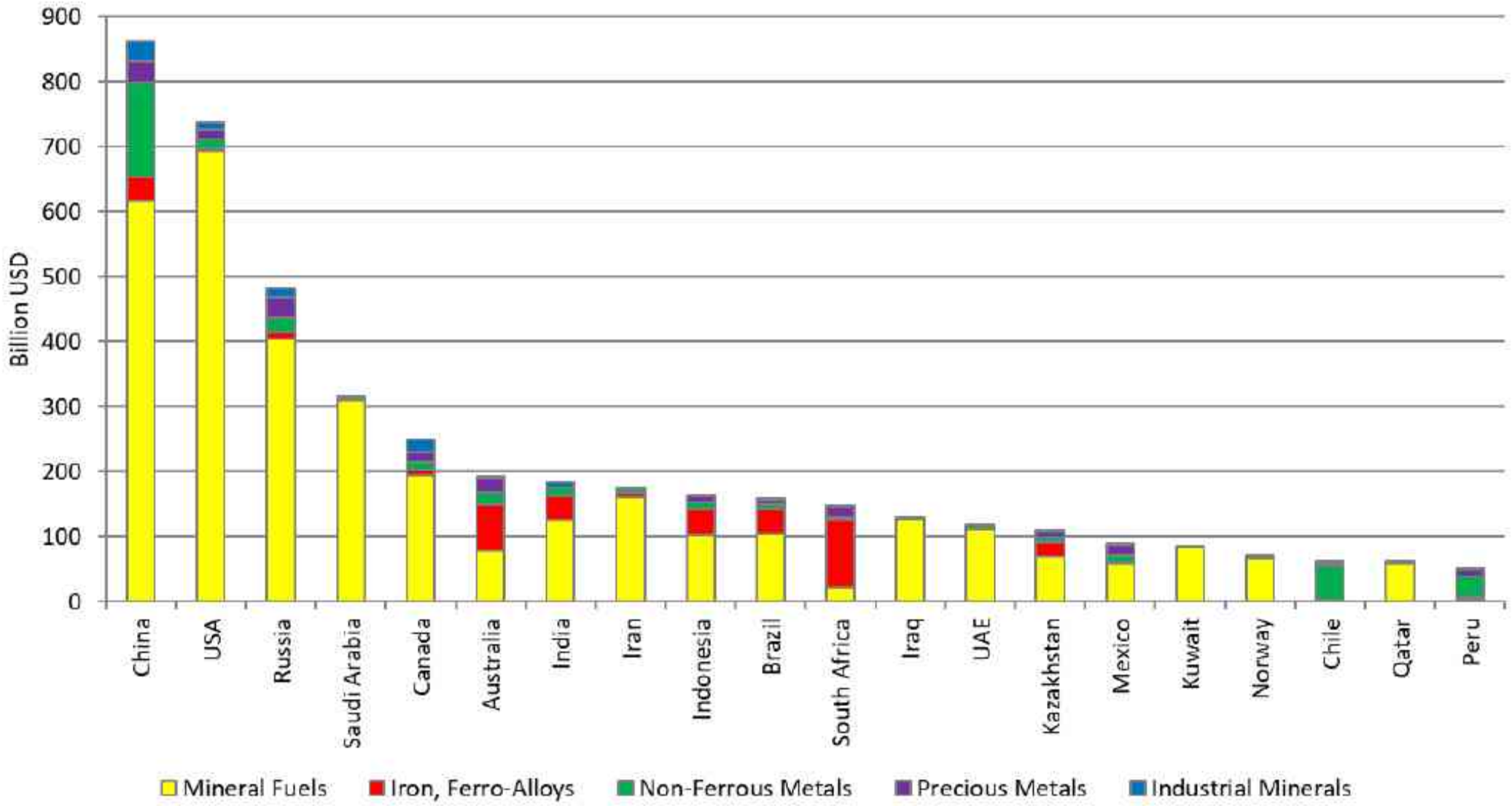
World Mining Production 2024 by Countries (Mt & %)





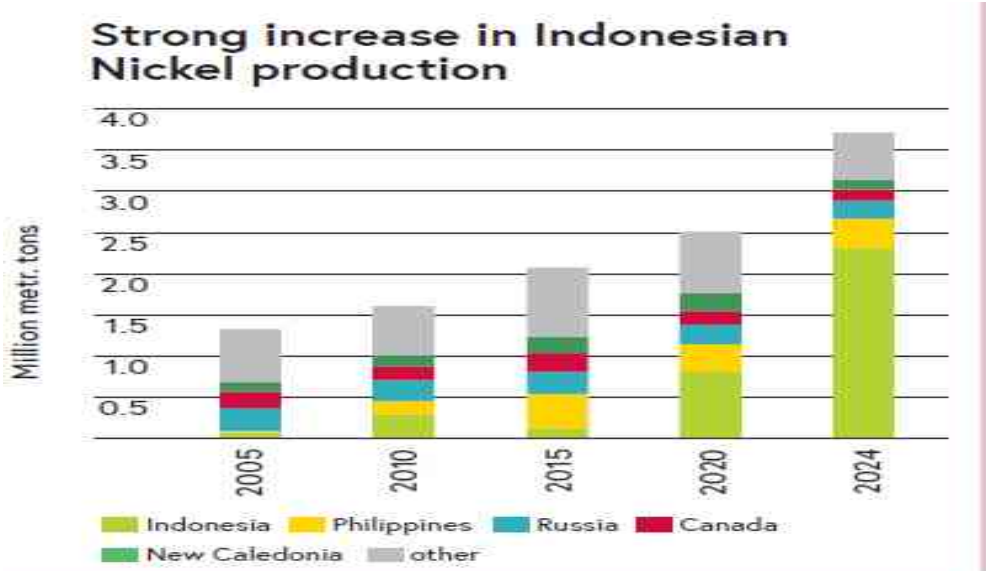
Source: World Mining Data April 2026

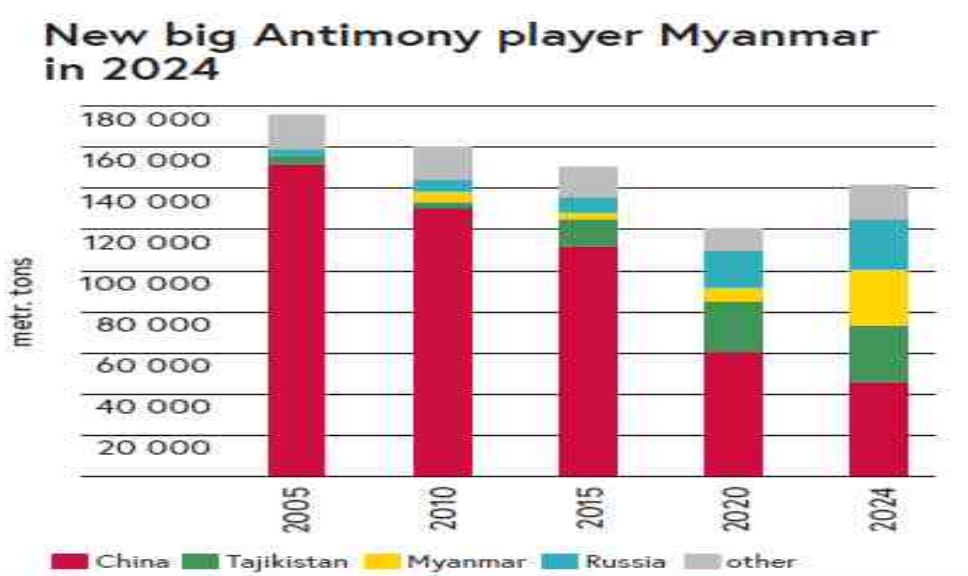
World Mining Production 2024 by Countries (GUS$)

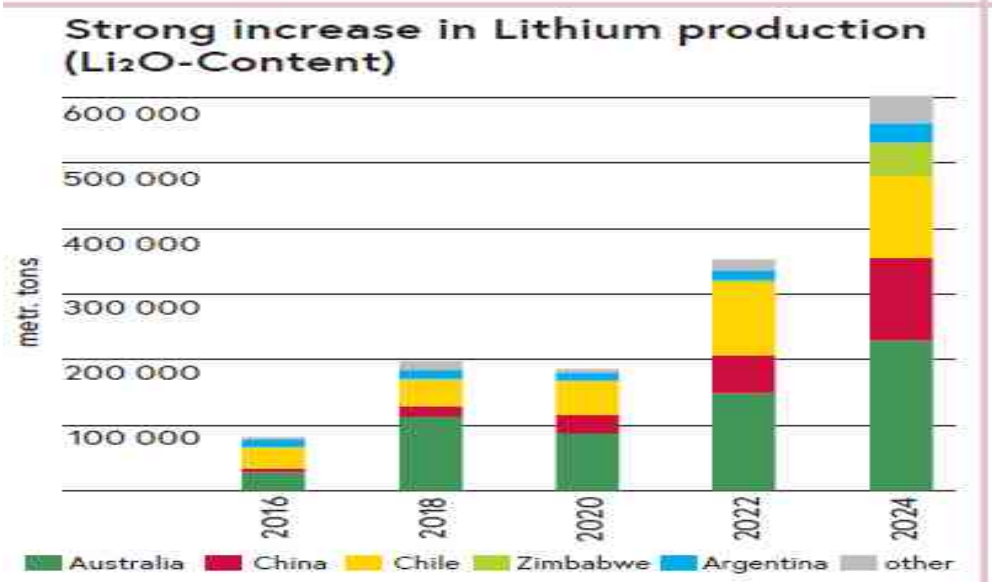


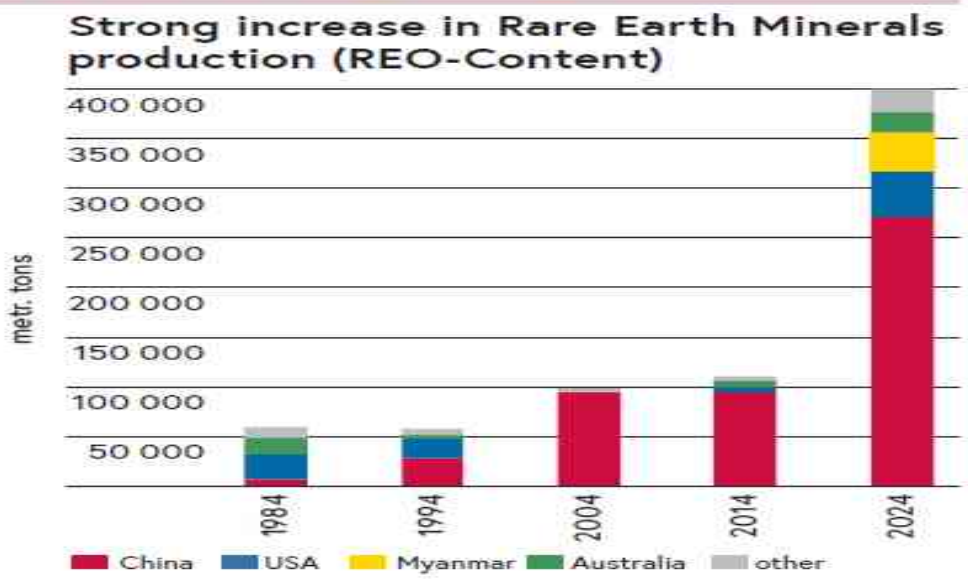
Source: World Mining Data April 2026

World Mining Production: Nickel, Lithium, Antimony, REE



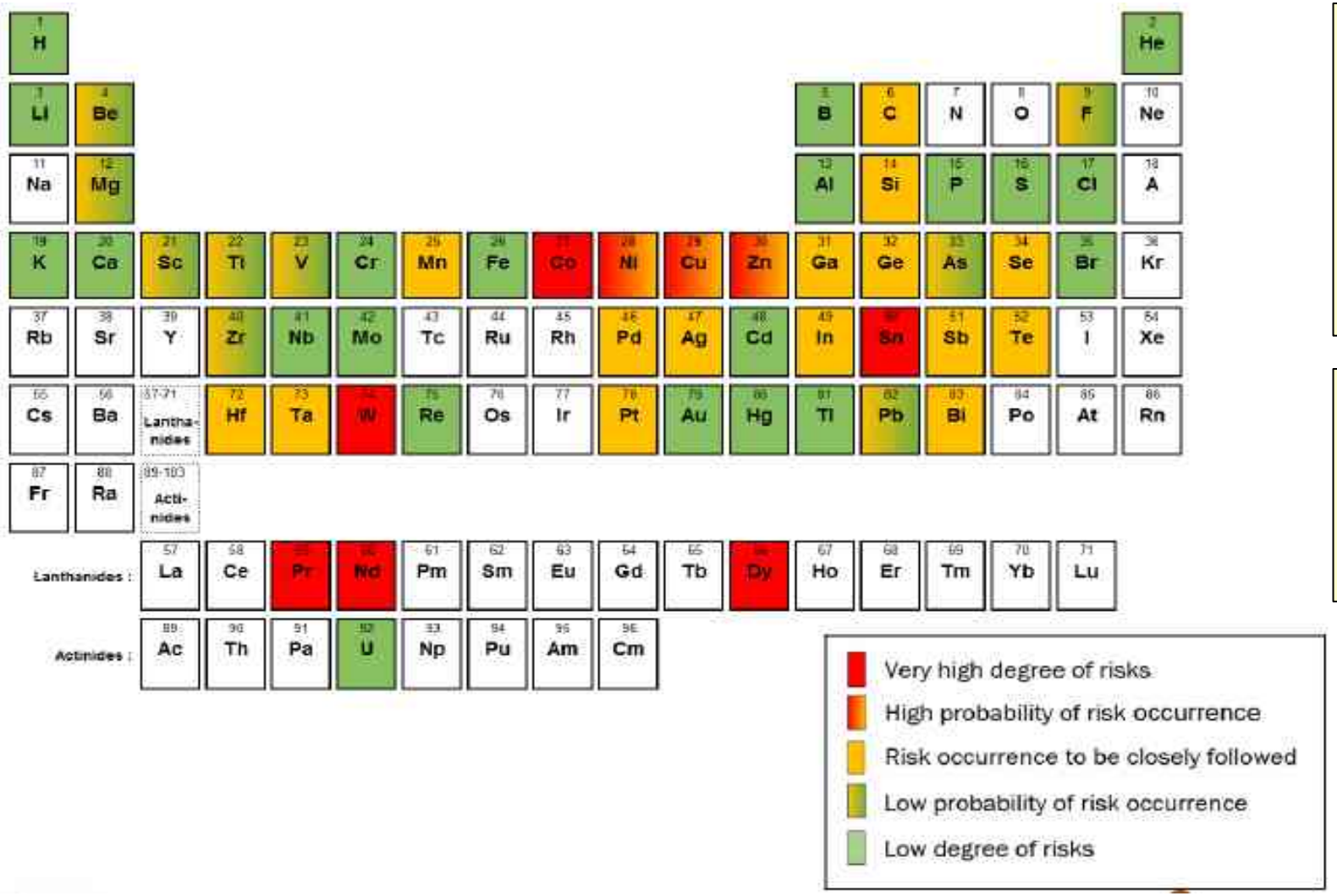






Source: World Mining Data April 2026

More and more Materials are needed for Industry
For some of them, a high degree of Risks



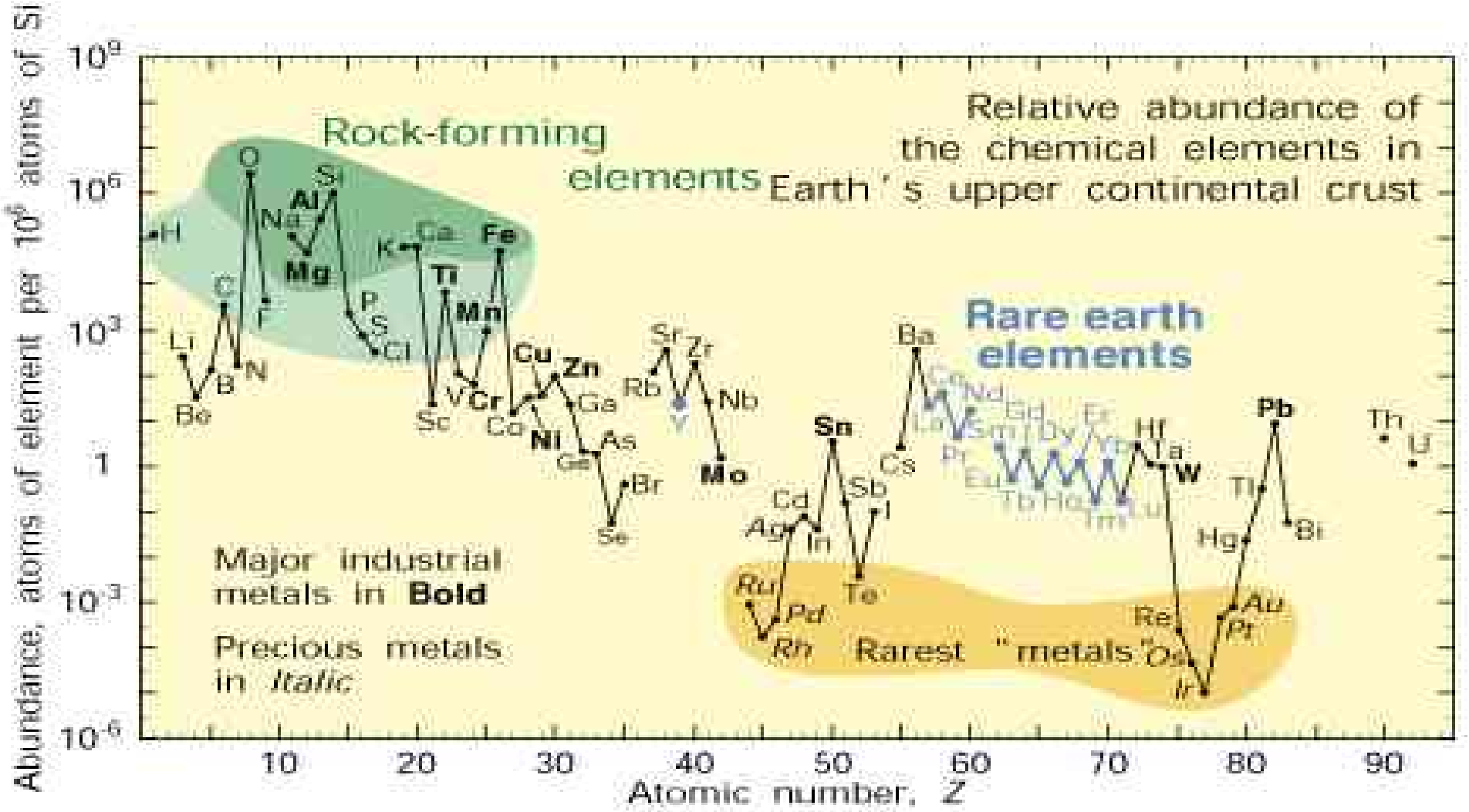
Co: Cobalt
Ni : Nickel
Cu: Copper
Zn: Zinc
Sn: Tin
W : Tungstene

Rare Earth Elements (REE)

Pr: Praséodyme
Nd: Neodymium
Dy: Dysprosium

Source: Institut Carnot/BRGM

Abundance of Elements vs Atomic number



Source: US Department of Interior/USGS 2005
Nota: Atomic number (Z) = number of protons in the nucleus

Most commun Metals & Mineral Materials used by Industry

Materials		At. Nb	Abundant	Rare/Scarce	Extremely rare
Iron	Fe	26			
Aluminium	Al	13			
Titanium	Ti	22			
Magnesium	Mg	12			
Manganese	Mn	25			
Chromium	Cr	24			
Silicon	Si	14			
Graphite	C	6			
Zinc	Zn	30			
Lead	Pb	82			
Copper	Cu	29			
Nickel	Ni	28			
Tin	Sn	50			
Cobalt	Co	27			
Molybdenum	Mo	42			
Tungsten	W	74			

Level of abundance in the earth crust:

Abundant Metals: Concentrations > 1000 ppm (0,1%)

Rare or scarce Metals: Concentrations between 1 and 1000 ppm

Extremely rare Metals: Concentrations < 1 ppm

Graphite: Mineral Material

ppm: parts per million

Source: ChG/Data from IEA, IFP EN, USGS, BRGM

Precious and Rare Metals & Mineral Materials used by Industry

Materials		At. Nb	Abundant	Rare/Scarce	Extremely rare
Gold	Au	79			
Silver	Ag	47			
Platinum Goup	Pt	78			
Antimony	Sb	51			
Indium	In	49			
Selenium	Se	34			
Tellurium	Te	52			
Cadmium	Cd	48			
Gallium	Ga	31			
Rare Earths					
Neodynium	Nd	60			
Dysprosium	Dy	66			
Terbium	Tb	65			

Level of abundance in the earth crust:

Abundant Metals:
Concentrations > 1000 ppm (0,1%)

Rare or scarce Metals:
Concentrations between 1 and 1000 ppm

Extremely rare Metals:
Concentrations < 1 ppm

Platinum Group Metals (PGM):
Platinum, Palladium, Rhodium, Iridium, Rythenium, Osmium

Rare Earth Elements:
Dispersed, difficult to extract, environmental impacts.
A group of 17 elements
Lanthanides + Scandium + Yttrium

TPA
Sharing Experience

Source: ChG/Data from IEA, IFP EN, USGS, BRGM

More and more Materials are needed for Industry - Criticality

A raw Material is considered as critical when:

- It is used in several industrial sectors.
- It is difficult to be subsituted on short term.
- It is subject to several industrial applications.
- It has a great economic value.
- It may have limited resources.
- Its resources, reserves and production are geographically concentrated.
- Its resources, reserves and production may be subject to geopolitical barriers.
- Prices reflect scarcity. High prices increase activity which expands supply. Low prices have the opposite effect..
- EU identified 30 critical Materials in 2020, vs 27 in 2017, 20 in 2014, 14 in 2011.

More and more Materials are needed for Industry - Criticality

An energy system powered by Clean Energy technologies requires much more Minerals than fossil fuels driven technologies.

Needs for Mineral Resources:
x6 for a typical electric car vs a conventional car with Internal combustion (IC)
Copper: 20kg for a conventional (IC) car, 40 kg for a hybrid car, 80kg for an electric car.
x9 for an onshore wind farm vs a gas-fired power plant.

Since 2010, the amount of Minerals needed for power generation worldwide has been increased by 50%. This percentage will increase substantially in the future in line with the Energy Transition process.

Increased production of Minerals and Metals will increase the energy and carbon footprint. Hopefully, this effect is dwarfed by the emissions reduction that can be achieved when those Minerals and Metals are deployed in Renewable Energy technologies.

More and more Materials are needed for Industry - Criticality

Some examples of crucial elements needed for various technologies, in relation with Energy Transition (Solar PV, Wind power, grid expansion, electromobility, motors and batteries)

Battery performance, energy density:
Lithium, Cobalt, Manganese, Graphite

Permanent magnets for Wind turbines and Electric Vehicles Batteries:
Rare Earth Elements (RER)

Electricity networks:
Copper, Aluminium

Critical Materials are needed for Industry

	Copper	Cobalt	Nickel	Lithium	REEs	Chromium	Zinc	PGMs	Aluminium*
Solar PV	●	○	○	○	○	○	○	○	●
Wind	●	○	◍	○	●	◍	●	○	◍
Hydro	◍	○	○	○	○	◍	◍	○	◍
CSP	◍	○	◍	○	○	●	◍	○	●
Bioenergy	●	○	○	○	○	○	◍	○	◍
Geothermal	○	○	●	○	○	●	○	○	○
Nuclear	◍	○	◍	○	○	◍	○	○	○
Electricity networks	●	○	○	○	○	○	○	○	●
EVs and battery storage	●	●	●	●	●	○	○	○	●
Hydrogen	○	○	●	○	◍	○	○	●	◍

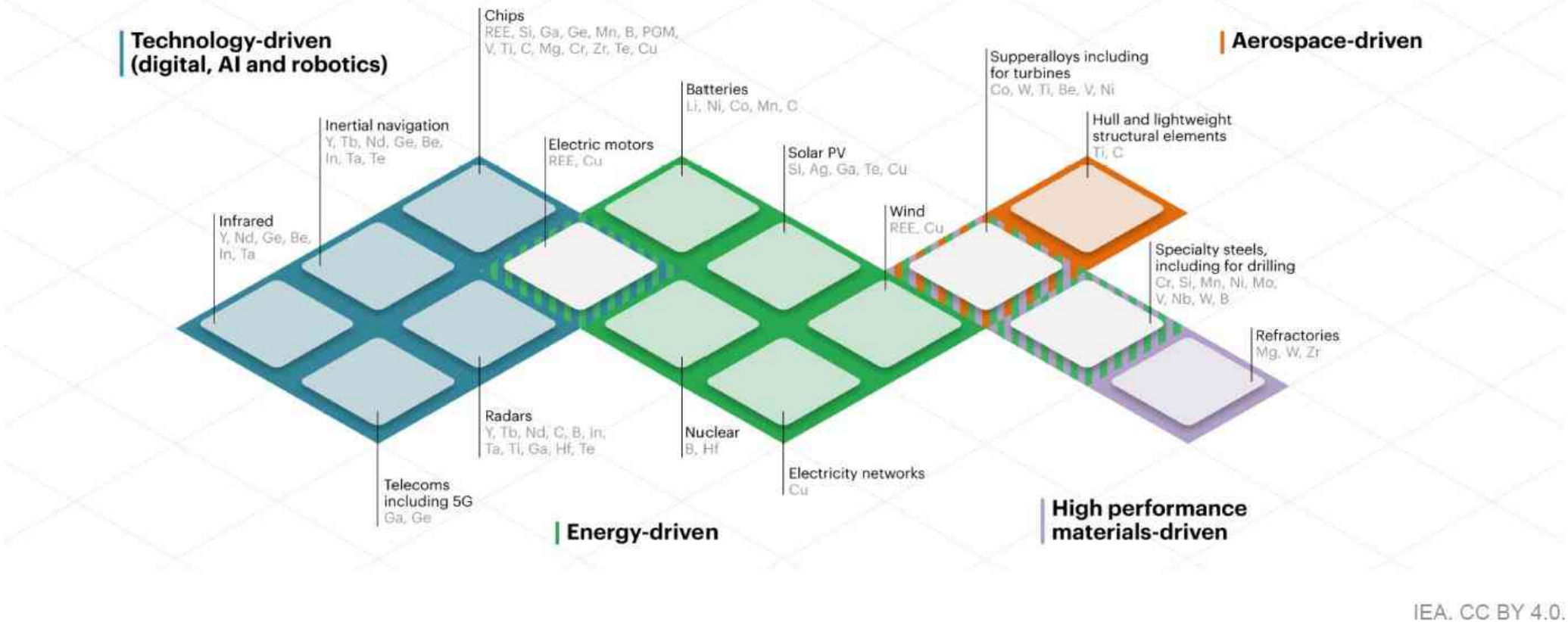
Notes: Shading indicates the relative importance of minerals for a particular clean energy technology (● = high; ◍ = moderate; ○ = low), which are discussed in their respective sections in this chapter. CSP = concentrating solar power; PGM = platinum group metals.

* In this report, aluminium demand is assessed for electricity networks only and is not included in the aggregate demand projections.

Source: IEA Special Report May 2021

Critical Materials are needed for Energy Industry

Overview of broader energy-related strategic minerals



IEA. CC BY 4.0.

Notes: Excludes base metals such as aluminium, lead, tin and zinc. Ag = silver; B = boron; Be = beryllium; C = graphite; Co = cobalt; Cr = chromium; Cu = copper; Ga = gallium; Ge = germanium; Hf = hafnium; In = indium; Ir = iridium; Li = lithium; Mg = magnesium; Mn = manganese; Mo = molybdenum; Nb = niobium; Nd = neodymium; Ni = nickel; PGM = platinum-group metals; REE = rare earth elements; Sb = antimony; Si = silicon; Ta = tantalum; Tb = terbium; Ti = titanium; V = vanadium; W = tungsten; Y = yttrium; Zr = zirconium.

Source: IEA Global Critical Materials Outlook 2025 – May 2025

Most commun Metals and Mineral Materials used by Energy Transition

Metals		Abundant	Rare/Scarce	Extrem. rare	Solar PV	Solar CSP	Wind	Elec. Netwk	EV/Battery	Fuel Cells
Aluminium	Al				High importance		Moderate import.			
Titanium	Ti									
Manganese	Mn									
Chromium	Cr				0/Low importance					
Lithium	Li									
Silicon	Si									
Graphite										
RER Elem.	RER									
Lanthanum	La									
Neodynium	Nd									
Dysprosium	Dy									
Terbium	Tb									
Zinc	Zn									
Molybdenum	Mo									
Copper	Cu									
Nickel	Ni									
Cobalt	Co									
Cadmium	Cd									
Gallium	Ga									
Platinum	Pt									
Palladium	Pd									
Rhodium	Rh									
Indium	In									
Selenium	Se									
Tellurium	Te									

Sharing Experience

Source: ChG/Data from IEA, IFP EN, USGS, BRGM

Mineral Matters
Resources, Reserves, Production

Scarcity, Reserves, Resources

For any material, it is important to distinguish Reserves and Resources.

As defined by the Committee for Mineral Reserves International Reporting Standards:

A Mineral Resource is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality and quantity that there are reasonable prospects for eventual economic extraction.

A Mineral Reserve is the economically mineable part of a measured and/or indicated Mineral Resource.

Evaluations of Reserves and Resources may evolve upon time.

Scarcity, Reserves, Resources, Production

To obtain Mineral Material, this one must be processed through successive industrial transformations from the ore extraction to the final product delivery.

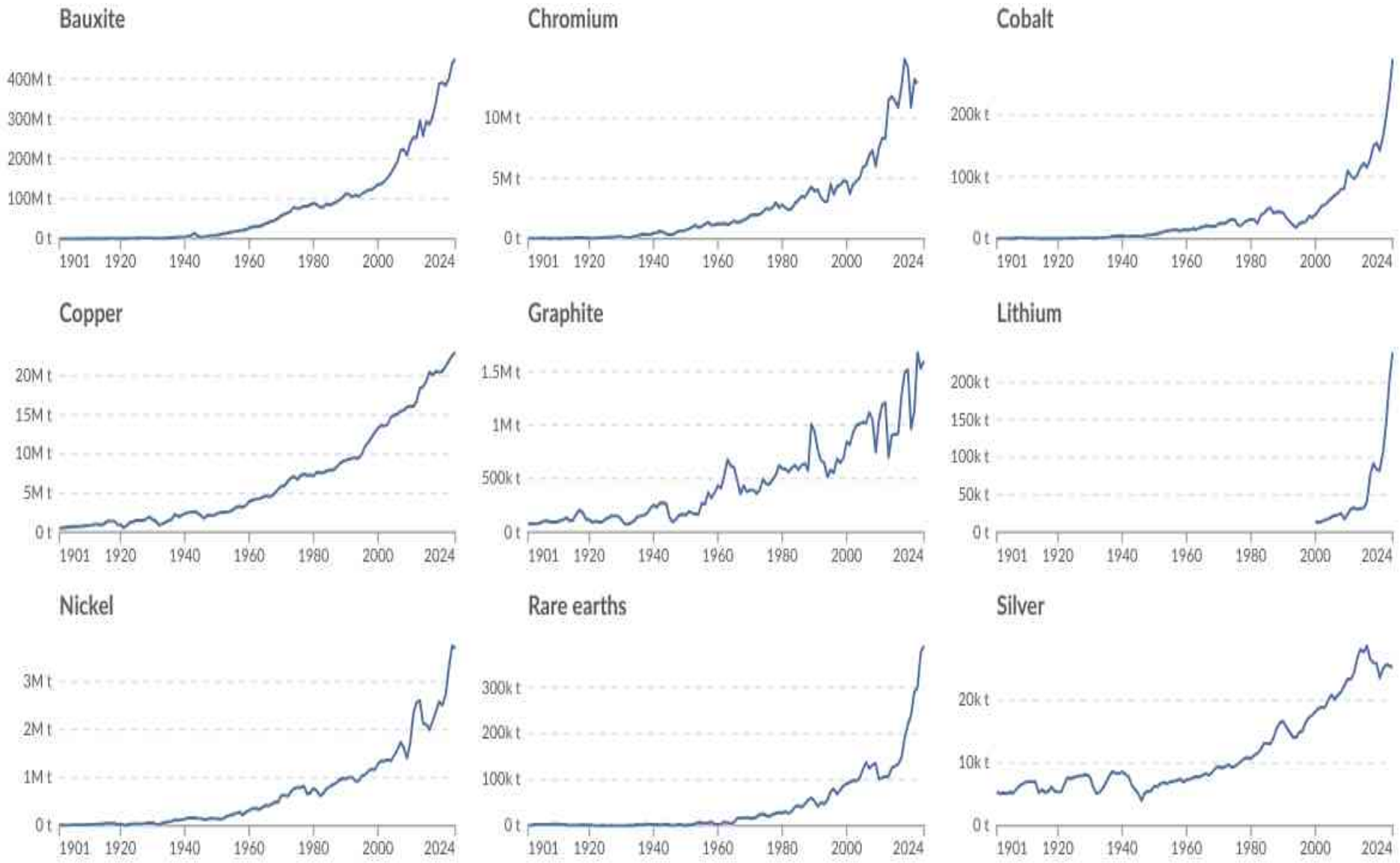
For example:

To produce 1 tonne of Iron, 1,7 tonne of Iron ore must be processed.
Iron ore is very abundant:
Reserves iron ore at end 2025 = 200 Gt
Reserves iron metal at end 2025 = 87 Gt
Resources iron ore > 900 Gt
Resources iron metal > 260 Gt
Production 2025 iron ore = 2600 Mt
Production 2025 iron metal = 1500 Mt

To produce 1 tonne of Aluminium, 4/5 tonnes of bauxite ore (composed of hydrated aluminium oxyde, silica and iron oxyde) which produce 2 tonnes of alumina must be processed.

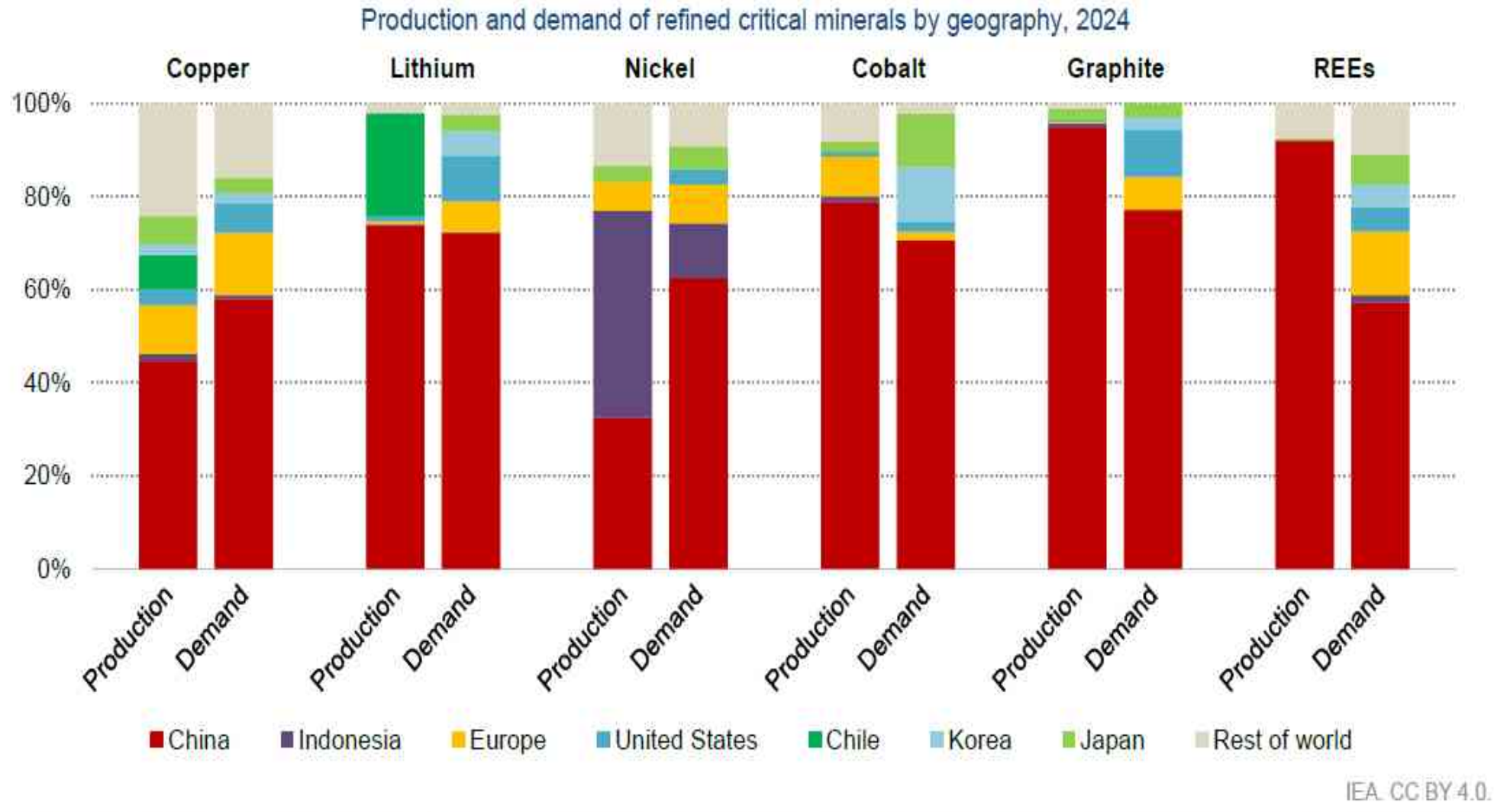
Some Mineral Material are by-product of others (Example: Indium vs Zinc,…)

Global Mines Production 1901 - 2024



Source: Our World in Data 2025

Production & Demand for Refined Critical Materials - 2024

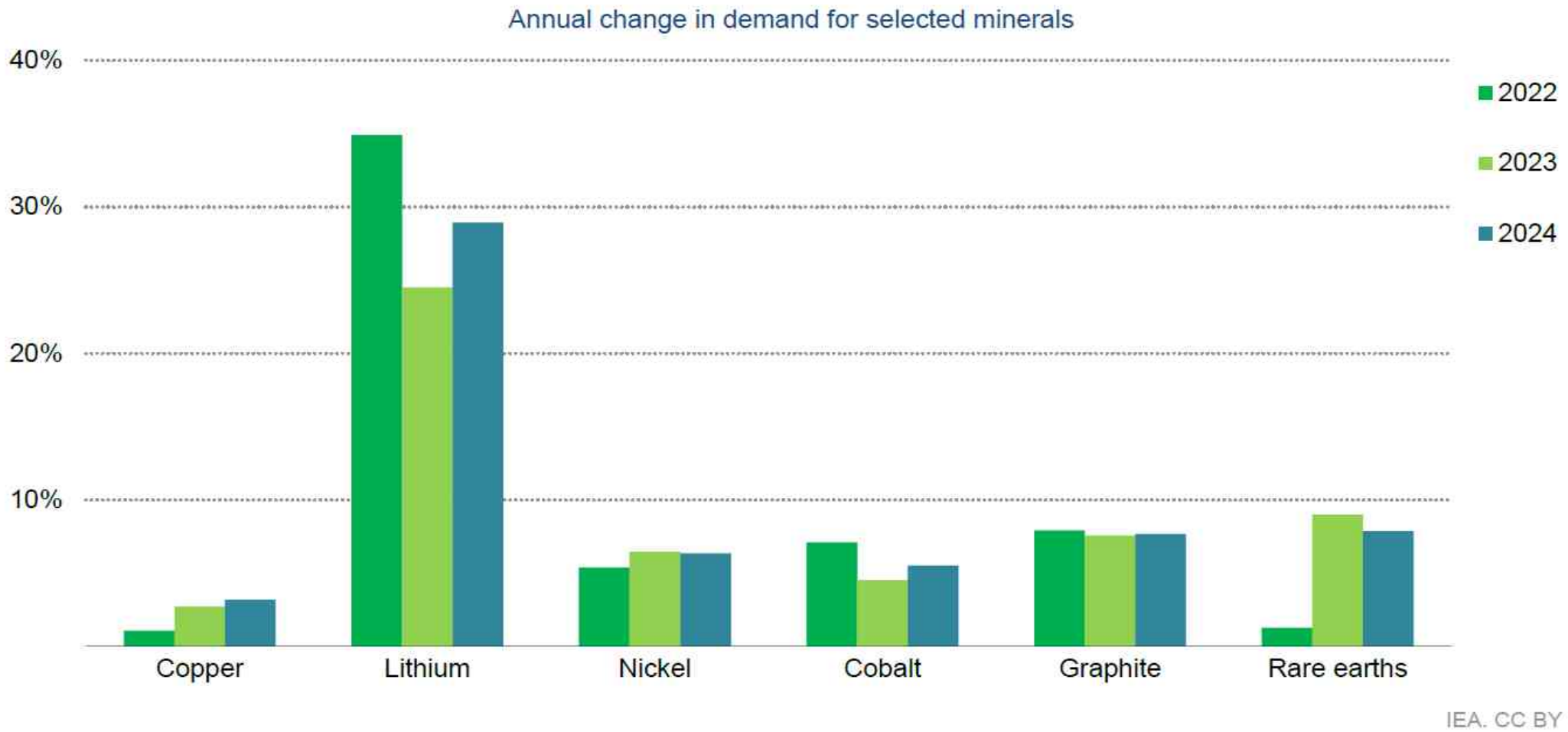


Notes: REEs = rare earth elements. Production refers to refined minerals production while demand refers to refined minerals consumption. Rare earths are magnet rare earths only.

Source: IEA Global Critical Materials Outlook 2025 – May 2025

Demand Growth for Critical Materials 2022 – 2024 increases substantially

Demand for critical minerals maintained robust growth in 2024, supported by robust energy technology deployment



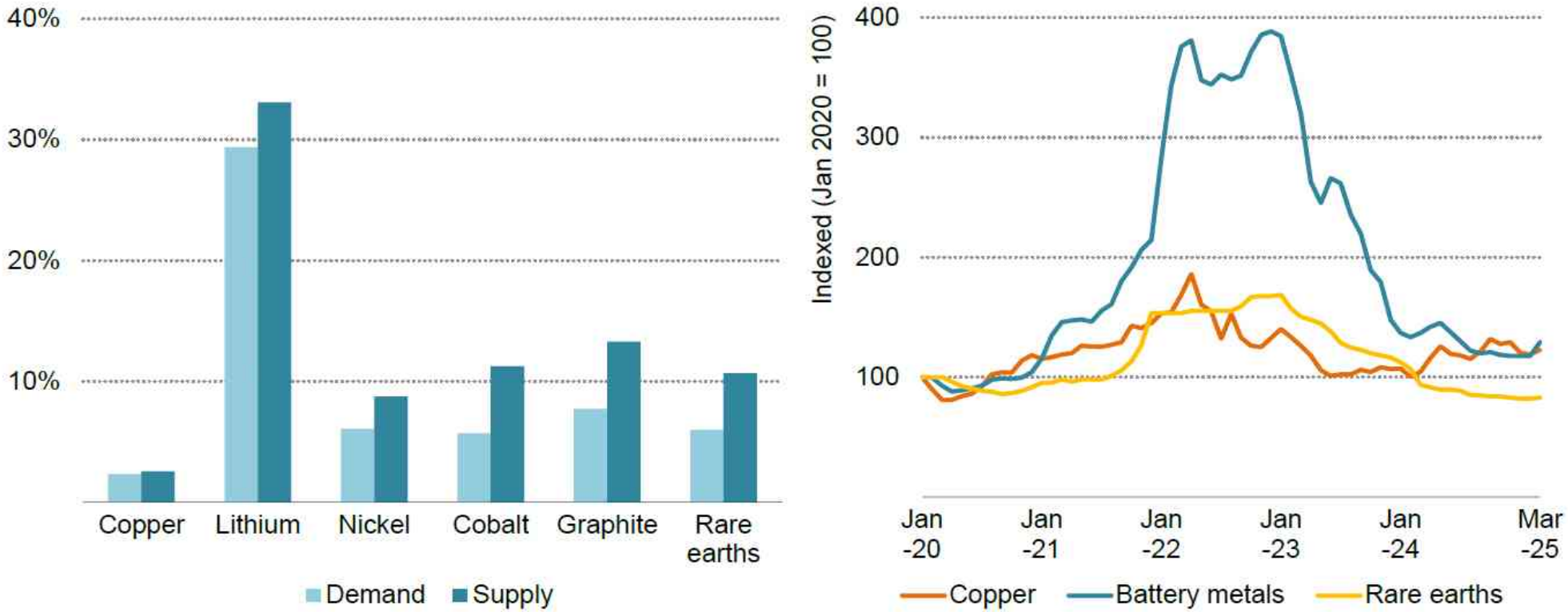
Note: Rare earths are magnet rare earths only.

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Supply greater than Demand 2021 – 2024 → Decrease of Prices

However, supply has expanded at a faster pace than demand, resulting in downward pressure on prices, especially for battery metals

Annual average demand and supply growth between 2021 and 2024 (left), price developments (right) for selected minerals



IEA. CC BY 4.0.

Notes: Supply growth rates are based on refined output. Rare earths are magnet rare earths only. Battery metals include lithium, nickel, cobalt, graphite and manganese.

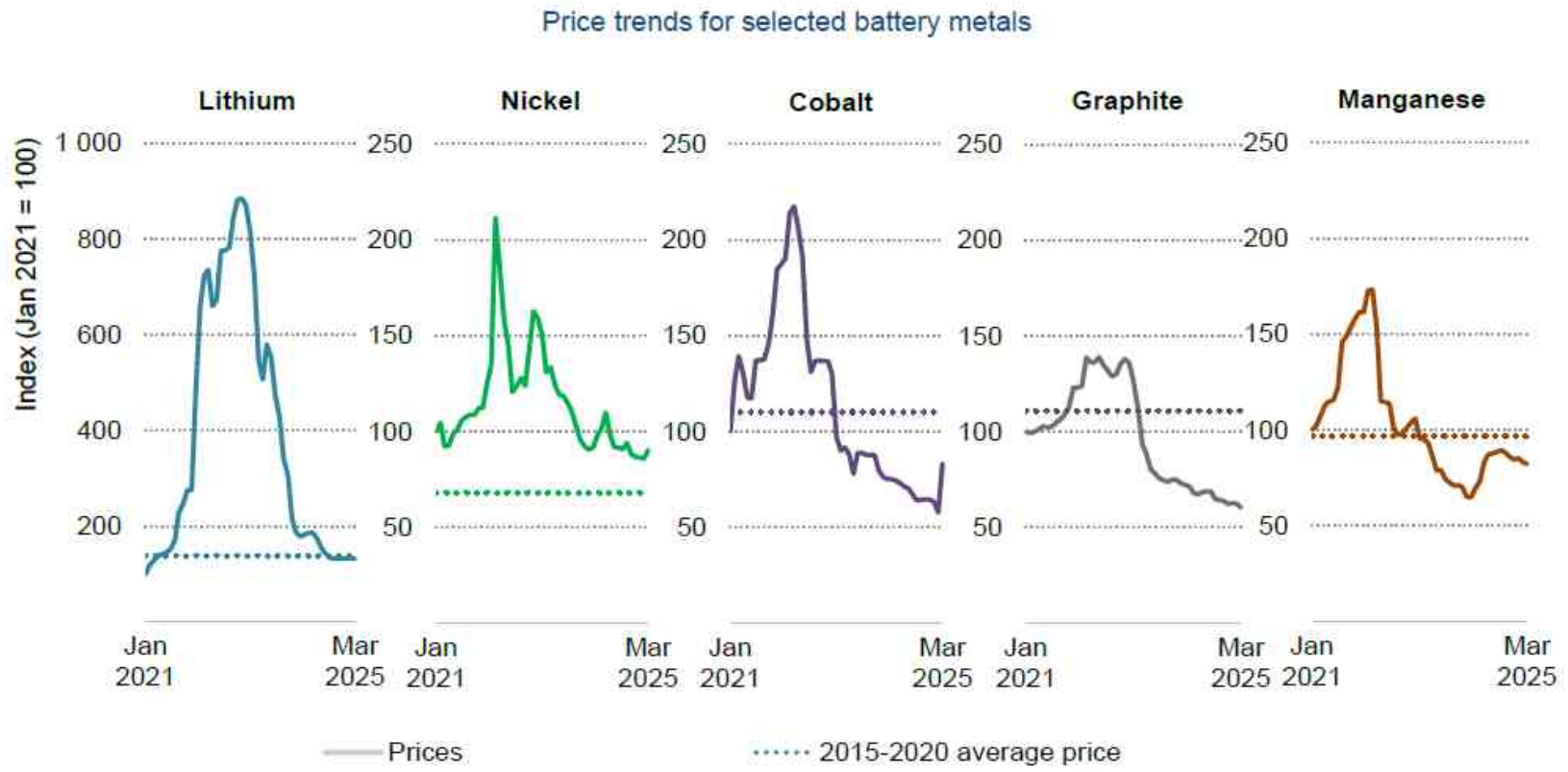
Sources: IEA analysis based on S&P Global and Bloomberg.

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Prices Development for key Materials

Prices development for key Materials - Evolution 2021 - 2025
A great volatility

Prices for battery metals continued to decline in 2024 amid growing supply, with the exception of manganese



Notes: Manganese historical average from 2018-2020. Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash, China Spherical Graphite 99.95% and manganese sulphate 32%. Nominal prices.
Sources: IEA analysis based on S&P Global and Bloomberg.

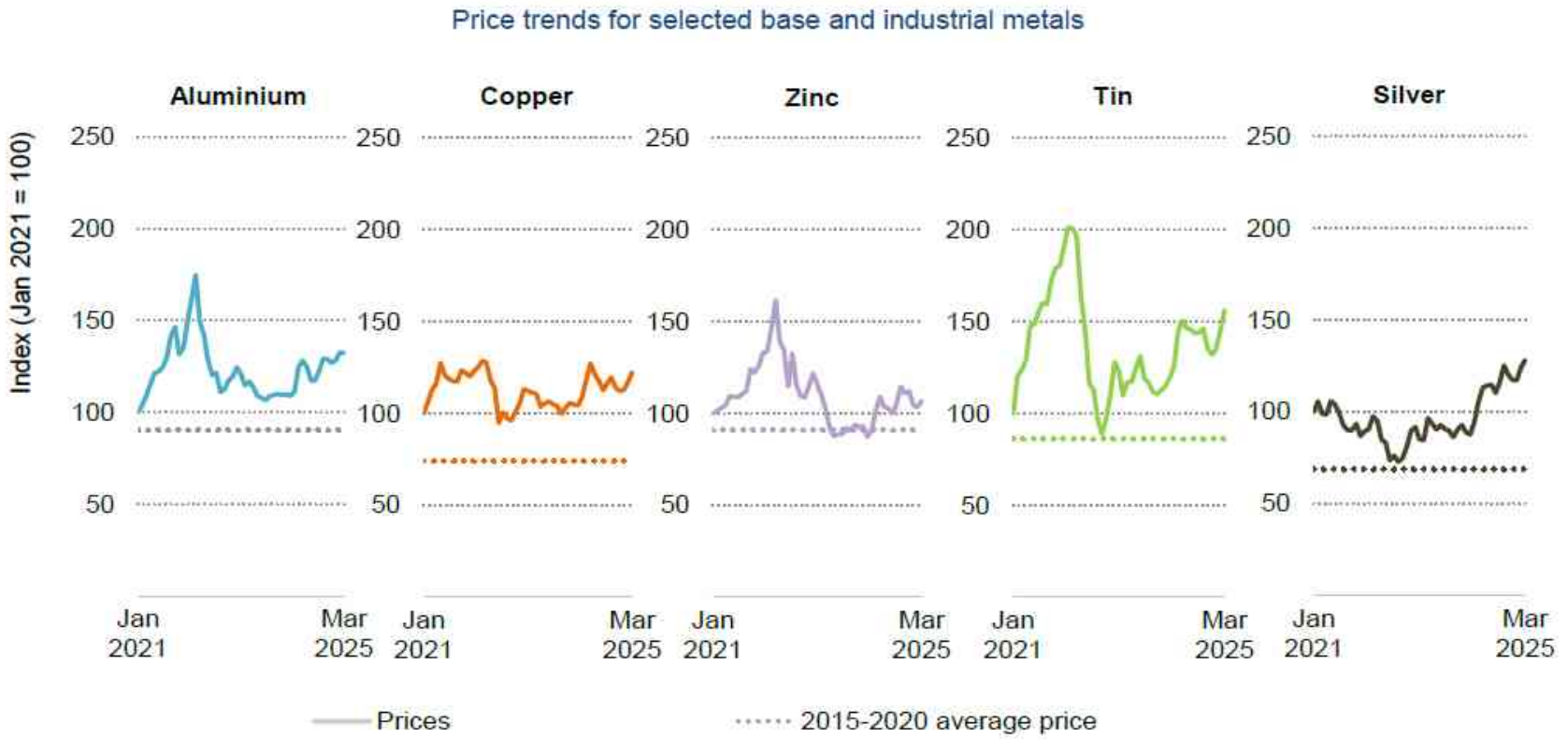
Several factors explain the drop in prices from 2022 to 2024 (Mainly Demand growth much less than Production) :

- **Slowing growth rate of EV battery.**
- **Large-scale cell and cathode production.**
- **China's expansion of battery plants, cathode and anode production capacity has far outpaced demand.**
- **Build-up of inventory throughout the supply chain.**
- **Correction of steep price rise in 2021-2022**

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Prices development for key Materials - Evolution 2021 - 2025
A great volatility

Base and industrial metal prices saw a modest rebound in 2024 and have continued to rise in 2025, driven by improving industrial demand prospects and tightening supply dynamics



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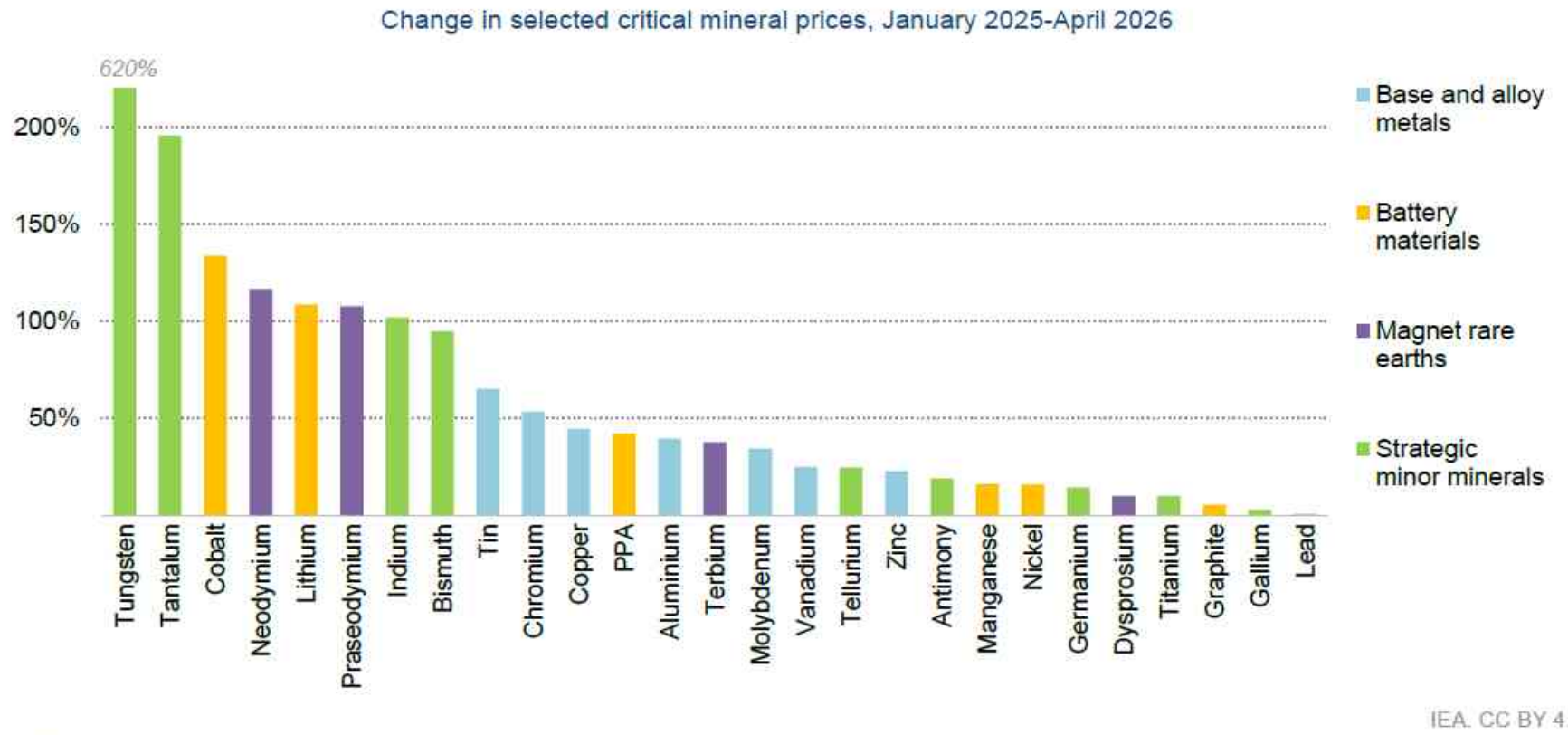
Note: Assessment based on the LME Aluminium 99.7%, LME Copper Grade A, LME special high-grade zinc 99.995%, LME-Tin 99.85% and London Bullion Market Association silver price.

Sources: IEA analysis based on S&P Global and Bloomberg.

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Recent Prices development for key Materials - Evolution Jan.2025 – Apr.2026
A great volatility

Tungsten, tantalum, cobalt, lithium and rare earth elements have recorded the largest price increases since 2025

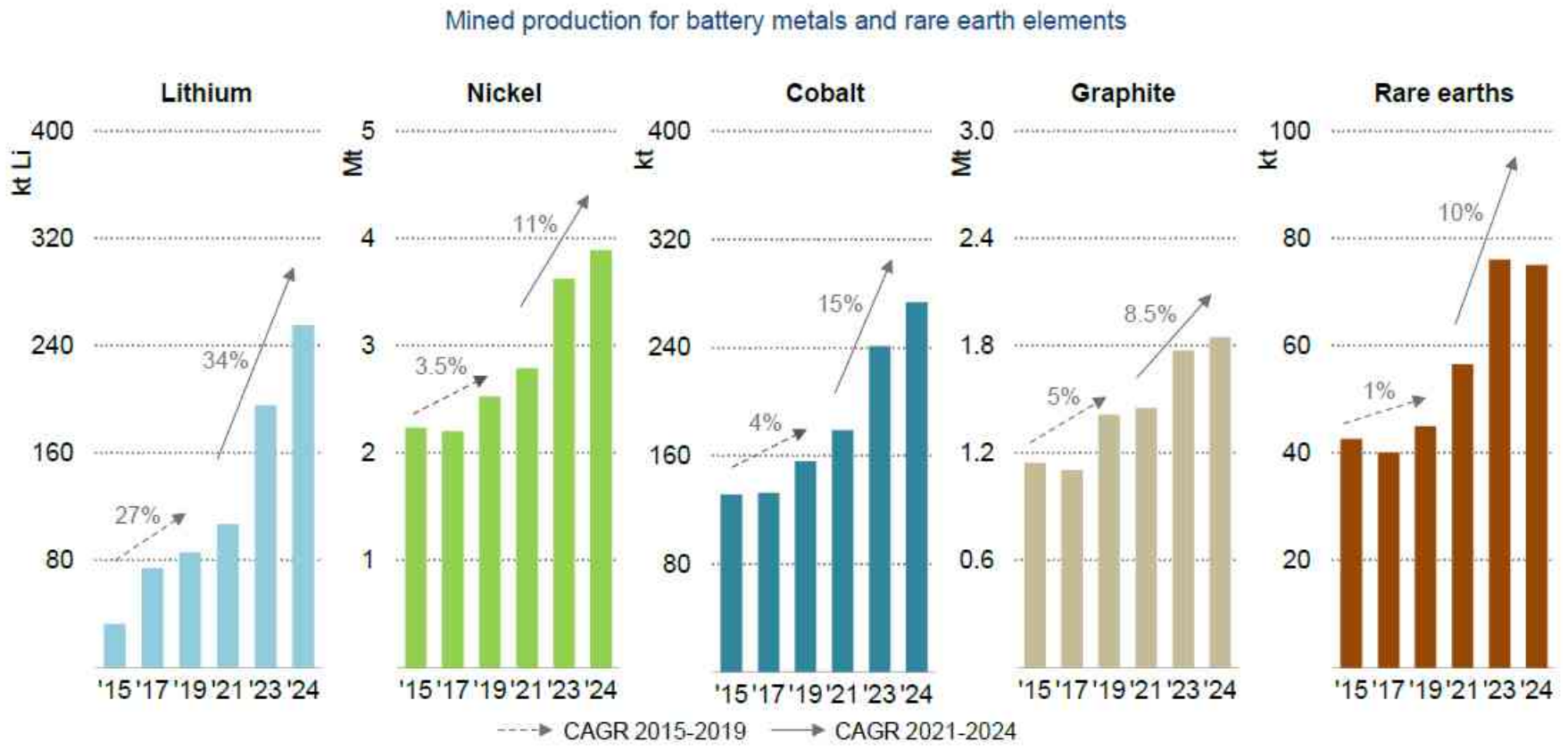


Notes: PPA = purified phosphoric acid. Manganese refers to manganese sulphate. Assessment based on London Metal Exchange cash prices for aluminium, copper, zinc, tin, nickel and cobalt; China domestic or export prices for molybdenum, graphite, phosphoric acid, manganese sulphate, gallium, germanium, antimony, bismuth, indium, magnet rare earths, tantalum, tellurium, titanium and tungsten; global average prices for lithium carbonate.
Sources: IEA analysis based on S&P Capital IQ, Bloomberg and KOMIS.

Source: IEA Global Critical Materials Outlook 2026 – July 2026

Mined outputs for key Materials - Evolution 2015 – 2024
A continuous growth

Mined output growth for battery metals and rare earth elements has markedly accelerated in recent years…

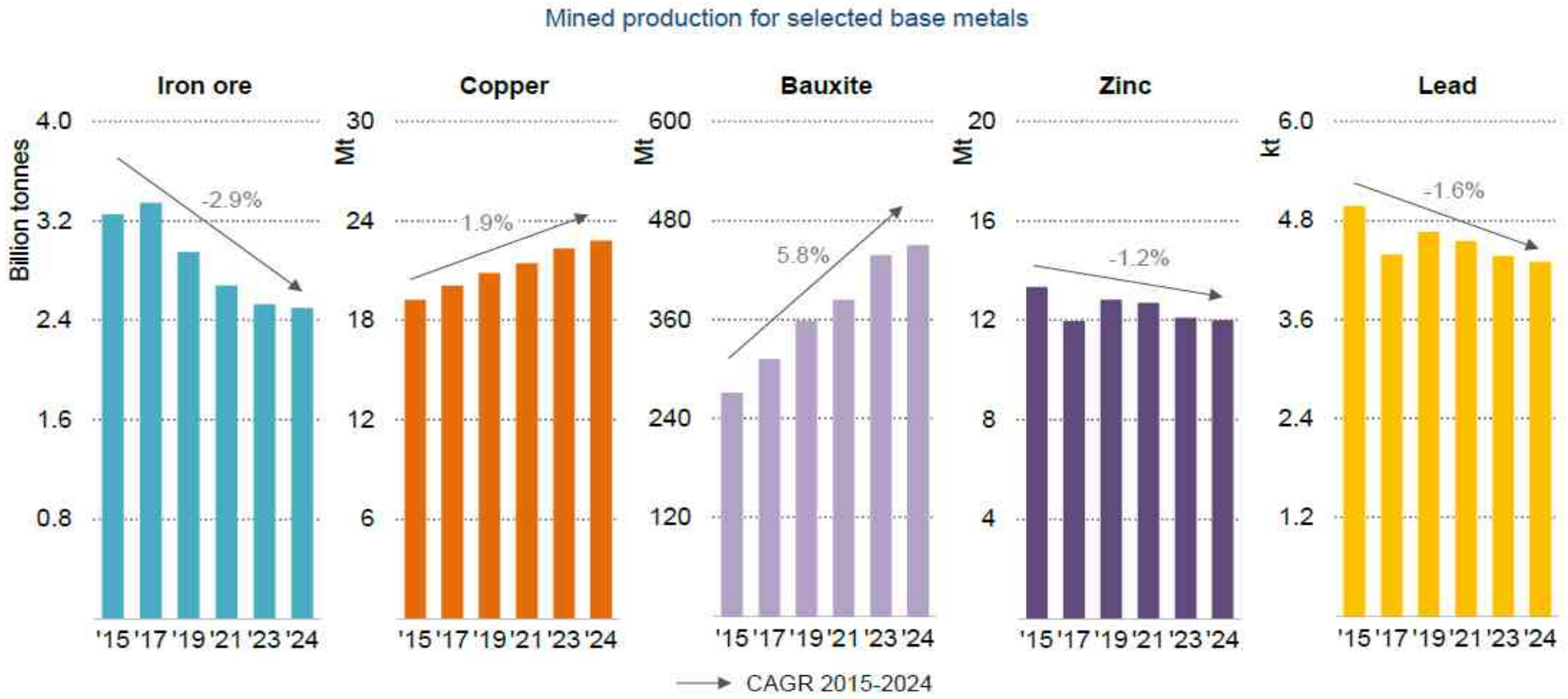


Notes: kt = kilotonnes; Li = lithium; Mt = million tonnes; CAGR = compound annual growth rate. Graphite is for natural flake graphite. Rare earths are magnet rare earths only.

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Mined outputs for based Metals - Evolution 2015 – 2024
For Iron ore, Zinc & Lead, decline of mined Production

…in contrast to relatively muted growth for base metals due to long lead times, declining ore quality and permitting challenges



Note: CAGR = compound annual growth rate.
Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and S&P Global.

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Reminder - More and more Materials are needed for Industry
IEA 2021 Scenarios



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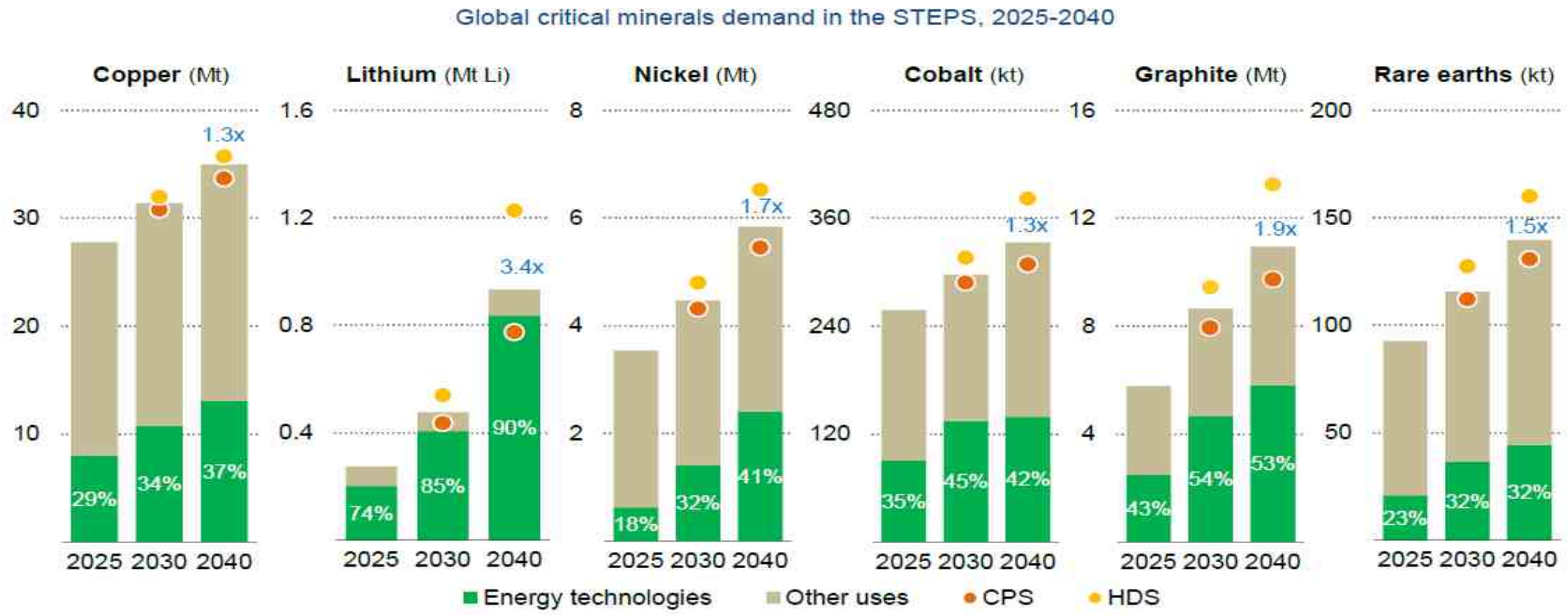
Notes: Primary demand is total demand net of recycled volume (also called primary supply requirements). Projected production profiles are sourced from the S&P Global Market Intelligence database with adjustments to unspecified volumes. Operating projects include the expansion of existing mines. Under-construction projects include those for which the development stage is indicated as commissioning, construction planned, construction started or preproduction. Mt = million tonnes.

Source: IEA analysis based on S&P Global (2021).

Source: IEA Special Report May 2021

More and more Materials are needed for Clean Energy Industry - IEA Scenarios

Energy technologies continue to drive strong demand growth for critical minerals across all scenarios

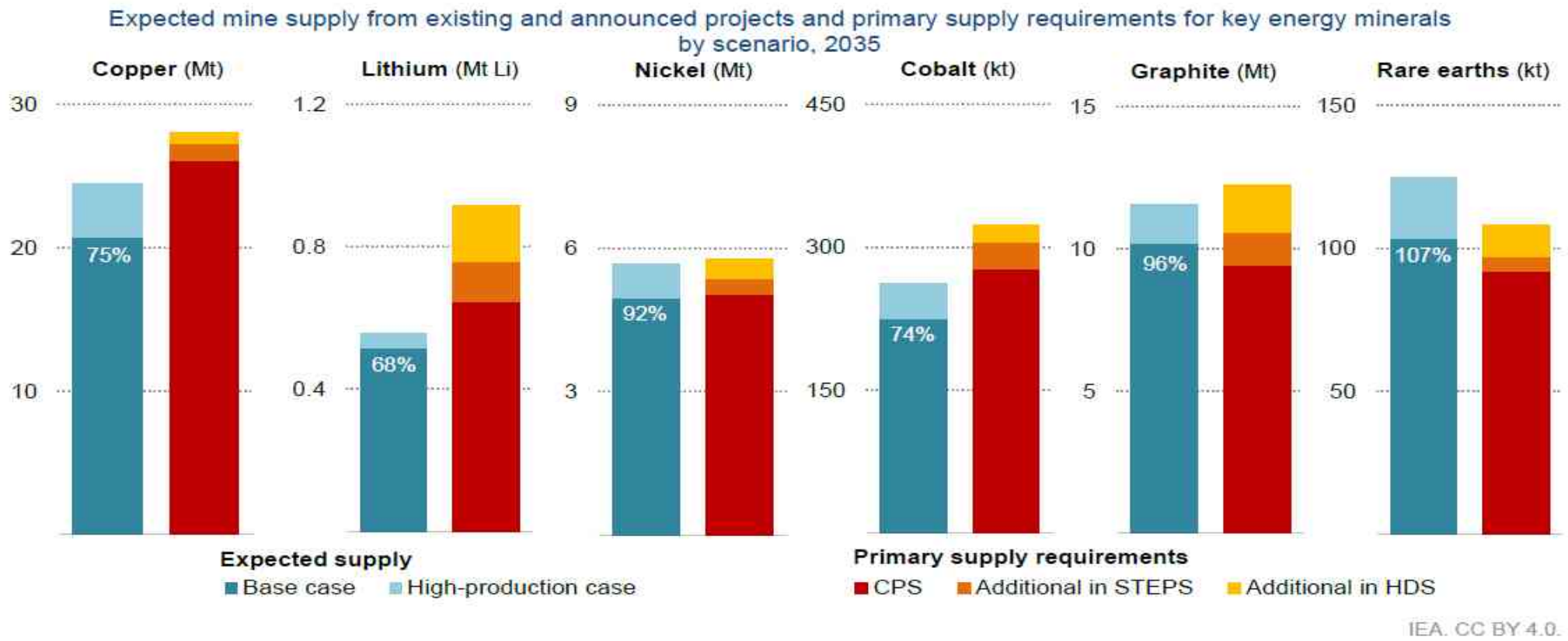


Notes: CPS = Current Policies Scenario; HDS = High Demand Scenario; kt = kilotonnes; Li = lithium; Mt = million tonnes; STEPS = Stated Policies Scenario. The figures for copper are based on refined copper demand (excluding direct-use scrap). Rare earths refer to magnet rare earth elements only. Growth rates (in blue) are between 2024 and 2040.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

More and more Materials are needed for Clean Energy Industry Expected Supply in 2035

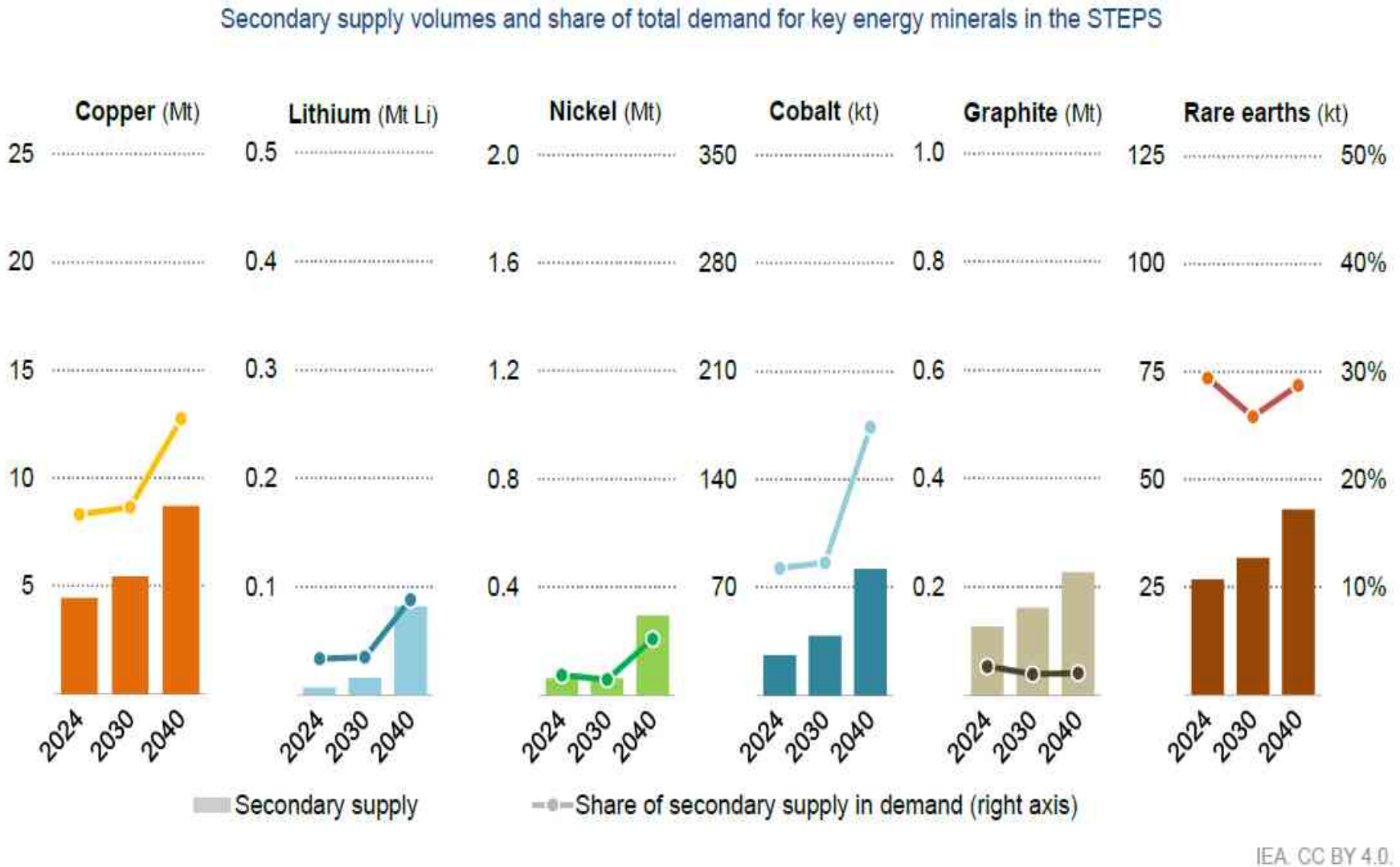
Accounting for recycling, global supply gaps persist through 2035 for copper and lithium and widen slightly for nickel



Notes: CPS = Current Policies Scenario; HDS = High Demand Scenario; STEPS = Stated Policies Scenario. The percentage values indicate the share of base case supply against 2035 primary supply requirements in the STEPS. Expected supply is based on mined or raw material output based on announced projects, except for graphite, where the figure refers to the sum of natural flake graphite and synthetic graphite supplies. Primary supply requirements are calculated as total demand net of secondary supply, also accounting for losses during refining operations. Rare earths refer to magnet rare earth elements only.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

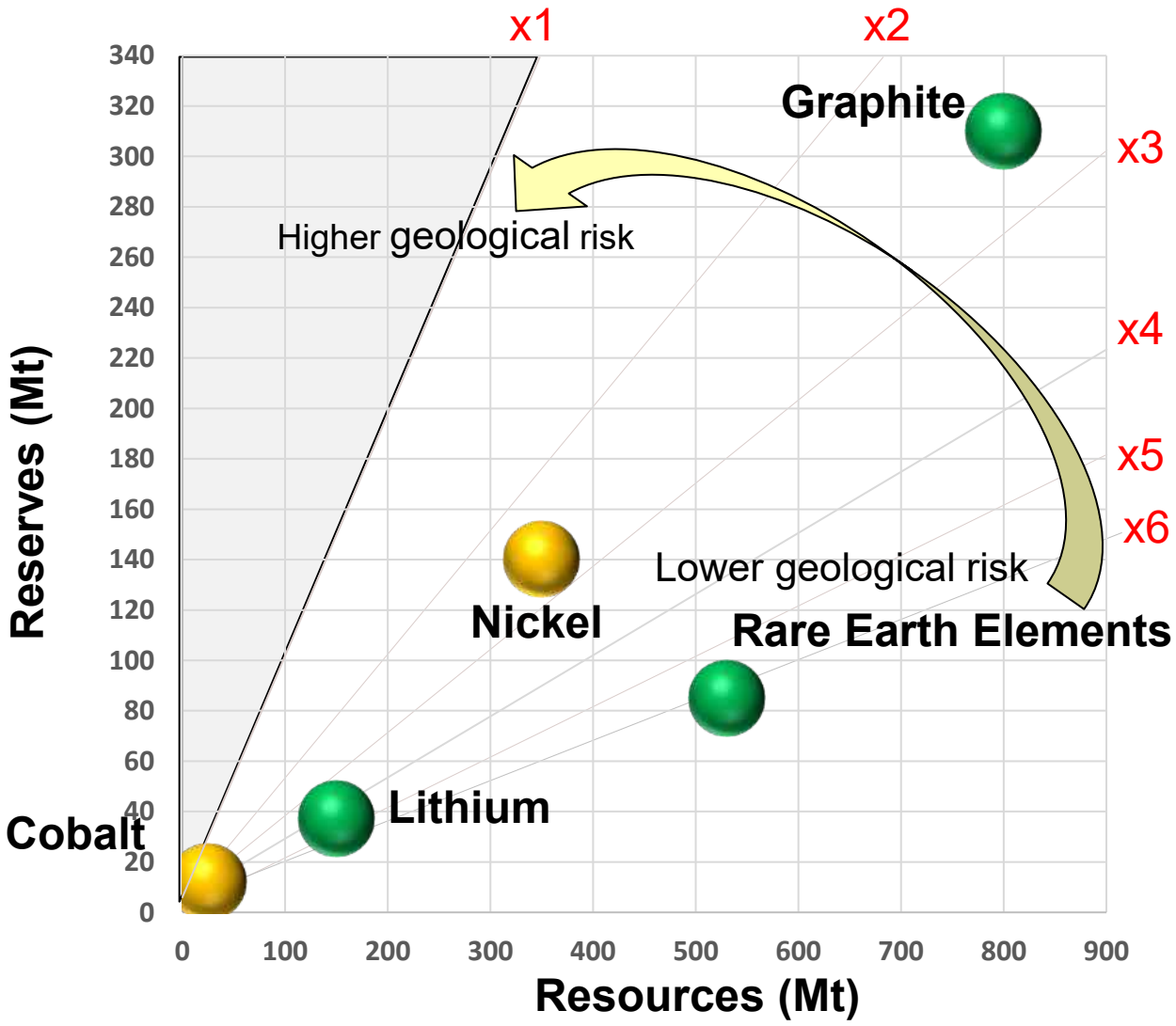
Share of secondary Supplies will become more and more important

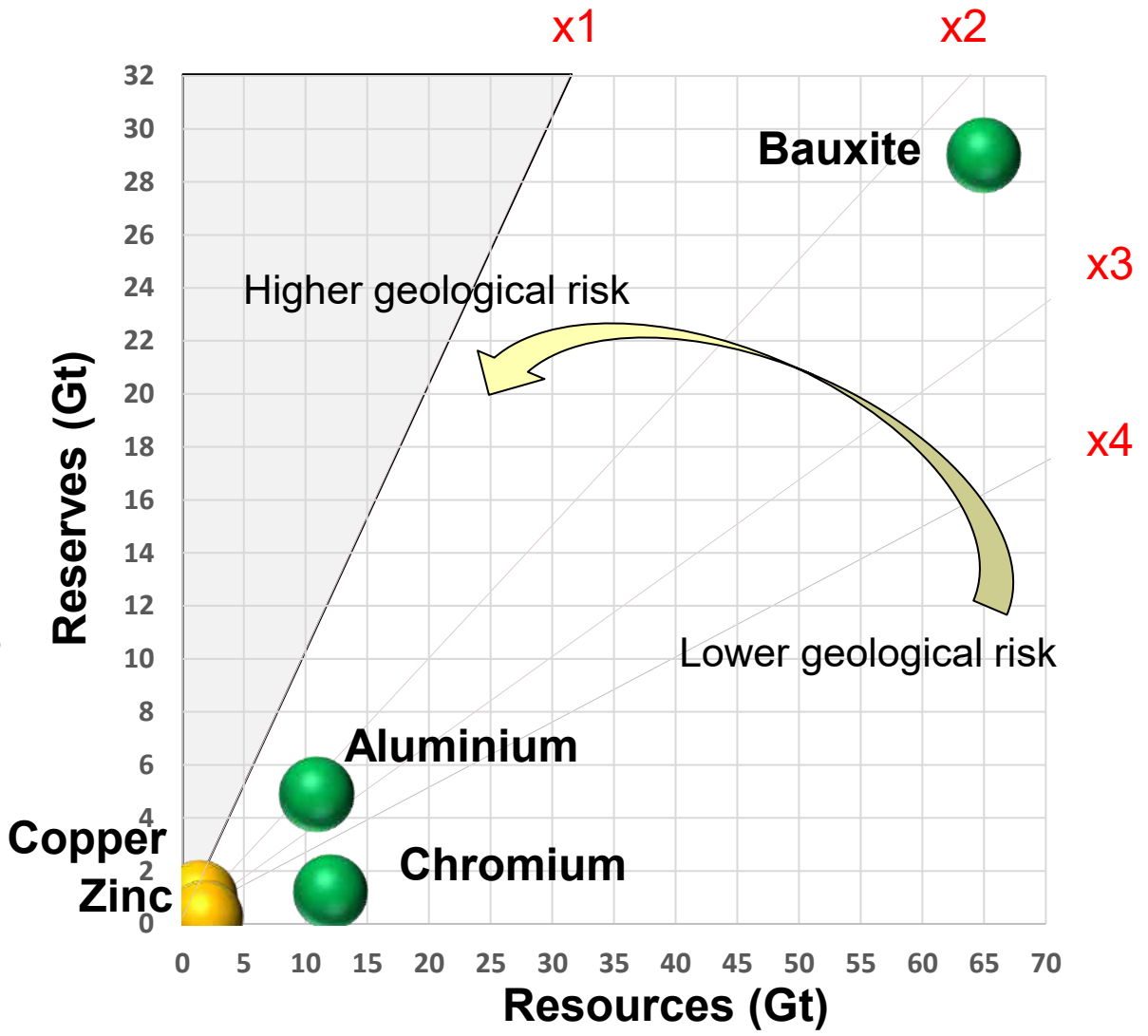


Notes: Includes recycled volumes from end-of-life equipment and manufacturing scrap. For copper, direct-use scrap is excluded.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

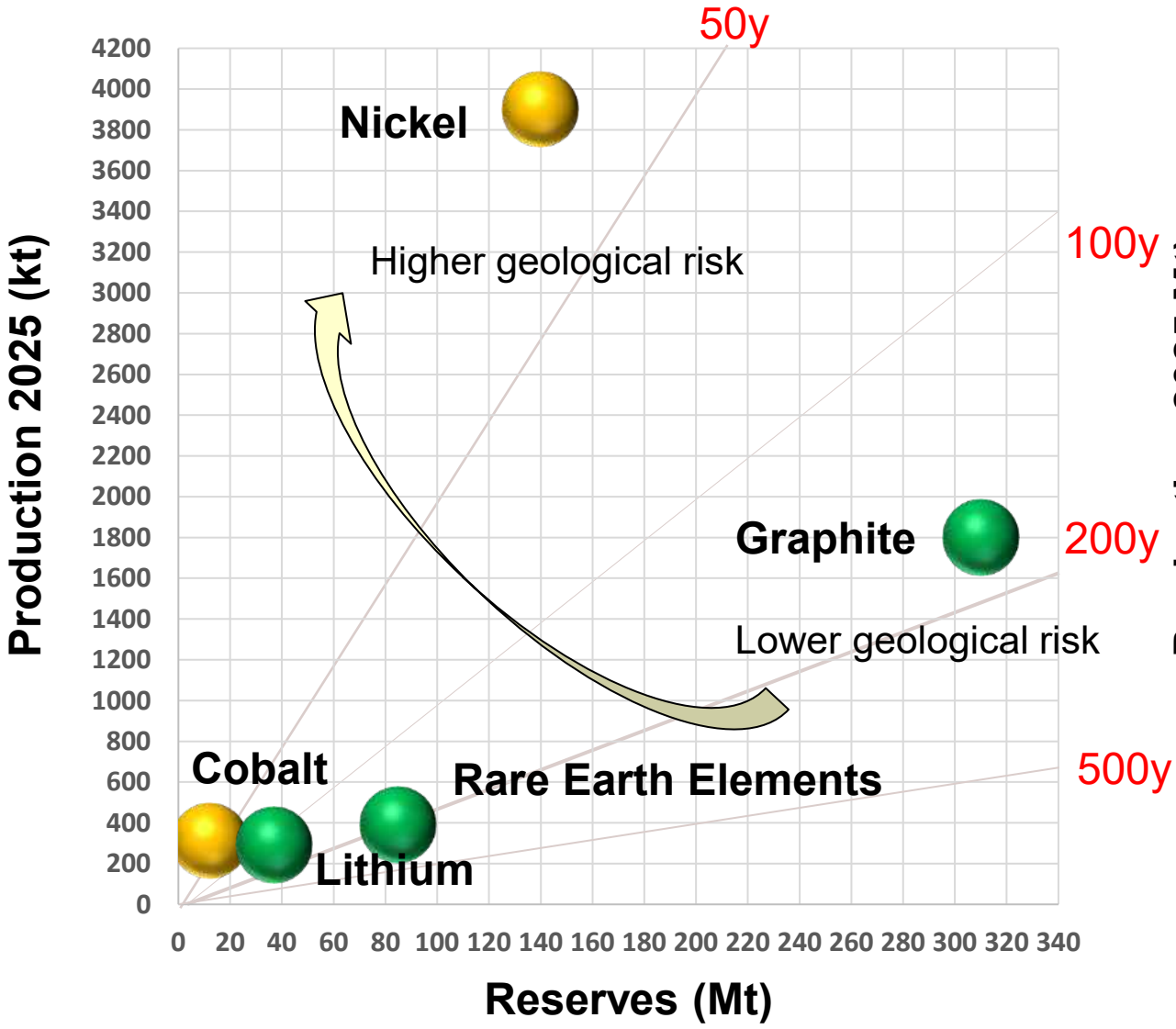
Mineral Materials - Scarcity, Reserves vs Resources

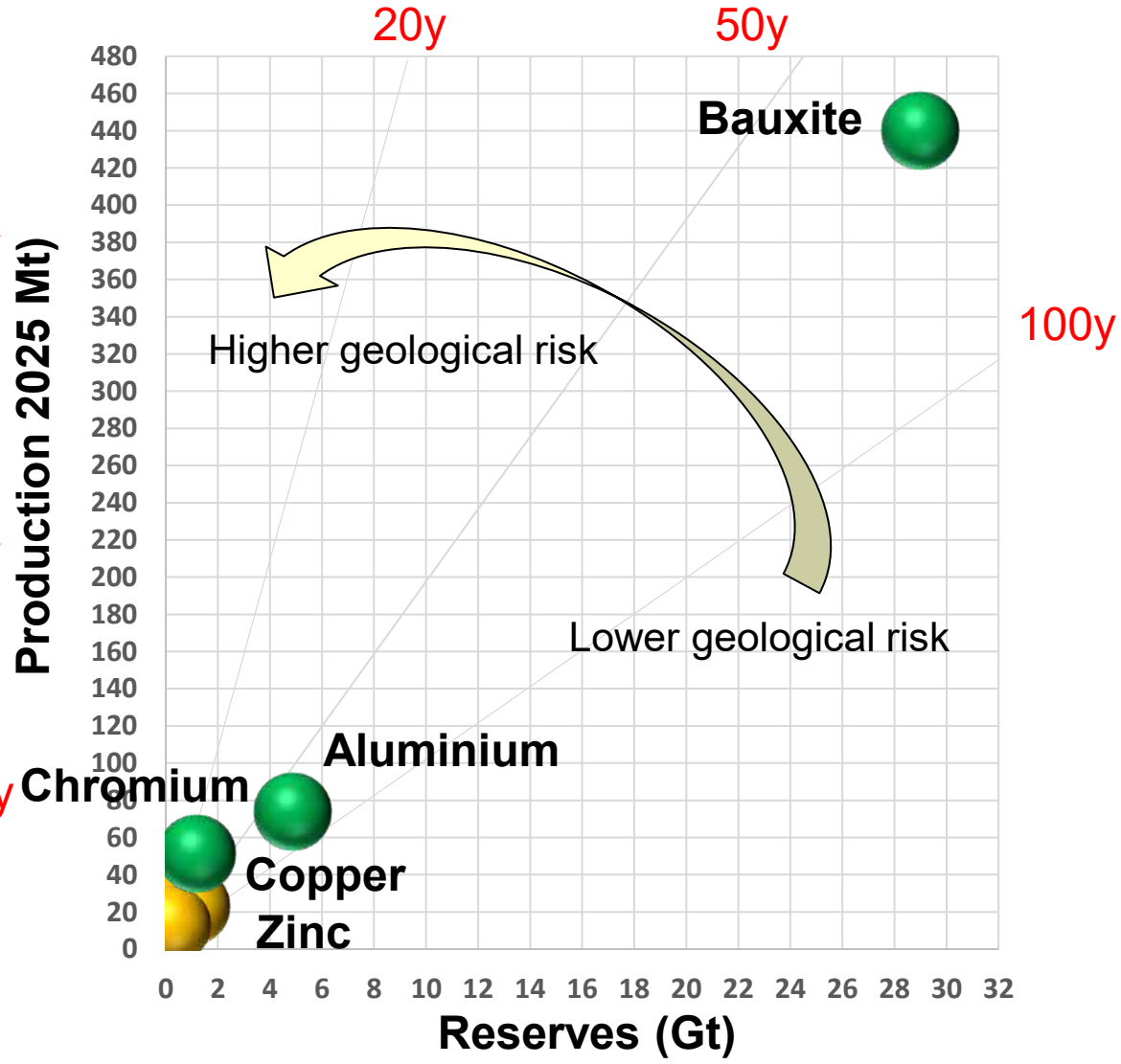




Source: ChG/Data from USGS 2026 Production/Reserves 2025

Mineral Materials - Scarcity, Reserves vs Production

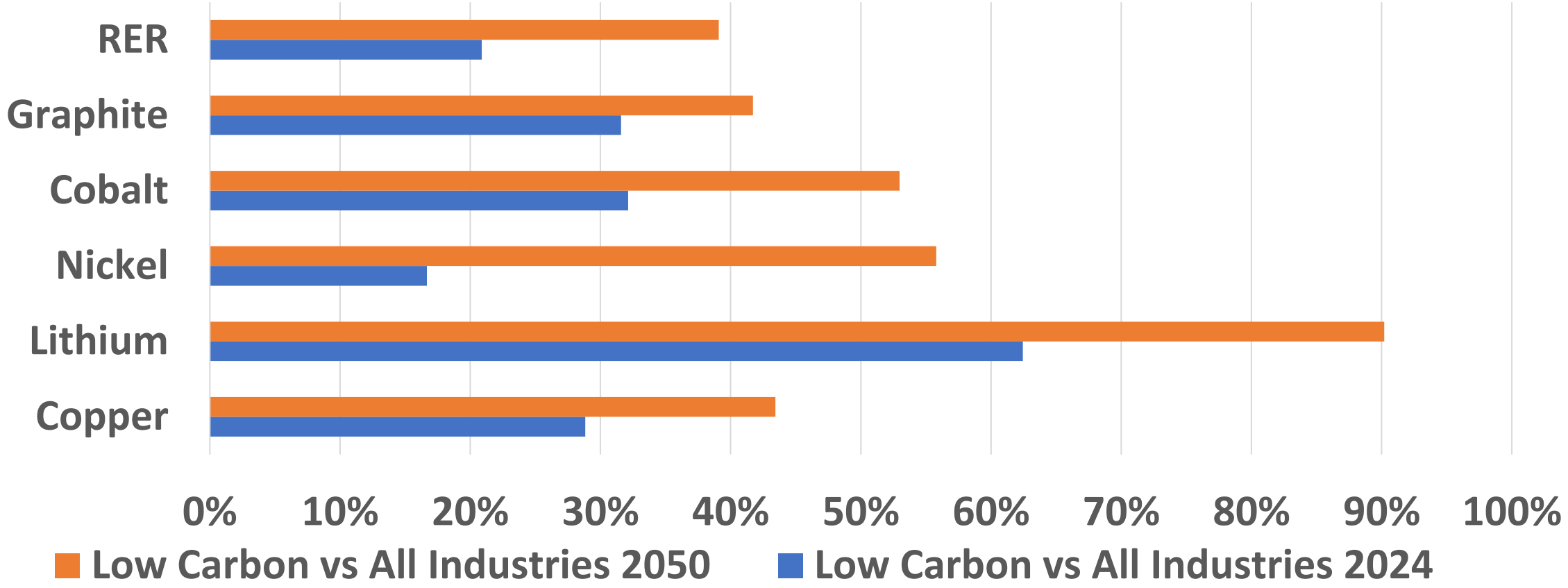




Source: ChG/Data from USGS 2026 Production/Reserves 2025

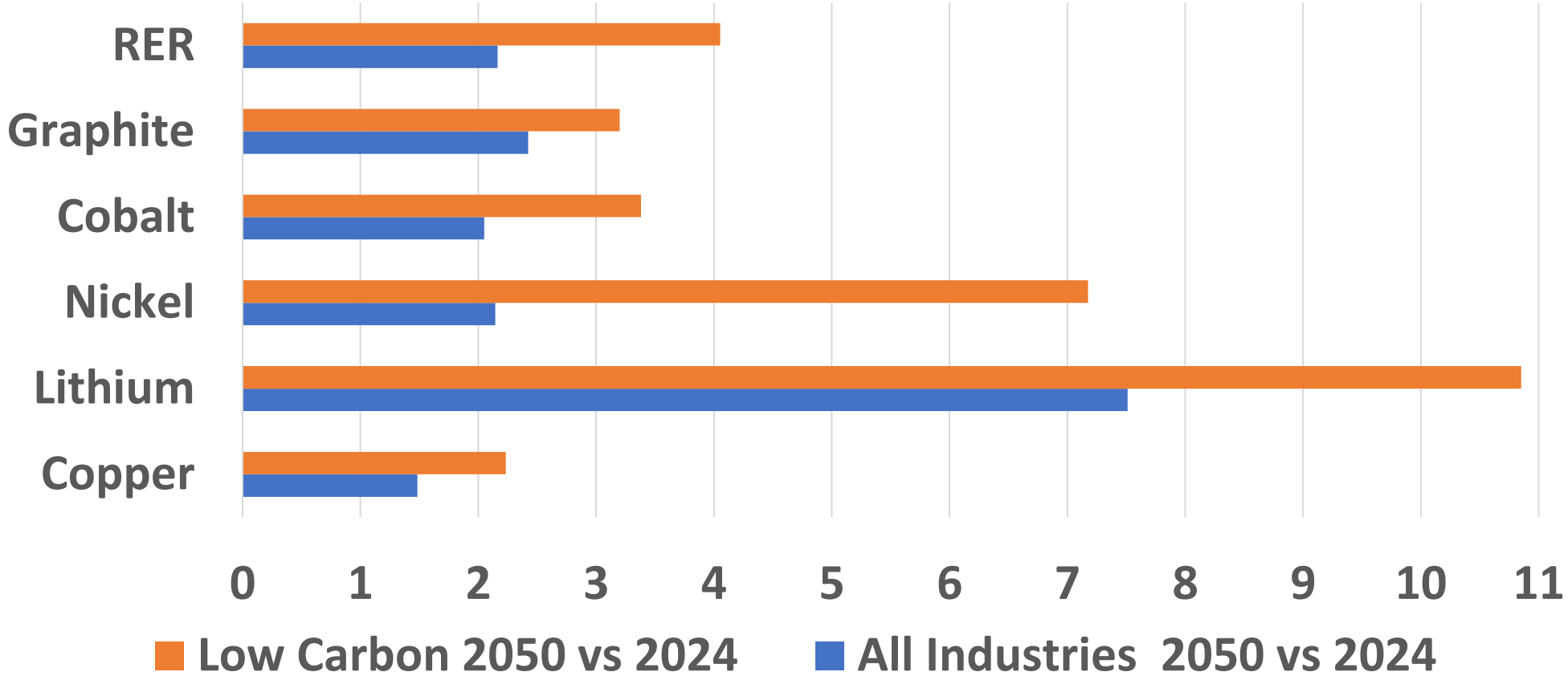
A projection by IEA 2025 – May 2025

Share of selected Mineral Materials Demand for Low Carbon Technologies vs needs for all Industries Year 2050 vs Year 2024 – IEA APS Scenario



Source: ChG/Data from IEA Global Critical Materials Outlook 2025
Low Carbon Technologies: Renewables, Nuclear, Hydro, Geothermal

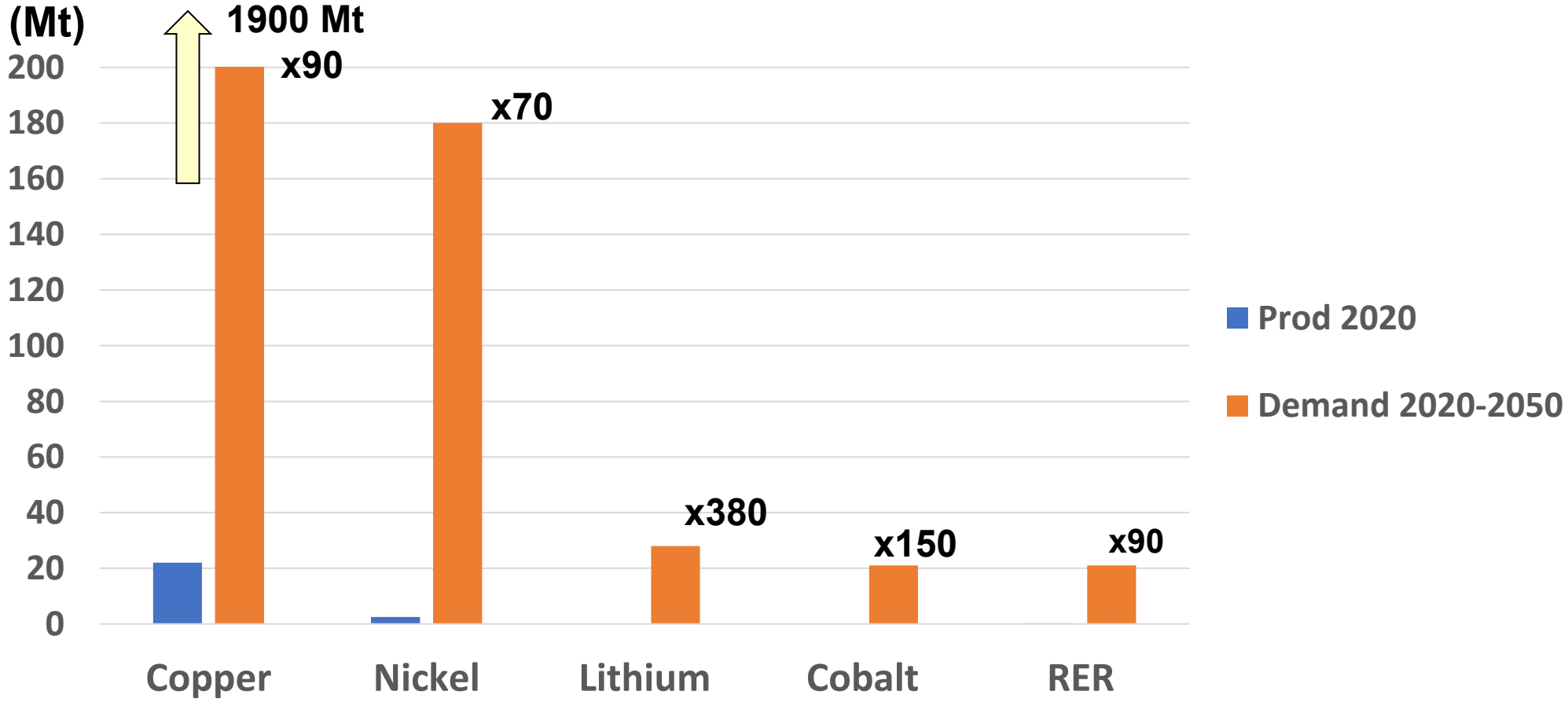
Multiplication factor of selected Mineral Materials Demand for Low Carbon Technologies vs all Industries Year 2050 vs Year 2024 – IEA APS Scenario



Source: ChG/Data from IEA Global Critical Materials Outlook 2025
Low Carbon Technologies: Renewables, Nuclear, Hydro, Geothermal

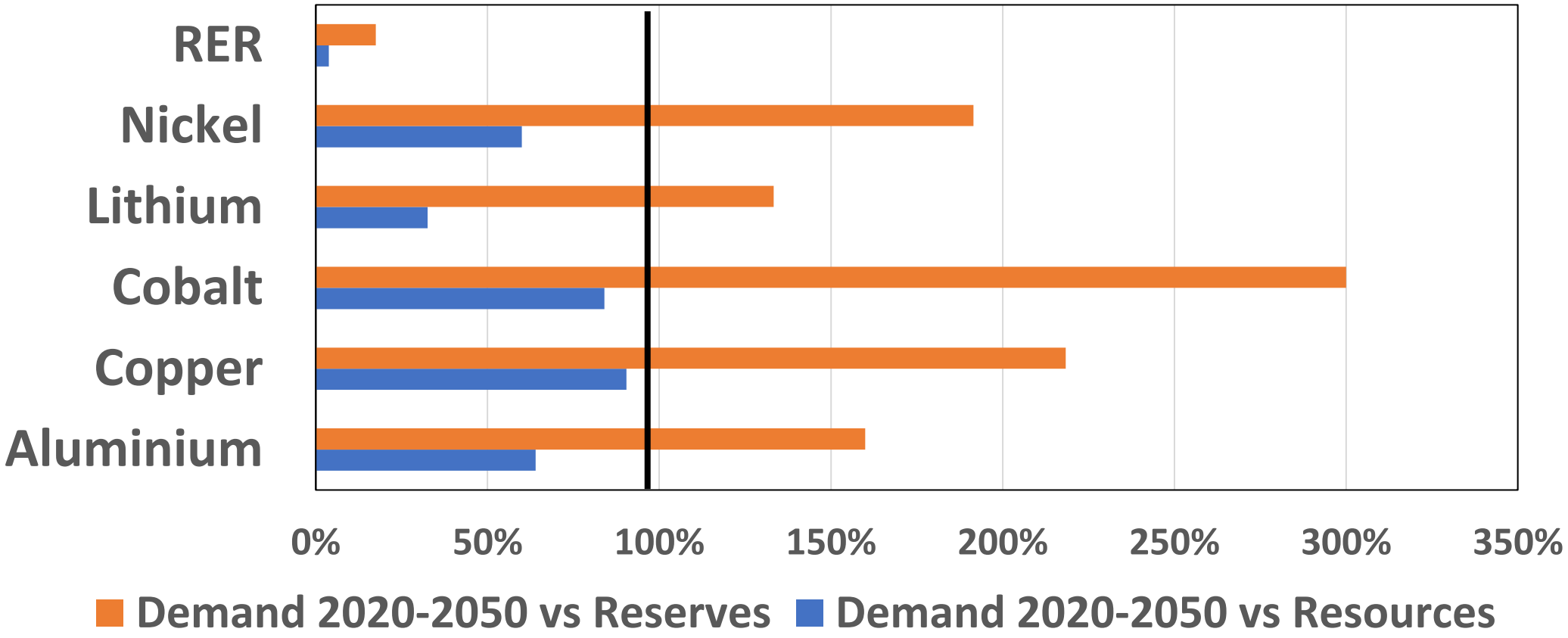
Reminder - A projection by IFP EN 2020

Selected Mineral Materials estimated Cumulative Demand 2020 – 2050 vs 2020 Production – All Industries - Scenario 2°C
New mines need to be exploited



Source: ChG/Data from IFP EN 2020
IFP EN estimates for Copper Demand in 2050 (102 Mt) much more important than IEA estimates

Selected Mineral Materials cumulative Demand 2020 – 2050 vs Resources and Reserves – All Industries Scenario 2°C - New mines need to be exploited



Source: ChG/Data from IFP EN 2020
For Aluminium, reserves & resources maximum

Focus on Low Carbon Technologies

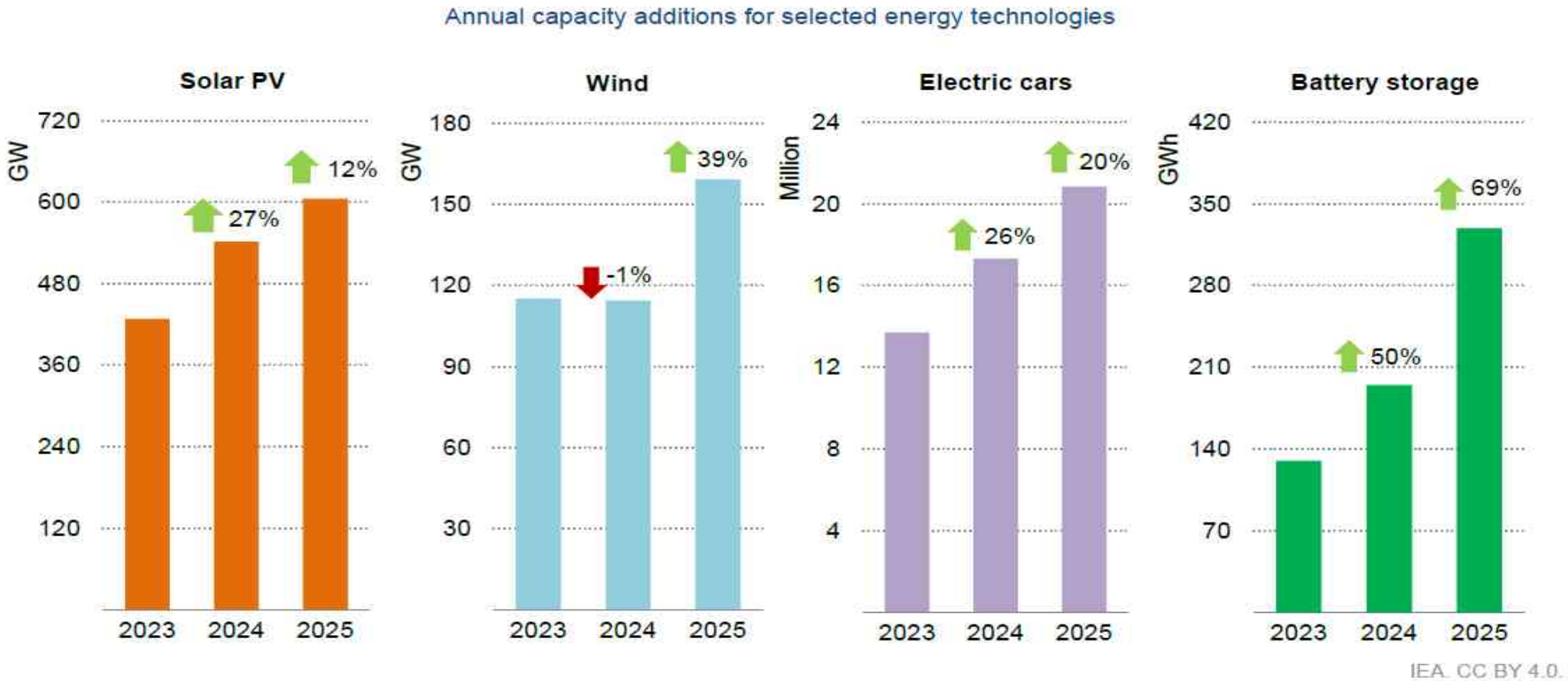
Most commun Metals and Mineral Materials used by Energy Transition

Metals		Abundant	Rare/Scarce	Extrem. rare	Solar PV	Solar CSP	Wind	Elec. Netwk	EV/Battery	Fuel Cells
Aluminium	Al				High importance		Moderate import.			
Titanium	Ti									
Manganese	Mn									
Chromium	Cr				0/Low importance					
Lithium	Li									
Silicon	Si									
Graphite										
RER Elem.	RER									
Lanthanum	La									
Neodynium	Nd									
Dysprosium	Dy									
Terbium	Tb									
Zinc	Zn									
Molybdenum	Mo									
Copper	Cu									
Nickel	Ni									
Cobalt	Co									
Cadmium	Cd									
Gallium	Ga									
Platinum	Pt									
Palladium	Pd									
Rhodium	Rh									
Indium	In									
Selenium	Se									
Tellurium	Te									

Sharing Experience

The Energy Sector – Energy Transition
Capacity additions Solar, Wind, EV & Battery Storage

Deployment of renewables, electric cars and battery storage demonstrated steady growth in 2025, with solar PV breaking new records



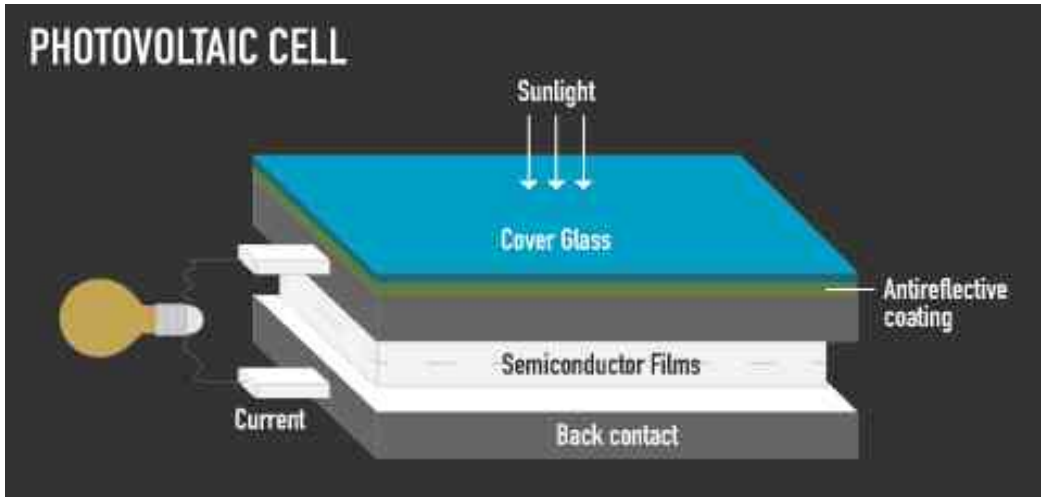
Note: GW = gigawatt; GWh = gigawatt-hour.

Source: IEA Global Critical Materials Outlook 2026 - July 2026

The Energy Sector – Energy Transition
A Drastic Growth for Raw Materials Demand

Solar Panels

Several of the 35 mineral commodities listed as critical by the Department of the Interior play an important role in solar panels, where the Sun's energy is transformed to electricity.





ARSENIC
High-purity arsenic is used to produce gallium-arsenide semiconductors for solar cells. In 2018, the United States was 100% reliant on foreign sources for arsenic.

Image Source: Gary PARENT



GALLIUM
Used in gallium-arsenide and copper-indium-gallium-diselenide thin-film solar cells. In 2018, the United States was 100% reliant on foreign sources for gallium.



GERMANIUM
Germanium-based solar cells are commonly used in satellites. In 2018, the United States was more than 50% reliant on foreign sources for germanium.

Image Source: Rob Lavinsky



INDIUM
Used in copper-indium-gallium-diselenide thin-film solar cells. In 2018, the United States was 100% reliant on foreign sources for indium.

Image Source: Nanttaker



TELLURIUM
Used in cadmium-tellurium thin-film solar cells. In 2018, the United States relied on foreign sources for more than 75% of its tellurium.

Image Source: Rob Lavinsky

Source: USGS

The Energy Sector – Energy Transition
A Drastic Growth for Raw Materials Demand

Wind Turbines

Wind turbines increasingly dot the American landscape, rising hundreds of feet in the air to capture electricity from the movement of the wind. Just like solar cells, wind turbines also rely on a few mineral commodities that have been designated as critical: aluminum and rare-earth elements.



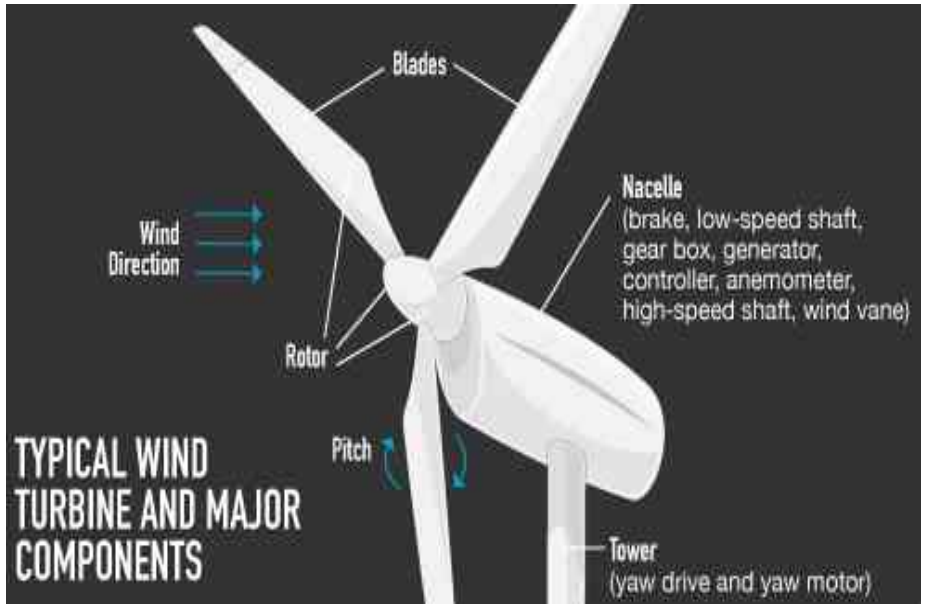
ALUMINUM

Aluminum plays a role in most parts of a wind turbine, particularly in the nacelle, where the transfer of wind power to electricity occurs. The United States was 50% reliant on foreign sources for aluminum in 2018.



RARE-EARTH ELEMENTS

Responsible for some of the most powerful and efficient magnets on the planet, rare-earth elements enable wind turbines to have smaller, lighter generators. Although the United States mined and exported rare-earth minerals in 2018, it relied on imports to meet its domestic demands for rare-earth compounds, metals, and manufactured products.



Source: USGS

The Energy Sector – Energy Transition
A Drastic Growth for Raw Materials Demand

Batteries

Batteries play an important supporting role for renewable energy sources like wind and solar, allowing excess power to be stored for usage when direct solar or wind power are unavailable. Just like the energy sources they complement, modern batteries rely on critical mineral commodities, particularly cobalt, graphite, lithium, and manganese.



COBALT

On a global basis, the leading use of cobalt is in rechargeable battery electrodes. In 2018, the United States relied on foreign sources for 61% of the cobalt it consumed.

Image Source: James St. John



GRAPHITE

Graphite serves as an electrode in many lithium batteries. In 2018, the United States was 100% reliant on foreign sources for graphite.



LITHIUM

Lithium has a long history in batteries and is a common material used in batteries today. In 2018, the United States was more than 50% reliant on foreign sources for lithium.

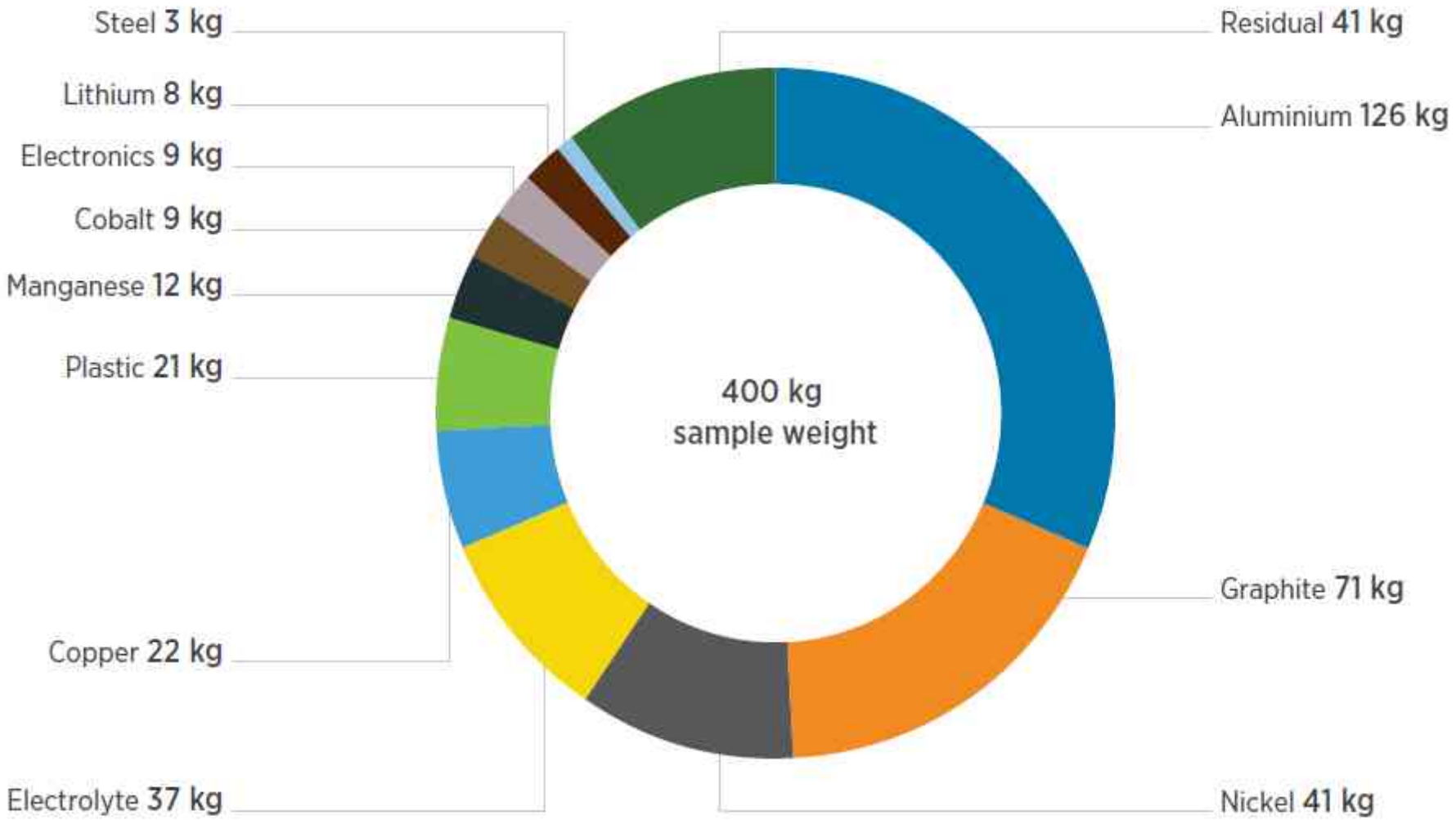


MANGANESE

Manganese serves as an electrode in many lithium batteries. The United States was 100% reliant on foreign sources for manganese in 2018.

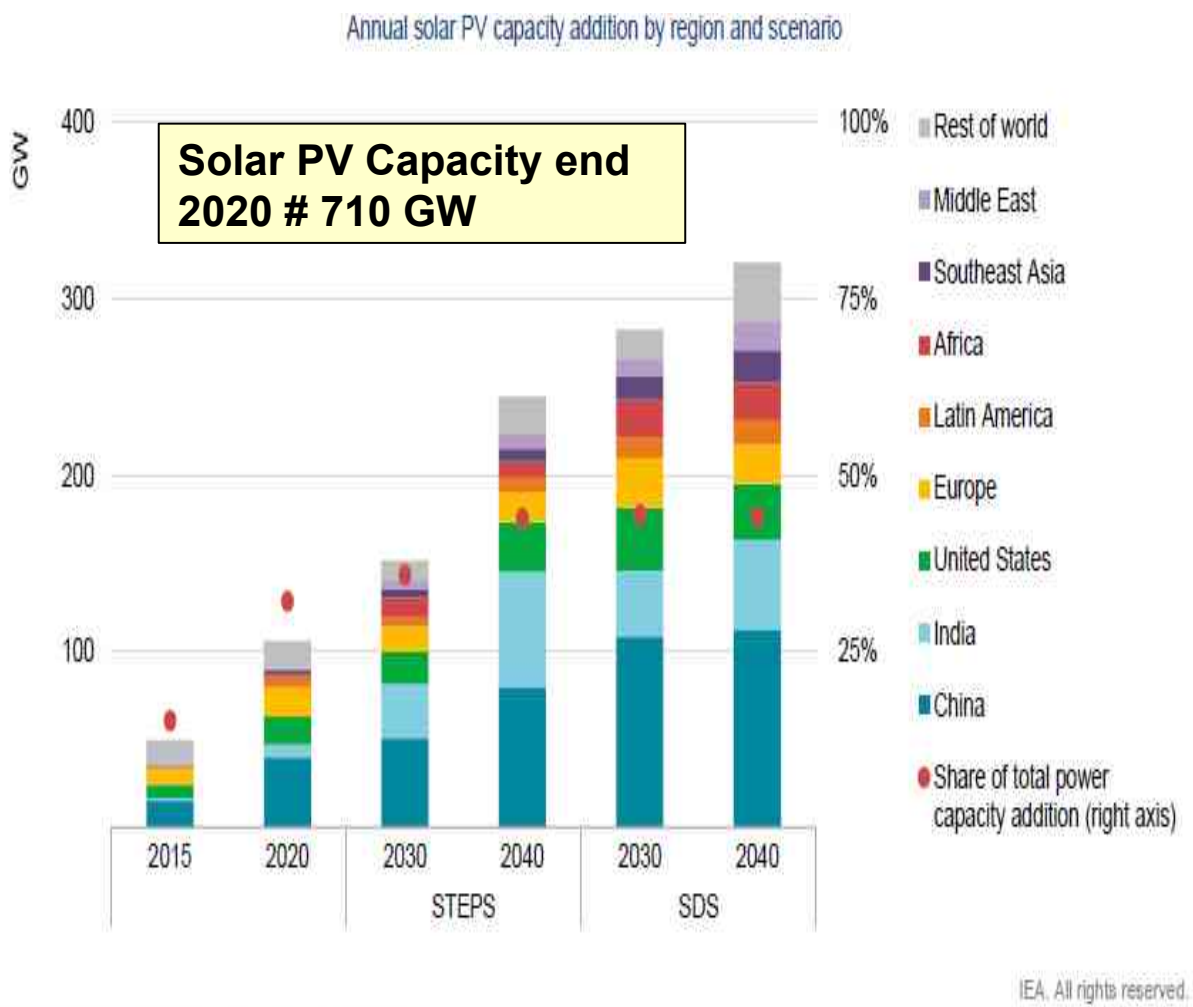
Source: USGS

A typical car Battery requirements

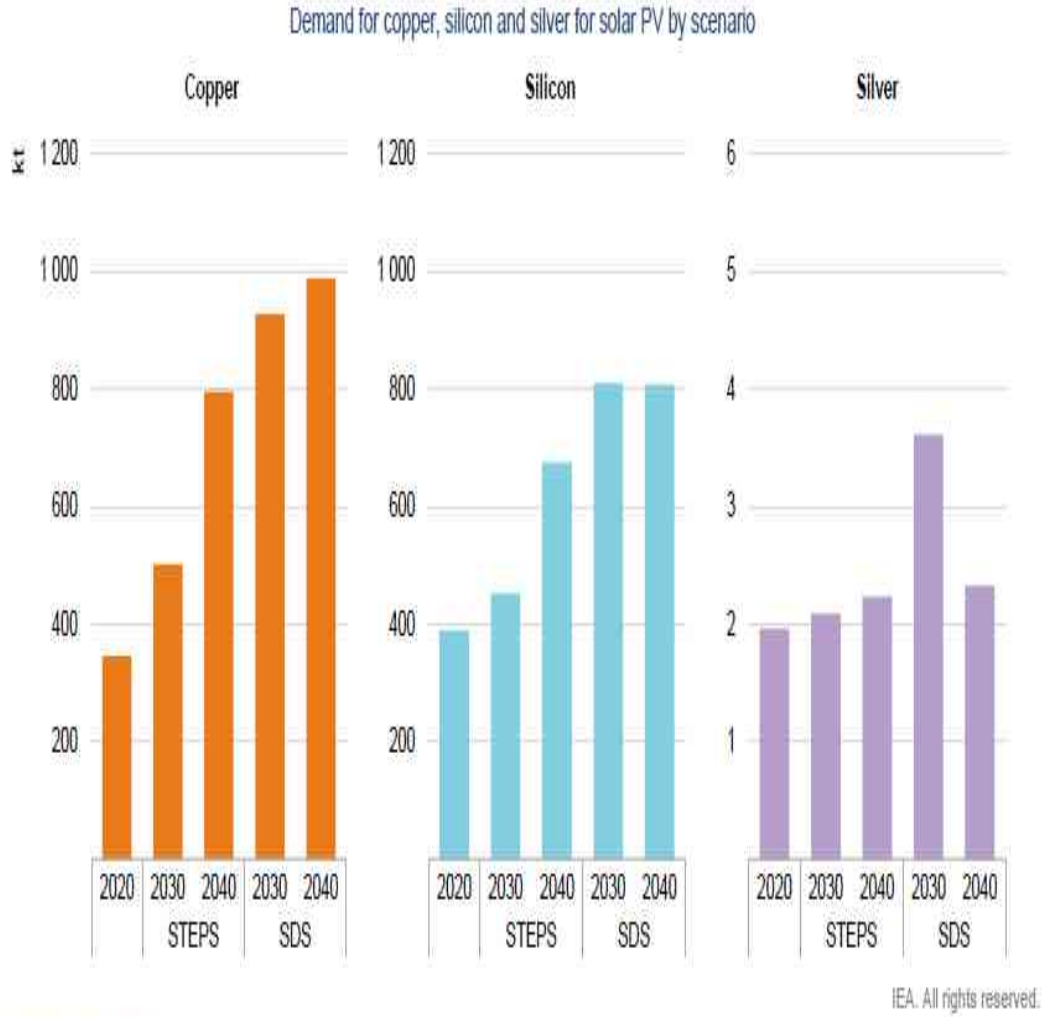


Source: IRENA/Volkswagen

The case of Solar PV – IEA vision 2021



Note: GW = gigawatt. China = People's Republic of China.
Source: IEA (2020c).

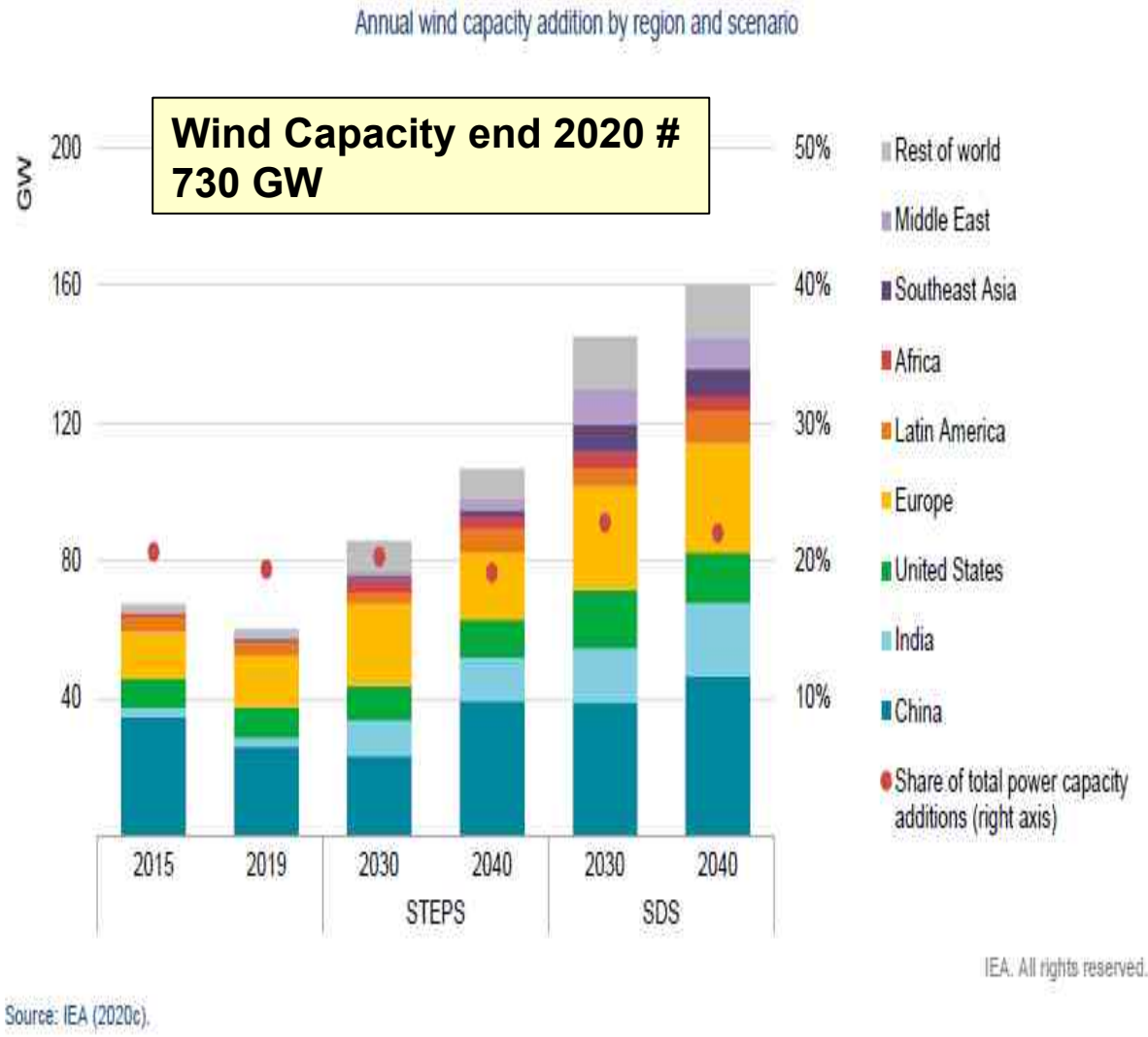


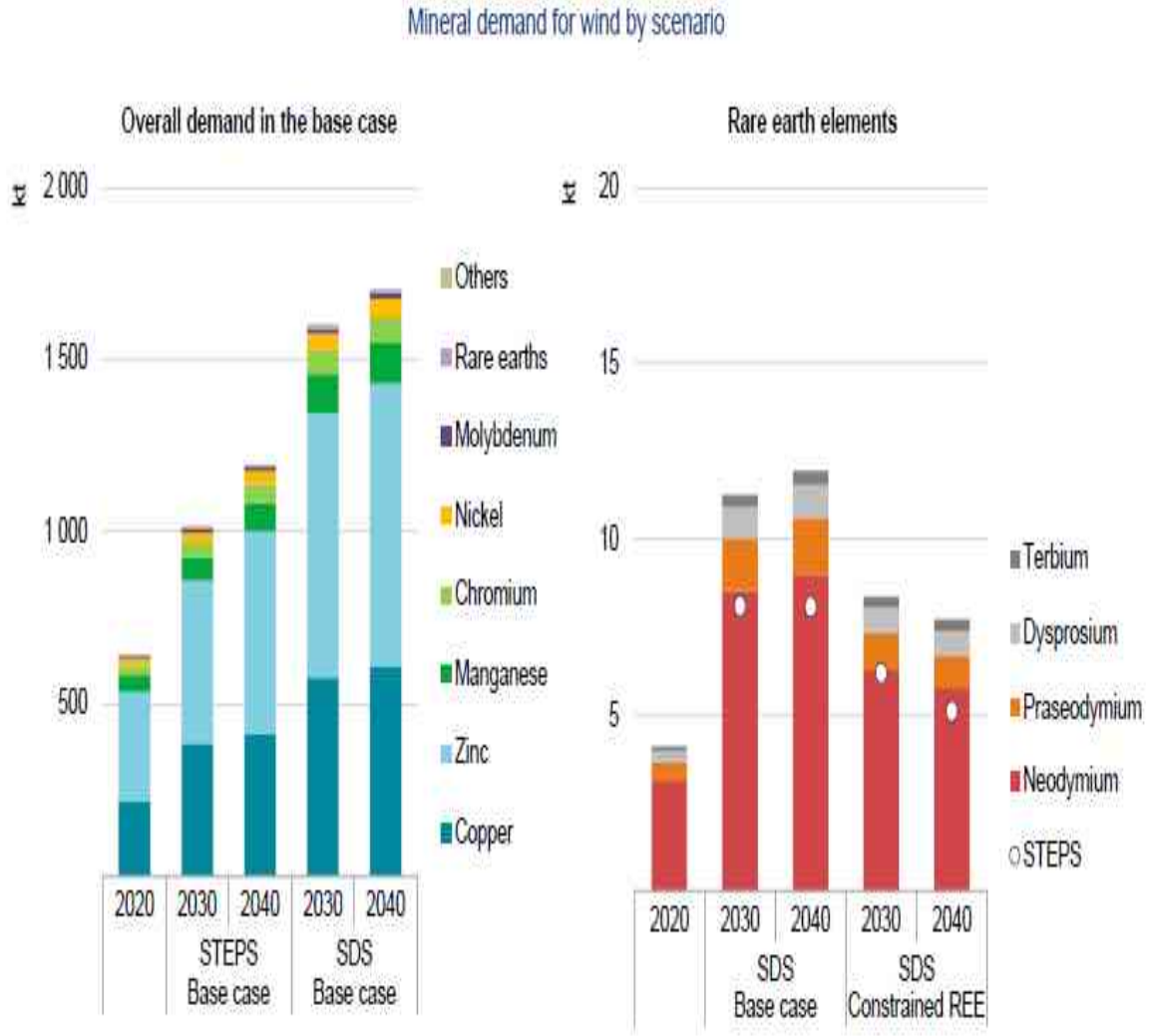
Note: kt = thousand tonnes.

Source: IEA Special Report May 2021

The case of Wind Energy – IEA vision 2021

Wind Capacity end 2020 # 730 GW





Source: IEA (2020c).

Source: IEA Special Report May 2021

Metal Intensity or Metal Footprint for Energy Transition – kg/MW or kg/kWh

Evolution of Metal Footprint or Metal Intensity of Power Generation (kg/MW) – 2010-2019

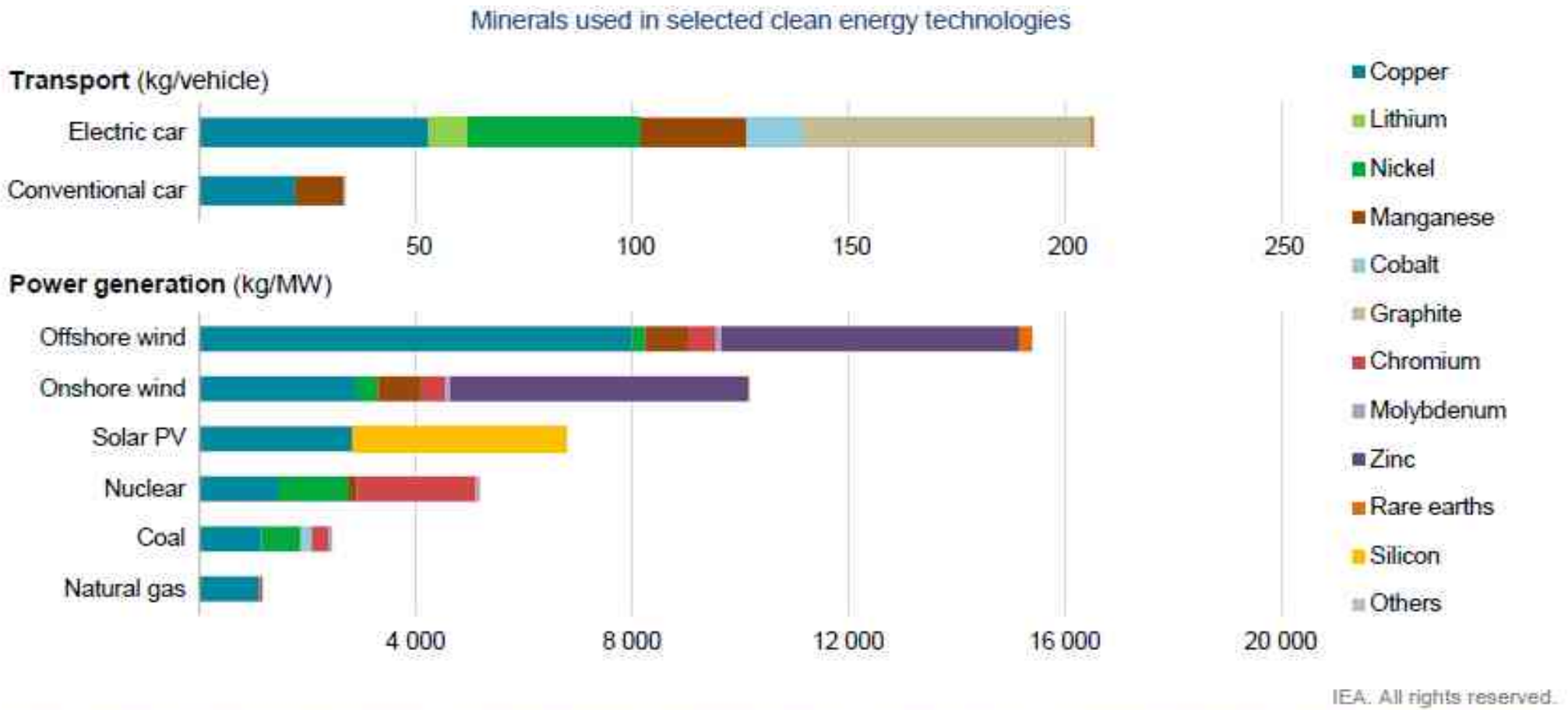


IEA. All rights reserved.

Note: Low-carbon technologies include renewables and nuclear.

Source: IEA Special Report May 2021
Iron & Aluminium not included

Metal Intensity for Energy Transition Sector



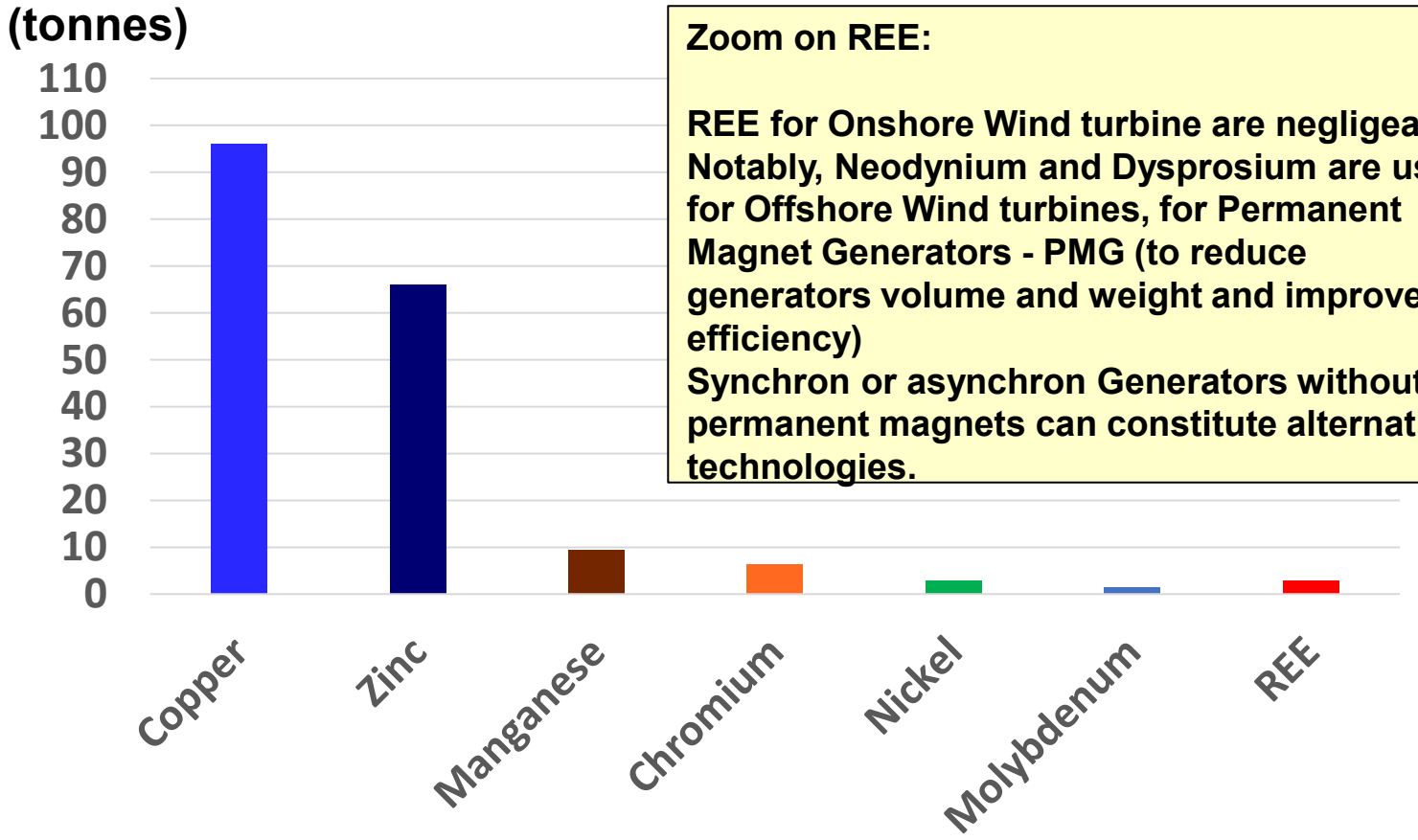
IEA. All rights reserved.

Notes: kg = kilogramme; MW = megawatt. The values for vehicles are for the entire vehicle including batteries, motors and glider. The intensities for an electric car are based on a 75 kWh NMC (nickel manganese cobalt) 622 cathode and graphite-based anode. The values for offshore wind and onshore wind are based on the direct-drive permanent magnet synchronous generator system (including array cables) and the doubly-fed induction generator system respectively. The values for coal and natural gas are based on ultra-supercritical plants and combined-cycle gas turbines. Actual consumption can vary by project depending on technology choice, project size and installation environment.

Source: IEA Special Report May 2021
Iron & Aluminium not included

Example: Materials needed for a Offshore Wind turbine 12 MW





Zoom on REE:

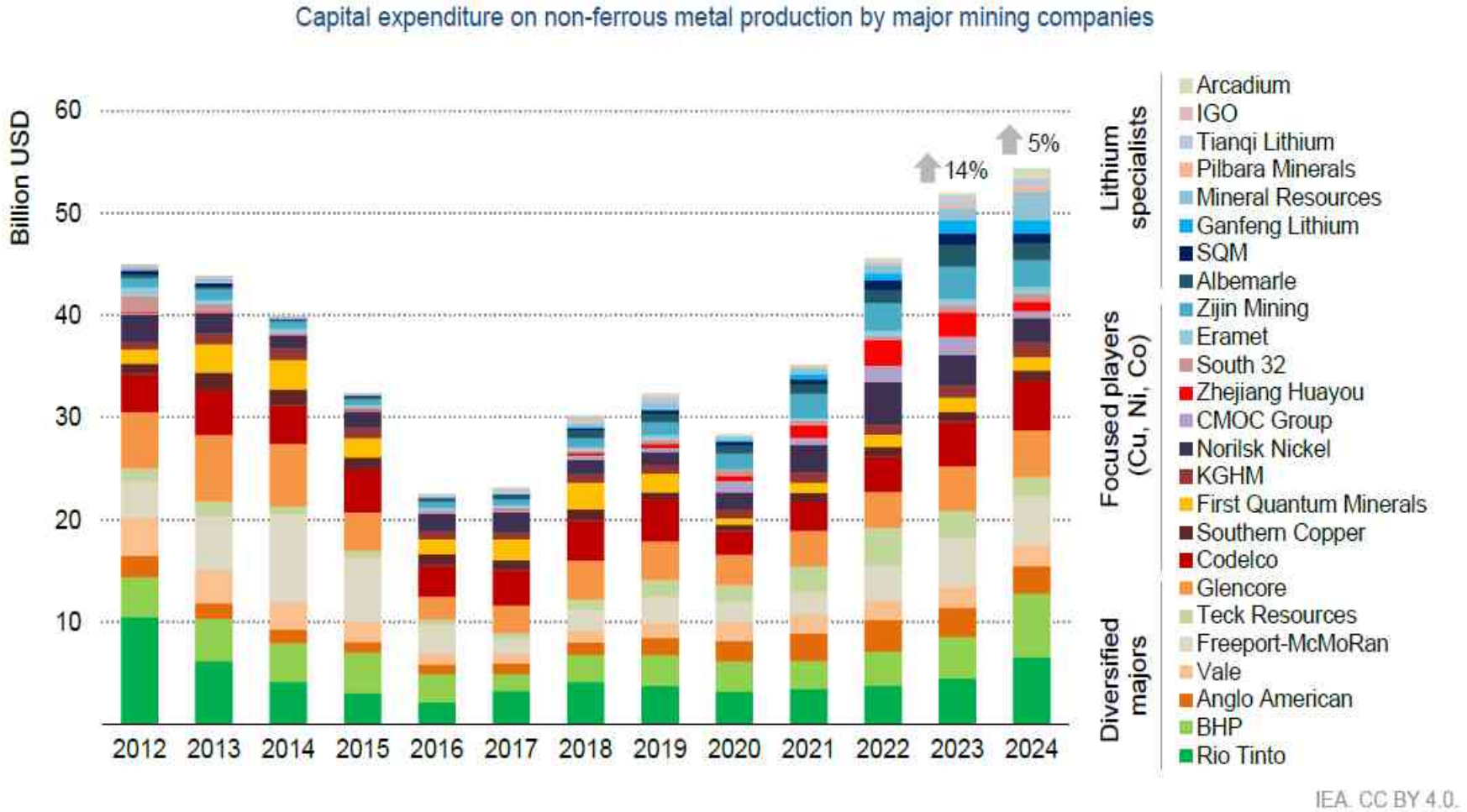
REE for Onshore Wind turbine are negligeable. Notably, Neodynium and Dysprosium are used for Offshore Wind turbines, for Permanent Magnet Generators - PMG (to reduce generators volume and weight and improve efficiency)
Synchron or asynchron Generators without permanent magnets can constitute alternative technologies.

Wind turbines require concrete, steel, iron, fiberglass, polymers, aluminium, copper, zinc, composite materials, REE's. Larger turbines offshore.
Mineral Intensities depend on the turbine size and turbine type (gearbox generator type, direct-drive generator type)

Source: ChG/Data from IEA Special Report May 2021
GE Haliade 12 MW

Investments

Energy Transition – Investment in Critical Materials Mining
Capex Evolution 2012 – 2024 ↘ 50 G$ expected in 2025



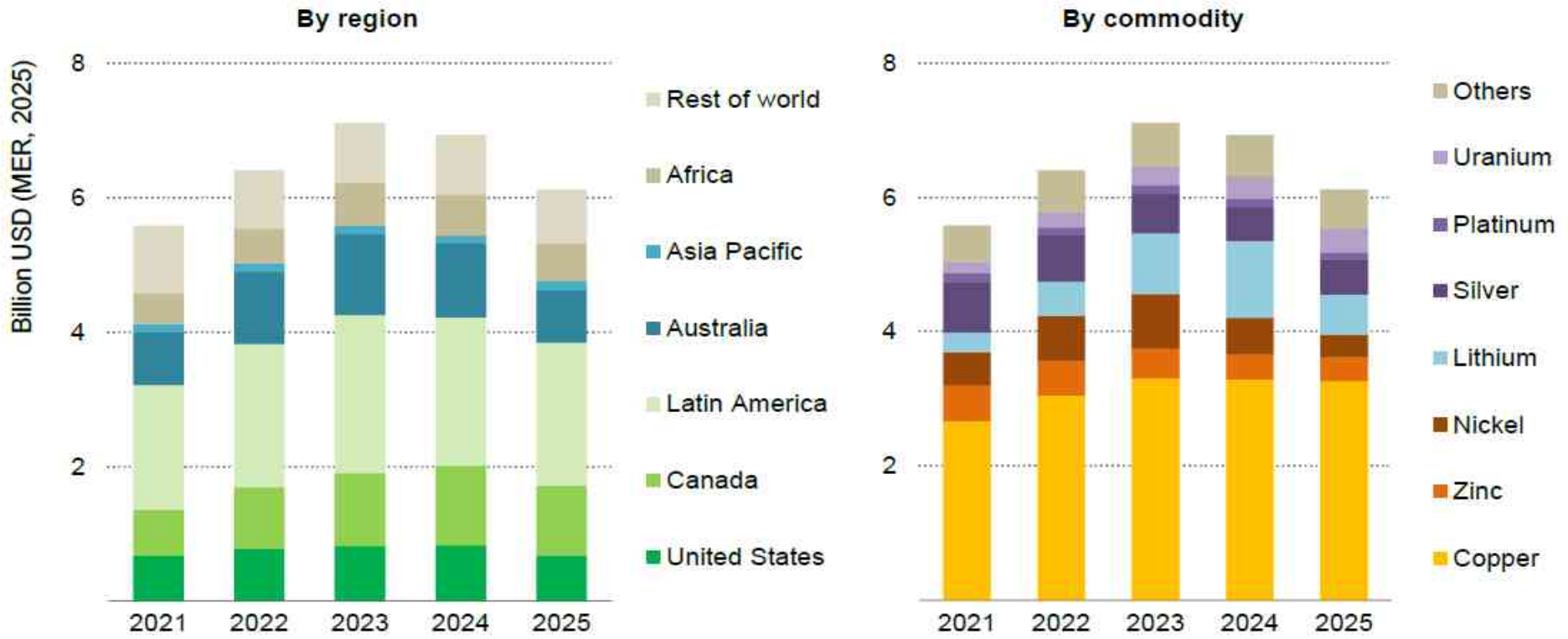
Notes: Co = cobalt; Cu = copper; Ni = nickel. For diversified majors, capex on the production of iron ore, gold, coal and other energy products was excluded. Nominal values. The results for Arcadium start from 2016.
Source: IEA analysis based on S&P Global.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Energy Transition – Investment in Critical Materials Mining Exploration Spendings 2021 - 2025

The growth in exploration spending seen since 2021 stalled in 2024 and declined in 2025…

Exploration spending for selected non-ferrous mineral resources, 2021-2025



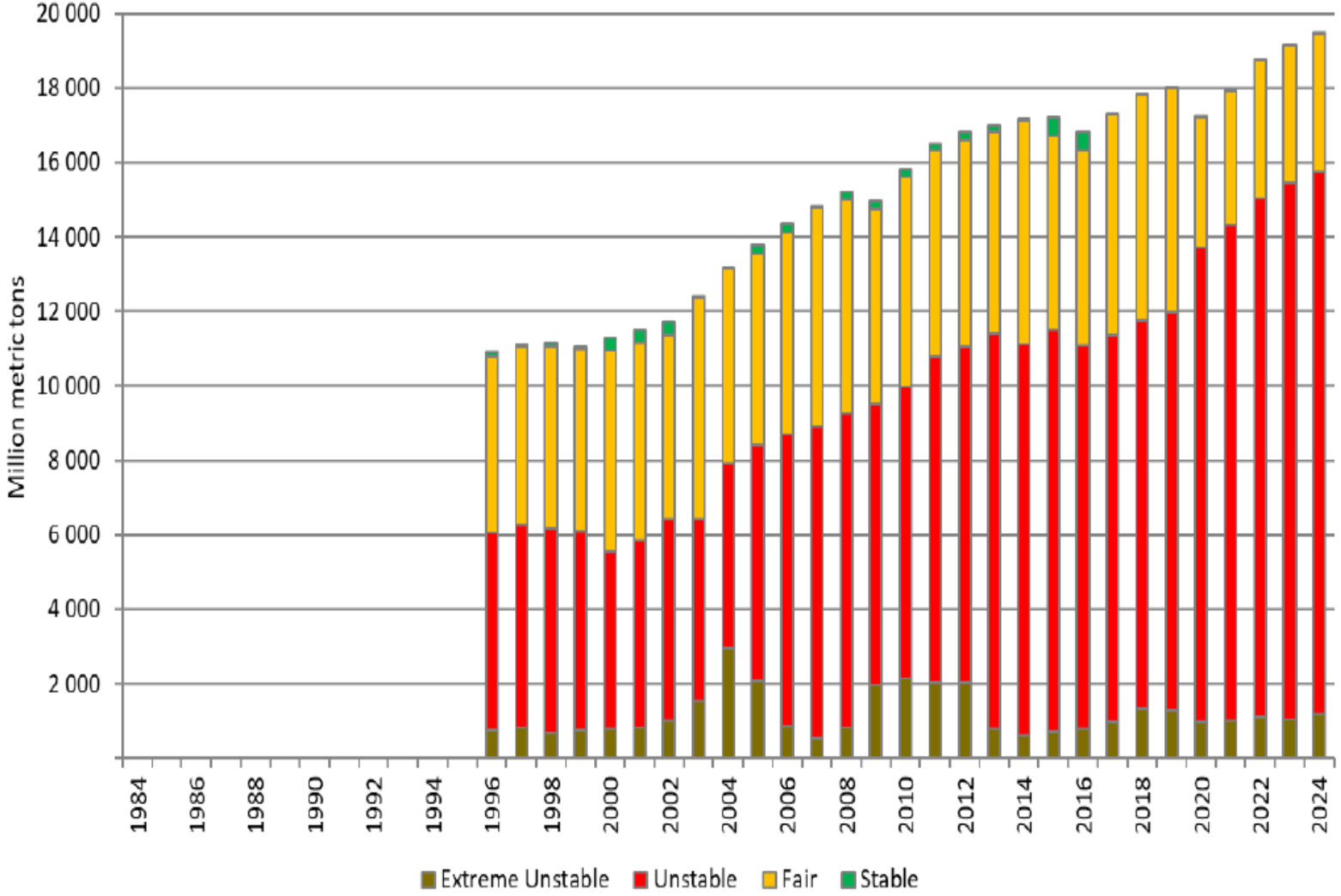
IEA. CC BY 4.0.

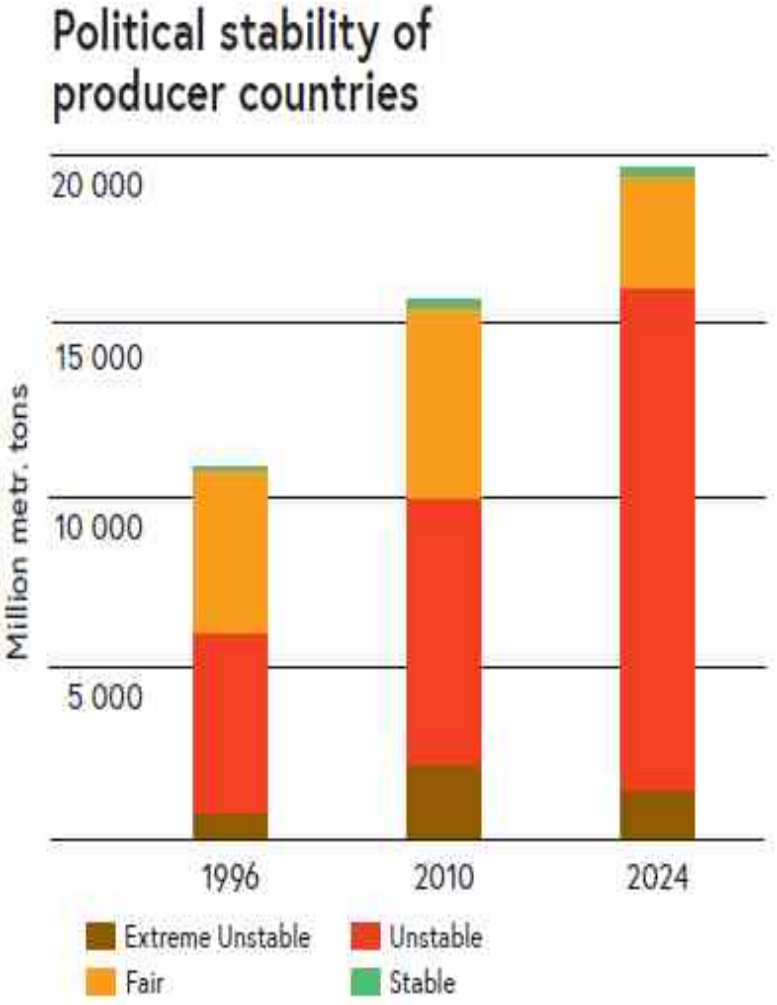
Notes: MER = market exchange rate. Excludes budgets for iron ore, coal, aluminium, gold and diamonds. Others refer to cobalt, rare earth elements, potash/phosphate and many other minor metals.
Source: IEA analysis based on data from S&P Capital IQ.

Source: IEA Global Critical Minerals Outlook 2026 – May 2026

The Geopolitical Aspects

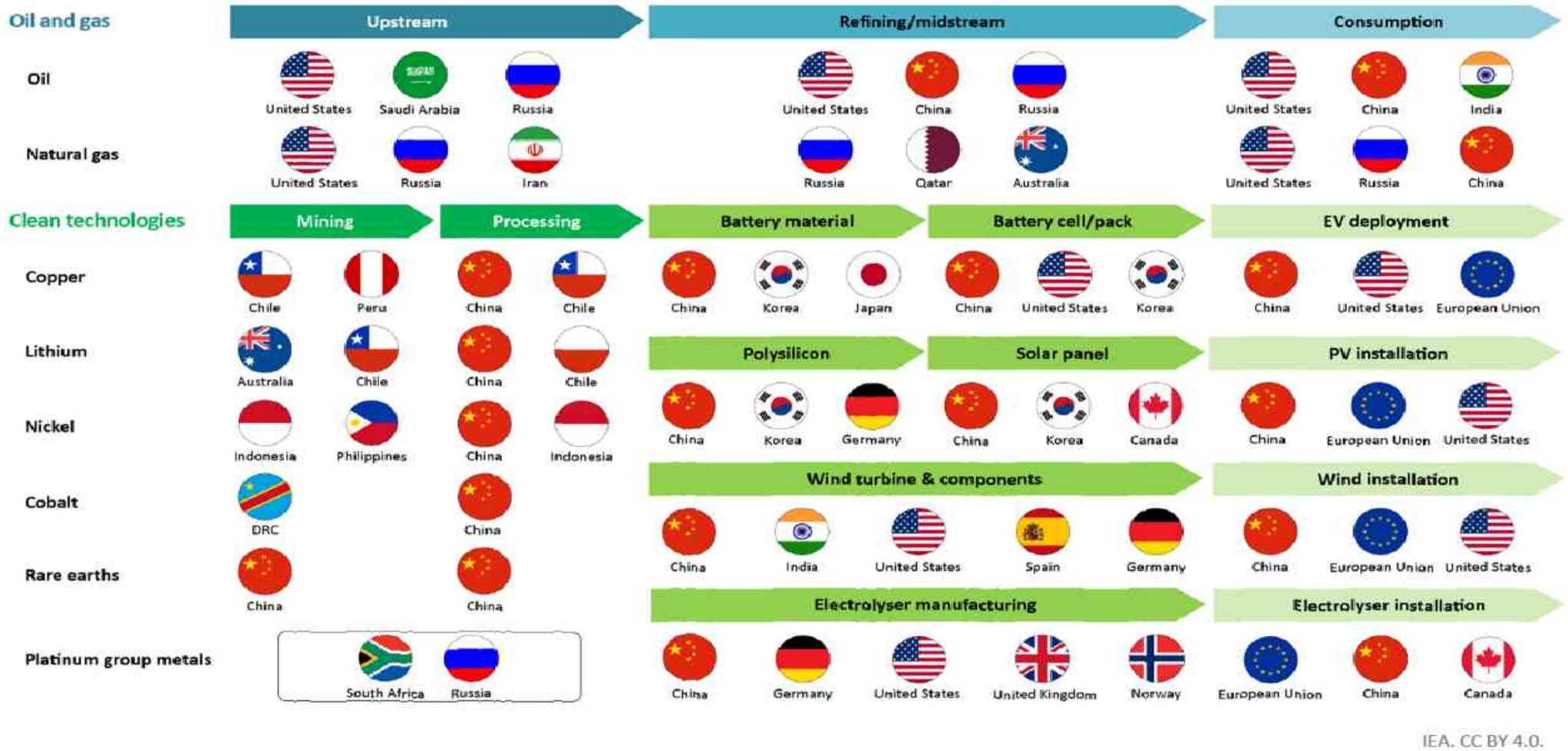
World Mining Production 1984 – 2024
by Political Stability of Producing Countries





Source: World Mining Data April 2026

An important concentration of Countries for Extraction and Processing of Raw Materials

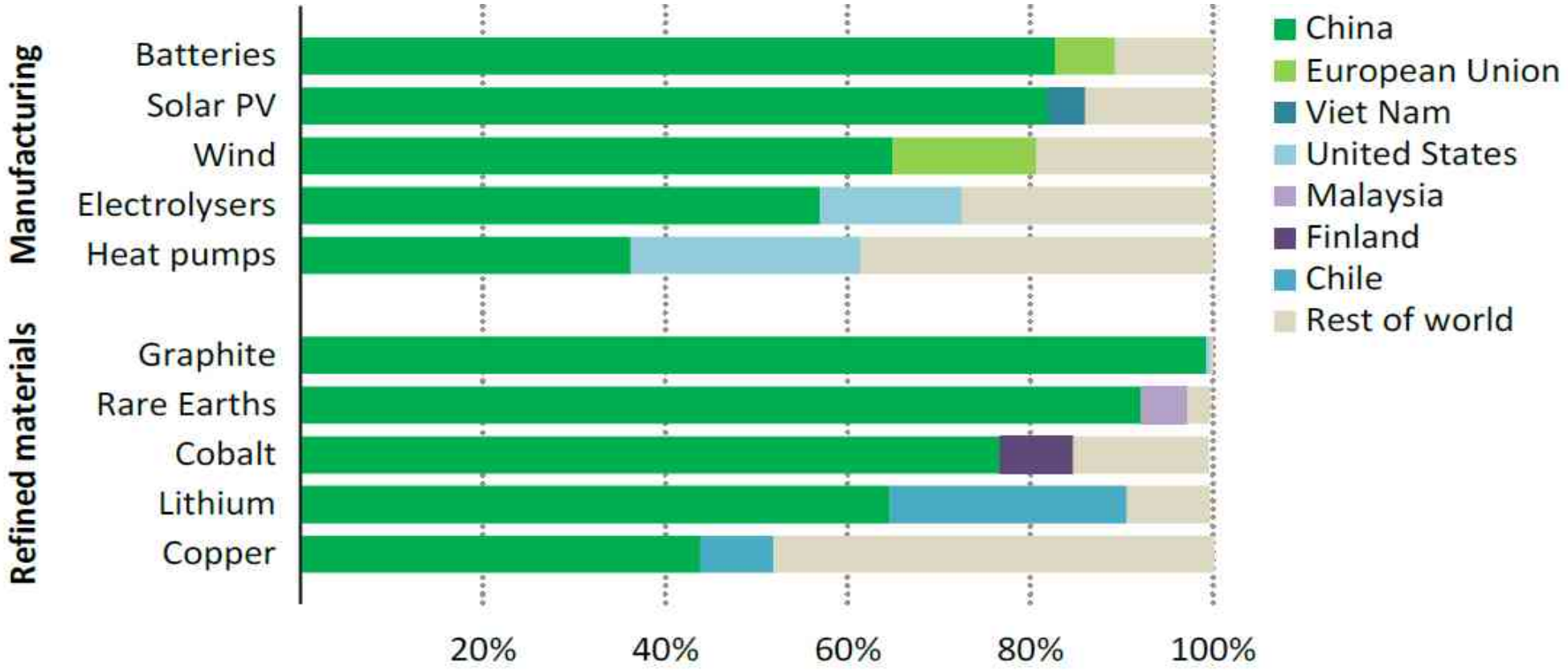


Transition to a clean energy system brings new energy trade patterns, countries and geopolitical considerations into play

Notes: DRC = Democratic Republic of the Congo. Largest producers and consumers are noted in each case to provide an indication, rather than a complete account.

Source: IEA WEO 2022

An important concentration of Countries for Manufacturing & Refining of Clean Technology & key Minerals Supply - 2024



IEA. CC BY 4.0.

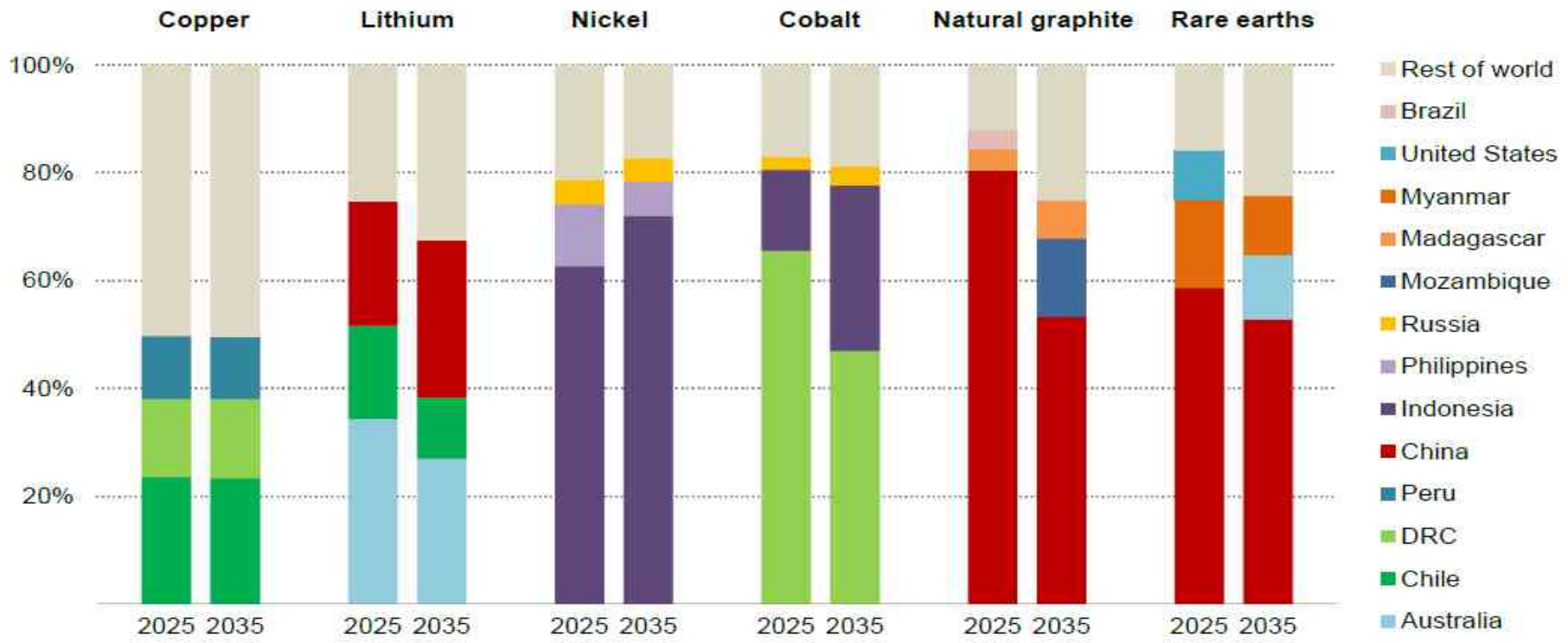
By far, China controls the largest share of manufacturing and critical material refining capacity for many clean energy technology supply chains

Source: IEA WEO 2024

An important concentration of Countries for Production of Mined or Raw Materials 2025 - 2035

Except for nickel, announced projects suggest gradual progress towards diversification of mining supply sources across regions…

Geographical distribution of mined or raw material production for key energy minerals in the base case, 2025-2035



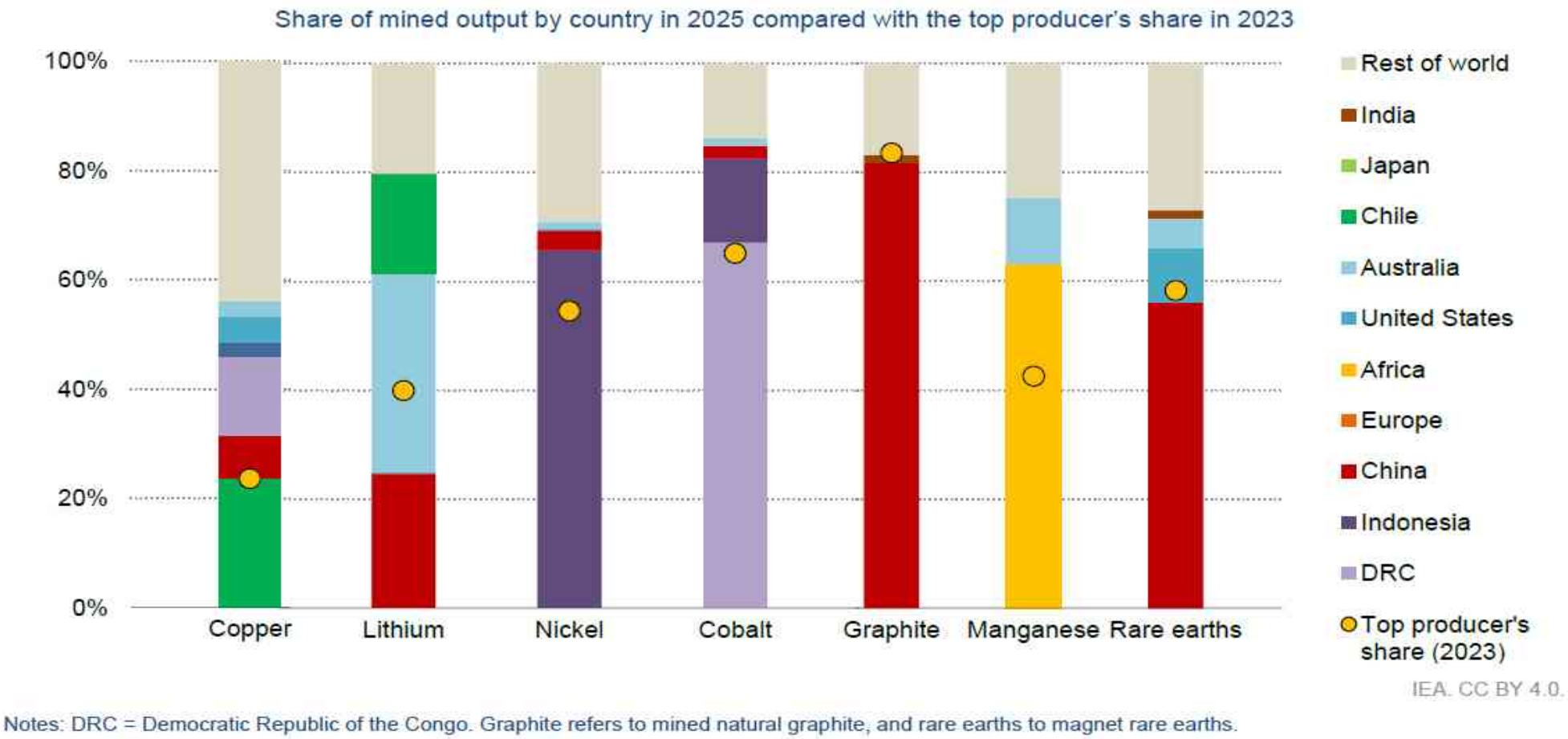
IEA. CC BY 4.0.

Notes: DRC = Democratic Republic of the Congo. Graphite mining is for natural flake graphite. Rare earths refer to magnet rare earth elements only. The figure shows the production shares of the top three producing countries in the given year.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

An important concentration of Countries for Production of Mined or Raw Materials – Situation 2025

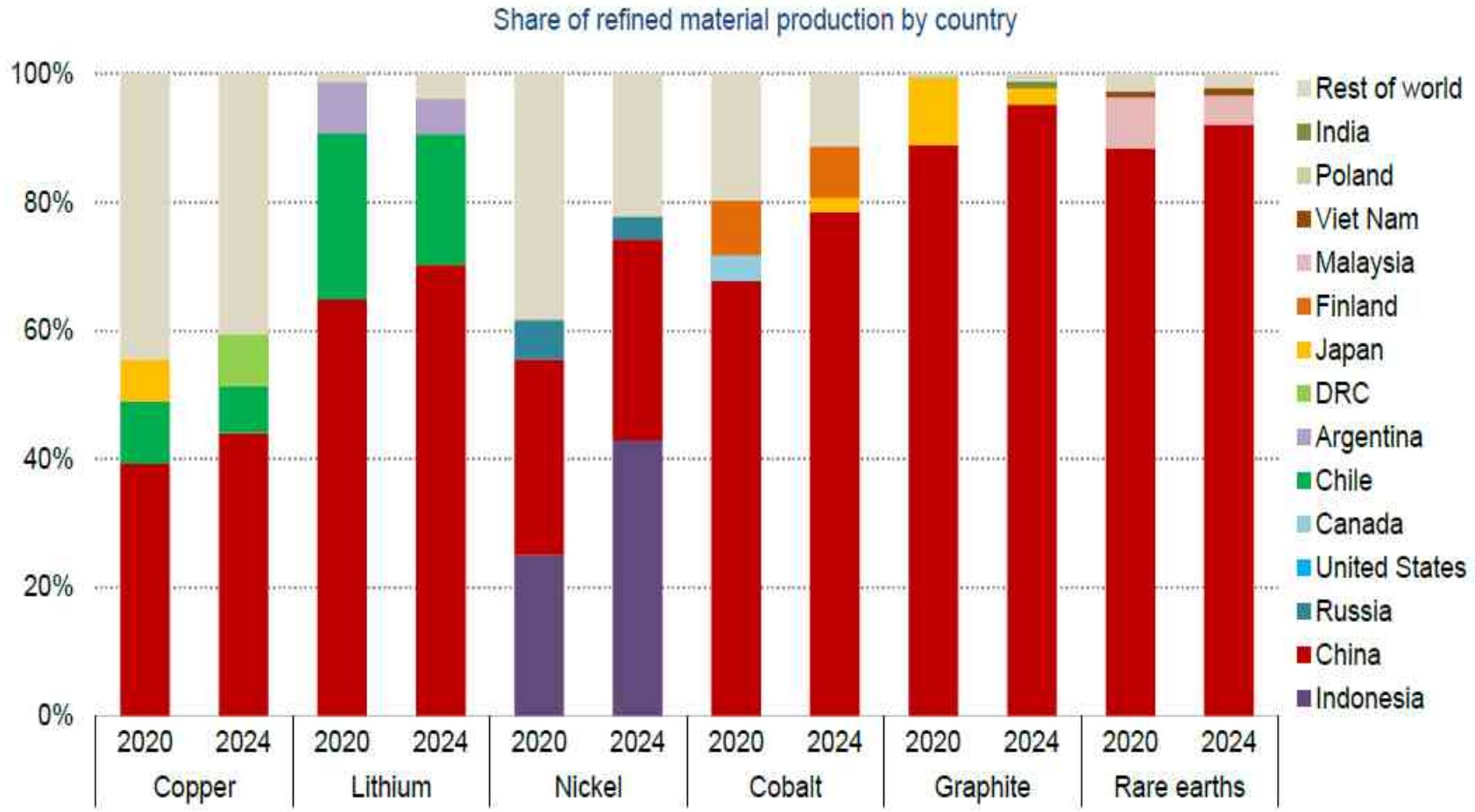
Mining concentration shows a mixed picture across minerals, with lithium, graphite and rare earths seeing modest improvement



Notes: DRC = Democratic Republic of the Congo. Graphite refers to mined natural graphite, and rare earths to magnet rare earths.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

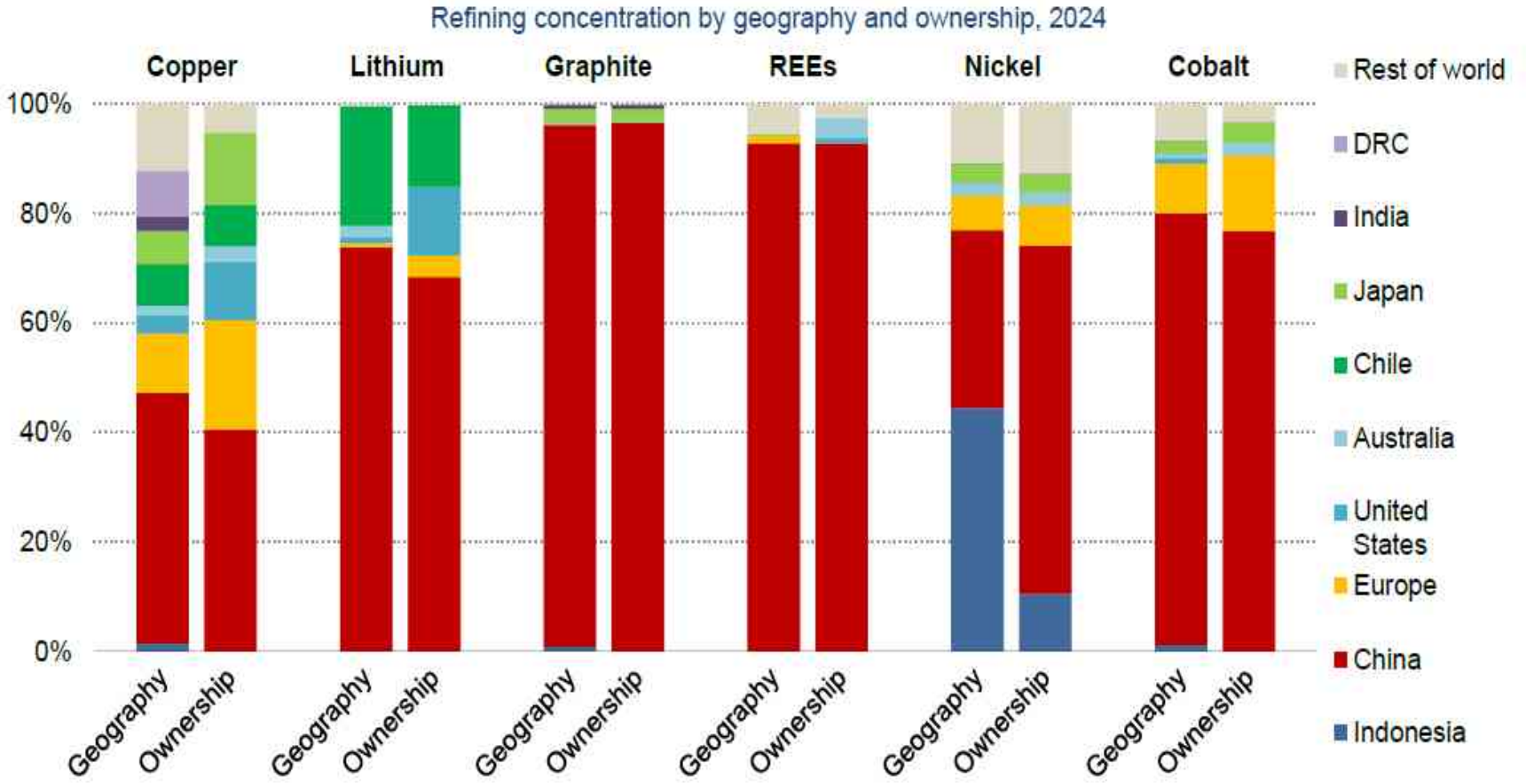
An important concentration of Countries of Refined Materials Evolution 2020 - 2024



Notes: DRC = Democratic Republic of the Congo. Graphite is based on battery-grade spherical and synthetic graphite. Rare earths are magnet rare earths only.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

An important concentration of Countries of Refined Materials - 2024



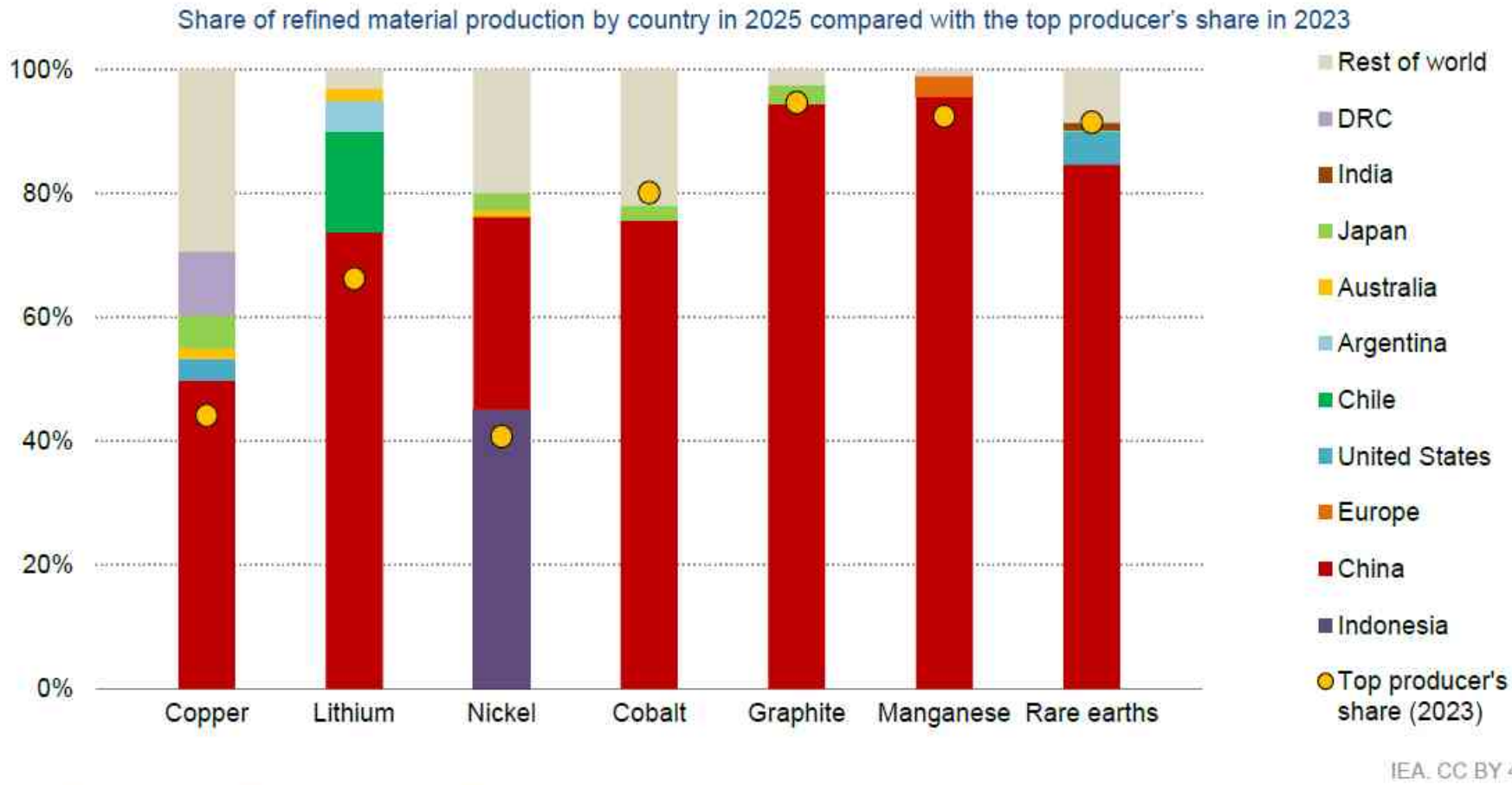
Notes: DRC = Democratic Republic of the Congo. Ownership based on company headquarters location. For projects run by multiple companies, production is assigned to the company with the largest share. For copper, data are on the top 20 mining companies in 2024 representing 56% of production. For lithium, data cover 100% of production in 2024. For rare earths, data cover 94% of production. For nickel, data cover 91% of production. For cobalt, data cover 94% of production. Rare earths are total rare earths.

Sources: IEA analysis based on S&P Global and Wood Mackenzie.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

An important concentration of Countries of Refined Materials Situation 2025

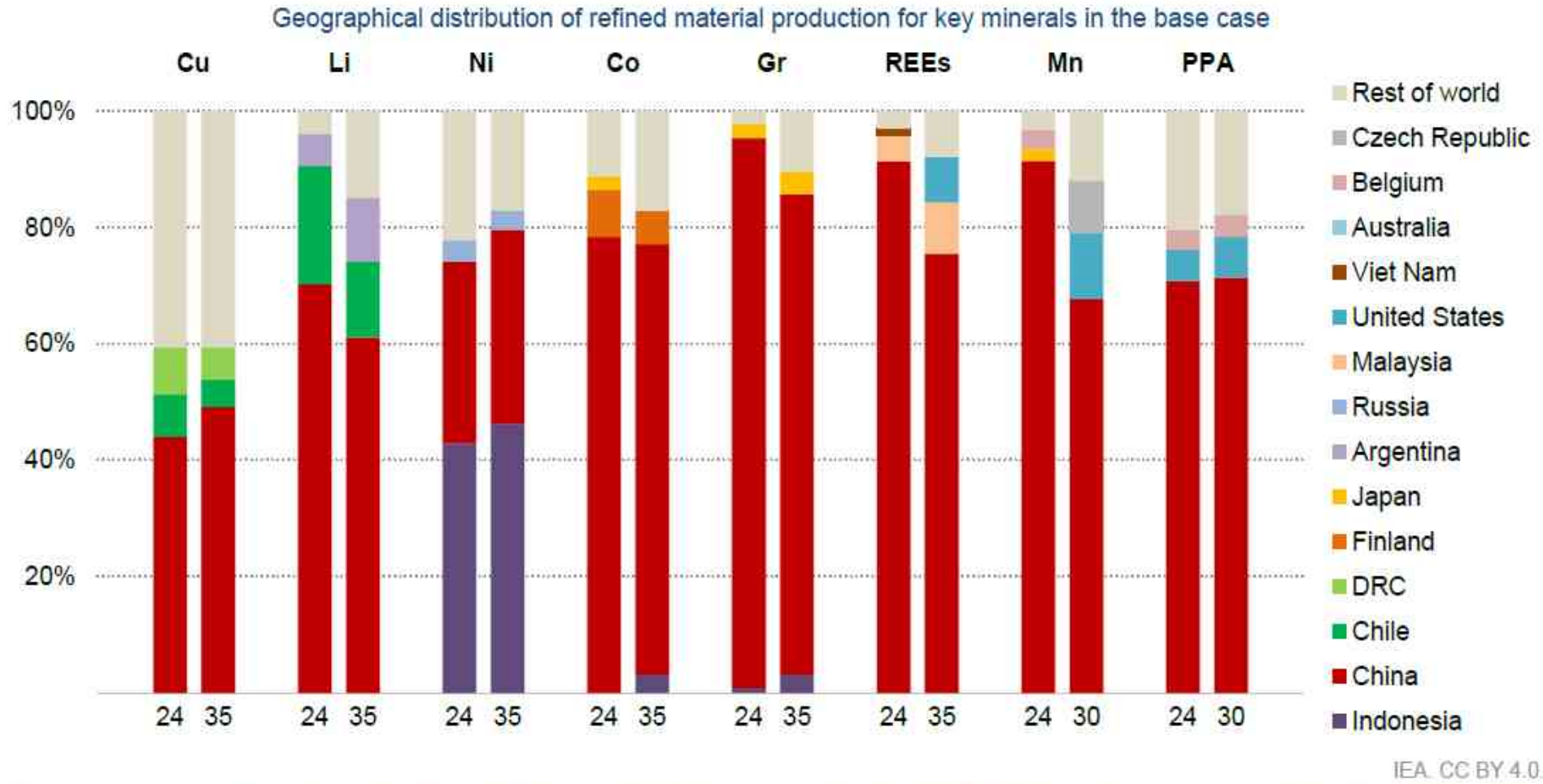
As a result, concentration in refined material production edged higher again in 2025 across most minerals, with rare earths being the exception



Notes: DRC = Democratic Republic of the Congo. Graphite refers to battery-grade graphite, and rare earths to magnet rare earths.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

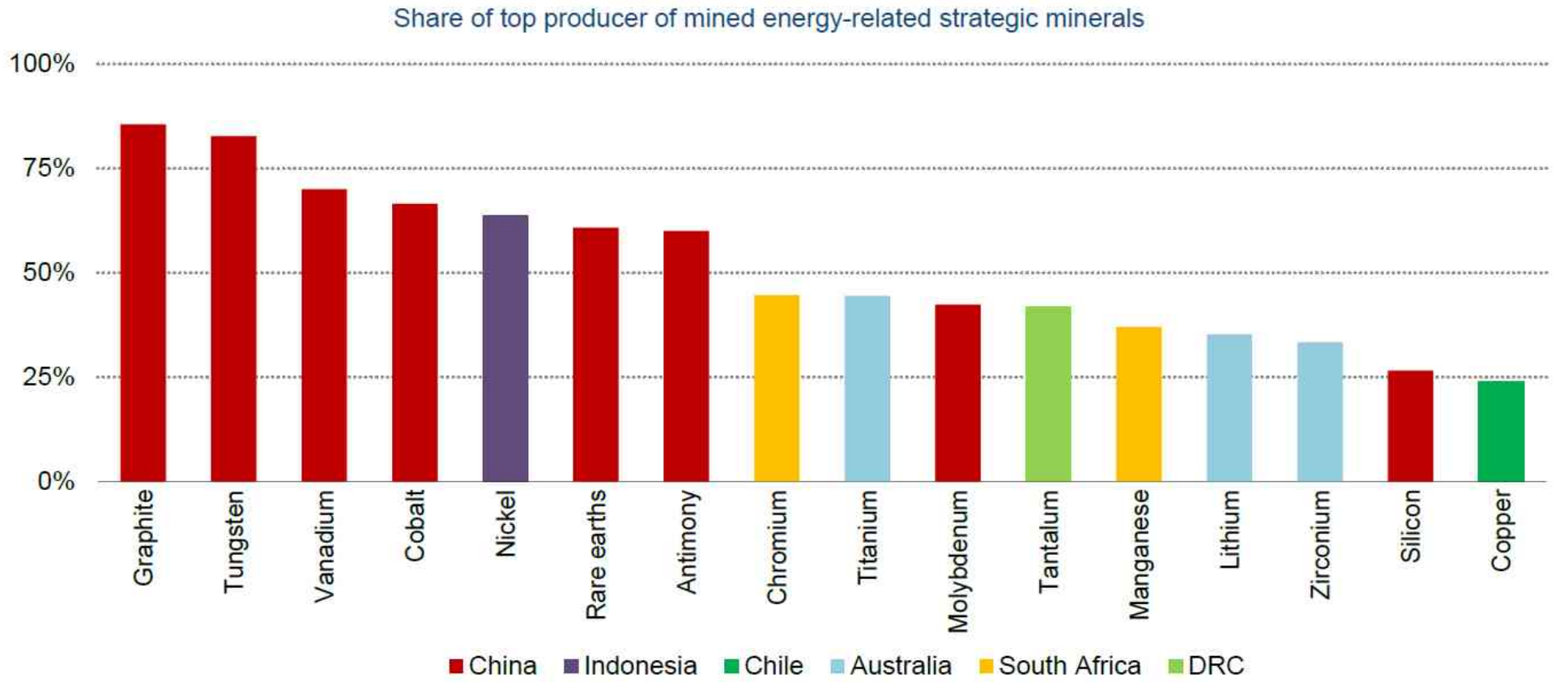
An important concentration of Countries of Refined Materials Evolution 2024 - 2035



Notes: Cu = copper; Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; REEs = rare earth elements; Mn = battery-grade manganese sulphate; PPA = battery-grade purified phosphoric acid; DRC = Democratic Republic of the Congo. The figures for graphite are based on battery-grade including spherical graphite and synthetic graphite. The figures for rare earths are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Mined Energy-related strategic Minerals
China dominates the market



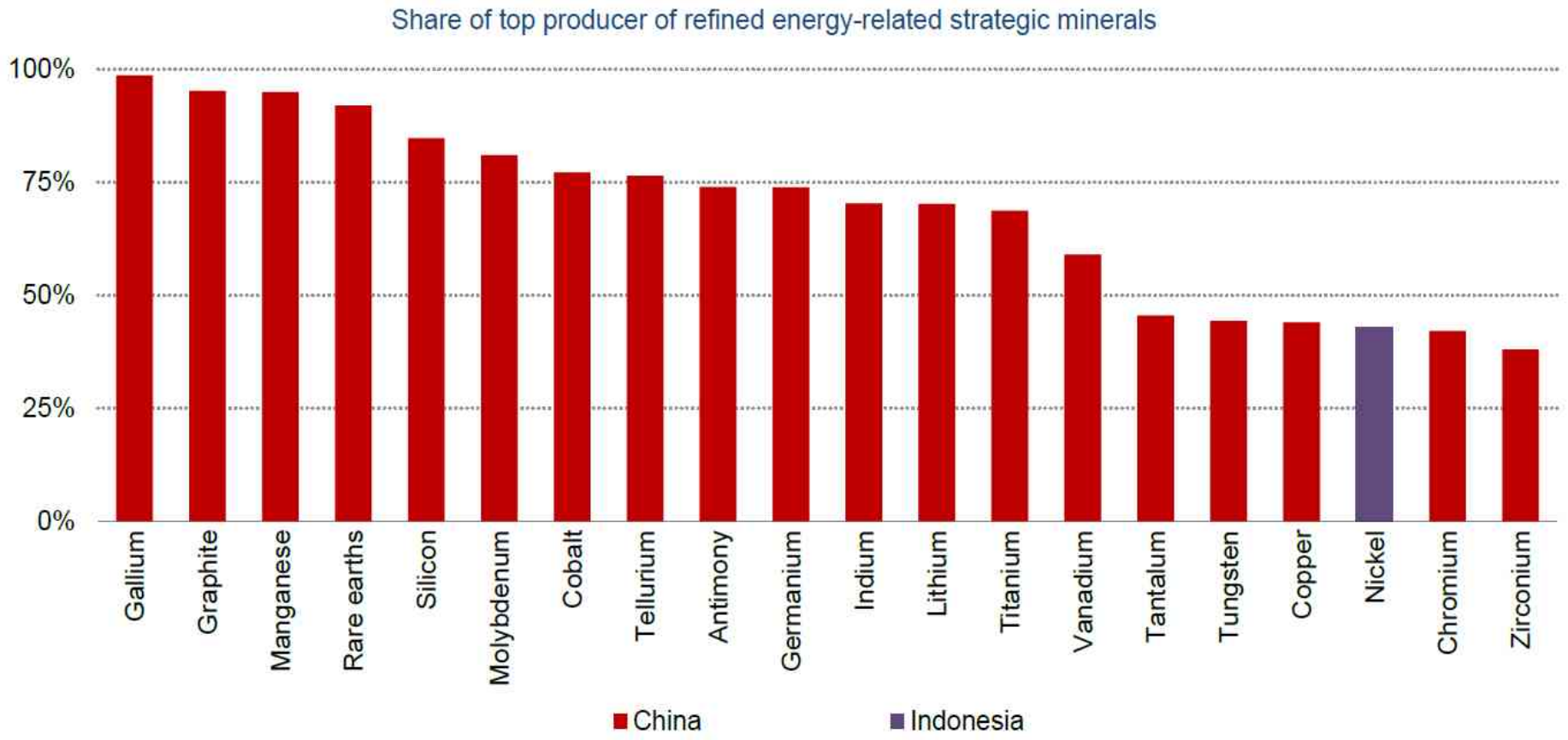
IEA. CC BY 4.0.

Notes: DRC = Democratic Republic of the Congo. Based on the most recent year for which data are available. The figure for silicon refers to silica mining. Gallium, germanium, indium and tellurium are not shown as they are almost entirely produced as a by-product.

Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and EU Raw Materials Information System (accessed April 2025).

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Refined Energy-related strategic Minerals
China dominates the market



IEA. CC BY 4.0.

Notes: Based on the most recent year for which data are available. The figure for titanium refers to titanium metal. The figure for manganese refers to high-purity manganese sulphate. The figure for molybdenum refers to ferromolybdenum.

Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and EU Raw Materials Information System (accessed April 2025).

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Africa: Mineral Resources and Commodities



Major Mining Companies for Production of Raw Materials

Vale: Brazil

Codelco: Chile
SQM: Chile

Southern Corp.: Mexico

BHP: Australia
Mineral Res.: Australia
Galaxy Res.: Australia

Freeport McMoRan: US
Albermale: US

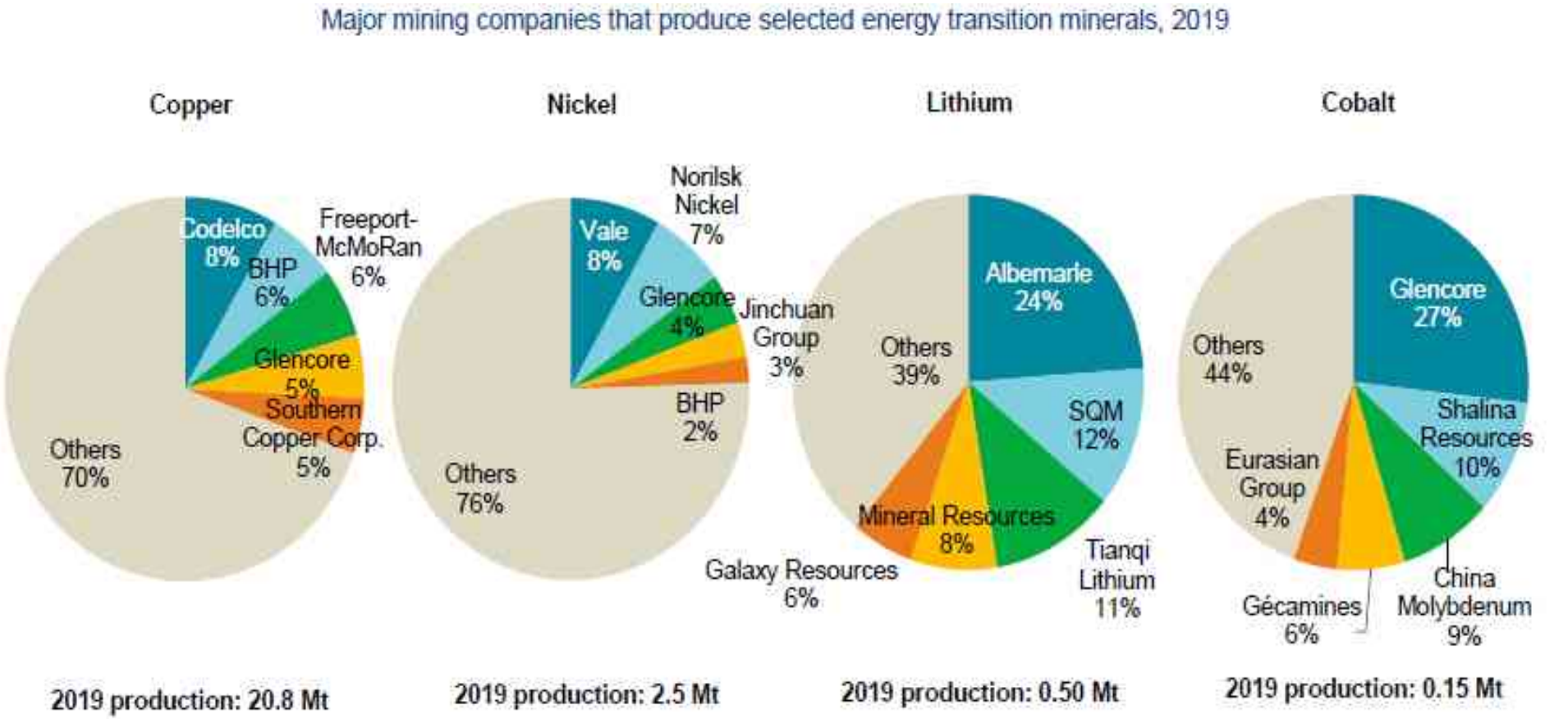
Glencore: Anglo-Swiss

Norilsk Nickel: Russia

Eurasian Group: Kazakhstan

Gécamines: DRC
Shalina Res.: DRC

Tianqui Lithium: China
China Molybdenum: China
Jinchuan Group: Hong Kong



Source: IEA Special Report May 2021

A measure of geopolitical concentrations
The Herfindahl – Hirschman Index (HHI)

A measure of the size of firms in relation to the industry in which they belong and an indicator of the amount of competition among them.

$$HHI = \sum_{i=1}^{i=N} S_i^2$$

S_i = Market share of firm *i* in the market in % (Whole numbers, from 0 to 100 or decimal number, from 0 to 1)
N = Number of firms . According to the numbers taken, HHI varies from 0 to 1 or 0 to 10000.

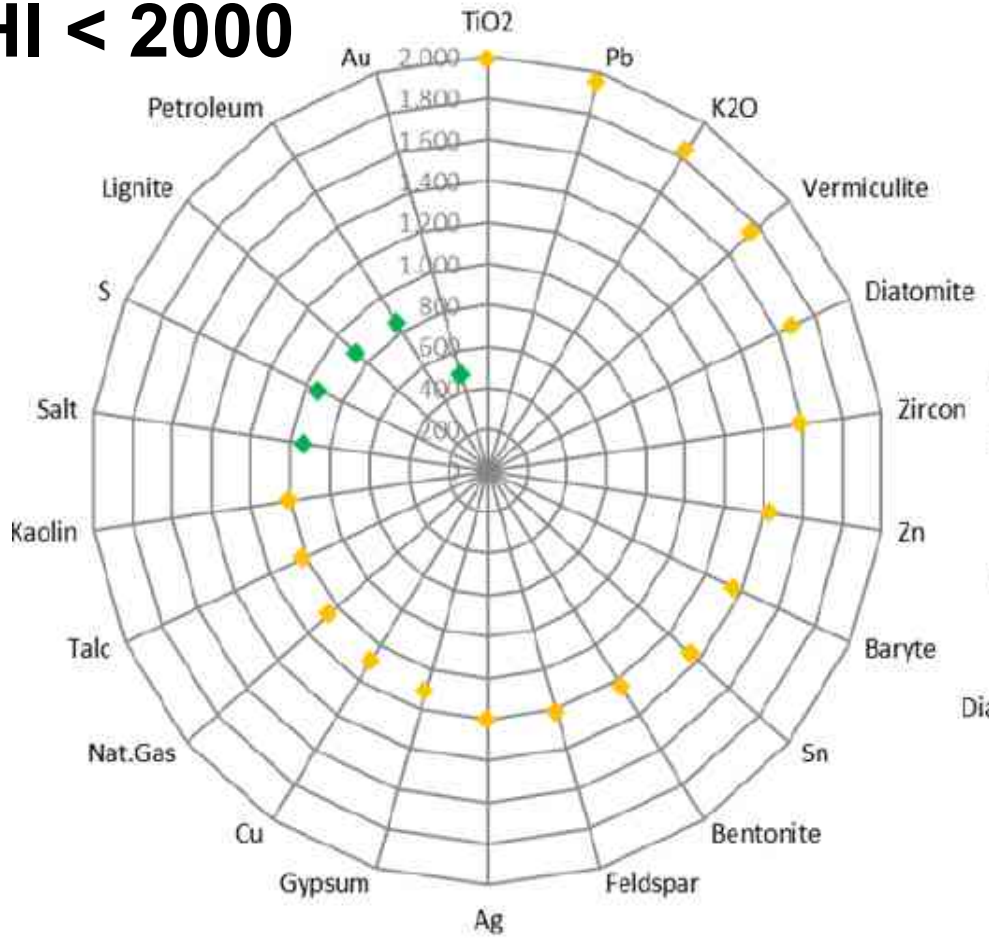
HHI < 100 or 0,01: Highly competitive Industry
HHI < 1500 or 0,15: Unconcentrated Industry
HHI between 1500 or 0,15 and 2500 or 0,25: Moderate concentration
HHI > 2500 or 0,25: Highly concentrated Industry

HHI may vary upon time. Various sources: IFP EN, World Mining Data, BRGM,….

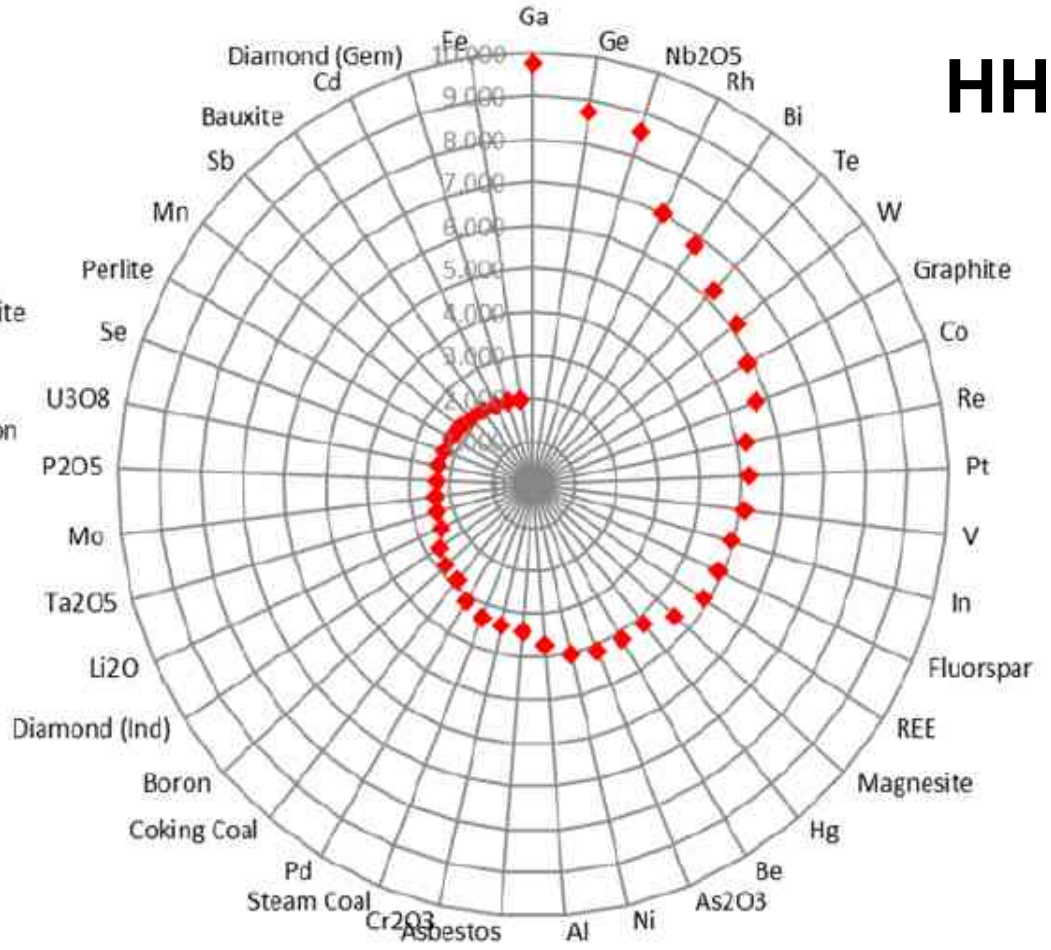
HHI can be evaluated for Materials mined Production (presented below), refined Production, Reserves.

A measure of geopolitical concentrations
The Herfindahl – Hirschman Index (HHI) 2024

HHI < 2000



HHI > 2000

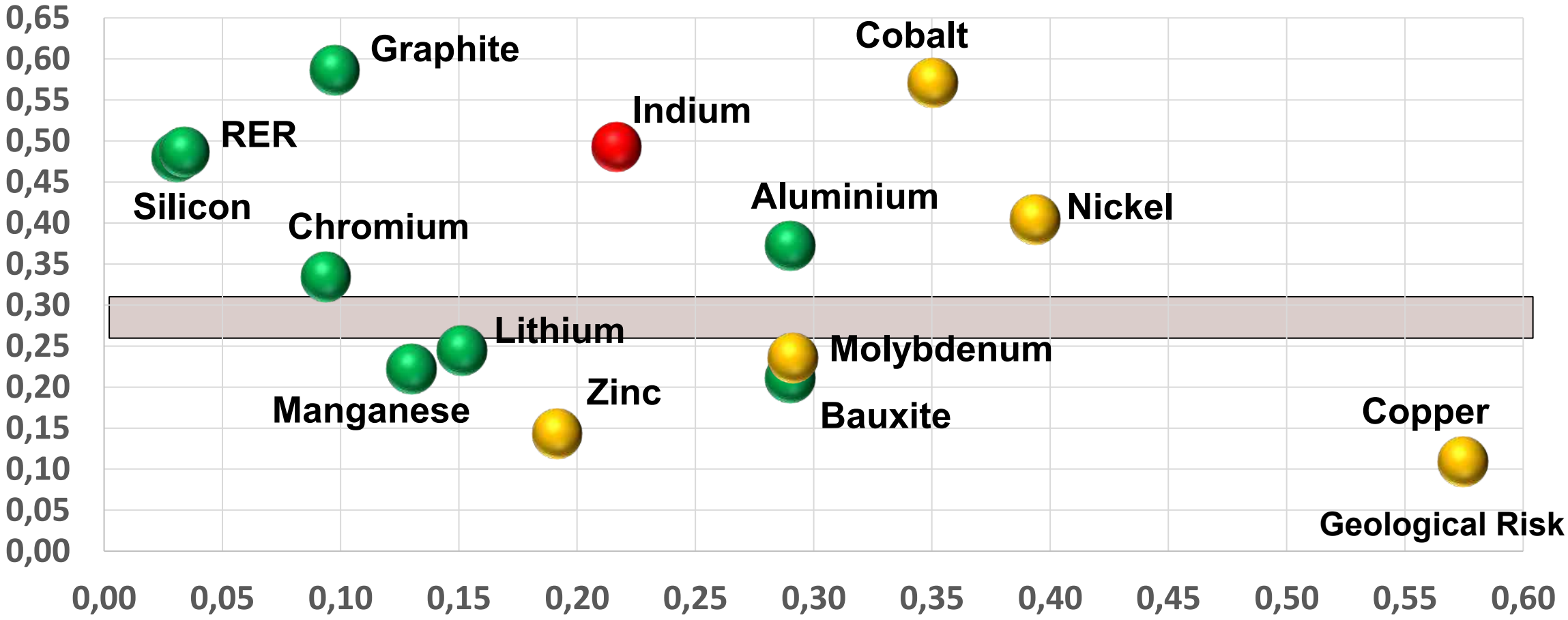


Source: World Mining Data April 2026

Criticality of Mineral Materials (All Industries)
Risk Matrix for selected Minerals (HHI based on Production)

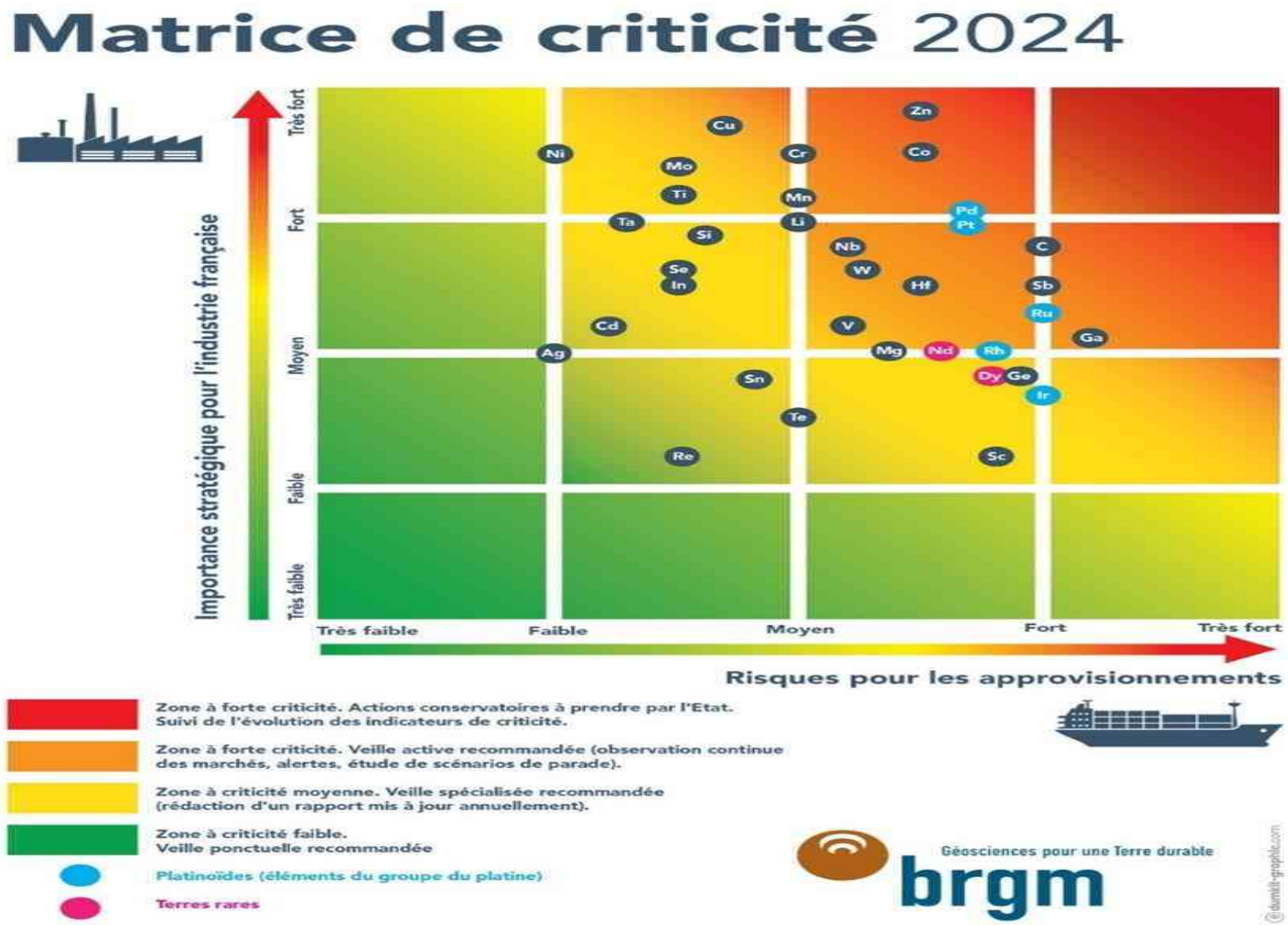
Geopolitical Risk (HHI 2025/10000)

Geological Risk expressed by: Est. Cumulated Demand 2024-2050/Resources – IEA/Mineral Info
Geopolitical Risk expressed by: HHI - Prod. 100% (Source: World Mining Data 2026, IFPEN)



Source: ChG/Data from IEA, BRGM, USGS, World Mining Data 2026, Mineral Info. Resources evaluation are subject to great uncertainties.

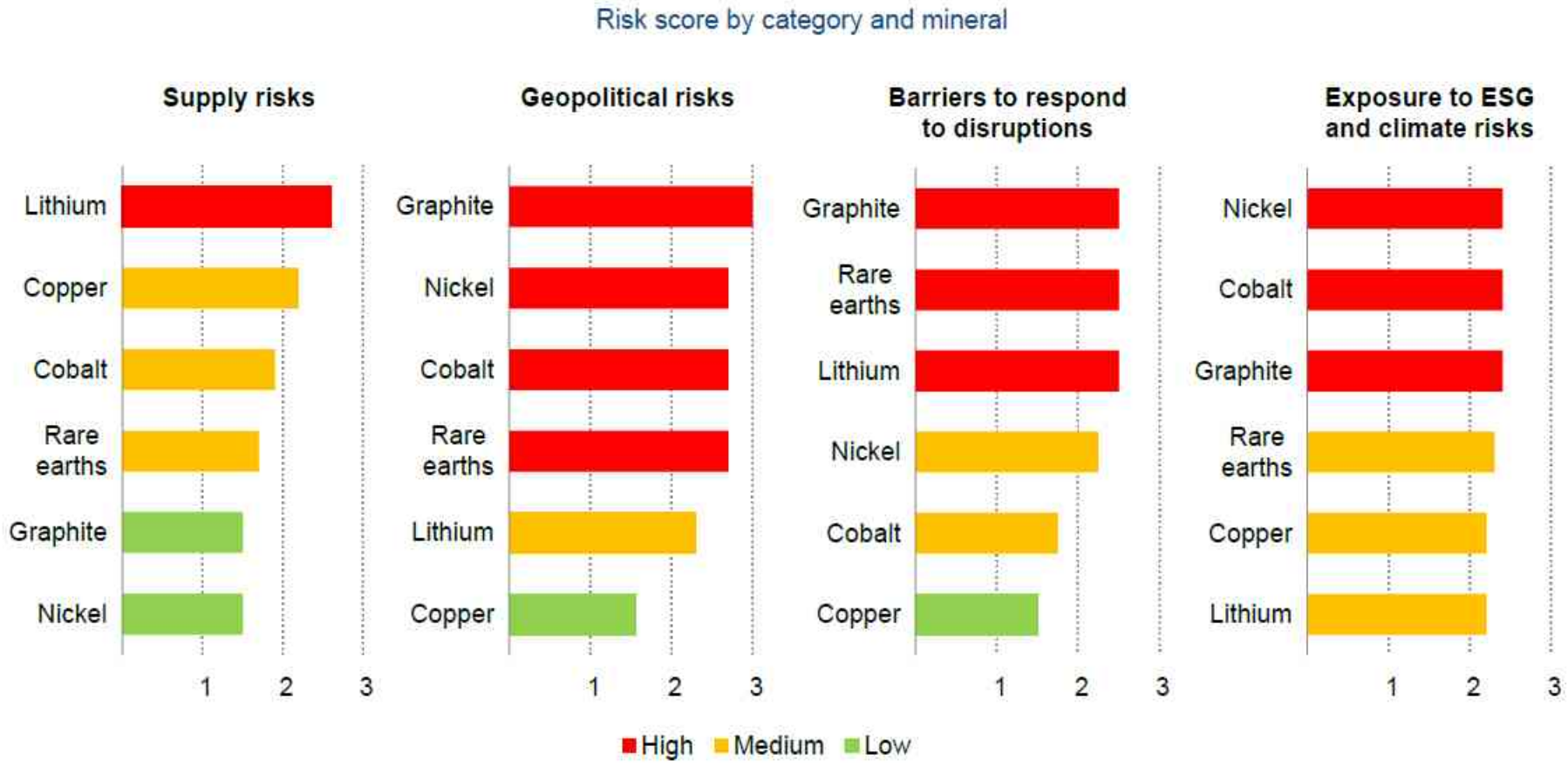
Criticality matrix 2024 for French Industry



Source: BRGM 2025

Risks score by IEA 2024

Risk score by category: Lithium and copper are more exposed to supply and volume risks whereas graphite, cobalt, rare earths and nickel face more substantial geopolitical risks



IEA. CC BY 4.0.

Note: High = score above 2.33, Medium = score between 2.33 and 1.67, Low = score less than 1.67.

Exports Restrictions

Exports restrictions by selected countries & Prices impacts

Export restrictions on energy-related minerals since 2023

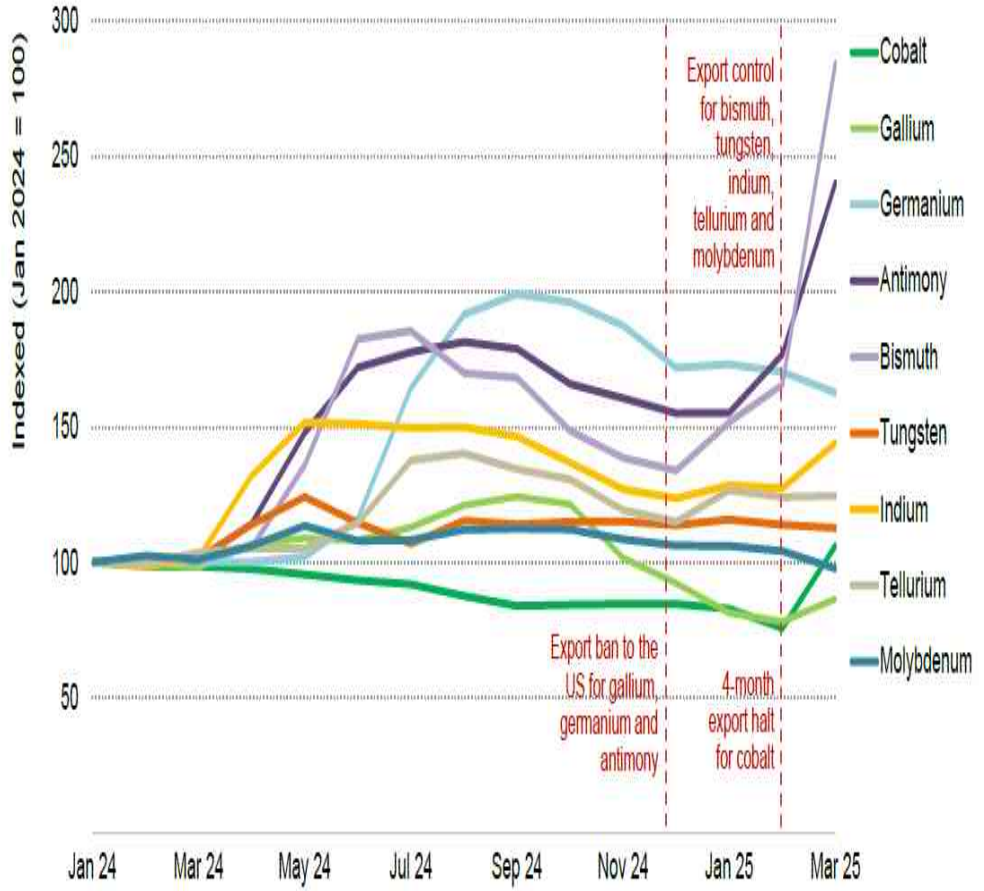
		By	Market share	Type of control
Material	Lithium	Zimbabwe	9%*	Imposed a ban on raw lithium ore exports in Dec 2022, followed by export licensing requirements for all unprocessed base minerals in Jan 2023
	Gallium	China	99%	Export licensing in Jul 2023, followed by an export ban to the US in Dec 2024
	Germanium	China	74%	Export licensing in Jul 2023, followed by an export ban to the US in Dec 2024
	Antimony	China	74%	Export licensing in Sep 2024, followed by an export ban to the US in Dec 2024
	Rare earths	China	92%	Export reporting requirements from Nov 2023 (effective until Oct 2025), followed by export licensing on seven medium and heavy rare earths in April 2025
	Graphite	China	98%	Export licensing in Dec 2023
	Cobalt	DRC	68%*	4-month halt to exports announced in Feb 2025
	Tungsten	China	44%	Export licensing in Feb 2025
	Bismuth	China	80%	Export licensing in Feb 2025
	Indium	China	70%	Export licensing in Feb 2025
	Tellurium	China	77%	Export licensing in Feb 2025
	Molybdenum	China	81%	Export licensing in Feb 2025
	Nickel	Philippines	9%*	Proposed ban on raw mineral exports in Feb 2025
Technology	Rare earths	China	92%	Export ban of rare earth extraction and separation technologies in Dec 2023
	LFP cathode	China	98%	Proposed technology export control in Jan 2025
	Lithium refining	China	72%	Proposed technology export control in Jan 2025

IEA. CC BY 4.0.

* Mined output. Notes: LFP = lithium iron phosphate. Market shares are based on refined output in 2024.

Sources: IEA analysis based on USGS (2025), Mineral Commodity Summaries 2025, and EC Raw Materials Information System (accessed April 2025).

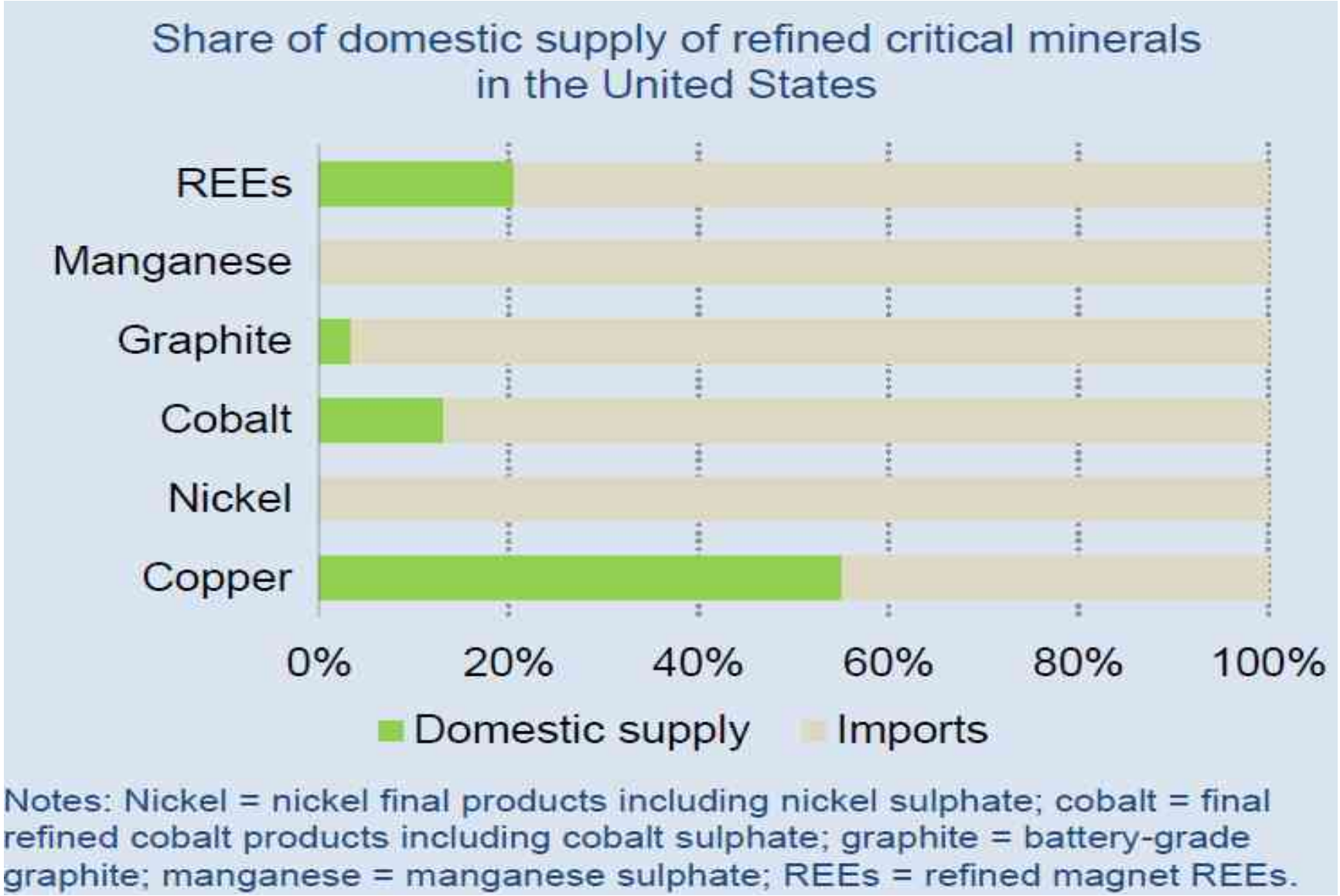
Price movement of selected materials subject to export restrictions in recent months



IEA. CC BY 4.0.

Sources: IEA analysis based on S&P Global and Bloomberg.

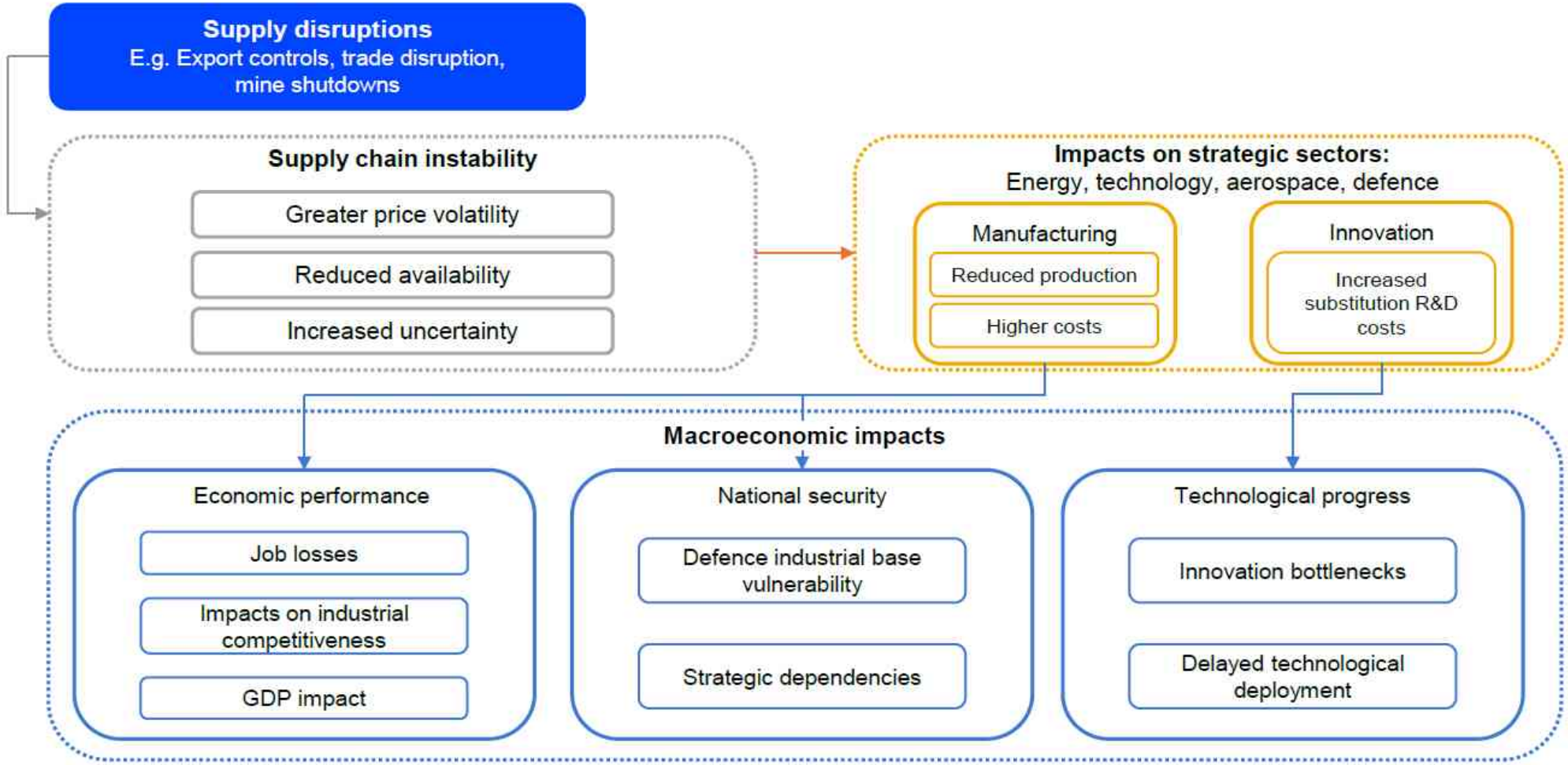
Potential impacts on the US?



Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Critical Minerals: Potential effects of disruptions

Effects of critical mineral disruptions on strategic sectors and downstream industries

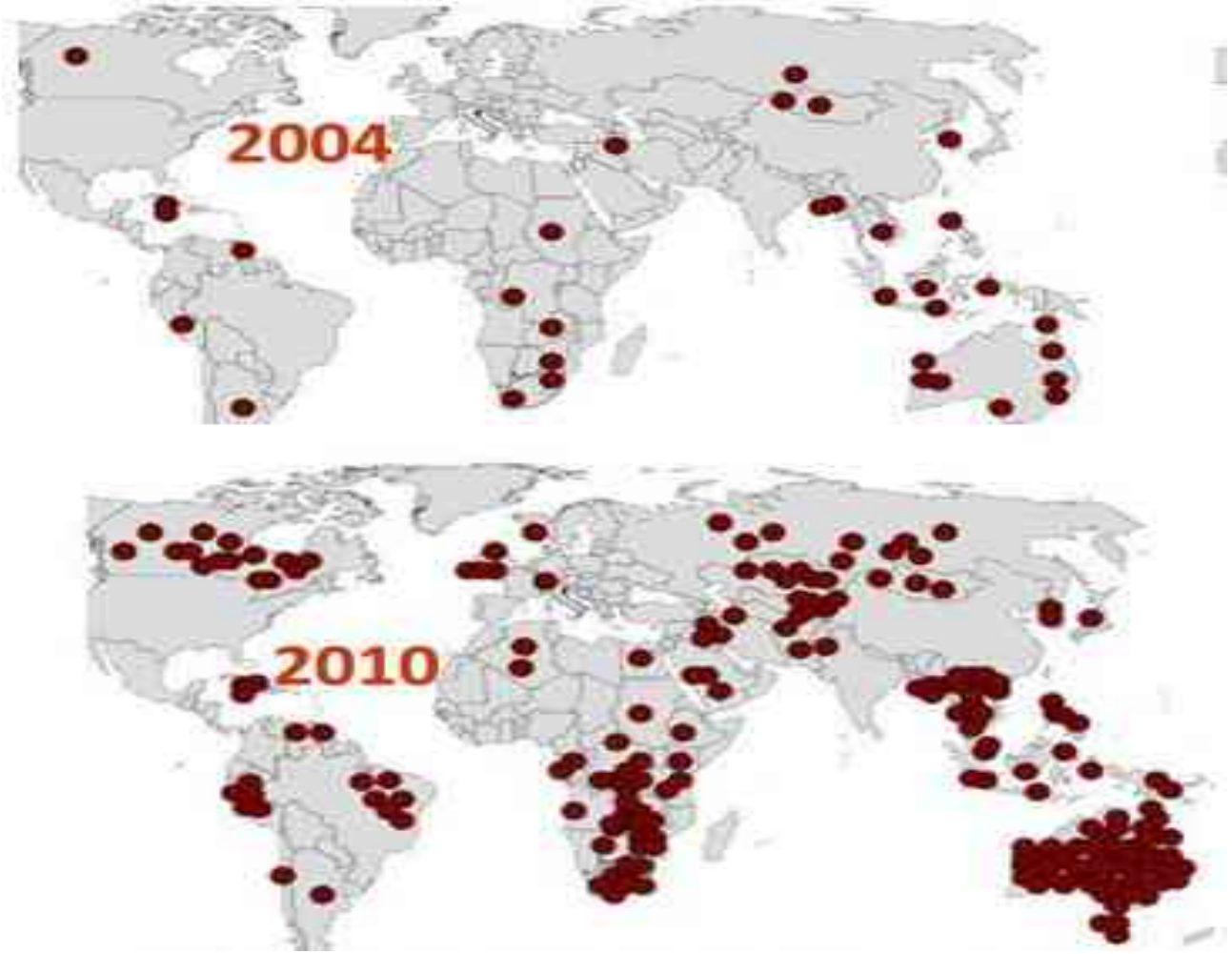


IEA. CC BY 4.0.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

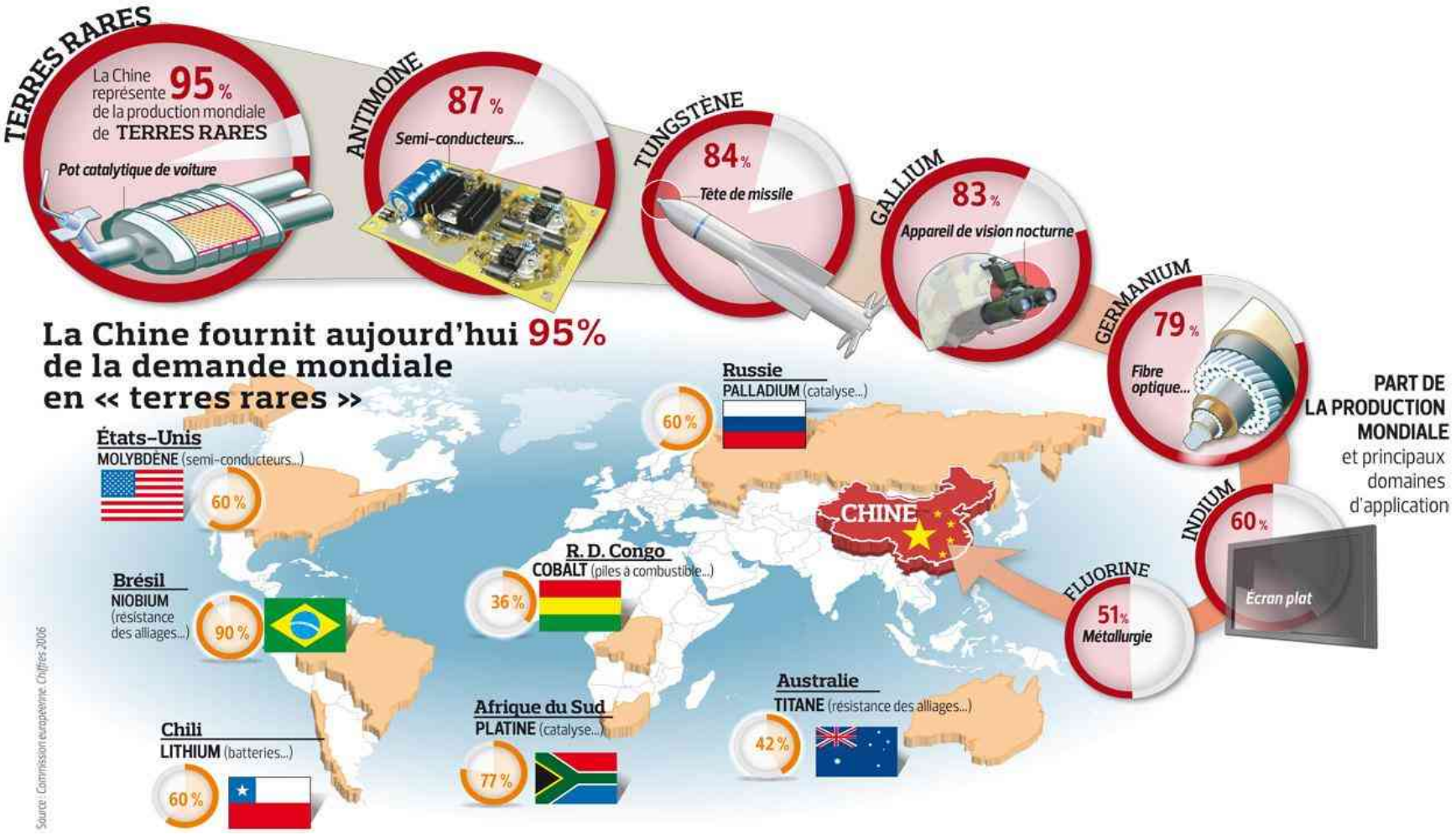
Focus on China

Chinese Companies more and more agressive to secure access to Mineral Resources



Source: Institut Carnot/BRGM

China is the World Leader for Mineral Resources Production – Situation 2010

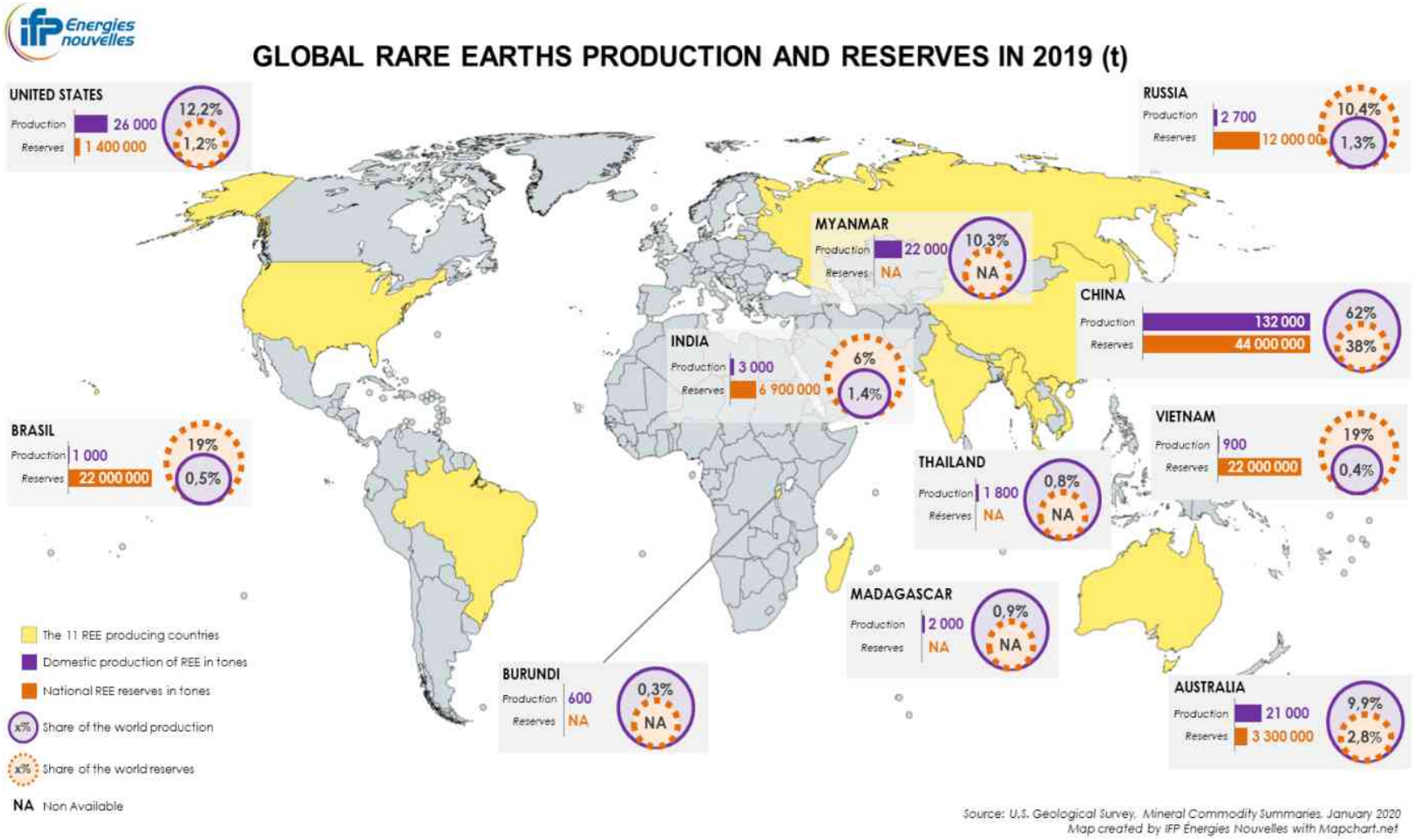


Source: Institut Carnot/BRGM

The Rare Earths crisis 2010 - 2011

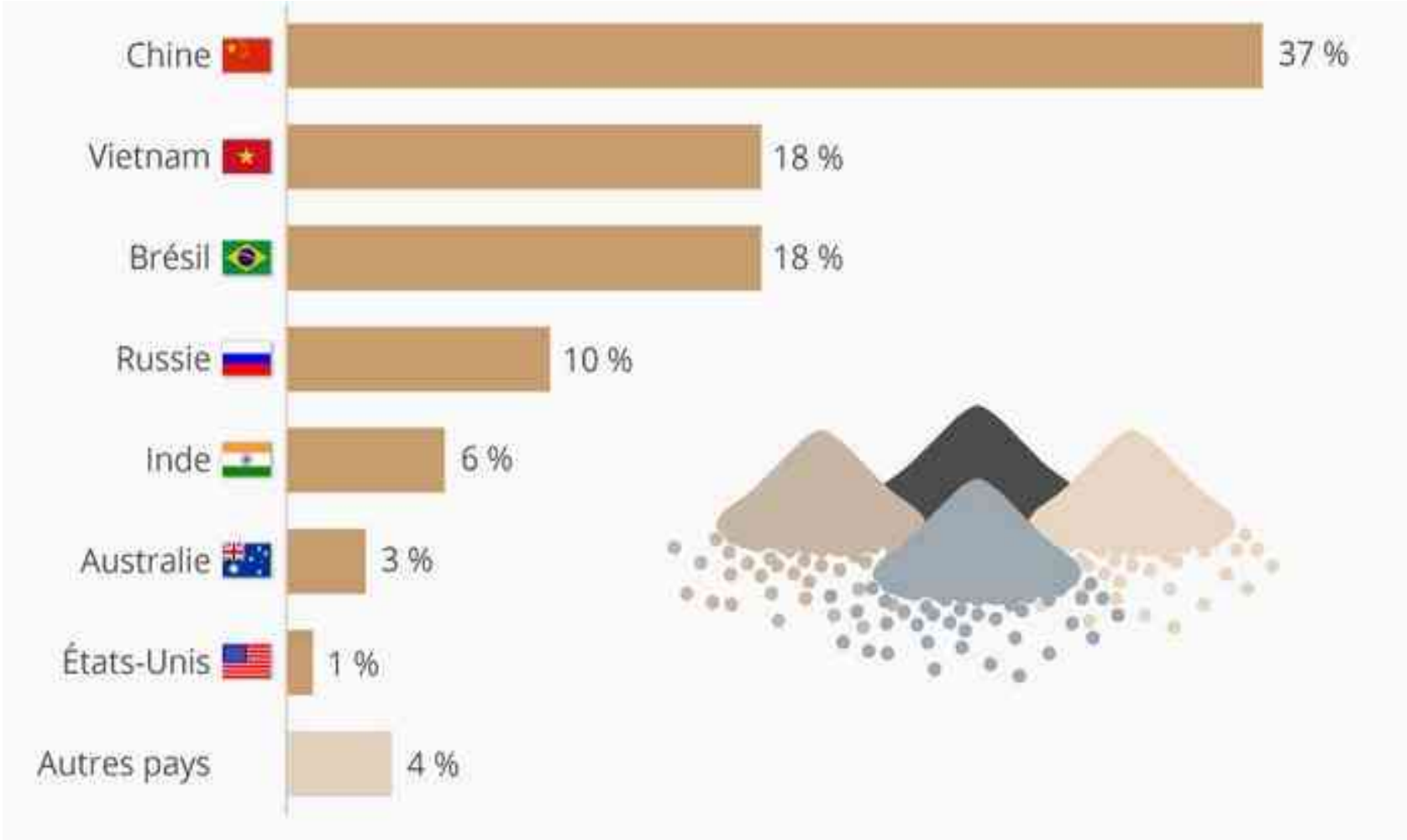
- In 2010, China produced 95% of Rare Earths in the world.
- Rare Earths are highly necessary in various industrial sectors. There production and refining is combined with severe environmental consequences.
- For said environmental reasons, China decided in 2011 to impose strict constraints on the Rare Earths trade by imposing exports quotas, with consequently an drastic price increase for these materials.
- A diplomatic crisis followed between US, EU, Japan and China.
- In 2015, China decided to give an end to the exports quotas. To avoid a too great dependancy, other countries launched new projects.
- Today, China remains the leader for Rare Earths production: In 2024, 270 kt out of 390 kt (Rare-Earth-Oxide - REO equivalent)

China is the World Leader for Rare Earths Elements (REE) Reserves and Production – Situation 2019



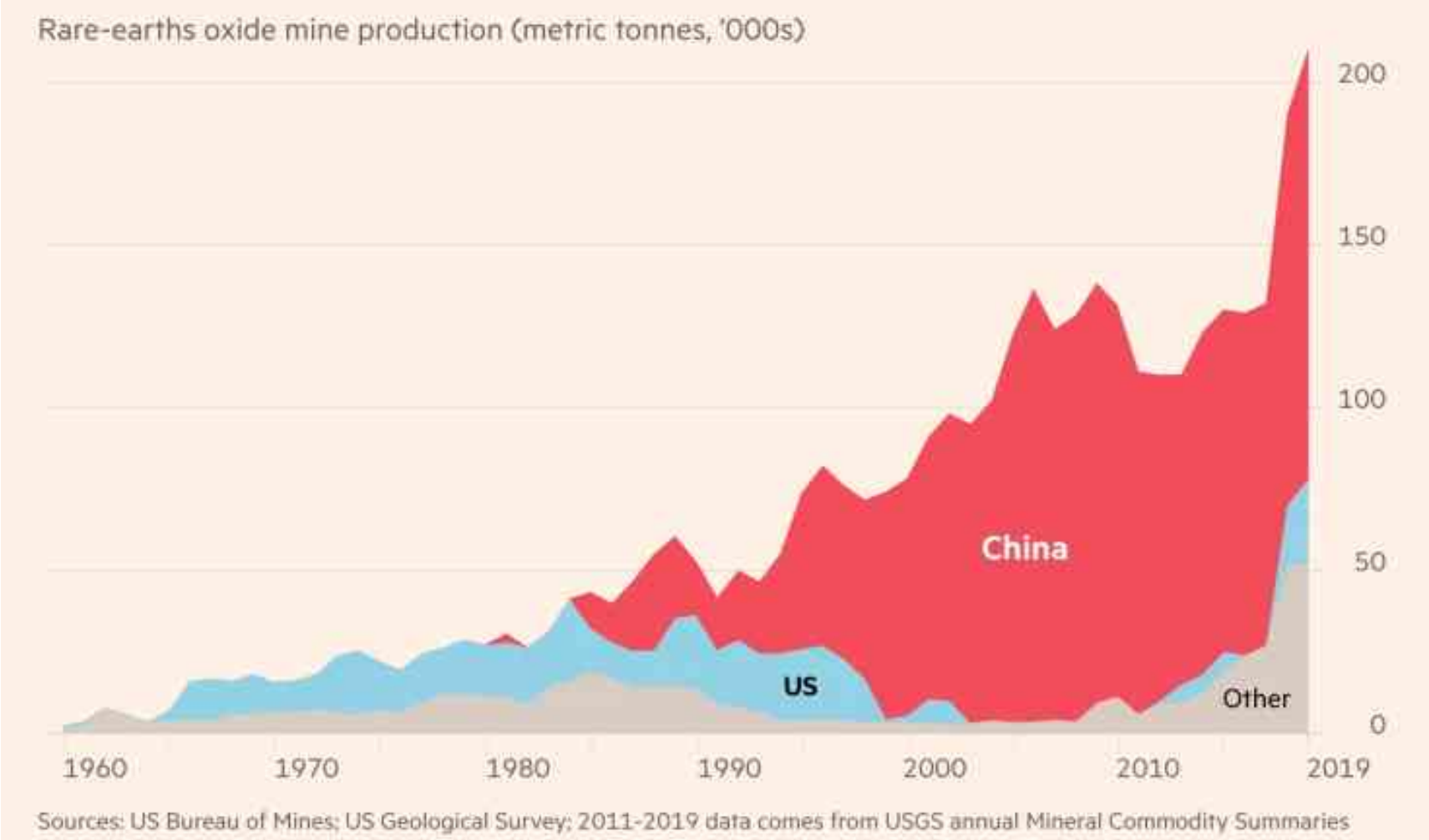
Source: IFP Energies Nouvelles/USGS

China is the World Leader for Rare Earth Elements (REE) Resources Reserves



Source: Statista/USGS - 2018

China N°1 for the World Production of Rare Earth Elements (REE) 1950 - 2019



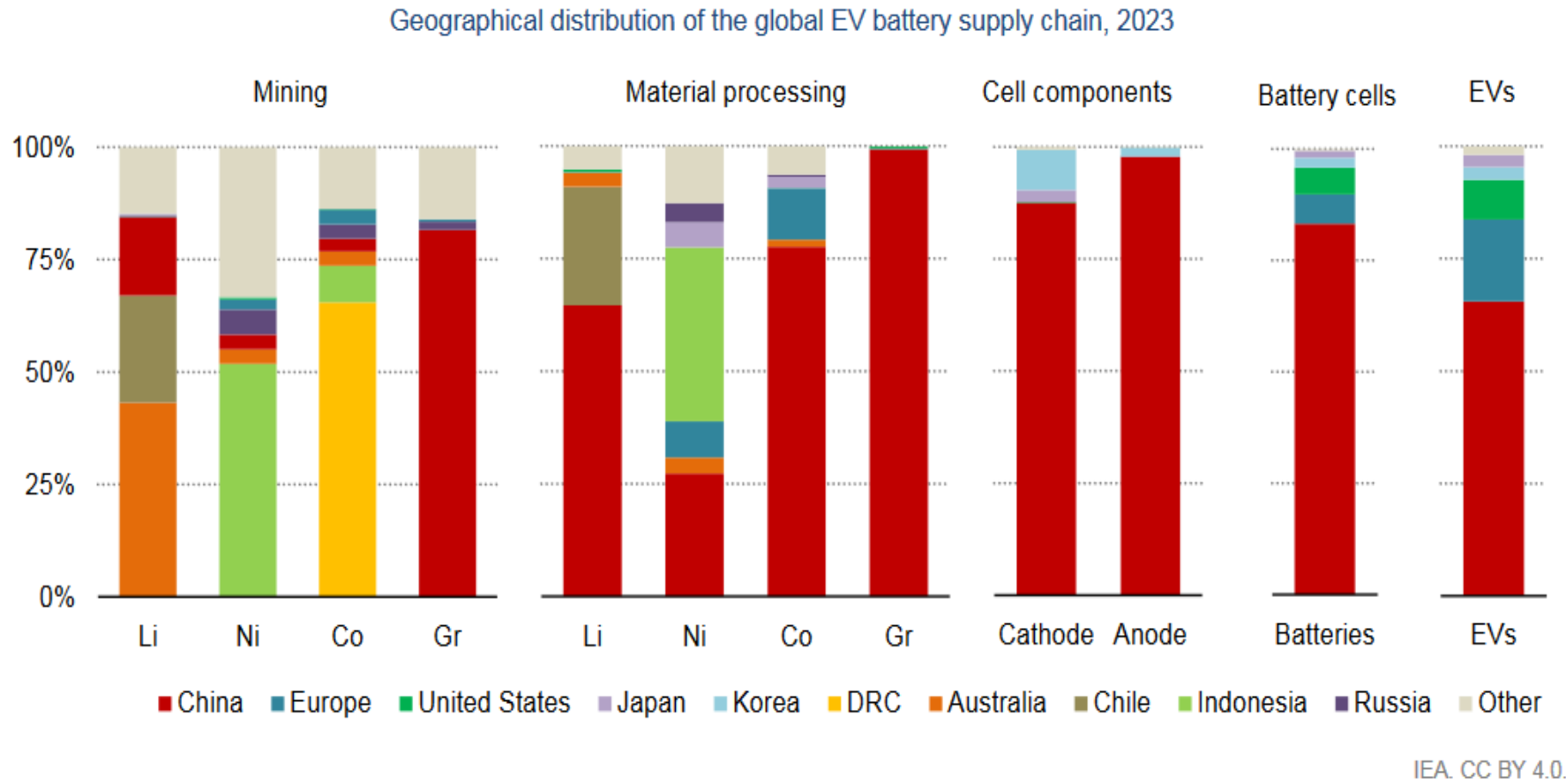
Source: USGS 2019

China N°1 for the World Production of Rare Earth Elements (REE)



Baya Obo Mine – Internal Mongolia

Global EV Battery supply chain
China dominates the downstream & midstream activity

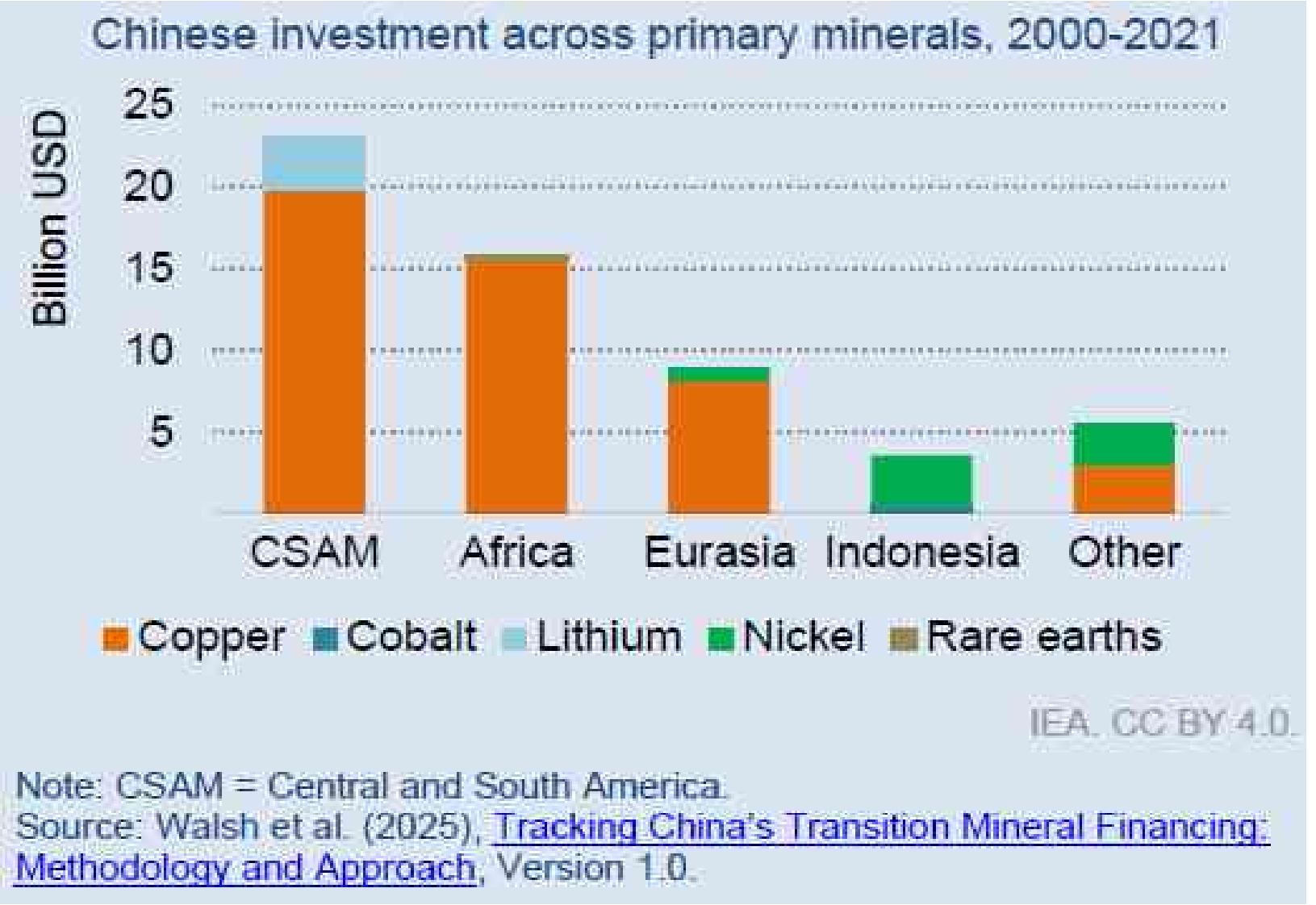


Notes: Li = lithium; Ni = nickel; Co = cobalt; Gr = graphite; DRC = Democratic Republic of the Congo. Geographical breakdown refers to the country where the production occurs. Mining is based on production data. Material processing is based on refining production data. Cell component production is based on cathode and anode material production capacity data. Battery cells are based on battery cell production capacity data. EVs is based on electric cars production data. For all minerals mining and refining shows total production not only that used in EVs. Graphite refining refers to spherical graphite production only.

Sources: IEA analysis based on EV Volumes; Benchmark Mineral Intelligence; BloombergNEF.

Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Chinese Investments in Critical Minerals 2000 - 2021



Source: IEA Global Critical Minerals Outlook 2025 – May 2025

The case of Aluminium (Bauxite)

Aluminium
From resource to consumer

Aluminium is the second most abundant element in the earth's crust after Silicon and the second most widely-used as metal after Iron.

Aluminium is used in many sectors of the world economy: construction, transport, packaging, machinery and equipment, electrical sector,…….

Bauxite ore is mined for aluminium production. The ore is rich in alumina (Al_2O_3) and iron oxyde which are refined into alumina. Alumina is then smelted into aluminium.

Recycling is a part of the production/consumption chain.

Bauxite – Reserves (29 Gt) and Production (440 Mt) in 2025

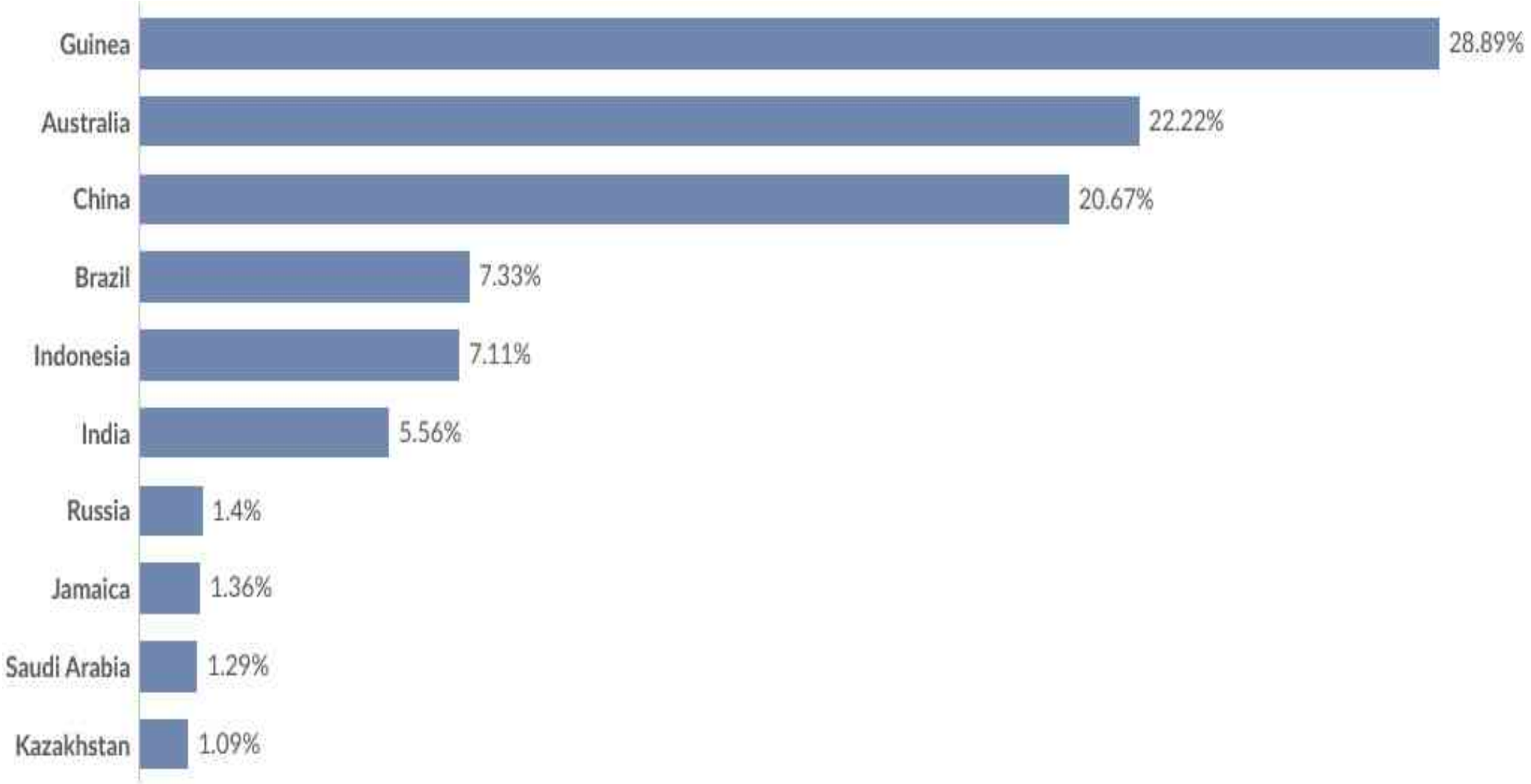
World Alumina Refinery and Bauxite Mine Production and Bauxite Reserves: Significant revisions were made to the 2024 production of alumina for Germany and of bauxite for Greece and Indonesia based on company and Government reports. Reserves for Australia, Brazil, China, Indonesia, Kazakhstan, and Russia were revised based on company and Government reports.

	Alumina production[5]		Bauxite production		Bauxite reserves[6]
	2024	2025[e]	2024	2025[e]	
United States	[e]700	710	W	W	20,000
Australia	17,100	17,000	100,000	97,000	[7]3,700,000
Brazil	[e]10,600	11,000	[e]33,000	33,000	1,700,000
Canada	1,460	1,500	—	—	—
China	85,500	93,000	[e]80,500	87,000	710,000
Germany	[e]450	460	—	—	—
Greece	865	850	[e]970	960	—
Guinea	351	360	142,000	150,000	7,400,000
India	[e]8,000	8,200	25,000	25,000	650,000
Indonesia	[e]1,200	1,500	[e]9,900	10,000	2,900,000
Ireland	1,720	1,700	—	—	—
Jamaica	1,480	1,500	5,890	6,200	2,000,000
Kazakhstan	[e]1,400	1,500	4,780	4,800	160,000
Russia	2,840	2,900	5,470	5,700	650,000
Saudi Arabia	1,870	1,900	[e]5,500	5,700	180,000
Spain	[e]800	810	—	—	—
Turkey	[e]300	310	3,660	3,800	69,000
United Arab Emirates	2,540	2,300	—	—	—
Vietnam	1,410	1,500	[e]3,710	3,800	3,100,000
Other countries	1,260	1,300	7,780	8,000	5,300,000
World total (rounded)	142,000	150,000	[8]428,000	[8]440,000	29,000,000

World Resources:[6] Bauxite resources are estimated to range from 55 billion to 75 billion tons, distributed in Africa (32%), Oceania (23%), South America and the Caribbean (21%), Asia (18%), and elsewhere (6%). Domestic resources of bauxite are inadequate to meet long-term U.S. demand, but the United States and most other major aluminum-producing countries have essentially inexhaustible subeconomic resources of aluminum in materials other than bauxite.

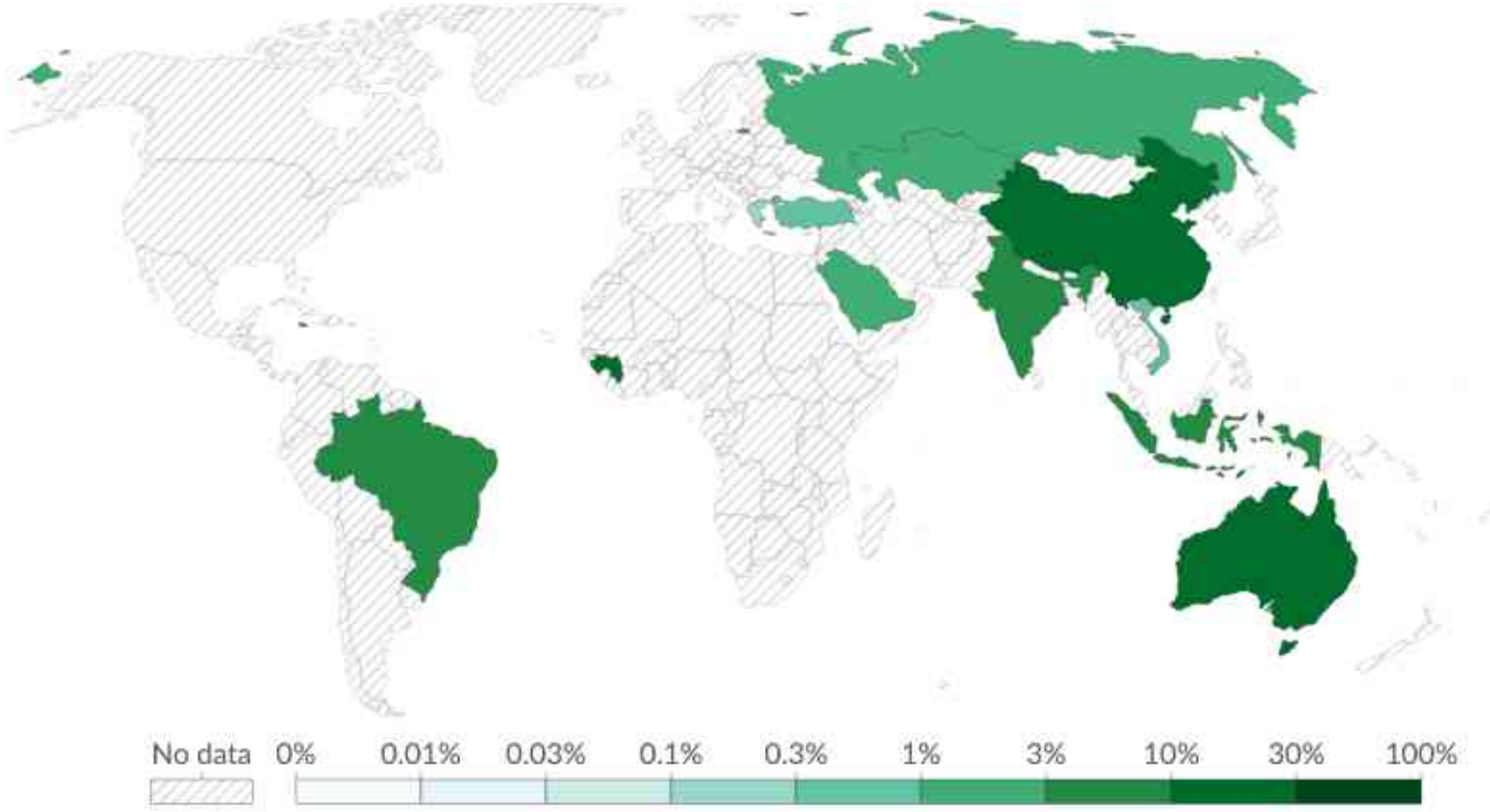
Source: USGS January 2026

Bauxite – Production (440 Mt) in 2025 – Shares of the total



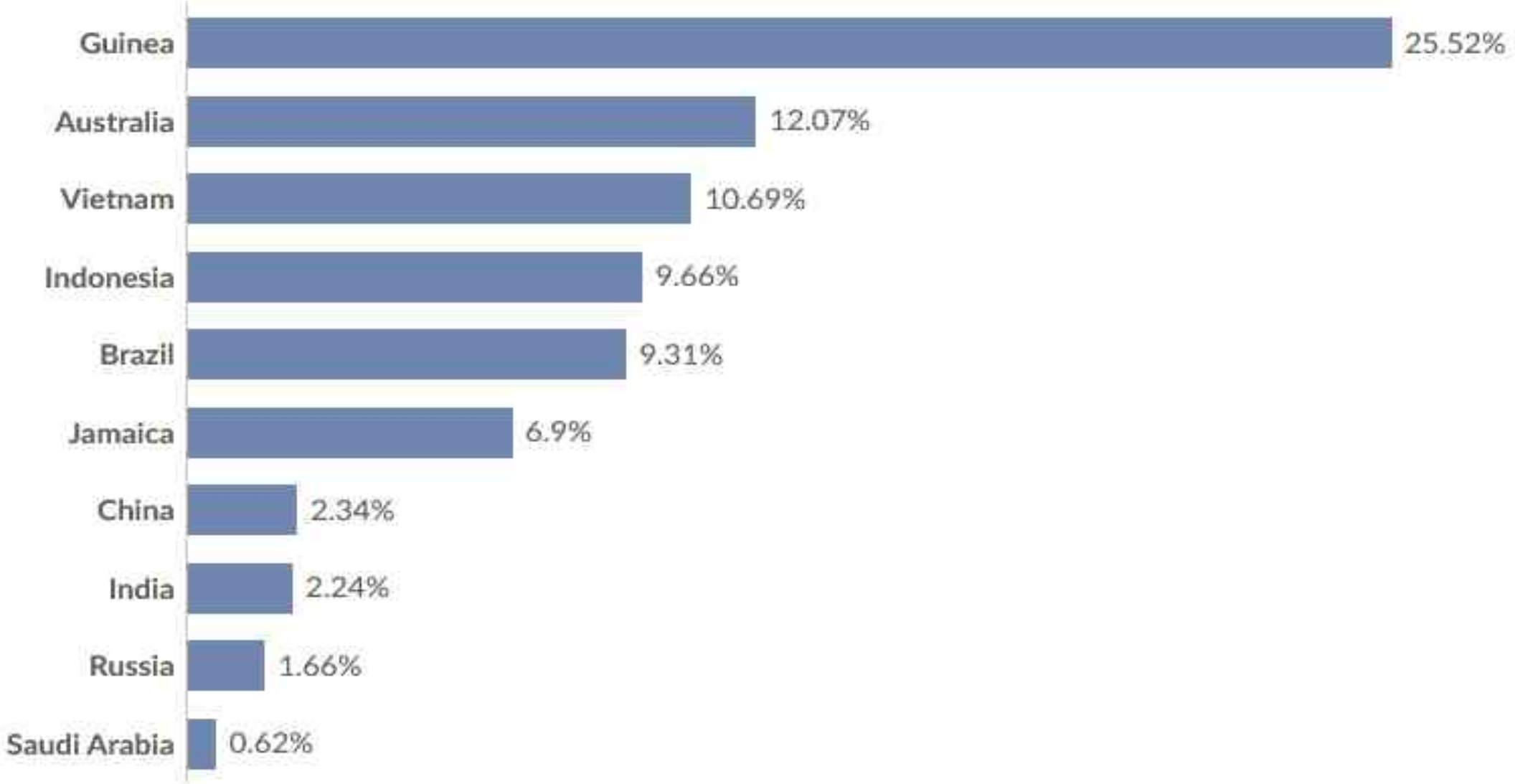
Source: IFP EN, USGS, Our World in Data 2025

Bauxite – Production (440 Mt) in 2025 – Shares of the total



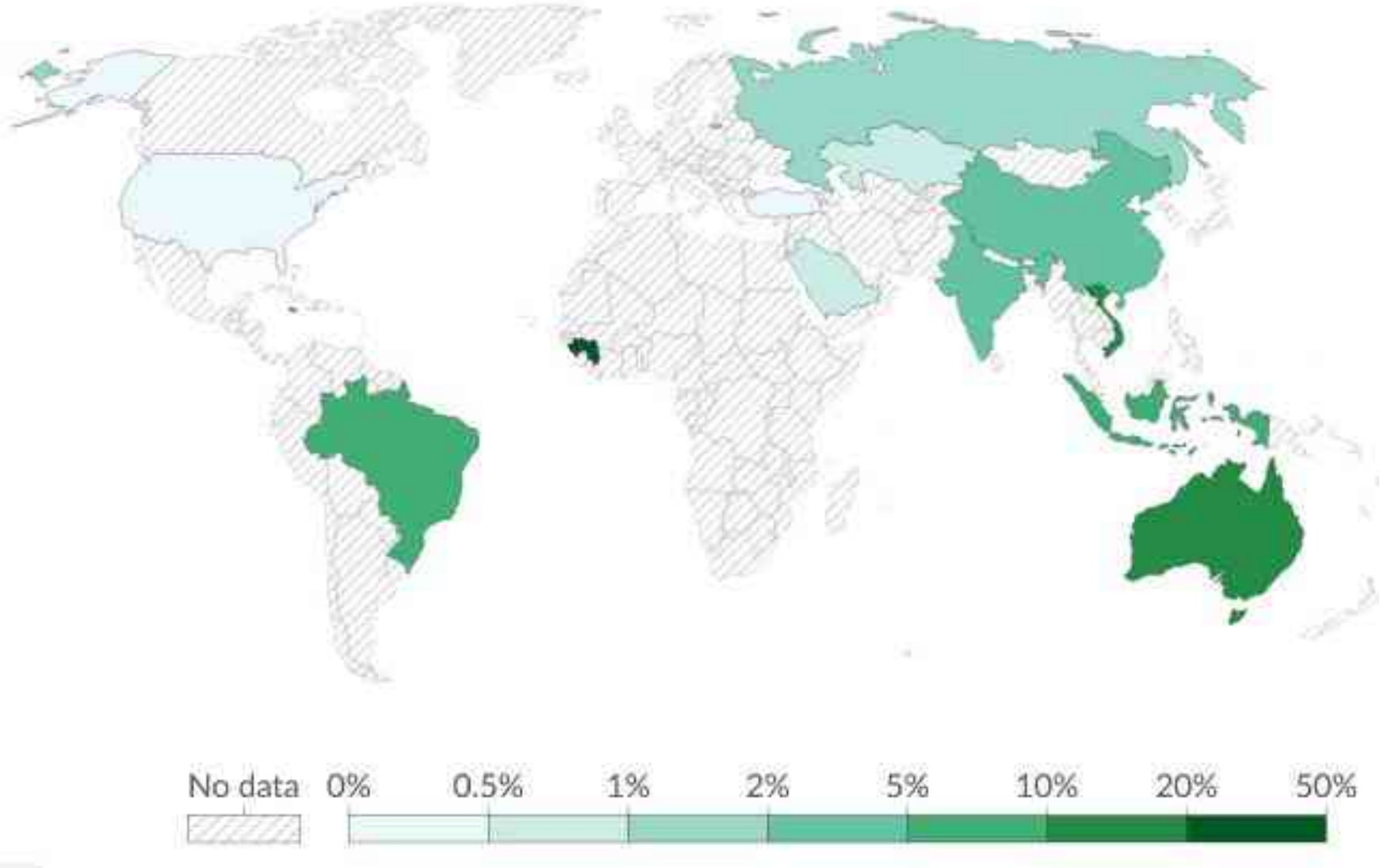
Source: IFP EN, USGS, Our World in Data 2025

Bauxite – Reserves (29 Gt) in 2025 – Shares of the total



Source: IFP EN, USGS, Our World in Data 2025

Bauxite – Reserves (29 Gt) in 2025 – Shares of the total



Source: IFP EN, USGS, Our World in Data 2025

The case of Copper

Copper
From resource to consumer

70% of Copper identified resources (excluding potential undiscovered resources) for electricity transport, transport sector, consumer goods, industrial and construction sectors (including the Energy Transition sector) might have been consumed by 2050.

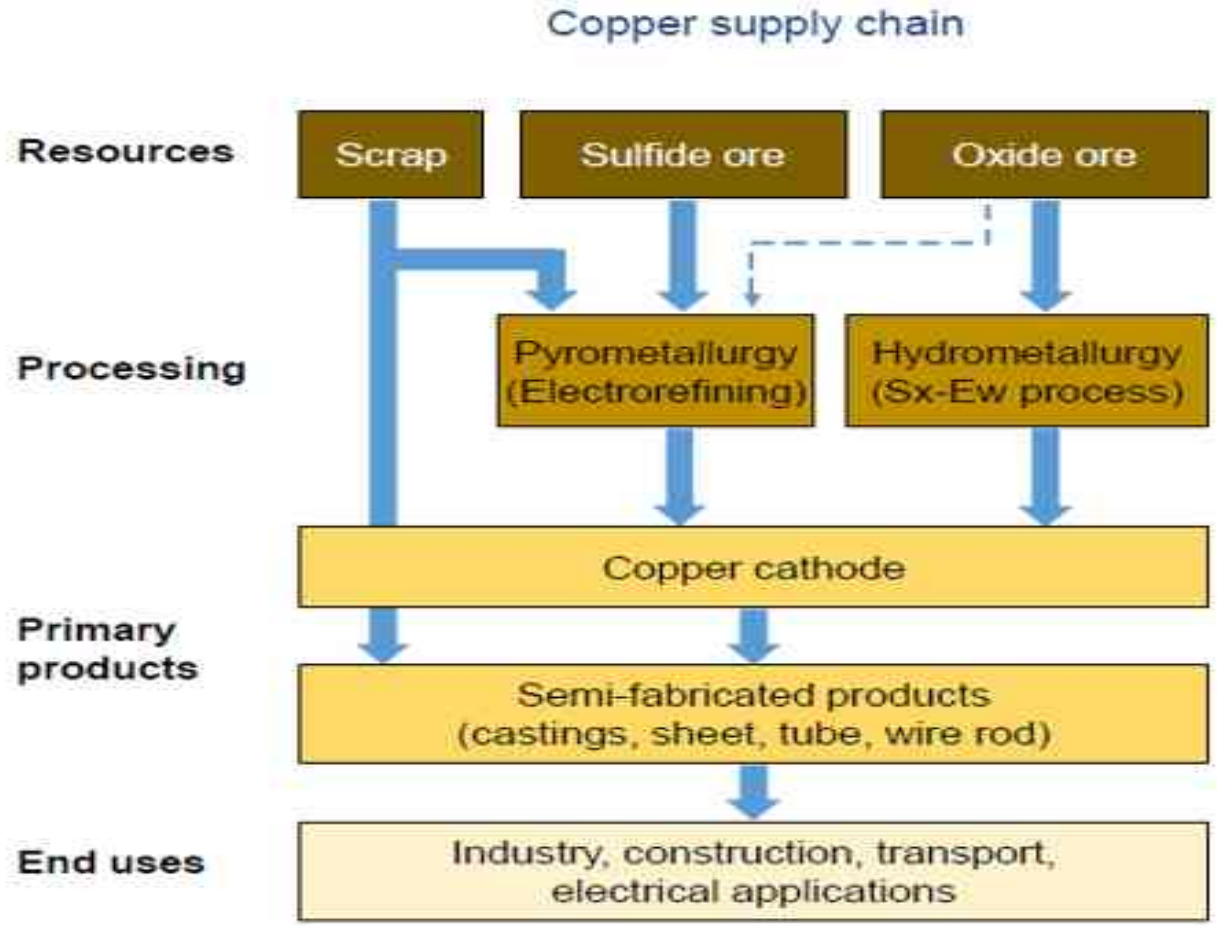
Great importance of recycling.

Needs for Copper to manufacture:
An internal combustion engine: 20kg
A hybrid vehicle: 40 kg
An electric vehicle: 80 kg

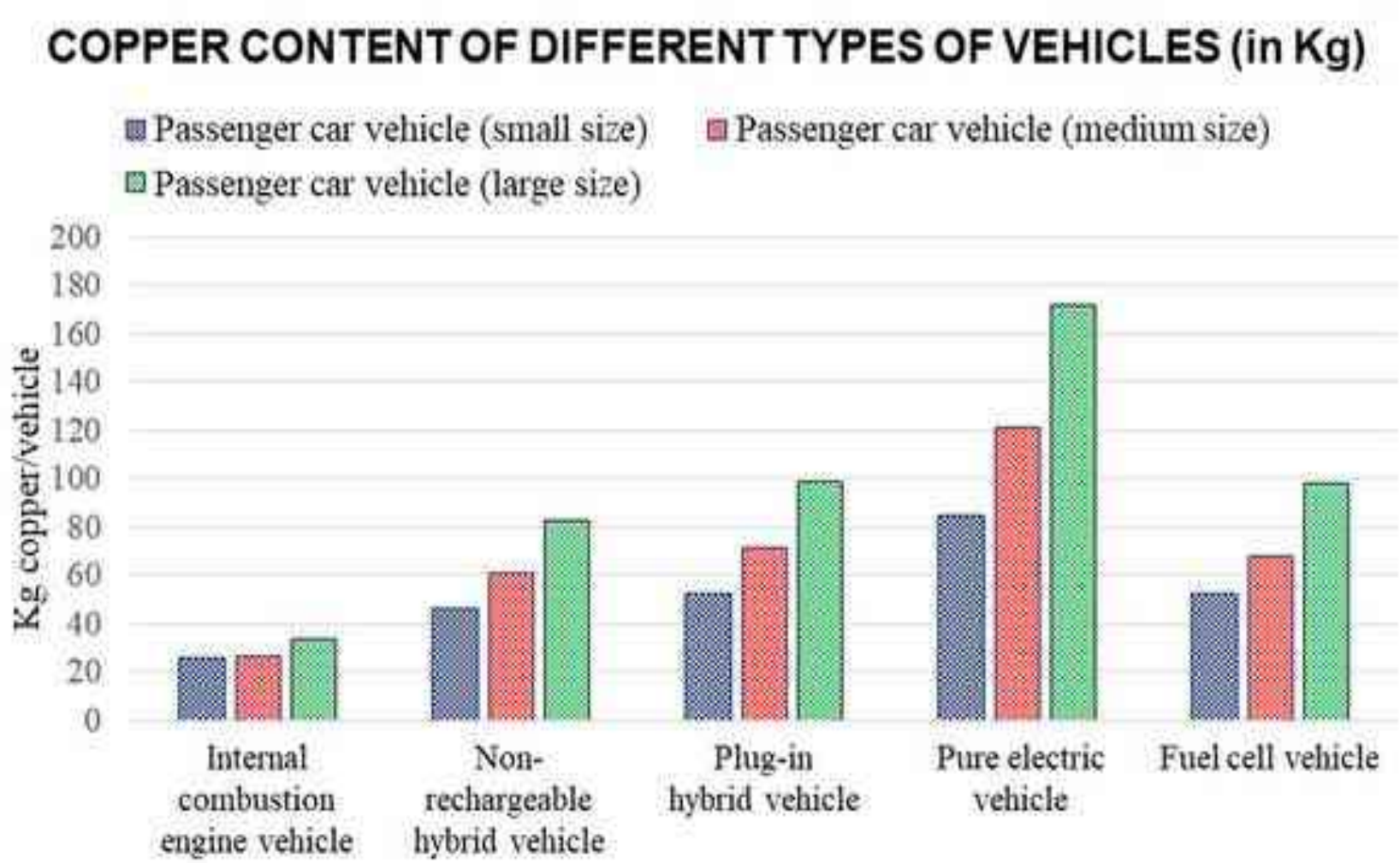
Cooper needs for Energy Transition will be more important than those related to traditional energies.

China controls 40% of the refining activity.

Copper
From resource to consumer

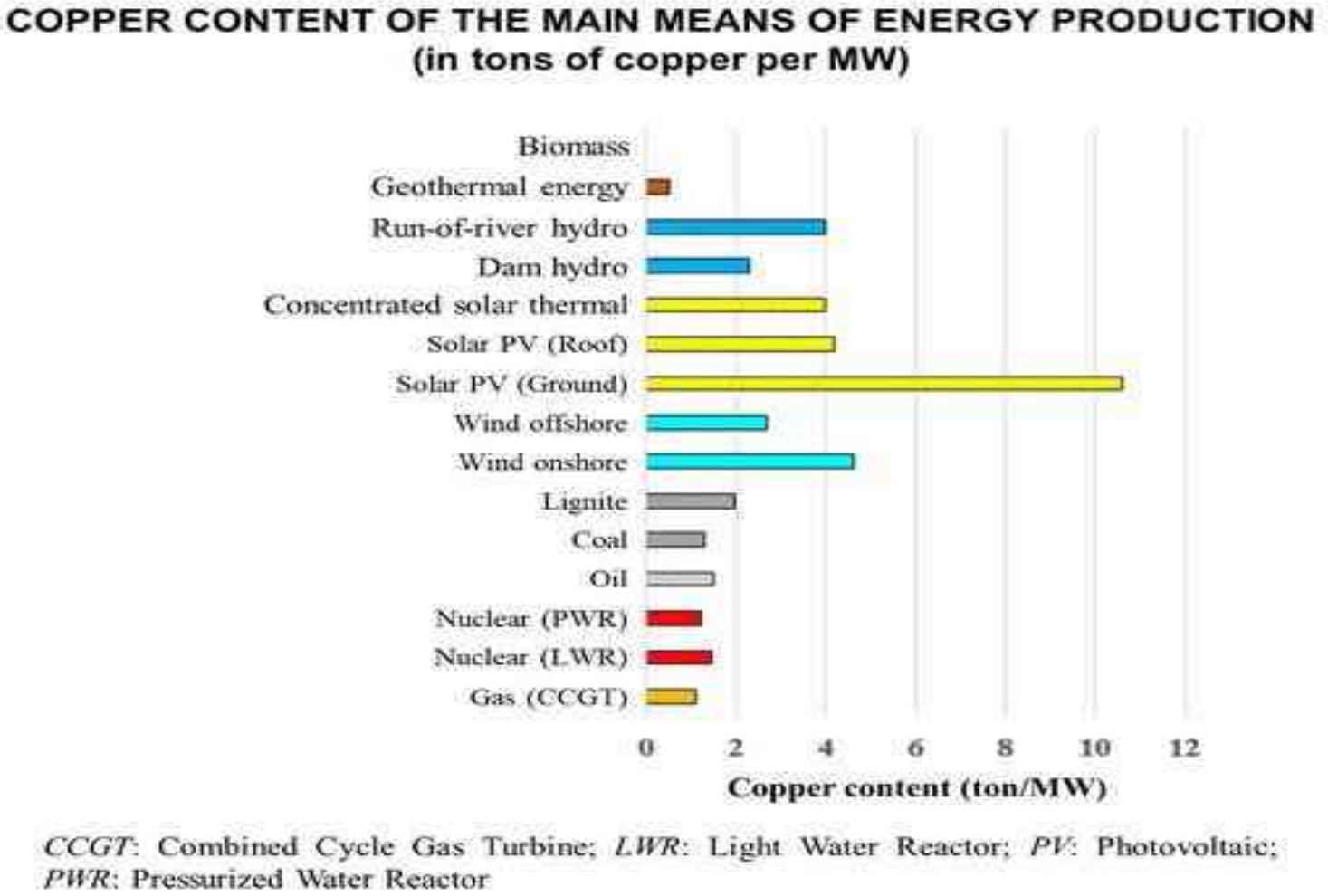


Copper
From resource to consumer



Source: IFP EN, USGS

Copper
From resource to consumer



Source: IFP EN, Ecoinvent

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

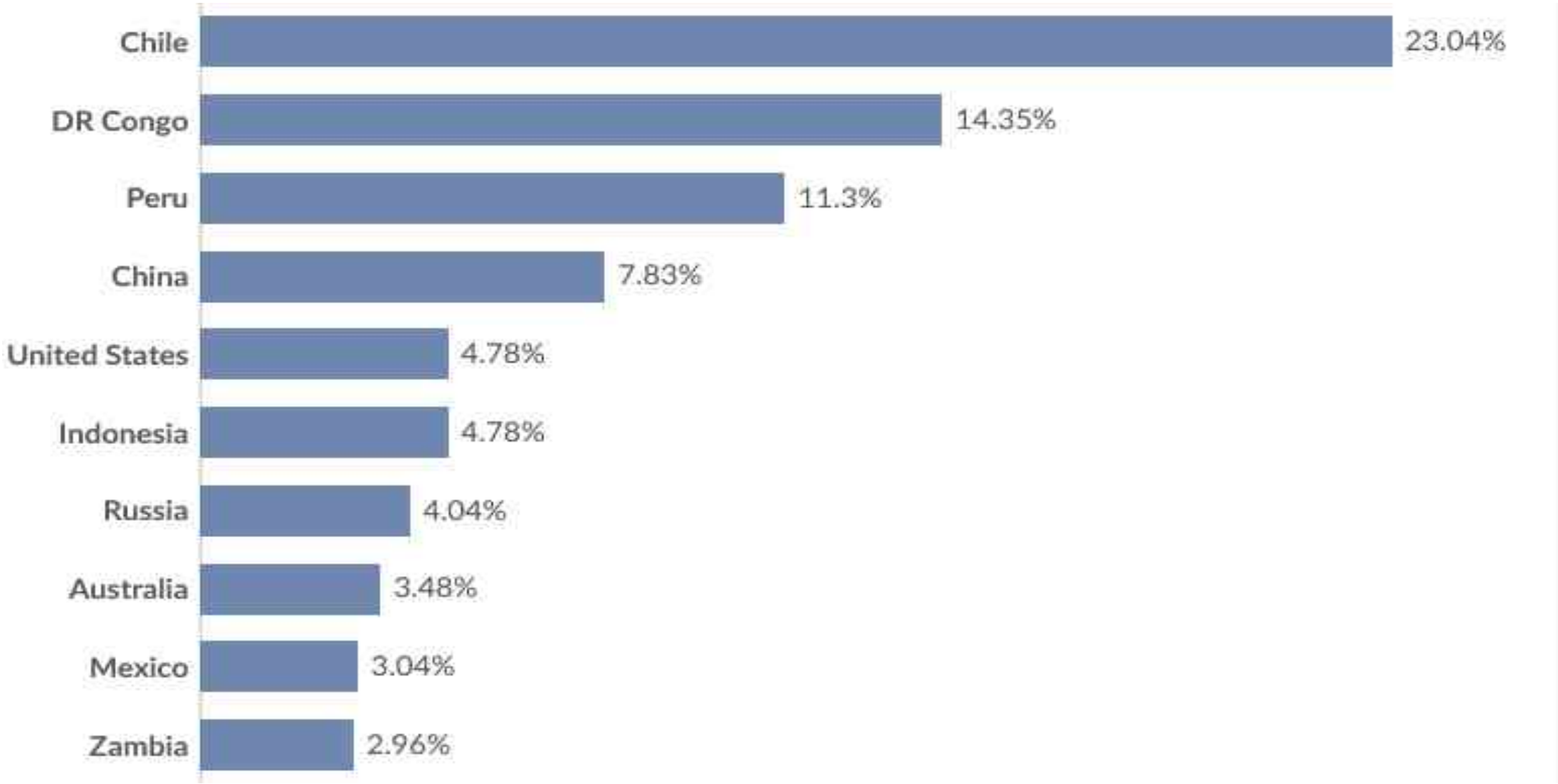
World Mine and Refinery Production and Reserves: Reserves for Canada, Chile, Peru, Poland, and "Other countries" were revised based on company, Government, and industry association reports.

	Mine production		Refinery production		Reserves[6]
	2024	2025[e]	2024	2025[e]	
United States	1,050	1,000	921	850	47,000
Australia	765	730	434	460	[7]100,000
Canada	515	500	324	320	7,000
Chile	5,510	5,300	1,940	1,700	180,000
China	1,840	1,800	12,400	14,000	41,000
Congo (Kinshasa)	2,990	3,200	2,560	2,800	80,000
Germany	—	—	597	610	—
India	27	23	545	620	2,200
Indonesia	1,010	710	349	400	21,000
Japan	—	—	1,570	1,400	—
Kazakhstan	724	710	498	500	20,000
Korea, Republic of	—	—	604	610	—
Mexico	717	690	489	480	53,000
Peru	2,740	2,700	385	340	85,000
Poland	400	410	589	560	33,000
Russia	1,020	1,300	896	950	80,000
Zambia	823	940	189	270	21,000
Other countries	2,850	3,000	2,310	2,100	210,000
World total (rounded)	23,000	23,000	27,600	29,000	980,000

World Resources:[6] The most recent USGS assessment of global copper resources indicated that, as of 2015, identified resources contained 1.5 billion tons of unextracted copper (2.1 billion tons when past production of 600 million tons is included) and undiscovered resources contained an estimated 3.5 billion tons of copper.[8]

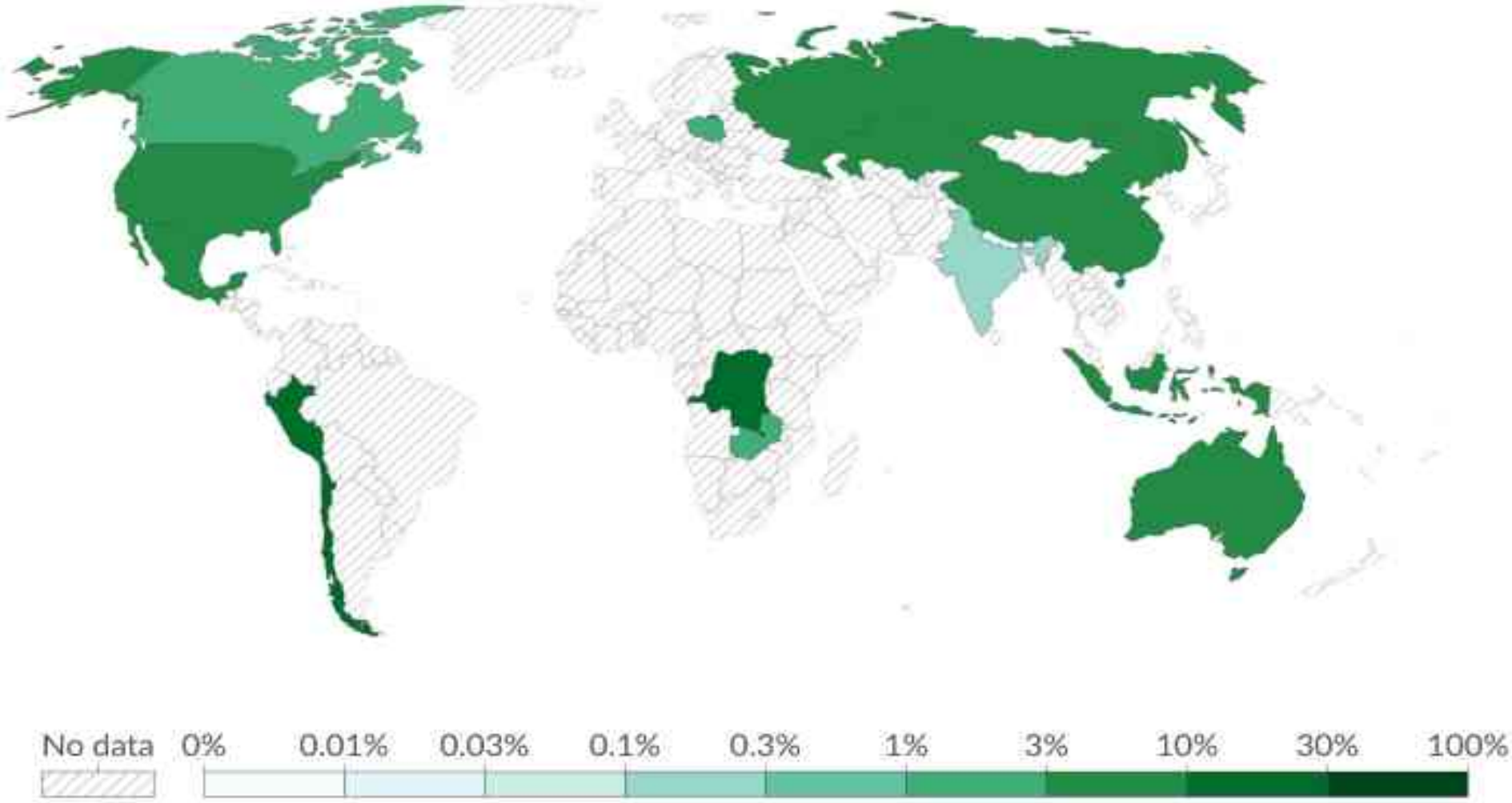
Source: USGS January 2026

Copper – Production (23 Mt) in 2025 – Shares



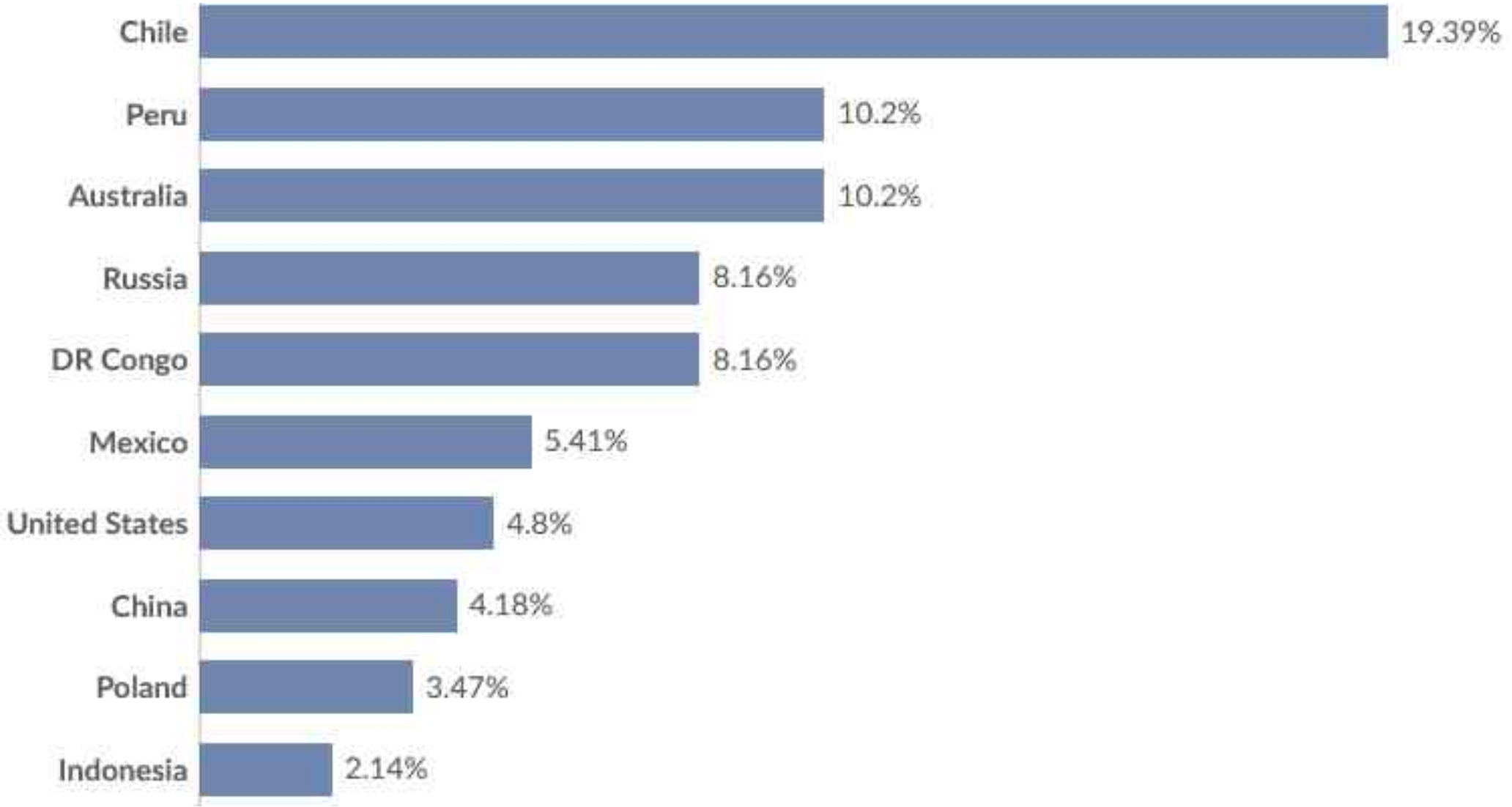
Source: Our World in Data 2025

Copper – Production (23 Mt) in 2025 – Shares



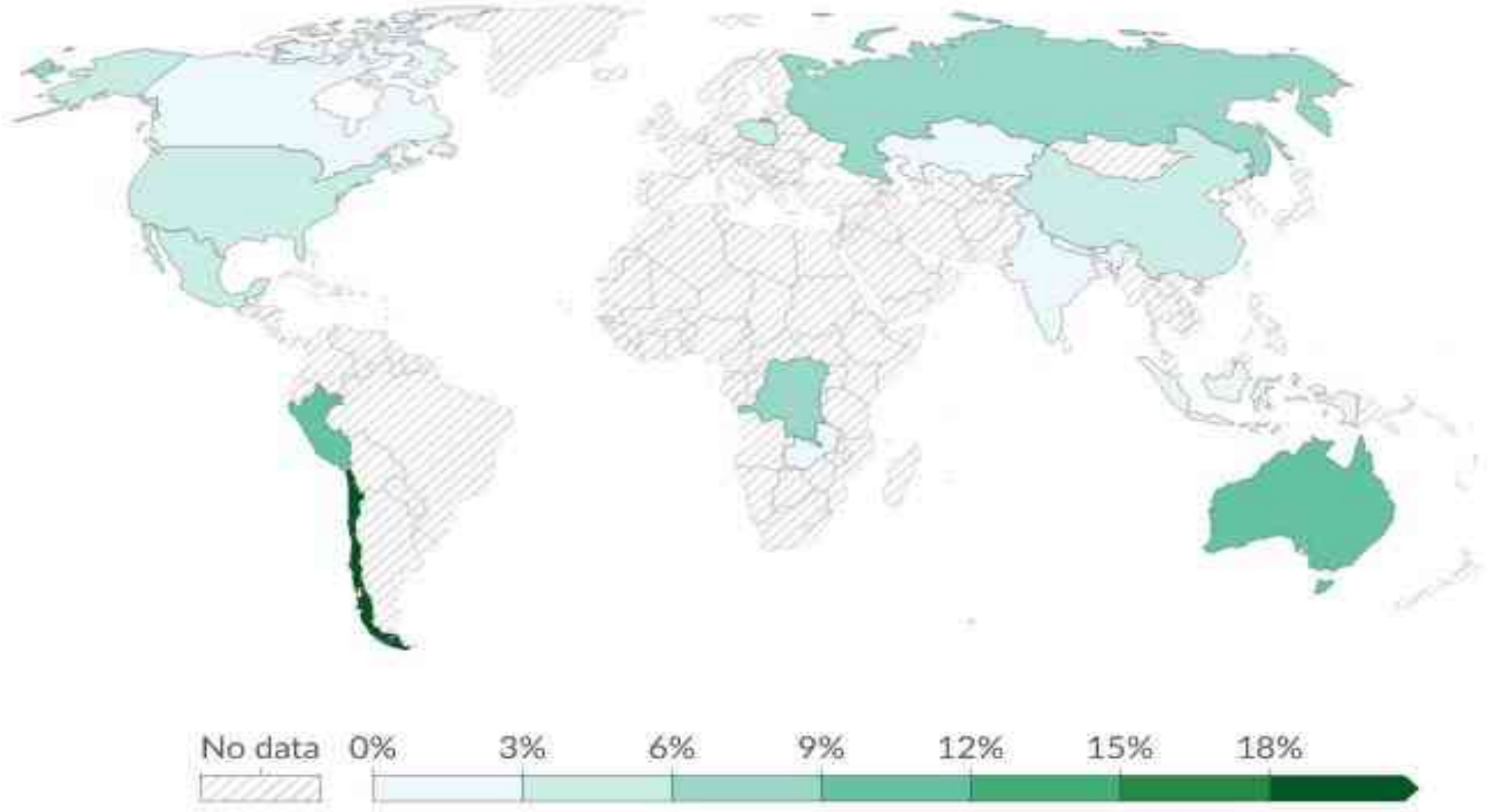
Source: Our World in Data 2025

Copper – Reserves (980 Mt) in 2025 – Shares



Source: Our World in Data 2025

Copper – Reserves (980 Mt) in 2025 – Shares



Source: Our World in Data 2025

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

Copper

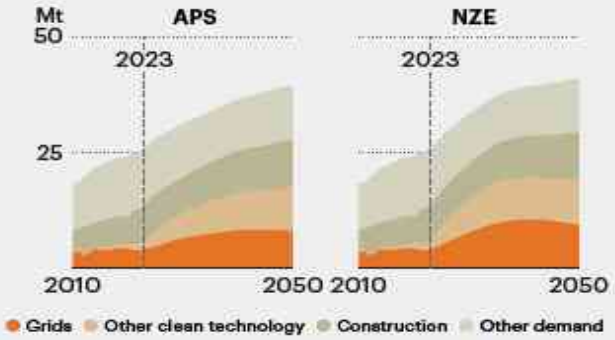
Cu

Top three producers 2030

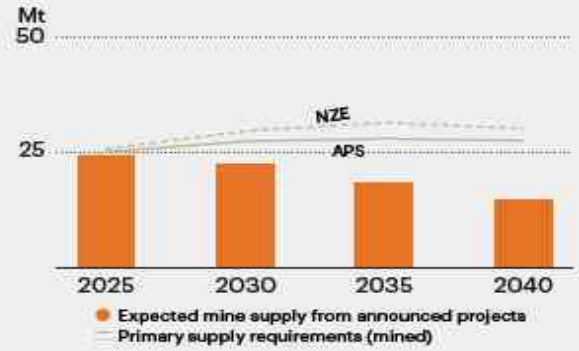




Demand outlook



Mining requirements



Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	5 380	6 311	12 001	16 343
Other uses (kt)	19 548	19 543	19 127	20 036
Total demand (kt)	24 928	25 855	31 128	36 379
Secondary supply and reuse (kt)	4 123	4 445	5 879	11 006
Primary supply requirements (kt)	20 805	21 409	25 249	25 373
Share of top three mining countries	46%	47%	48%	54%
Share of top three refining countries	57%	59%	59%	59%

Clean energy transition risk assessment

Low Mod High

Supply risks

31%

shortfall in project pipeline vs. 2035 APS mining requirements

Geopolitical risks

Relatively diversified supply sources

Barriers to responding to supply disruption

Mature markets with sizeable volumes of secondary supply

ESG and climate risk exposure

52%

of mines located in high water stress areas

Source: IEA Global Critical Minerals Outlook 2024 - May 2024

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

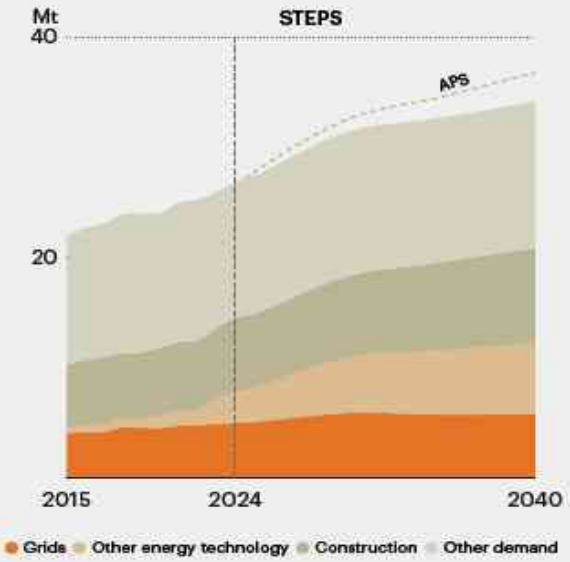
Copper

Cu

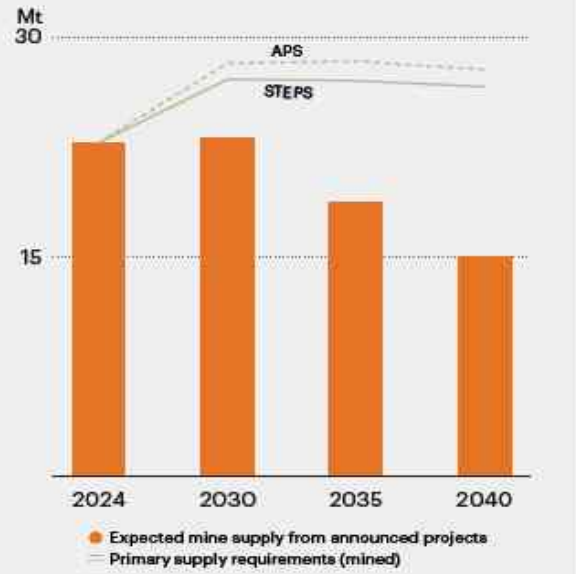
Top three producers 2030



Demand outlook



Mining requirements

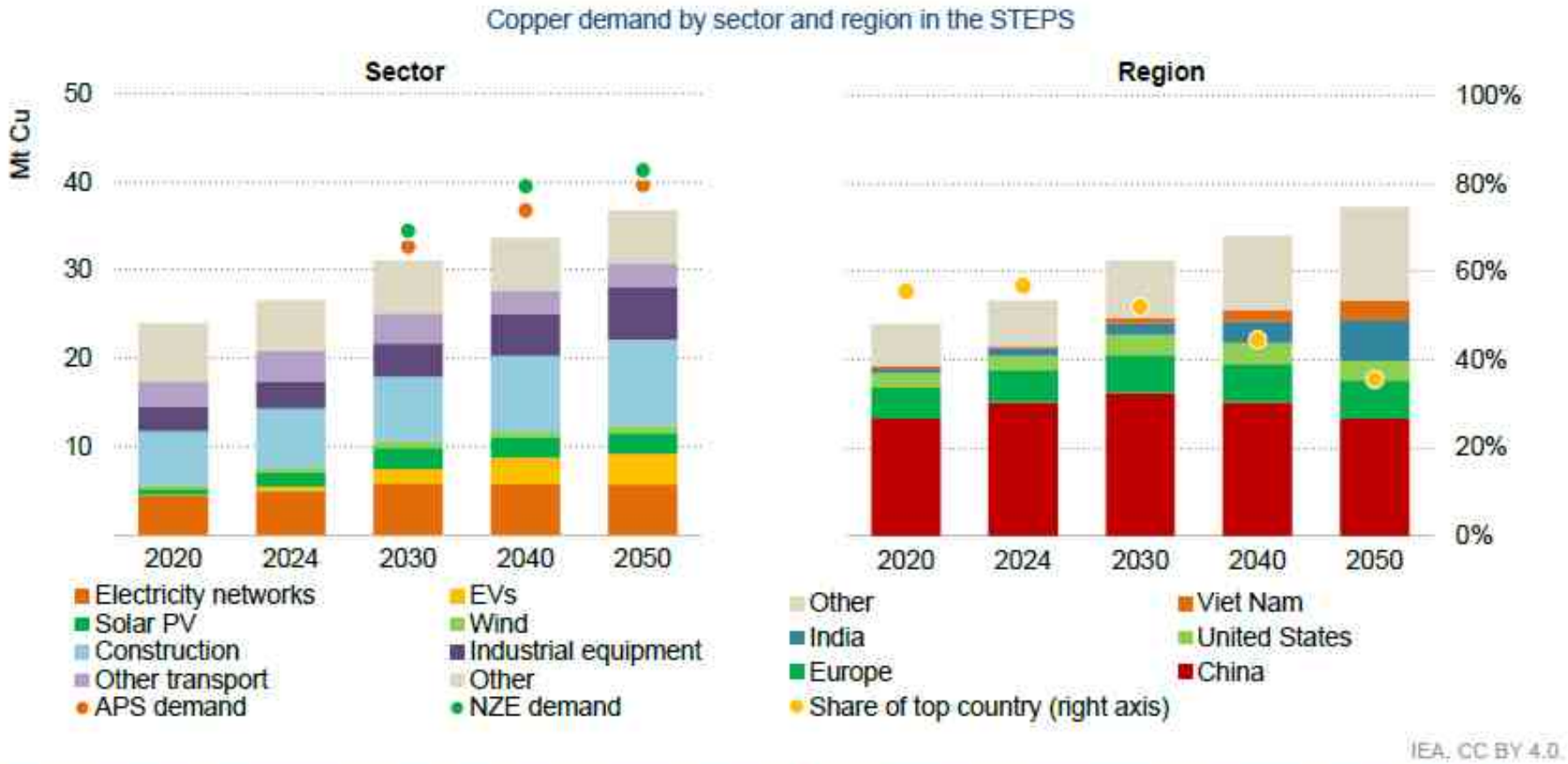


STEPS	2021	2024	2030	2040
Cleantech demand (kt)	**6 002**	**7 737**	**10 910**	**12 162**
Other uses (kt)	18 944	18 980	20 438	21 975
Total demand (kt)	**24 946**	**26 717**	**31 348**	**34 137**
Secondary supply and reuse (kt)	4 123	4 441	5 431	8 702
Primary supply requirements (kt)	**20 851**	**22 503**	**25 917**	**25 428**
Share of top three mining countries	46%	48%	50%	53%
Share of top three refining countries	57%	59%	60%	60%

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

Demand: Construction, grids, industrials and EVs drive growth in copper demand with China the leading demand driver, though new major demand centres emerge in India and Viet Nam

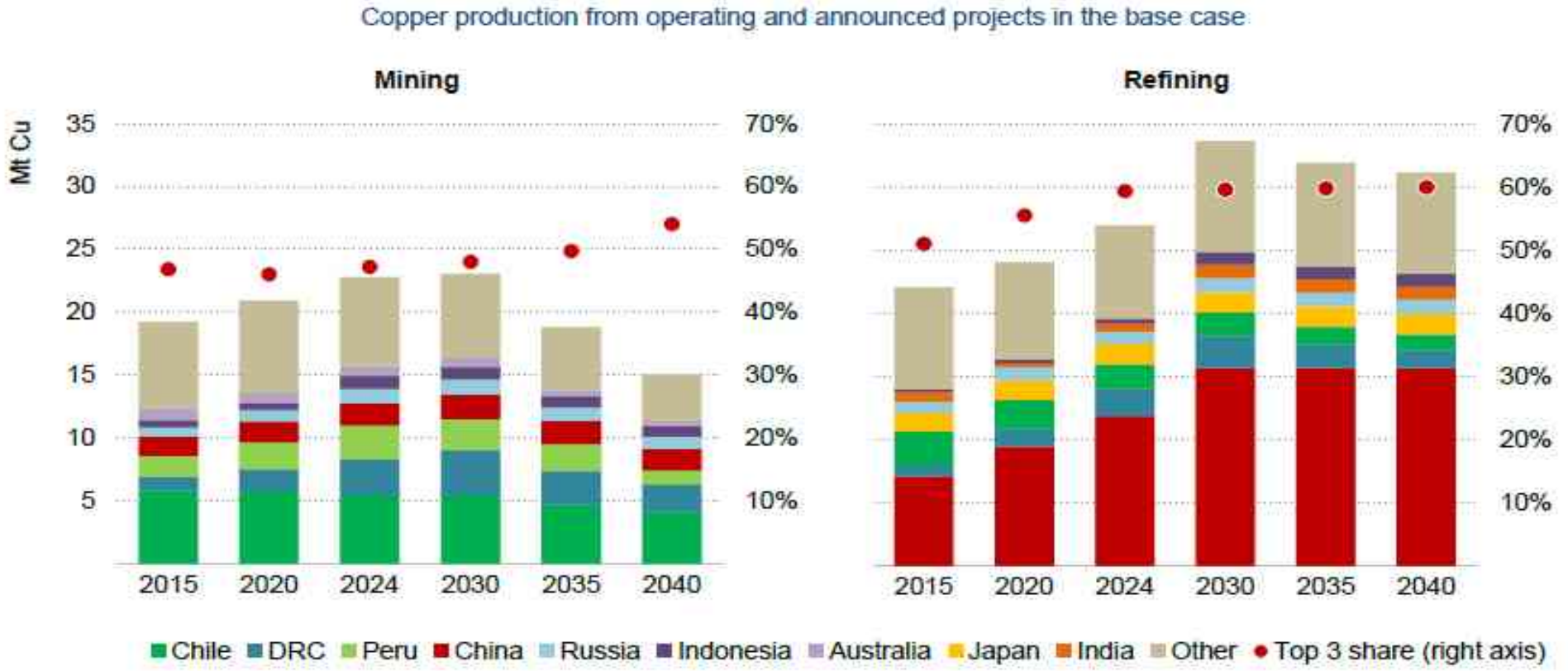


Notes: Copper refined demand excluding direct-use scrap. EVs demand includes both EV batteries and EV motors demand. Other demand includes consumer products, cooling, communications and other electronics.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

Supply: The DRC cements itself as the second-largest copper mining producer after Chile, while China maintains its dominance in copper refining



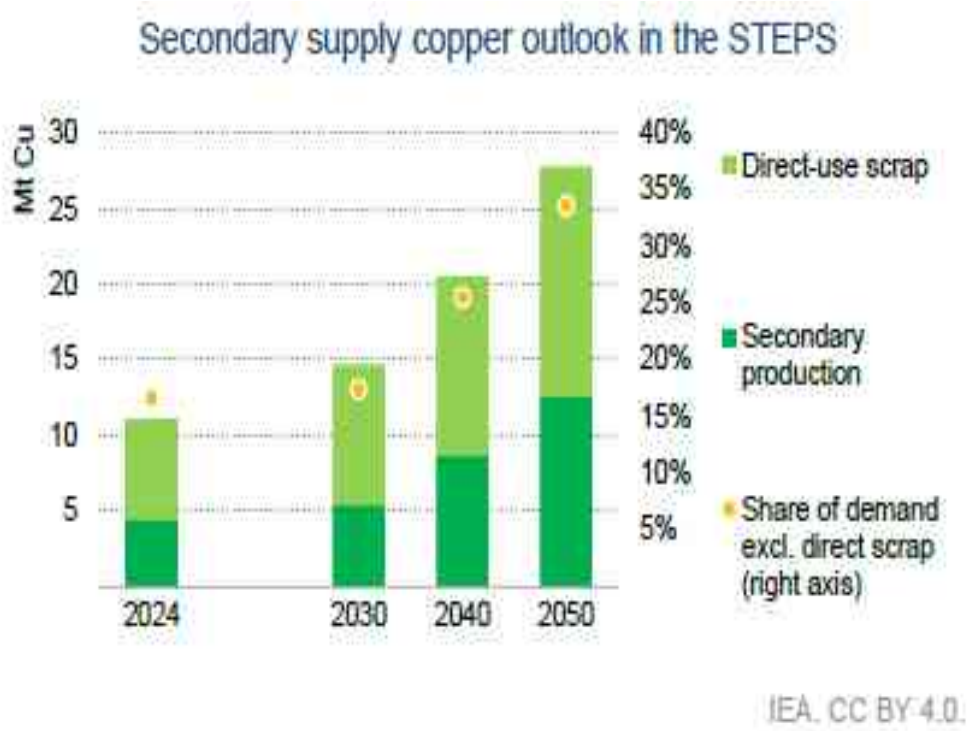
Notes: DRC = Democratic Republic of the Congo. Refined supplies are independently assessed based on announced refining projects and are not constrained by mined supply. Refining also includes both primary and secondary refining.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

Secondary supply: Copper recycling and direct use of scrap is set to increase substantially from 2030 providing a major source of supply in the future

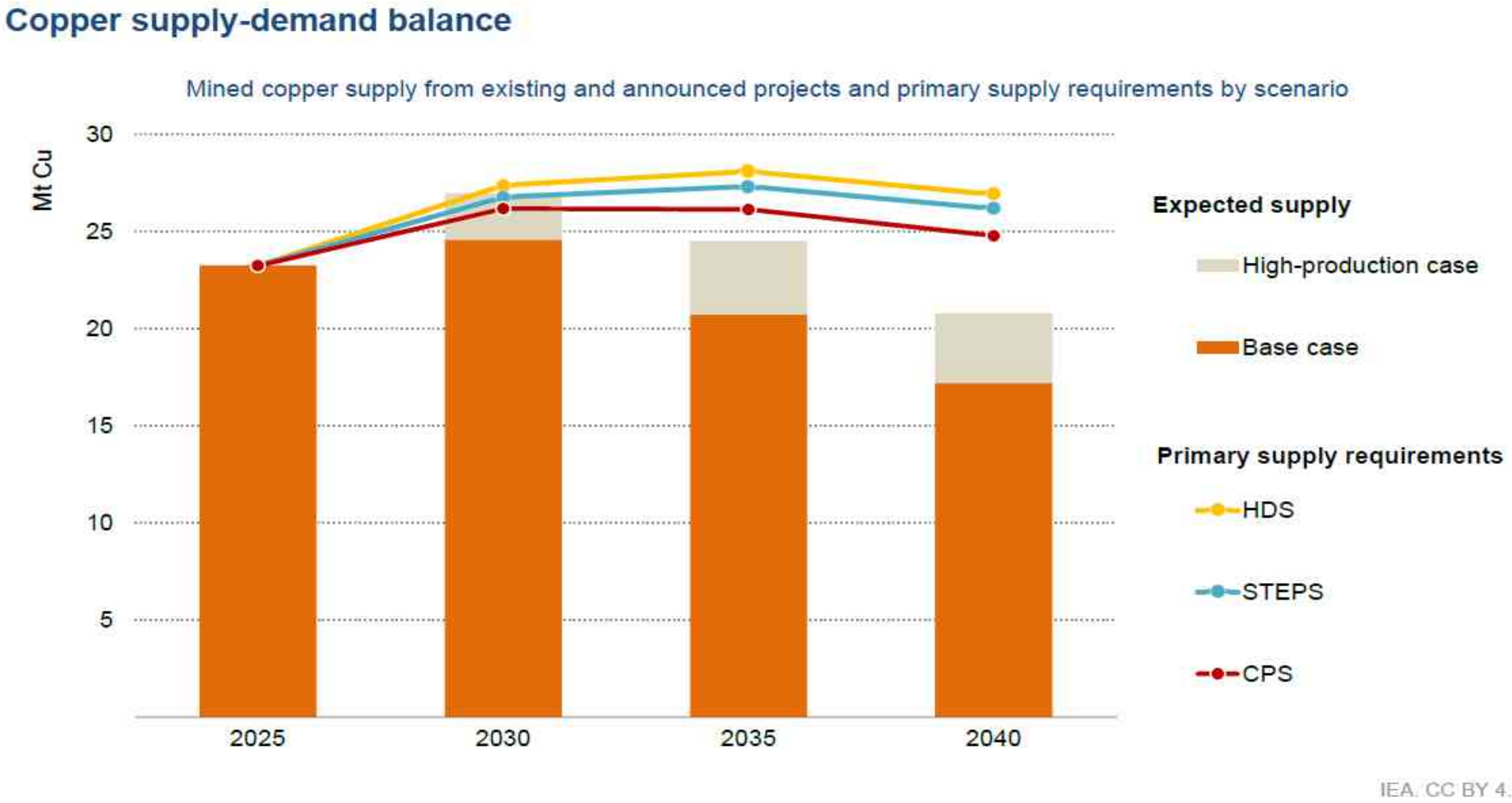




Note: Secondary supply copper volumes are recovered from recycling from secondary production and direct-use scrap, accounting for collection and recycling process yield losses.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025



Notes: HDS = High Demand Scenario; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario. Based on mined output. Primary supply requirements are calculated as the "total demand net of secondary supply", also accounting for losses during refining operations. See Introduction section for definitions of the base and high-production cases.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

Copper demand

	Historical		Current Policies			Stated Policies			High Demand		
Unit: kt Cu	2021	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	5 654	8 003	10 232	11 822	12 174	10 725	13 073	13 559	12 302	15 668	16 572
Electricity networks	4 189	4 544	5 637	6 693	6 430	5 713	6 631	6 316	6 002	7 181	6 815
Electric vehicles	264	794	1 623	2 359	2 391	1 763	3 046	3 476	2 017	4 143	4 750
Solar PV	707	1 970	2 044	1 755	2 099	2 222	2 219	2 300	2 803	2 626	2 758
Other	493	695	927	1 015	1 253	1 066	1 177	1 466	1 480	1 719	2 249
Other uses	19 296	19 772	20 560	21 757	23 714	20 605	21 911	24 014	19 665	20 051	21 495
Total demand	24 950	27 775	30 792	33 580	35 888	31 370	34 984	37 572	31 967	35 719	38 066
Share of clean energy	23%	29%	33%	35%	34%	34%	37%	36%	38%	44%	44%

Notes: kt = kilotonnes. Demand is based on refined copper and excludes the direct use of scrap. Demand for electric vehicles includes both electric vehicle battery and electric vehicle motor demand.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

Copper – Reserves (980 Mt) and Production (23 Mt) in 2025

Copper supply

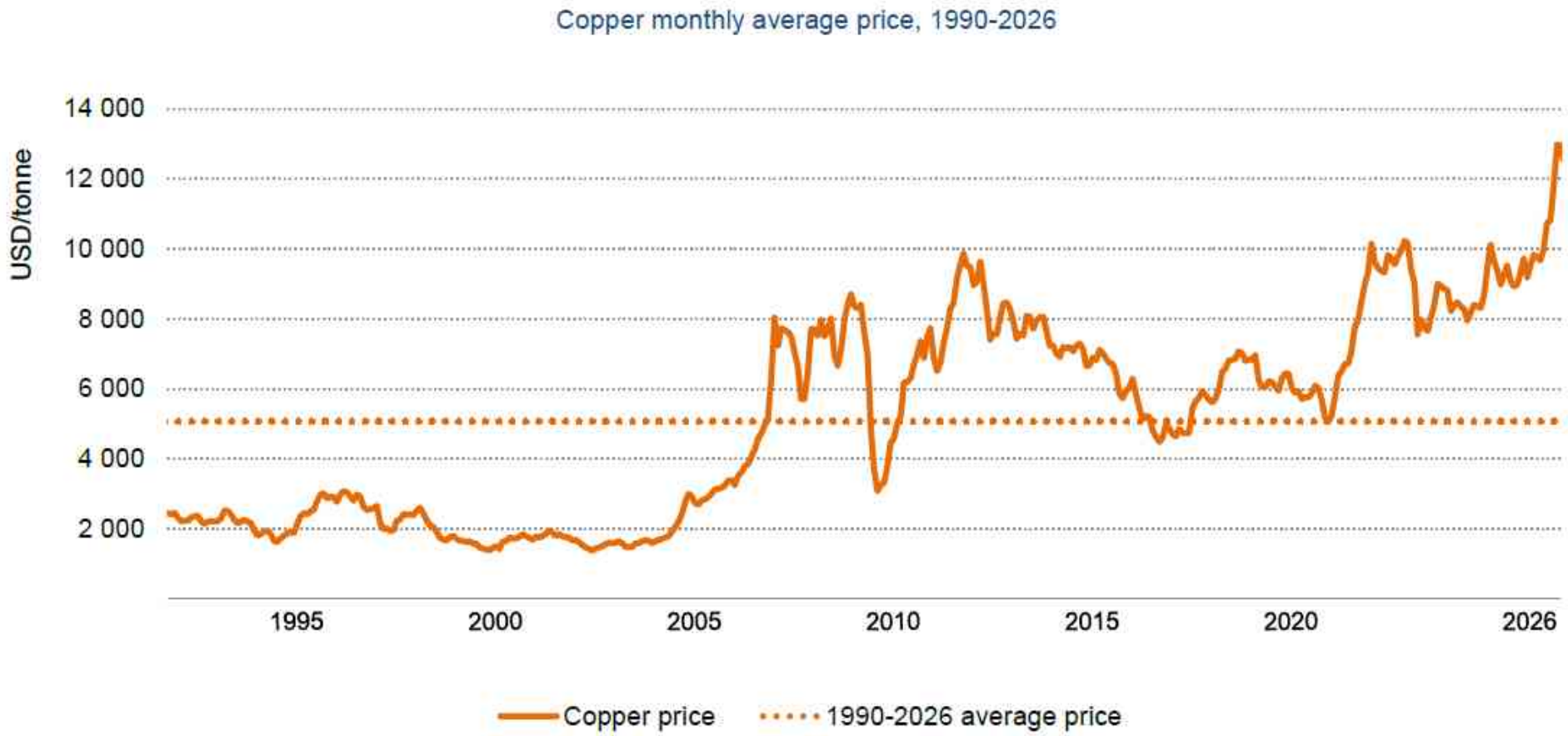
	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt Cu	2021	2025	2030	2040		2021	2025	2030	2040
Chile	5 672	5 485	5 369	4 165	China	10 378	13 069	17 121	17 221
DRC	2 019	3 338	4 212	2 696	DRC	2 019	3 338	4 212	2 696
Peru	2 284	2 726	2 712	1 859	Chile	2 282	1 741	1 846	1 359
China	1 823	1 838	2 040	1 852	Japan	1 514	1 431	1 624	1 624
Russia	867	1 145	1 244	1 343	Russia	954	990	1 110	1 105
United States	1 262	1 101	1 196	632	India	490	646	1 500	1 500
Rest of world	7 530	7 594	7 798	4 636	Rest of world	7 328	6 740	8 970	8 205
World	21 457	23 227	24 571	17 183	World	24 965	27 955	36 383	33 710
Top 3 share	46%	50%	50%	51%	Top 3 share	57%	62%	61%	62%

Notes: kt = kilotonnes. DRC = Democratic Republic of the Congo.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

Erratic fluctuation of Copper Price

Copper prices hit record highs in 2026 as structural and short-term pressures converge



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Notes: The copper price is the LME Copper Grade A Cash price. Prices are nominal.
Source: IEA analysis based on data from S&P Capital IQ.

The case of Lithium

Lithium
From Resource to Consumer

Low geological criticality.

Estimated resources # 115 Mt

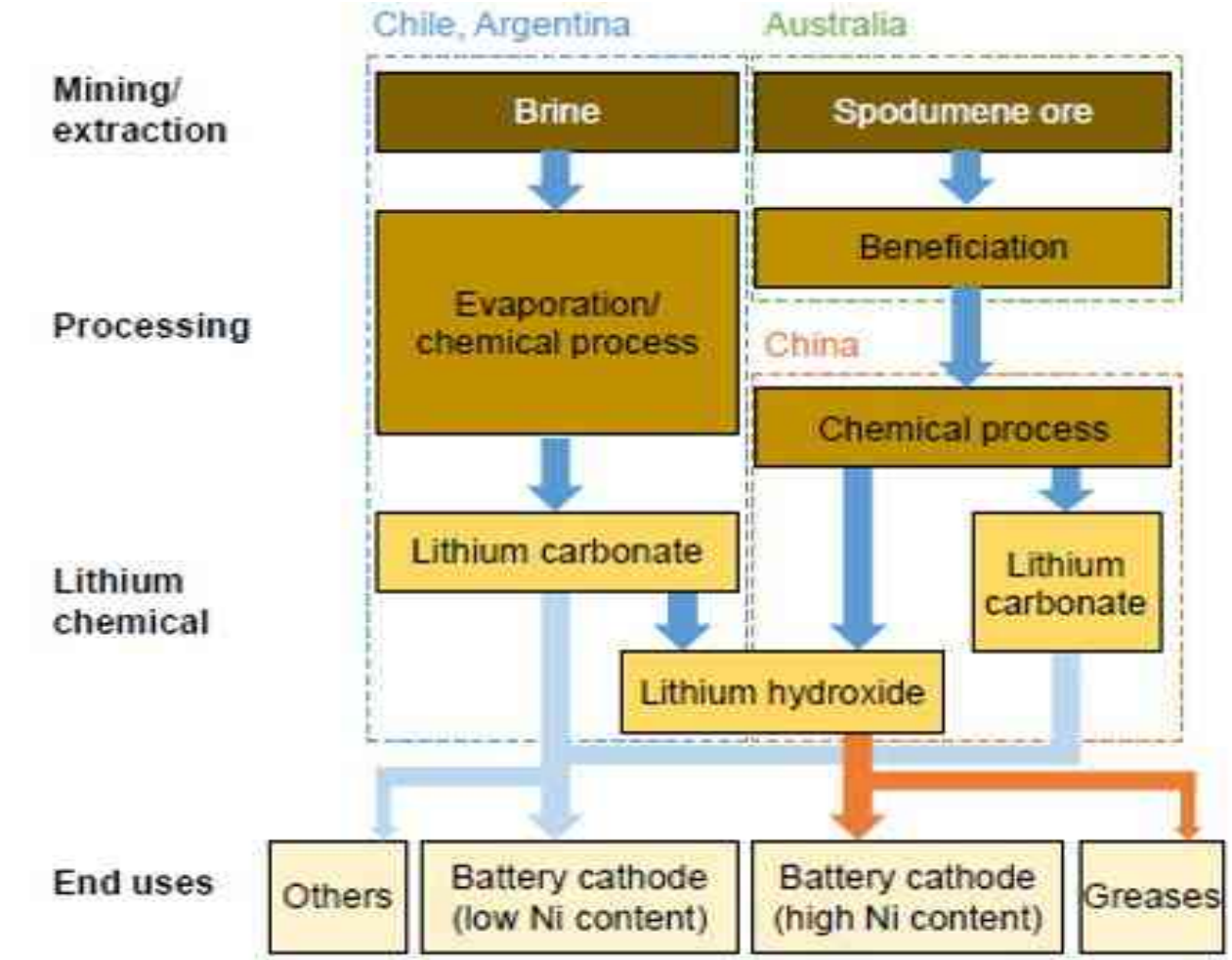
Extraction generates environmental impacts.

Cumulative needs for industry/Known resources # 20% in 2050 to cope with the SDS IEA Scenario.

5 players control 90% of the Lithium market (Chile, Australia, Argentina, China)

Lithium
From Resource to Consumer

Lithium Supply chain



Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries

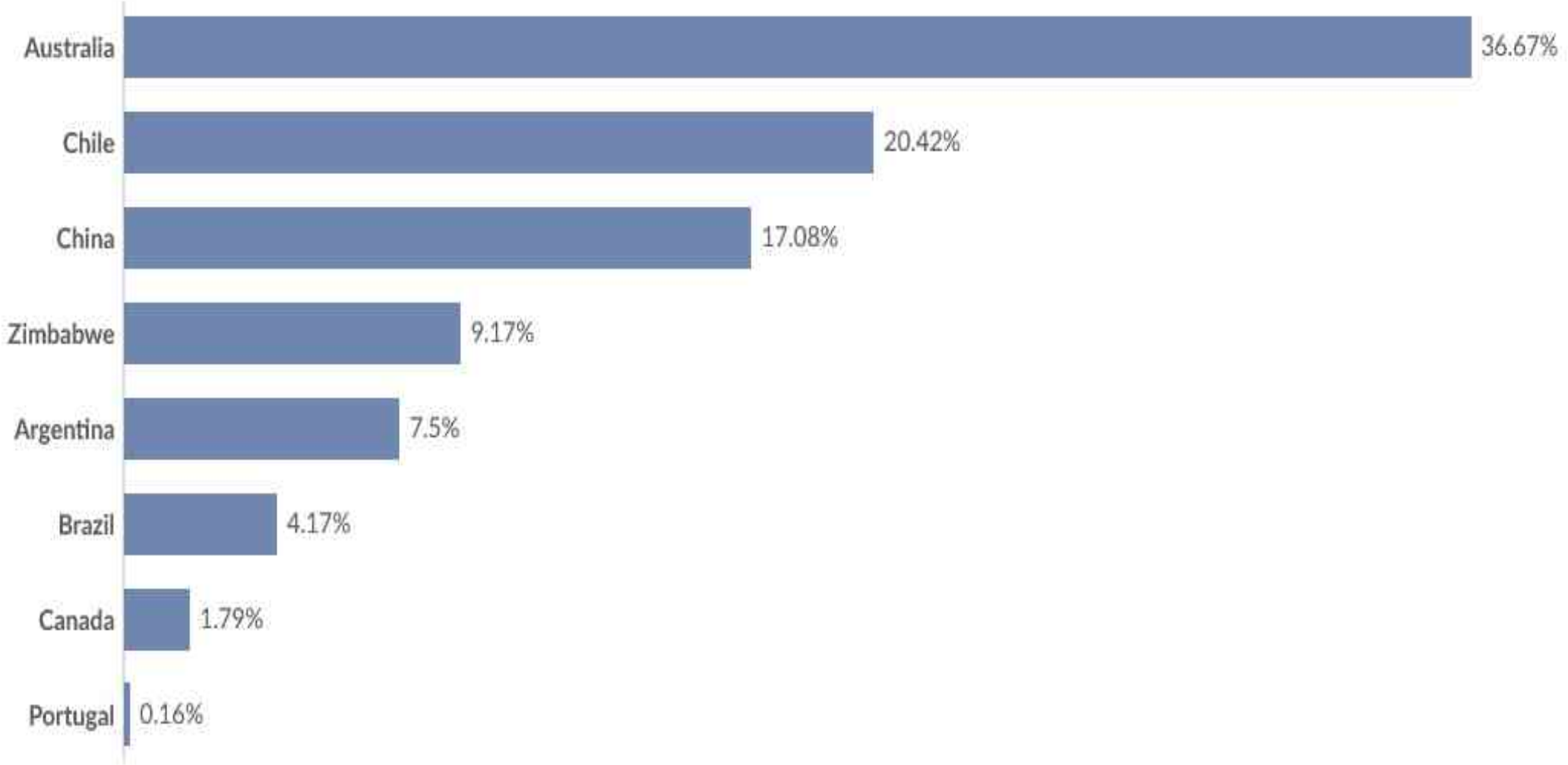
World Mine Production and Reserves: Significant revisions were made to the 2024 production for Argentina based on company reports and for Mali based on two new operations started in 2024. Reserves for Argentina, Australia, Brazil, Canada, Chile, China, the United States, and Zimbabwe were revised based on company and Government reports.

	Mine production[e]		Reserves[4]
	2024	2025	
United States	W	W	4,400,000
Argentina	[5]13,800	23,000	4,400,000
Australia	82,700	92,000	[6]8,400,000
Brazil	10,200	12,000	540,000
Canada	4,820	5,600	1,600,000
Chile	[5]48,900	56,000	9,200,000
China	41,400	62,000	4,600,000
Mali	770	9,400	370,000
Portugal	380	380	60,000
Zimbabwe	20,000	28,000	500,000
Other countries[7]	—	—	2,400,000
World total (rounded)	[8]222,000	[8]290,000	37,000,000

World Resources:[4] Owing to continuing exploration, measured and indicated lithium resources have increased substantially worldwide and total about 150 million tons. Measured and indicated lithium resources in the United States—from continental brines, claystone, geothermal brines, hectorite, oilfield brines, and pegmatites—are 30 million tons. Measured and indicated lithium resources in other countries have been revised to 120 million tons. Resources are distributed as follows: Argentina, 28 million tons; Bolivia, 23 million tons; Chile, 13 million tons; Australia, 10 million tons; China, 10 million tons; Germany, 8.9 million tons; Canada, 8.1 million tons; Congo (Kinshasa), 3 million tons; Mexico, 1.7 million tons; Brazil, 1.4 million tons; Czechia, 1.3 million tons; Mali, 1.2 million tons; Serbia, 1.2 million tons; France, 1 million tons; Peru, 1 million tons; Russia, 1 million tons; Zimbabwe, 860,000 tons; Spain, 320,000 tons; Portugal, 260,000 tons; Namibia, 230,000 tons; Ghana, 200,000 tons; United Kingdom, 61,000 tons; Austria, 60,000 tons; Finland, 55,000 tons; and Kazakhstan, 45,000 tons.

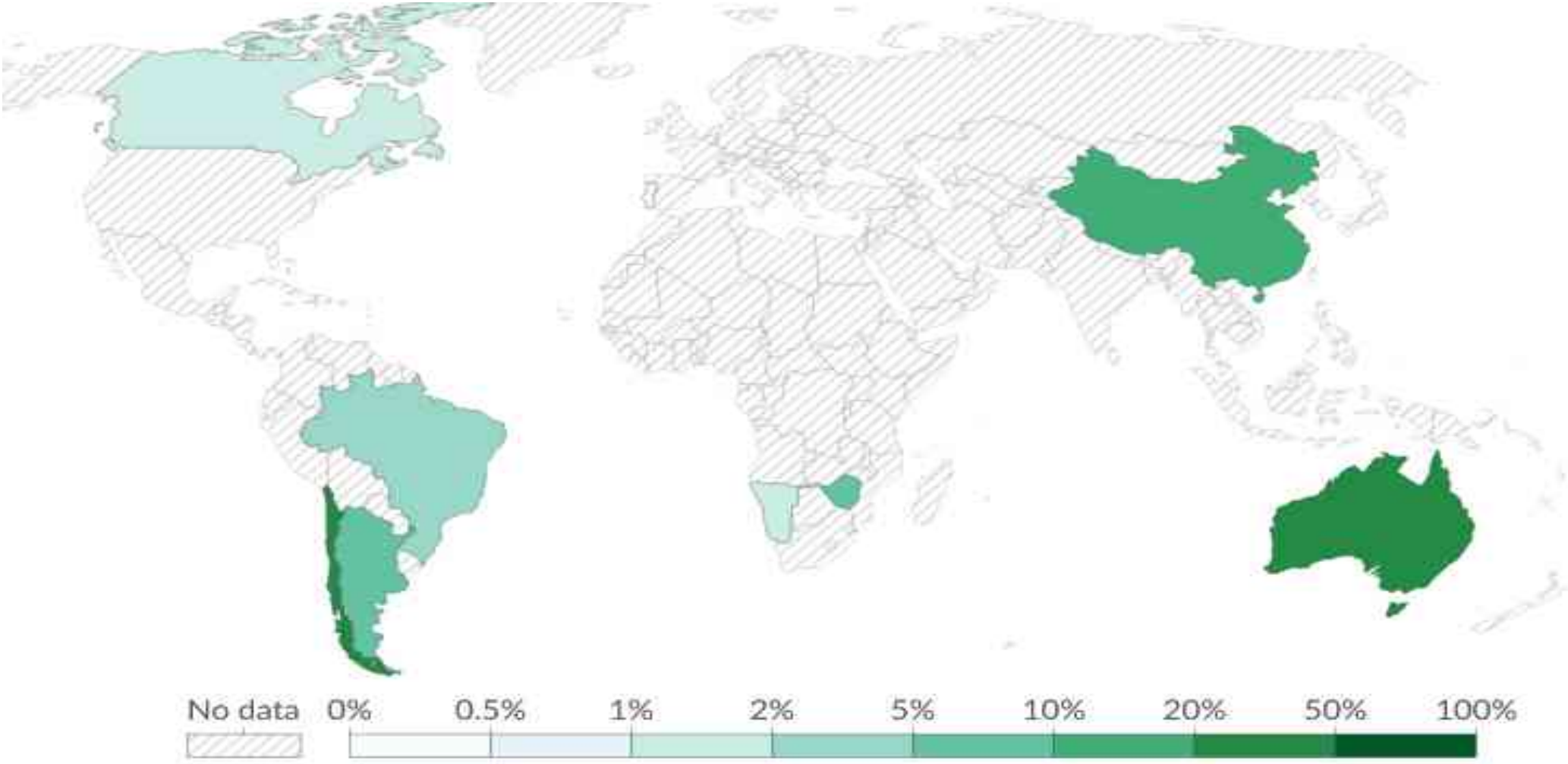
Substitutes: Substitution for lithium compounds is possible in batteries, ceramics, greases, and manufactured glass. Examples are calcium, magnesium, mercury, and zinc as anode material in primary batteries; calcium and aluminum soaps as substitutes for stearates in greases; and sodic and potassic fluxes in ceramics and glass manufacture.

Lithium – Production (290 kt) in 2025 – Shares of the total
Lithium is an essential element for Batteries



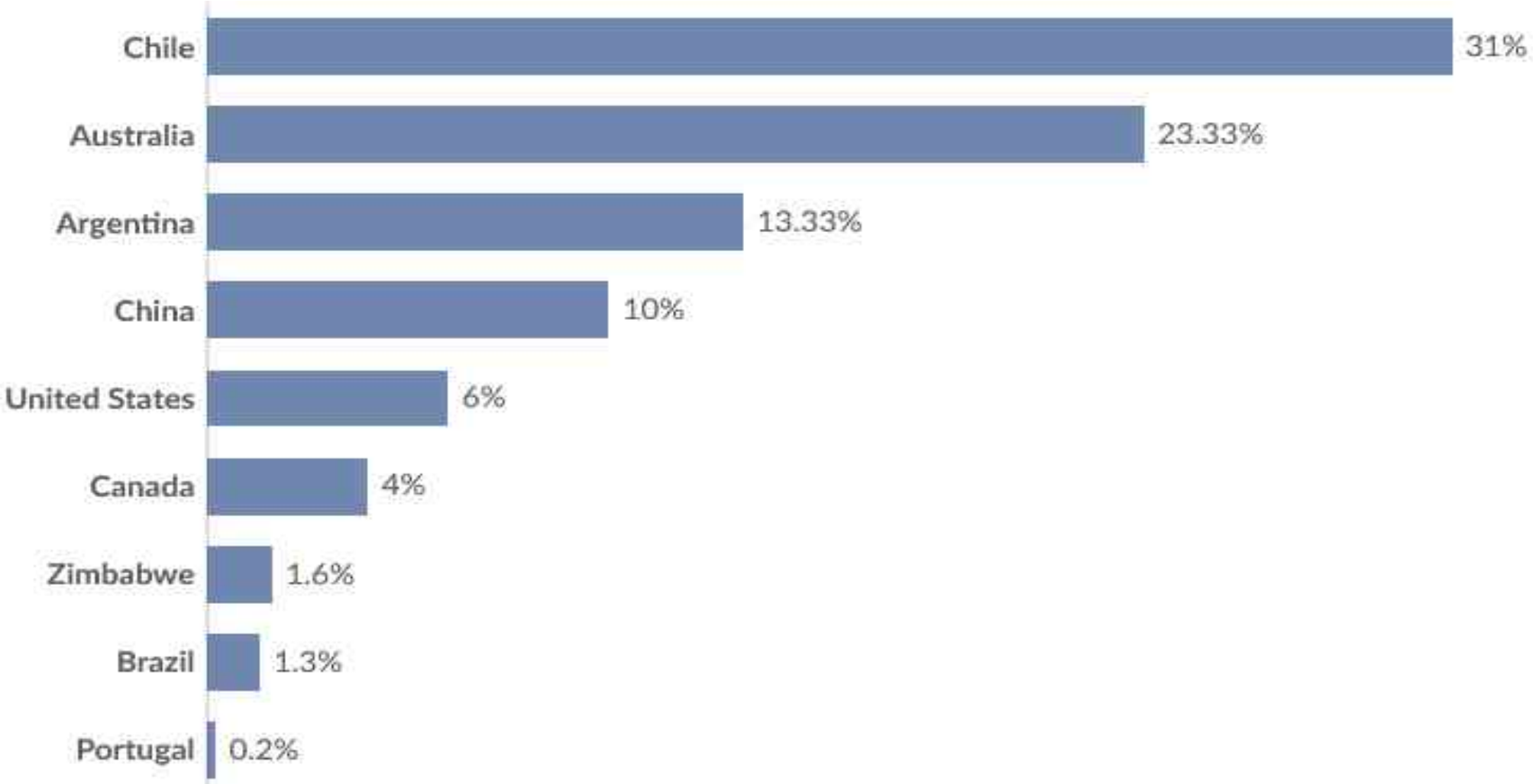
Source: Our World in Data 2025

Lithium – Production (290 kt) in 2025 – Shares of the total
Lithium is an essential element for Batteries



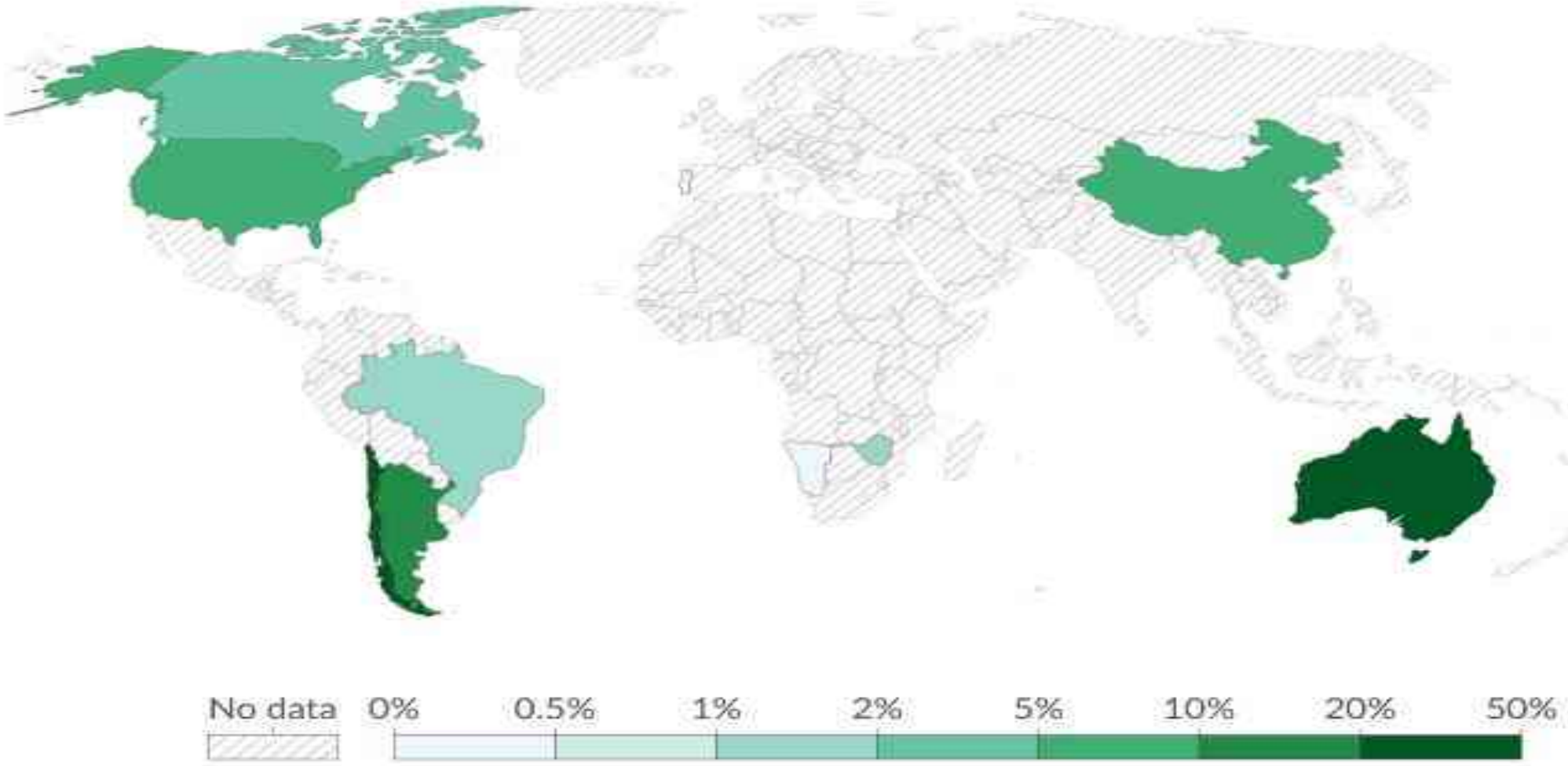
Source: Our World in Data 2025

Lithium – Reserves (37 Mt) in 2025 – Shares of the total
Lithium is an essential element for Batteries



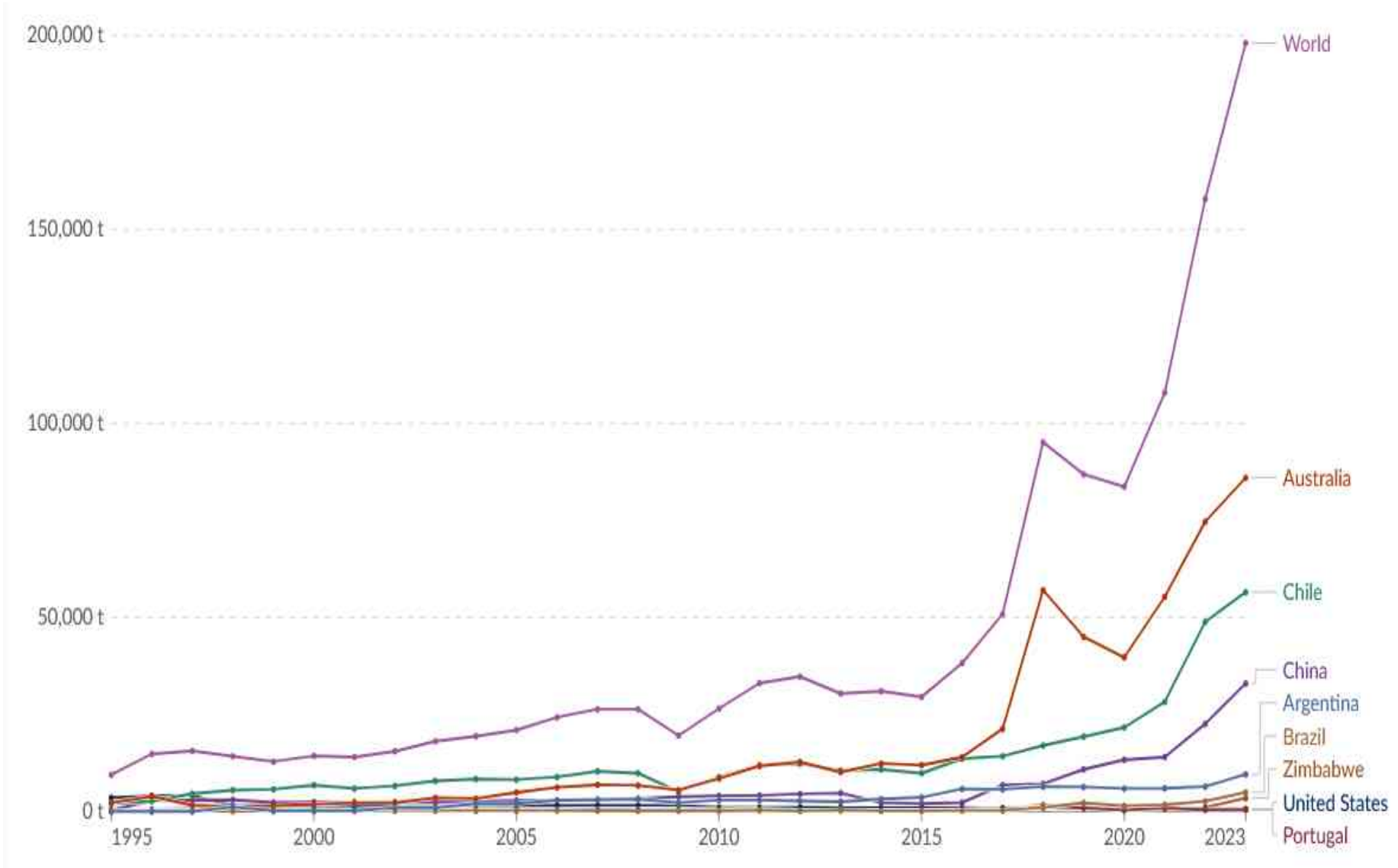
Source: Our World in Data 2025

Lithium – Reserves (37 Mt) in 2025 – Shares of the total
Lithium is an essential element for Batteries



Source: Our World in Data 2025

Lithium - History of Production

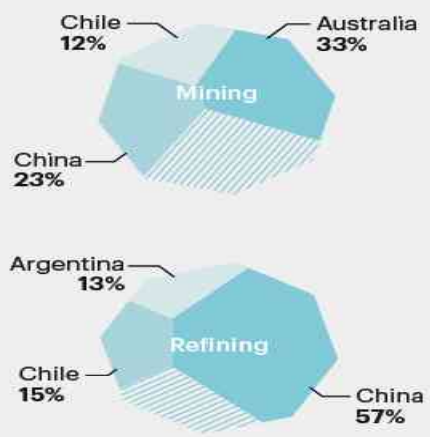


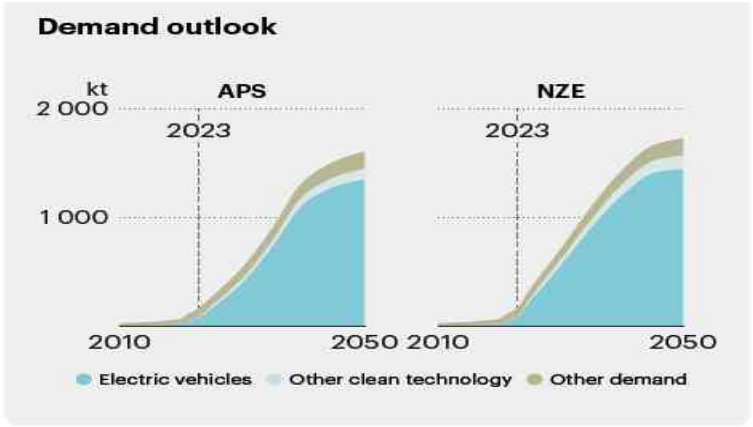
Source: Our World in Data 2025

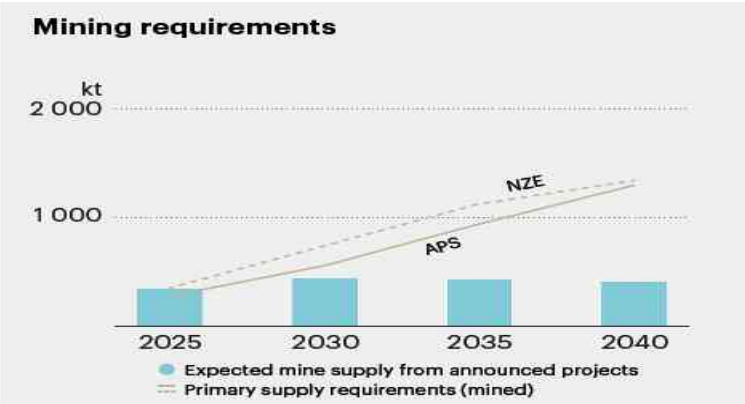
Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries

Lithium

Li





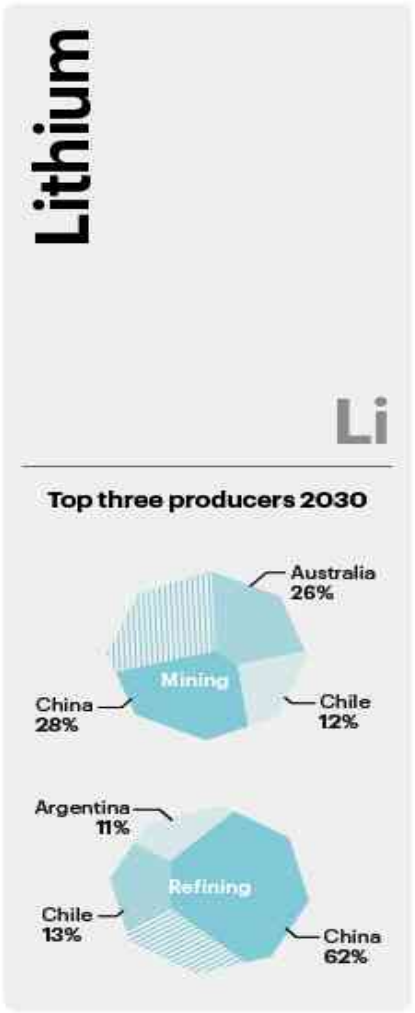


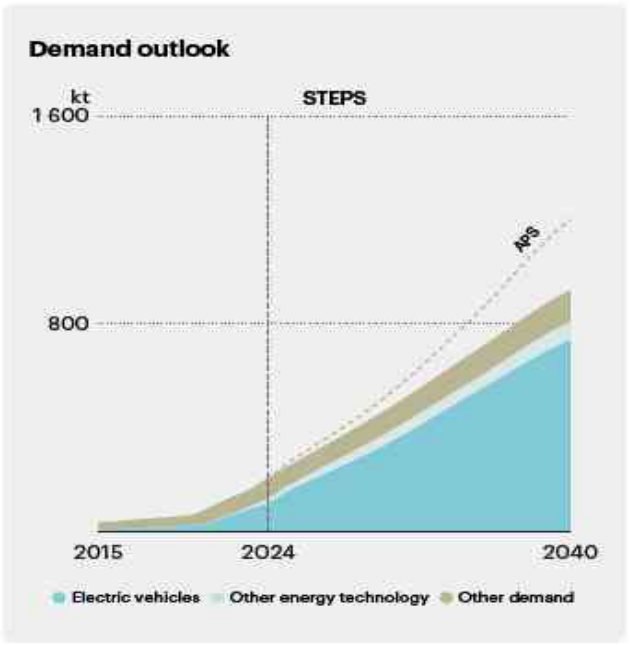
Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	38	92	442	1 203
Other uses (kt)	63	73	90	123
Total demand (kt)	101	165	531	1 326
Secondary supply and reuse (kt)	2	5	28	154
Primary supply requirements (kt)	100	160	503	1 172
Share of top three mining countries	89%	85%	68%	70%
Share of top three refining countries	100%	96%	85%	84%

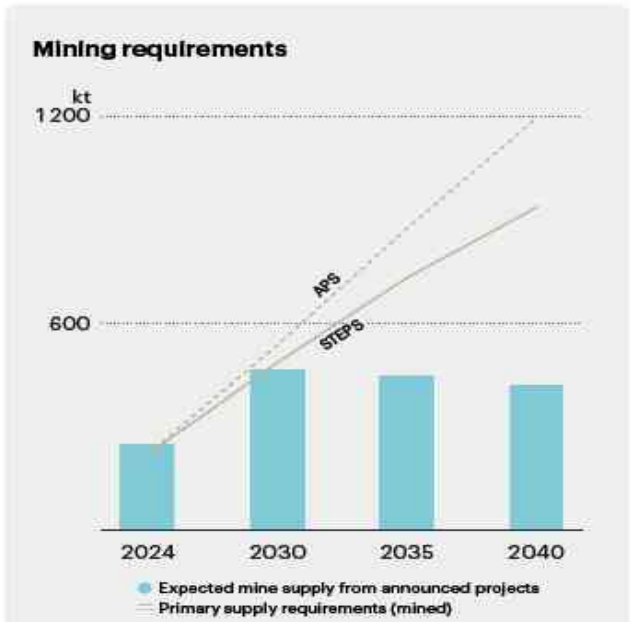


Source: IEA Global Critical Minerals Outlook 2024 - May 2024

Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries





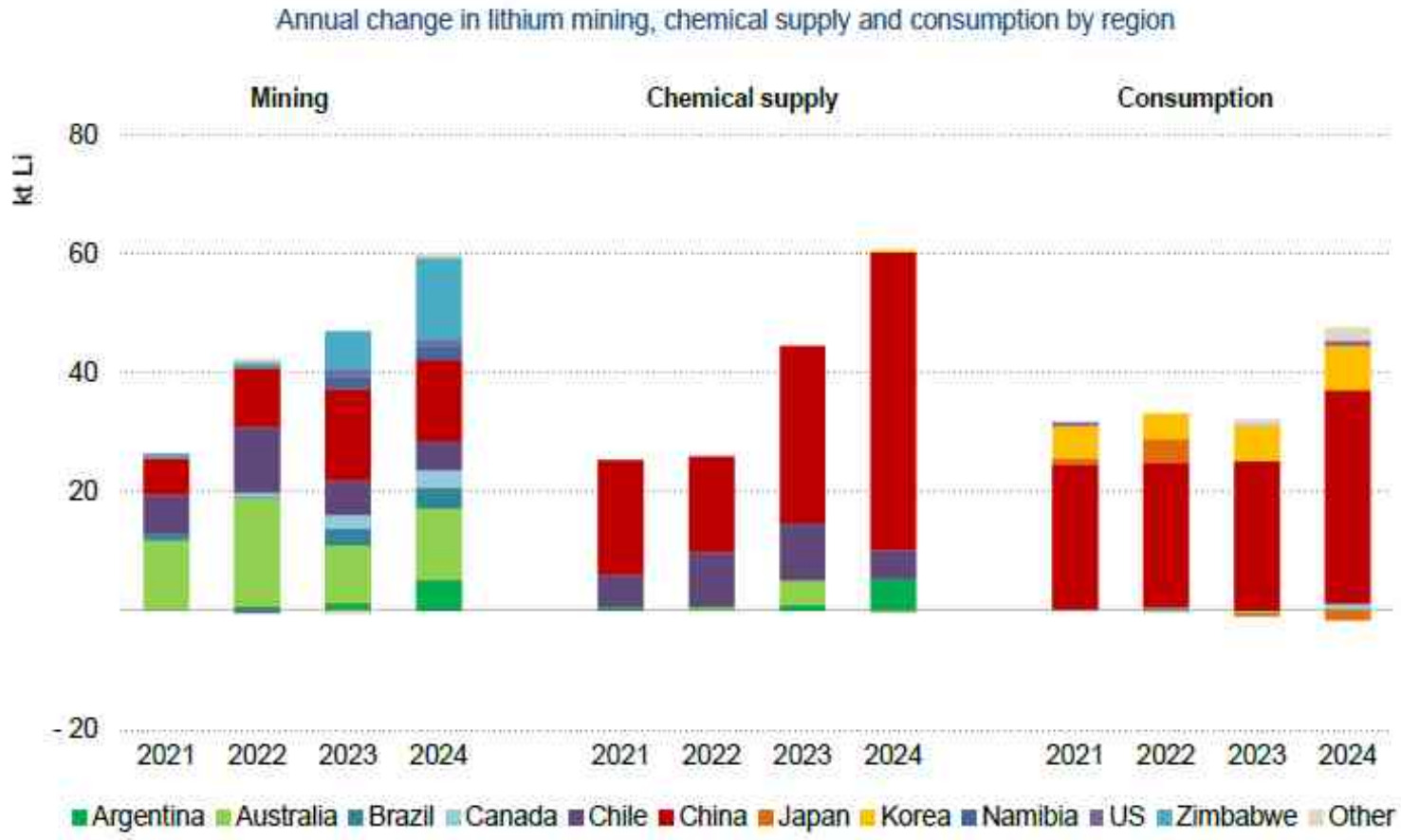


STEPS	2021	2024	2030	2040
Cleantech demand (kt)	38	128	369	809
Other uses (kt)	57	77	87	119
Total demand (kt)	95	205	455	928
Secondary supply and reuse (kt)	2	7	16	82
Primary supply requirements (kt)	100	198	439	844
Share of top three mining countries	89%	77%	67%	69%
Share of top three refining countries	99%	96%	85%	85%

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Lithium – Mining, Chemical Supply, Consumption 2012 - 2024

Recent market developments: remarkable supply growth as mines ramp up in new regions, but refining remains concentrated

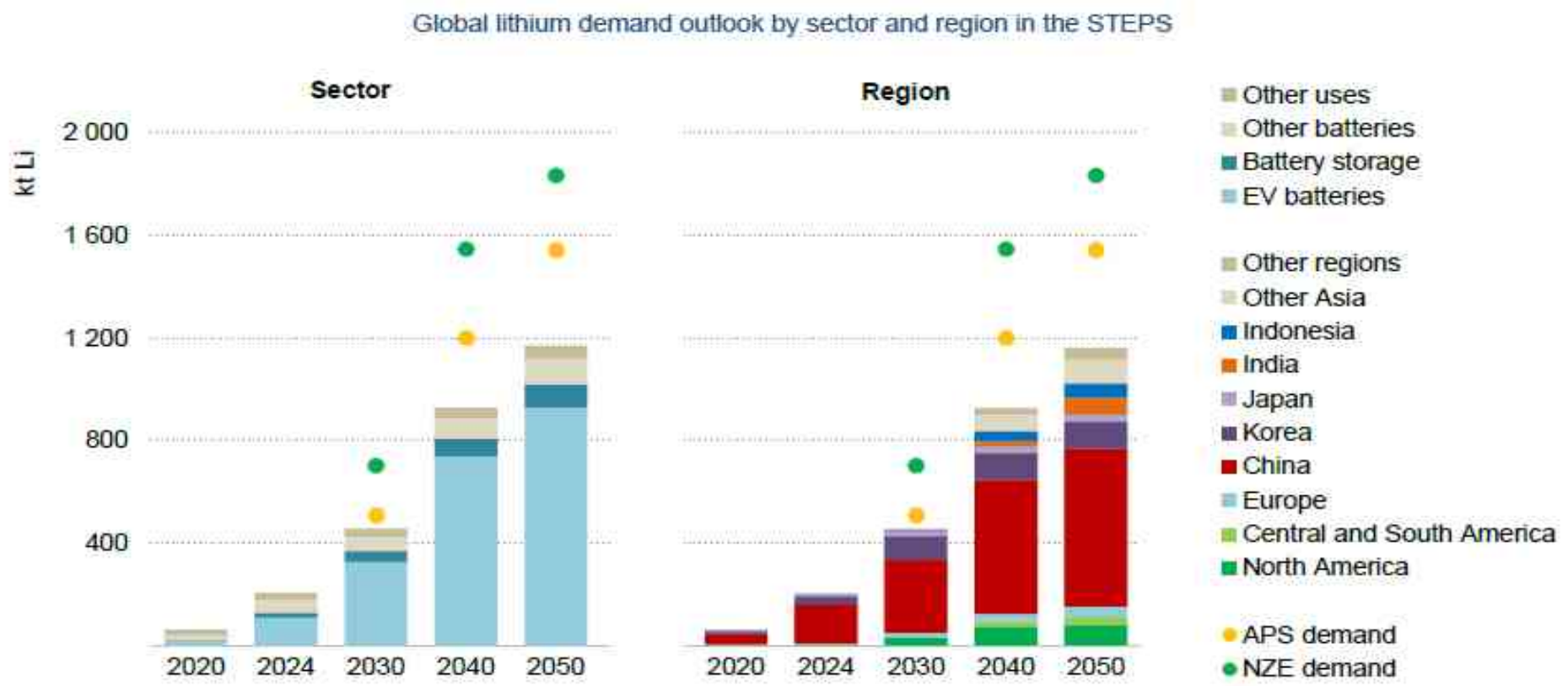


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Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Lithium – Demand evolution by Scenarios
Lithium is an essential element for Batteries

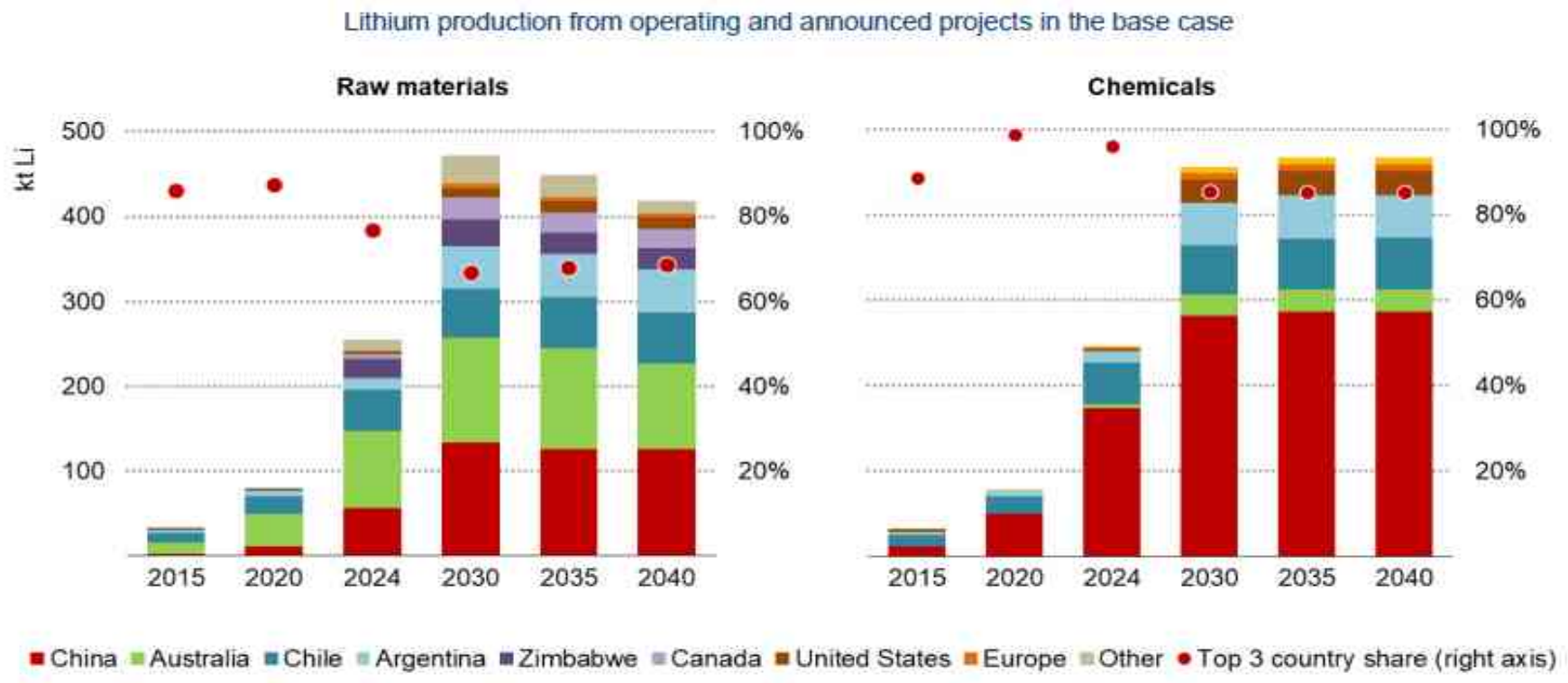
Demand: EV and storage batteries dominate lithium consumption; consumer geography diversifies



Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries

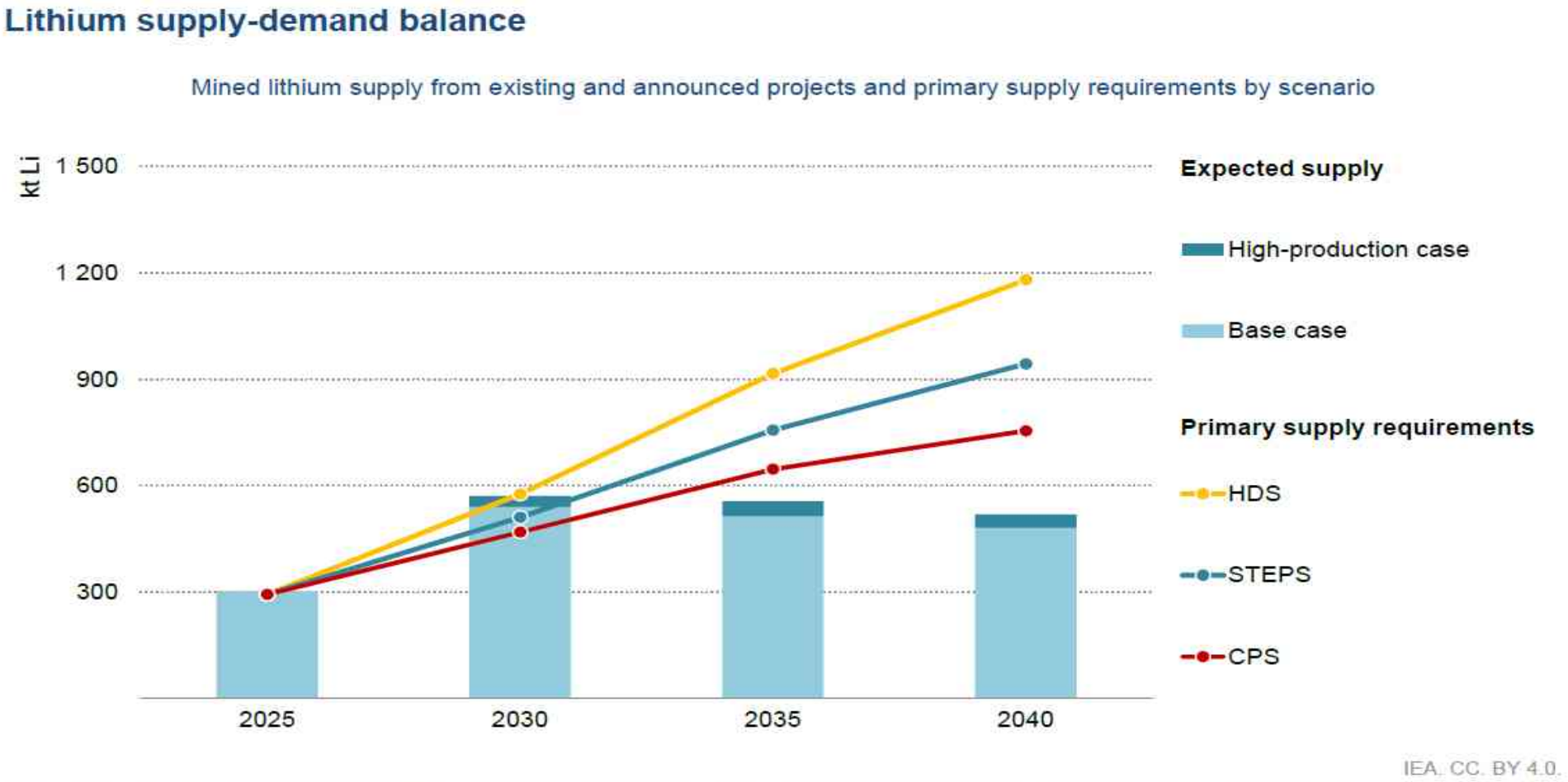
Supply: New lithium extraction activities emerge in a number of regions; China continues to dominate refining of hard rock ore



Notes: Raw materials cover extraction of lithium from hard rock ore, as well as from clays and brines. Lithium chemicals cover the first production of lithium carbonate, hydroxide, sulphates and chlorides, and excludes reprocessing.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries



Notes: HDS = High Demand Scenario; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario. Based on raw material output covering the extraction of lithium from hard-rock ore, clays and brines. Primary supply requirements are calculated as the "total demand net of secondary supply", also accounting for losses during refining operations. See the Introduction section for definitions of the base and high-production cases.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries

Lithium demand

	Historical		Current Policies			Stated Policies			High Demand		
Unit: kt Li	2021	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	67	203	368	652	708	368	836	1 002	470	1 131	1 381
Electric vehicles	63	171	333	594	636	333	765	911	416	1 037	1 260
Battery storage	5	32	35	57	72	35	71	90	54	94	121
Other uses	36	72	70	96	120	70	96	120	70	96	120
Total demand	103	275	438	748	828	438	932	1 122	540	1 227	1 501
Share of clean energy	65%	74%	84%	87%	85%	84%	90%	89%	87%	92%	92%

Note: kt = kilotonnes.

Source: IEA Global Critical Minerals Outlook 2025 - July 2026

Lithium – Reserves (37 Mt) and Production (290 kt) in 2025
Lithium is an essential element for Batteries

Lithium supply

	Raw materials					Chemicals			
	Historical		Base case			Historical		Base case	
Unit: kt Li	2021	2025	2030	2040		2021	2025	2030	2040
Australia	50	104	143	120	China	70	235	369	374
China	17	70	162	150	Chile	25	52	57	59
Chile	28	52	57	59	Argentina	7	16	51	54
Zimbabwe	2	28	27	27	Australia	0	6	16	26
Argentina	6	19	51	54	Germany	0	3	6	7
Canada	0	7	24	22	United States	1	1	19	20
Rest of world	4	23	77	50	Rest of world	0	5	25	28
World	107	302	540	482	World	103	319	544	568
Top 3 share	89%	75%	67%	68%	Top 3 share	99%	95%	88%	86%

Notes: kt = kilotonnes. Raw materials cover the extraction of lithium from hard-rock ore, as well as from clays and brines. Lithium chemicals cover the first production of lithium carbonate, hydroxide, sulphates and chlorides, and exclude reprocessing.

Source: IEA Global Critical Minerals Outlook 2026 - July 2026

Lithium - Reserves and Production
The case of France

- Lithium is a very light alkali element that is a critical component in the manufacture of batteries for the automotive industry. Pure lithium is a soft alkali element, which is white or silver in color. It is the lightest solid element on the planet, and floats on water. Being highly reactive, lithium is not found in its native state in the natural environment, but only in the form of ionic compounds.

- Lithium is found in nature in aqueous salt solutions (brine) in salt flats (large, partially evaporated salt lakes) or – as at our Kaolin site in Beauvoir, France – in clay and hard rock such as granite and pegmatite.

- Lithium has the atomic number 3 on the table of elements. molecular mass = 6,94. The chemical formula for the lithium hydroxide used by battery manufacturers is: LiOH, molecular mass = 24.

- Lithium is widely abundant, but there are only a few places on earth where it exists in adequate concentrations to make lithium mining economically viable. The biggest resources currently being mined are in Chile, Australia and China. There are only a few ongoing lithium mining projects in Europe, and most are still in the initial stages.

- Lithium's physical properties including a high electrochemical potential make it an essential raw material in the highly strategic market for lithium-ion batteries.

Source: Imerys

Lithium - Reserves and Production
The case of France

- Imerys has launched the EMILI project to mine lithium at its Beauvoir site in central France (Allier)
- Imerys' lithium initiative is designed to address the dual challenge of the energy transition and economic sovereignty. It will aid in the creation of an integrated European supply chain for electric vehicle batteries by offering a local solution for one of the most strategic raw materials.
- The EMILI project is one of the biggest lithium extraction projects in Europe to date. The site is expected to begin production in 2028. Mining activity will be combined with a processing plant.
- Imerys intends to design this project in an environmentally-friendly manner, in consultation with all stakeholders, and aligning with the IRMA benchmark, the international reference certification for responsible mining.
- The ongoing geological survey campaigns have already confirmed the presence of lithium in attractive quantities and quality at the Beauvoir site. Concurrent with the study on industrialization of the project, the geological teams are continuing this campaign until the end of the year 2022 in order to refine modeling of the granite massif.
- According to the latest estimates, completion of this industrial project would deliver 34,000 t of lithium hydroxide per year over 25 years (Total reserves # 900 000 t of LiOH, i.e # 300 000 t of Lithium) . This production corresponds to 10 000 t of Lithium content (10% 2021 world production). This quantity would allow 700,000 batteries of electric vehicles to be equipped at full capacity.

Source: Imerys

Lithium - Reserves and Production
The case of France



Source: Imerys

The case of Cobalt

Cobalt
From Resource to Consumer

Important needs for Electric Vehicle and Batteries. 80% of Cobalt is consumed in manufacturing lithium-ion batteries.

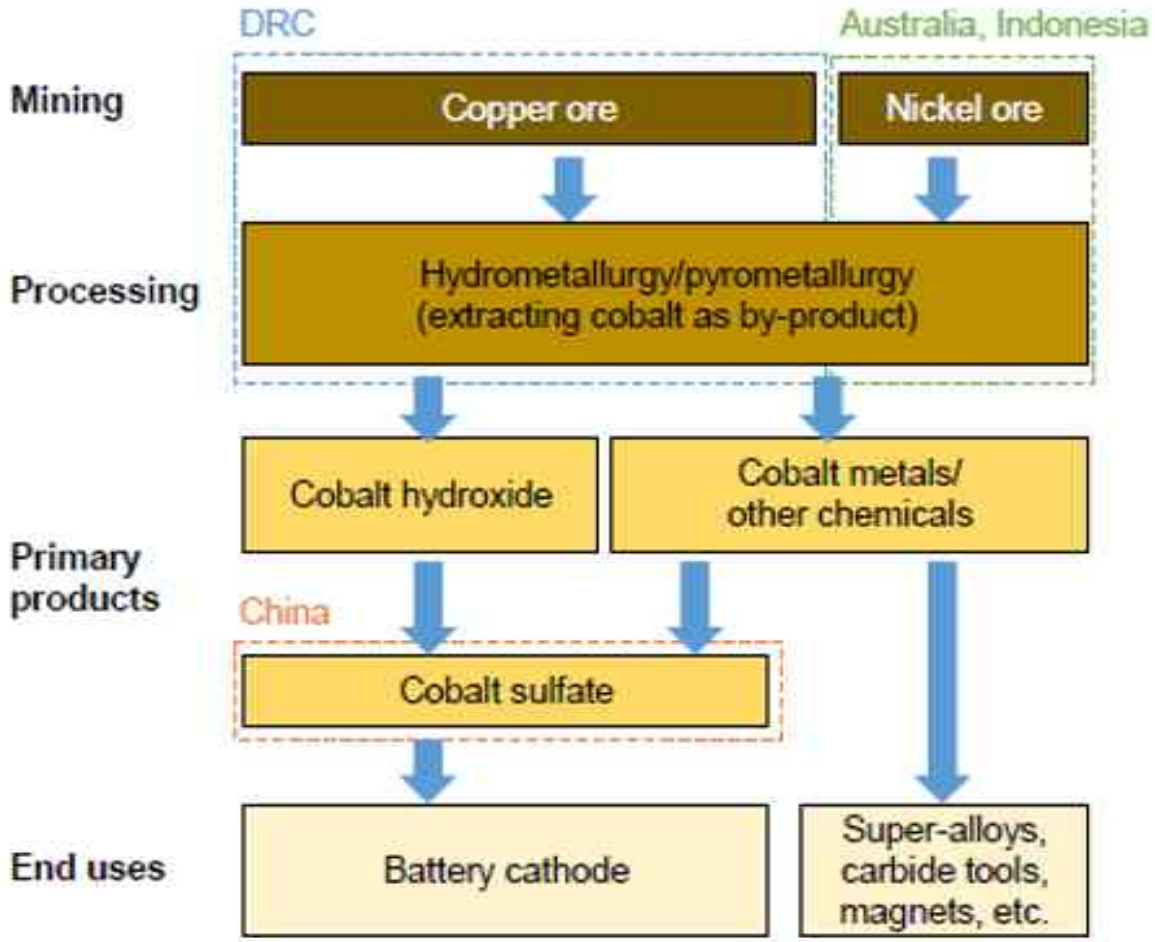
Also, by-product of Copper and Nickel mines.

High degree of geopolitical constraints: mining production concentrated in RDC (République Démocratique du Congo 70% of world production, 52% of world reserves)

Cumulative needs for industry/Known resources # 40% in 2050 to cope with the SDS IEA Scenario.

Cobalt
From Resource to Consumer

Cobalt Supply chain



Source: IEA Global Critical Minerals Outlook 2024 - May 2024

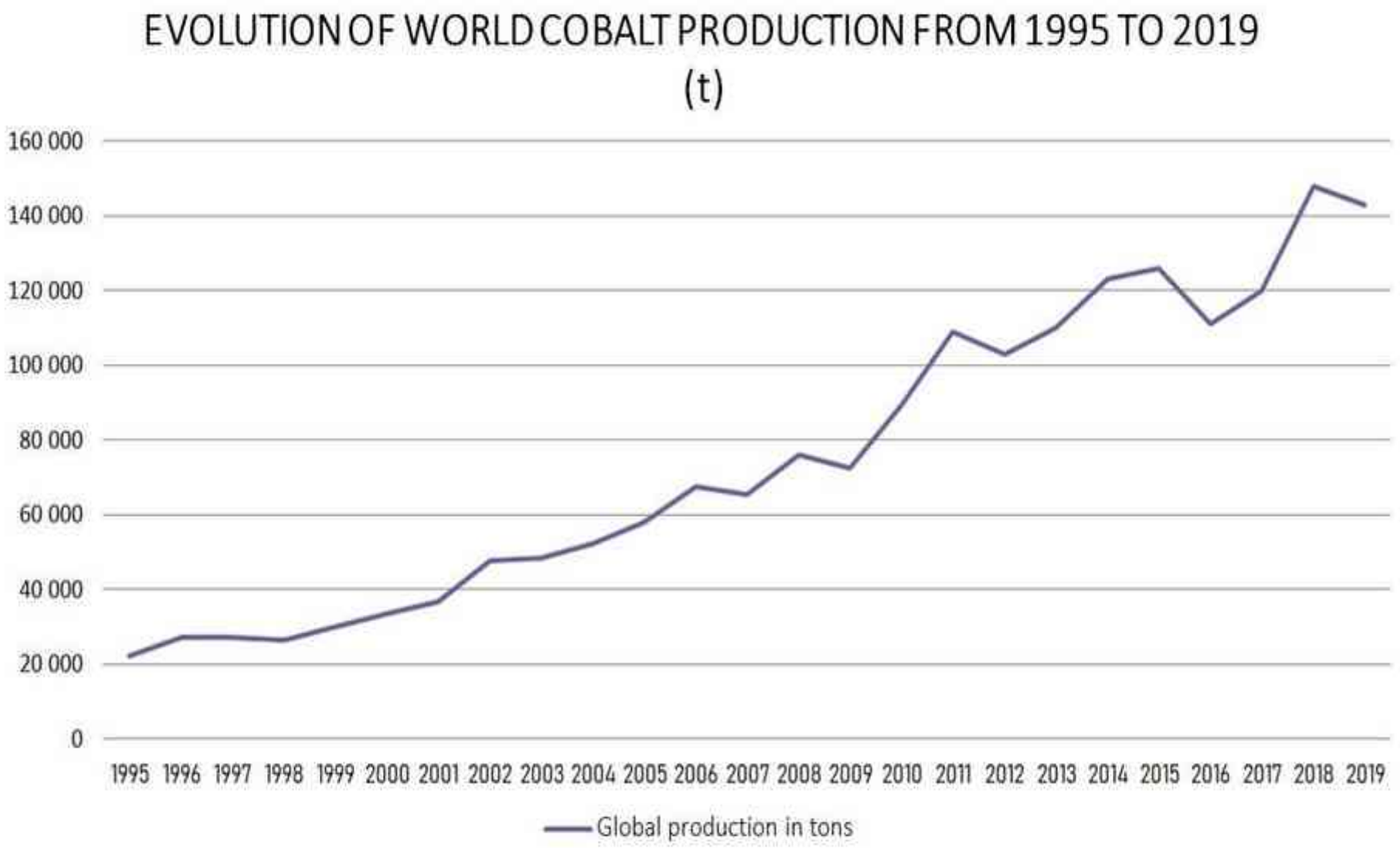
Cobalt - Tesla Gigafactory in Nevada - US

Objective: Production of 500 000 EV Batteries per year, 35 GWh/year

⟹ 6 kt Cobalt/year = 4% world production



Cobalt – Evolution of production



Source: IFP EN, USGS

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

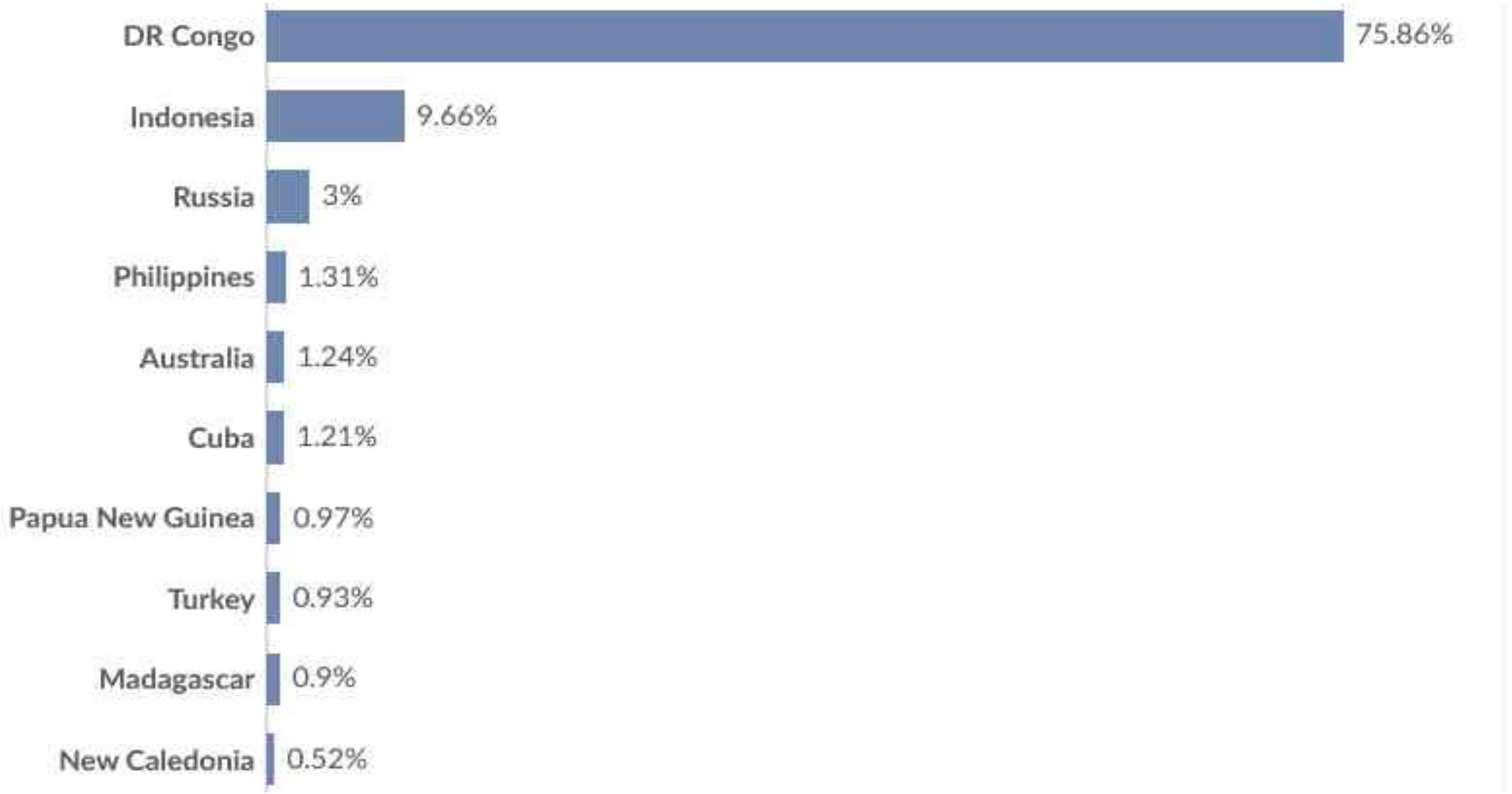
World Mine Production and Reserves: Significant revisions were made to the 2024 production for Australia, Canada, and Indonesia based on company and Government reports. Reserves for Indonesia, Papua New Guinea, Russia, and "Other countries" were revised based on company and Government reports.

	Mine production[e]		Reserves[9]
	2024	2025	
United States	200	300	70,000
Australia	4,780	3,700	[10]1,700,000
Canada	3,350	3,500	220,000
China	2,000	2,000	160,000
Congo (Kinshasa)	226,000	230,000	6,000,000
Cuba	3,450	2,000	500,000
Indonesia	35,000	44,000	760,000
Madagascar	3,100	3,900	100,000
Papua New Guinea	2,630	2,800	84,000
Philippines	3,100	3,700	260,000
Russia	8,000	7,700	[11]800,000
Turkey	2,200	1,900	91,000
Other countries	7,780	9,100	780,000
World total (rounded)	302,000	310,000	12,000,000

World Resources:[9] Identified cobalt resources of the United States are estimated to be about 1 million tons. Most of these resources are in Minnesota. Other notable occurrences are in Alaska, California, Idaho, Michigan, Missouri, Montana, Oregon, and Pennsylvania. Identified world terrestrial cobalt resources are about 25 million tons, the vast majority of which are in sediment-hosted stratiform copper deposits in Congo (Kinshasa) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulfide deposits of mafic and ultramafic rocks in Australia, Canada, Russia, and the United States. An estimated 5 billion tons of cobalt is contained globally in sea floor polymetallic nodules.

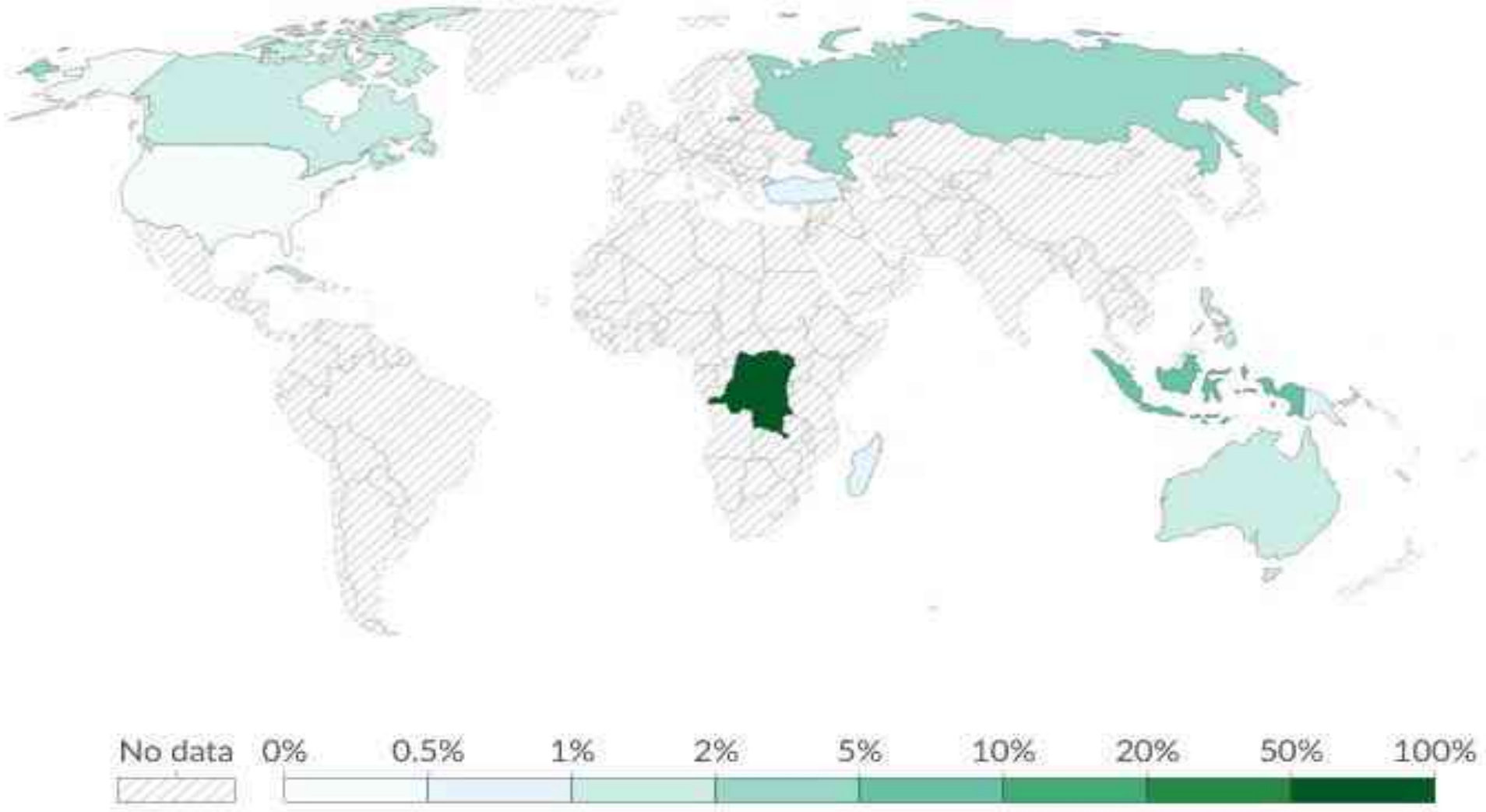
Source: USGS January 2026

Cobalt – Production (310 kt) in 2025 – Shares of the total



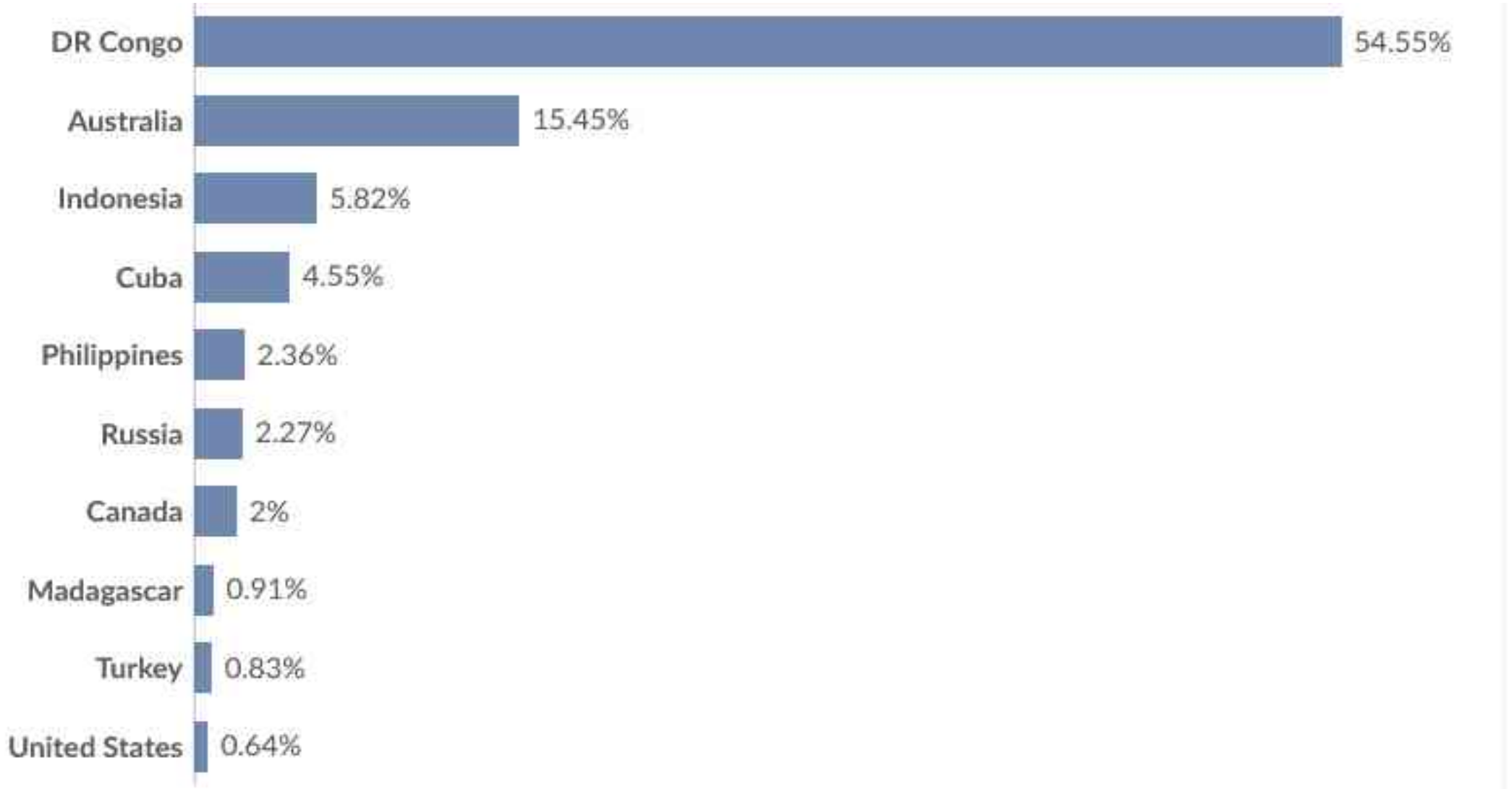
Source: Our World in Data 2025

Cobalt – Production (310 kt) in 2025 – Shares of the total



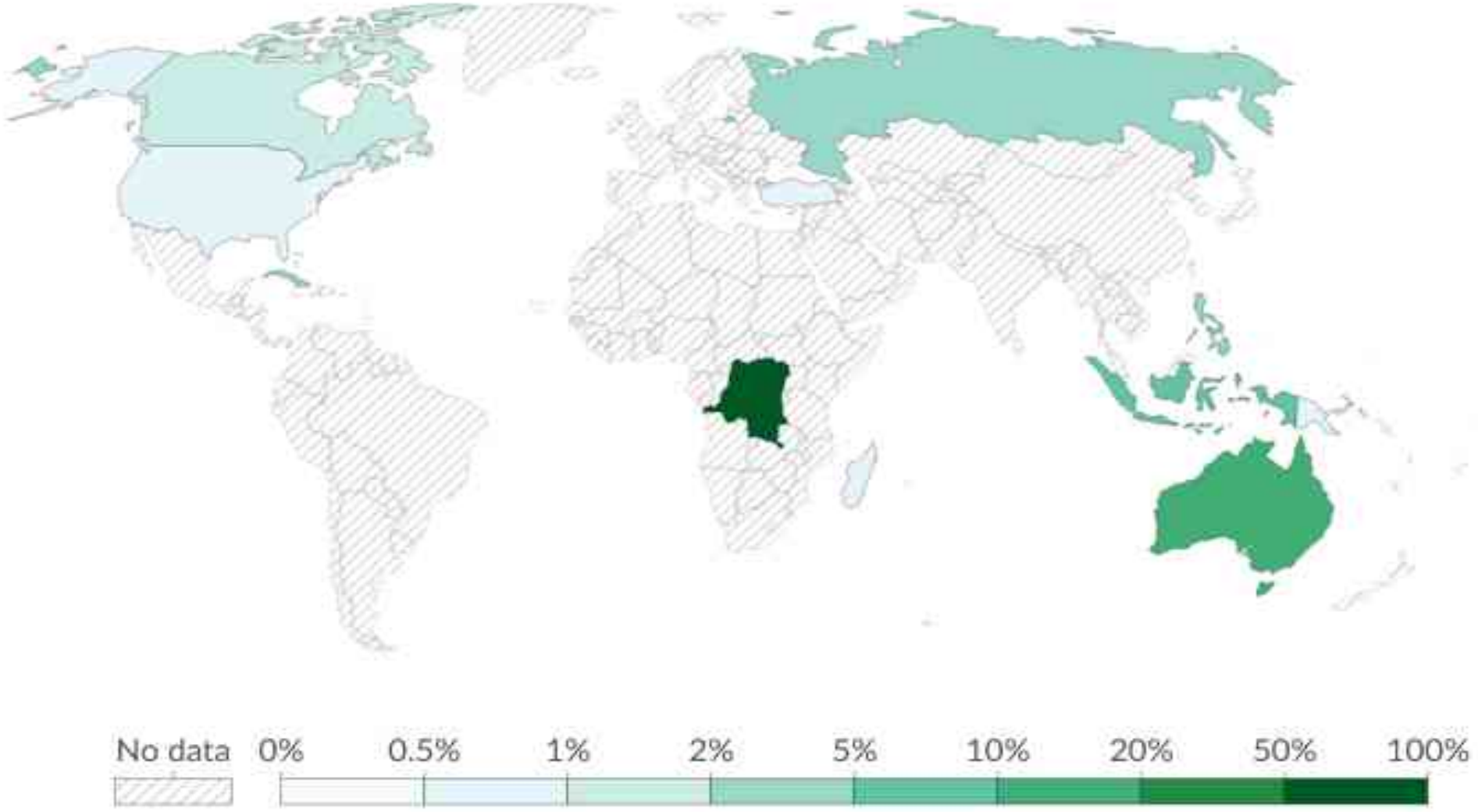
Source: Our World in Data 2025

Cobalt – Reserves (12 Mt) in 2025 – Shares of the total



Source: Our World in Data 2025

Cobalt – Reserves (12 Mt) in 2025 – Shares of the total



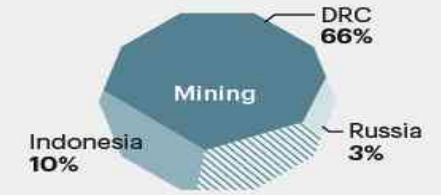
Source: Our World in Data 2025

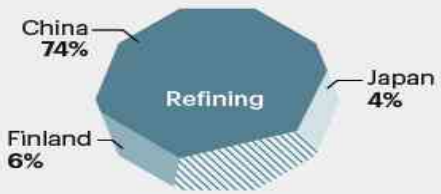
Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

Cobalt

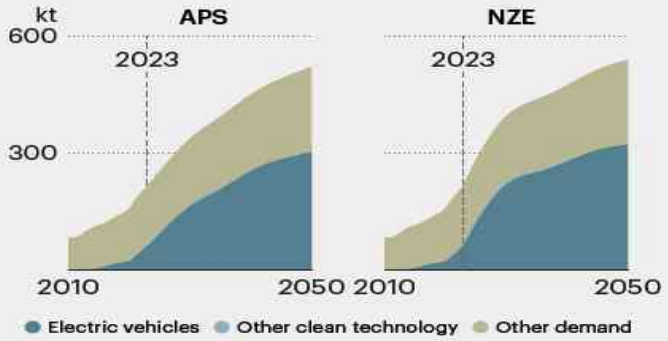
Co

Top three producers 2030





Demand outlook



Mining requirements



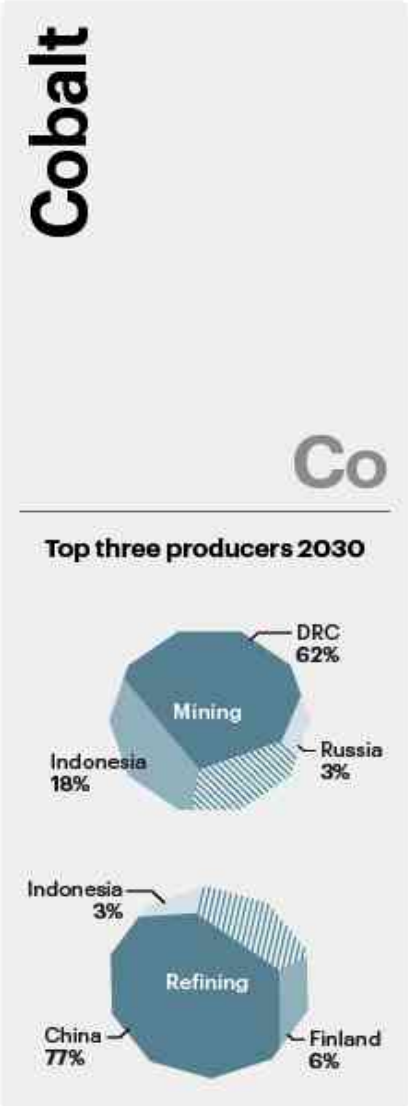
Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	36	64	177	260
Other uses (kt)	145	150	167	194
Total demand (kt)	181	215	344	454
Secondary supply and reuse (kt)	15	24	45	131
Primary supply requirements (kt)	100	166	299	323
Share of top three mining countries	75%	77%	84%	84%
Share of top three refining countries	86%	88%	84%	85%

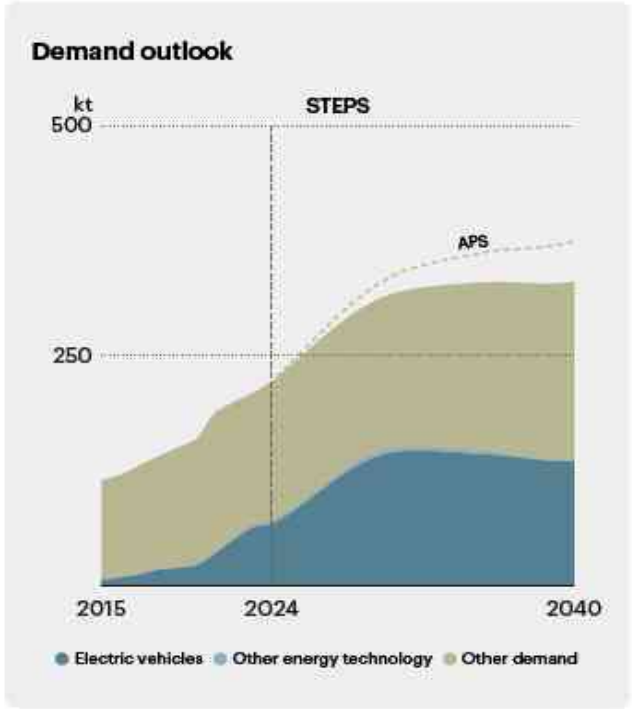
Clean energy transition risk assessment

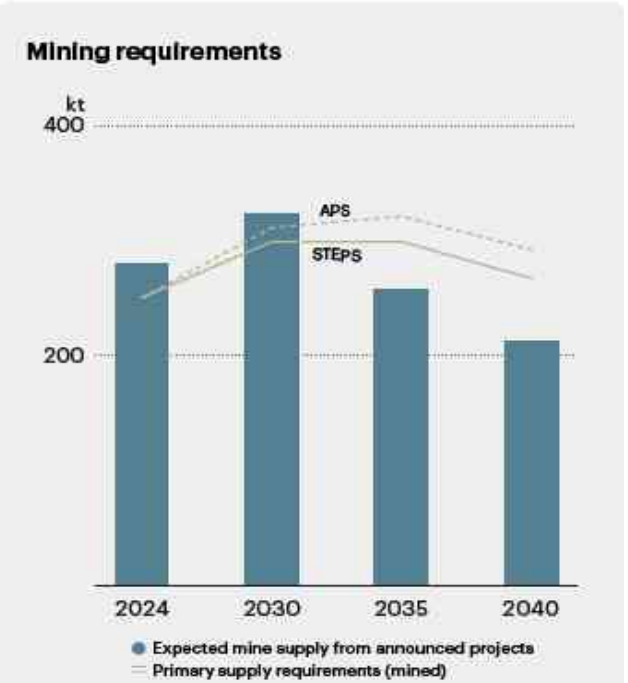


Source: IEA Global Critical Minerals Outlook 2024 - May 2024

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025





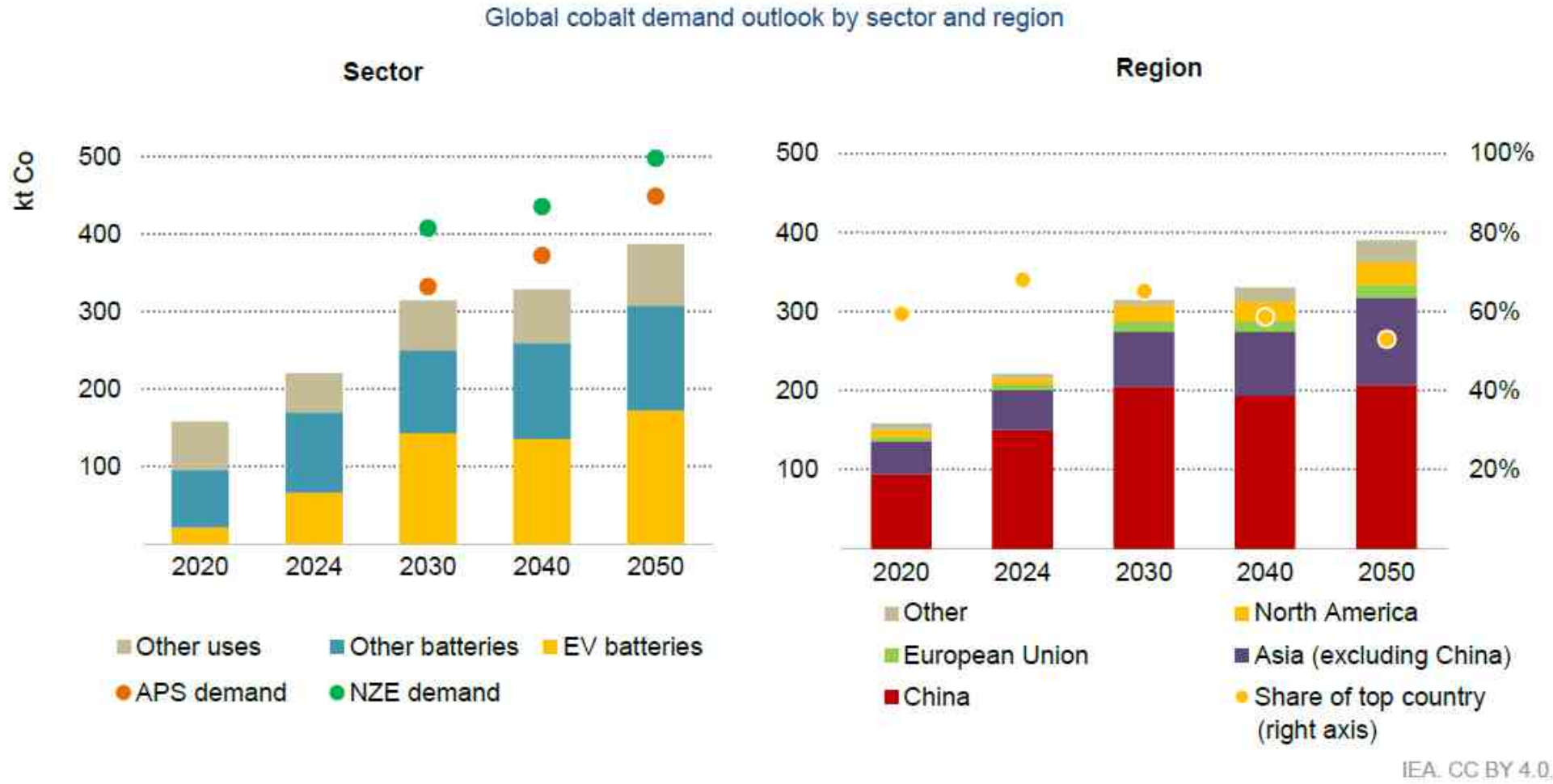


STEPS	2021	2024	2030	2040
Cleantech demand (kt)	**37**	**71**	**148**	**136**
Other uses (kt)	150	150	166	194
Total demand (kt)	**187**	**221**	**314**	**330**
Secondary supply and reuse (kt)	15	26	39	82
Primary supply requirements (kt)	**182**	**250**	**276**	**247**
Share of top three mining countries	76%	81%	83%	82%
Share of top three refining countries	82%	89%	87%	86%

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

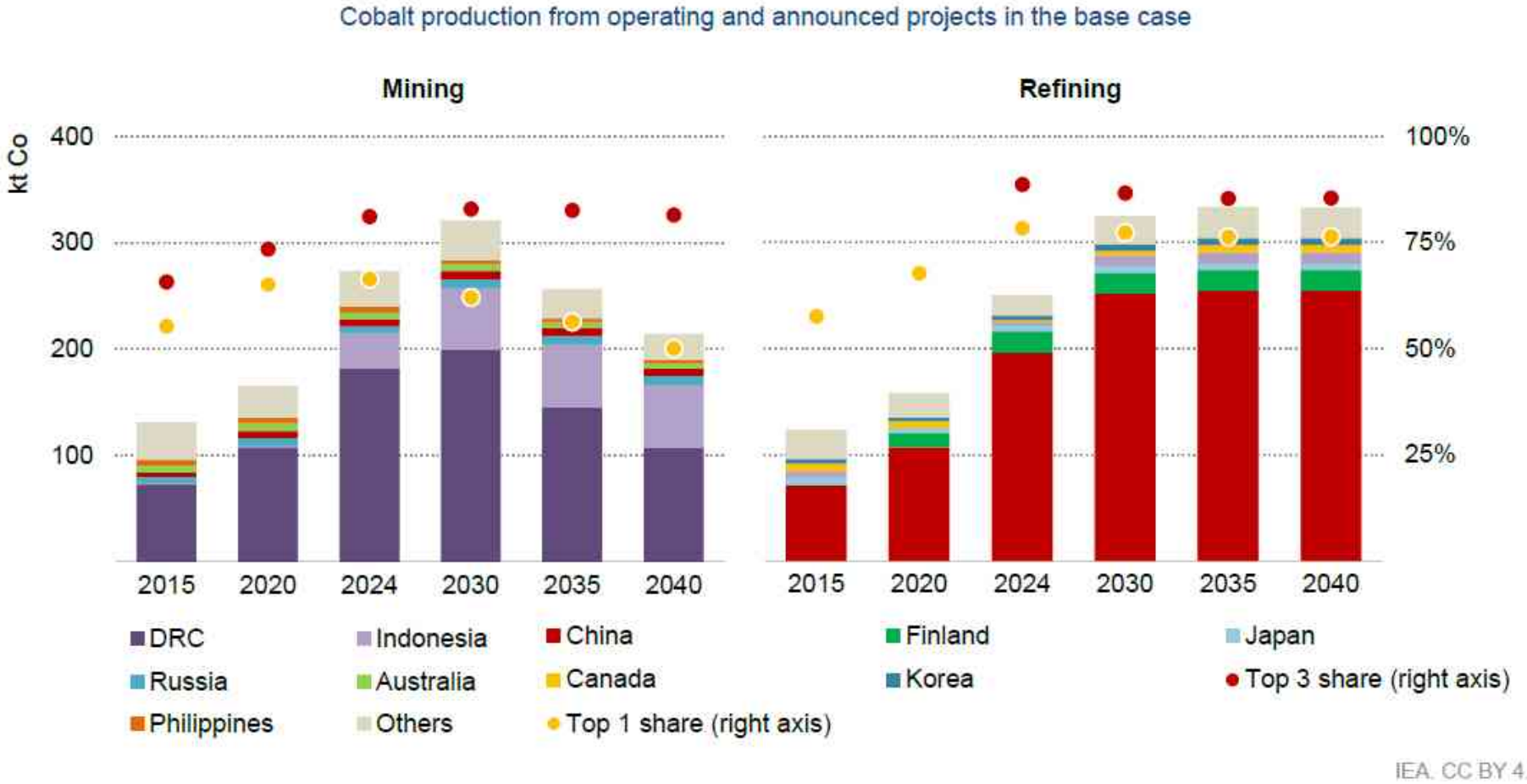
Demand: China continues to dominate cobalt demand as EV battery demand surpasses consumer electronics by the late 2020s



Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

Supply: Rising mined cobalt production in Indonesia diminishes the DRC's dominant market position, bringing its market share down to 50% by 2040

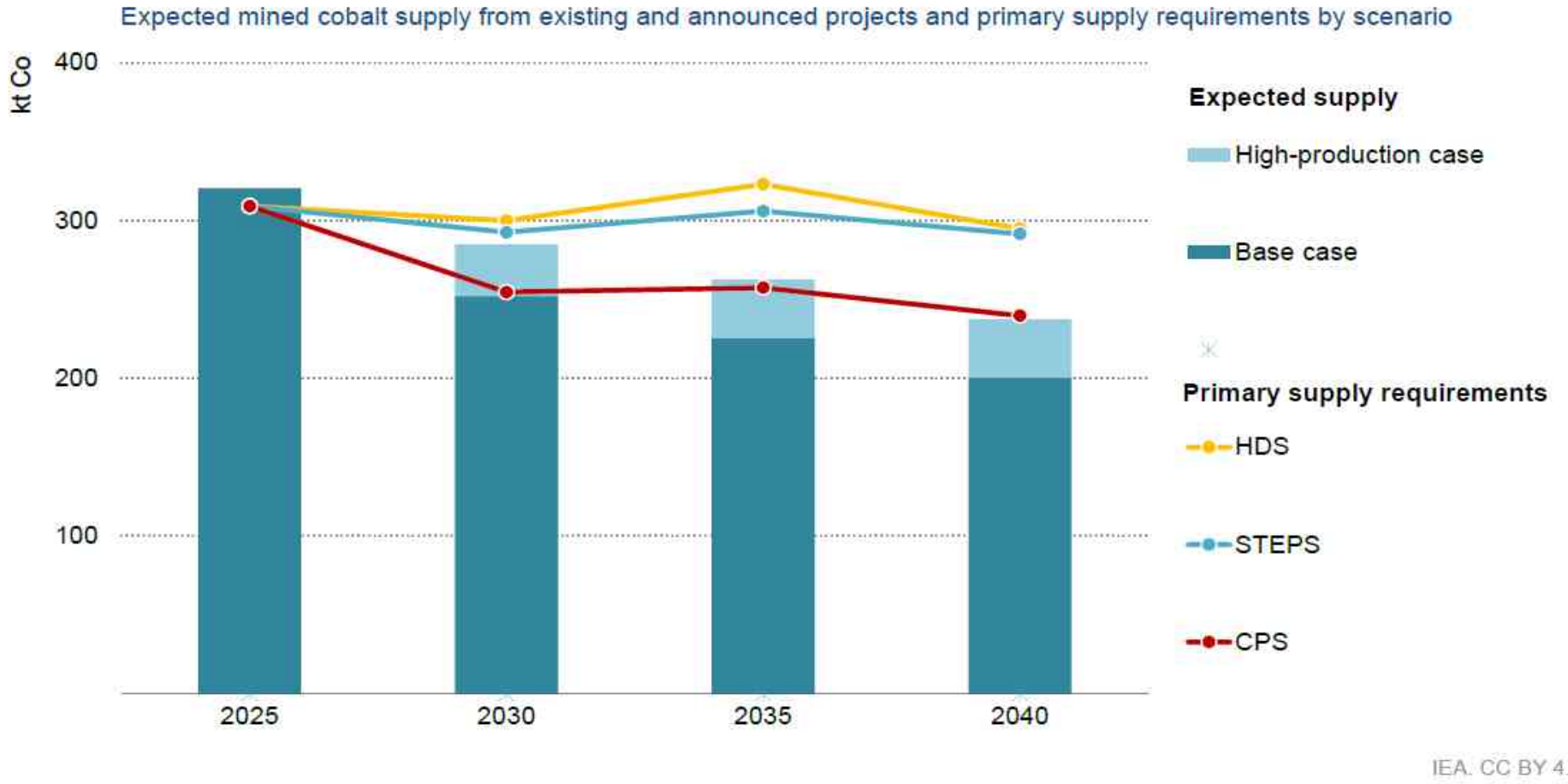


Note: DRC = Democratic Republic of the Congo.

Source: IEA Global Critical Minerals Outlook 2025 - May 2025

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

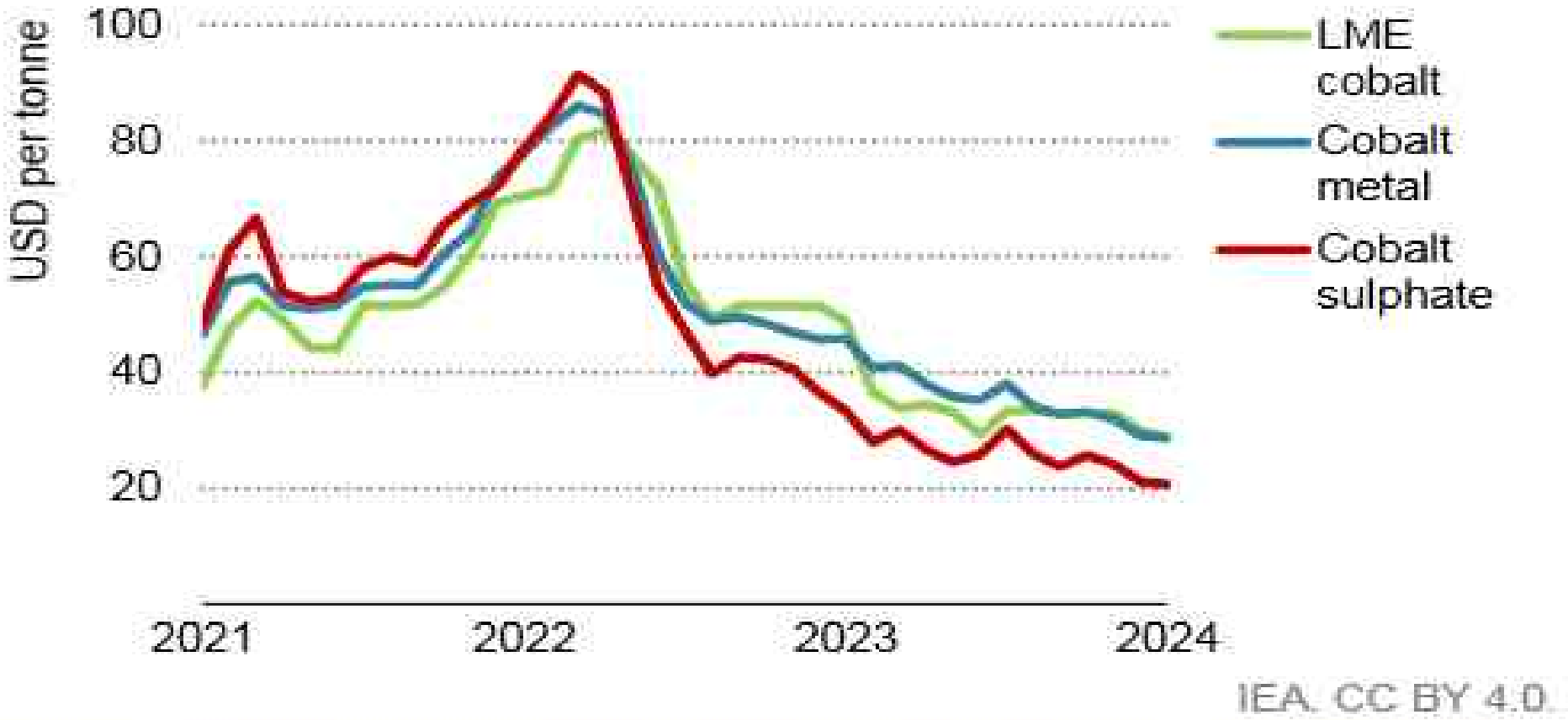
Cobalt supply-demand balance



Notes: HDS = High Demand Scenario; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario. Based on mined output. Primary supply requirements are calculated as the "total demand net of secondary supply", also accounting for losses during refining operations. See Introduction section for definitions of the base and high-production cases. The export quota is assumed to remain in place both in the base case and the high-production case.

Source: IEA Global Critical Minerals Outlook 2026 - May 2026

Price Development for Cobalt 2021 - 2024



Notes: Cobalt metal is based on China Cobalt Metal 99.8%. Cobalt sulphate is based on Cobalt sulphate 20.5% China. Quality adjusted.

Sources: IEA analysis based on S&P Global and Bloomberg.

Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

Cobalt demand

	Historical		Current Policies			Stated Policies			High Demand		
Unit: kt Co	2021	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	52	90	123	109	118	134	139	167	153	190	233
Electric vehicles	50	84	119	109	118	130	139	167	147	190	233
Battery storage	2	6	4	0	0	5	0	0	6	0	0
Other uses	135	169	165	197	225	171	204	234	165	195	222
Total demand	187	259	287	306	343	305	343	401	318	385	455
Share of clean energy	28%	35%	43%	36%	34%	44%	41%	42%	48%	49%	51%

Note: kt = kilotonnes.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

Cobalt – Reserves (12 Mt) and production (310 kt) in 2025

Cobalt supply

	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt Co	2021	2025	2030	2040		2021	2025	2030	2040
DRC	122	210	121	88	China	132	180	217	260
Indonesia	4	48	69	67	Finland	14	20	20	20
Russia	6	8	8	8	Japan	5	6	7	7
China	7	7	7	7	Indonesia	0	6	17	17
Australia	8	4	5	4	Canada	4	6	6	2
Zambia	4	4	7	6	Norway	4	3	3	3
Rest of world	35	39	34	21	Rest of world	19	17	26	27
World	186	320	252	200	World	177	238	295	335
Top 3 share	73%	83%	79%	81%	Top 3 share	85%	87%	86%	89%

Notes: kt = kilotonnes. DRC = Democratic Republic of the Congo.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

The case of Graphite

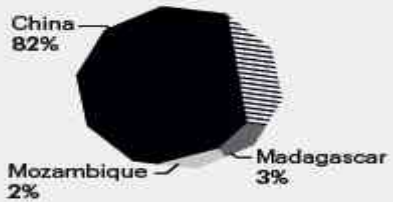
Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025

Graphite

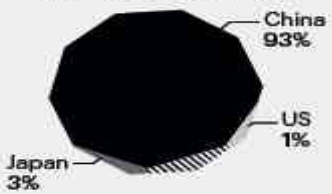
C

Top three producers 2030

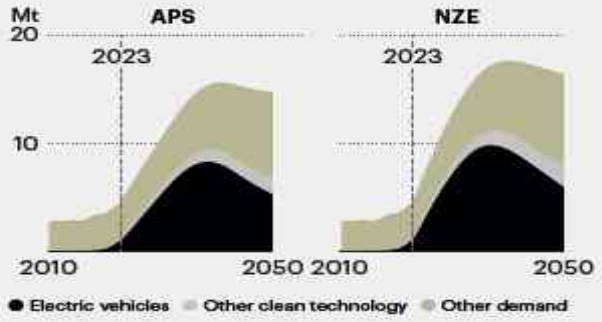
Total supply (all grades)



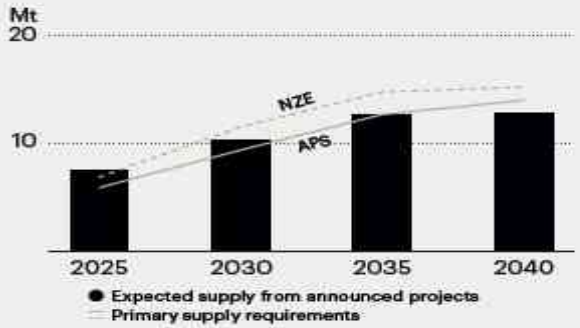
Battery grade supply



Demand outlook

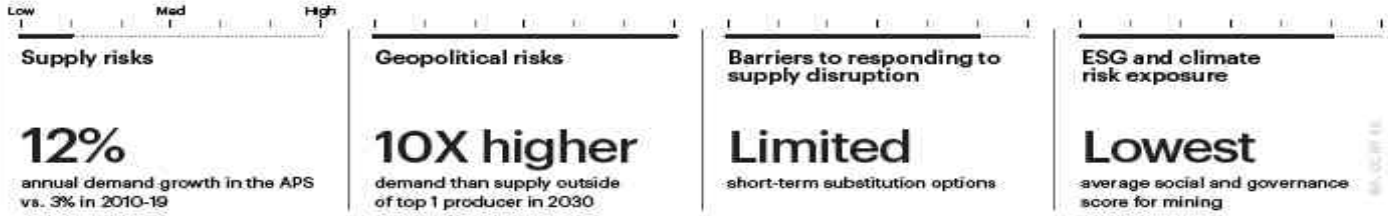


Supply requirements



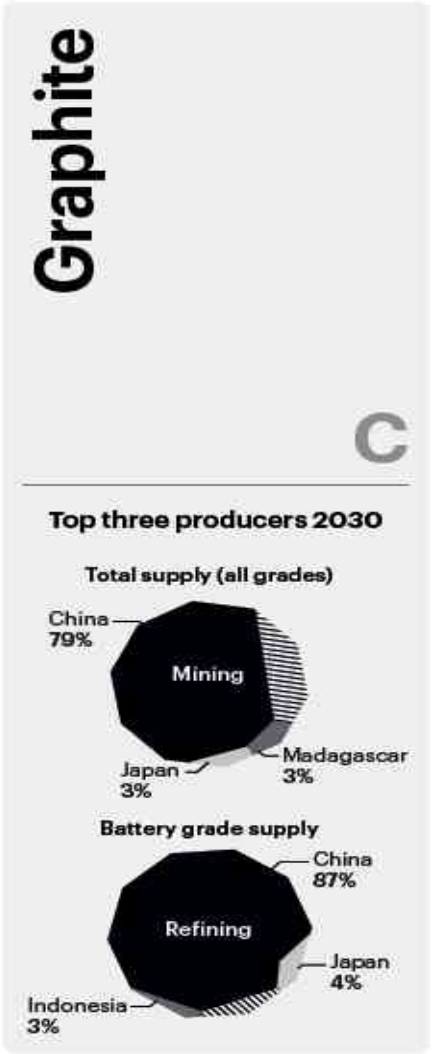
Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	532	1 292	6 013	9 839
Other uses (kt)	3 388	3 340	4 406	6 185
Total demand (kt)	3 920	4 632	10 419	16 023
Secondary supply and reuse (kt)	149	308	1 333	2 489
Primary supply requirements (kt)	3 771	4 324	9 086	13 535
Share of top three mining countries	89%	92%	88%	89%
Share of top three refining countries	97%	98%	97%	95%

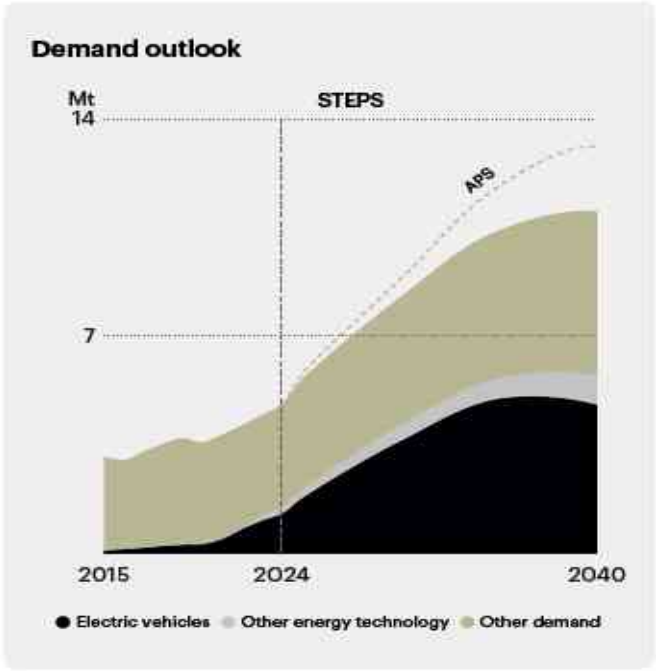
Clean energy transition risk assessment

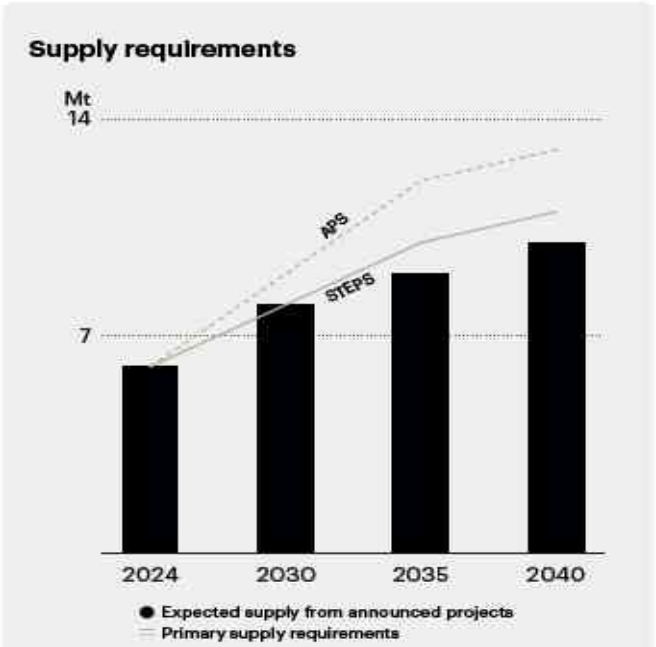


Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025







STEPS	2021	2024	2030	2040
Cleantech demand (kt)	487	1 505	4 114	5 700
Other uses (kt)	3 326	3 260	4 105	5 309
Total demand (kt)	3 813	4 766	8 219	11 010
Secondary supply and reuse (kt)	108	127	162	227
Primary supply requirements (kt)	4 269	6 157	8 057	10 762
Share of top three mining countries	90%	93%	86%	86%
Share of top three refining countries	100%	99%	93%	92%

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025

World Mine Production and Reserves: Significant revisions were made to the 2024 production for Austria, Brazil, Canada, India, the Republic of Korea, Mexico, Mozambique, Norway, Tanzania, Ukraine, and Vietnam based on company and Government reports. Reserves for China were revised based on Government reports.

	Mine production		Reserves[3]
	2024	2025[e]	
United States	—	—	(4)
Austria	100	200	(4)
Brazil	58,000	65,000	74,000,000
Canada	11,700	8,000	5,900,000
China	1,270,000	1,400,000	100,000,000
Germany	140	140	(4)
India	17,600	17,000	8,600,000
Korea, North	[e]8,100	8,000	2,000,000
Korea, Republic of	1,000	500	1,800,000
Madagascar	85,000	80,000	27,000,000
Mexico	706	740	3,100,000
Mozambique	39,000	60,000	25,000,000
Norway	5,340	6,600	600,000
Russia	[e]20,000	25,000	14,000,000
Sri Lanka	3,000	3,200	1,500,000
Tanzania	[e]27,000	75,000	18,000,000
Turkey	2,600	2,200	6,900,000
Ukraine	900	800	(4)
Vietnam	500	500	9,700,000
World total (rounded)	1,550,000	1,800,000	310,000,000

World Resources:[3] Domestic resources of graphite are relatively small, but the rest of the world's resources exceed 800 million tons of recoverable graphite.

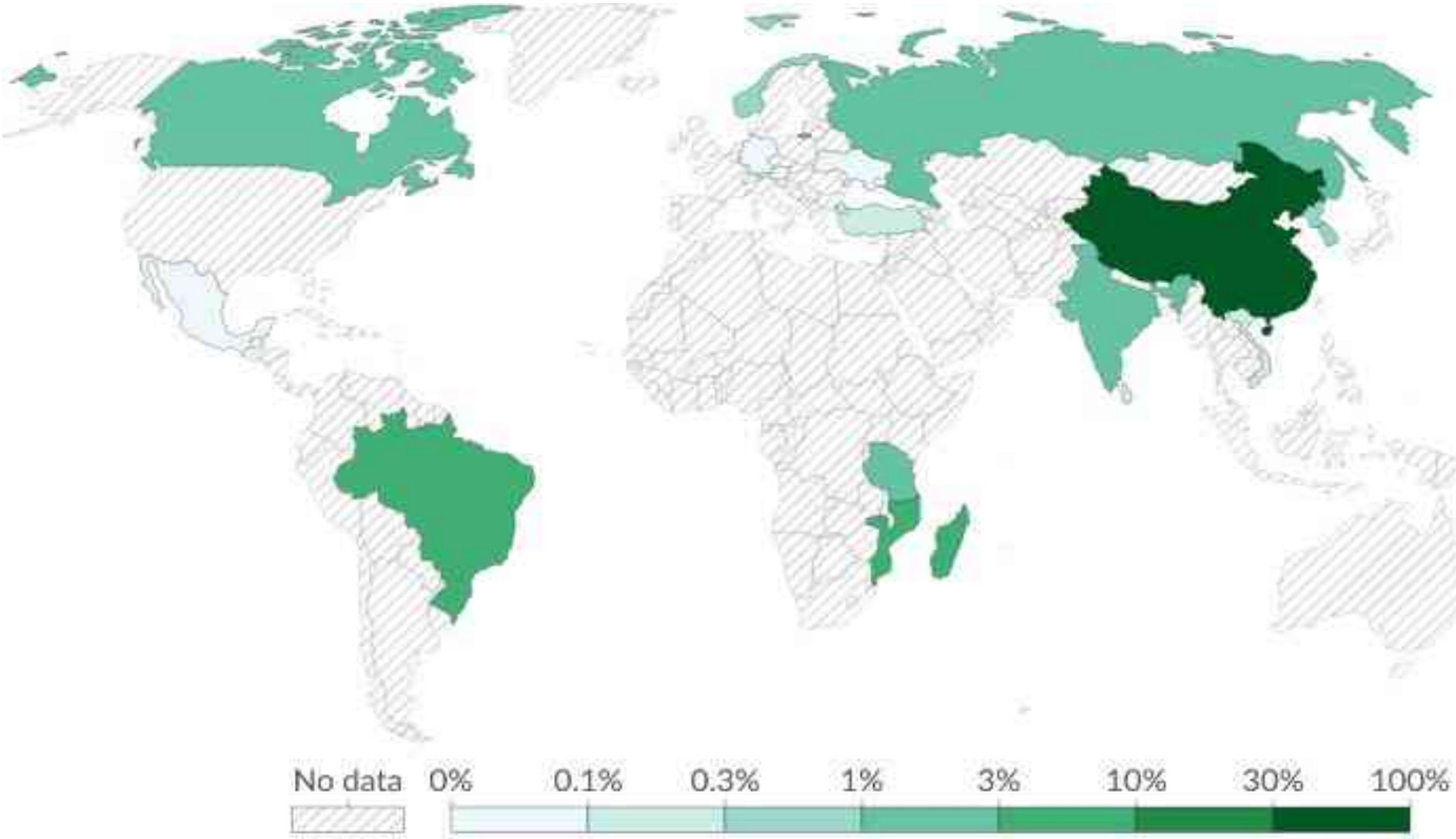
Source: USGS January 2026

Natural Graphite – Production (1,8 Mt) in 2025 – Shares of the total



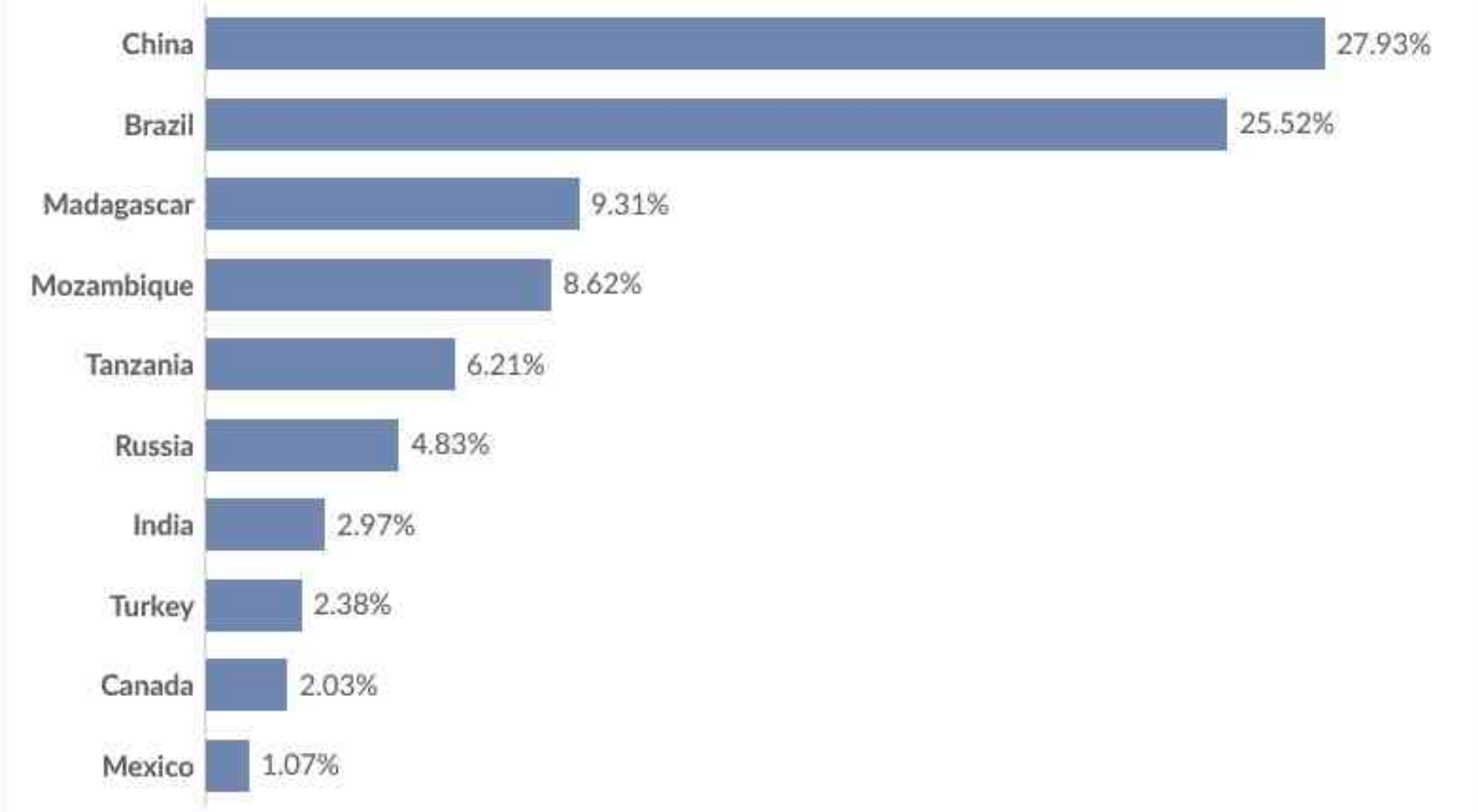
Source: Our World in Data 2025

Natural Graphite – Production (1,8 Mt) in 2025 – Shares of the total



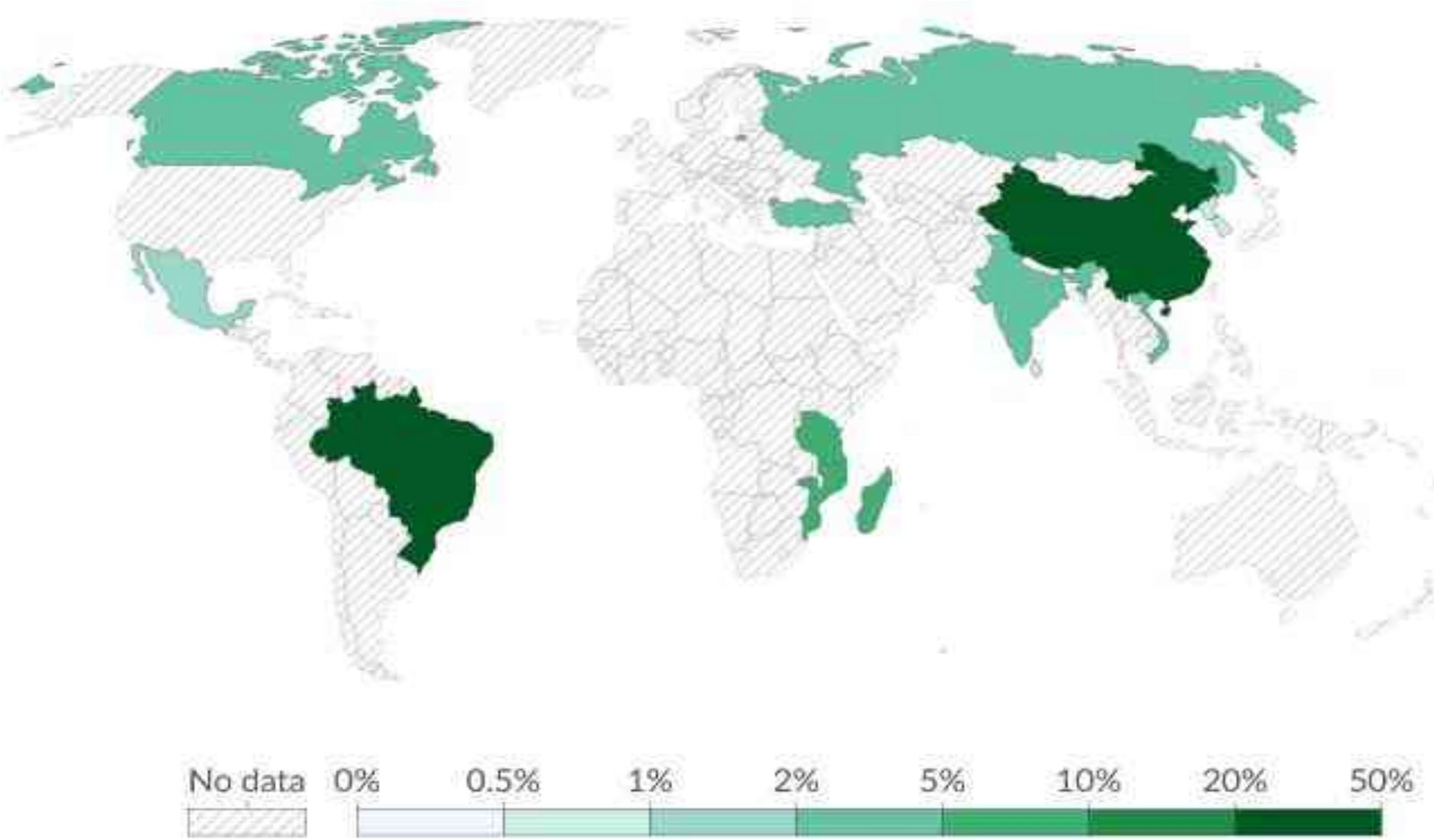
Source: Our World in Data 2025

Natural Graphite – Reserves (310 Mt) in 2025 – Shares of the total



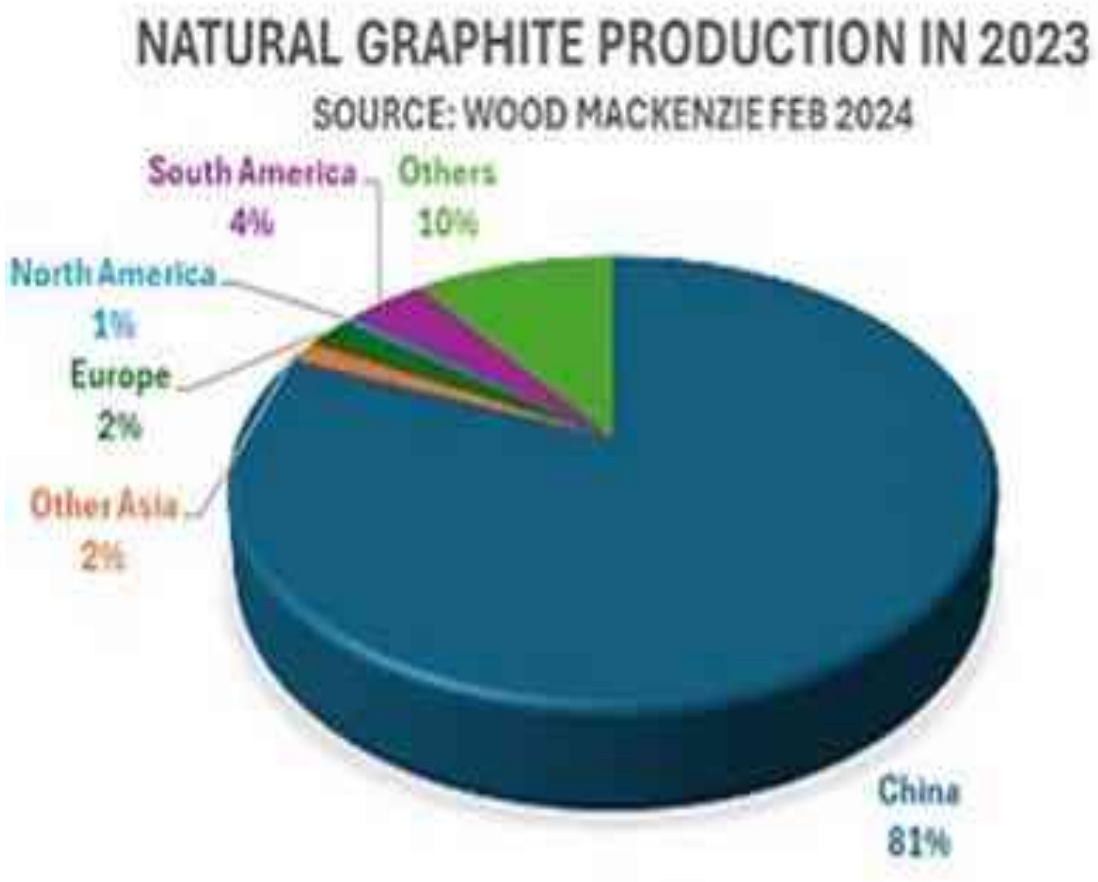
Source: Our World in Data 2025

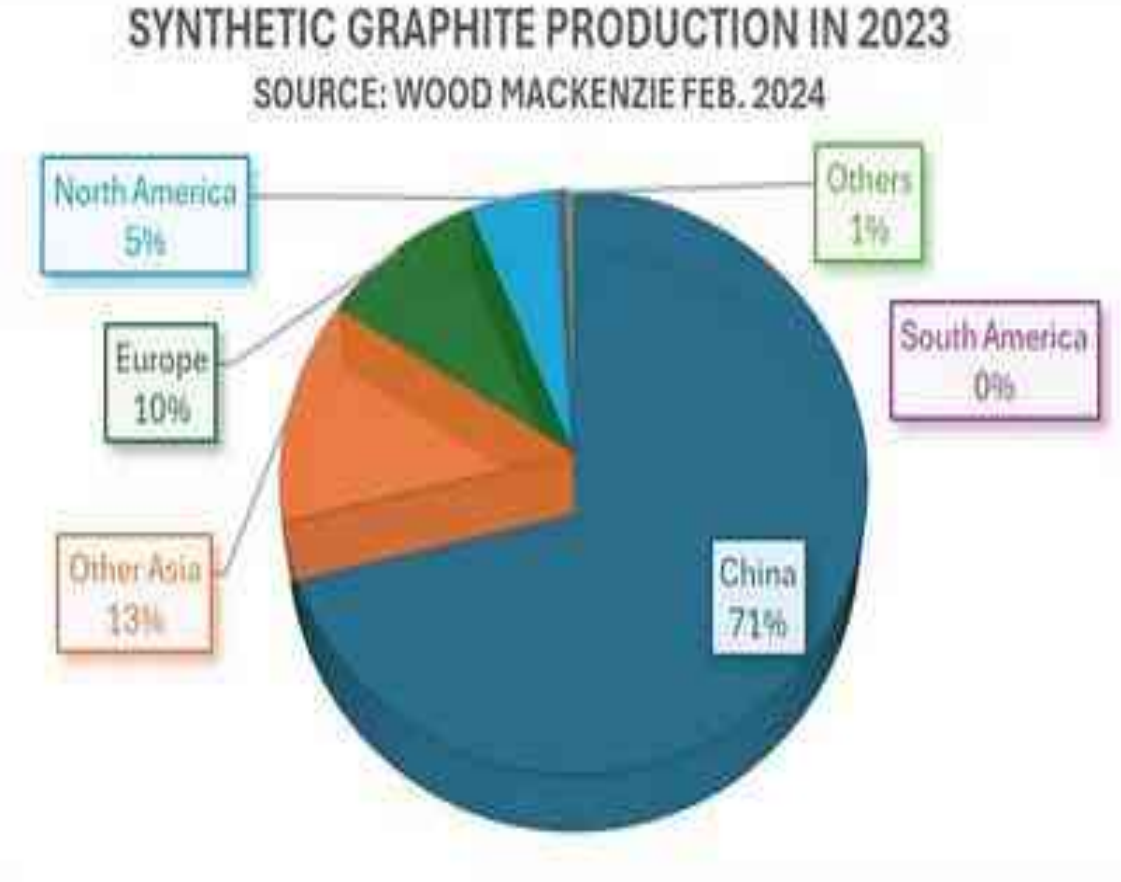
Natural Graphite – Reserves (310 Mt) in 2025 – Shares of the total



Source: Our World in Data 2025

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025



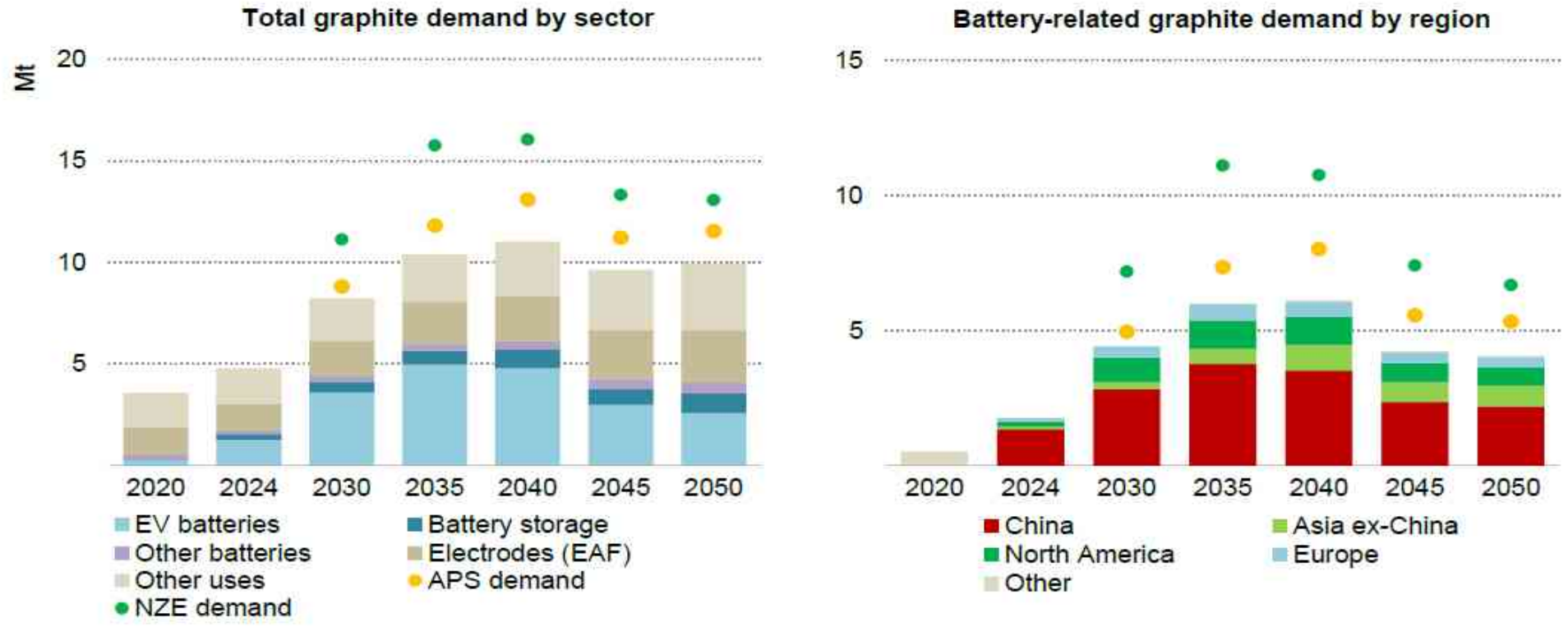


Source: CRM Alliance 2024

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025

Demand: EVs are driving the future of the graphite market, although the increasing use of silicon is expected to play a larger role in the longer term

Global graphite demand by sector and region in the STEPS



IEA. CC BY 4.0.

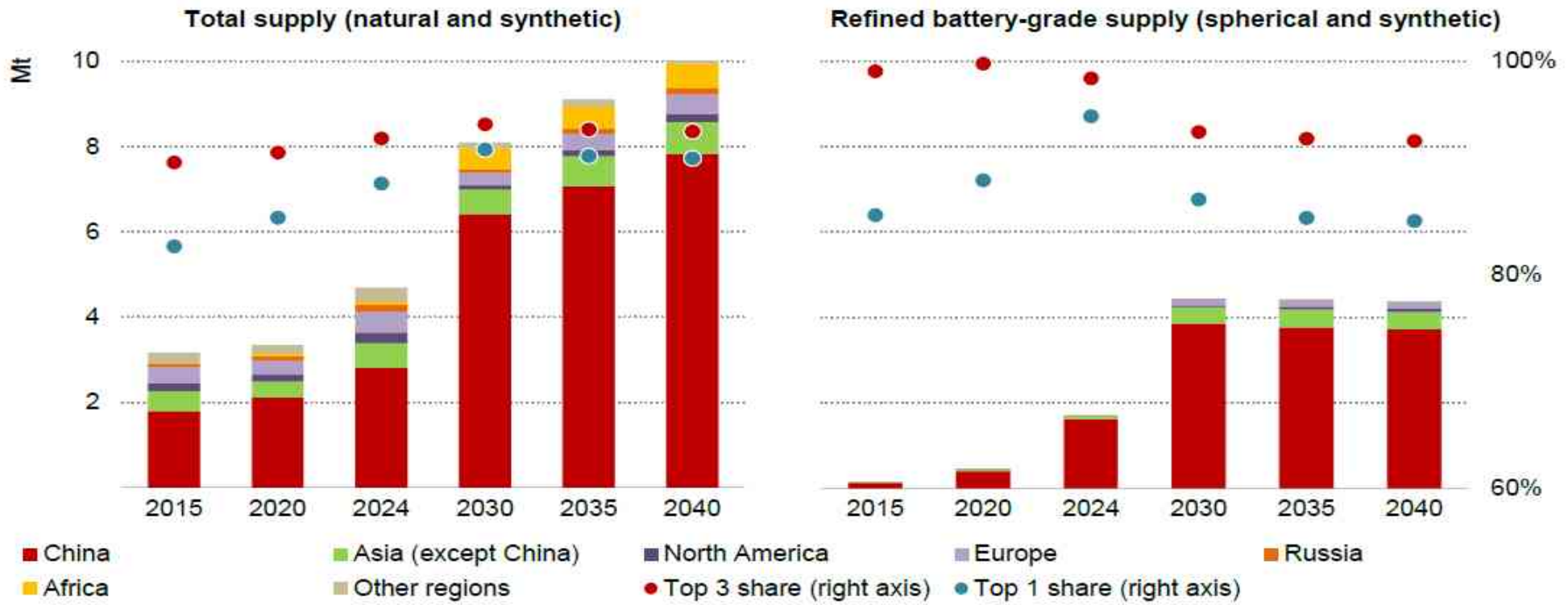
Note: EAF = electric arc furnace.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025

Supply: Despite progress in new projects in diversified regions, supply concentration remains durably high, particularly for battery-grade graphite

Total and battery-grade graphite supply from existing and announced projects in the base case

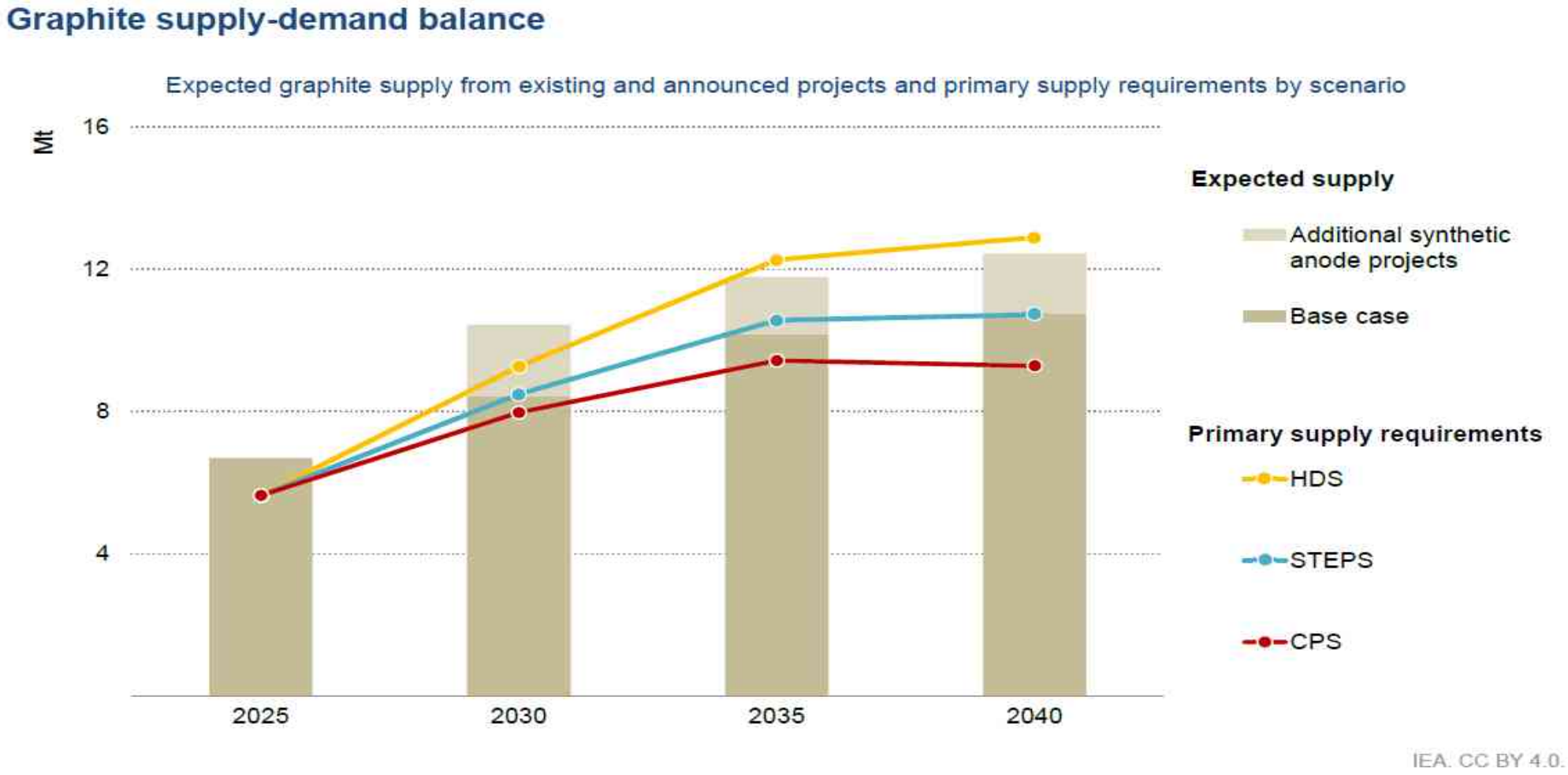


IEA. CC BY 4.0.

Notes: Total supply includes all grades of mined and synthetic graphite. Refined battery-grade supply includes spherical graphite made from natural flake graphite and synthetic anode production.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025



Notes: Mt = million tonnes; HDS = High Demand Scenario; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario. Primary supply requirements are calculated as the "total demand net of secondary supply" and include raw natural graphite and synthetic graphite. See Introduction section for definitions of the base and high-production cases.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025

Graphite demand

	Historical		Current Policies			Stated Policies			High Demand		
Unit: kt	2021	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	849	2 491	4 227	4 519	2 649	4 675	5 809	3 687	5 408	7 871	5 079
Electric vehicles	786	2 087	3 804	3 776	1 871	4 162	4 884	2 711	4 747	6 644	3 774
Battery storage	62	404	424	743	778	513	925	976	661	1 227	1 305
Other uses	3 391	3 287	3 906	5 009	5 961	3 975	5 138	6 170	4 031	5 383	6 444
Total demand	4 240	5 779	8 133	9 529	8 610	8 650	10 947	9 856	9 438	13 254	11 523
Share of clean energy	20%	43%	52%	47%	31%	54%	53%	37%	57%	59%	44%

Notes: kt = kilotonnes. Demand covers raw natural graphite and synthetic graphite.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

Graphite (Natural & Synthetic)
Natural Graphite: Reserves (310 Mt) and Production (1,8 Mt) in 2025

Graphite supply

	Mining (natural graphite)					Refined battery-grade supply			
	Historical		Base case			Historical		Base case	
Unit: kt	2021	2025	2030	2040		2021	2025	2030	2040
China	1 234	1 432	1 239	1 337	China	638	2 139	3 026	4 039
Madagascar	82	70	170	165	Japan	41	68	149	165
Mozambique	77	67	259	368	Indonesia	0	32	93	103
Tanzania	0	62	263	283	United States	0	13	15	17
Brazil	67	64	99	84	Korea	0	5	10	11
Russia	28	28	30	49	Germany	0	5	10	10
Rest of world	51	51	154	174	Rest of world	4	3	53	121
World	1 540	1 774	2 214	2 460	World	683	2 266	3 356	4 467
Top 3 share	90%	88%	80%	81%	Top 3 share	100%	99%	97%	96%

Notes: kt = kilotonnes. Refined battery-grade supply includes spherical graphite made from natural flake graphite and synthetic anode production.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

The case of Nickel

Nickel
From Resource to Consumer

An essential element for the stainless steel industry (corrosion, high temperature,…)

Moderate geological criticality.

Land resources # 350 Mt.

Reserves # 130+ Mt

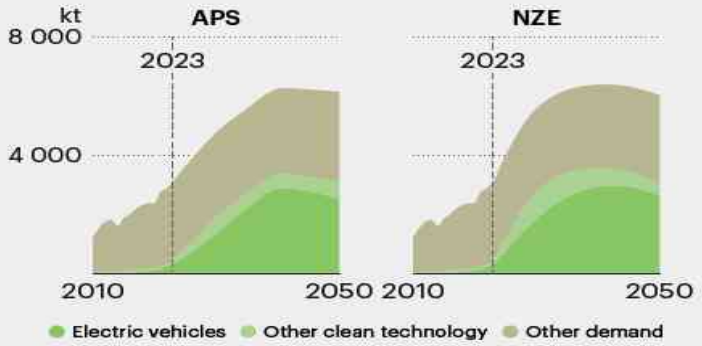
Cumulative needs for industry/Known resources # 40% in 2050 to cope with the SDS IEA Scenario.

Nickel – Reserves (>140 Mt) and Production (3,9 Mt) in 2025

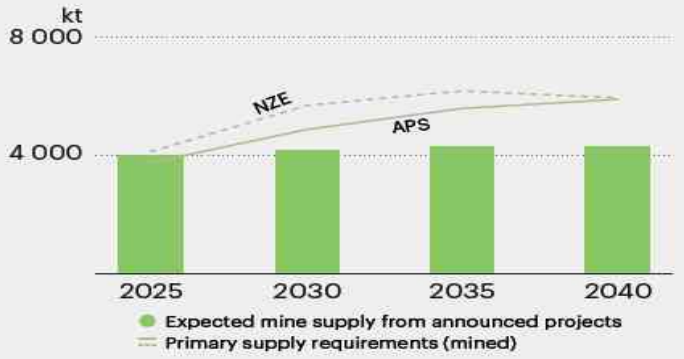
Nickel

Ni

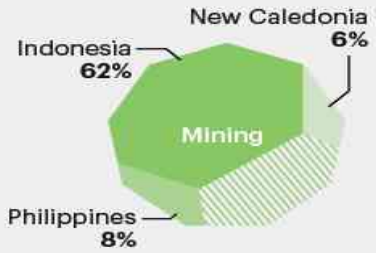
Demand outlook

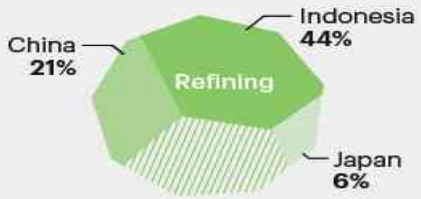


Mining requirements



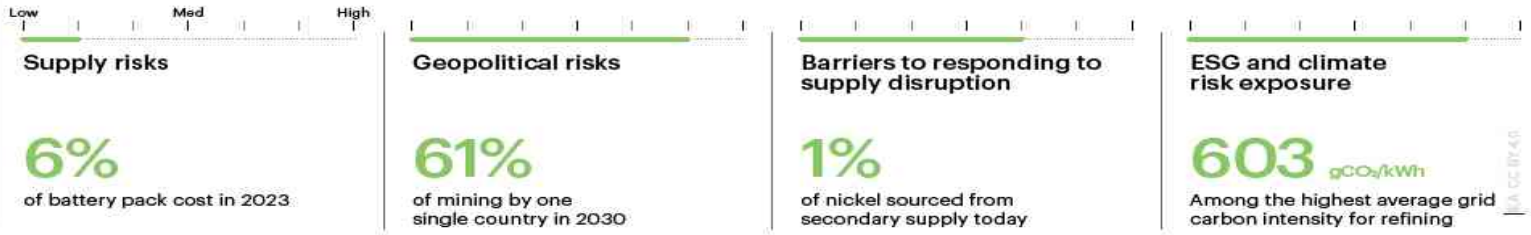
Top three producers 2030





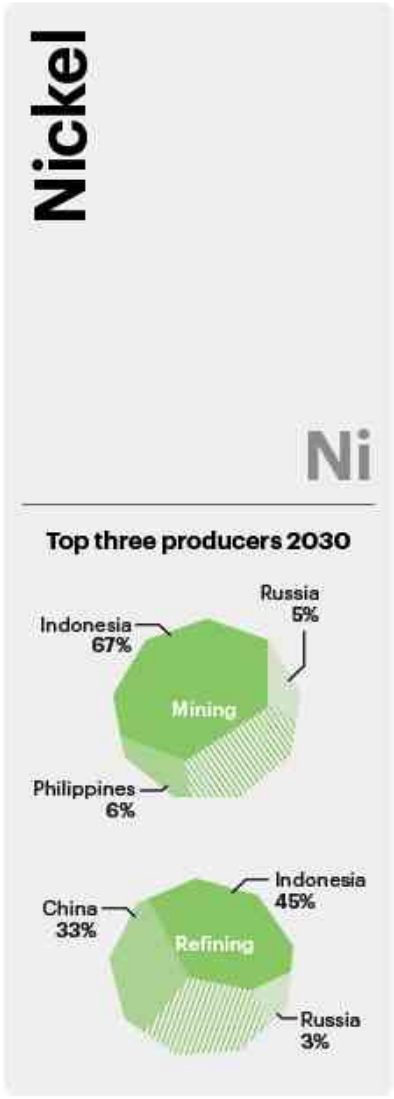
Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	**240**	**478**	**1 953**	**3 381**
Other uses (kt)	2 519	2 627	2 802	2 857
Total demand (kt)	**2 759**	**3 104**	**4 754**	**6 238**
Secondary supply and reuse (kt)	10	43	139	613
Primary supply requirements (kt)	**2 749**	**3 061**	**4 615**	**5 625**
Share of top three mining countries	60%	69%	76%	83%
Share of top three refining countries	66%	71%	71%	73%

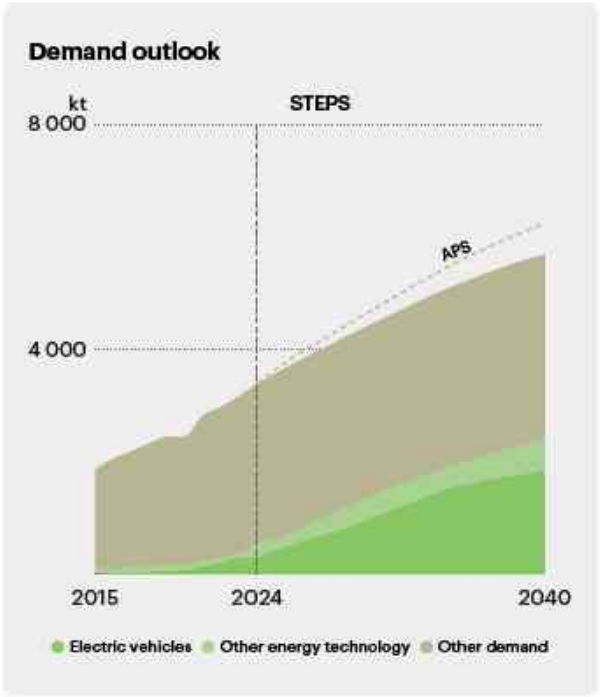
Clean energy transition risk assessment

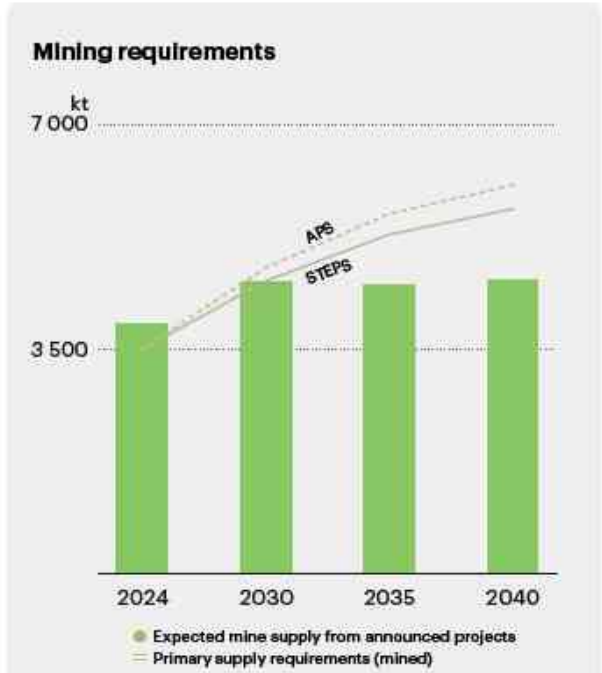


Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Nickel – Reserves (>140 Mt) and Production (3,9 Mt) in 2025







STEPS	2021	2024	2030	2040
Cleantech demand (kt)	226	562	1 349	2 381
Other uses (kt)	2 600	2 809	3 039	3 304
Total demand (kt)	2 825	3 371	4 389	5 685
Secondary supply and reuse (kt)	25	62	63	295
Primary supply requirements (kt)	2 709	3 484	4 326	5 382
Share of top three mining countries	64%	77%	78%	84%
Share of top three refining countries	66%	78%	81%	83%

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Nickel – Reserves (>140 Mt) and Production (3,9 Mt) in 2025

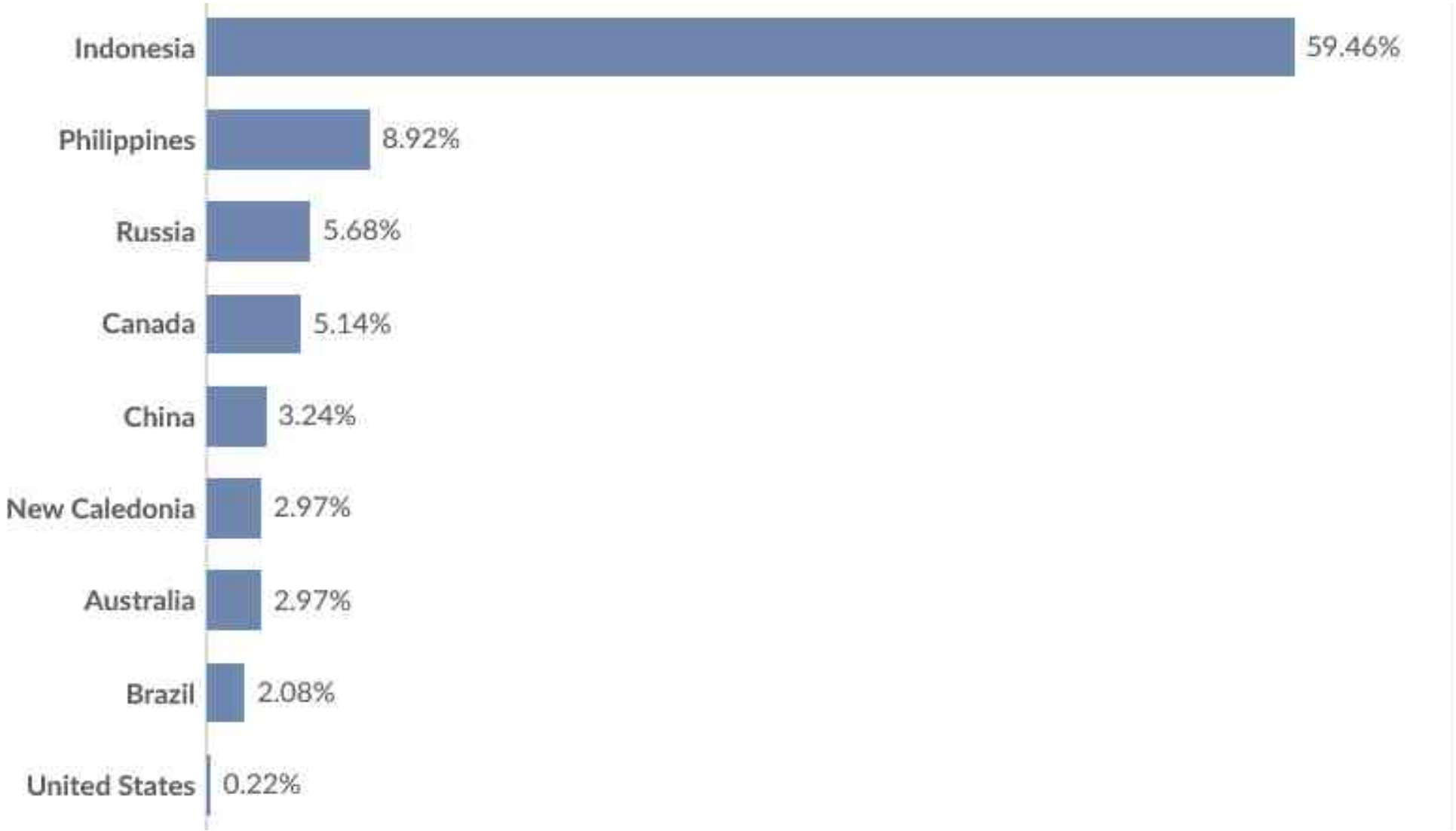
World Mine Production and Reserves: Production in 2024 for Canada was revised significantly based on a Government report. Reserves for Australia, Indonesia, and the United States were revised based on company and Government reports.

	Mine production		Reserves[8]
	2024	2025[e]	
United States	7,490	10,000	340,000
Australia	98,000	45,000	[9]25,000,000
Brazil	67,500	70,000	16,000,000
Canada	125,000	140,000	2,200,000
China	[e]115,000	120,000	4,400,000
Indonesia	2,310,000	2,600,000	62,000,000
New Caledonia[10]	116,000	140,000	7,100,000
Philippines	354,000	270,000	4,800,000
Russia	205,000	200,000	8,300,000
Other countries	308,000	290,000	>9,100,000
World total (rounded)	3,710,000	3,900,000	>140,000,000

World Resources:[8] Globally, nickel resources have been estimated to contain more than 350 million tons of nickel, with 54% in laterites and 35% in magmatic sulfide deposits. Hydrothermal systems such as iron-nickel alloy, sedimentary-hosted polymetallic, and volcanogenic massive sulfide deposits, as well as seafloor manganese crusts and nodules contain 10%, and miscellaneous resources such as tailings, 1%.

Source: USGS January 2026

Nickel – Production (3,9 Mt) in 2025 – Shares of the total



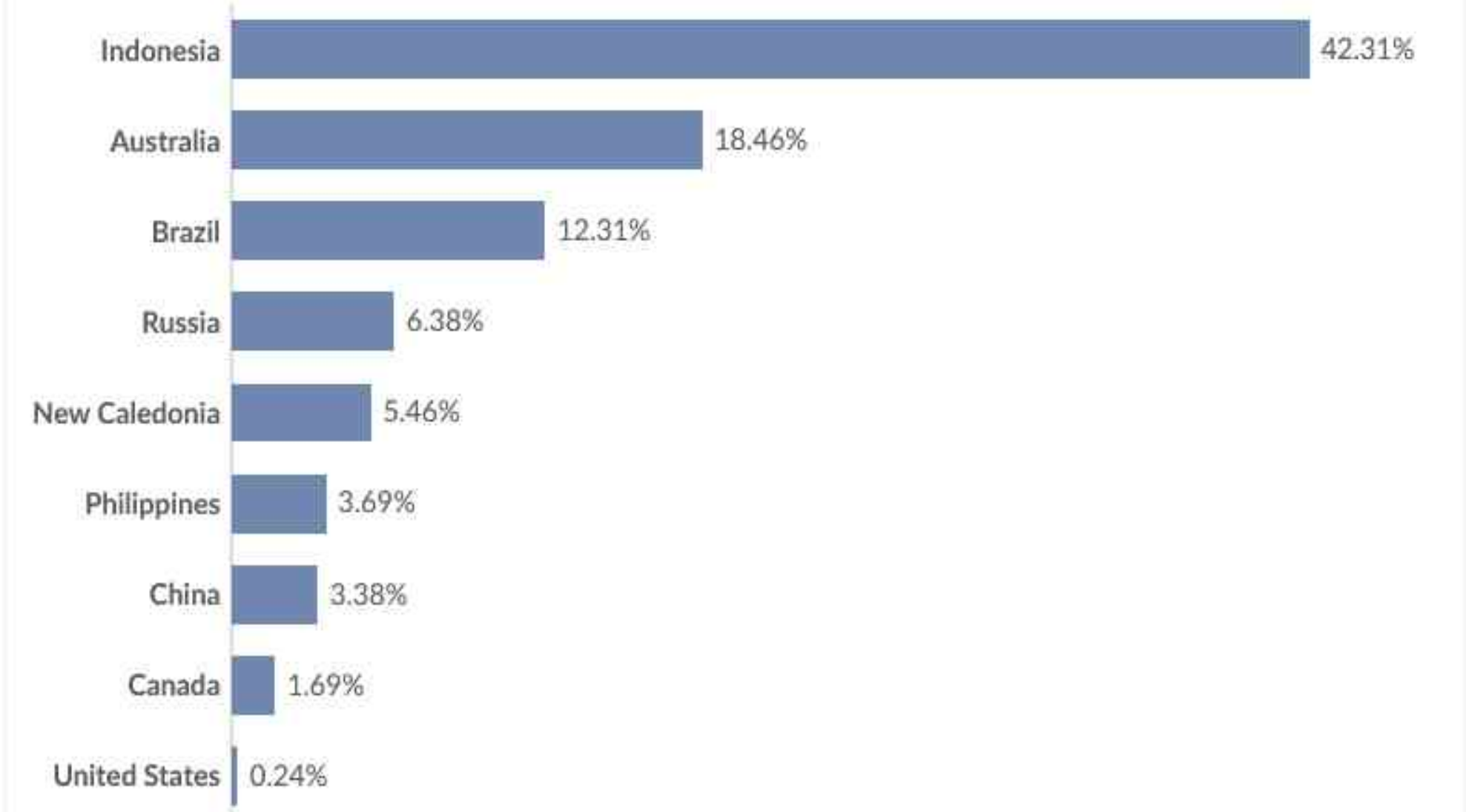
Source: Our World in Data 2025

Nickel – Production (3,9 Mt) in 2025 – Shares of the total



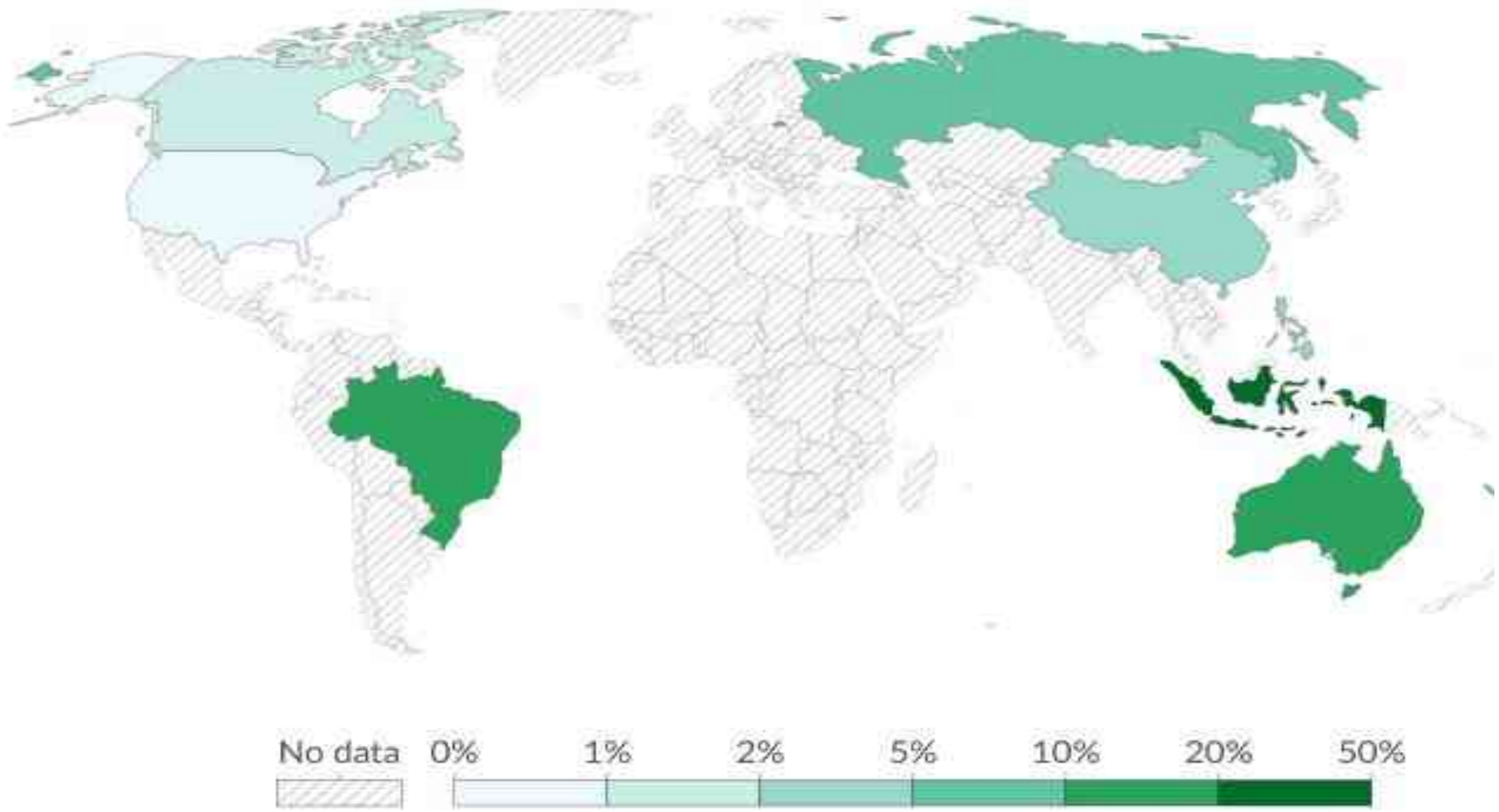
Source: Our World in Data 2025

Nickel – Reserves (140 Mt) in 2025 – Shares of the total



Source: Our World in Data 2025

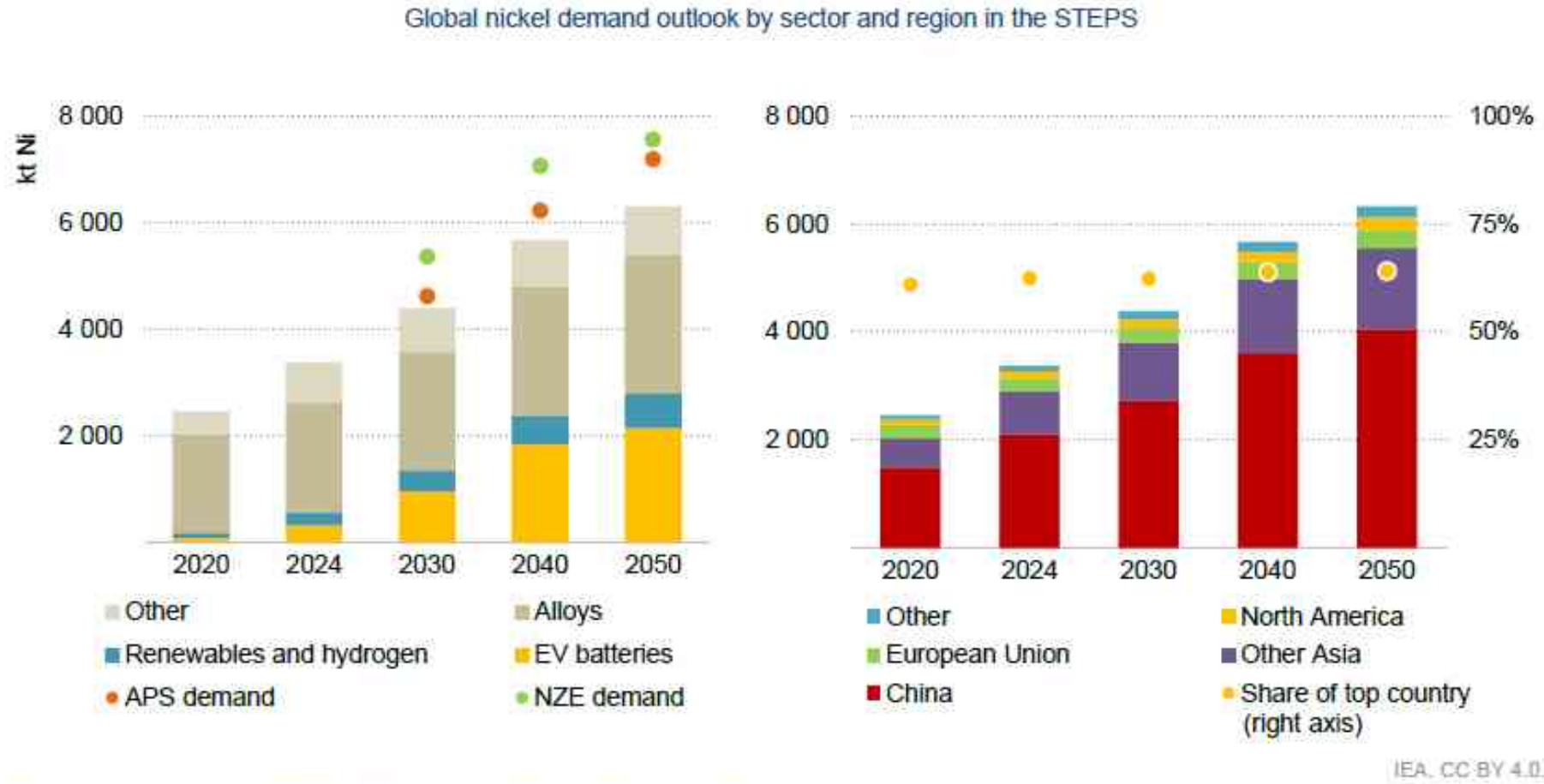
Nickel – Reserves (140 Mt) in 2025 – Shares of the total



Source: Our World in Data 2025

Nickel – Reserves (140 Mt) and Production (3,9 Mt) in 2025

Demand: Growth in nickel demand is driven by energy applications, with China as the largest consumer of primary nickel, followed by Indonesia

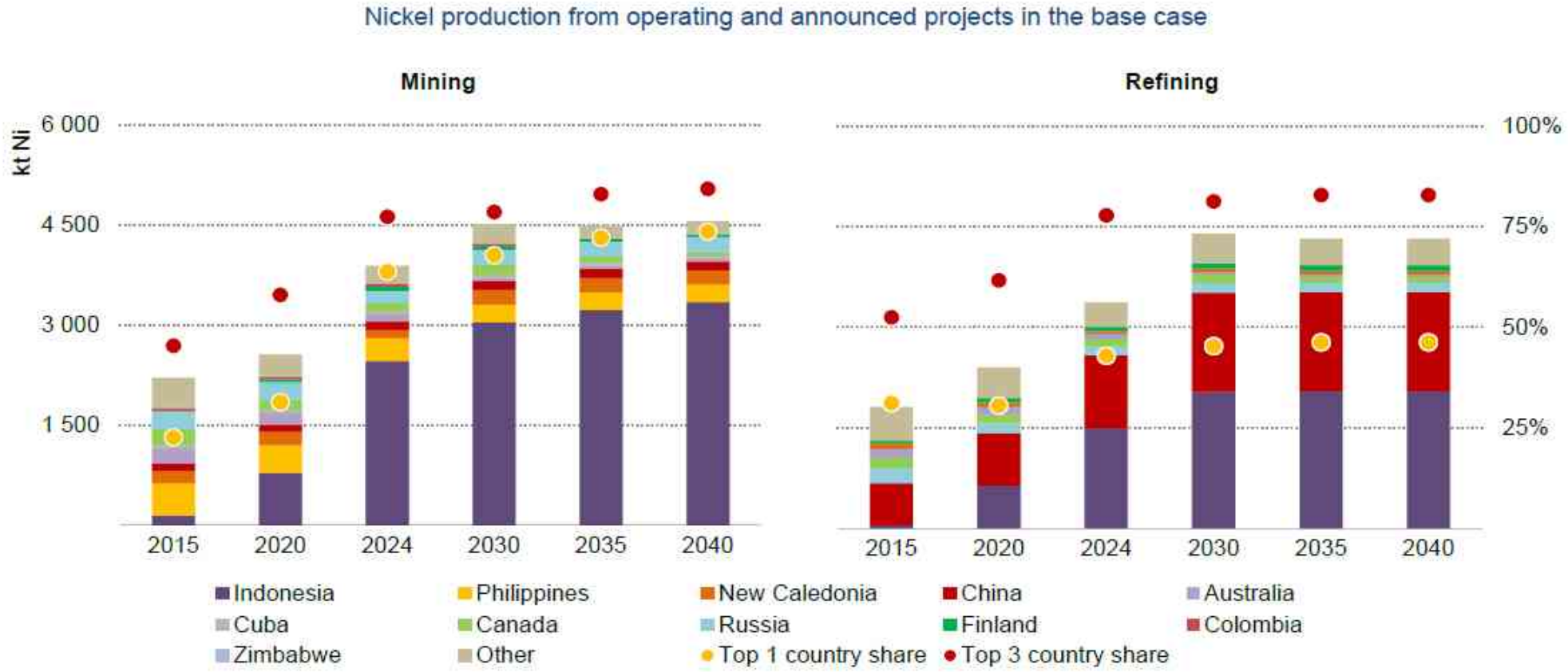


Note: Alloys include demand for both stainless steel and for non-ferrous applications.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Nickel – Reserves (140 Mt) and Production (3,9 Mt) in 2025

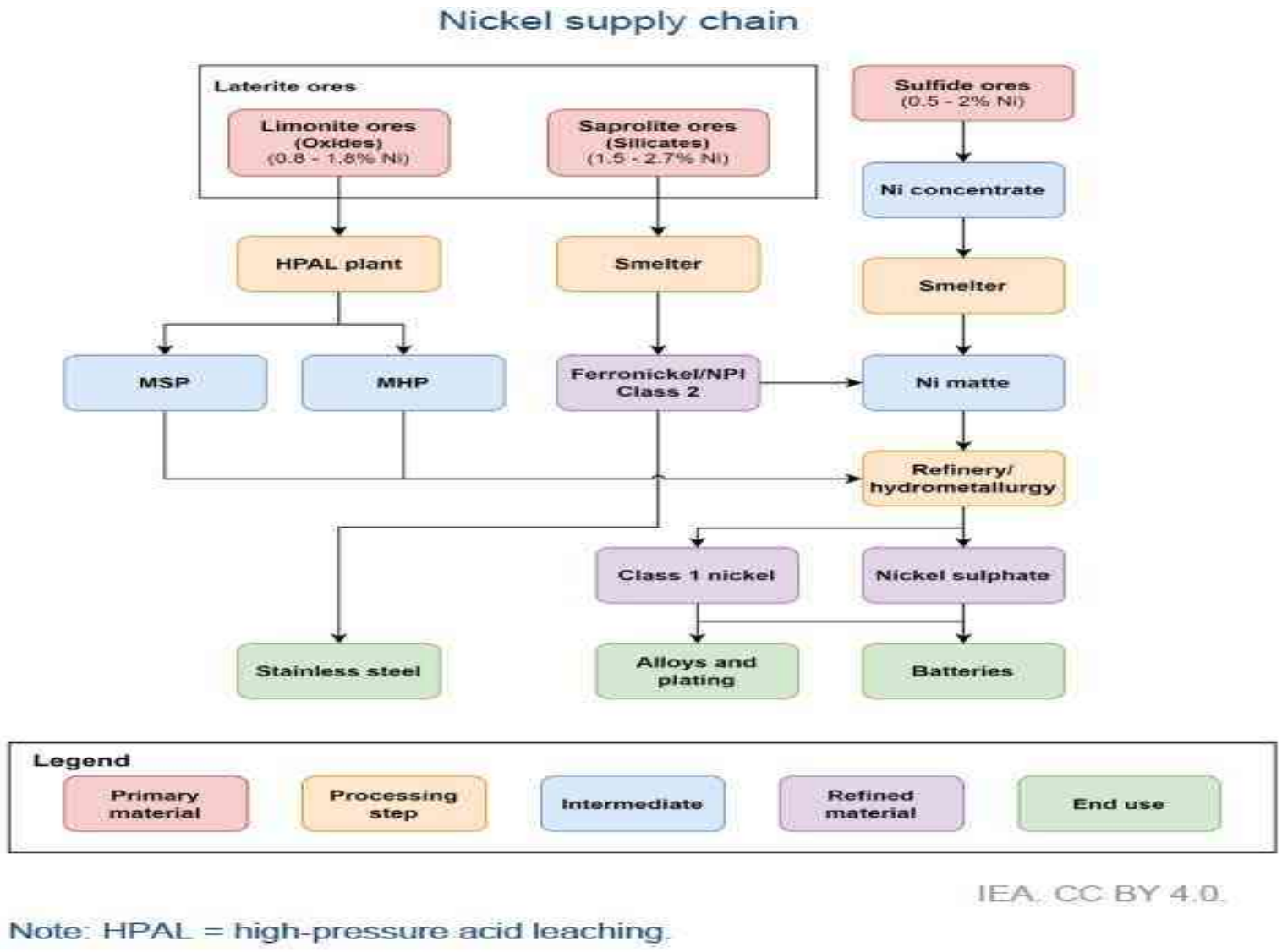
Supply: Geographical concentration for mining and refining increases as projects in diversified regions are impacted by low prices



IEA. CC BY 4.0.

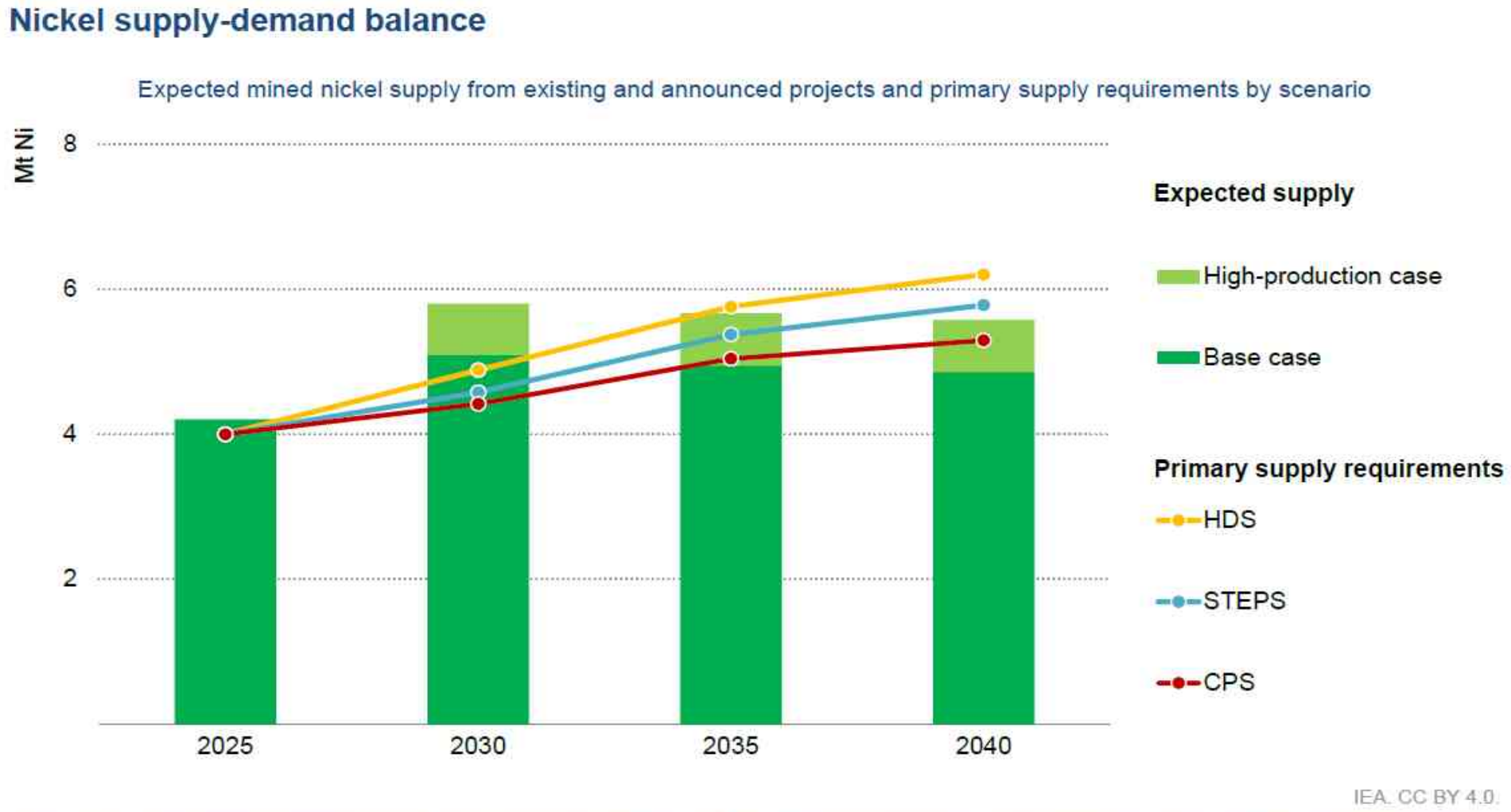
Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Nickel – Reserves (140 Mt) and Production (3,9 Mt) in 2025



Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Nickel – Reserves (140 Mt) and Production (3,9 Mt) in 2025



Notes: HDS = High Demand Scenario; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario. Based on mined output. Primary supply requirements are calculated as the "total demand net of secondary supply", also accounting for losses during refining operations. See Introduction section for definitions of the base and high-production cases.

Source: IEA Global Critical Minerals Outlook 2026 – May 2026

Nickel – Reserves (140 Mt) and Production (3,9 Mt) in 2025

Nickel demand

	Historical		Current Policies			Stated Policies			High Demand		
Unit: kt Ni	2021	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	308	625	1 276	1 932	2 051	1 409	2 403	2 763	1 698	3 253	3 963
Electric vehicles	222	439	909	1 449	1 448	989	1 851	2 054	1 119	2 500	2 839
Battery storage	9	28	59	160	305	71	199	382	92	264	512
Other	77	159	308	323	297	348	353	326	486	488	611
Other uses	2 536	2 906	3 055	3 429	3 746	3 055	3 429	3 746	3 100	3 270	3 375
Total demand	2 845	3 532	4 331	5 361	5 797	4 464	5 832	6 509	4 799	6 523	7 338
Share of clean energy	11%	18%	29%	36%	35%	32%	41%	42%	35%	50%	54%

Note: kt = kilotonnes.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

Nickel – Reserves (140 Mt) and Production (3,9 Mt) in 2025

Nickel supply

	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt Ni	2021	2025	2030	2040		2021	2025	2030	2040
Indonesia	1 105	2 637	3 567	3 568	Indonesia	907	1 681	2 080	2 081
Philippines	476	482	308	308	China	746	1 160	1 194	1 194
Russia	205	192	218	218	Canada	113	125	134	90
China	108	147	161	152	Russia	121	123	142	142
New Caledonia	186	138	207	207	Japan	128	108	107	107
Canada	134	138	147	52	Norway	91	100	92	92
Brazil	76	85	82	82	Brazil	61	64	73	65
Rest of world	480	388	408	271	Rest of world	541	367	409	387
World	2 770	4 207	5 098	4 858	World	2 709	3 729	4 231	4 159
Top 3 share	65%	79%	80%	84%	Top 3 share	66%	80%	81%	82%

Notes: kt = kilotonnes. Nickel refining includes nickel that is processed into a metal, oxide, nickel pig iron, ferronickel, or sulphate and excludes outputs from intermediate production steps.

Source: IEA Global Critical Minerals Outlook 2026 – May 2026

The case of Manganese

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025



Fig. 1. Distribution, size and types of terrestrial manganese deposits. Data from Cannon et al. [18]. Numerous small to moderate sized deposits are located in China, the United States and Canada, but are not depicted here. World map sourced from Vecteezy.

Source: Elsevier 2025

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025

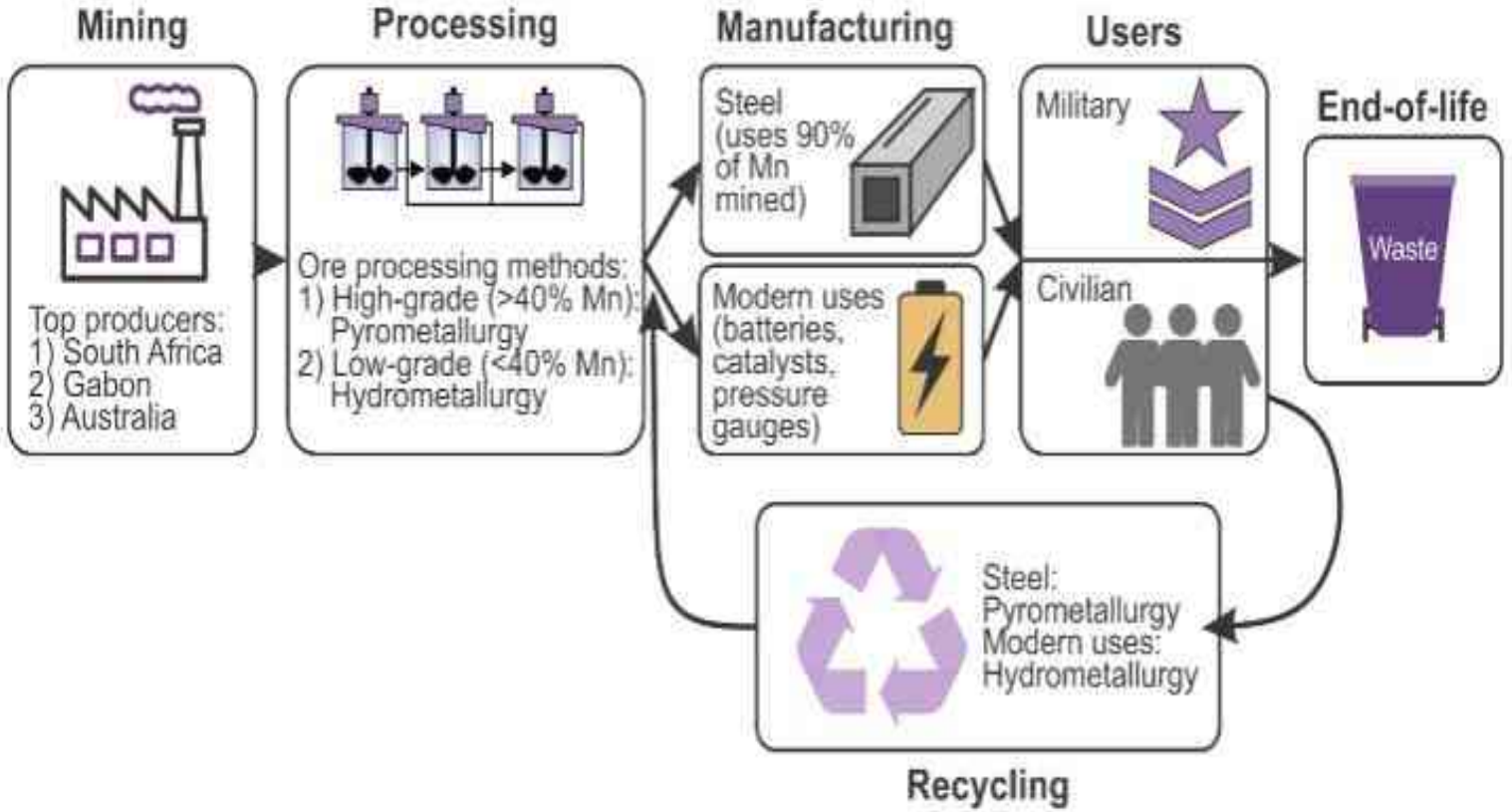
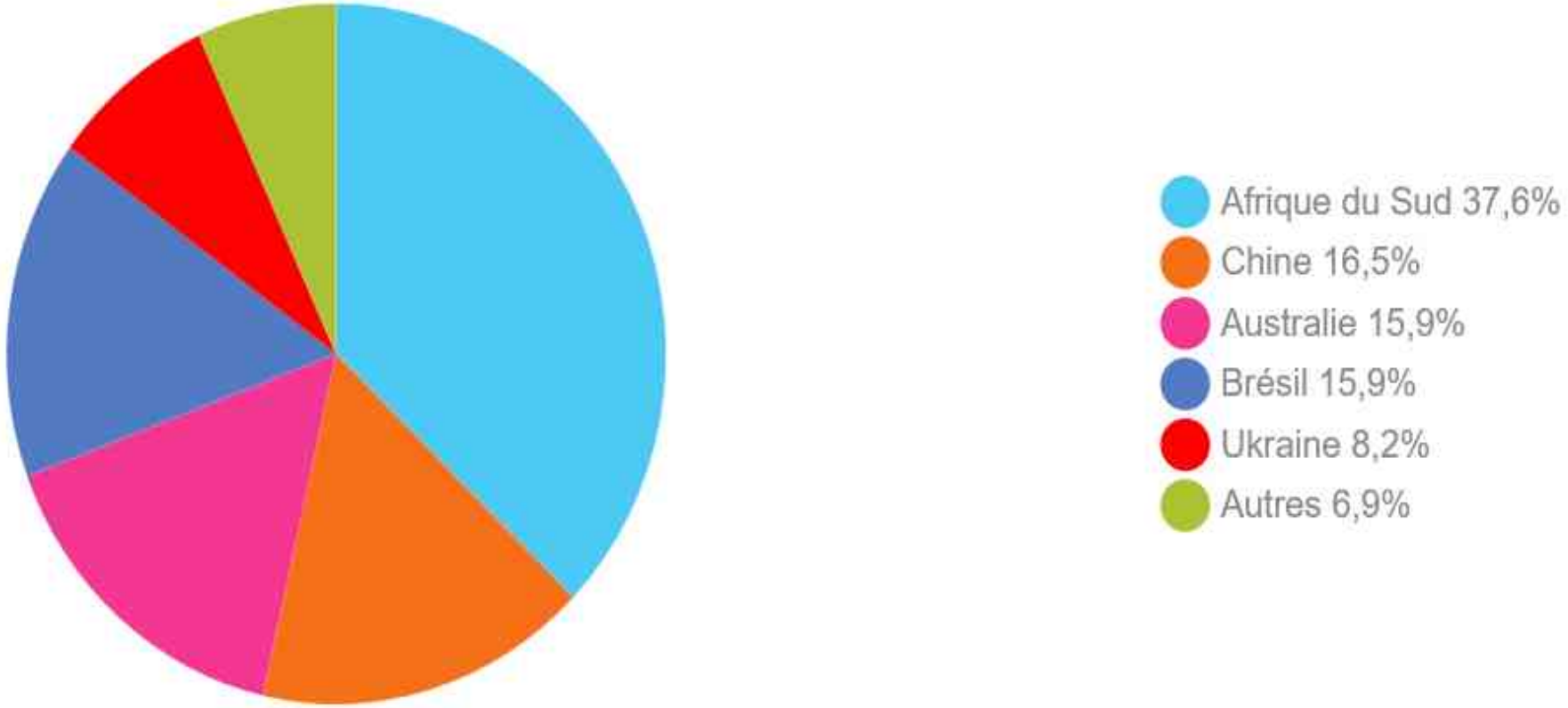


Fig. 3. Simplified manganese supply chain framework. The framework begins from the left and progresses to the right. Details of the ore processing methods can be obtained in Table 2.

Source: Elsevier 2025

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025

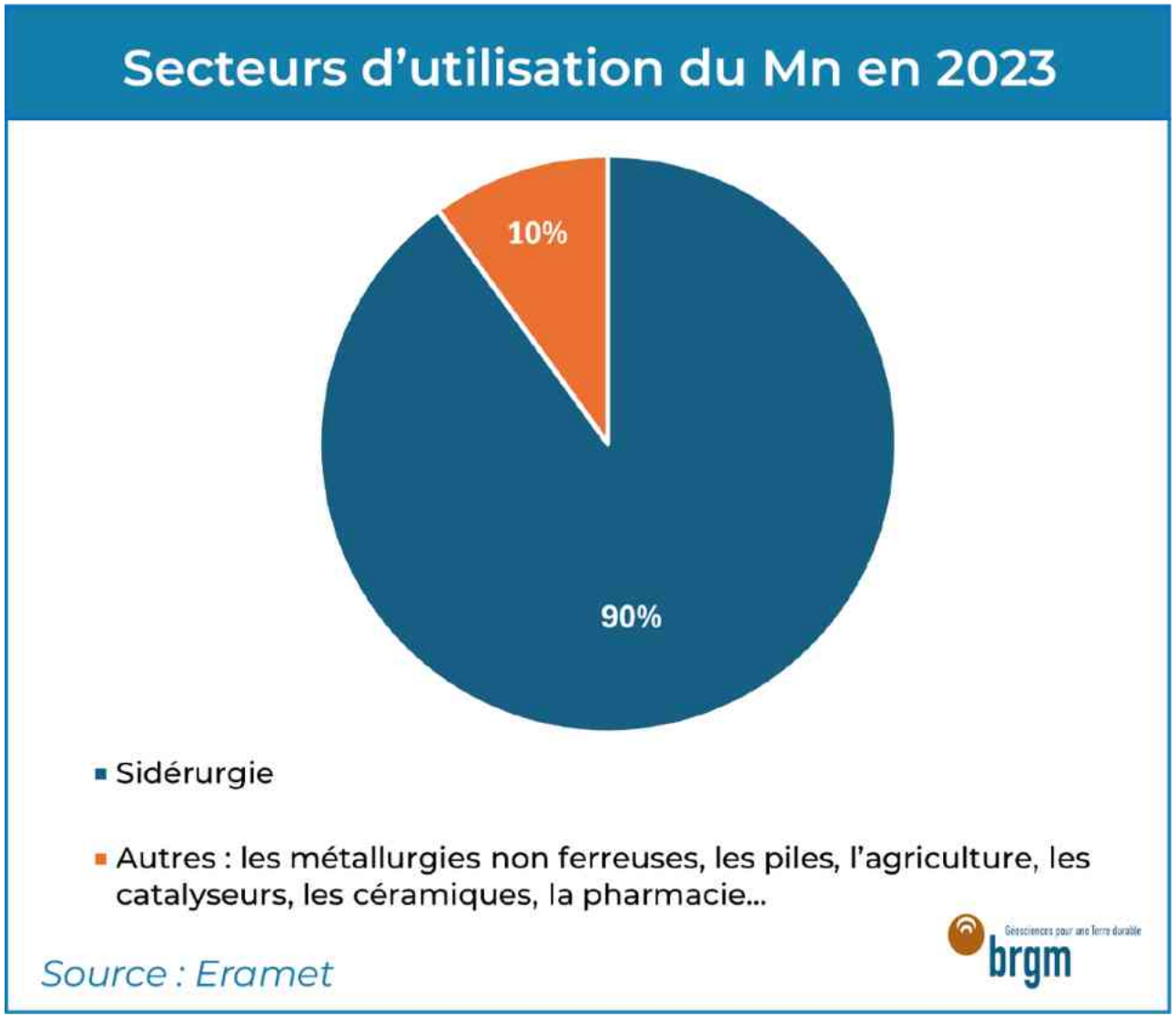
Répartition mondiale des réserves de manganèse en 2022



Réserves mondiales en 2022 : **1 700 Mt Mn**

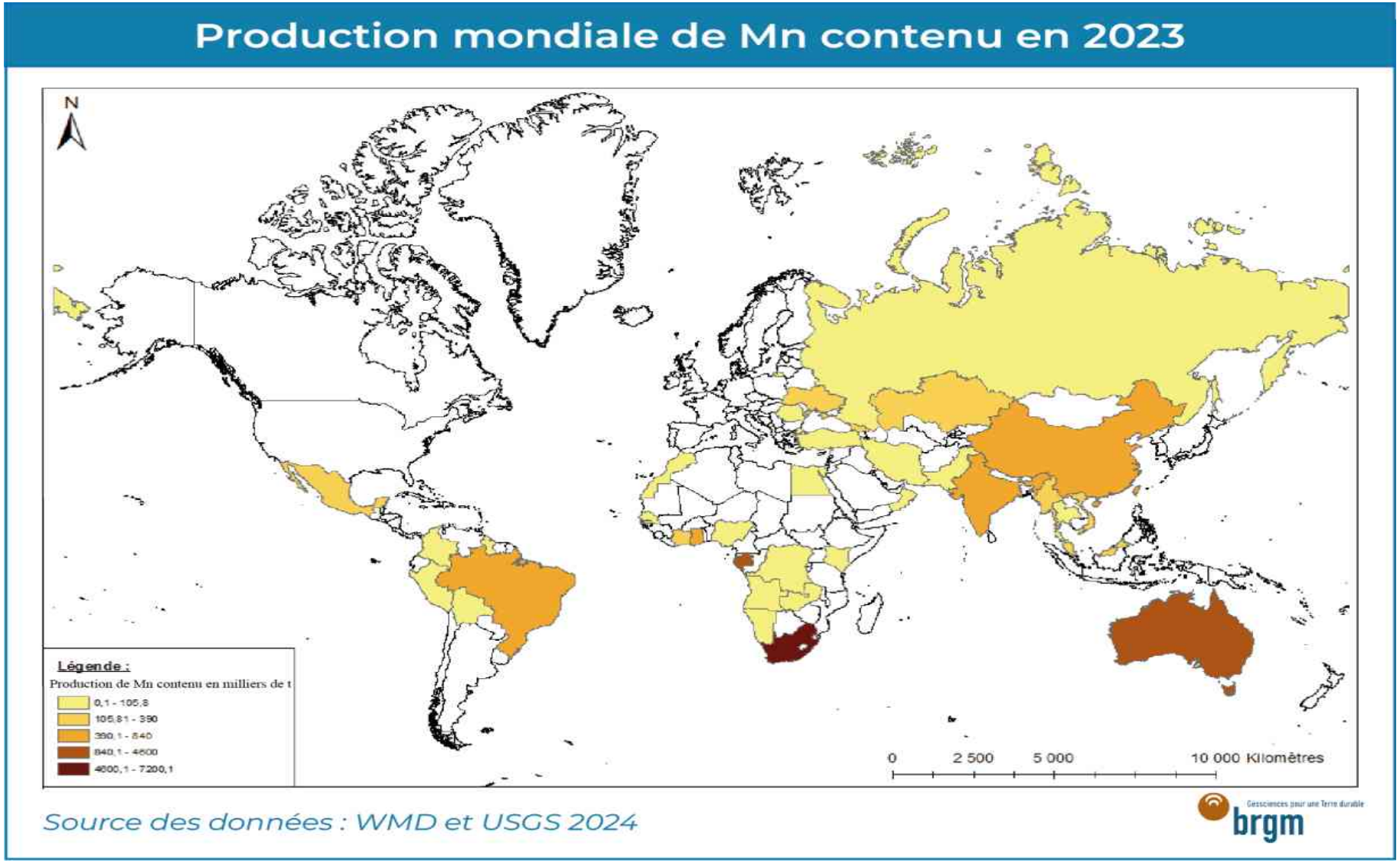
Source: Mineralinfo – February 2025

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025



Source: Mineralinfo – February 2025

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025



Source: Mineralinfo – February 2025

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025

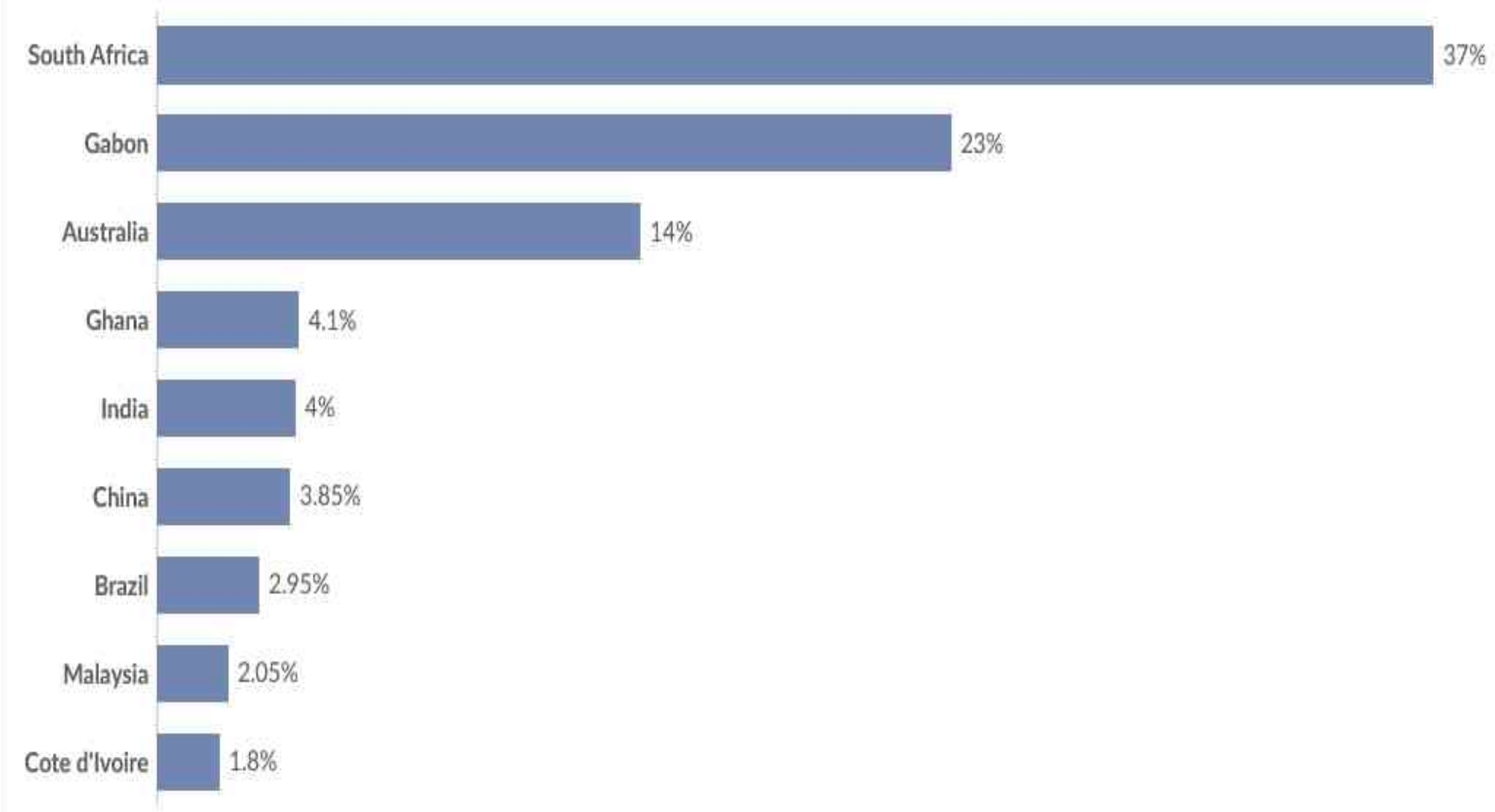
World Mine Production (manganese content) and Reserves: Significant revisions were made to the 2024 production for Australia and Ghana based on company and Government reports. Reserves for Australia, Brazil, China, Malaysia, and South Africa were revised based on company and Government reports.

	Mine production		Reserves[10]
	2024	2025[e]	
United States	—	—	—
Australia	[e]1,600	1,600	[11]580,000
Brazil	705	800	300,000
China	690	700	260,000
Côte d'Ivoire	340	350	NA
Gabon	4,640	5,000	61,000
Ghana	1,280	2,000	13,000
India	731	790	34,000
South Africa	7,490	7,600	550,000
Other countries	1,240	1,300	Small
World total (rounded)	18,700	20,000	1,800,000

World Resources:[10] Land-based manganese resources are large but irregularly distributed; those in the United States are very low grade and have potentially high extraction costs. South Africa accounts for an estimated 70% of the world's manganese resources.

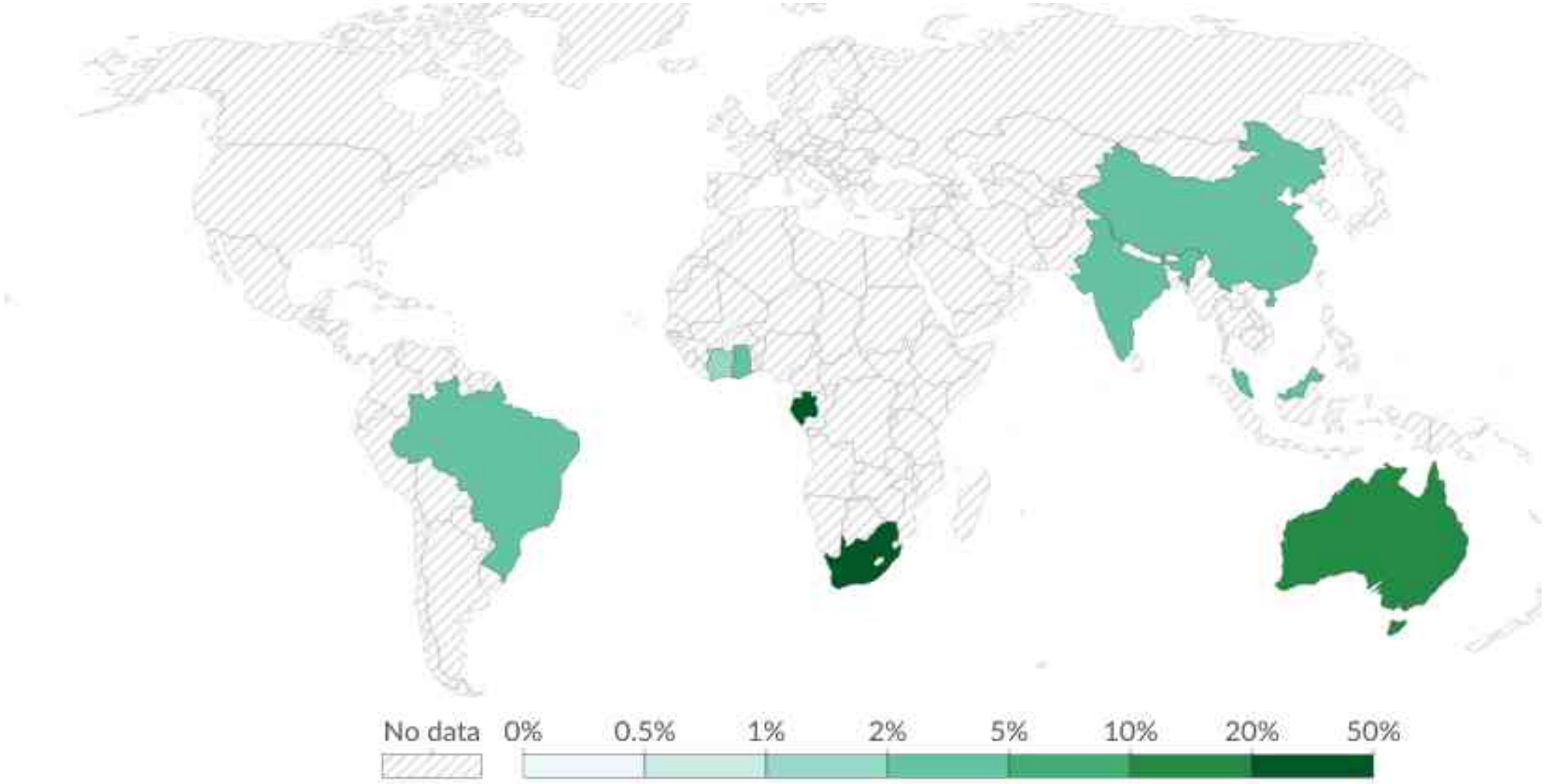
Source: USGS January 2026

Manganese – Production (20 Mt) in 2025 – Shares of the total



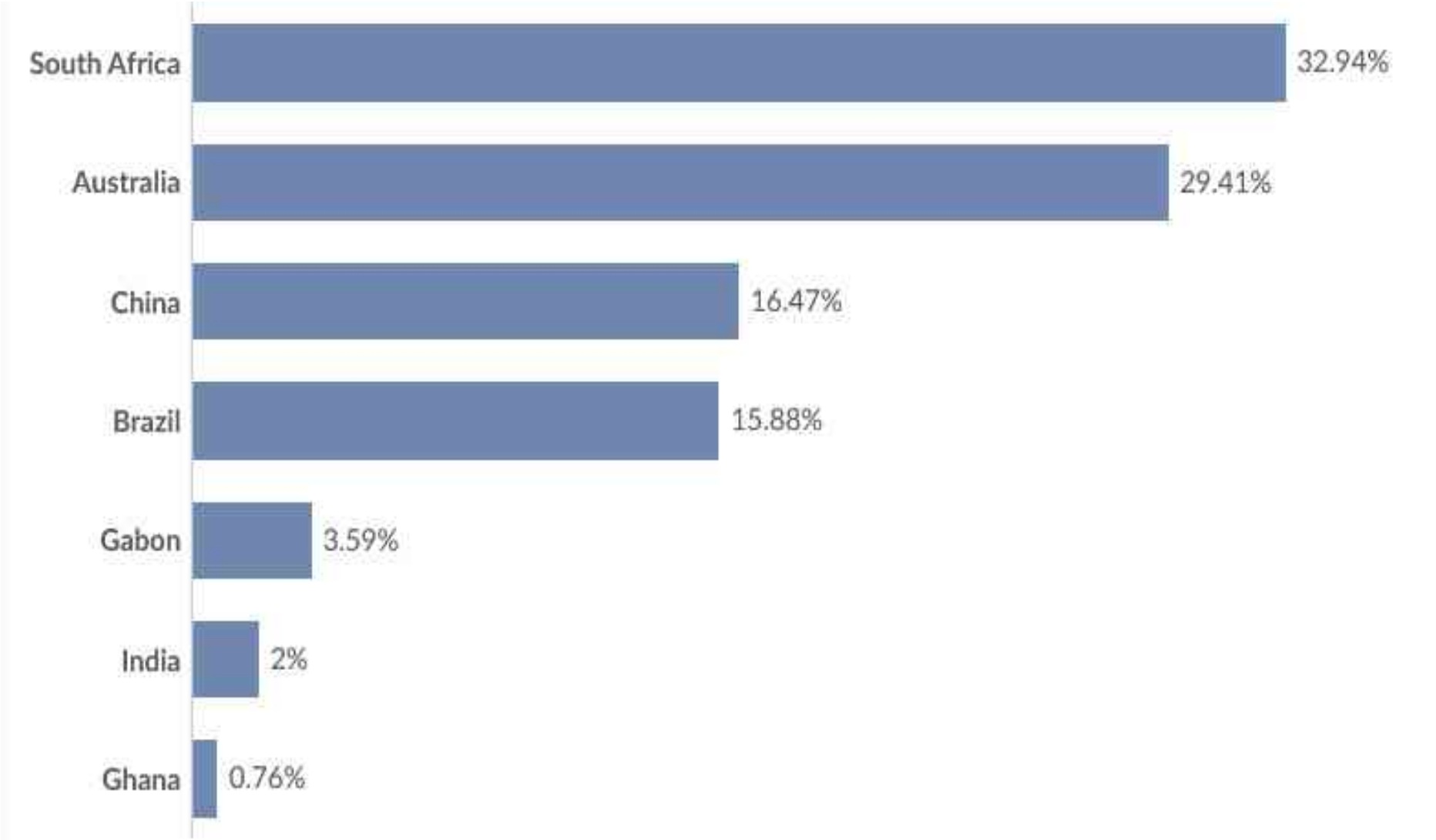
Source: Our World in Data 2025

Manganese – Production (20 Mt) in 2025 – Shares of the total



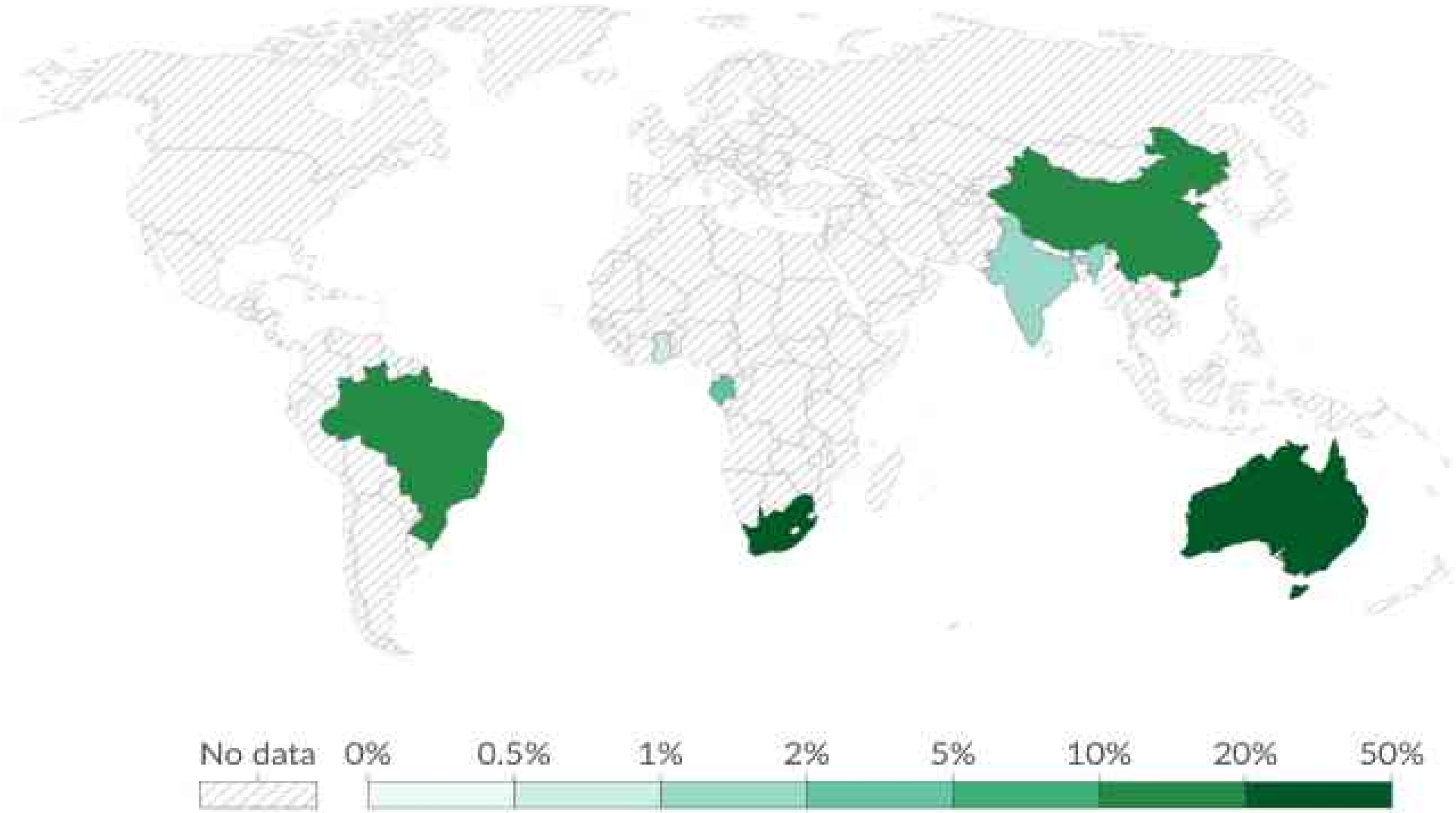
Source: Our World in Data 2025

Manganese – Reserves (1,8 Gt) in 2025 – Shares of the total



Source: Our World in Data 2025

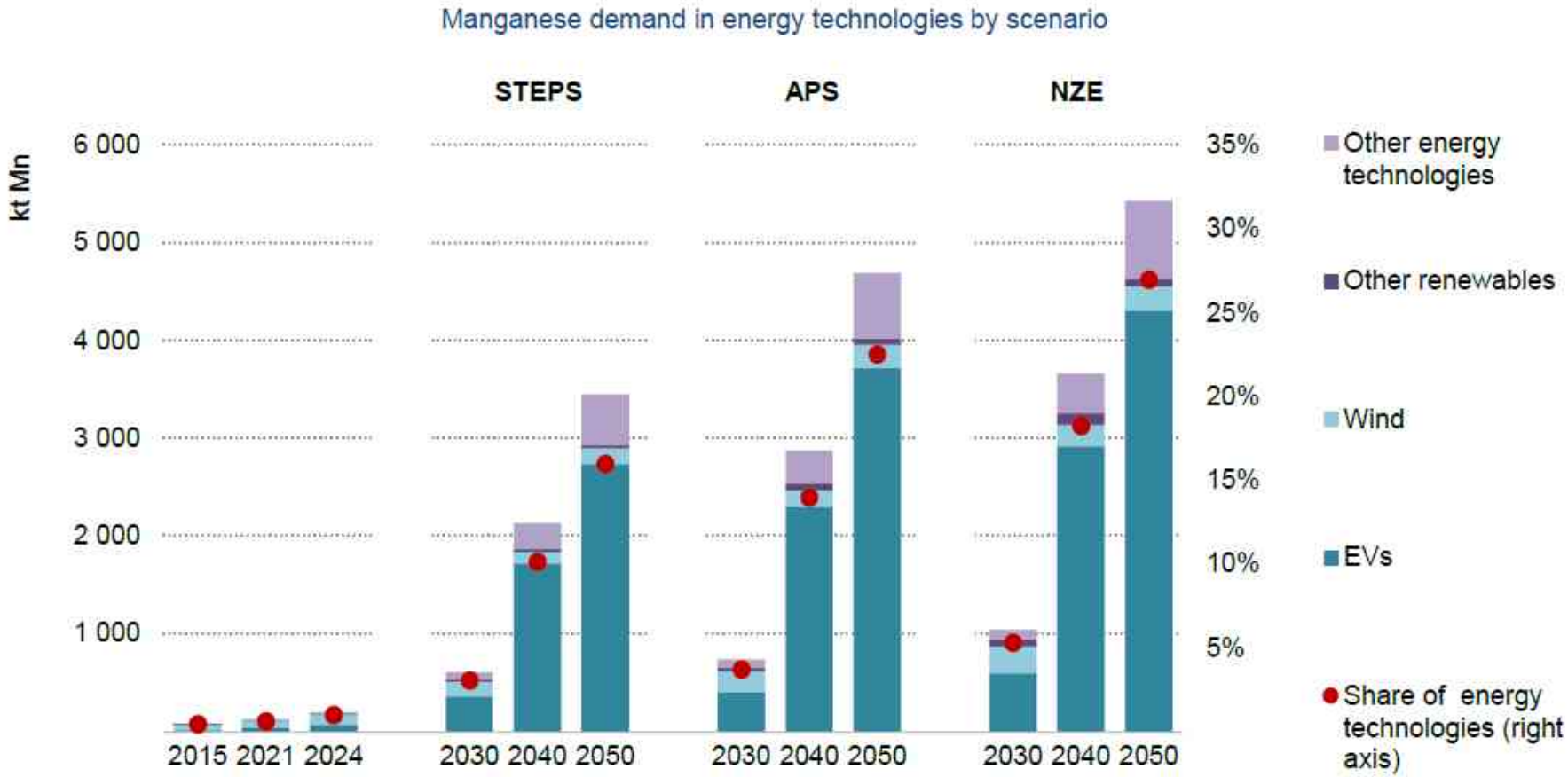
Manganese – Reserves (1,8 Gt) in 2025 – Shares of the total



Source: Our World in Data 2025

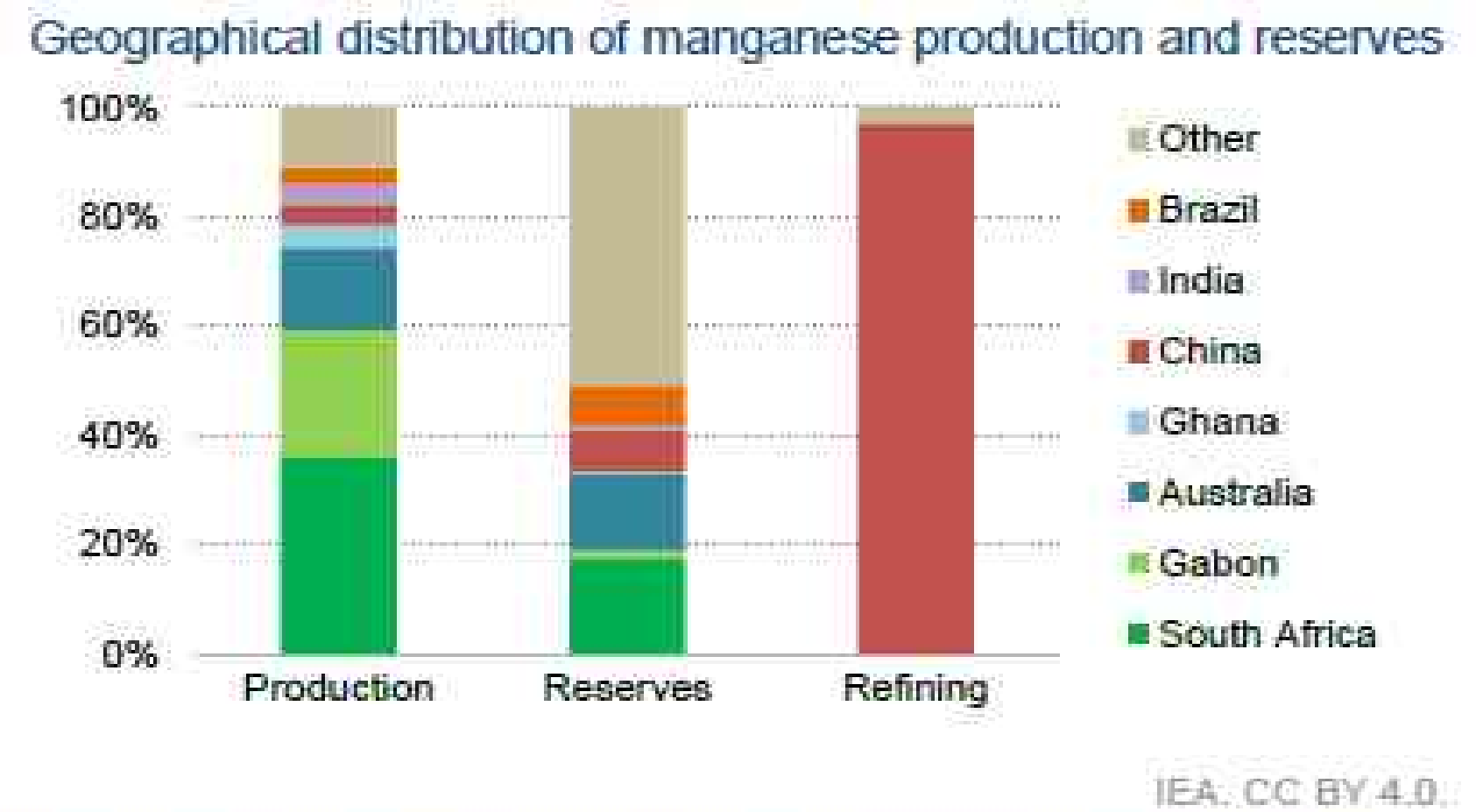
Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025

Manganese: The growth in manganese in EV batteries drives a surge in demand for battery-grade manganese sulphate, which is almost entirely supplied by China



Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Manganese – Reserves (1,8 Gt) and Production (20 Mt) in 2025

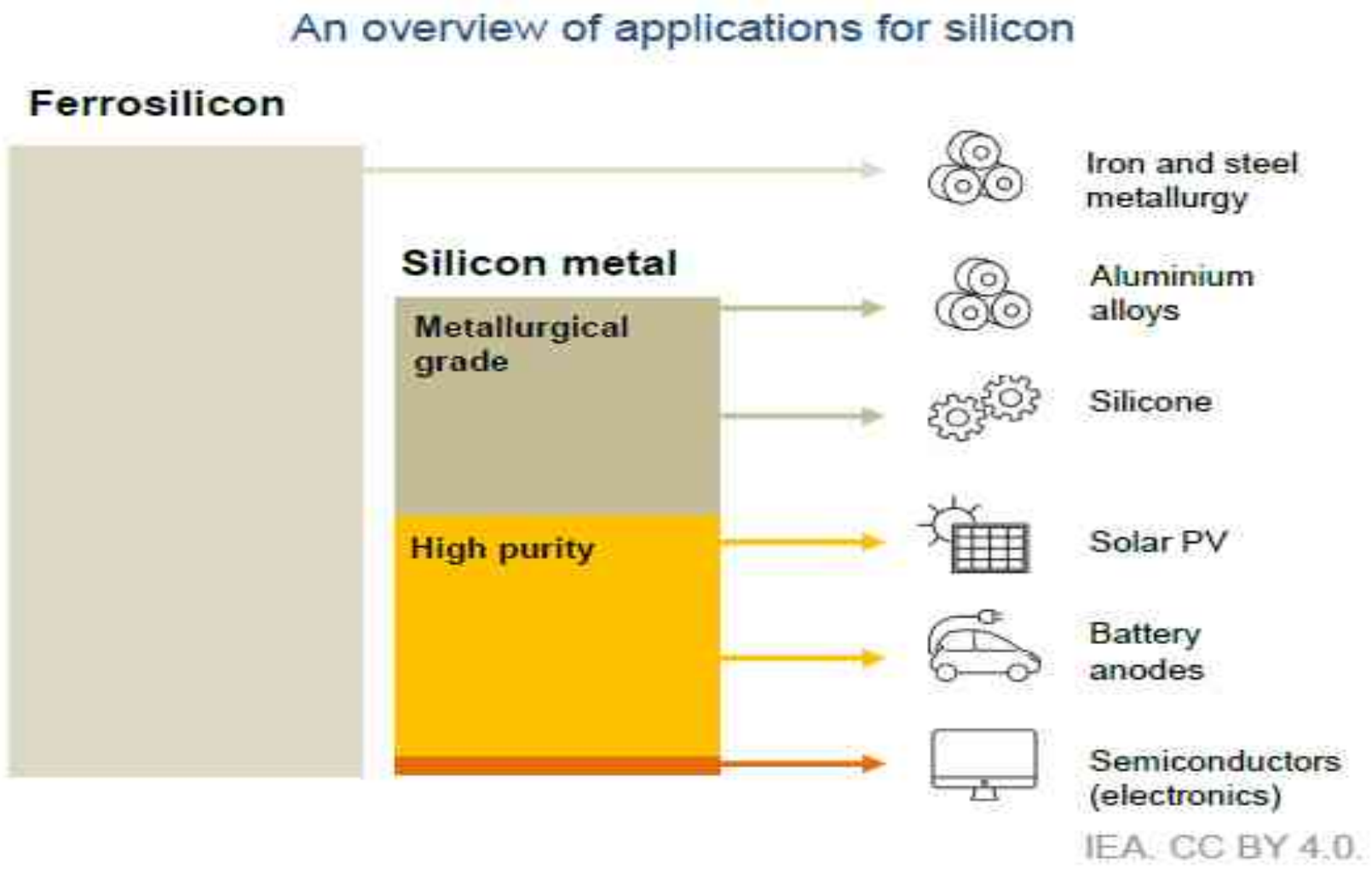


Note: Refining refers to production of battery-grade manganese sulphate.
Sources: US Geological Survey (2024), Minerals Commodity Summaries 2024 and IEA (2023), Critical Minerals Market Review 2023.

Source: IEA Global Critical Minerals Outlook 2024 – May 2024

The case of Silicon

Silicon – An overview of applications



Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Silicon Metal – Reserves (2,5 Gt) and Production (4,6 Mt) in 2025

World Production:

	Ferrosilicon[e]		Silicon metal[e]	
	2024	2025	2024	2025
United States	W	W	W	W
Australia	—	—	47	47
Bhutan	98	98	—	—
Brazil	160	170	190	180
Canada	23	23	34	34
China	3,100	3,500	4,800	4,000
France	21	21	90	68
Germany	—	—	29	13
Iceland	90	72	28	16
India	59	59	—	—
Kazakhstan	120	120	7	7
Malaysia	120	120	—	—
Norway	160	150	140	130
Russia	420	420	59	35
South Africa	36	35	15	10
Spain	41	40	6	4
Other countries	120	40	42	46
World total (rounded)	[7]4,600	[7]5,000	[7]5,500	[7]4,600

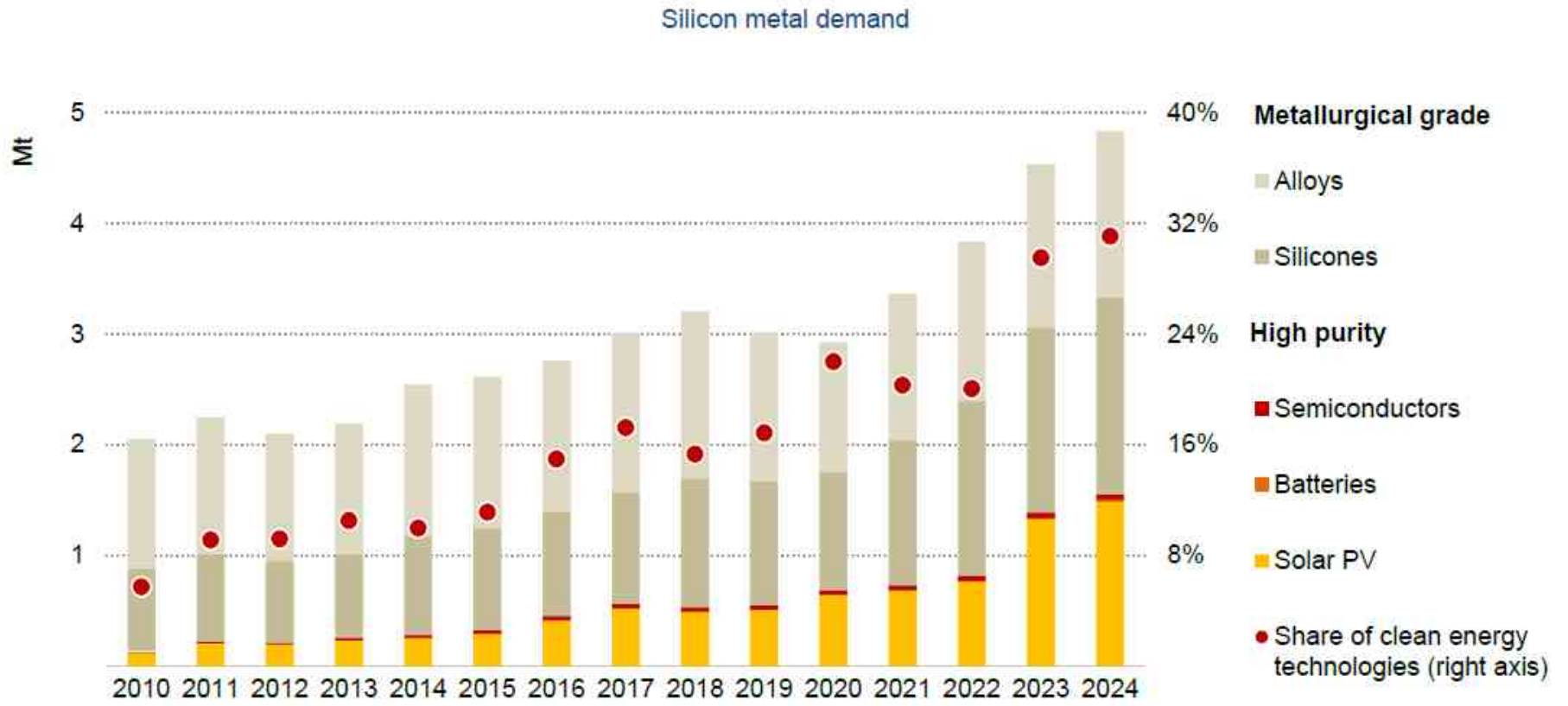
World Resources:[8] World and domestic resources for making silicon metal and alloys are abundant and, in most producing countries, adequate to supply world requirements for many decades. The source of the silicon is silica in various natural forms, such as quartzite.

Substitutes: Aluminum, silicon carbide, and silicomanganese can be substituted for ferrosilicon in some applications. Gallium arsenide and germanium are the principal substitutes for silicon in semiconductor and infrared applications.

Source: USGS January 2026

Silicon – Reserves (2,5 Gt) and Production (4,6 Mt) in 2025

Silicon: Rapid deployment of solar PV technologies in recent years has driven a step change in demand for high-purity silicon



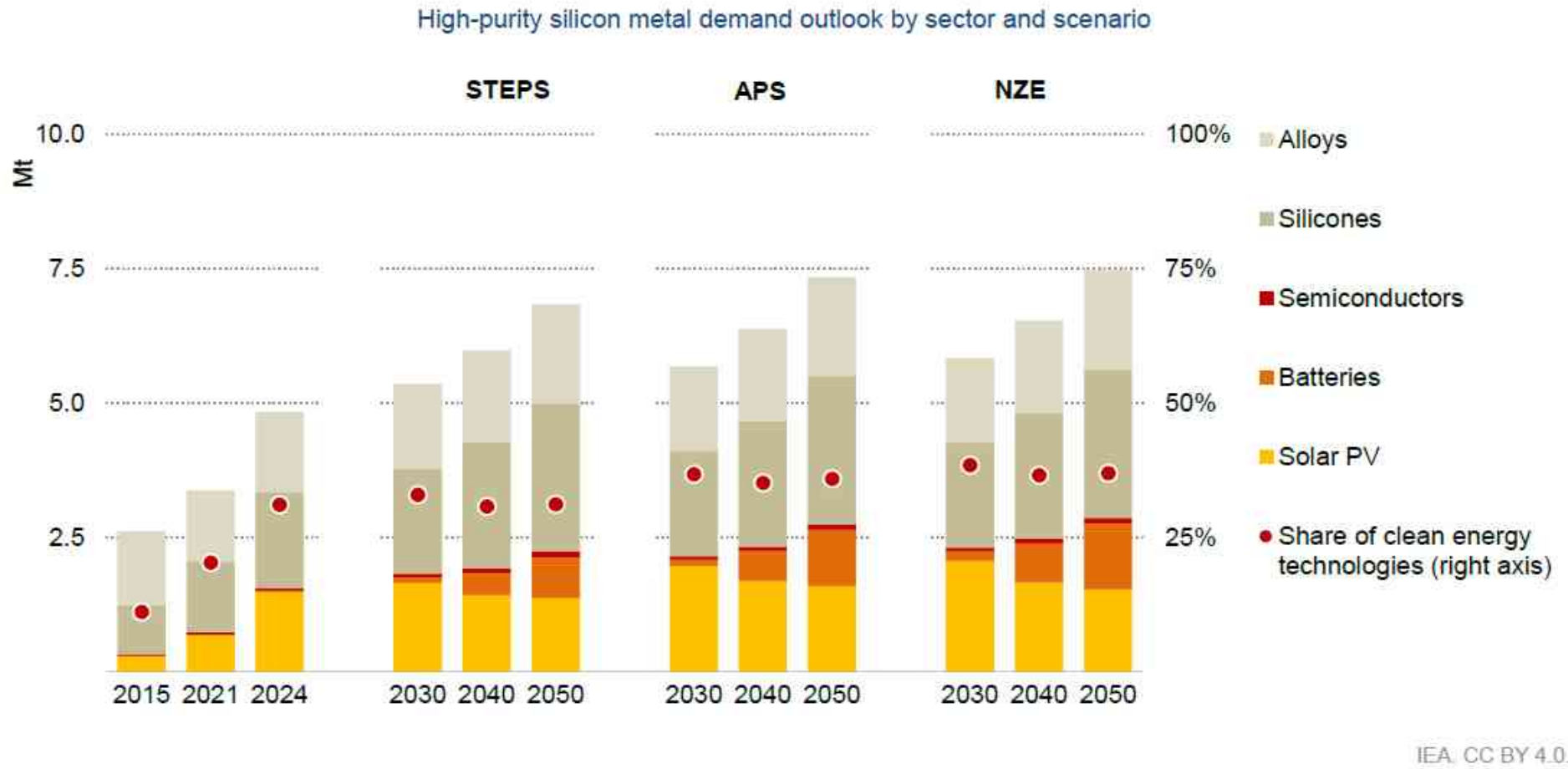
IEA. CC BY 4.0.

Note: Silicon metal = generally accepted trading name for elemental silicon refined in its metalloid form, covering both metallurgical grade and higher purity grades.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Silicon – Reserves (2,5 Gt) and Production (4,6 Mt) in 2025

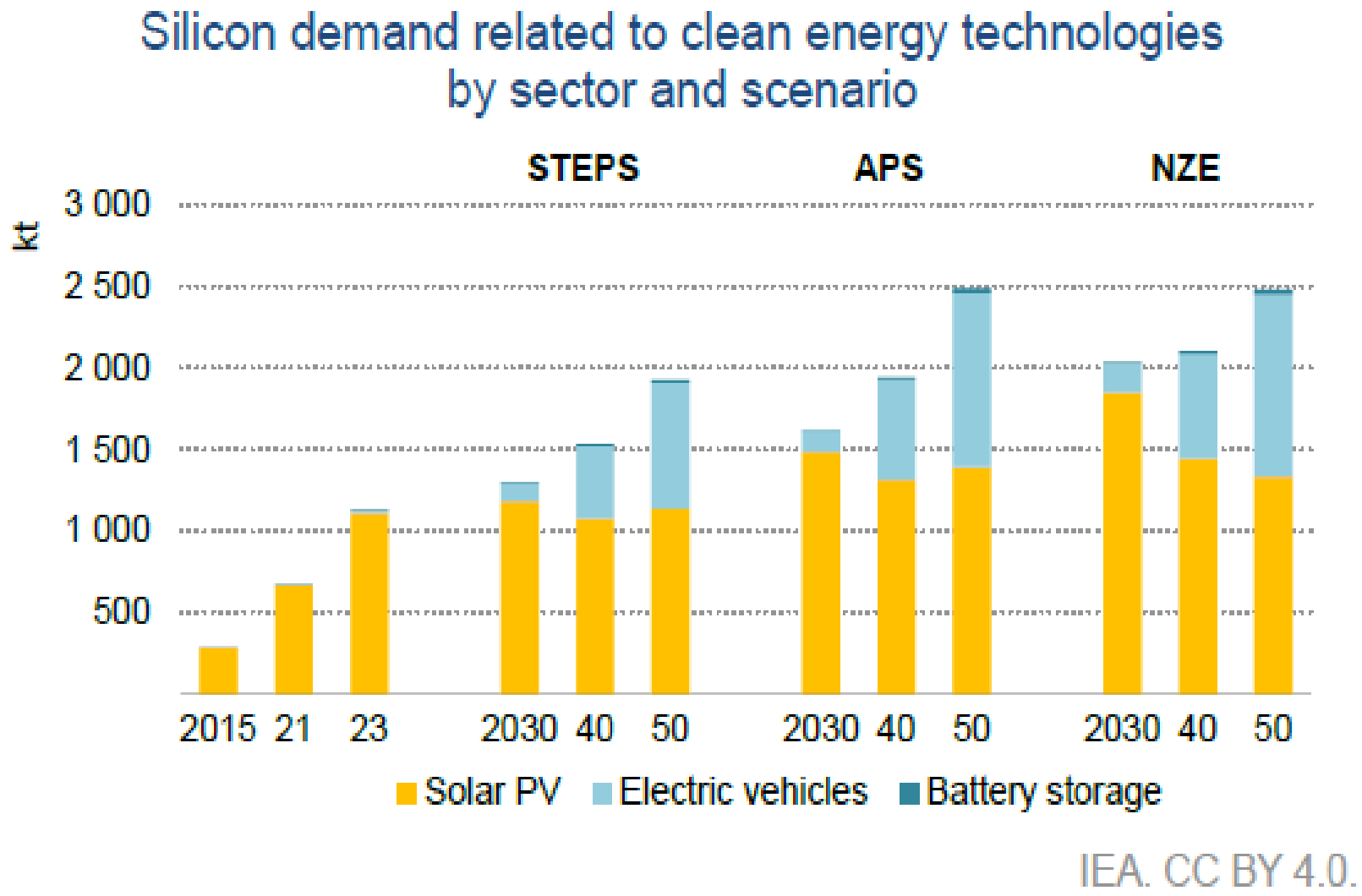
Silicon: As solar PV demand stabilises due to material efficiency, EV batteries play an increasing role in driving future demand growth for high-purity silicon in anodes



Note: High-purity silicon includes both polysilicon for solar PV and semiconductor applications as well as silicon in battery applications.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Silicon – Reserves (2,5 Gt) and Production (4,6 Mt) in 2025



Source: IEA Global Critical Minerals Outlook 2024 – May 2024

The case of Rare Earth Elements

Rare Earth Elements

17 chemical elements. Dispersed and difficult to extract.

Used for high-tech industry (Screen of smartphones, computers, flat panel televisions) and low-carbon technologies (permanent magnets for wind turbines, batteries for hybrid and electric cars)

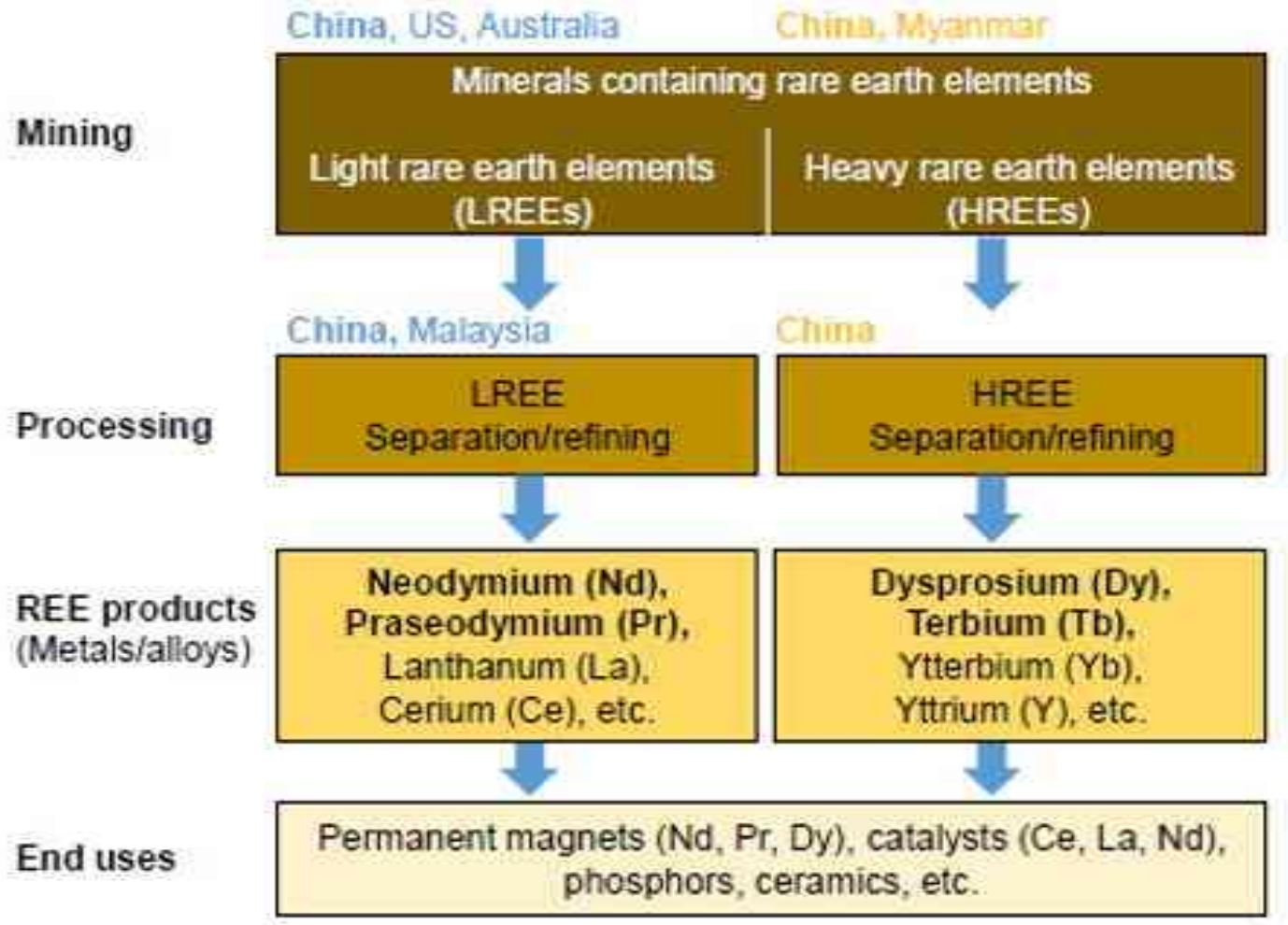
Moderate geological criticality. Heavy Rare Earths (Dysprosium, Terbium,…) more critical than lighter Rare Earths (Neodynium)

Possible presence of Thorium and Uranium in source rock generating radioactive pollution.

China dominates the entire value chain (> 60% for production)

Environmental challenges (Mining, large quantities of water,…)

Rare Earth Elements
From Resource to Consumer



Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Rare Earth Elements – Multiple Applications



Source: USGS 2019

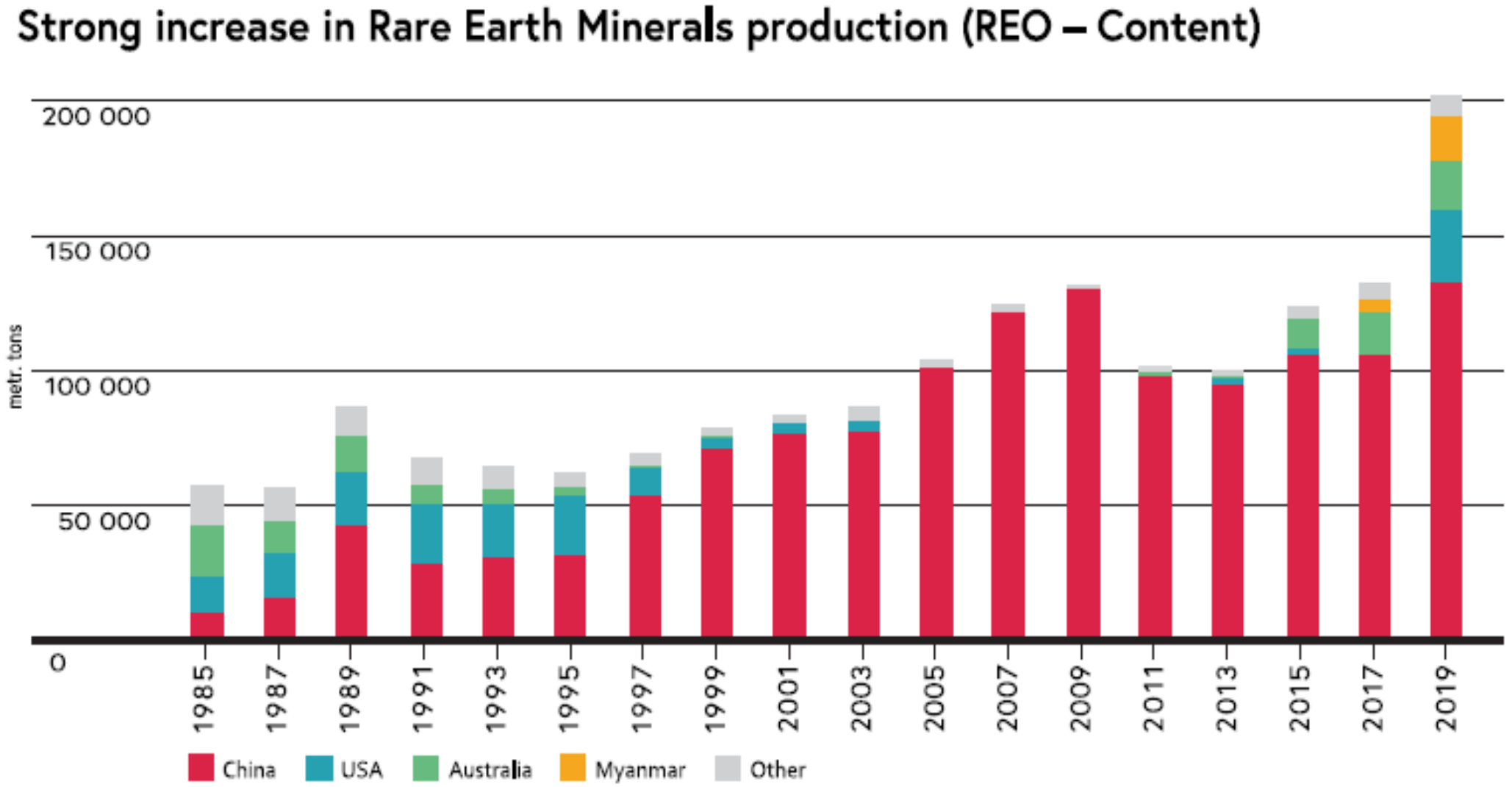
Rare Earth Elements – Multiple Applications

Civil and military aviation sector needs Aluminium, Titanium and RER, in particular Yttrium, Terbium, for advanced targeting systems.



Source: USGS 2019

Rare Earth Elements – Evolution of Production (213 kt in 2019)



Source: World Mining Data 2021

Main Use of Rare Earth Elements

REEs	Magnets	Batteries (NiMh)	Metallurgy/ Alloys	Catalysts	Polishing/ glass	Phosphors	Ceramics	Luminescent compounds	Other*
Lanthanum		X	X	X	X	X	X		X
Cerium		X	X	X	X	X	X		X
Praseodymium	X		X	X	X	X	X		X
Neodymium	X		X	X	X	X	X		X
Samarium	X								X
Europium						X			X
Gadolinium	X		X			X			X
Terbium	X					X			X
Dysprosium	X								X
Erbium					X	X			X
Yttrium					X	X	X		X
Holmium									X
Thulium									X
Ytterbium									X
Lutetium									X
Scandium									X
Promethium								X	

Source: IFP EN, USGS

*** Electronic devices, fibre optics, lasers, …**

Light & Heavy Rare Earth Elements and Applications

Element	Symbol	Atomic number	Example applications
Light rare earth elements			
Lanthanum	La	57	Optical glass, nickel-metal-hydride batteries
Cerium	Ce	58	Colored glass (flat-panel displays), automobile catalytic converters
Praseodymium	Pr	59	Super-strong magnets, metal alloys, specialty glass, lasers
Neodymium	Nd	60	Permanent magnets
Samarium	Sm	62	Permanent magnets, nuclear reactor control rods, lasers
Europium	Eu	63	Optical fibers, visual displays, lighting
Gadolinium	Gd	64	Shielding in nuclear reactors, X-ray and magnetic resonance imaging scanning systems
Heavy rare earth elements			
Terbium	Tb	65	Visual displays, fuel cells, lighting
Dysprosium	Dy	66	Permanent magnets, lighting
Holmium	Ho	67	Lasers, high-strength magnets, glass coloring
Erbium	Er	68	Glass coloring, fiber optic cables
Thulium	Tm	69	Lasers, portable X-ray machines
Ytterbium	Yb	70	Stainless steel, lasers
Lutetium	Lu	71	Petroleum refining
Yttrium	Y	39	Metal alloys, visual displays, lasers, lighting

Source: USGS 2019

Light & Heavy Rare Earth Elements

[Average crustal abundance values are from Lide (2004, p. 17); REE, rare-earth element]

Element[1]	Symbol	Atomic number	Atomic weight	Crustal abundance (part per million)
Light REEs				
Lanthanum	La	57	138.91	39
Cerium	Ce	58	140.12	66.5
Praseodymium	Pr	59	140.91	9.2
Neodymium	Nd	60	144.24	41.5
Samarium	Sm	62	150.36	7.05
Europium	Eu	63	151.96	2.0
Gadolinium	Gd	64	157.25	6.2
Heavy REEs				
Yttrium	Y	39	88.91	33
Terbium	Tb	65	158.92	1.2
Dysprosium	Dy	66	162.50	5.2
Holmium	Ho	67	164.93	1.3
Erbium	Er	68	167.26	3.5
Thulium	Tm	69	168.93	0.52
Ytterbium	Yb	70	173.04	3.2
Lutetium	Lu	71	174.97	0.8

[1]Promethium (Pm, atomic number = 61) is not included in this list because it is extremely rare in nature.

Source: US Department of Interior/USGS 2021

Outcrop Light of Upper Ordovicien
High-grade REE phosporite in Arkansas - US



Source: USGS 2019 Photo: Poul Emsbo

Light & Heavy Rare Earth Elements



Figure 04. World map showing locations of active or recently active rare-earth-element (REE) mines and ongoing advanced exploration projects. The exploration projects are at the assessment stage, meaning that they are being evaluated to determine if they are economic to develop. REE resource estimates, which are usually based on extensive drilling programs, have been conducted on all the projects. Tables 03 and 04 contain additional information about the deposits shown on this map. Mountain Pass Mine in California (United States) was placed on care-and-maintenance status in 2015.

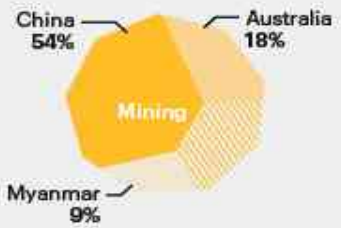
Source: US Department of Interior/USGS 2021

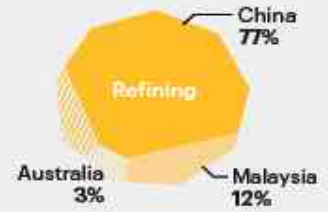
Rare Earth Elements (REO) – Reserves (> 90 Mt) and Production (390 kt) in 2024

Rare earth elements

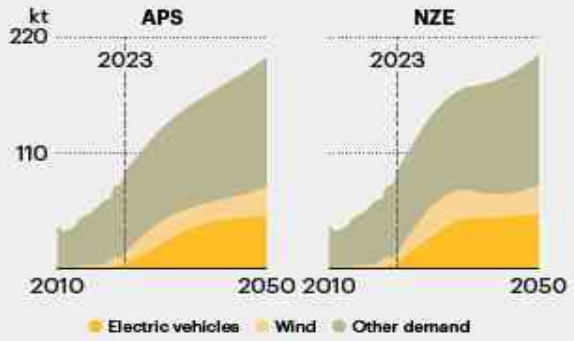
Nd Pr Dy Tb

Top three producers 2030

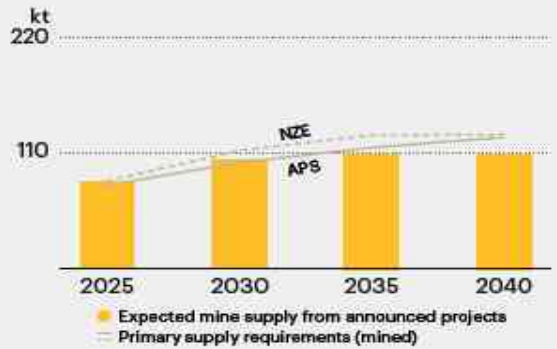




Demand outlook



Mining requirements



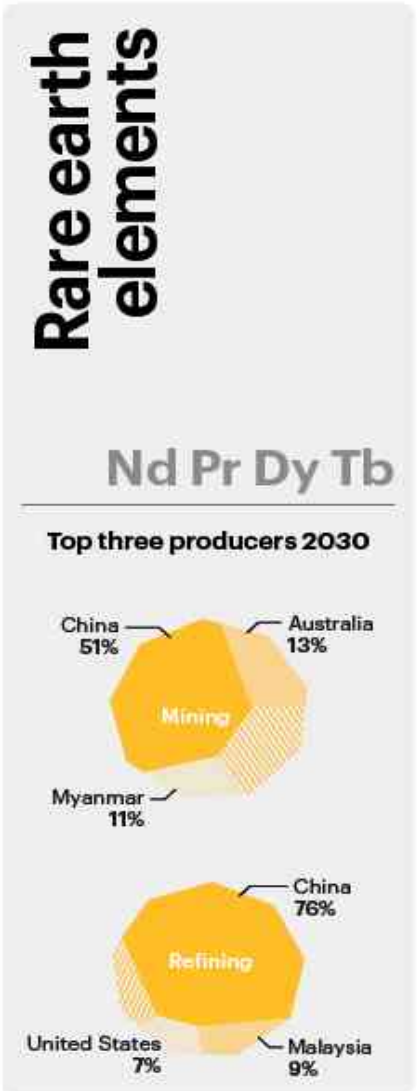
Milestones (APS)	2021	2023	2030	2040
Cleantech demand (kt)	11	16	46	64
Other uses (kt)	67	76	87	105
Total demand (kt)	78	93	134	169
Secondary supply and reuse (kt)	22	25	36	48
Primary supply requirements (kt)	57	67	98	121
Share of top three mining countries	81%	85%	81%	81%
Share of top three refining countries	98%	98%	92%	93%

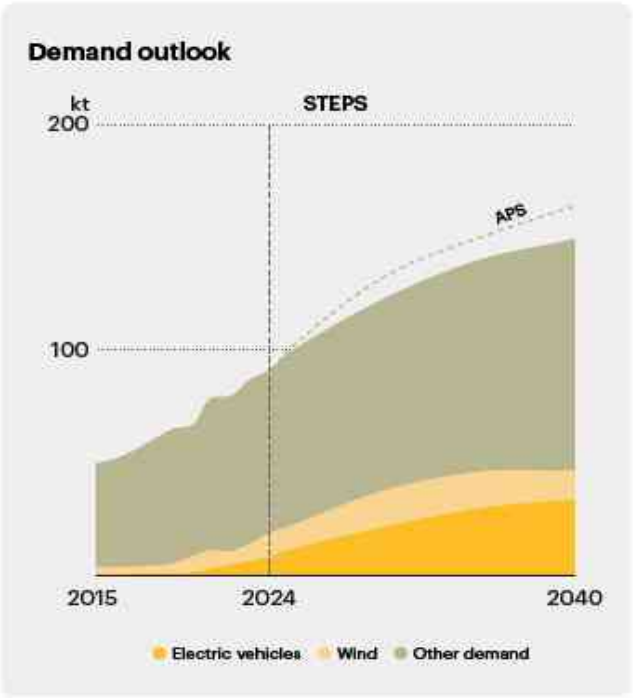
Clean energy transition risk assessment

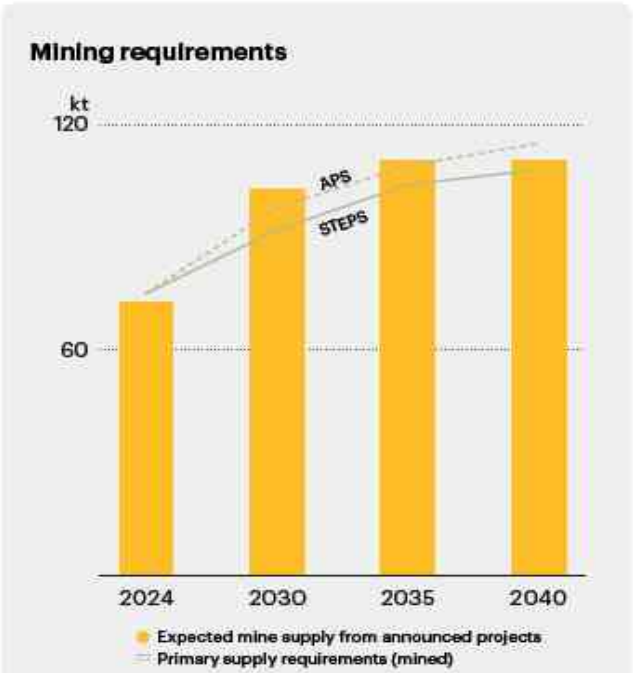


Source: IEA Global Critical Minerals Outlook 2024 – May 2024

Rare Earth Elements (REO) – Reserves (> 90 Mt) and Production (390 kt) in 2024







STEPS	2021	2024	2030	2040
Cleantech demand (kt)	11	19	38	47
Other uses (kt)	67	72	85	103
Total demand (kt)	78	91	123	150
Secondary supply and reuse (kt)	22	27	32	43
Primary supply requirements (kt)	55	69	91	107
Share of top three mining countries	81%	86%	74%	76%
Share of top three refining countries	98%	97%	92%	92%

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Rare Earth Elements (REO) – Reserves (> 90 Mt) and Production (390 kt) in 2024

World Mine Production and Reserves: Reserves for Russia, South Africa, the United States, and Vietnam were revised based on company and Government reports.

	Mine production[e]		Reserves[11]
	2023	2024	
United States	41,600	45,000	1,900,000
Australia	[12]16,000	[12]13,000	[13]5,700,000
Brazil	140	20	21,000,000
Burma	[12]43,000	[12]31,000	NA
Canada	—	—	830,000
China	[14]255,000	[14]270,000	44,000,000
Greenland	—	—	1,500,000
India	2,900	2,900	6,900,000
Madagascar	[12]2,100	[12]2,000	NA
Malaysia	[12]310	[12]130	NA
Nigeria	[12]7,200	[12]13,000	NA
Russia	2,500	2,500	3,800,000
South Africa	—	—	860,000
Tanzania	—	—	890,000
Thailand	[12]3,600	[12]13,000	4,500
Vietnam	[12]300	[12]300	3,500,000
Other	1,440	1,100	NA
World total (rounded)	376,000	390,000	>90,000,000

World Resources:[10] Rare earths are relatively abundant in the Earth's crust, but minable concentrations are less common than for most other mineral commodities. In North America, measured and indicated resources of rare earths were estimated to include 3.6 million tons in the United States and more than 14 million tons in Canada.

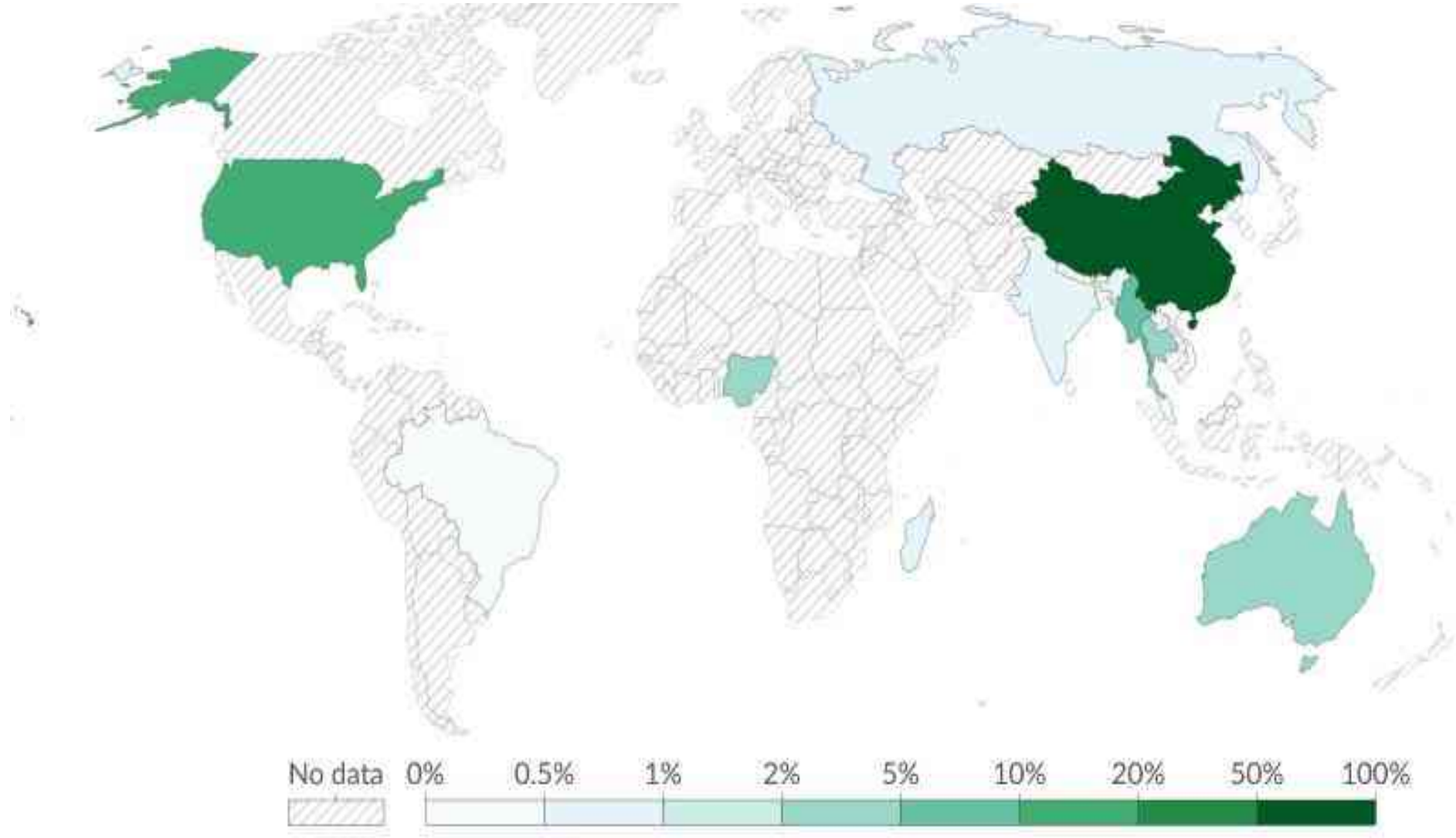
Source: USGS January 2025

REE – Production (390 kt) in 2025 – Shares of the total



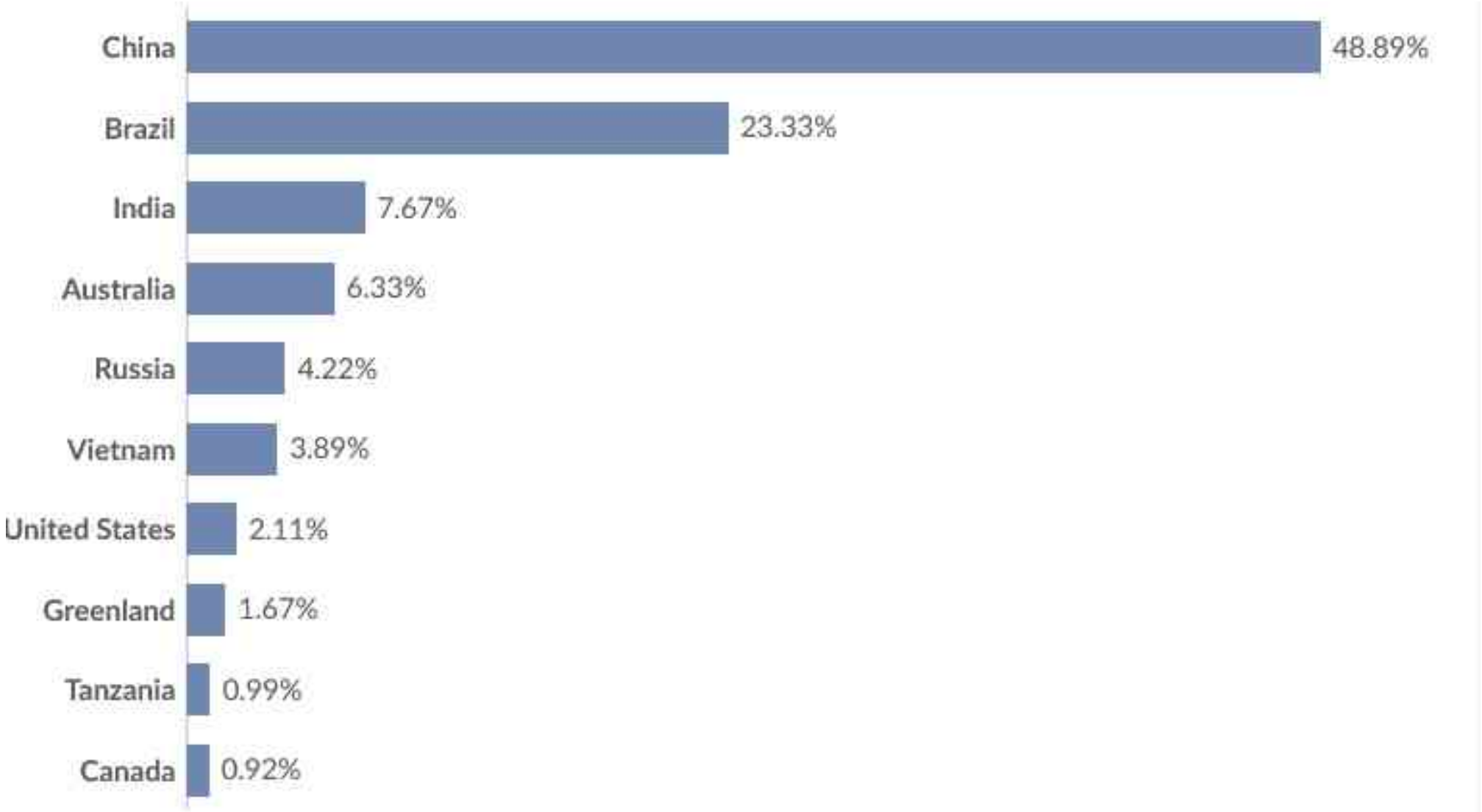
Source: Our World in Data 2025

REE – Production (390 kt) in 2025 – Shares of the total



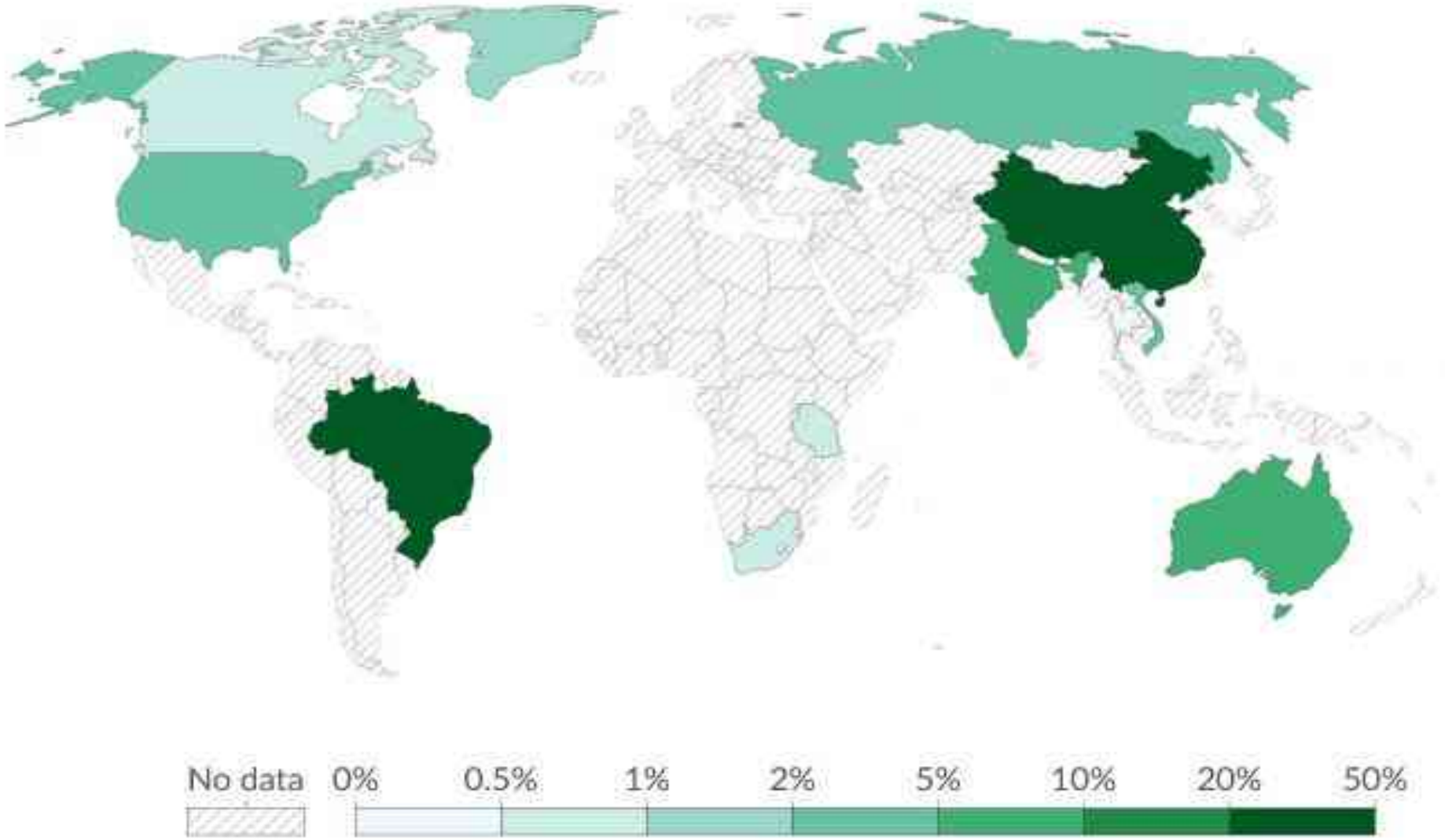
Source: Our World in Data 2025

REE – Reserves (> 90 Mt) in 2025 – Shares of the total



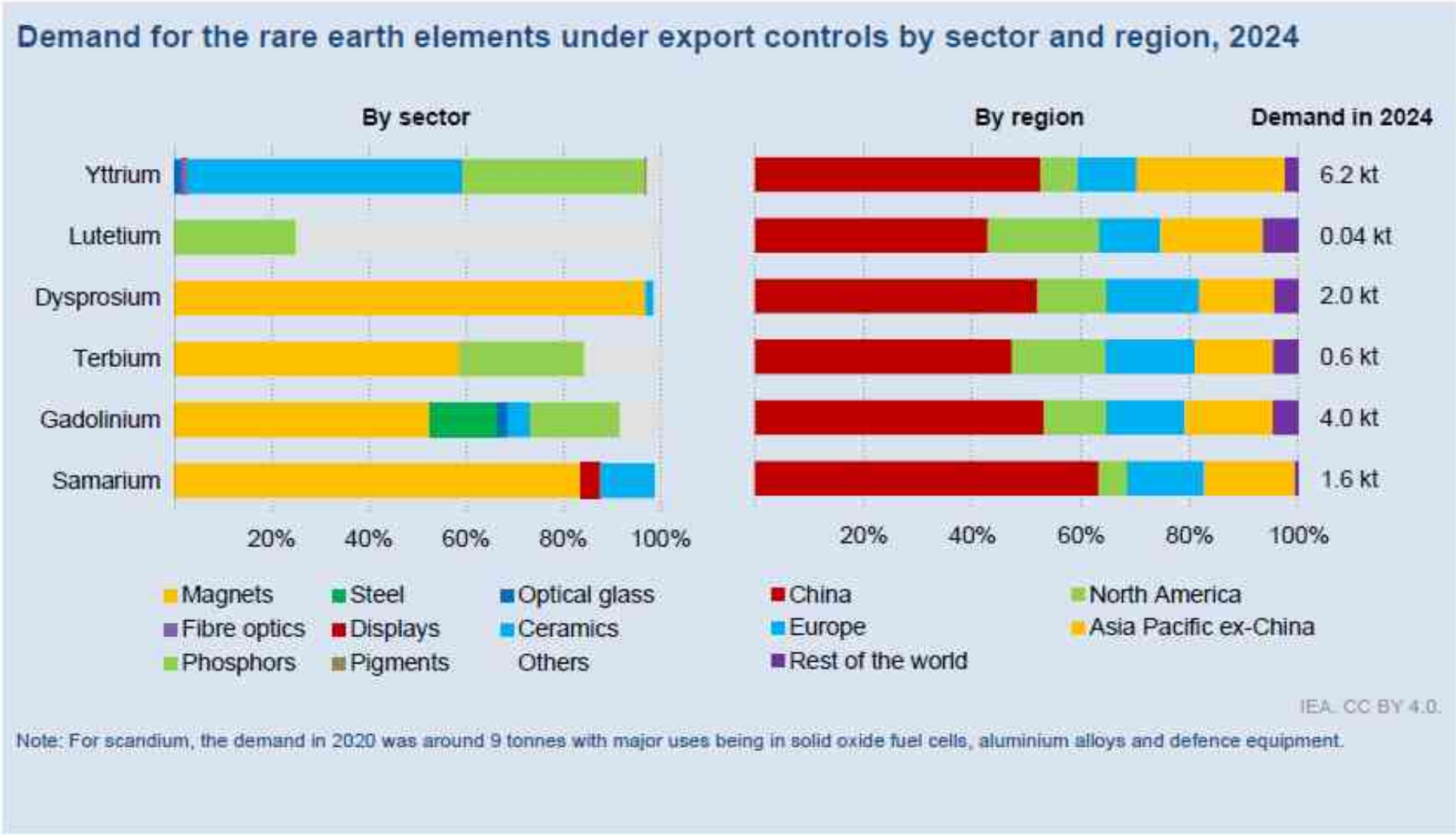
Source: Our World in Data 2025

REE – Reserves (> 90 Mt) in 2025 – Shares of the total



Source: Our World in Data 2025

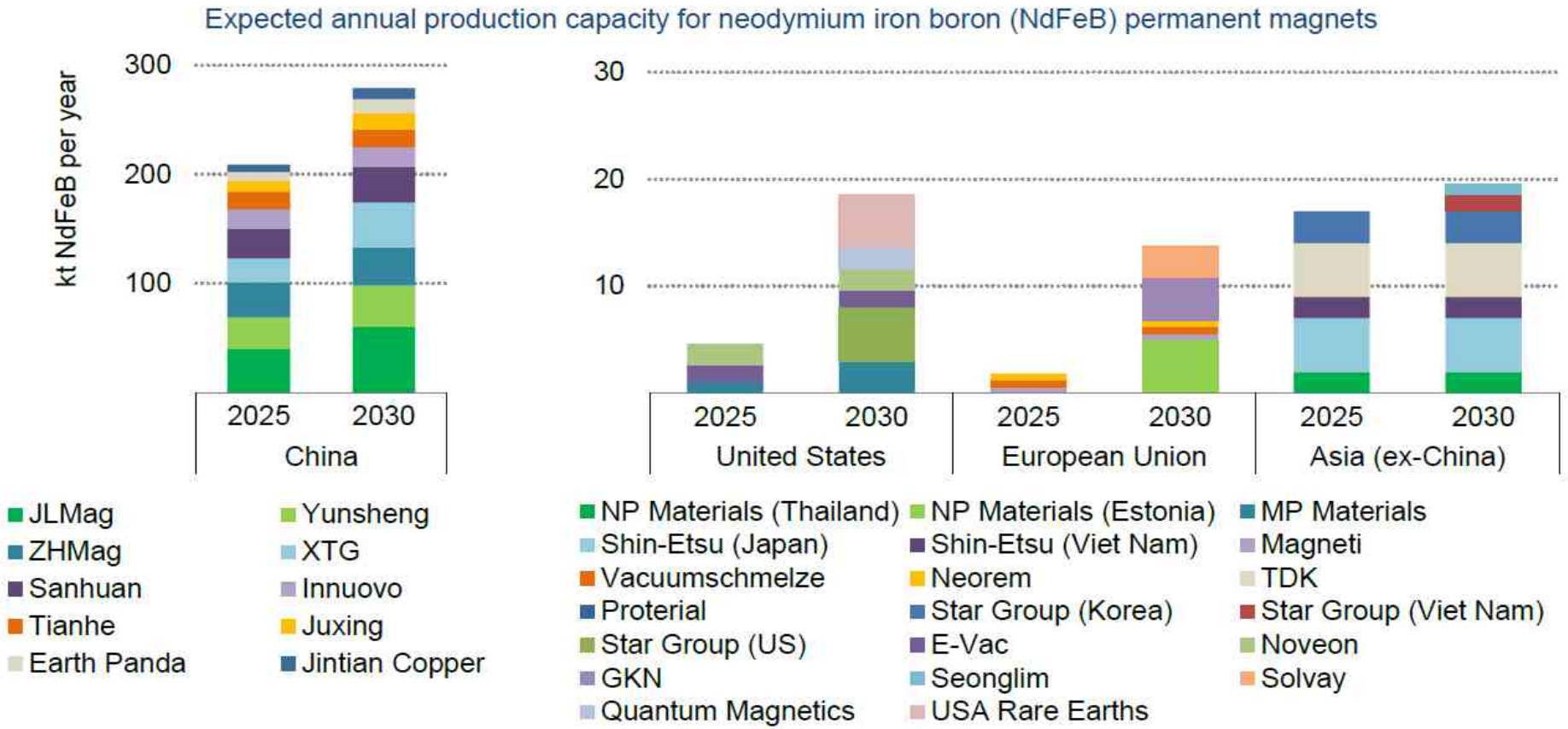
Rare Earth Elements (REO) – Restrictions



Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Rare Earth Elements (REO) – Reserves (> 90 Mt) and Production (390 kt) in 2024

Demand: Permanent magnet manufacturing is led by China, but several new players are emerging



IEA. CC BY 4.0.

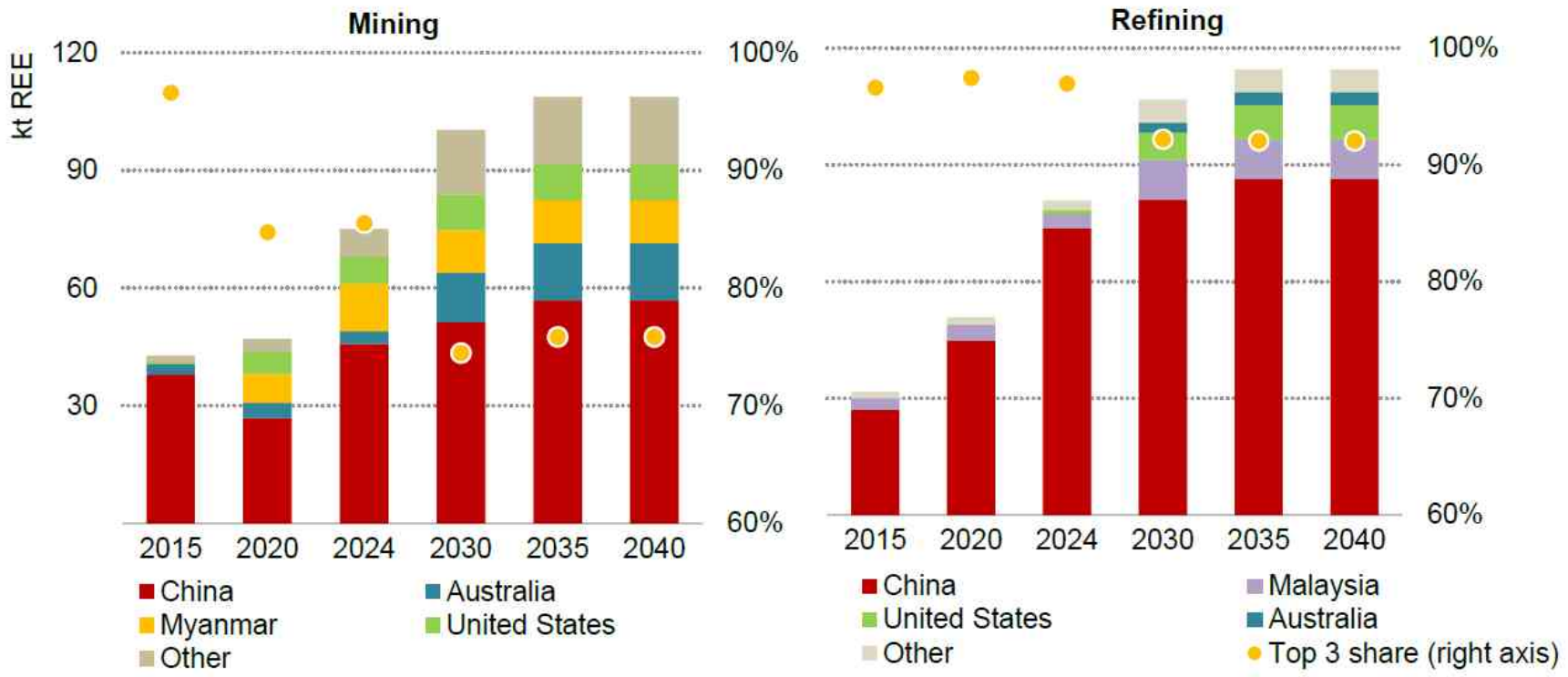
Note: The list of projects is indicative of future magnet production capacity based on today's announcements, it is not meant to be exhaustive.
Source: IEA analysis based on Project Blue.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Rare Earth Elements (REO) – Reserves (> 90 Mt) and Production (390 kt) in 2024

Supply: Geographical concentration for mining sees slight improvements, but refining remains the most concentrated of all critical minerals

Magnet rare earths production from operating and announced projects in the base case



IEA. CC BY 4.0.

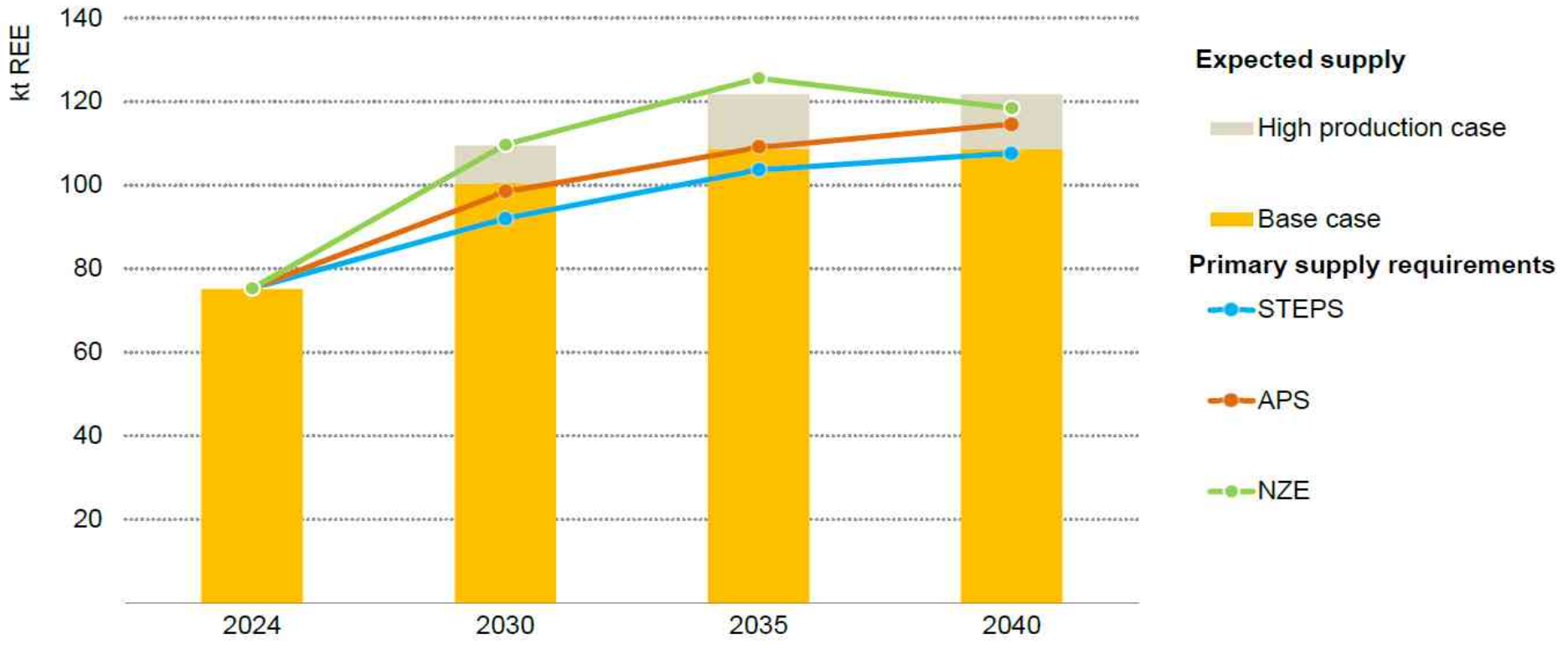
Notes: REE = rare earth elements. The figures are for magnet rare earths only.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Rare Earth Elements (REO) – Reserves (> 90 Mt) and Production (390 kt) in 2024

Supply: Expected supply nearly in line with requirements to 2030, but limited announcements of new projects and geopolitical events pose risks to security

Expected mined magnet rare earths supply from existing and announced projects and primary supply requirements by scenario

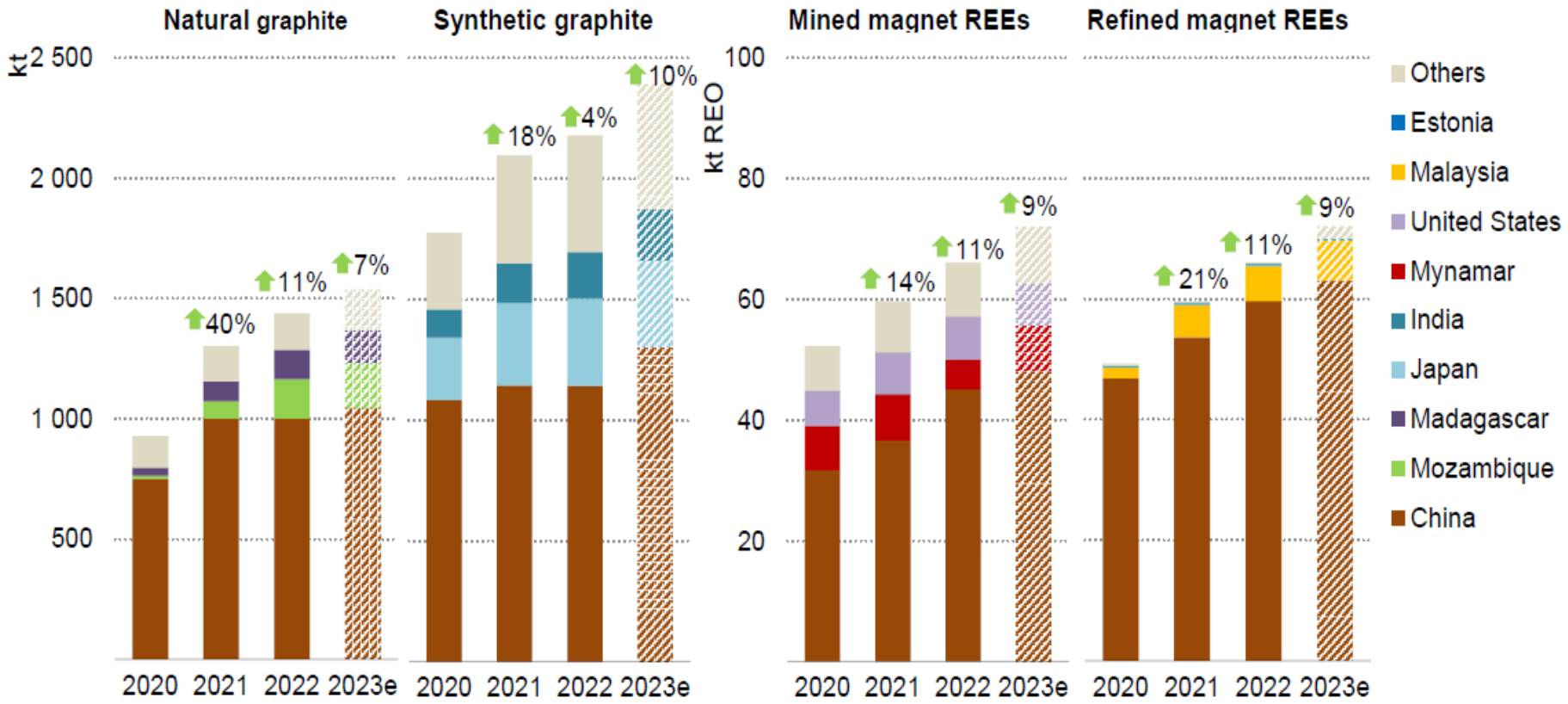


IEA. CC BY 4.0.

Notes: REE = rare earth elements. The figures are for magnet rare earths only. Primary supply requirements is the demand net of reuse and recycling.

Source: IEA Global Critical Minerals Outlook 2024 – May 2025

RER & Graphite
From Resource to Consumer



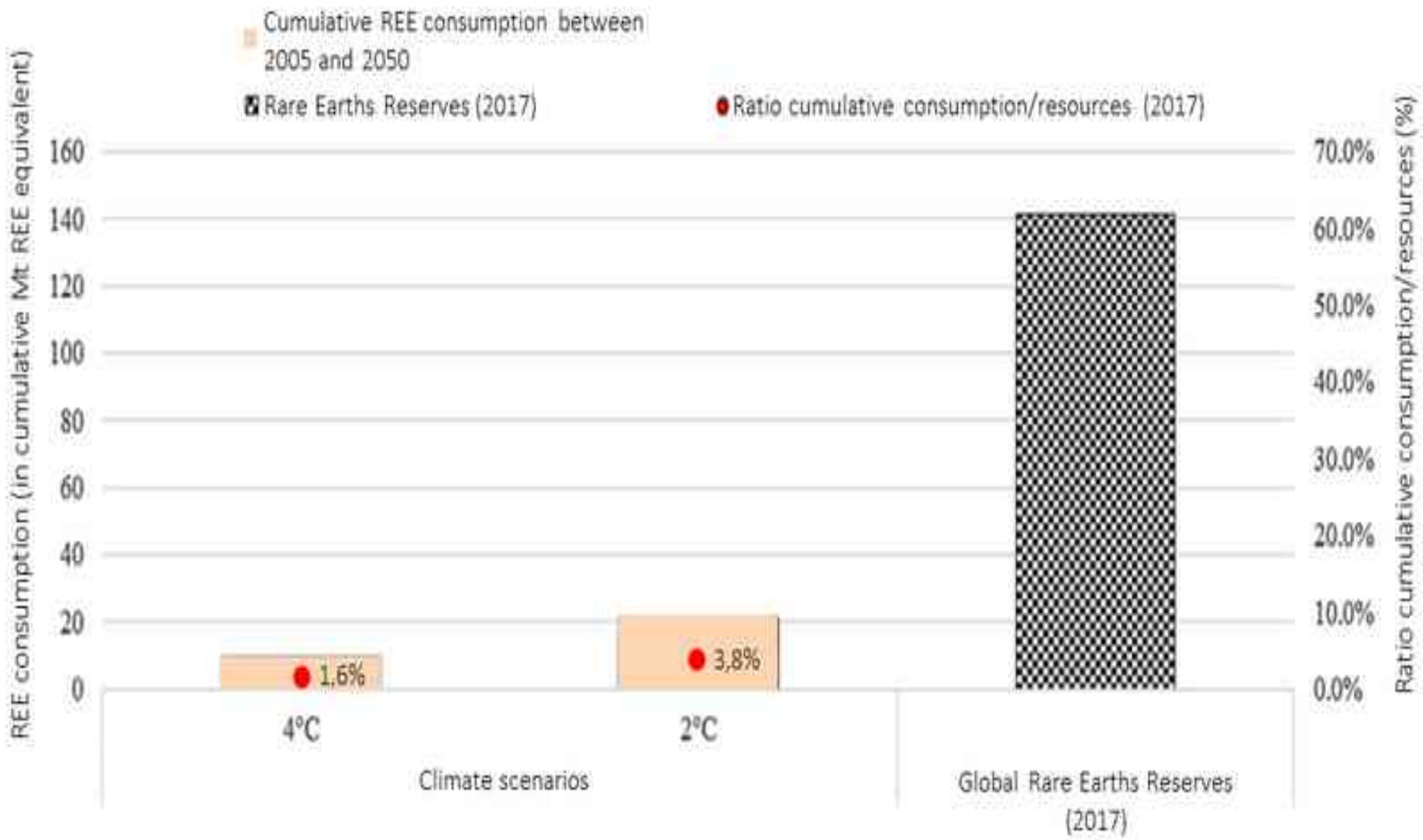
IEA. CC BY 4.0.

Notes: t = tonne; REE = rare earth elements, REO = rare earth oxide. Natural graphite is based on production of natural flake graphite, Magnet REEs include neodyminium, praseodymium, dysprosium and terbium.

Source: IEA analysis based on Wood Mackenzie and Adamas Intelligence.

Source: IEA Critical Mineral Market Review July 2023

Rare Earth Elements



Source: IFP EN, USGS

4 Rare Earth Elements: Neodynium, Praseodynium, Dysprosium, Terbium

Rare earth elements demand

	Historical		Current Policies			Stated Policies			High Demand		
Unit: kt REE	2021	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050
Clean energy	11	21	33	36	40	37	44	56	48	64	80
Electric vehicles	3	11	20	25	26	21	33	41	24	46	54
Wind	8	10	13	10	13	16	11	15	24	18	27
Other uses	64	72	79	95	111	79	95	111	79	95	112
Total demand	75	93	112	131	151	116	140	167	127	160	192
Share of clean energy	15%	22%	30%	27%	26%	32%	32%	34%	38%	40%	42%

Notes: kt = kilotonnes. REE = rare earth elements. Rare earth elements refer only to four magnet rare earths: neodymium, praseodymium, dysprosium and terbium.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

4 Rare Earth Elements: Neodynium, Praseodynium, Dysprosium, Terbium

Rare earth elements supply

	Mining					Refining			
	Historical		Base case			Historical		Base case	
Unit: kt REE	2021	2025	2030	2040		2021	2025	2030	2040
China	32	47	51	57	China	53	75	81	86
Myanmar	8	13	11	11	United States	0	5	9	11
United States	6	7	9	9	Malaysia	4	5	10	10
Australia	4	4	11	12	France	0	1	1	1
Lao PDR	0	4	8	8	Viet Nam	1	1	1	1
Rest of world	7	5	6	6	Rest of world	2	3	8	9
World	57	80	97	104	World	60	89	111	118
Top 3 share	81%	85%	76%	77%	Top 3 share	97%	94%	91%	91%

Notes: kt = kilotonnes. Lao PDR = Lao People's Democratic Republic. Rare earth elements refer only to four magnet rare earths: neodymium, praseodymium, dysprosium and terbium.

Source: IEA Global Critical Minerals Outlook 2026 – July 2026

China N°1 for the World Production of Rare Earth Elements (REE)



Baya Obo Mine – Internal Mongolia

US is an important producer of Rare Earth Elements (REE)



Mountain Pass Mine San Bernardino - California

US is an important producer of Rare Earth Elements (REE)



Mountain Pass Mine San Bernardino - California

The challenge of Recycling and CO_2 Emissions

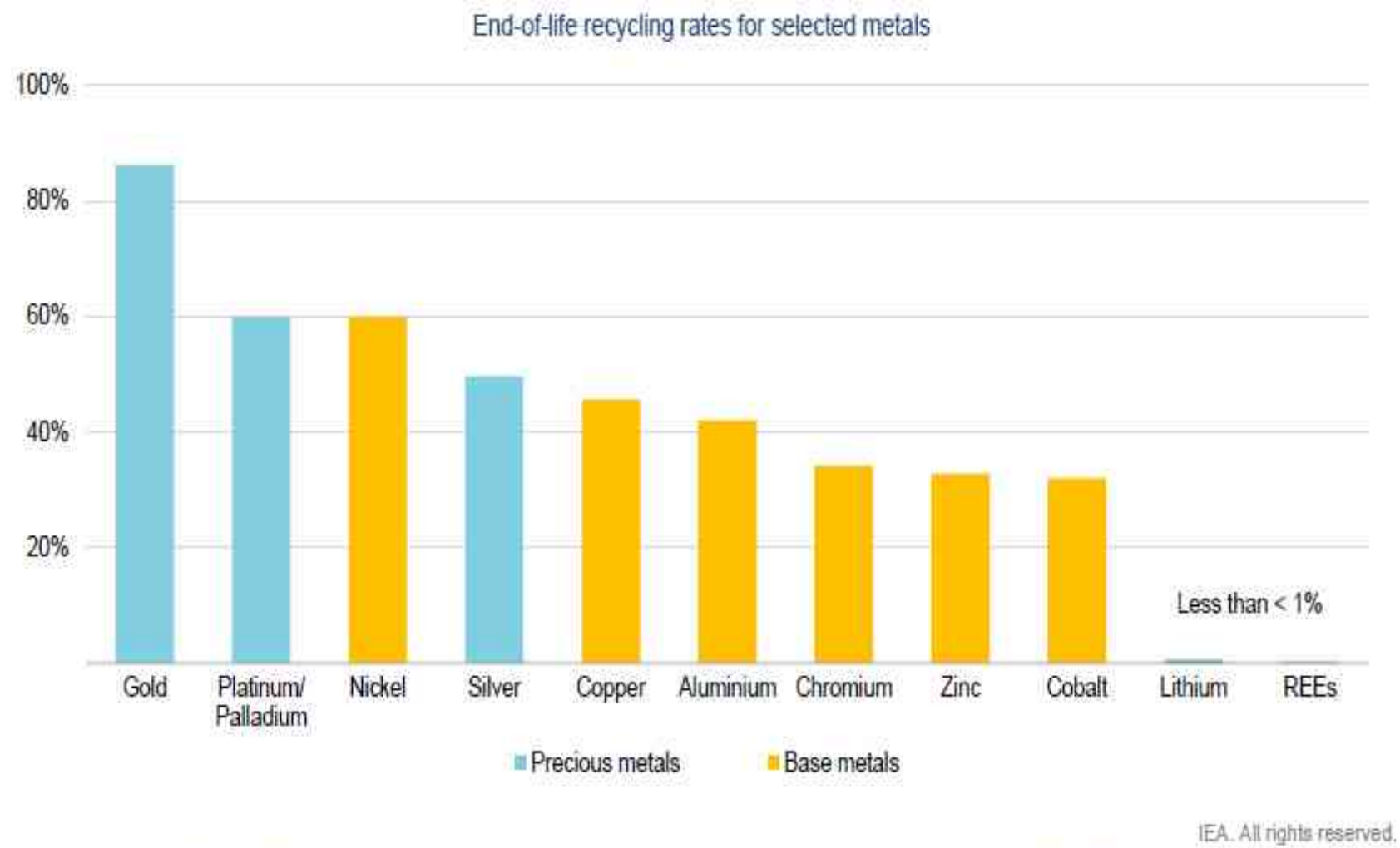
Technology choice, material substitution, and technological improvements will shift the demand for individual minerals under different low-carbon scenarios.
Any lower-carbon pathway will increase the overall demand of minerals.

While the recycling and reuse of minerals can play a key role in reducing emissions, mining will still be required to supply the critical minerals needed to produce these low-carbon technologies, even with large future increases in recycling rates.

Despite the higher mineral intensity of renewable energy technologies, the scale of associated greenhouse gas emissions is a fraction of that of fossil fuel technologies.
However, the carbon and material footprints cannot be overlooked.

Recycling Potential

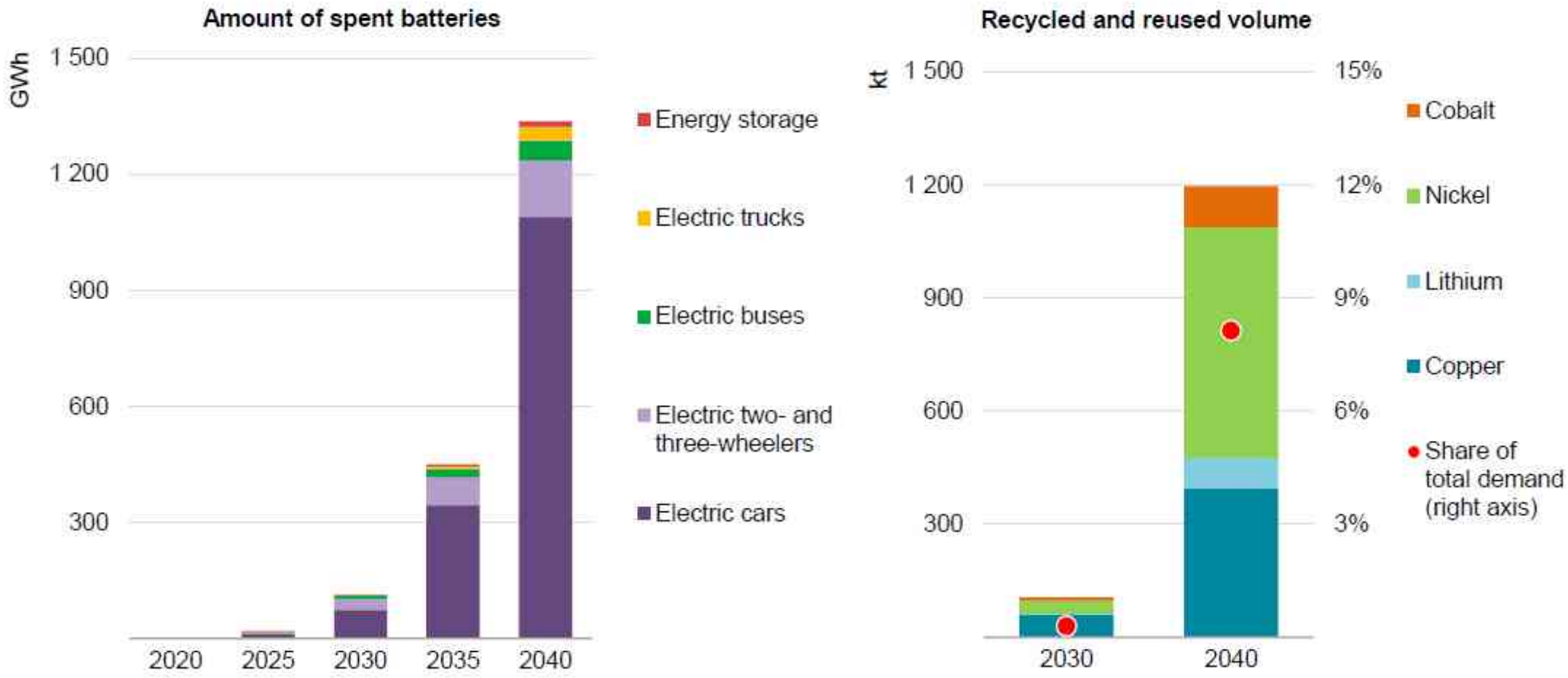
Today's Recycling Rates



Source: IEA WEO October 2021

Great Necessity to improve Recycling Rates

Amount of spent lithium-ion batteries from EVs and storage and recycled and reused minerals from batteries in the SDS



Source: IEA WEO October 2021

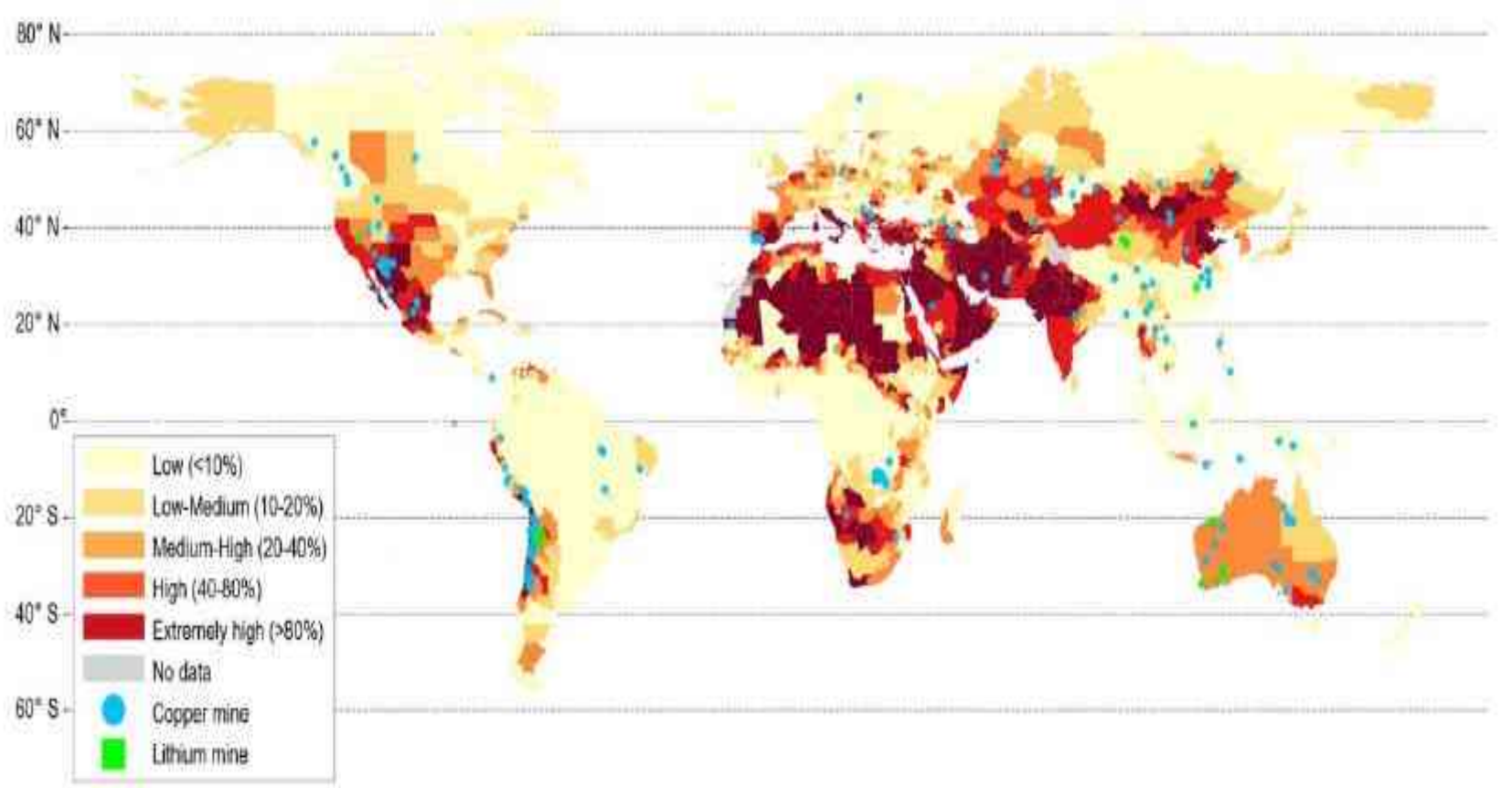
The challenge of Mining conditions and CO_2 Emissions



Source: World Bank - Minerals for Climate Action 2020

Environmental Aspects

Water Stress Levels

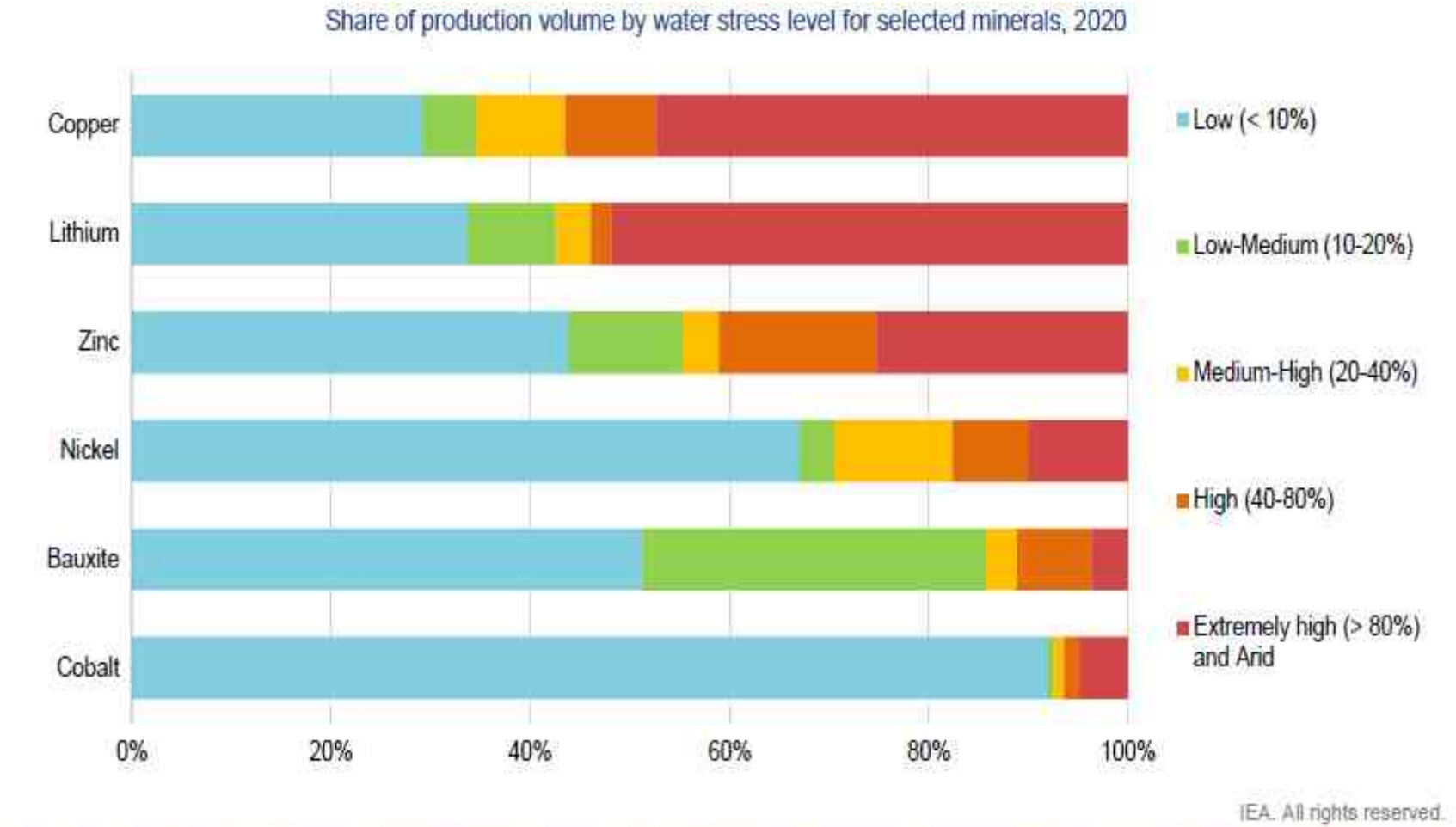


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Note: The exact water stress levels vary by location. While we assessed the share of mines located in water stress areas according to granular regional representations (shown on the following page), we aggregated them at the sub-national level on the map for the sake of simplification. Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.
Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Source: IEA WEO October 2021

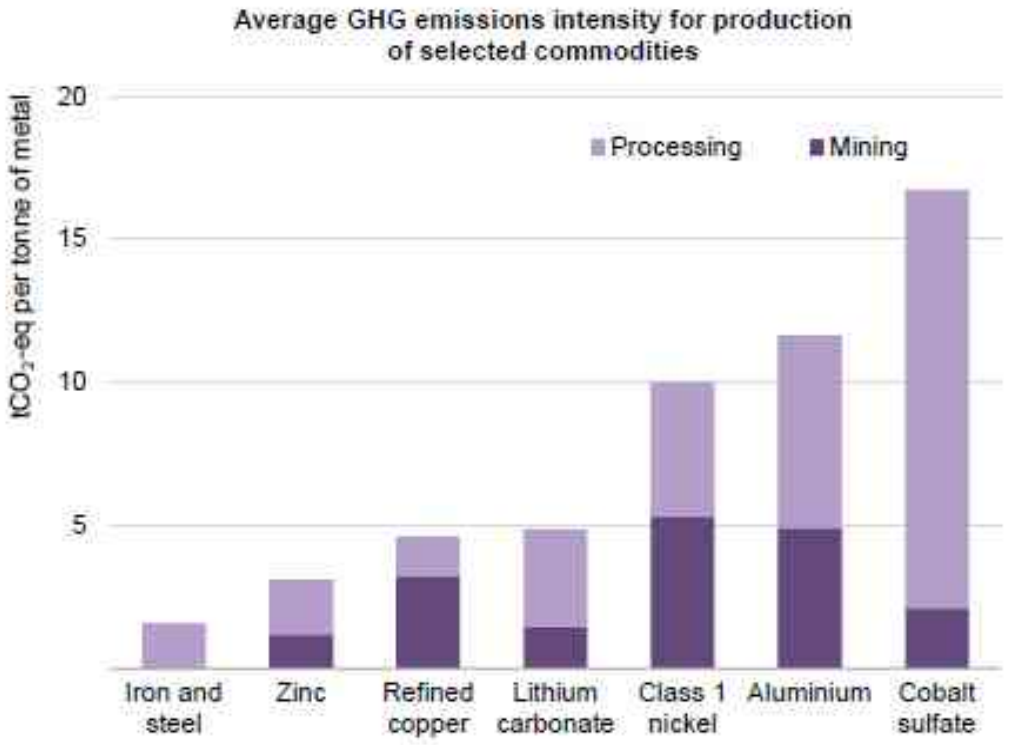
Water Stress Levels

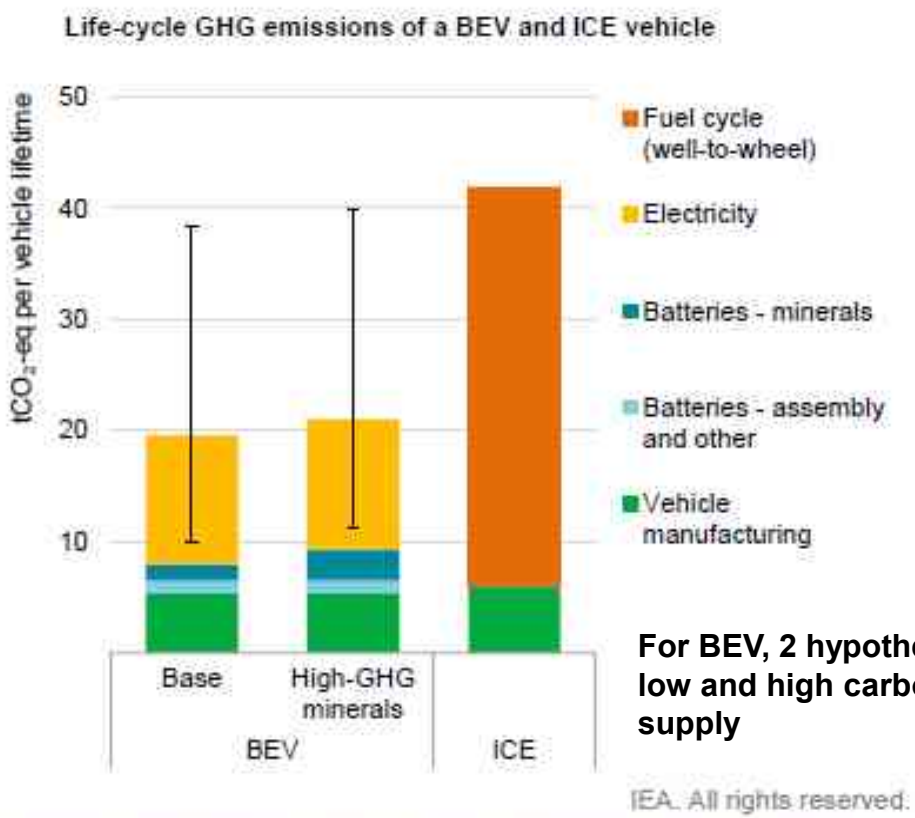


Note: Water stress levels are as defined in the Aqueduct 3.0 dataset according to the ratio of total water withdrawals over the total available surface and groundwater supplies.
Source: IEA analysis based on WRI Aqueduct 3.0 dataset.

Source: IEA WEO October 2021

Upward pressure on CO_2 Emissions for Minerals Production





For BEV, 2 hypothesis: low and high carbon electricity supply

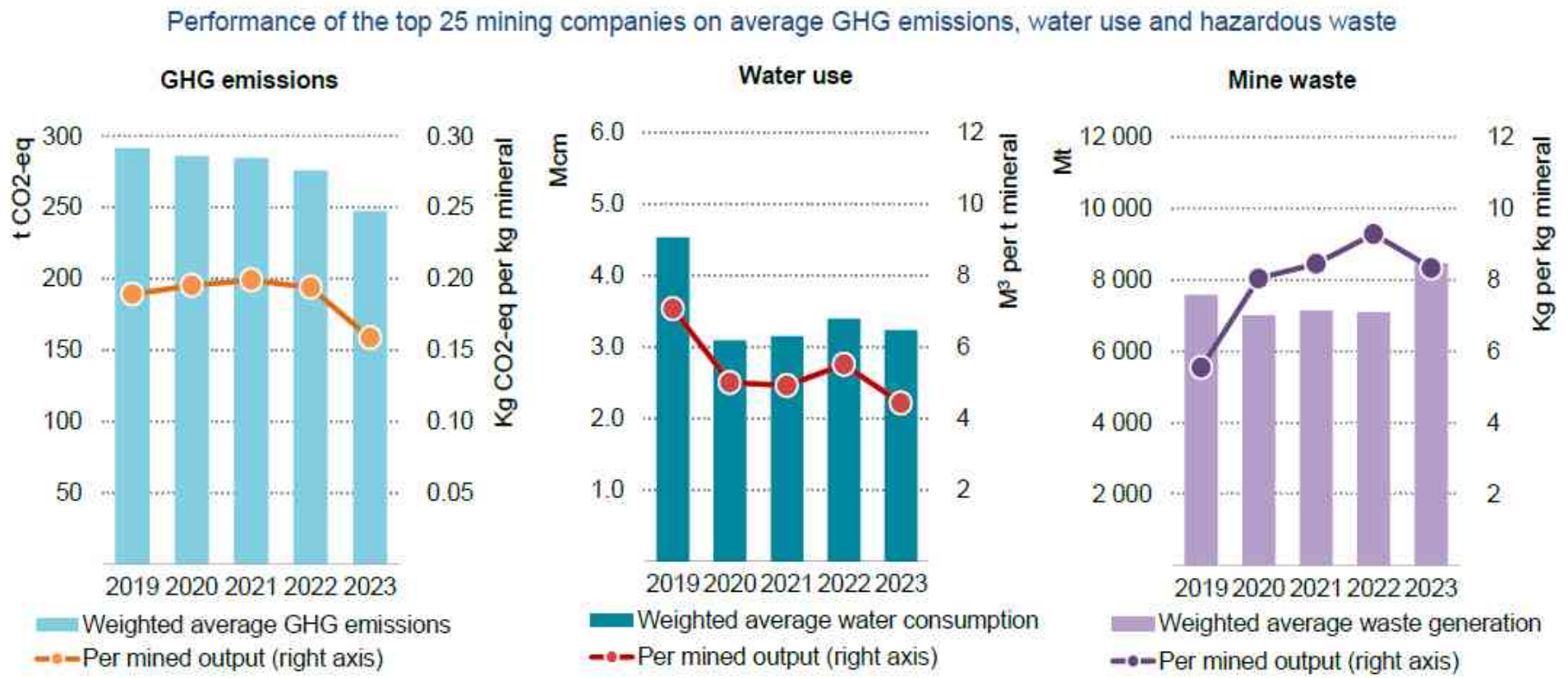
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Notes: BEV = battery electric vehicle; ICE = internal combustion engine. The "High-GHG minerals" case assumes double the GHG emissions intensity for battery minerals. Includes both Scope 1 and 2 emissions of all GHG from primary production. See Chapter 4 for more detailed assumptions.

Source: IEA analysis based on IEA (2020a); IEA (2020b); Kelly et al. (2020); Argonne National Laboratory (2020); Argonne National Laboratory (2019); Rio Tinto (2020); S&P Global (2021); Skarn Associates (2021); Marx et al. (2018).

Source: IEA Special Report May 2021

Environmental Performances by Mining Companies



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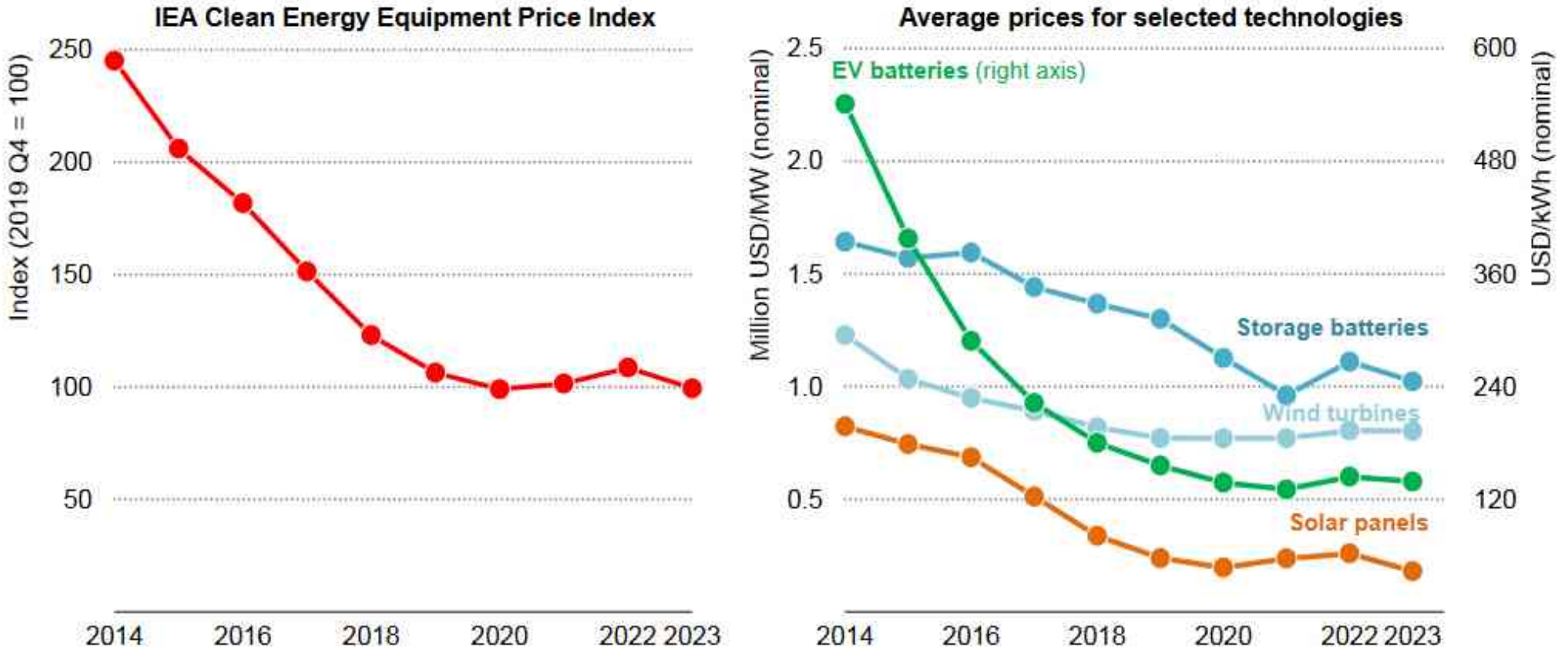
Notes: kg = kilogrammes; mcm = million cubic metres; M^3 = cubic metres; t = tonne. GHG emissions refers to greenhouse gas emissions per mined output (kilogrammes of CO_2 equivalent per kg mineral); water use refers to water consumption per mined output (cubic metre/tonne of mineral); and hazardous waste refers to the waste generated per mined output (kg/mineral).

Sources: IEA analysis based on the latest sustainability reports of Albemarle, Allkem and Livent (Arcadium Lithium), Anglo American, BHP, CMOC Group, Codelco, Eramet, First Quantum, Freeport Mc-MoRan, Ganfeng Lithium, Glencore, IGO, KGHM, NorNickel, Pilbara Minerals, Rio Tinto, South32, Southern Copper, SQM, Teck Resources, Tianqi Lithium, Vale, Zhejiang Huayou, and Zijin Mining Group Co. Ltd.

Source: IEA Global Critical Minerals Outlook 2025 – May 2025

Prices

The Energy Sector – Energy Transition
General context of Prices development – Evolution 2014 - 2023

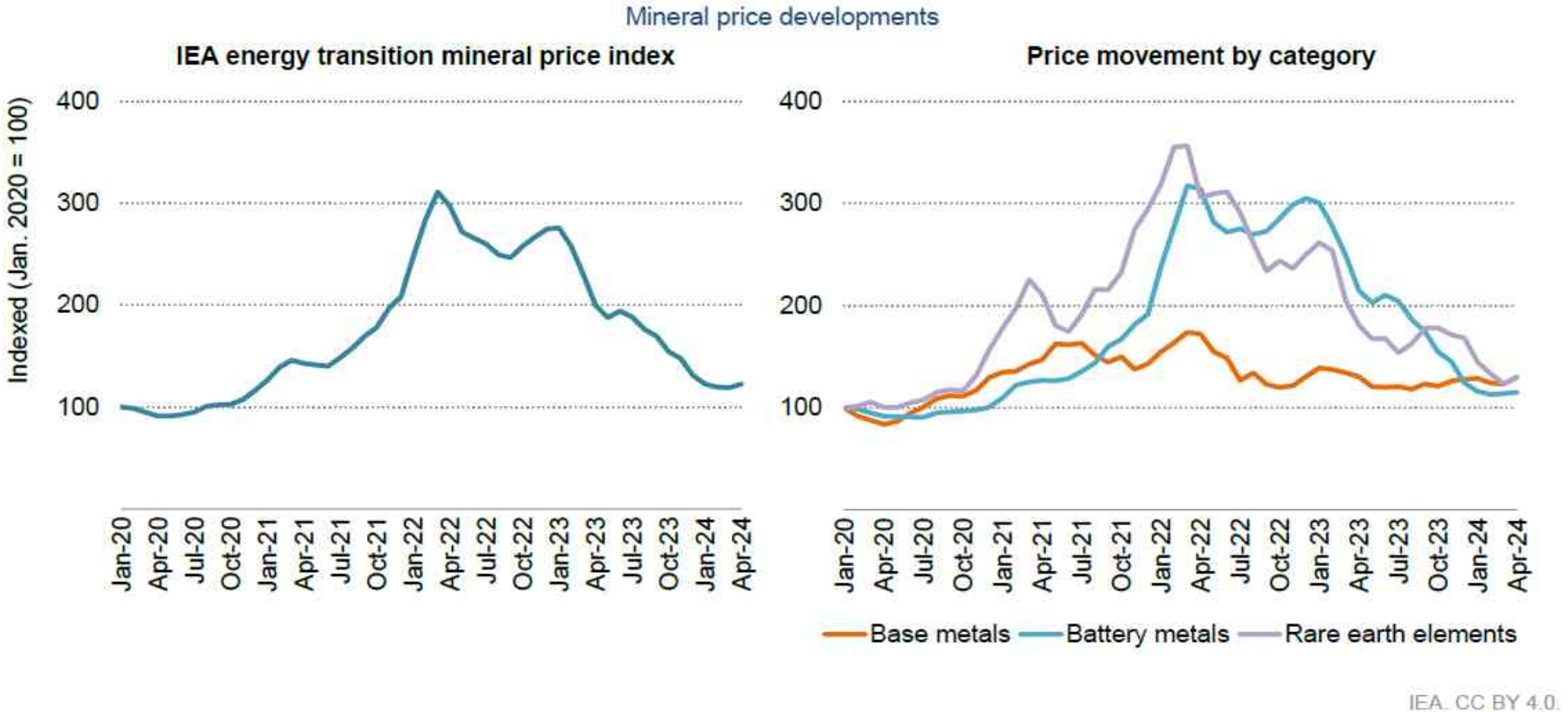


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Notes: The IEA Clean Energy Equipment Price Index tracks price movements of a fixed basket of solar PV panels, wind turbines and lithium-ion batteries (for EVs and energy storage). Prices are weighted based on the shares of global average annual investment.
Sources: IEA analysis based on company financial reports and BloombergNEF.

Source: IEA Critical Minerals Outlook 2024 - May 2024

The Energy Sector – Energy Transition
General context of Prices development – Evolution 2020 - 2024

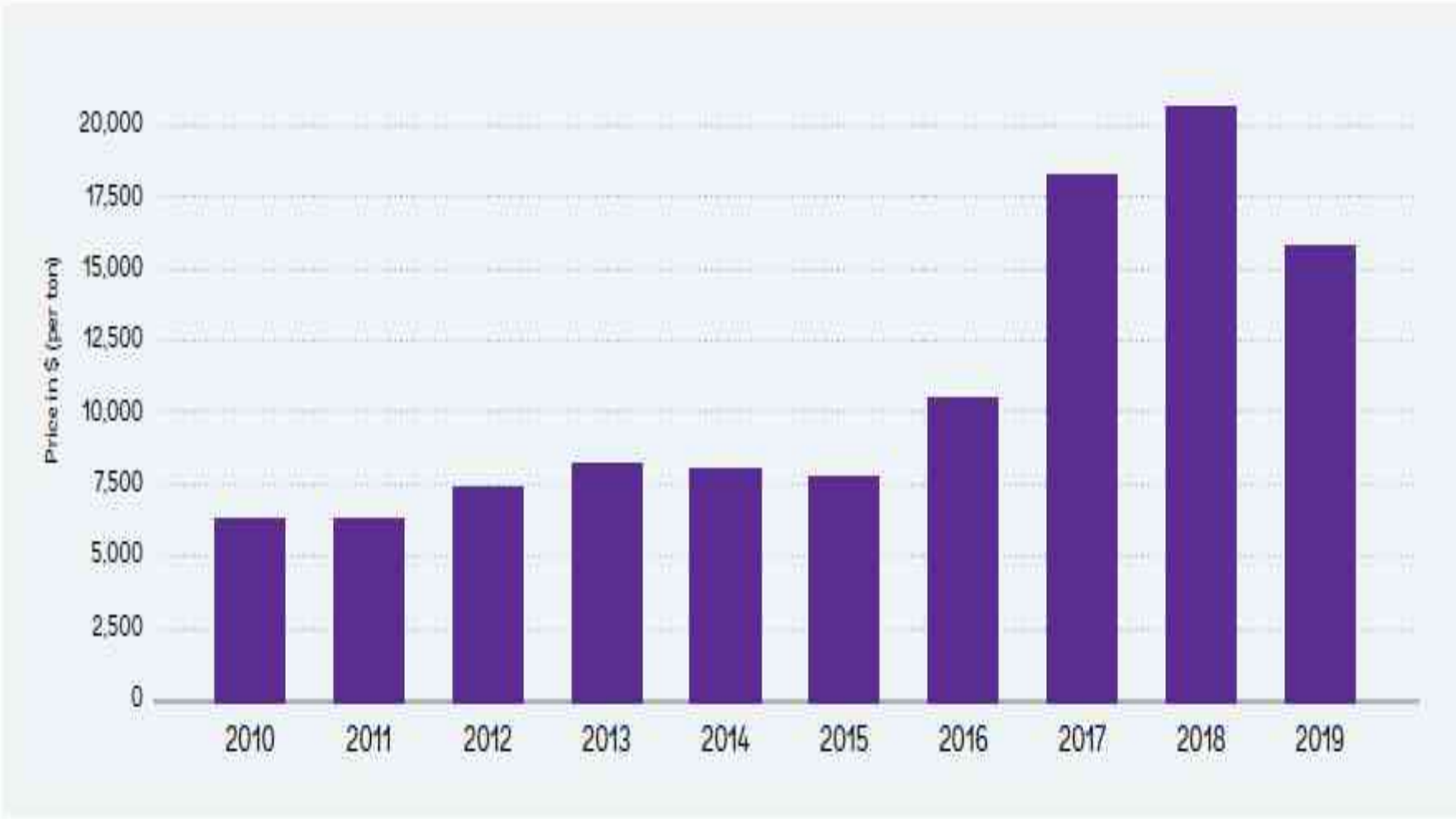


Notes: IEA Energy Transition Minerals price index is a basket price of copper, lithium, nickel, cobalt, graphite, manganese and neodymium. On the right-hand chart, base metals include iron, aluminium, zinc and copper. Battery metals include lithium, nickel, cobalt, graphite and manganese. Rare earth elements include neodymium, praseodymium, dysprosium and terbium.

Sources: IEA analysis based on Bloomberg and S&P Global.

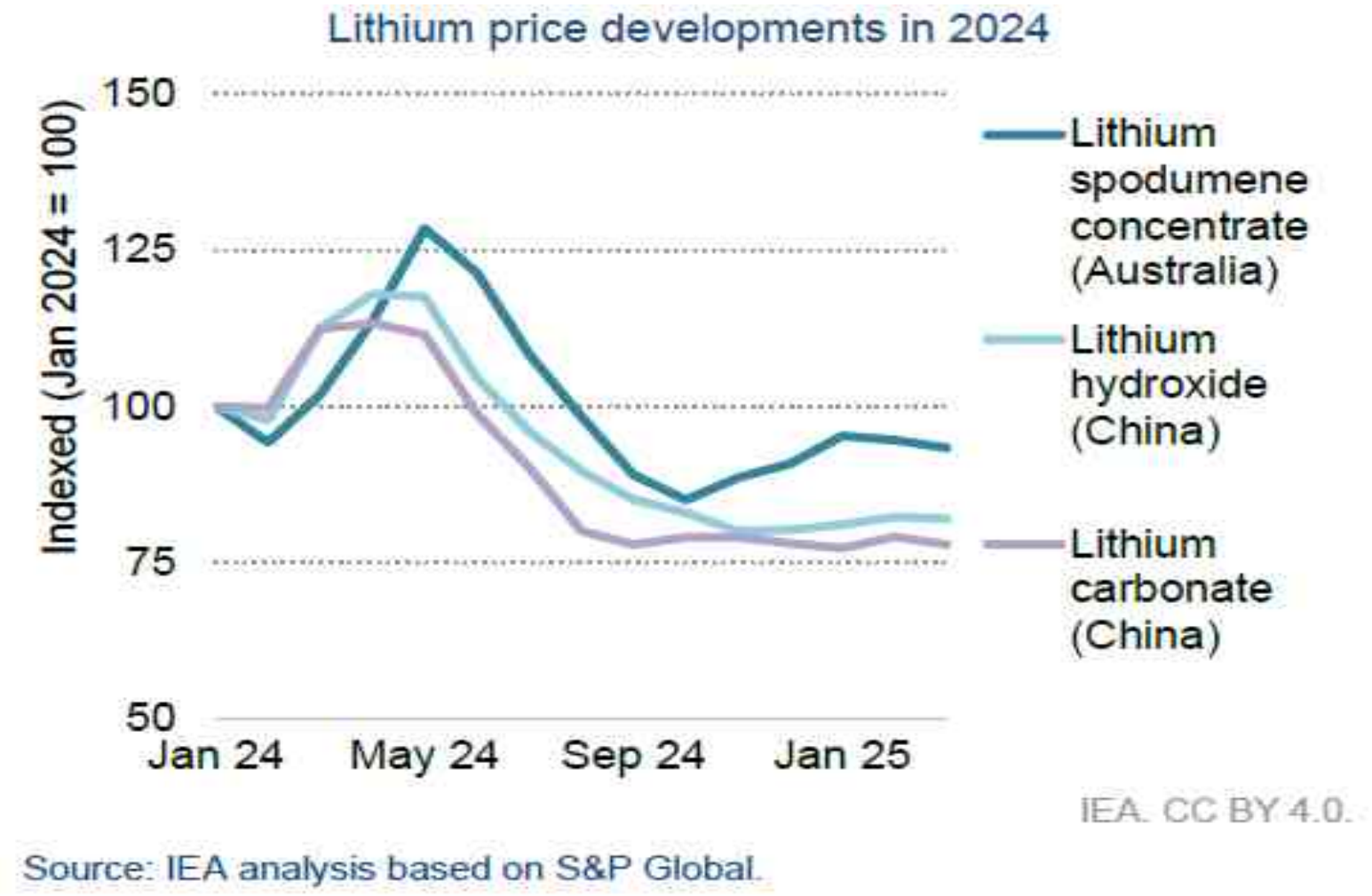
Source: IEA Critical Minerals Outlook 2024 - May 2024

Example: Lithium Price Evolution 2010 - 2019



Source: World Bank

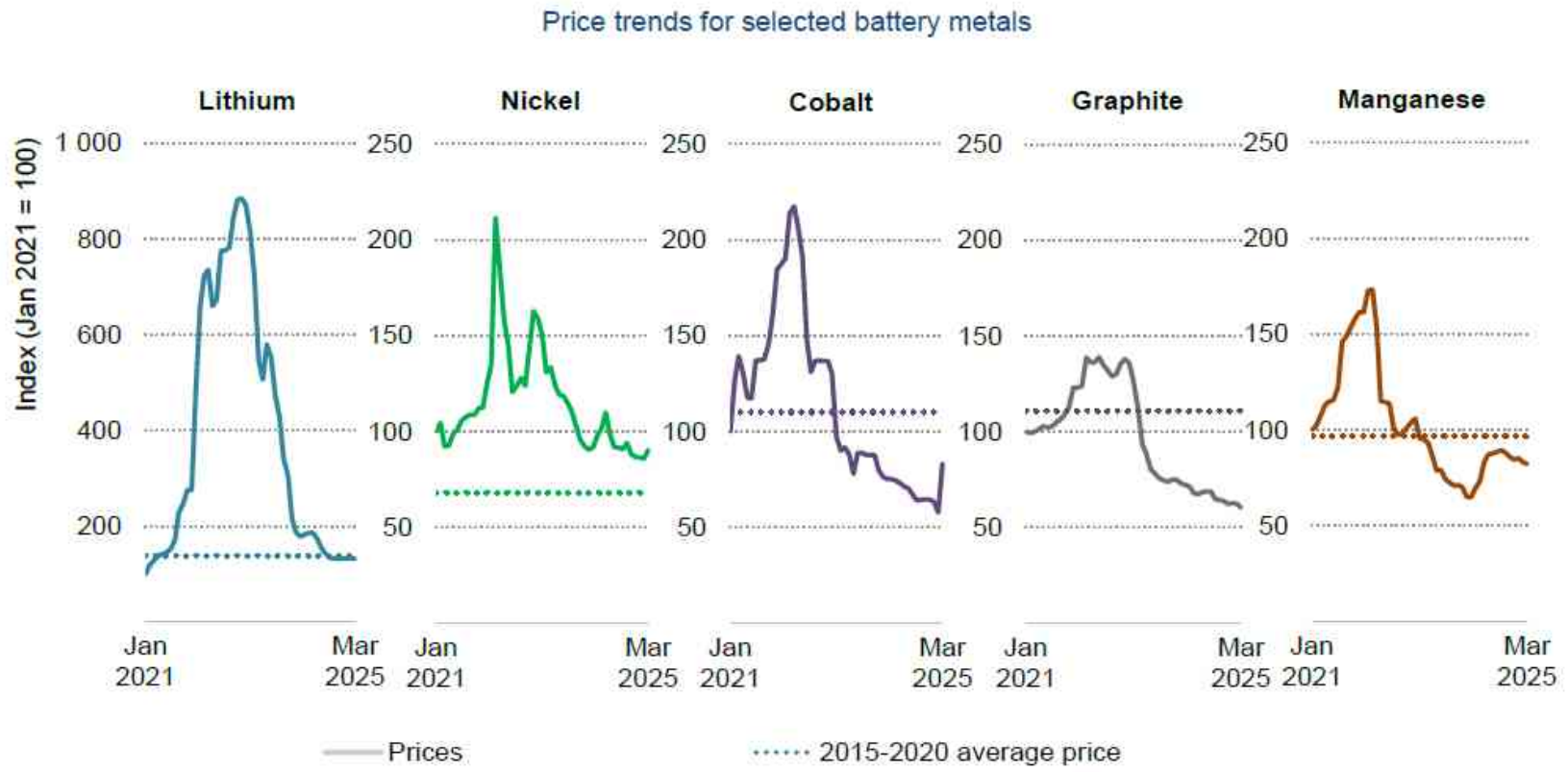
Example: Lithium Price Evolution - 2024



Source: IEA analysis based on S&P Global.

Prices development for key Materials - Evolution 2021 - 2025
A great volatility

Prices for battery metals continued to decline in 2024 amid growing supply, with the exception of manganese



Notes: Manganese historical average from 2018-2020. Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash, China Spherical Graphite 99.95% and manganese sulphate 32%. Nominal prices.
Sources: IEA analysis based on S&P Global and Bloomberg.

Several factors explain the drop in prices from 2022 to 2024 (Mainly Demand growth much less than Production) :

- **Slowing growth rate of EV battery.**
- **Large-scale cell and cathode production.**
- **China's expansion of battery plants, cathode and anode production capacity has far outpaced demand.**
- **Build-up of inventory throughout the supply chain.**
- **Correction of steep price rise in 2021-2022**

Source: IEA Global Critical Materials Outlook 2025 – June 2025

Conclusion - Important points to keep in mind

Low Carbon Technologies consume more Materials than traditional Technologies.

Criticality of a Material may vary very much between Countries (Geological and geopolitical aspects)

Copper is probably the Metal which will be more constraint for the next decades to come (For Energy Transition and also all industrial sectors)

Lithium might be more constrained economically.

Cobalt might be more constrained geopolitically

Recycling is a must.

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Prices of energy commodities and needs for investments

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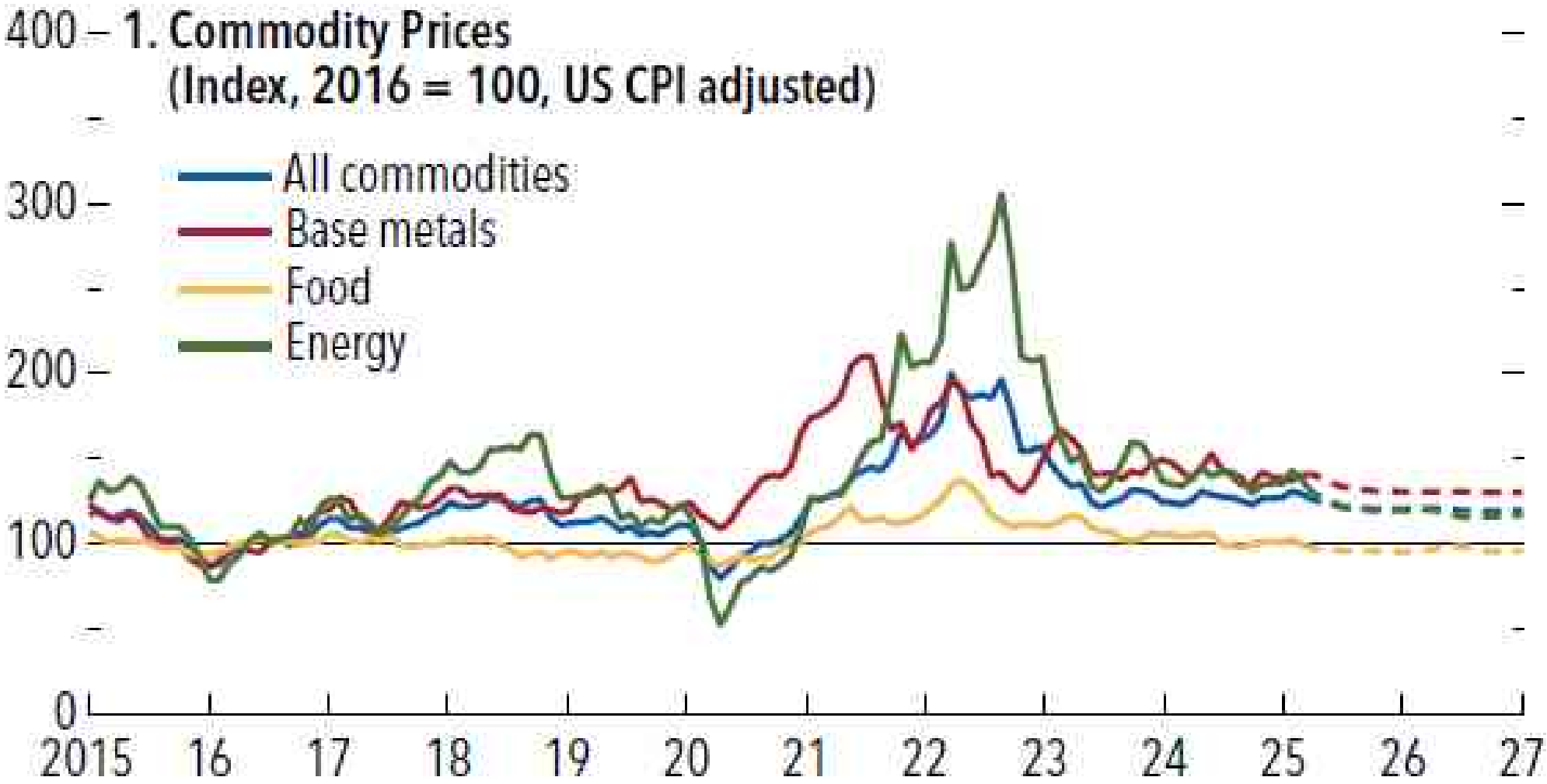
- 1. Energy: a major element of economic development
- 2. Energy consumption vs Gross Domestic Product
- 3. Evolution of Energy Intensity
- 4. Energy: past evolution, present situation
- 5. Energy: A zoom on France
- 6. Demography: A key element
- 7. Global Energy Growth – Scenarios from various organizations
- 8. Global Energy Growth – Mobility/Transport
- 9. Global Energy Growth – A zoom on Hydrogen
- 10. Global Energy Growth – Electricity Demand & Generation
- 11. Global Energy Growth – Electricity storage
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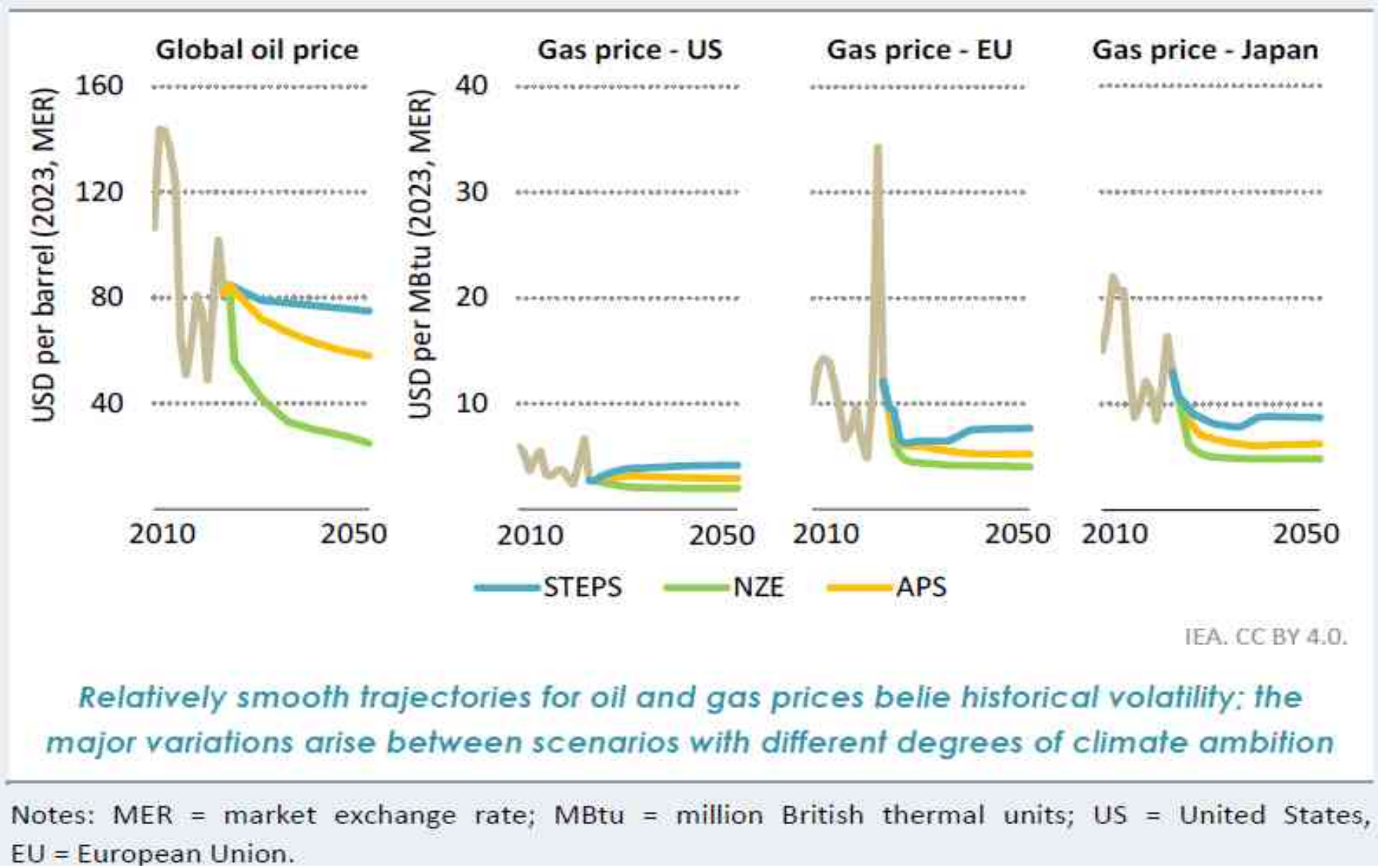
Prices of Energy Commodities

Commodity Prices – IMF April 2025



Source: IMF WEO April 2025

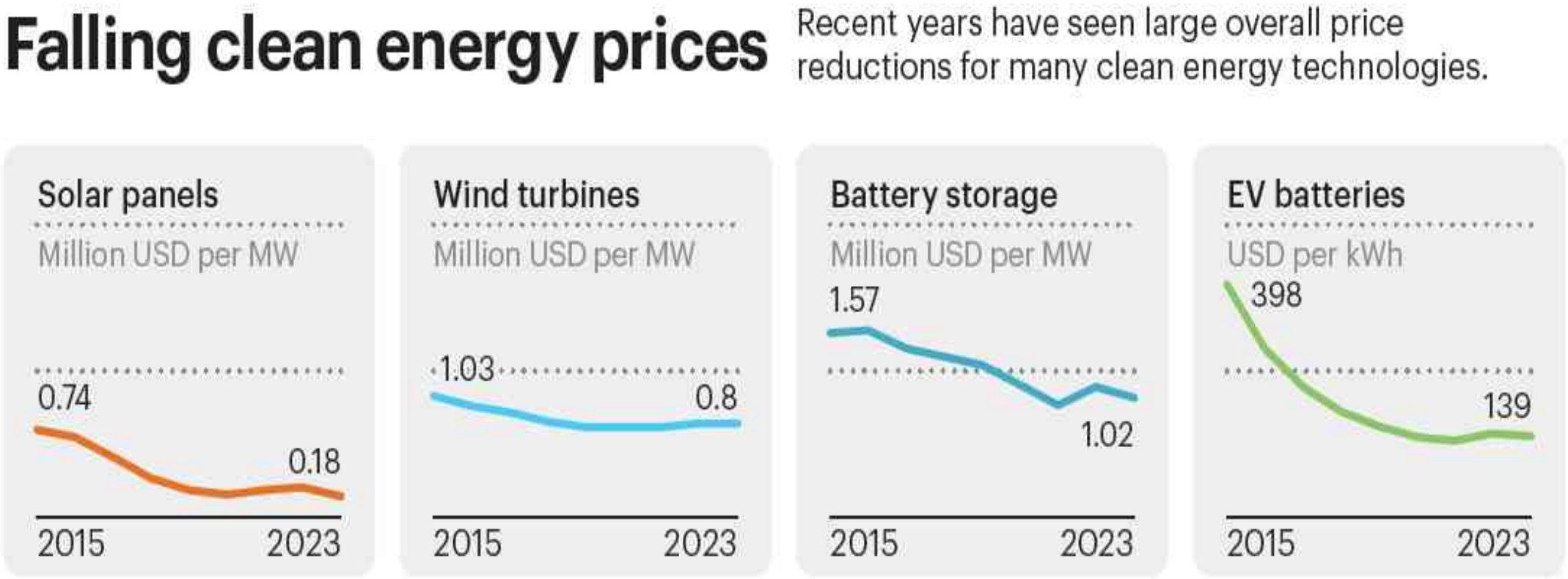
Energy Prices Indicators 2010 – 2050 vs Scenarios – IEA 2024



Notes: MER = market exchange rate; MBtu = million British thermal units; US = United States, EU = European Union.

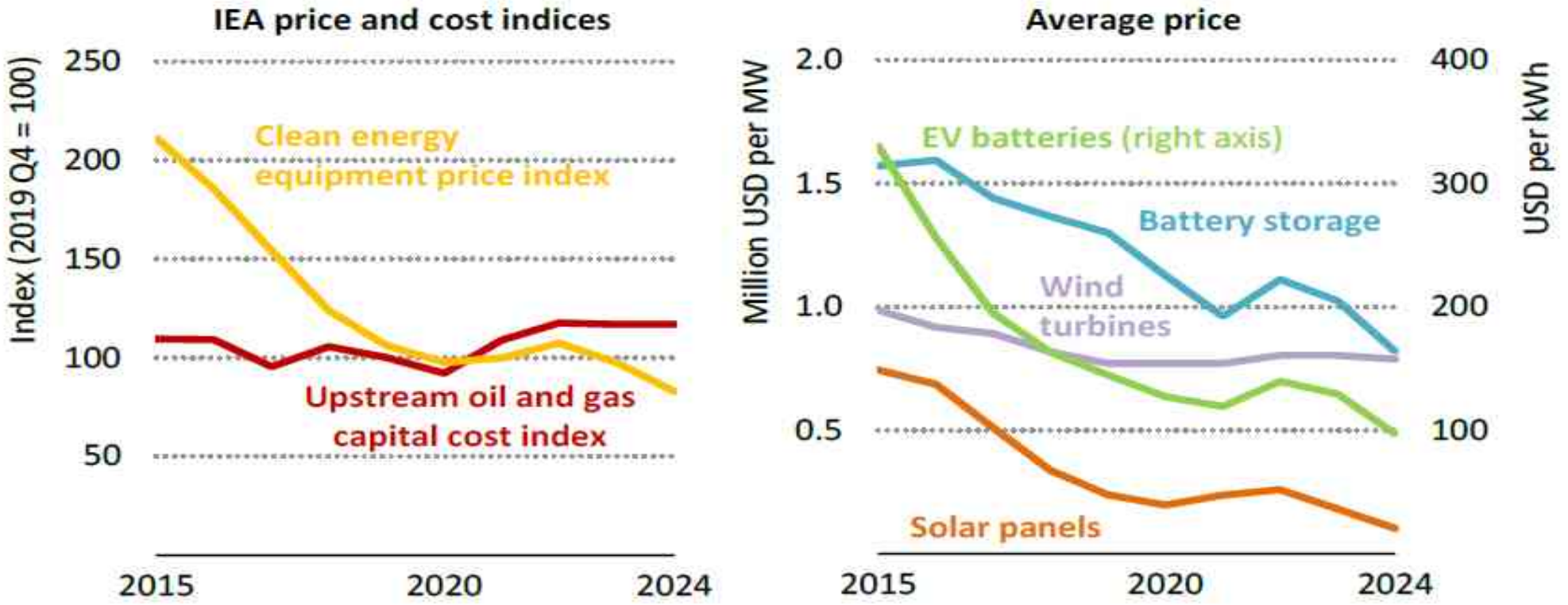
Source: IEA WEO 2024

……And falling Clean Energy Prices



Source: IEA WEO 2024

……And falling Clean Energy Prices



Falling critical minerals prices and fierce competition stemming from excess manufacturing capacity have driven major price reductions in batteries and solar PV

Notes: Q4 = 4th quarter; MW = megawatt; kWh = kilowatt-hour. Nominal prices.

Sources: IEA analysis based on company financial reports and BNEF (2024).

Source: IEA WEO 2025

Wholesale Fossil Fuels Prices by Scenarios IEA WEO 2025

		CPS		STEPS		NZE	
USD (MER, 2024)	2024	2035	2050	2035	2050	2035	2050
IEA crude oil (USD/barrel)	79	89	106	80	76	33	25
Natural gas (USD/MBtu)							
United States	2.2	4.5	5.0	3.9	4.6	2.1	2.2
European Union	10.3	9.1	10.6	6.5	8.4	4.2	4.0
China	10.3	9.9	11.2	7.5	9.1	4.9	4.8
Japan	13.5	11.2	12.9	8.4	9.7	4.9	4.9
Steam coal (USD/tonne)							
United States	56	56	53	41	41	25	23
European Union	112	92	82	78	66	47	39
Japan	151	112	105	100	84	57	49
Coastal China	131	115	105	99	84	59	49

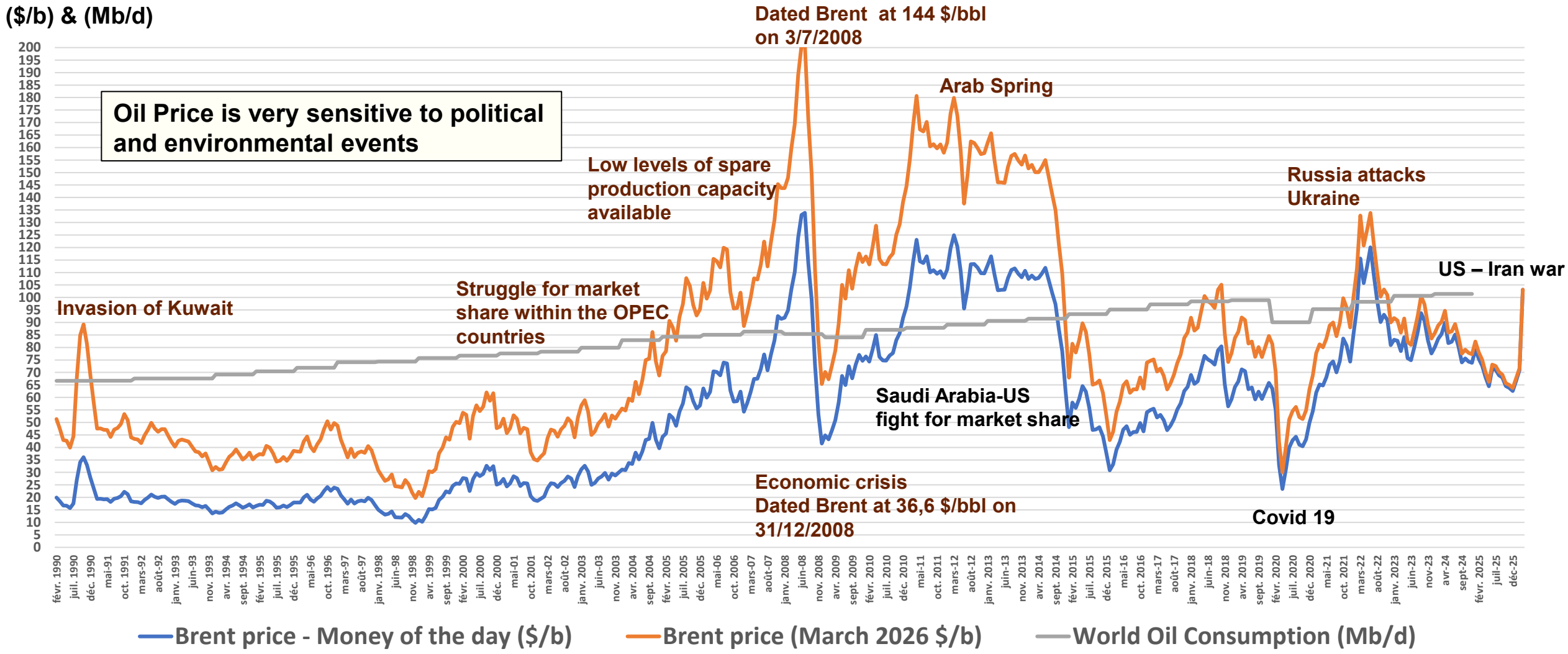
Notes: CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. MER = market exchange rate; MBtu = million British thermal units. The IEA crude oil price is a weighted average of import prices among IEA member countries. Natural gas prices are weighted averages expressed on a gross calorific-value basis. The US natural gas price reflects the wholesale price prevailing on the domestic market. Natural gas prices in the European Union and China reflect a balance of pipeline and liquefied natural gas (LNG) imports, while the Japan gas price is solely for LNG imports. LNG prices are those at the customs border prior to regasification. Steam coal prices are weighted averages adjusted to 6 000 kilocalories per kilogramme. The US steam coal price reflects mine mouth prices plus transport and handling costs. Coastal China steam coal price reflects a balance of imports and domestic sales, while the European Union and Japanese steam coal prices are solely for imports. Wholesale prices exclude any emissions pricing applied at the point of use.

Source: IEA WEO 2025

Price of Oil

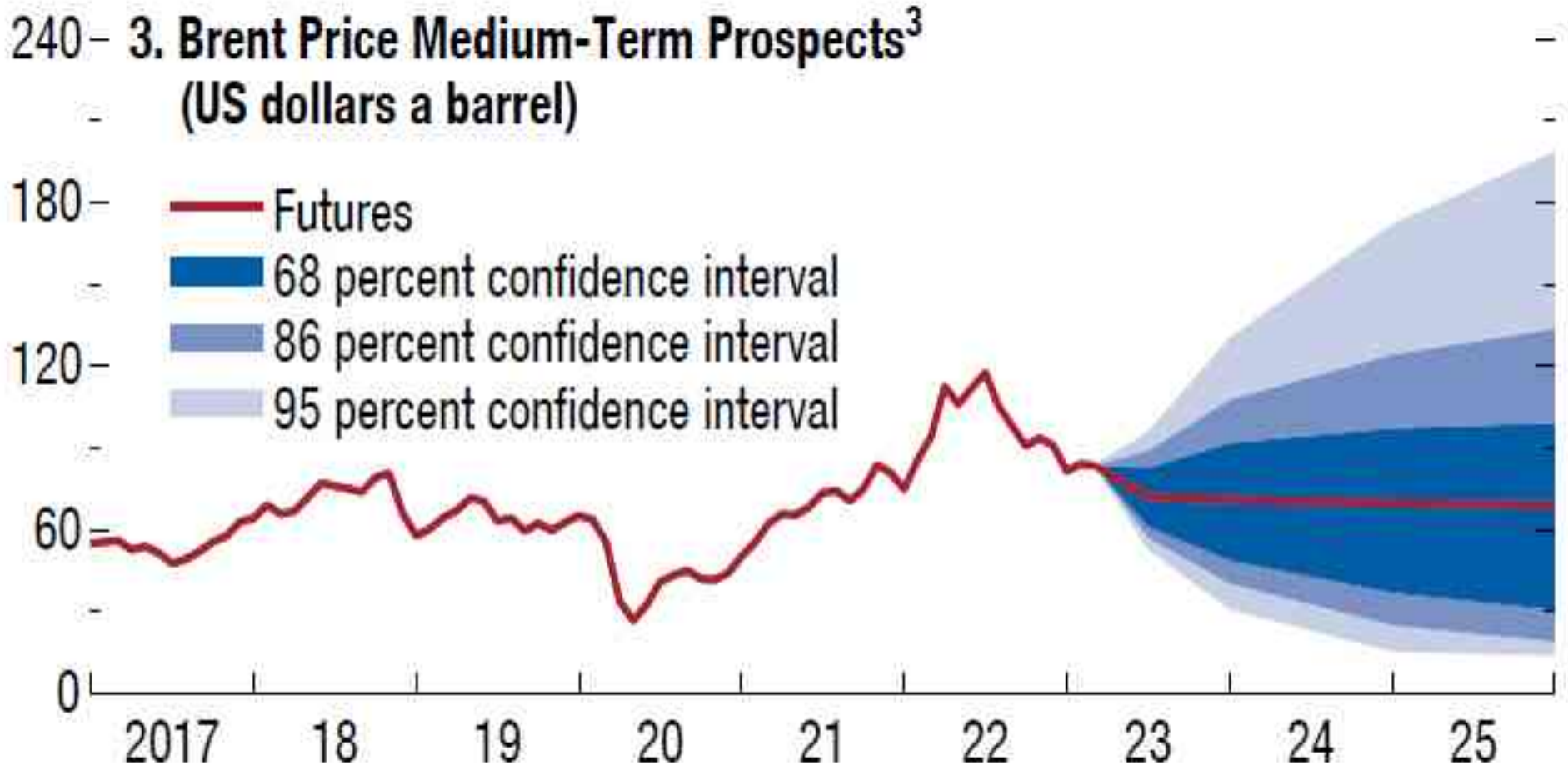
Oil Price prediction is a perilous exercize!
See also Book 4 - Oil

Crude Oil Price and Oil Consumption since 1990 till March 2026
(Monthly Average - Prices are fluctuating within a month)



Source: ChG/Price: Data from EIA Index Mundi – US CPI: Bur. of Labor Statistics
Oil Consumption: EI Stat. Review 2025

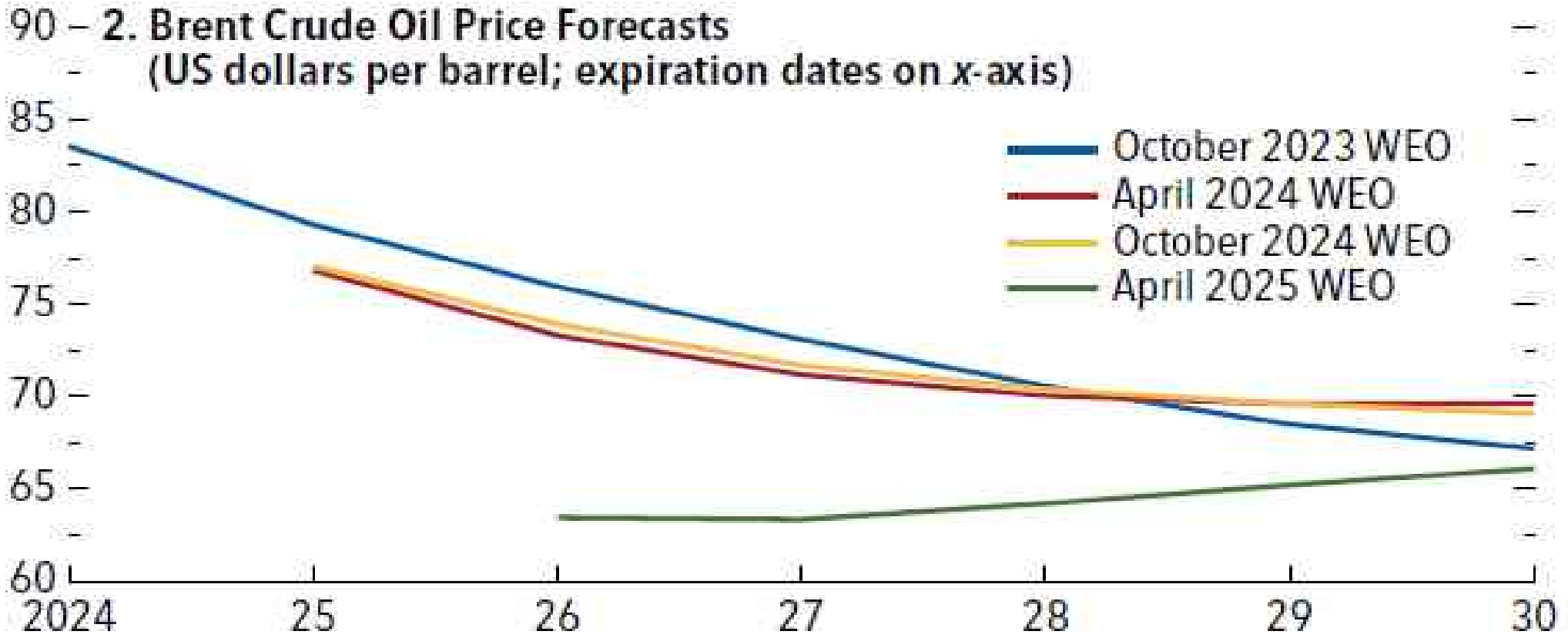
Reminder: Oil Price Prospects according to IMF April 2023



3: Derived from prices of futures options on 17 March 2023

Source: IMF WEO April 2023

Oil Price Prospects according to IMF April 2025

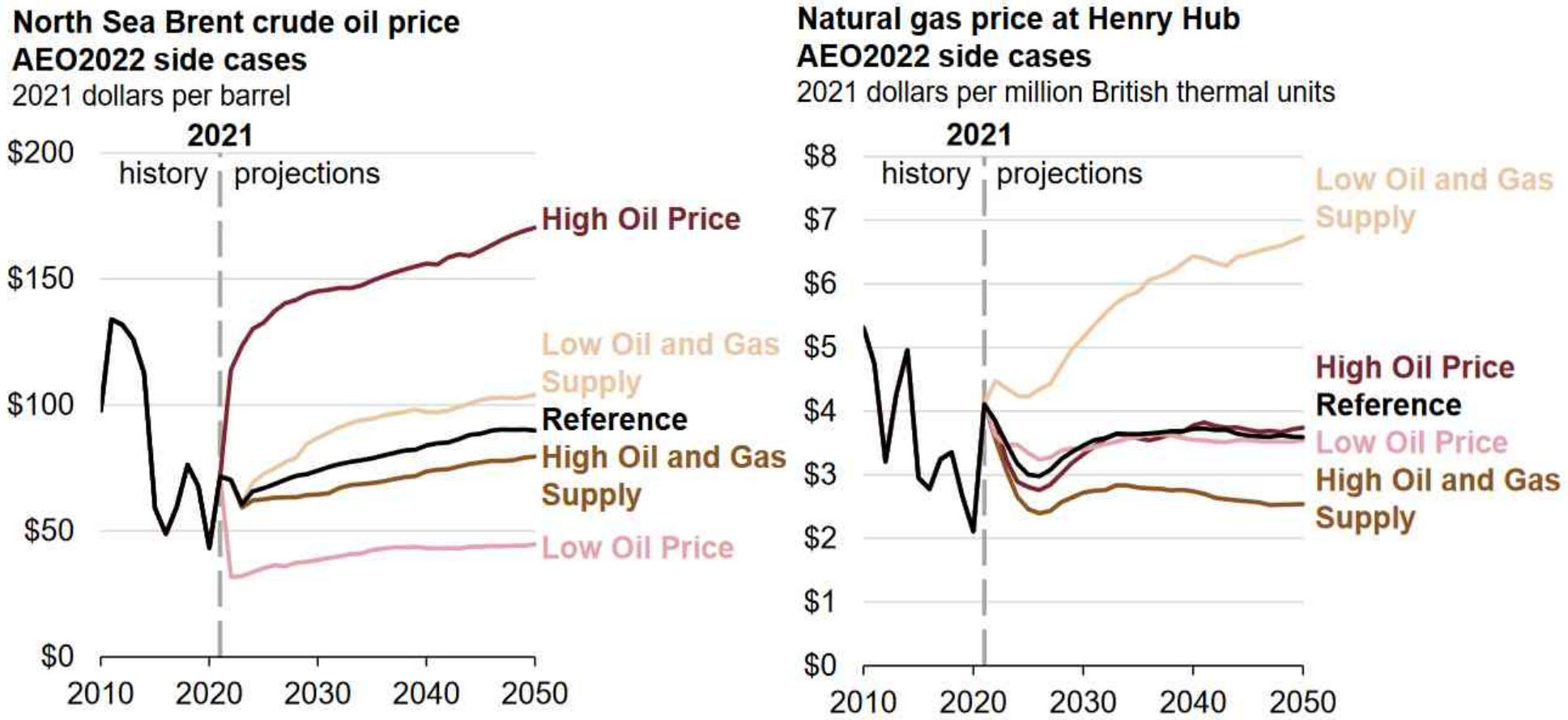


Sources: Bloomberg, L.P.; Haver Analytics; IMF, Primary Commodity Price System; International Energy Agency; and IMF staff calculations.

Source: IMF WEO April 2025

Reminder - OIL & GAS PRICES – US EIA SCENARIOS 2022

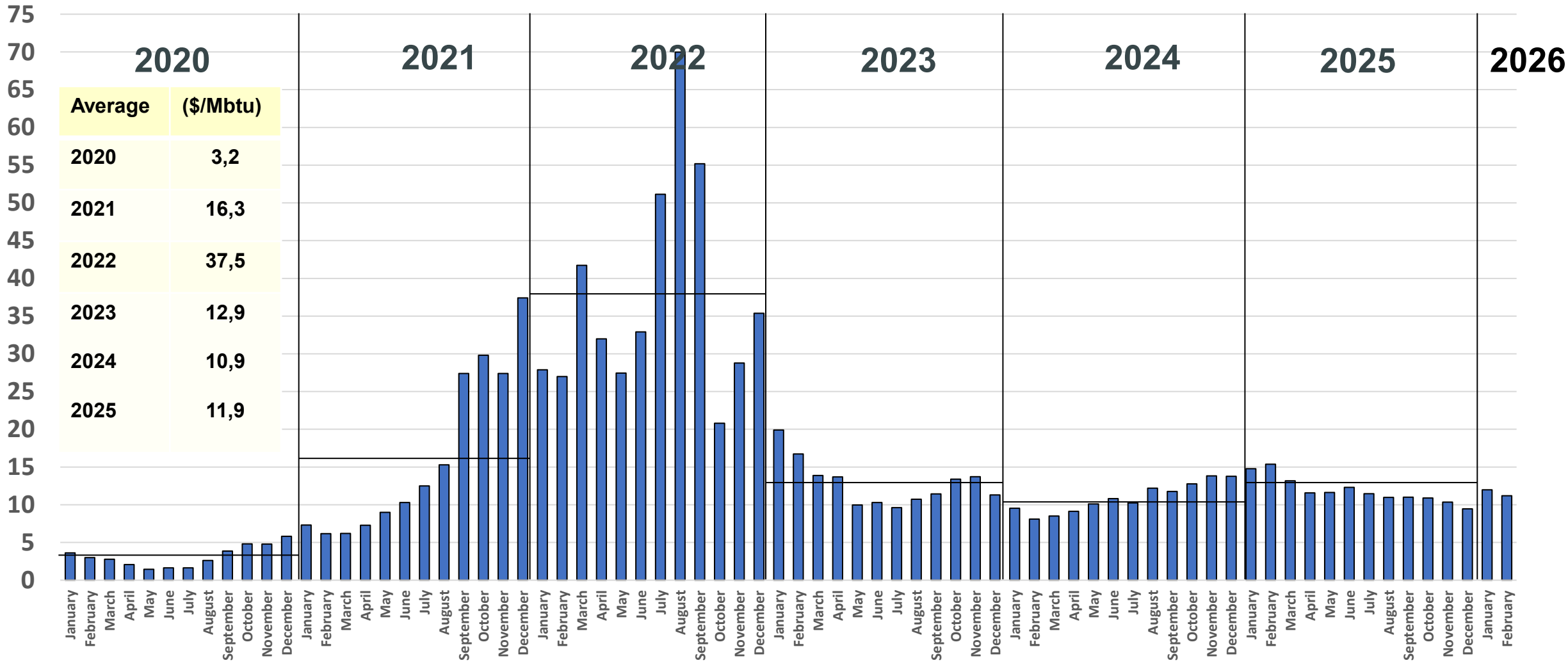
Crude oil price projections and natural gas price projections



Source: US EIA AEO 2022

Prices of Gas in Europe

Monthly German Border Gas Prices Evolution 2020 – 2025 ($/Mbtu)
The impacts of economic & geopolitical turmoils are great

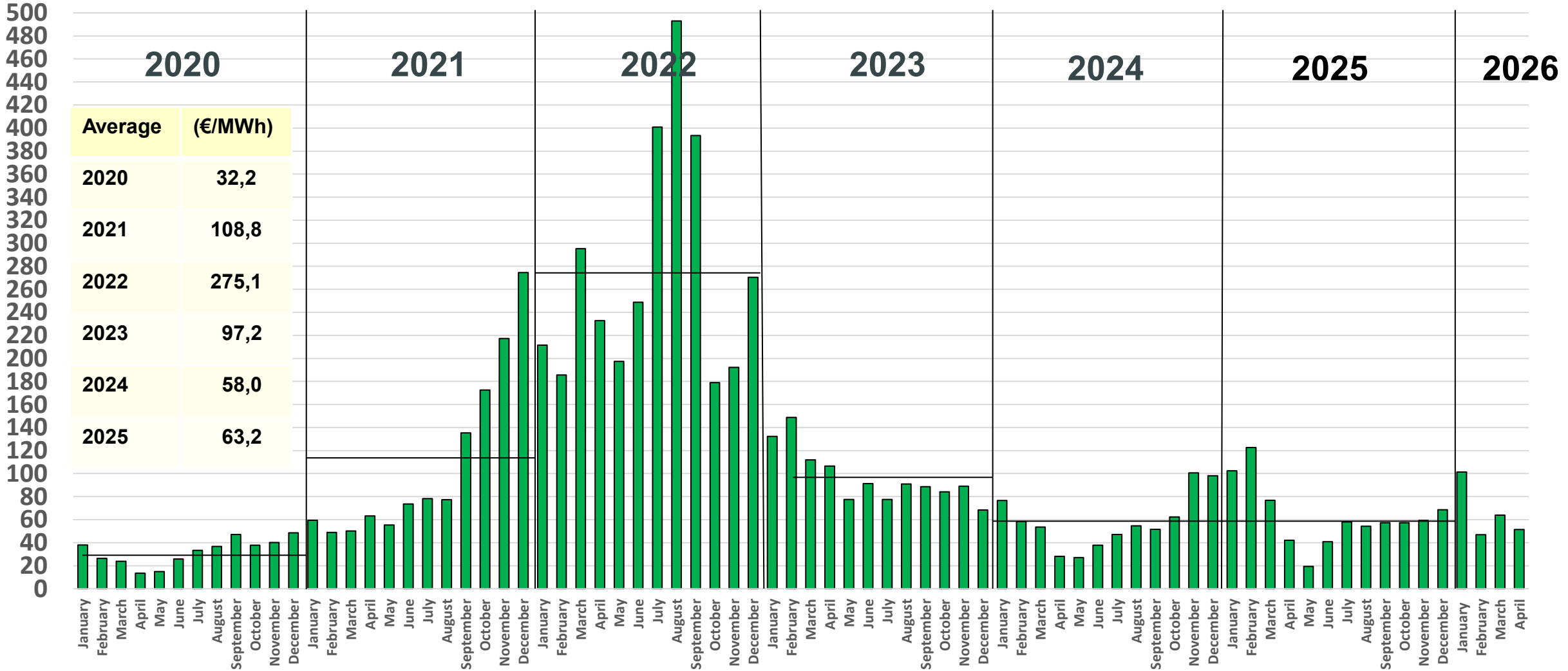


Average	($/Mbtu)
2020	3,2
2021	16,3
2022	37,5
2023	12,9
2024	10,9
2025	11,9

Source: Ch.Guéritte/Data from IMF Primary Commodity Prices

Monthly Wholesale Electricity Prices France 2020 – 2025 (€/MWh)

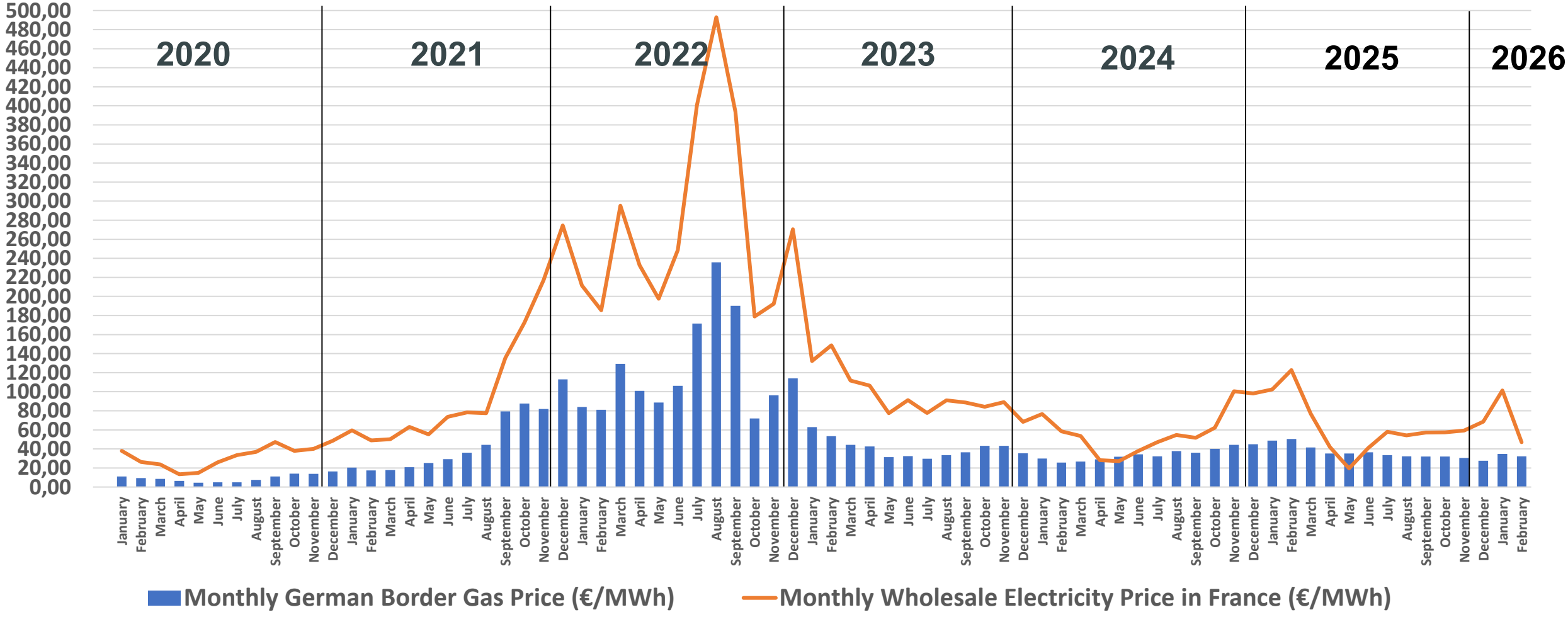
The impacts of economic & geopolitical turmoils are great



Average	(€/MWh)
2020	32,2
2021	108,8
2022	275,1
2023	97,2
2024	58,0
2025	63,2

Source: Ch.Guéritte/Data from Ember

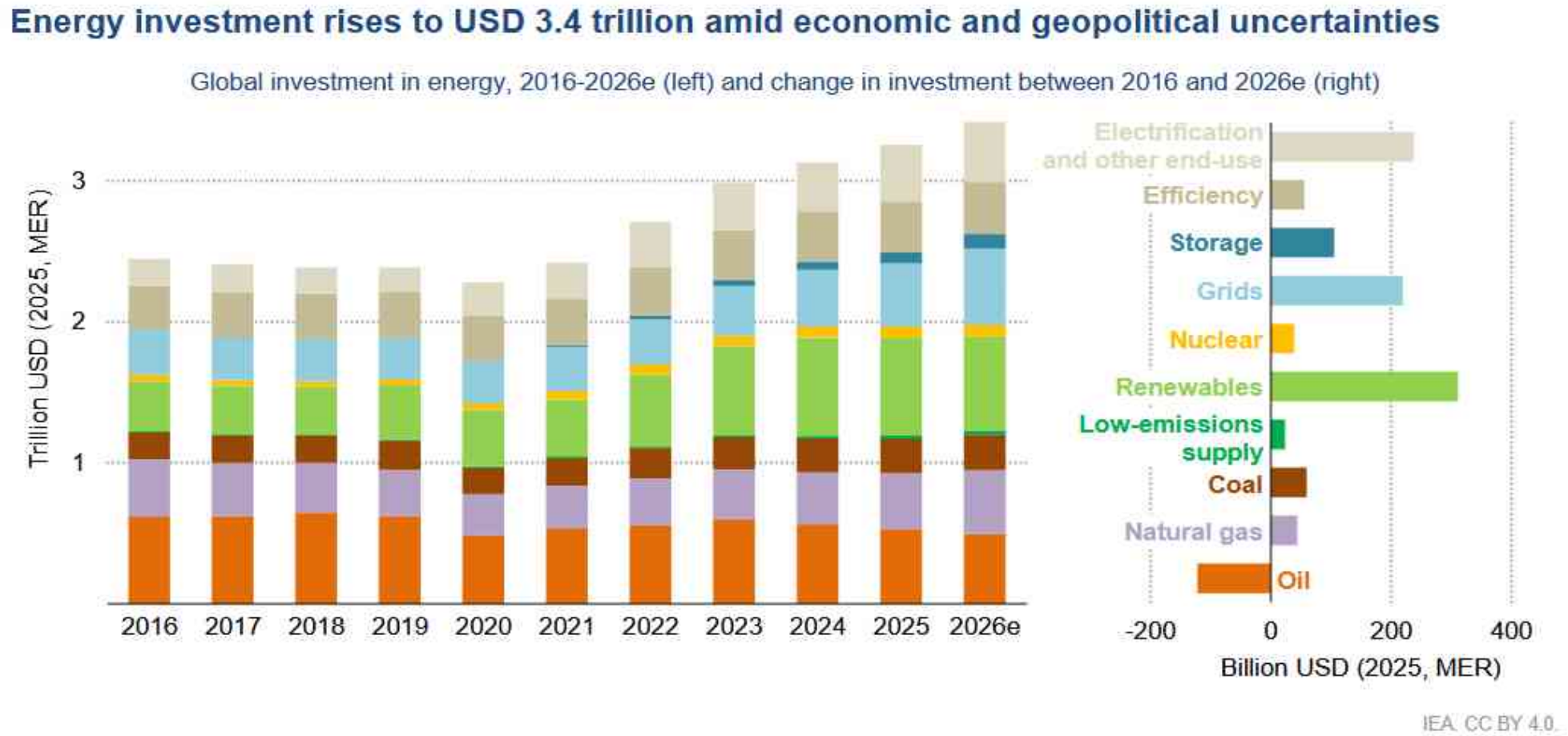
Strong correlation Electricity Price/ Gas Price in Europe (€/MWh)
The impacts of economic & geopolitical turmoils are great



Source: Ch.Guéritte/Data from Ember, IMF
Exchange Rate: FRED, US Fed. Reserve system

Investments

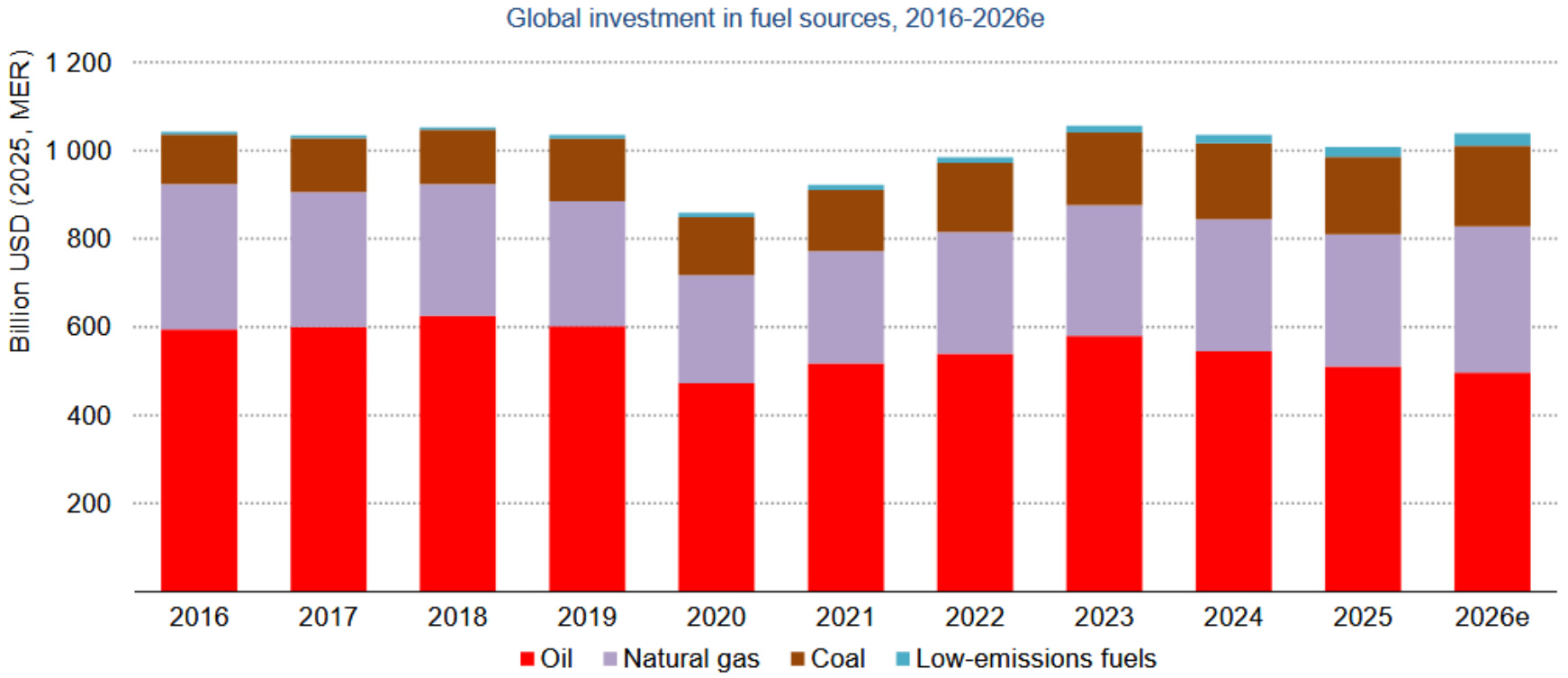
Energy Annual Average Investments 2016 - 2026 by IEA 2026
3,4 T$ in 2026 - A global boost for Clean Energy Investments



Source: IEA World Energy Investments 2026 – June 2026

Global Investments in Fuel sources 2016 - 2026 by IEA 2026

Despite the Middle East conflict, capital outlays on fuels are expected to rise about 3% in 2026, driven mainly by investment in natural gas projects



IEA. CC BY 4.0.

Announced investment plans suggest a third consecutive year of lower oil supply spending in 2026. Still, overall fuel investment is set to rise marginally as expenditures in natural gas increase to USD 330 billion and in coal supply increase to the highest level since 2012.

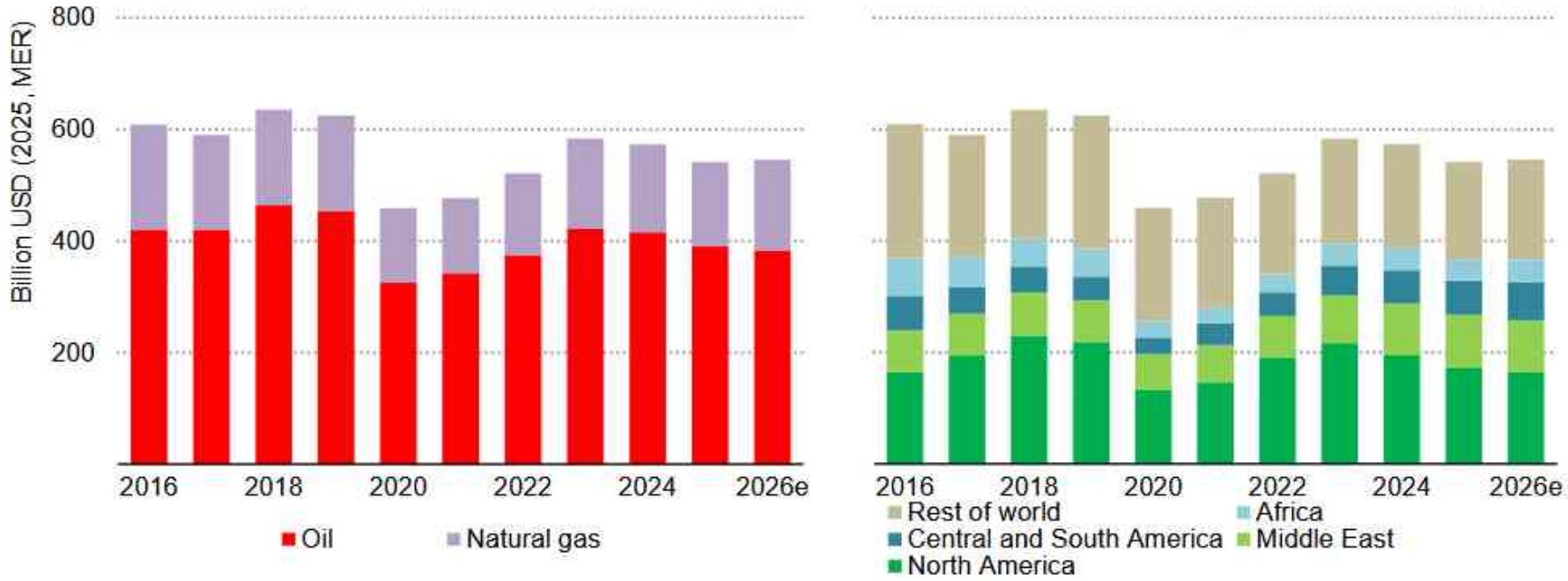
Notes: MER = market exchange rate. 2026e = estimated. capex = capital expenditure. Oil, natural gas and coal include upstream, refining and infrastructure investment. "Low-emissions fuels" comprises modern bioenergy, low-emissions hydrogen, hydrogen-based fuels and carbon capture, utilisation and storage (CCUS).

Source: IEA World Energy Investments 2026 – June 2026

Global Upstream Investments 2016 - 2026 by IEA 2026

Global upstream investment rises marginally in 2026, with declines in North America and the Middle East offset by increases in Africa and Central and South America

Oil and gas upstream investment (left) and by region (right), 2016-2026e



IEA. CC BY 4.0.

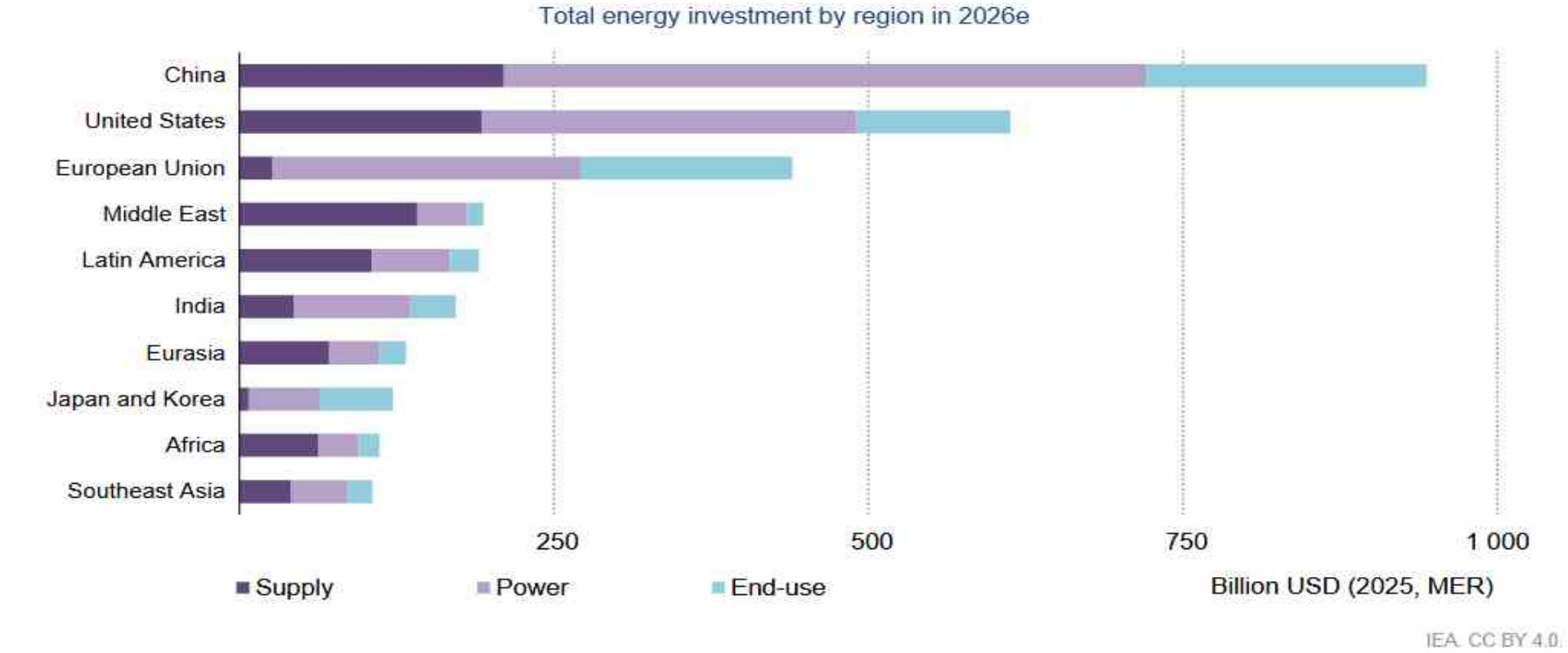
North American investment falls in 2026 due to capital discipline and technological gains, while the conflict weighs on investment in the Middle East; these drops are offset mainly by increases in Central and South America and Africa as recent discoveries are developed.

Notes: MER = market exchange rate. 2026e = estimated. For regional definitions, see the Methodology Annex.
Sources: IEA analysis based on Bloomberg (2026), Bloomberg Terminal; FRED (2026), Producer Price Indexes; IEA (2025), WEO Database (accessed 20 May 2026); IMF (2026), World Economic Outlook database (accessed 20 May 2026); Rystad (2026), Rystad Energy Cube Browser; and company reporting.

Source: IEA World Energy Investments 2026 – June 2026

Energy Annual Average Investments 2026 by Regions
Chine takes the lead

Advanced economies and China make up over 70% of total energy investments in 2026, with nearly half of all global spending going to the power sector

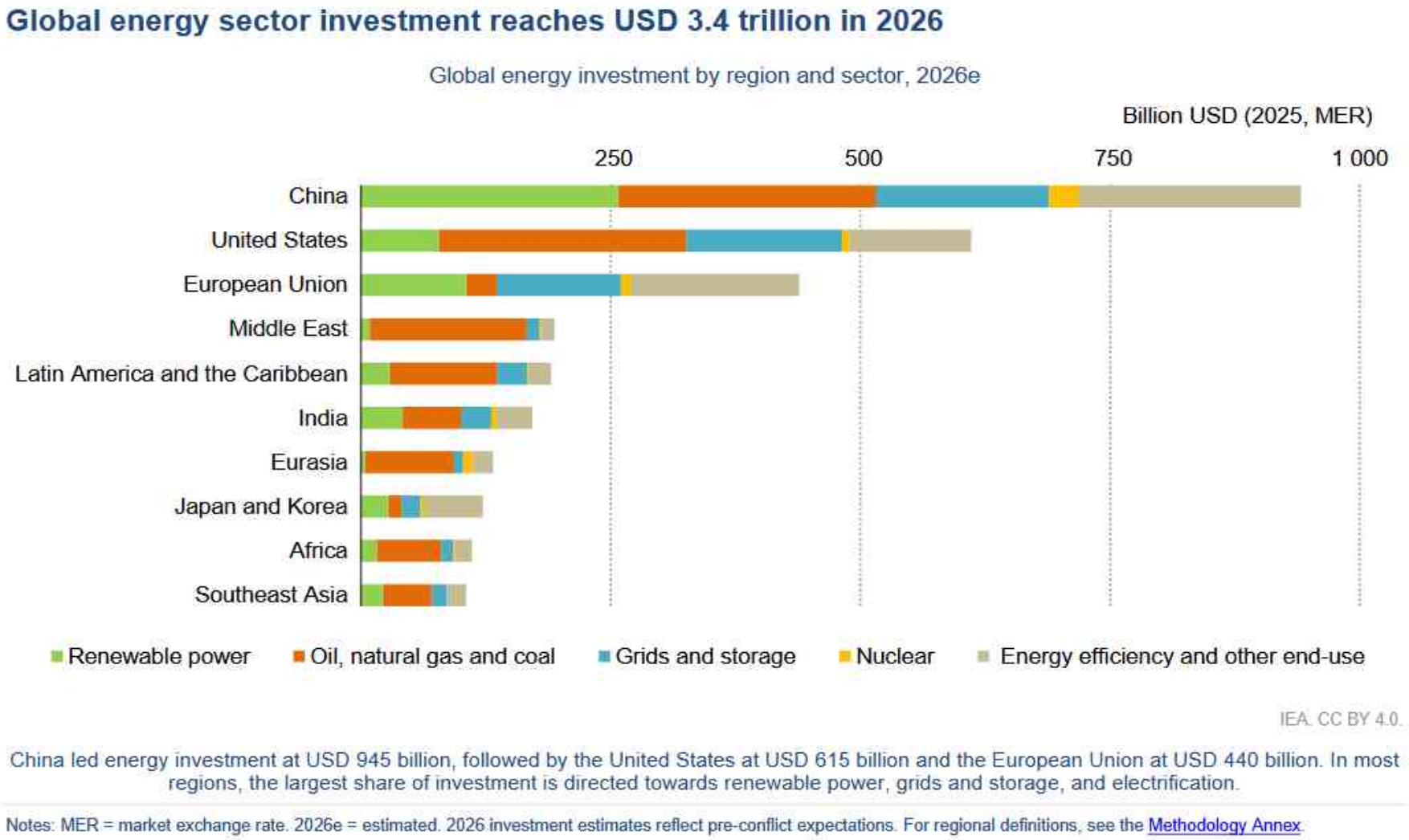


Emerging market and developing economies other than China account for less than 30% of total energy investment and 20% of power sector investment, despite having two-thirds of the world's population.

Note: MER = market exchange rate.

Source: IEA World Energy Investments 2026 – June 2026

Energy Annual Average Investments 2026 by Regions # 3,4 T$ China takes the lead



Source: IEA World Energy Investments 2026 – June 2026

Clean Energy Investments 2026 by Regions # 2,2 T$ China takes the lead

In 2026, global investment in clean energy and related infrastructure reaches USD 2.2 trillion, almost double that of fossil fuels

Global clean energy investment (left) and fossil fuel investment (right) by composition and region, 2026e



IEA. CC BY 4.0.

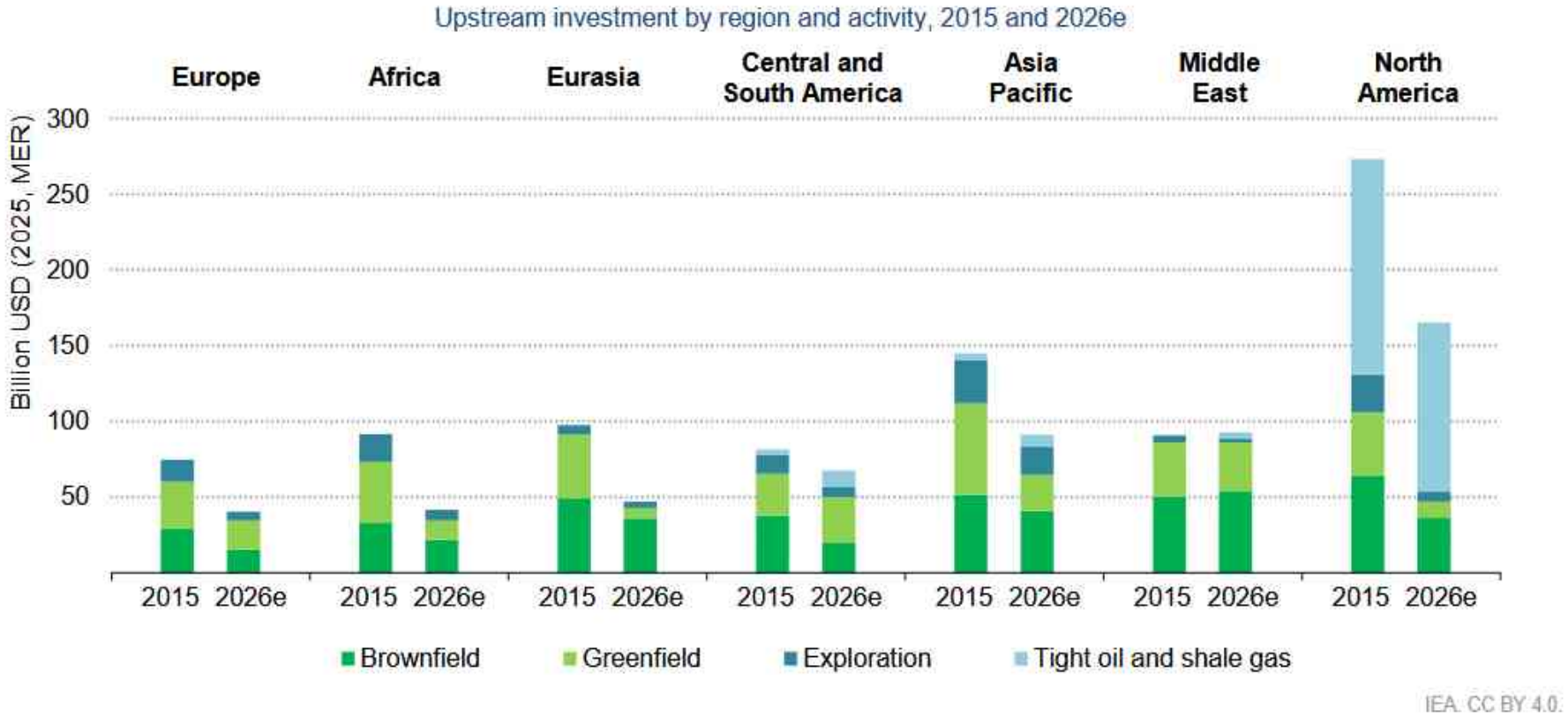
China, the European Union and the United States make up USD 1.5 trillion (66%) of total investment in clean energy. China, the largest investor in fossil fuels, together with the United States and the Middle East, account for total investments of USD 640 billion.

Notes: EMDE = emerging market and developing economies. 2026e = estimated. 2026 investment estimates reflect pre-conflict expectations.

Source: IEA World Energy Investments 2026 – June 2026

Upstream Oil Investments 2026 is declining

Overall upstream investment has been lower in the post-Covid period with the share of exploration spending declining across all regions



A shift towards shorter cycle projects, structurally lower costs, and stronger capital discipline underpinned an 55% decline in global upstream oil and gas spending between 2015 and 2026.

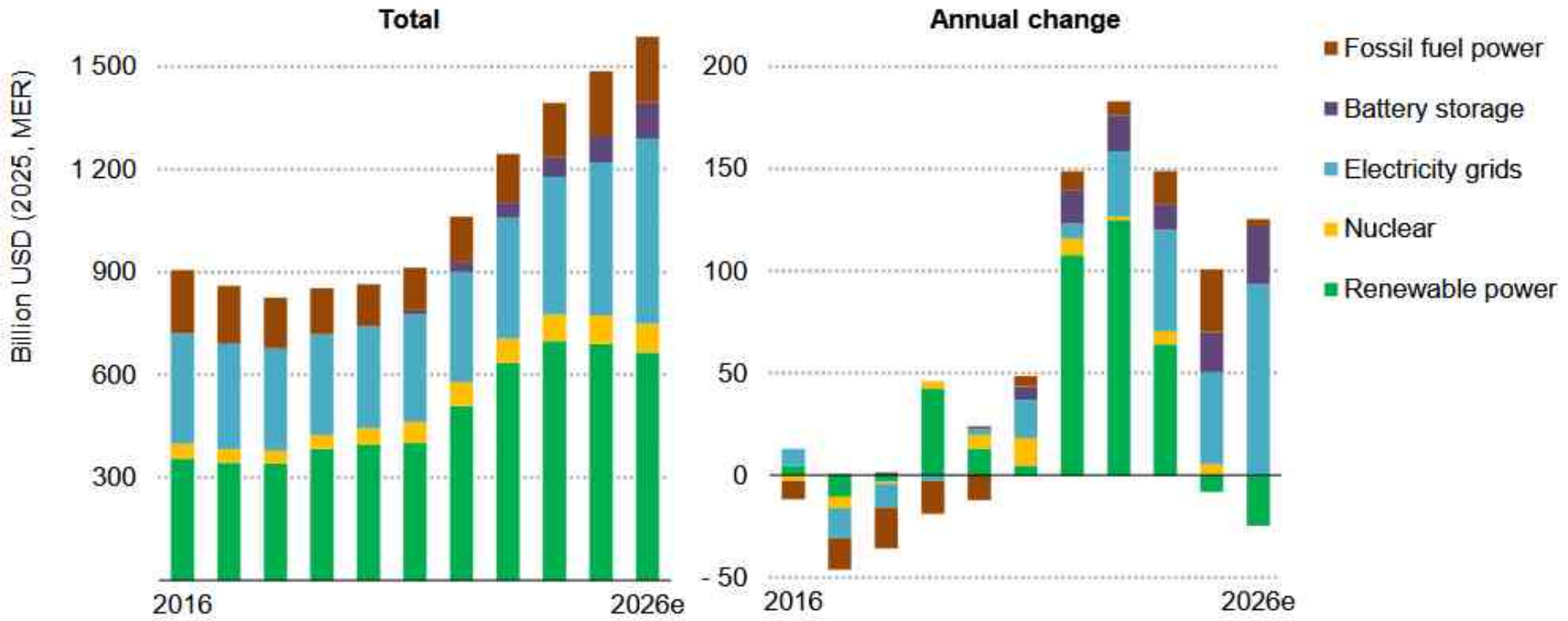
Note: MER = market exchange rate.
Source: IEA analysis based on Rystad (2026), Rystad Energy Cube Browser.

Source: IEA World Energy Investments 2026 – June 2026

Global Power sector Investments 2016 - 2026 by category

Total power sector investment rose an impressive 7% in 2025 despite a slow-down in renewables

Global annual power sector investment (left) and net growth (right) by category share, 2016-2026e



IEA. CC BY 4.0.

A decline in renewables investment, due in large part to cost reductions, was offset by robust growth for battery storage, grids and fossil power in 2025 – a trend that is expected to continue into 2026.

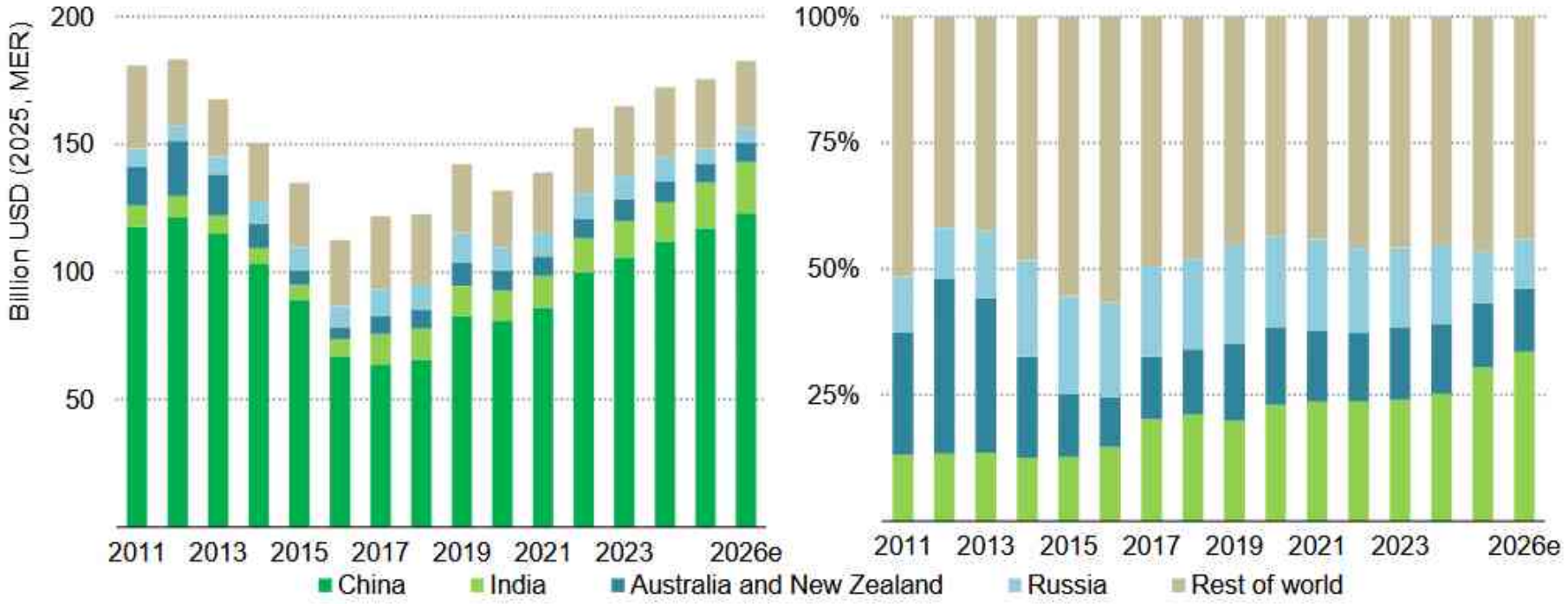
Notes: MER = market exchange rate. 2026e = estimated. Investment throughout is measured as ongoing capital spending on new and existing power capacity. "Fossil fuel power" includes unabated and abated power. Pumped hydro storage is included in "renewable power", not "battery storage".

Source: IEA World Energy Investments 2026 – June 2026

Coal Production Investments 2011 - 2026 led by China

Coal investment has been rising steadily in the past six years, dominated by China and growth in India, albeit from a much lower base

Investment in coal supply (left) and by region excluding China (right), 2016-2026



IEA. CC BY 4.0.

More than 65% of the USD 180 billion in coal supply investment globally in 2026 comes from China. Investment in India is much lower, but it doubled from 2016 to 2017 and has grown steadily this decade as the country seeks to reduce imports.

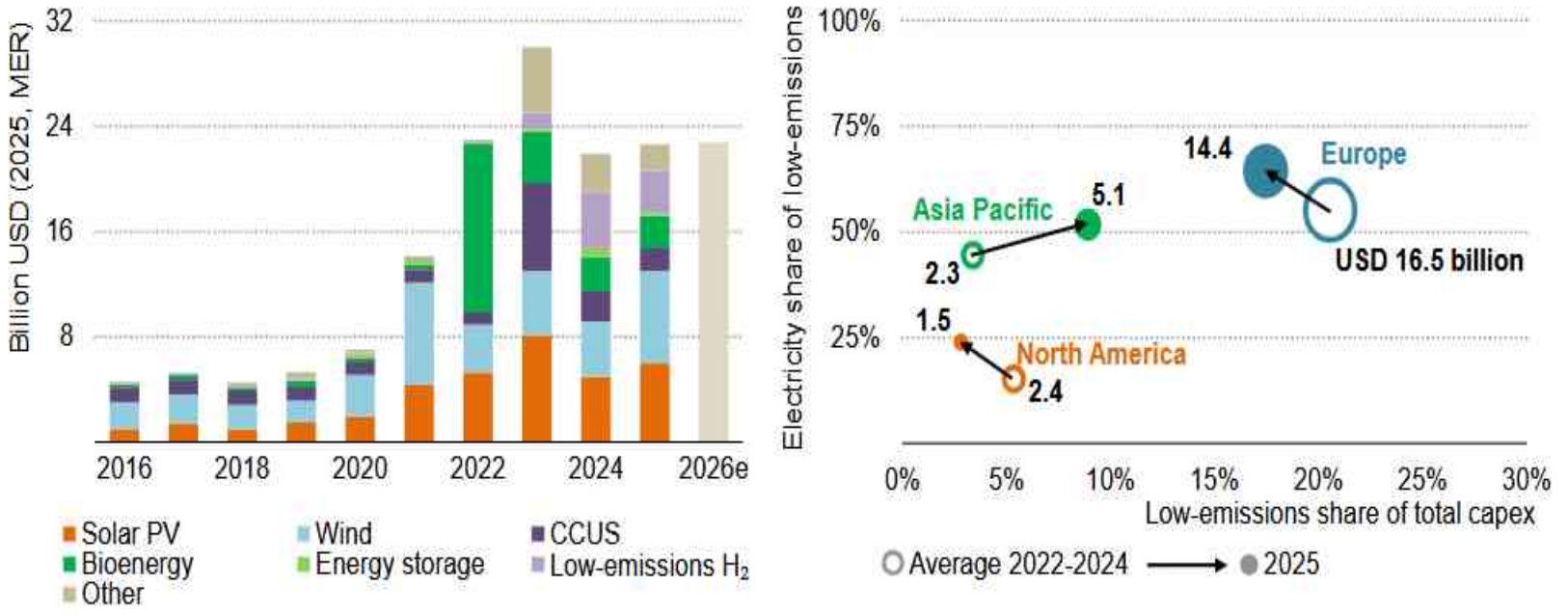
Notes: MER = market exchange rate. 2026e = estimated. "Rest of world" includes Africa, Central and South America, Other Southeast Asia, Other Asia, the Caspian region, Europe and North America.

Source: IEA World Energy Investments 2026 – June 2026

Low-emissions Investments by O&G companies 2016 - 2026

Low-emissions investment by oil and gas companies is growing again following a significant drop in 2024, with an increasing focus on direct generation

Investment by low-emissions technology (left) and allocation metrics by selected headquarter region and period (right)



IEA. CC BY 4.0.

Wind and solar PV accounted for over half of the USD 22.6 billion invested by oil and gas companies in low-emissions technologies in 2025. European companies led investment levels, while Asia-Pacific peers more than doubled their share from the 2022-2024 average.

Notes: MER = market exchange rate. 2026e = estimated. CCUS = carbon capture, utilisation and storage. H_2 = hydrogen. "Other" includes low-emissions transport infrastructure, geothermal, hydropower, lithium, and mergers and acquisitions. Electricity-related investments cover wind, solar PV, hydropower and geothermal. All dollars are inflation-adjusted to 2025 real dollars. For regional definitions, see the Methodology Annex.

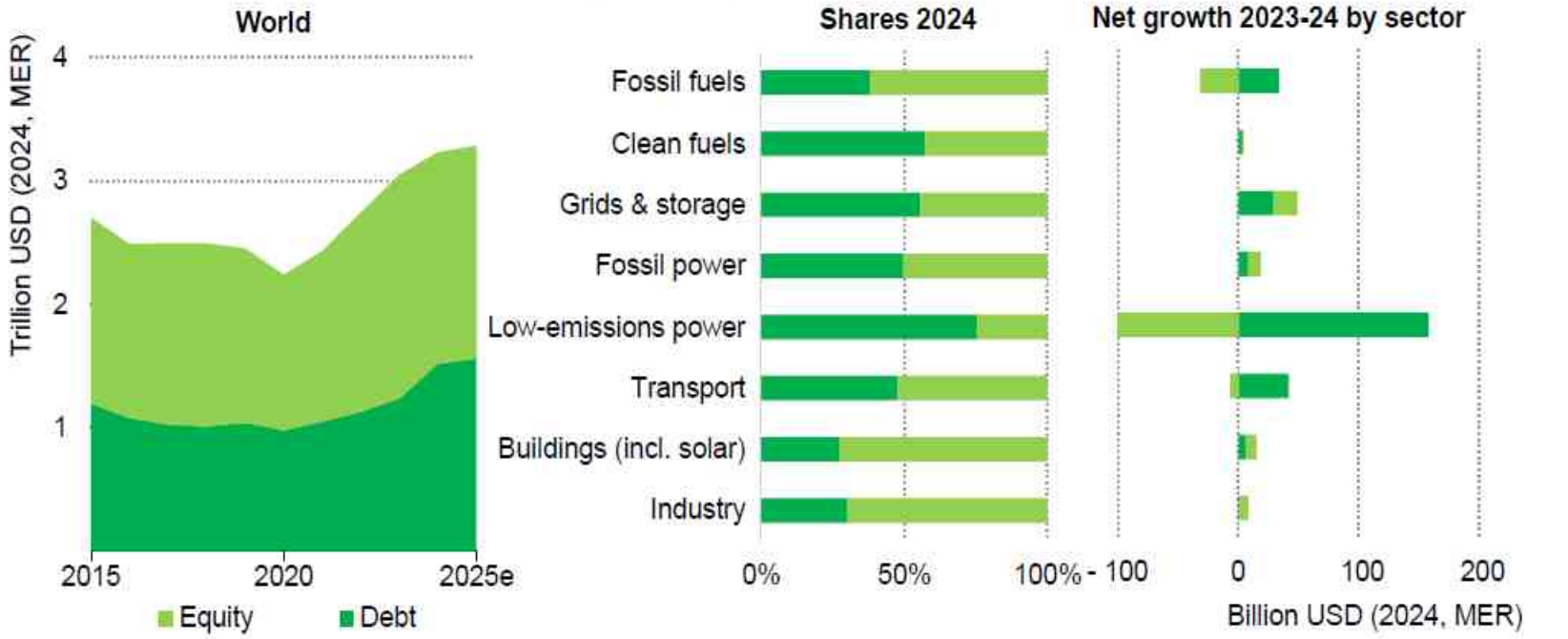
Sources: IEA analysis based on Bloomberg (2026), Bloomberg Terminal; Clean Energy Pipeline (2026), Clean Energy Pipeline homepage; and companies' annual reports and presentations.

Source: IEA World Energy Investments 2026 – June 2026

Reminder - Financing Energy Investments 2015 - 2025

More positive debt dynamics emerged in 2024 in response to benchmark rate cuts, creating better conditions for clean energy financing, which is typically sensitive to borrowing costs

Capital structure of energy finance by instrument and sector, 2015-2025



IEA. CC BY 4.0.

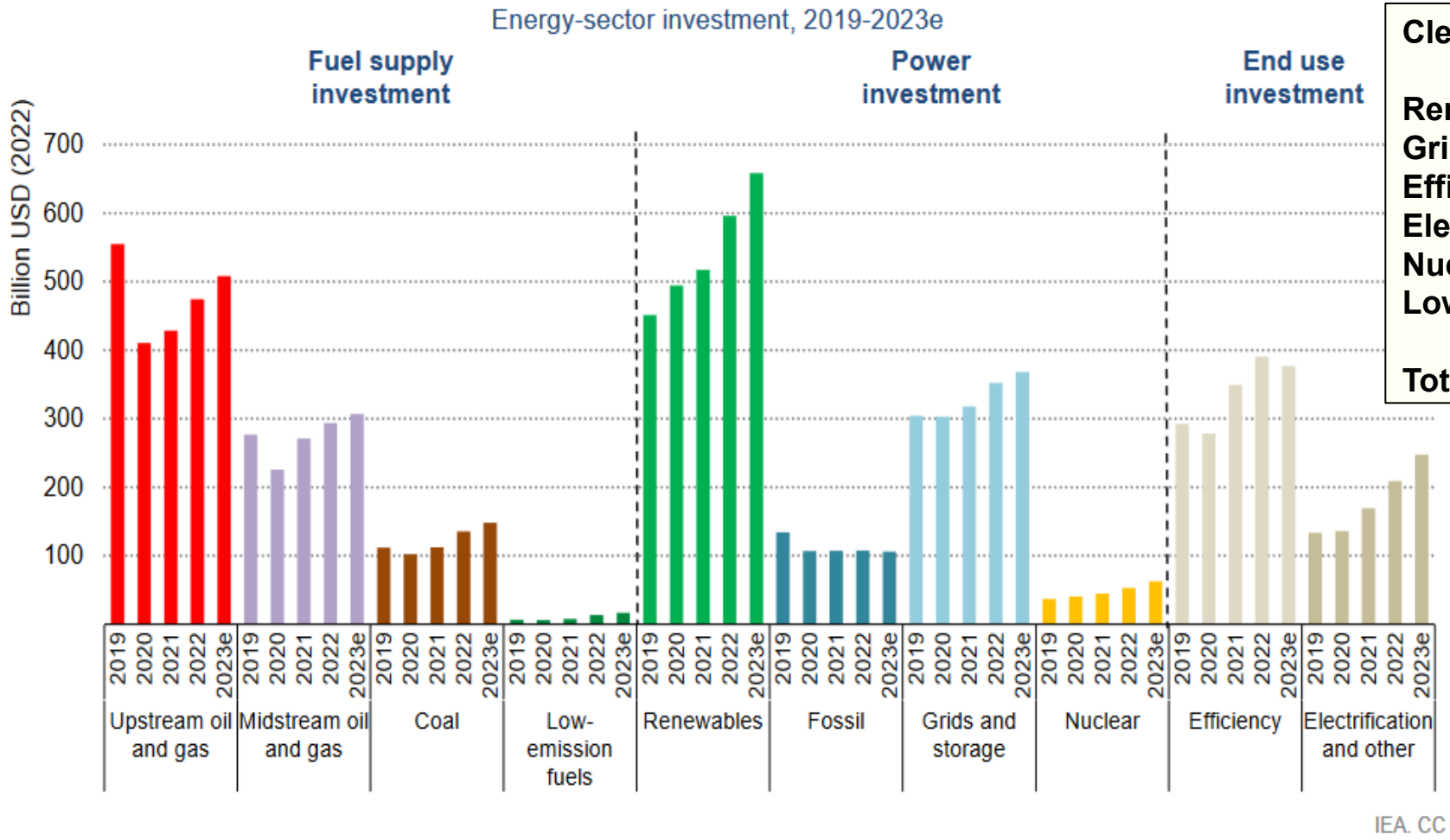
Sectors with high capex and stable cashflows, such as clean power, rely heavily on debt finance and hence benefit from recent rate cuts.

Notes: Building rooftop solar here is grouped with buildings to clearly demarcate differing trends for utility-scale solar and distributed solar. Elsewhere throughout this report, rooftop solar is included in the power sector, not end use. Debt includes both bond issuances and loans for private enterprises, state-owned enterprises (SOEs) and households. Equity includes equity investments made by private enterprises, SOEs, development finance institutions (DFIs) and households, as well as state subsidies and tax incentives, and finance from export credit agencies and central banks. MER = market exchange rates; 2025e = estimated values for 2025.

Sources: IEA analysis based on data from S&P Capital IQ (2025), IJGlobal (2025), Rystad (2025), World Bank (2025) PPI, OECD (2025) CRS, AidData (2023) Global Chinese Development Finance Dataset version 3.0.

Source: IEA World Energy Investments 2025 – June 2025

Dynamics in the Energy sector Investments: A global boost for Clean Energy Investments
Global Investments 2025e: 3,3 T$ out of which 2,2 T$ for Clean Investments
A regular increase for Renewables: 660 G$ (including Hydro)



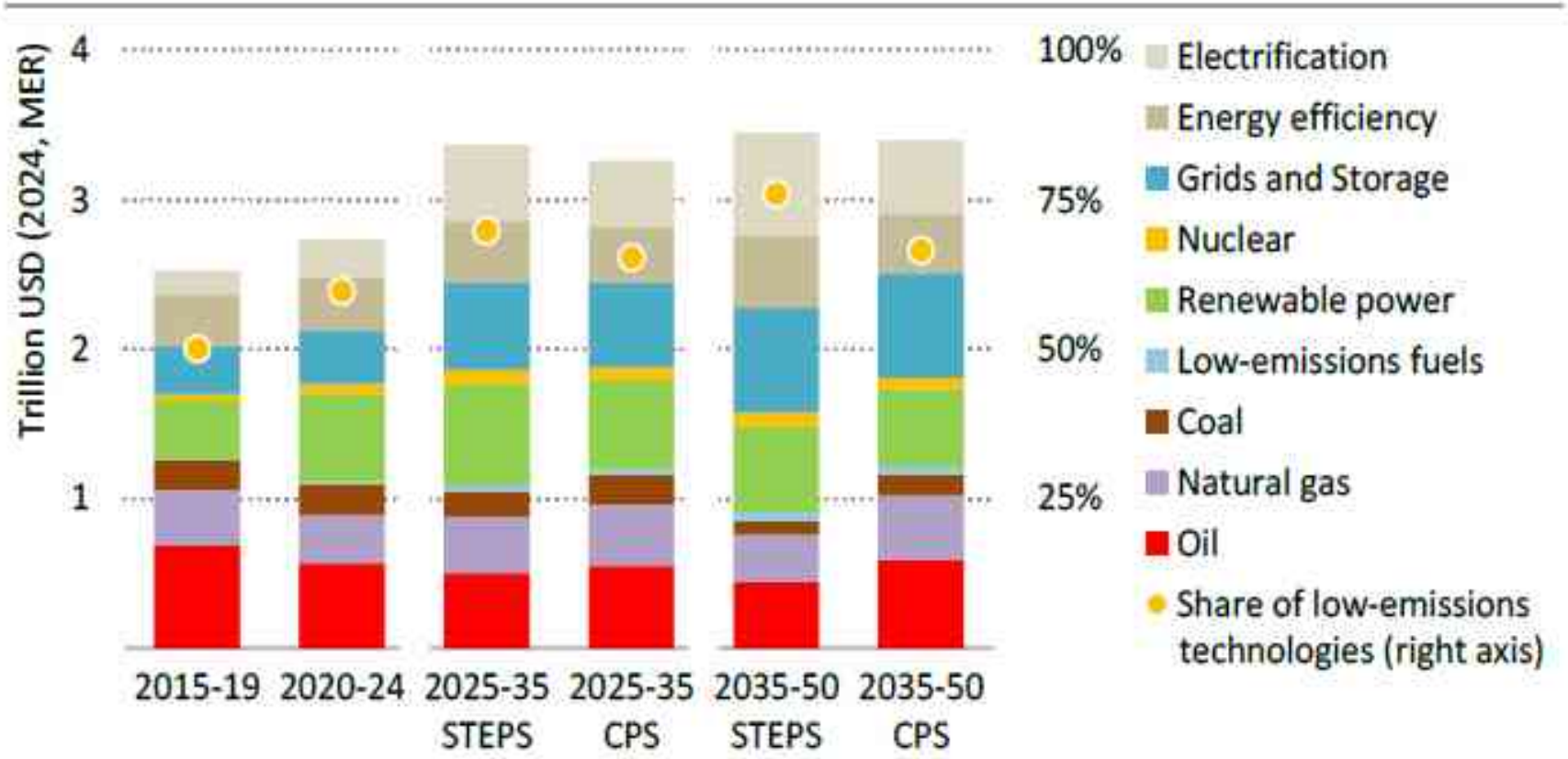
Clean Energy Investments 2025e

Renewables	: 850 G$
Grids & storage	: 500 G$
Efficiency	: 450 G$
Electr. & others	: 300 G$
Nuclear	: 70 G$
Low-emis. Fuels	: 30 G$
Total	# 2,2 T$

Notes: "Low-emission fuels" include modern liquid and gaseous bioenergy, low-emission hydrogen and low-emission hydrogen-based fuels; "Other end use" refers to renewables for end use and electrification in the buildings, transport and industrial sectors. The terms grids and networks are used interchangeably in this report and do not distinguish between transmission and distribution; 2023e = estimated values for 2023..

Source: IEA 2023 & June 2025 World Energy Investment

Annual average Energy Investments & Share of low-emissions technologies



Share of low-emissions technologies in total global energy investment continues to rise in both scenarios, though marginally less in the CPS

Note: MER = market exchange rate; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario.

Source: IEA WEO 2025

A rough calculation – Ref.: Scenario APS IEA WEO 2024
Clean Energy Investments vs avoided GHG emissions 2025 - 2050

Clean Energy Investments 2025: 2,2 T$
Clean Energy Investments 2050: 4,1 T$
Yearly average : 3,2 T$
Cumul 2025 - 2050 : 80 T$ = 80 000 G$

CO_2 Emissions 2025 : 35 $GtCO_2eq$
CO_2 Emissions 2050 : 11 $GtCO_2eq$
Cumul avoided emissions # 575 $GtCO_2eq$

Ratio: # 140 $/t CO_2eq (Implicit CO_2 resulting price……)

Source: ChG/Data from IEA WEO 2024 and IEA Investments 2025
GHG: Green House Gas APS: Announced Pledges Scenario WEO 2024
Clean Energy Investments include clean electrification, low emission fuels and energy efficiency

Global Investment for Renewables by Technology – Year 2024 vs Oil and Gas E&P and Coal Supply Capex Rebound for Oil & Gas Investments

Year 2024		(G$)
Solar PV	:	521
Wind	:	195
Biomass	:	10
Biofuels	:	1
Geothermal	:	1
Small Hydro	:	1
Marine	:	ε
Total	:	# 730

Year 2024	(G$)
Oil and Gas E&P	: 500
Coal Supply	:140





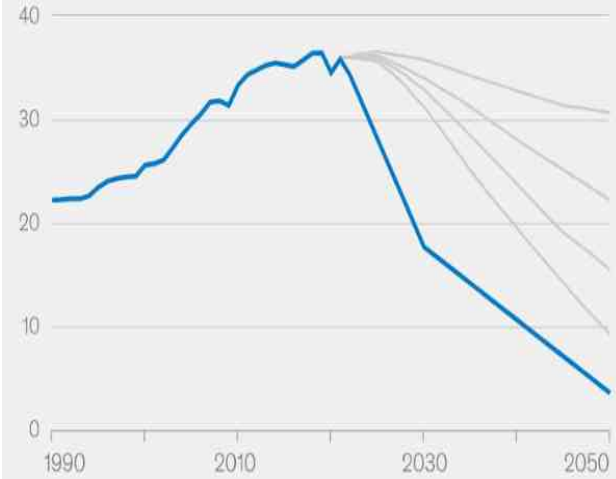




Data from REN21 Renewables 2025 Global Status Report for Renewables
from IEA World Energy Investment 2024 for O&G and Coal
Excludes Oil & Gas Power Generation and Refining & Marketing

McKinsey Scenarios
Implied CO_2 price vs avoided GHG emissions 2023 - 2050

Global CO_2 emissions from combustion and industrial processes,[1] $GtCO_2$ per year

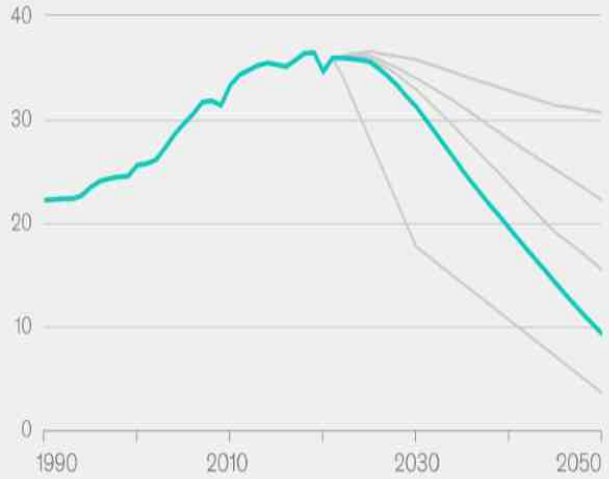


1.5° Trajectory

A 1.5° pathway is adopted globally, driving rapid decarbonization investment and behavioral shifts.

Implied CO_2 price[2]
$/tCO$_2$, 2030–50
$180+

Temperature increase[3]
1.5°C
(1.1–1.7)

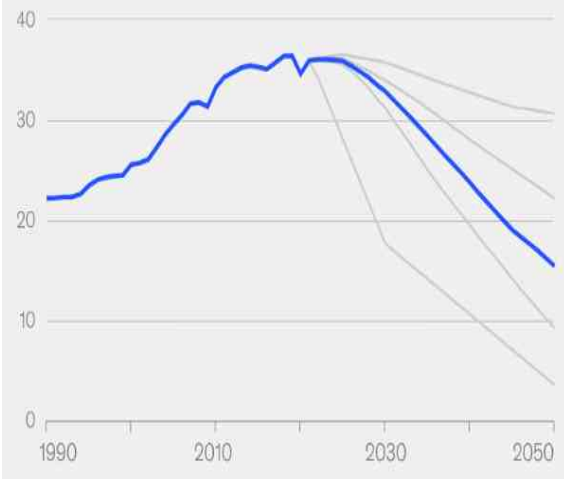


Achieved Commitments

Net-zero commitments[4] achieved by leading countries through purposeful policies; followers transition at slower pace.

Implied CO_2 price[2]
$/tCO$_2$, 2030–50
$130–$180

Temperature increase[3]
1.6°C
(1.3–2.0)

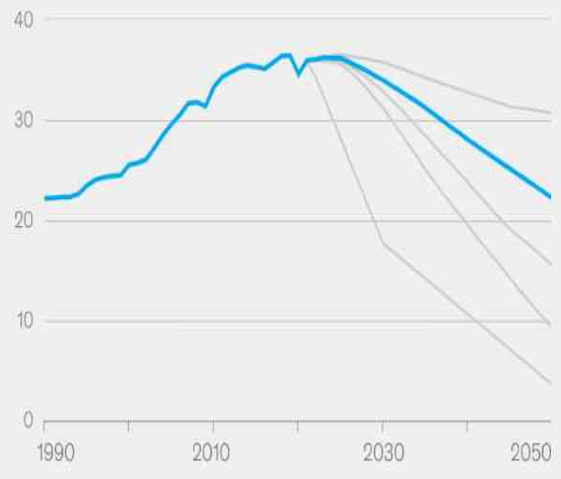


Further Acceleration

Further acceleration of transition driven by country-specific commitments, though financial and technological restraints remain.

Implied CO_2 price[2]
$/tCO$_2$, 2030–50
$70–$140

Temperature increase[3]
1.9°C
(1.5–2.3)



Current Trajectory

Current trajectory of renewables cost decline continues, however currently active policies remain insufficient to close gap to ambition.

Implied CO_2 price[2]
$/tCO$_2$, 2030–50
$60–$90

Temperature increase[3]
2.3°C
(1.9–2.8)

Source: McKinsey 2024

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Energy National Subsidies

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Preliminary Remarks

Definition of Subsidies

- IEA estimates of subsidies concern **Consumer Subsidies.**
- The IEA estimates of subsidies use the Price-Gas approach.
- It compares average end-user prices paid by consumers with reference prices that correspond to the full cost of supply.
- In a given Economy,
  Subsidies =(Reference Price - End-user Price)x Nb of Units consumed.
- Electricity Reference Prices are derived from annual average cost-pricing, including cost of production, transmission and distribution.
- Subsidies have important impact on National Budgets.
- Example: Fossil net exporters can charge less than the export parity price in their domestic market. In such a case, the export parity price is the price of the product at the nearest international hub minus the cost of freight and insurance back to the net exporter, plus the cost of internal distribution and marketing and any VAT.
- Example: Fossil net importers subsidies represent the budget expenditures deriving from selling the product on the domestic market at subsidized prices. In such a case, the import parity price is the price of the product at the nearest international hub plus the cost of freight and insurance to the net importer, plus the cost of internal distribution and marketing and any VAT.
-

Definition of Subsidies – The IRENA View

Subsidies can arise as the result of deliberate interventions by governments, or as the unintended consequences of policy decisions, or from market failures. Energy subsidies are not necessarily bad *per se*, but this depends on how and why they are being implemented.[2] What matters are the objectives being pursued and how the subsidies may interact with other policy priorities.

Energy subsidies can be pursued in order to achieve specific policy goals, such as:

- Provide affordable energy for low income members of society.
- Correct markets for unpriced externalities.
- Induce technology learning and drive down the costs of new technologies.
- Reduce import dependence and enhance energy security.
- Create new economic activity and jobs.

Source: Energy Subsidies IRENA 2020

Definition of Subsidies – The IRENA View

Different definitions of energy subsidies

Today, there is no systematically applied, standardised definition of what an energy sector subsidy is, despite the prevalence of subsidies in the energy system. Even without this uncertainty around definitions, given the breadth and complexity of support given to different energy sub-sectors or fuels, calculating subsidy levels or unpriced externalities can be difficult (Sovacool, 2017).

Source: Energy Subsidies IRENA 2020

Different Definitions of Subsidies – The IRENA View (1)

DEFINITION	FOCUS/ METHODOLOGY	STRENGTHS	WEAKNESSES
WORLD TRADE ORGANIZATION (WTO) "A financial contribution by a government or any public body within the territory of a Member", or when "There is any form of price support...(where) a benefit is thereby conferred."	• How energy subsidies distort trade • Dispute settlement	• Near universal acceptance • Often referenced • Used by many as basis for their analysis	• Not widely used by some of the main institutions involved in subsidy reform
INTERNATIONAL ENERGY AGENCY (IEA) "Any government action directed primarily at the energy sector that lowers the cost of energy production, raises the price received by energy producers or lowers the price paid by energy consumers. It can be applied to fossil and non-fossil energy in the same way."	• On consumer subsidies, rather than producer subsidies • Fossil and renewables • Price-gap approach	• Broad definition • Explicitly covers all energy	• Applied only to consumer subsidies • Disagreement over reference prices • Can miss a range of subsidies • No nuclear numbers
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT (OECD) "Both direct budgetary transfers and tax expenditures that in some way provide a benefit or preference for fossil fuel production or consumption relative to alternatives."	• The inventory of support is first step to identifying subsidies to a sector • Inventory approach	• Broad definition of "support" • Inventory approach adds to transparency	• Can miss a range of supports delivered via price measures (prevalent in developing countries) • No estimates for nuclear or renewable subsidies

Source: Energy Subsidies IRENA 2020

Different Definitions of Subsidies – The IRENA View (2)

DEFINITION	FOCUS/ METHODOLOGY	STRENGTHS	WEAKNESSES
WORLD BANK (WB) "A deliberate policy action by the government that specifically targets fossil fuels, or electricity or heat generated from fossil fuels."	• Support countries in their subsidy measurement	• Good overview of approaches to subsidy calculation	• No recent subsidy calculations of their own • No estimates for nuclear or renewable subsidies
INTERNATIONAL MONETARY FUND (IMF) "Pre-tax consumer subsidies arise when the prices paid by consumers, including both firms (intermediate consumption) and households (final consumption), are below supply costs including transport and distribution costs. Producer subsidies arise when prices are above this level. Post-tax consumer subsidies arise when the price paid by consumers is below the supply cost of energy plus an appropriate "Pigouvian" (or "corrective") tax..."	• Understanding magnitude of subsidies to support reform • Price-gap and inventory approach	• Includes unpriced negative externalities	• Data intensive • No estimates for nuclear or renewables

Source: Energy Subsidies IRENA 2020

Different Types of Subsidies – The IRENA View (1)

TYPE OF SUBSIDY	EXAMPLE(S)	HOW IT WORKS		
		LOWERS COST OF PRODUCTION	RAISES PRICE TO DISFAVORED PRODUCER	LOWER PRICE TO CONSUMER
DIRECT FINANCIAL TRANSFER	• Grants to producers • Grants to consumers • Low-interest or preferential loans	● ●		●
PREFERENTIAL TAX TREATMENT	• Rebates or exemptions on royalties, sales taxes, producer levies and tariffs • Investment tax credits • Production tax credits • Accelerated depreciation • State sponsored loan guarantees	● ● ● ● ●		●
TRADE RESTRICTIONS	• Quotas, technical restrictions, and trade embargoes • Import duties and tariffs		● ●	

Source: Energy Subsidies IRENA 2020

Different Types of Subsidies – The IRENA View (2)

TYPE OF SUBSIDY	EXAMPLE(S)	HOW IT WORKS		
		LOWERS COST OF PRODUCTION	RAISES PRICE TO DISFAVORED PRODUCER	LOWER PRICE TO CONSUMER
ENERGY-RELATED SERVICES PROVIDED BY GOVERNMENT AT LESS THAN FULL COST	• Direct investment in energy infrastructure	●		
	• Publicly sposored R&D	●		
	• Liability insurance	●		
	• Free storage of waste or fuel	●		
	• Free transport	●		
REGULATION OF THE ENERGY SECTOR	• Demand guarantees and mandated deployment rates	●	●	
	• Price controls and rate caps		●	●
	• Market-access restrictions and standards		●	

Source: Based on Sovacool, 2017.

Source: Energy Subsidies IRENA 2020

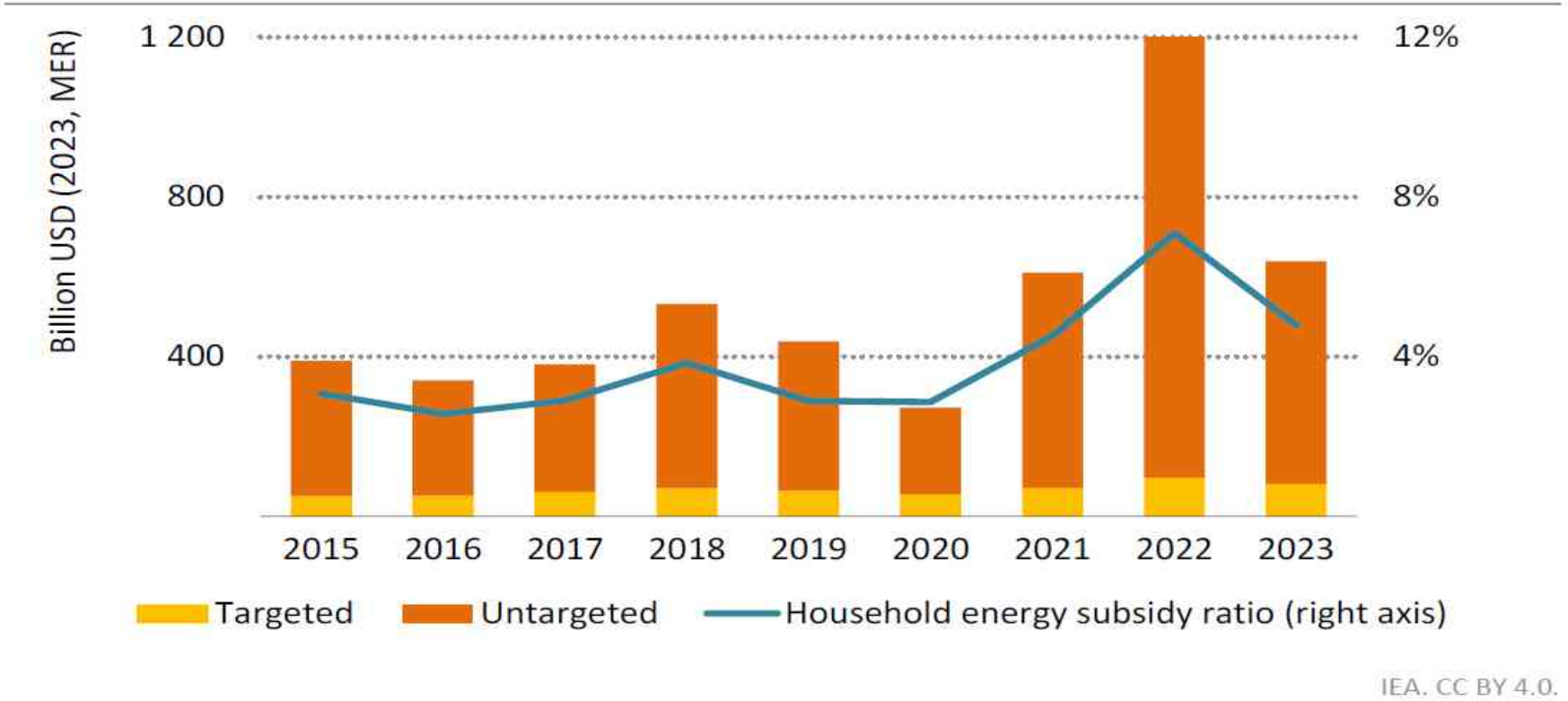
Today, Fossil Fuels subsidies are significant in many Countries.
Today, most of New Renewable Energies is subsidized in certain Countries
On the long term, any industrial project must be justified in itself on the economic stand-point
(Figures on subsidies may vary according to sources and categorization)

Estimated Fossil Fuels Energy Subsidies by IEA 2024 (2023 GUS $)
Sharp decline in 2020 for (Covid-19)
In 2022, the highest figure ever recorded: 1200 G$, then a decline down to 620 G$ in 2023

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
All Products	466	538	596	547	490	376	328	367	512	423	263	588	1 178	616
Oil	195	269	309	289	253	152	114	159	210	192	124	190	346	235
Electricity	155	158	156	139	132	131	154	141	183	155	77	221	446	217
Natural Gas	113	108	128	117	103	91	58	65	117	73	59	173	377	163
Coal	3	4	4	2	1	1	2	3	3	3	2	4	9	2

Source: Data from IEA fossil fuels subsidies database 2024

Fossil Fuels subsidies 2015 – 2023 (G$ 2023) A huge drop in 2020, Covid 10 (# 260 G$) A record high in 2022 # 1200 G$, then a huge decrease in 2023

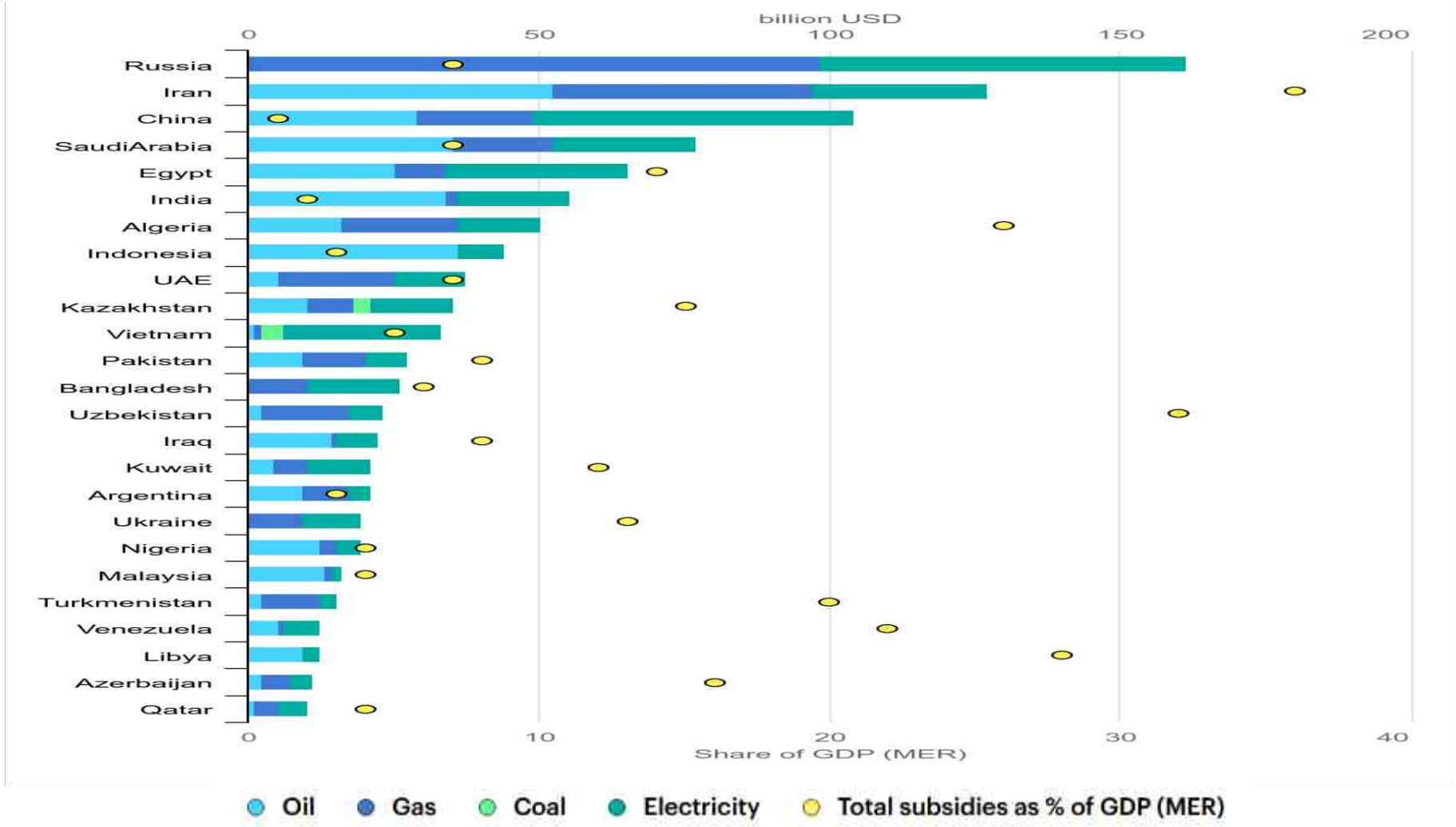


The vast majority of fossil fuel consumption subsidies are untargeted and disproportionately benefit wealthier high-consumption segments of the population

Note: Targeted subsidies include agriculture and household (LPG and kerosene fuels only) sector subsidies. Household energy subsidy ratio is calculated by dividing household subsidies by total household energy expenditure.

Source: IEA Strategies for Affordable and Fair Clean Energy Transition - June 2024

Costs of Fossil Fuels Subsidies by Country & type of Fuels 2022 (G$ nominal and % GDP) A huge drop 2020 (# 260 G$) vs 2019 : - 40% but a huge rebound in 2021: x 2,2! # 560 G$. A record high in 2022



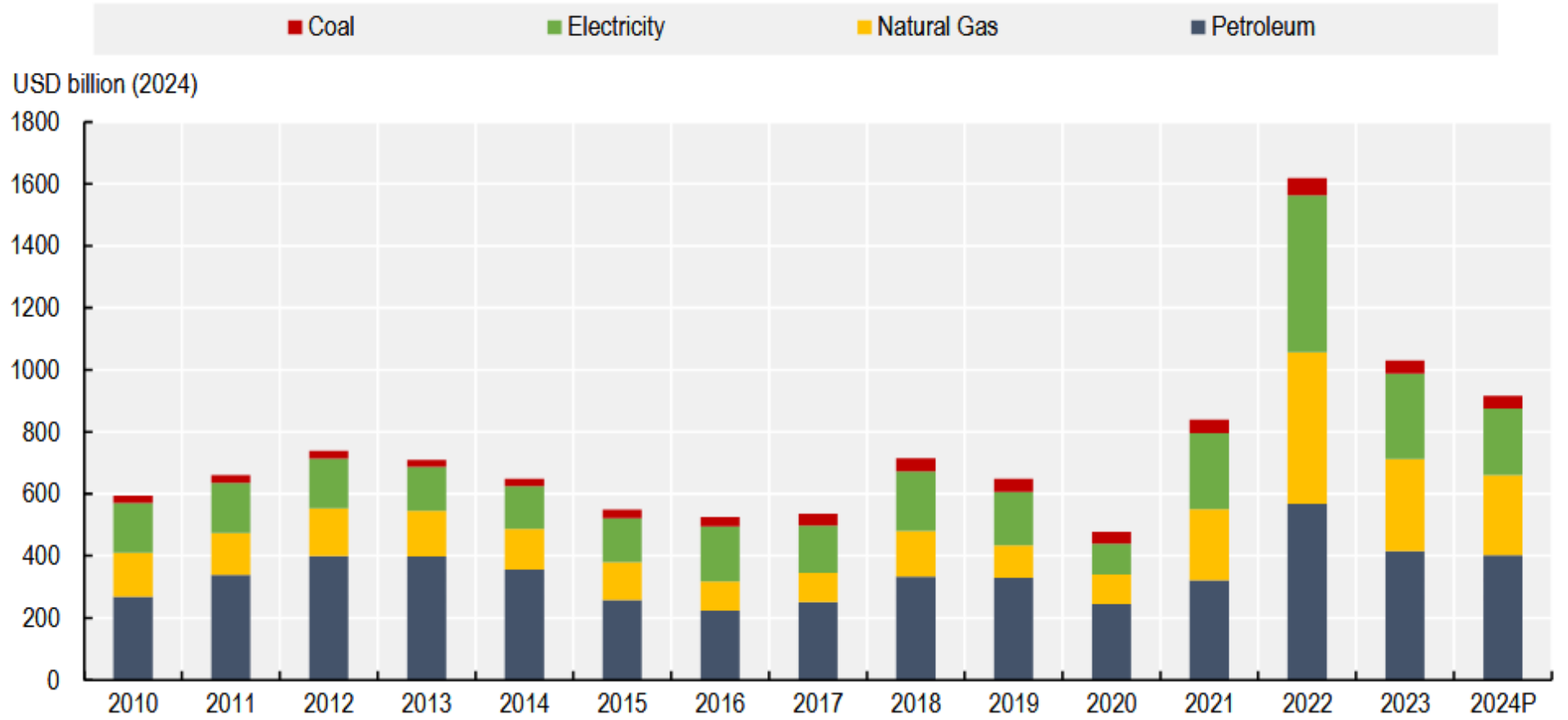
Source: IEA 2023 Energy subsidies

There is considerable debate about the best way to measure support for fossil fuels.
While budgetary transfers are relatively straight-forward, support conferred via tax expenditures or exemptions is more complex, including in the context of the different incentives provided by countries in terms of their overall policies for taxing different fuel sources.

Source: OECD Inventory of Support Measures for Fossil Fuels 2025
December 2025

Estimated Fiscal Cost of Support Measures for Fossil Fuels by OECD 2025 (2024 GUS $)
Sharp decline in 2020 (Covid-19)
In 2022, the highest figure ever recorded: 1600 G$, then a decline down to 920 G$ in 2024

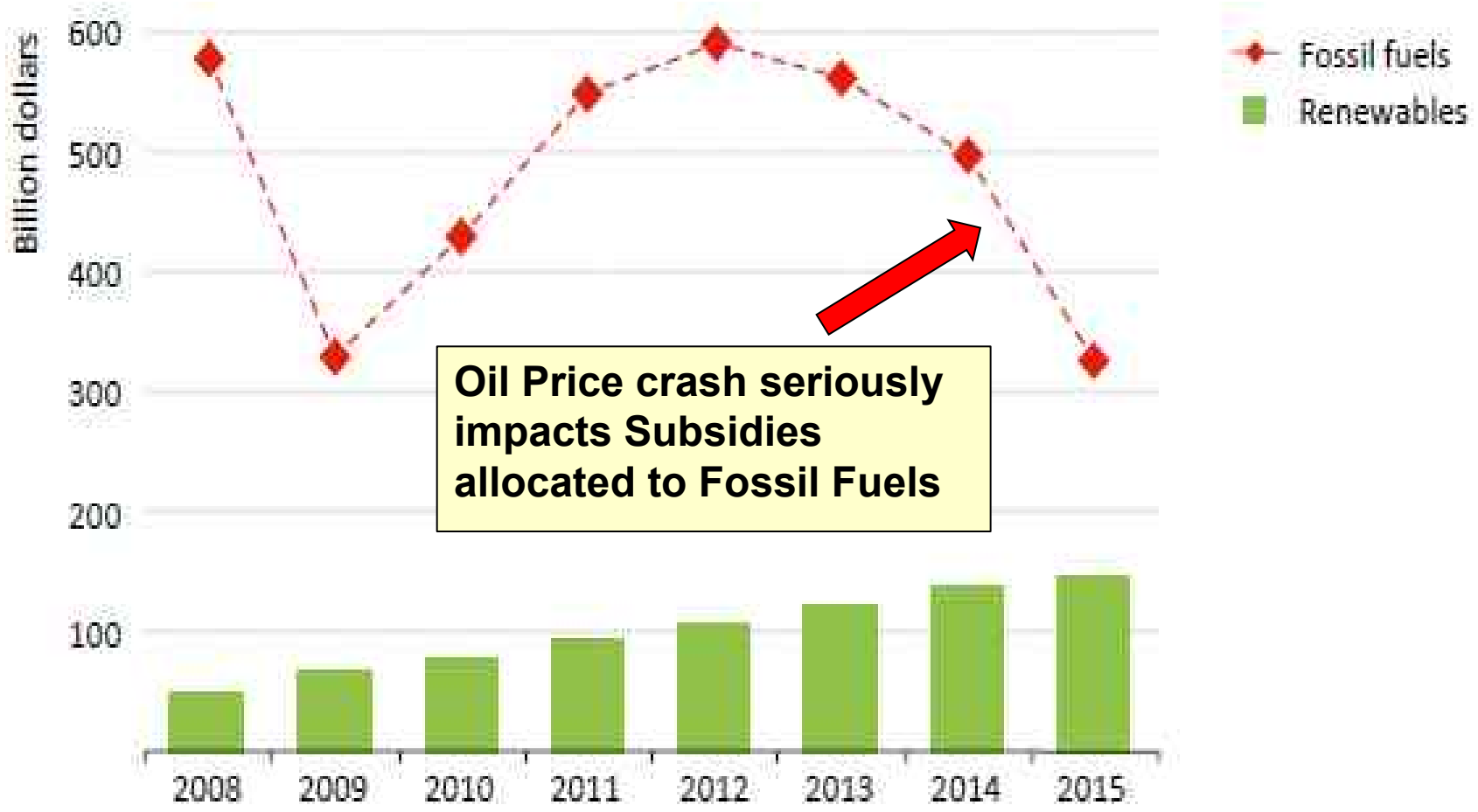
OECD-IEA combined estimate of the fiscal cost of support measures for fossil fuels (82 economies), by fuels



Source: OECD Inventory of Support Measures for Fossil Fuels 2025
December 2025

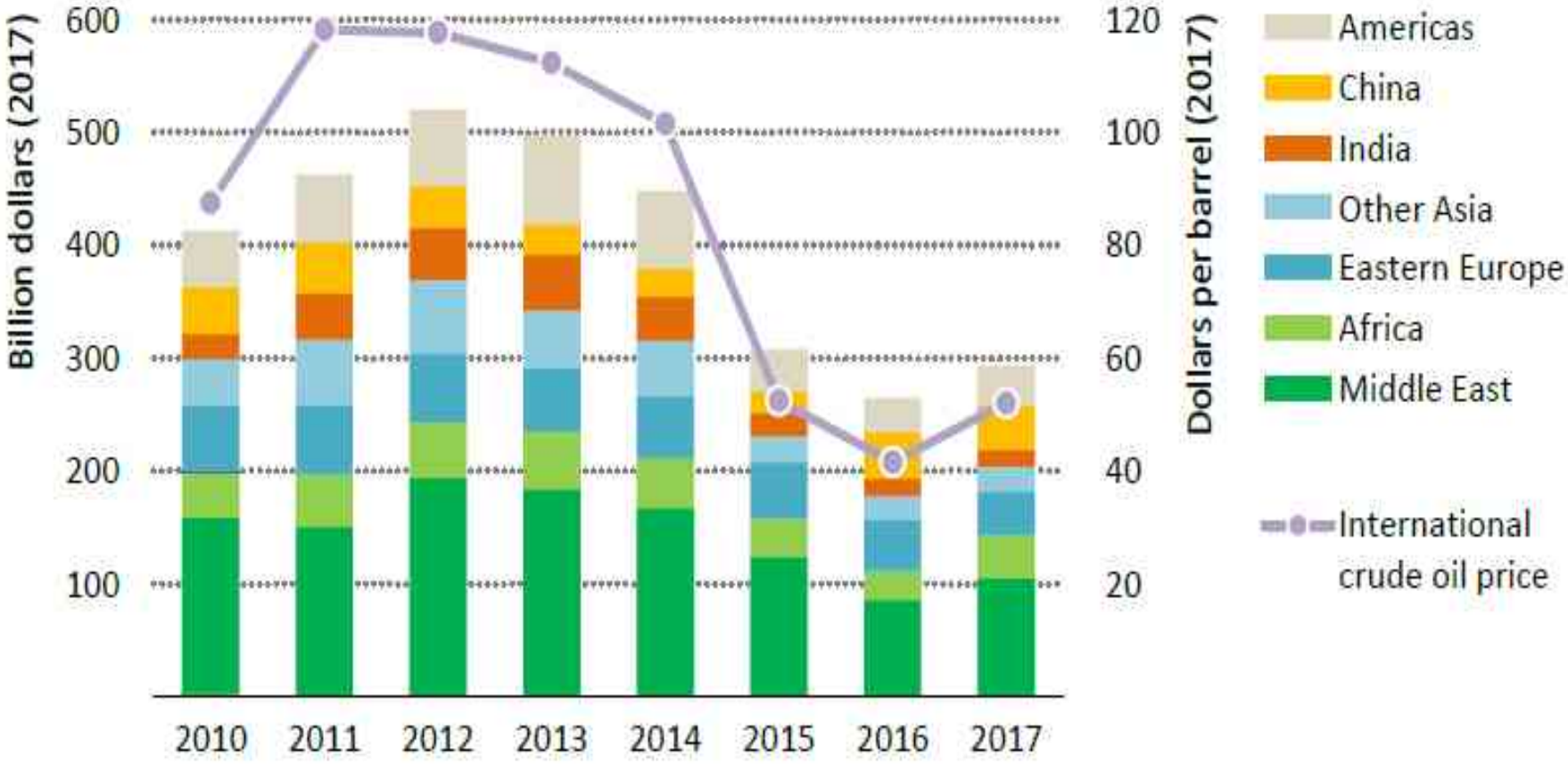
Fossil Fuels National Subsidies have been challenged by the sharp decrease of the Crude Oil Price in 2015 – 2016 and in 2020

Reminder - Subsidies allocated to Fossil Fuels and Renewables 2008 - 2015



Source: IEA WEO 2016

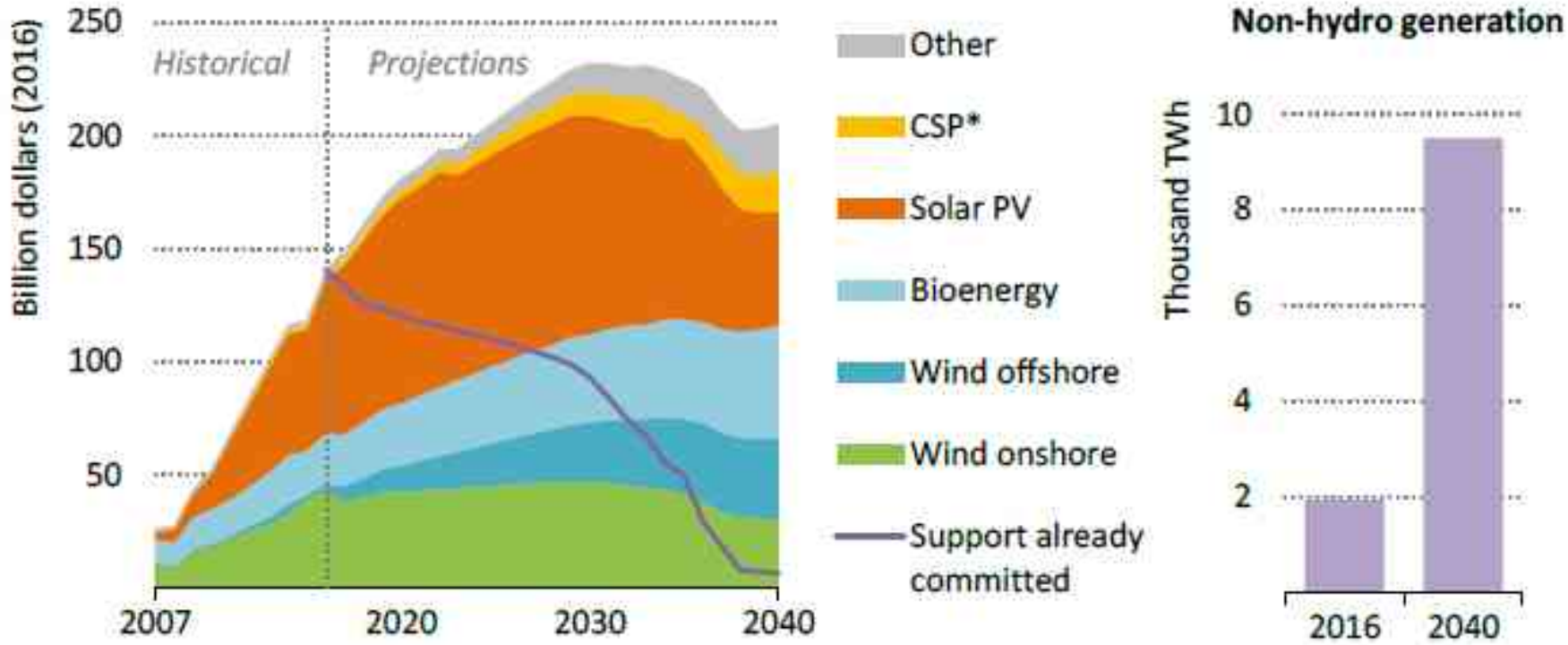
Reminder - Subsidies allocated to Fossil Fuels 2010 – 2017
A sharp Decrease in 2015 – 2016. Rebound in 2017



Subsidies increased slightly in 2017, but by less than the rise in oil price

Source: IEA WEO 2018

Reminder - Renewables Subsidies by Type IEA 2017 Central Scenario

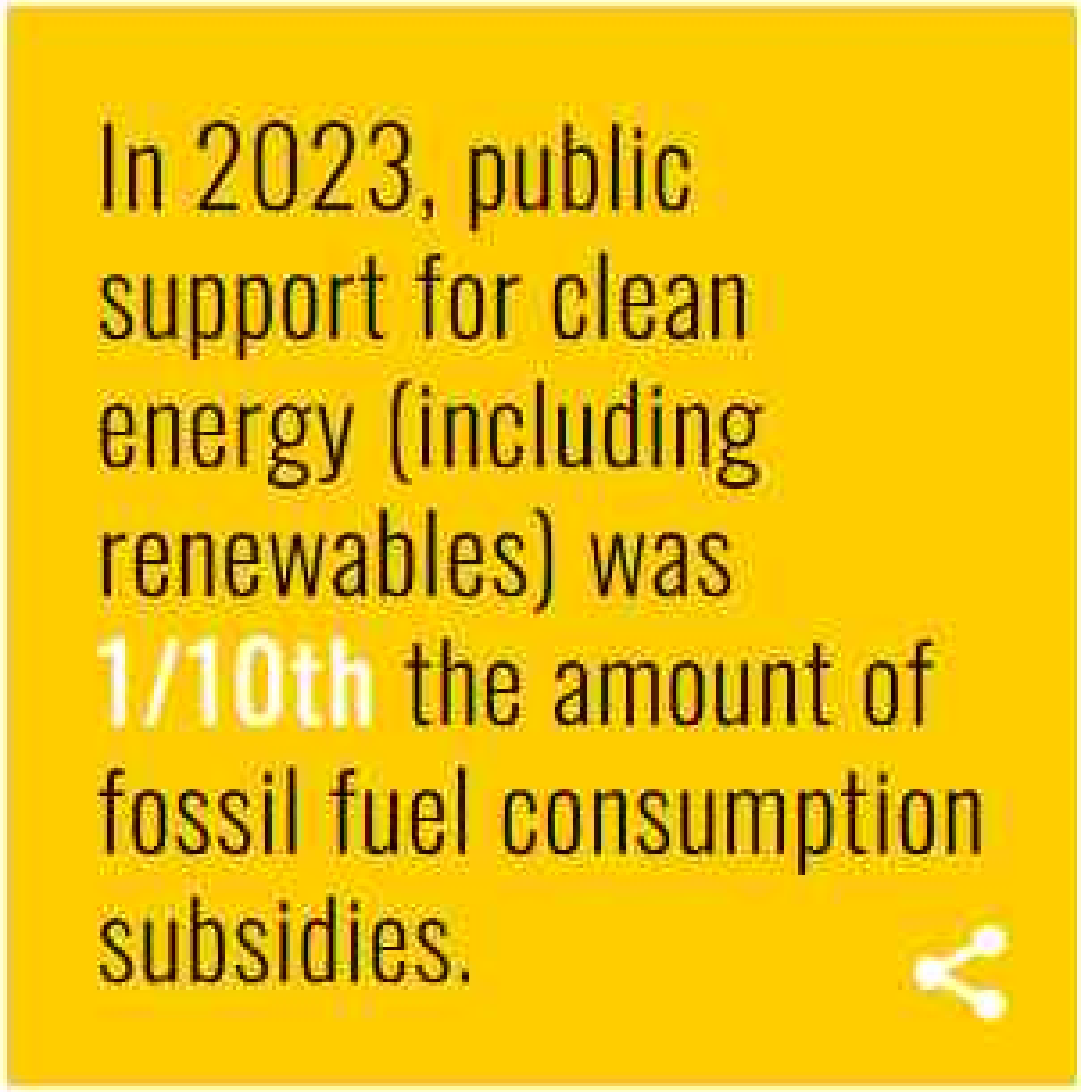


Global subsidies to renewables increase from $140 billion today to $200 billion in 2040, while non-hydro generation more than quadruples

*CSP = concentrating solar power.

Source: IEA WEO 2017

Subsidies for Renewables by REN21 2024



Source: REN21 GSR 2024 – Economic & Social Value Creation

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Energy sources competitivity
The Levelized Cost Of Electricity (LCOE)

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Energy Return on Energy Invested
ERoEI or EROI

EROI :Definition

$$EROI = E_R/E_I$$

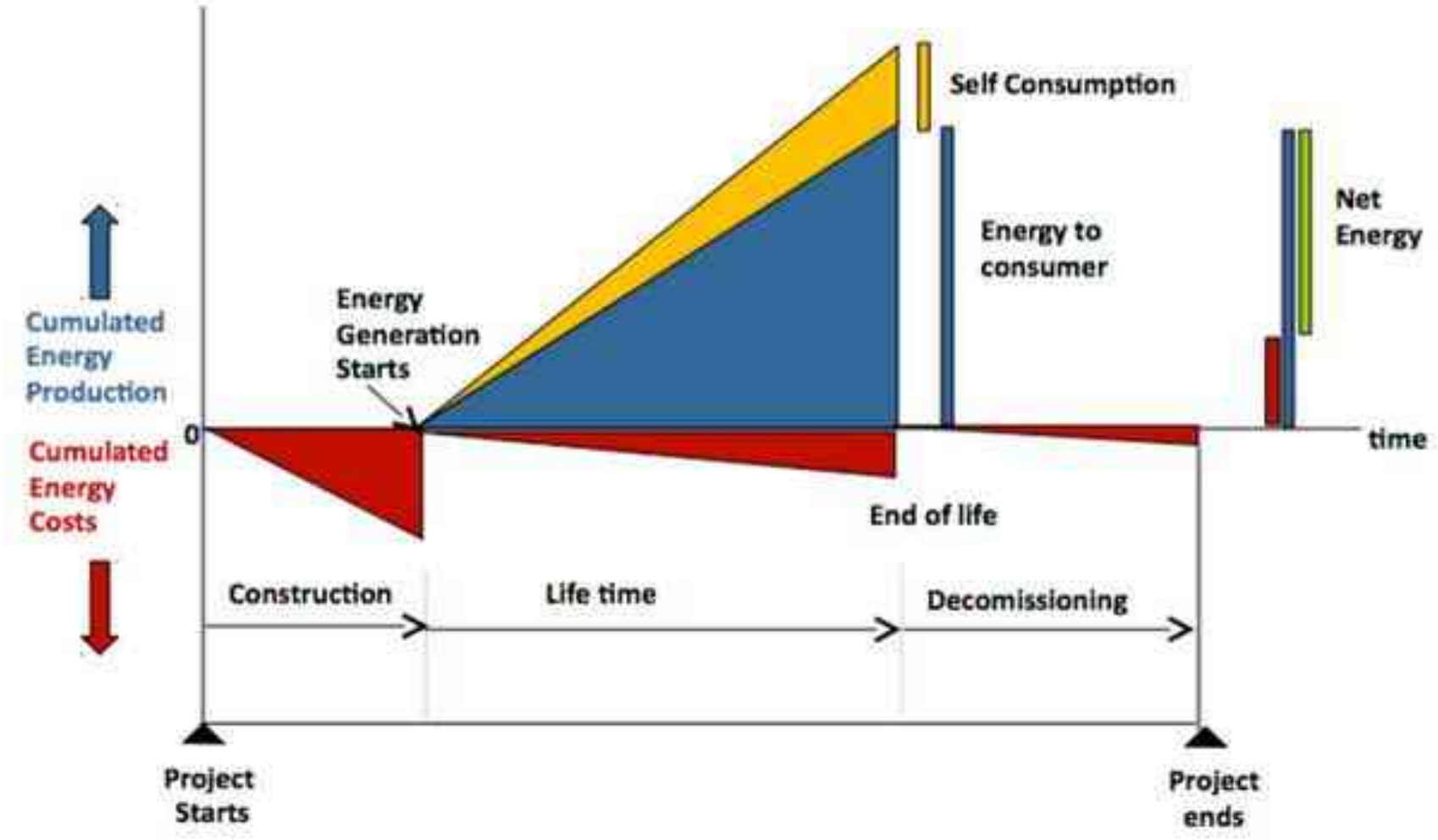
E_R = The usable Energy (J or Wh) the Plant returns during its lifetime

E_I = The Invested Energy (J or Wh) needed to make this Energy usable

Warning!

The calculations of the constituants of the formula are complex and subjects to possible different definitions. The values of EROI can vary substantially from one author/researcher to the other one….

EROI – basic principle



Source: Energy Matters

EROI – basic principle

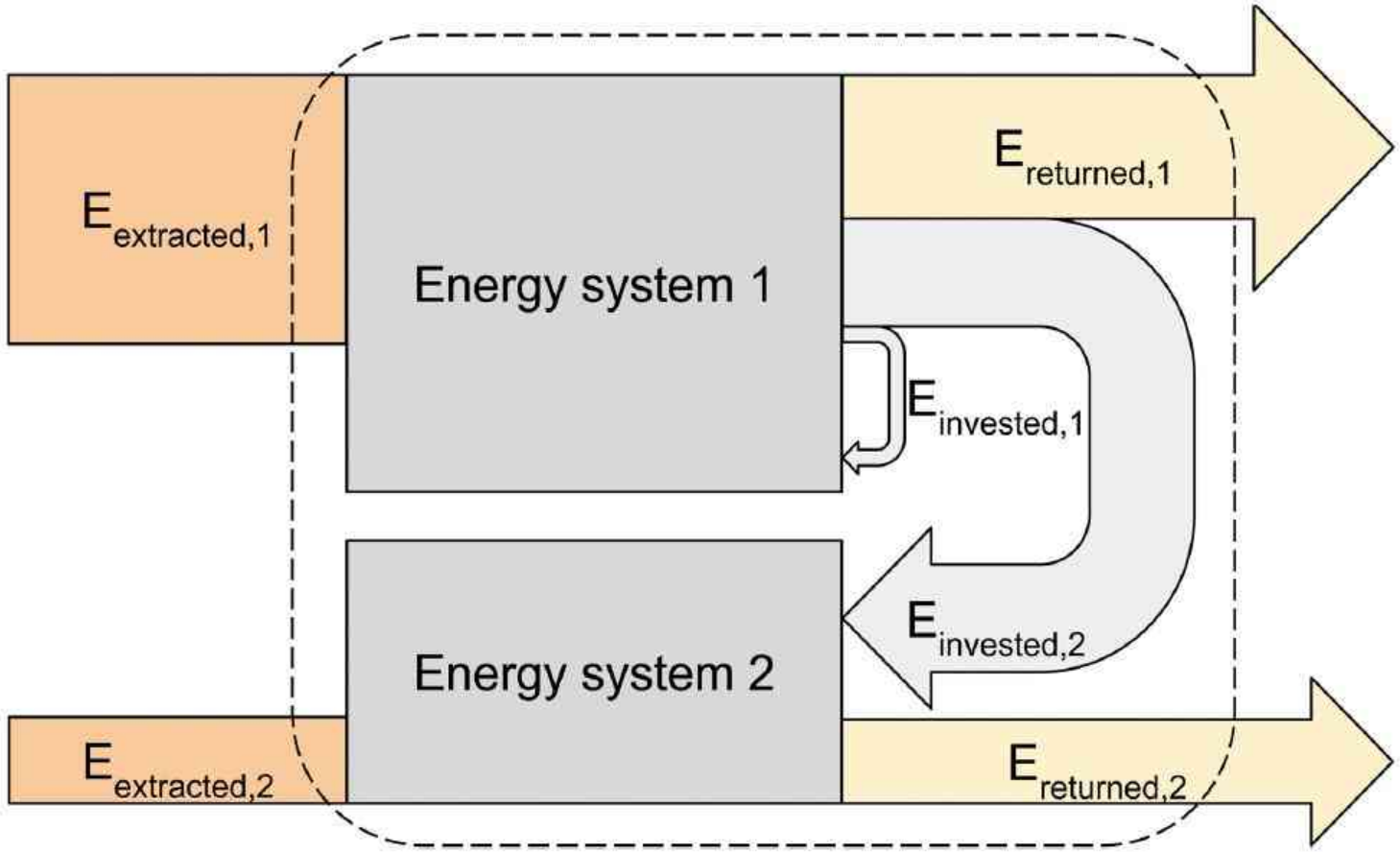


Fig. 1 Returned energy as a function of the extracted and the invested energy for two systems. EROI (global) = $(E_{returned,1} + E_{returned,2})/(E_{invested,1} + E_{invested,2})$. EROI (energy system 2) = $(E_{returned,2})/(E_{invested,2})$. Energy losses are omitted for clarity.

Source: Energy & Environmental Science – Royal Society of Chemistry
March 2023
Delannoy, Auzanneau et al.

EROI – basic principle

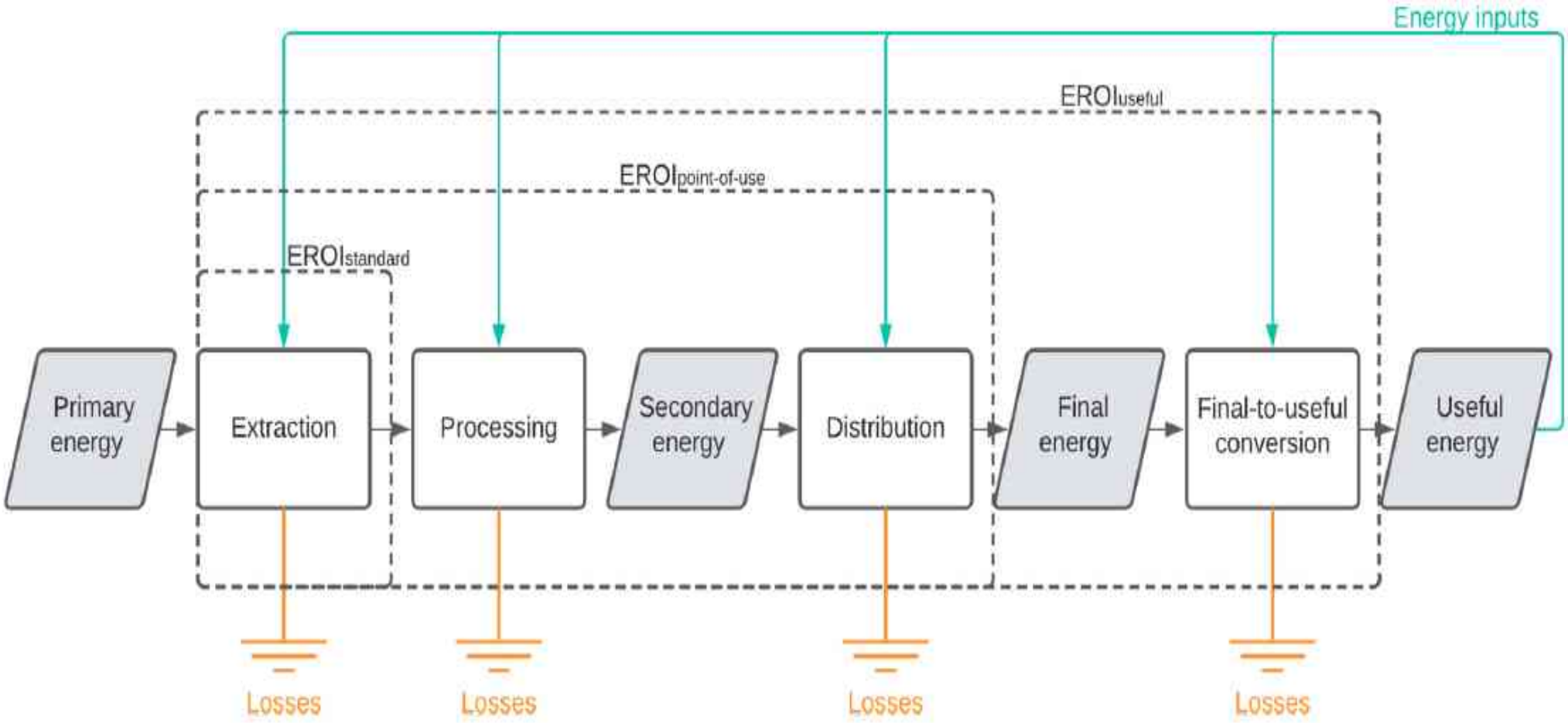


Fig. 2 Standard, or primary stage EROI ($EROI_{standard}$), point-of-use or final stage EROI ($EROI_{point\text{-}of\text{-}use}$) and useful EROI ($EROI_{useful}$).

Source: Energy & Environmental Science – Royal Society of Chemistry
March 2023
Delannoy, Auzanneau et al.

EROI – Diagram of comparison
Specific example

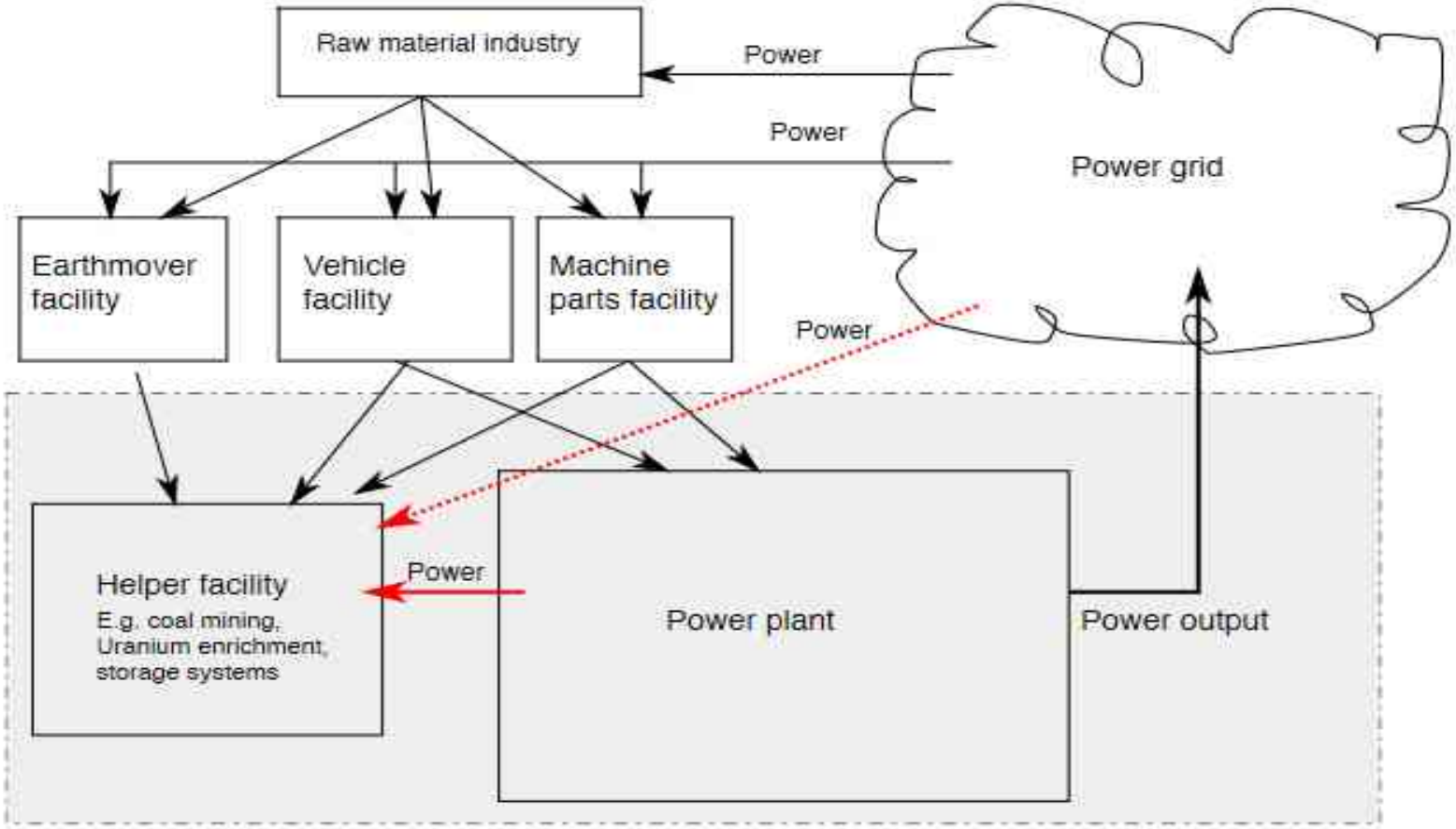


Figure 1: System borders for a typical power plant. It makes a difference if electricity for a helper facility like a coal mine is taken from the grid (dashed line) or from the power plant.

Source: D.Weissbach & co, Institut fur Festkorper-Kernphysic Gmbh Berlin - 2013

EROI – Diagram of comparison
Specific example

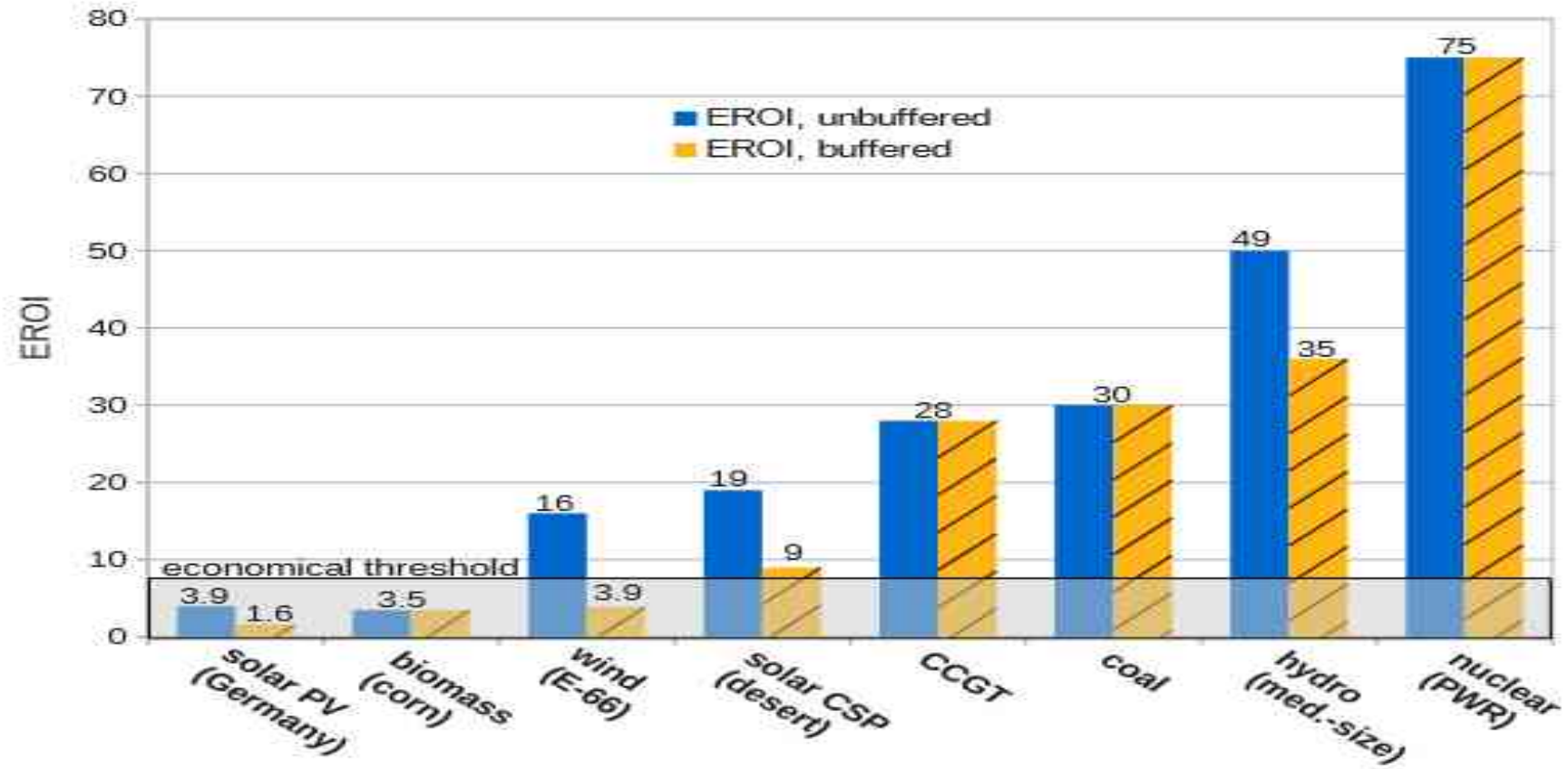
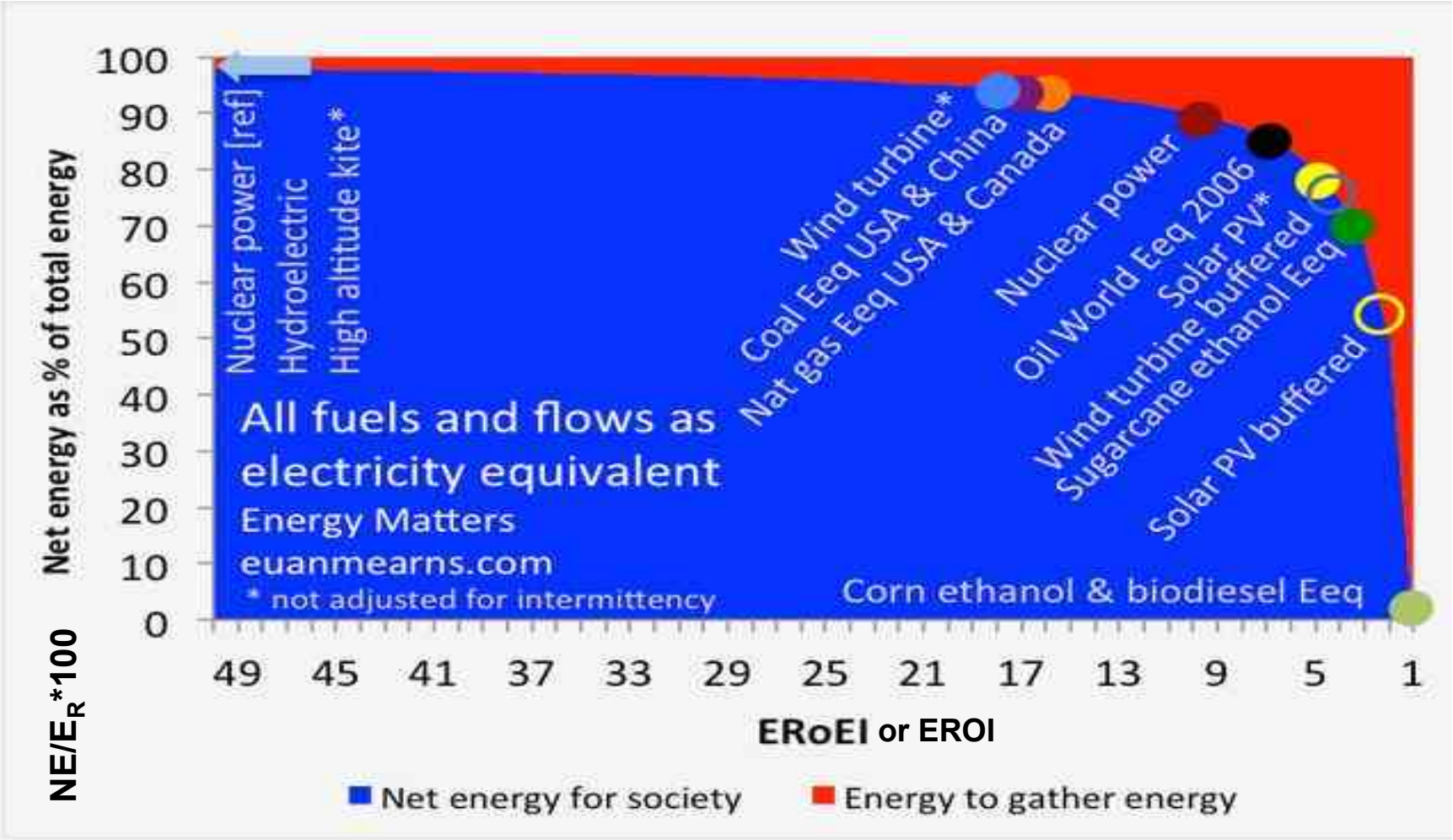


Figure 3: (Color online.) EROIs of all energy techniques with economic "threshold". *Biomass:* Maize, 55 t/ha per year harvested (wet). *Wind:* Location is Northern Schleswig Holstein (2,000 full-load hours). *Coal:* Transportation not included. *Nuclear:* Enrichment 83 % centrifuge, 17 % diffusion. *PV:* Roof installation. *Solar CSP:* Grid connection to Europe not included.

Source: D.Weissbach, Institut fur Festkorper-Kernphysic Gmbh Berlin – 2013
Unbuffered: excluding storage, buffered: including storage

EROI – Another view
Great variations on some figures
NE/ER*100 = 100 – 100/EROI



Source: Energy Matters
Eeq: Electricity equivalent

Impact on Energy Transition agenda

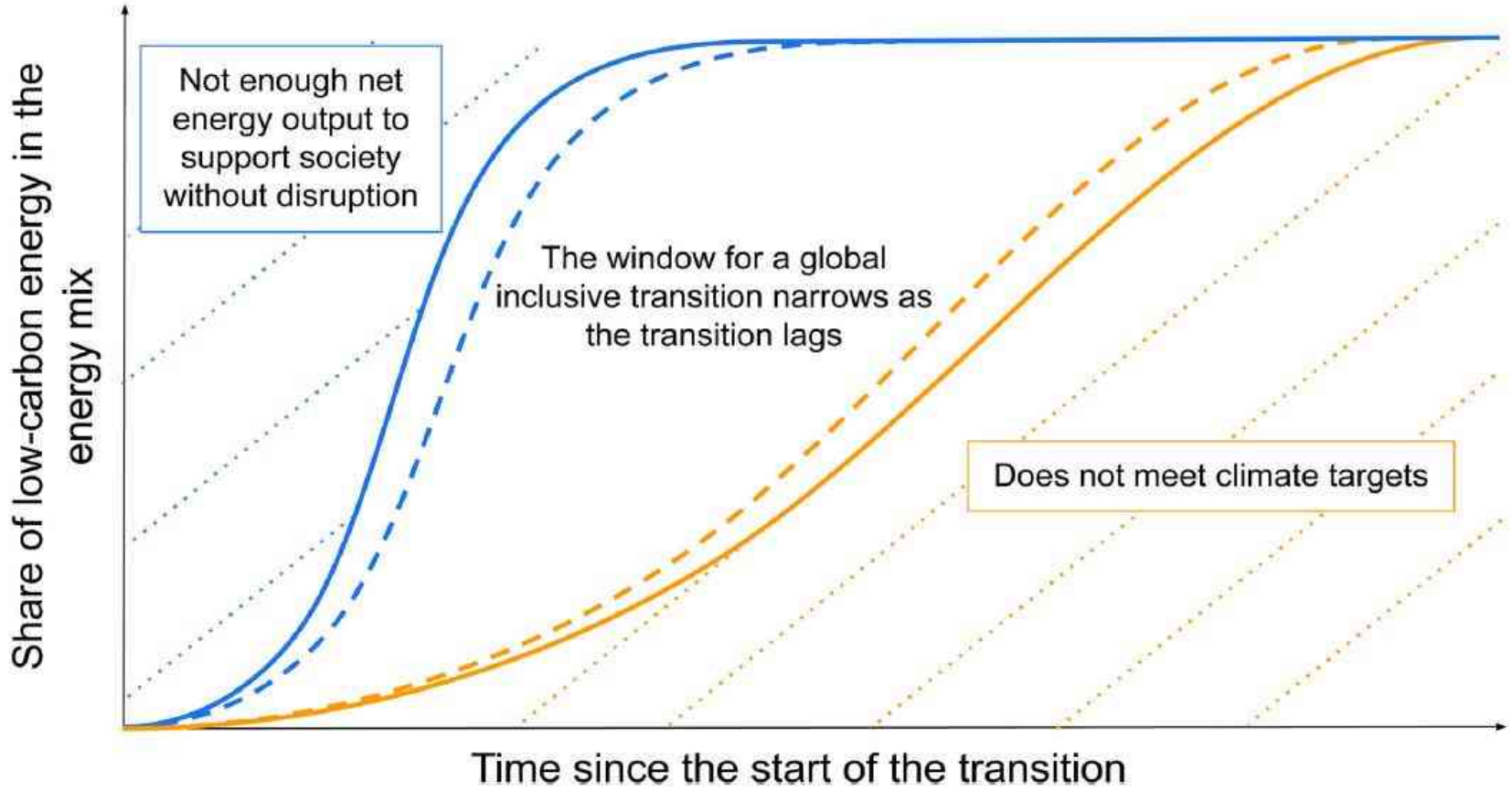


Fig. 3 Sketch of principle of an evolving window of opportunity for the global inclusive transition to low-carbon energy as a function of normalized time at the start of the transition. The solid lines delineate the current window of opportunity. The dashed lines represent a future window in which action has not been taken quickly enough such that climate and net energy increasingly constrain the window of opportunity.

Source: Energy & Environmental Science – Royal Society of Chemistry
March 2023
Delannoy, Auzanneau et al.

The Levelized Cost of Electricity
LCOE

The competitivity of Energy Sources
Levelized Cost Of Electricity (LCOE)

Levelized Cost of Electricity production (LCOE)
= Discounted Costs/Discounted Production

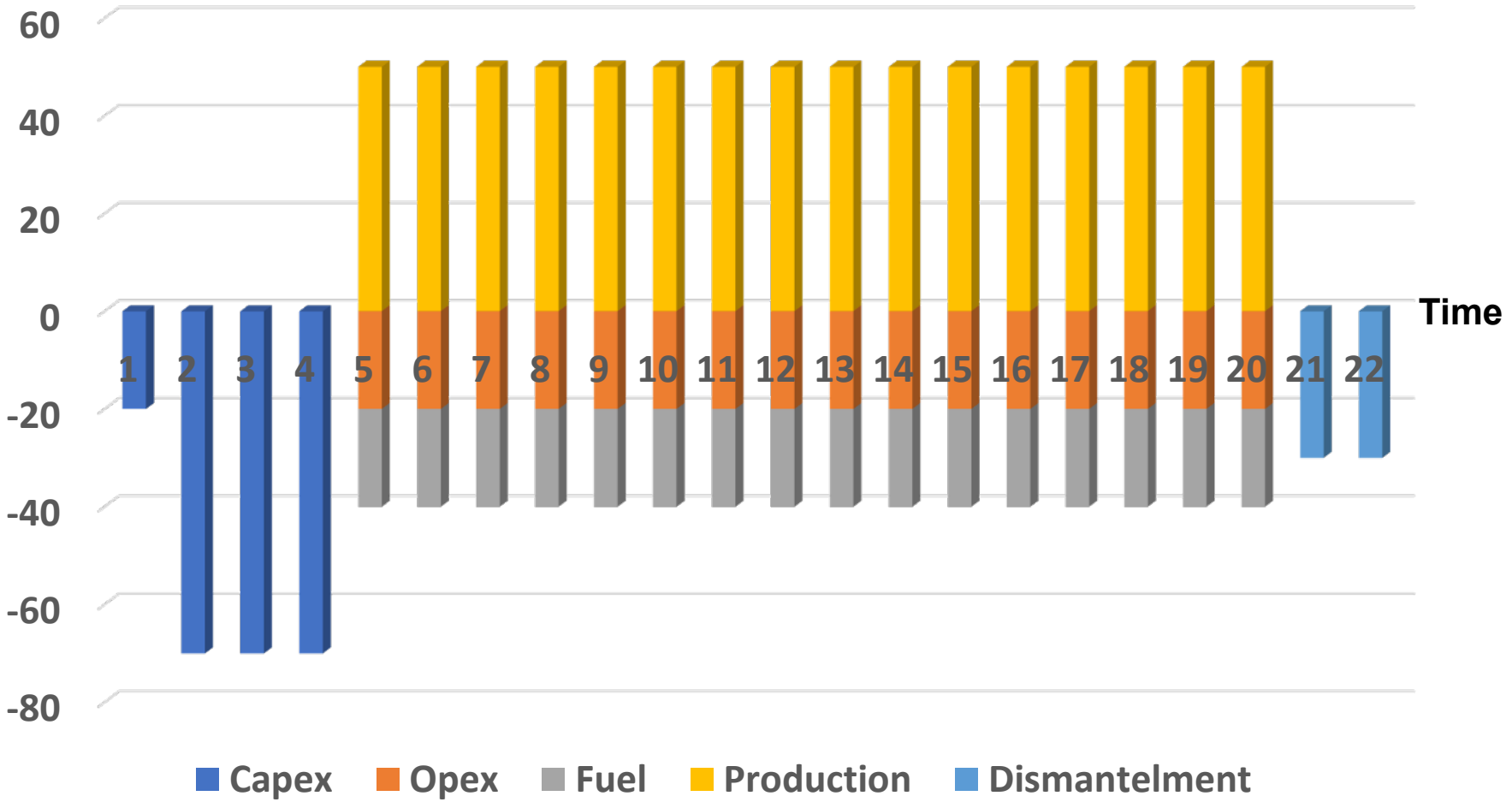
$$LCOE = \sum_{k=0}^{k=n} \frac{C_k + O_k + F_k}{(1+i)^k} \Big/ \sum_{k=0}^{k=n} \frac{Q_k}{(1+i)^k}$$

- *Q : Production of Electricity*
- *C : Capital Expenditures*
- *O : Operating Expenses*
- *F : Fuel Expenses*
- *n : Economic Plant Life*
- *i : Discount Rate*

- *Due to discounting, decommissioning costs have a negligeable effect (included in Capex)*
- *For Renewables, Intermittency Costs are not included*

Nota: In the following, raw data from IEA, US DOE, UK DBEIS, IRENA, Lazard, Fraunhofer ISE, WNA,……

A typical schedule for an Industrial Project for Electricity Generation (illustration)



Example: the case of a Offshore Wind Farm
Location: OECD Region (Saint-Nazaire/France) – 2022

Nominal Capacity	**MW**	**480**
Capacity each turbine	MW	6
Nb of turbines		80
Duration life	**Years**	**25**
Load factor	**%**	**40**
Electricity Generation	**MWh/year**	**1681920**
Total Electricity Generation	MWh	42048000
Capex	€/kW	3800
Total Capex	**M€**	**1824**
Constant Annuity @ 0%	M€	77
Constant Annuity @ 5%	M€	131
Constant Annuity @ 8%	M€	172
Opex	€/kW/year	80
Opex per year	M€	38
Total Opex	**M€**	**960**
Fuel cost	**M€**	**0**
Decommissioning	**M€**	**91,2**
Total cost	M€	2875
LCOE (not discounted)	**€/MWh**	**68**
LCOE @ 5%	**€/MWh**	**101**
LCOE @ 8%	**€/MWh**	**125**

Levelized Cost of Electricity production
Application to various Technologies








From top to down, from left to right:
- Nuclear Power plant, France, Cruas in Ardèche - PWR - 4x900 MW
- Nuclear EPR, France, Flamanville - 1650 MW
- Gas fired CCGT power plant, Bouchain, Northern France – 580 MW
- Heavy Fuel power plant, Liberia - 10 MW
- Coal supercritical power plant, Turkey - 2x600 MW
- Coal IGCC, Japan, Nakoso - 250 MW
- Coal IGCC with CCS, US, Kemper County Mississipi - 580 MW, CO2 for EOR



Levelized Cost of Electricity production
Application to various Technologies








From top to down, from left to right:
- Onshore Wind Farm, Germany
- Offshore Wind Farm, France, Saint-Brieuc, Brittany, 500 MW
- Solar PV Utility Scale, UK, West Raynann Norfolk, 50 MWp
- Solar PV Rooftop
- Solar CSP, US
- Hydro Large, Norway, Alta Dam
- Biomass Power Plant, Japan, Omuta, 50 MW
- Geothermal, Iceland, Svartsengi, 75MW_e + 150 MW_{th}




LCOE is very dependant upon changes of the environment (Inflation, prices of fuels, cost of new nuclear, production costs of solar energy, access to mineral materials in particular)
For wind energy and solar energy, cost of intermittency has to be added.

LCOE is also very dependant upon the selected Discount Rate

The following graphs have been established taking into account the most recent data of the various components of the LCOE (Capex, Opex, Cost of Fuels) deriving from external pertinent sources. For reason of simplicity, they are illustrating the mean values for LCOE of all technologies generating Electricity. They refer to European/OECD sites, knowing that there exist large disparities according to the various sites and locations in the World

Levelized Cost of Electricity production - LCOE Assumptions (2023/2024 Environment)

- Crude oil price : 75 $/b (Brent price 2024)
- Gas price : 14 $/Mbtu (German Import price 2024)
- Coal price : 140 $/t (NW Europe price 2024)
- Uranium price : 80 $/lb$U_3O_8$ (Spot price 2024)
- Exchange rate : 1€ = 1,07 $
- Discount rate : 5%
- Standard power ranges
- Reference : European/OECD sites
- Mean values, ranges differ depending upon technologies
- For Renewables, costs of intermittency are not included and have to be added.

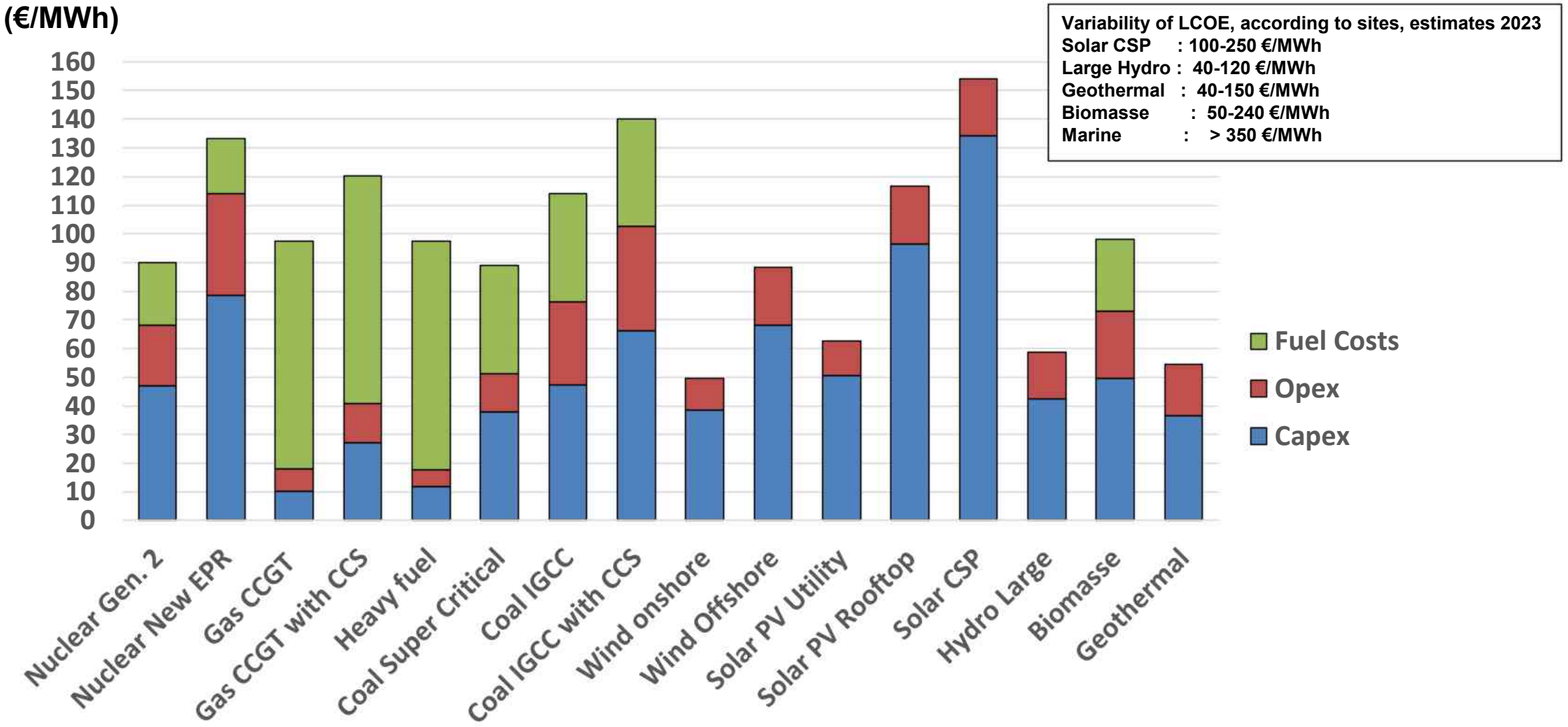
Nota: A large range of LCOE can be observed depending upon the publications and the location of the projects
Data below from IEA, NREL, EIA, Lazard, Fraunhofer, DBEIS UK.....

Levelized cost of Electricity production
Assumptions: 2023/2024 Environment

		Nuclear	Nuclear	Gas	Gas	Heavy	Coal	Coal	Coal	Wind	Wind	Solar PV	Solar PV	Solar	Hydro	Biomass	Geother.
		Gener. 2	EPR	CCGT	CCGT&CCS	Fuel	Sup. crit.	IGCC	IGCC&CCS	Onshore	Offshore	Utility	Rooftop	CSP	Large		
Power reference	Mwe	1000	1650	600	600	600	700	700	700	120	250	100	0	150	1000	50	50
Construction lead	Years	7,0	8,0	3,0	3,0	3,0	5,0	5,0	5,0	1,5	2,5	2,0	0,3	2,0	6,0	3,0	3,0
Duration life	Years	60	60	30	30	30	40	40	40	25	25	25	25	25	80	25	80
Availability	%	90%	90%	80%	80%	80%	80%	80%	80%	33%	45%	17%	17%	45%	35%	80%	85%
Thermal Energy Efficiency	%	33%	37%	60%	60%	42%	40%	40%	40%								
Capex	€/kW	6000	10000	1000	2700	1200	4000	5000	7000	1500	3400	1000	2000	7000	2300	4400	5000
Opex (incl. Maintenance)	€/MWh	21	35	8	14	6	13	29	36	11	20	12	20	20	16	25	18

CCGT: Combined-Cycle Gas Turbine
IGCC: Integrated Gasification Combined-Cycle
CCS: Carbon Capture & Storage
Note: Gas CCGT & CCS and Coal IGCC & CCS includes 10€/MWh for CO2 transport & storage

Cost price of Electricity produced by the various types of Power Plants @ 5% excluding CO_2 price (**2023/2024** Environm., European/OECD sites, **Mean values**)



Source: Ch.Guéritte - Data on technical costs from IEA, IRENA, Lazard, ATB NREL, Fraunhofer, DBEIS UK…

Wind Offshore
Some considerations on LCOE

Wind Offshore/OECD Region/Average figures – LCOE Comparison 2019 & Perspectives 2030

Wind Offshore – Standard Project Year 2019

Nominal Capacity	**MW**	**250**
Capacity each turbine	MW	5
Nb of turbines		50
Duration life	**Years**	**25**
Load factor	**%**	**40**
Electricity Generation	**MWh/year**	**876000**
Total Electricity Generation	MWh	21900000
Capex	€/kW	4000
Total Capex	**M€**	**1000**
Constant Annuity @ 0%	M€	42
Constant Annuity @ 5%	M€	72
Constant Annuity @ 8%	M€	94
Opex	€/MWh	30
Opex per year	M€	26
Total Opex	**M€**	**657**
Fuel cost	**M€**	**0**
Decommissioning	**M€**	**50**
Total cost	M€	1707
LCOE (not discounted)	**€/MWh**	**78**
LCOE @ 5%	**€/MWh**	**112**
LCOE @ 8%	**€/MWh**	**138**

Constant Annuity @ 0%	%	4,00
Constant Annuity @ 5%	%	7,10
Constant Annuity @ 8%	%	9,37

Wind Offshore – Standard Project Year 2030

Nominal Capacity	**MW**	**500**
Capacity each turbine	MW	10
Nb of turbines		50
Duration life	**Years**	**25**
Load factor	**%**	**45**
Electricity Generation	**MWh/year**	**1971000**
Total Electricity Generation	MWh	49275000
Capex	€/kW	2500
Total Capex	**M€**	**1250**
Constant Annuity @ 0%	M€	53
Constant Annuity @ 5%	M€	90
Constant Annuity @ 8%	M€	118
Opex	€/MWh	15
Opex per year	M€	30
Total Opex	**M€**	**739**
Fuel cost	**M€**	**0**
Decommissioning	**M€**	**63**
Total cost	M€	2052
LCOE (not discounted)	**€/MWh**	**42**
LCOE @ 5%	**€/MWh**	**61**
LCOE @ 8%	**€/MWh**	**75**

Constant Annuity @ 0%	%	4,00
Constant Annuity @ 5%	%	7,10
Constant Annuity @ 8%	%	9,37

Wind Offshore/OECD Region/Average figures – LCOE Comparison 2019 & Perspectives 2030

Wind Offshore – Standard Project Year 2019

Nominal Capacity	**MW**	**250**
Capacity each turbine	MW	5
Nb of turbines		50
Duration life	**Years**	**25**
Load factor	**%**	**40**
Electricity Generation	**MWh/year**	**876000**
Total Electricity Generation	MWh	21900000
Capex	€/kW	4000
Total Capex	**M€**	**1000**
Constant Annuity @ 0%	M€	42
Constant Annuity @ 5%	M€	72
Constant Annuity @ 8%	M€	94
Opex	€/MWh	30
Opex per year	M€	26
Total Opex	**M€**	**657**
Fuel cost	**M€**	**0**
Decommissioning	**M€**	**50**
Total cost	M€	1707
LCOE (not discounted)	**€/MWh**	**78**
LCOE @ 5%	**€/MWh**	**112**
LCOE @ 8%	**€/MWh**	**138**

Constant Annuity @ 0%	%	4,00
Constant Annuity @ 5%	%	7,10
Constant Annuity @ 8%	%	9,37

Floating Wind Offshore Year 2030

Nominal Capacity	**MW**	**500**
Capacity each turbine	MW	10
Nb of turbines		50
Duration life	**Years**	**25**
Load factor	**%**	**45**
Electricity Generation	**MWh/year**	**1971000**
Total Electricity Generation	MWh	49275000
Capex	€/kW	4000
Total Capex	**M€**	**2000**
Constant Annuity @ 0%	M€	84
Constant Annuity @ 5%	M€	144
Constant Annuity @ 8%	M€	189
Opex	€/MWh	22
Opex per year	M€	43
Total Opex	**M€**	**1084**
Fuel cost	**M€**	**0**
Decommissioning	**M€**	**100**
Total cost	M€	3184
LCOE (not discounted)	**€/MWh**	**65**
LCOE @ 5%	**€/MWh**	**95**
LCOE @ 8%	**€/MWh**	**118**

Constant Annuity @ 0%	%	4,00
Constant Annuity @ 5%	%	7,10
Constant Annuity @ 8%	%	9,37

LCOE Estimates 2023-2024

Other sources of energy, according to sites:

- **Solar CSP : 100-250 €/MWh**
- **Large Hydro : 40-120 €/MWh**
- **Geothermal : 40-150 €/MWh**
- **Biomass : 60-240 €/MWh**
- **Marine : > 350 €/MWh**

Carbon Pricing is one important element to mitigate the effects of CO_2 Emissions

Business Leadership Criteria

CARBON PRICING

Caring for Climate | THE GLOBAL COMPACT | UNEP | UNFCCC

CDP | THE CLIMATE GROUP | UNITED NATIONS FOUNDATION | PRI Principles for Responsible Investment

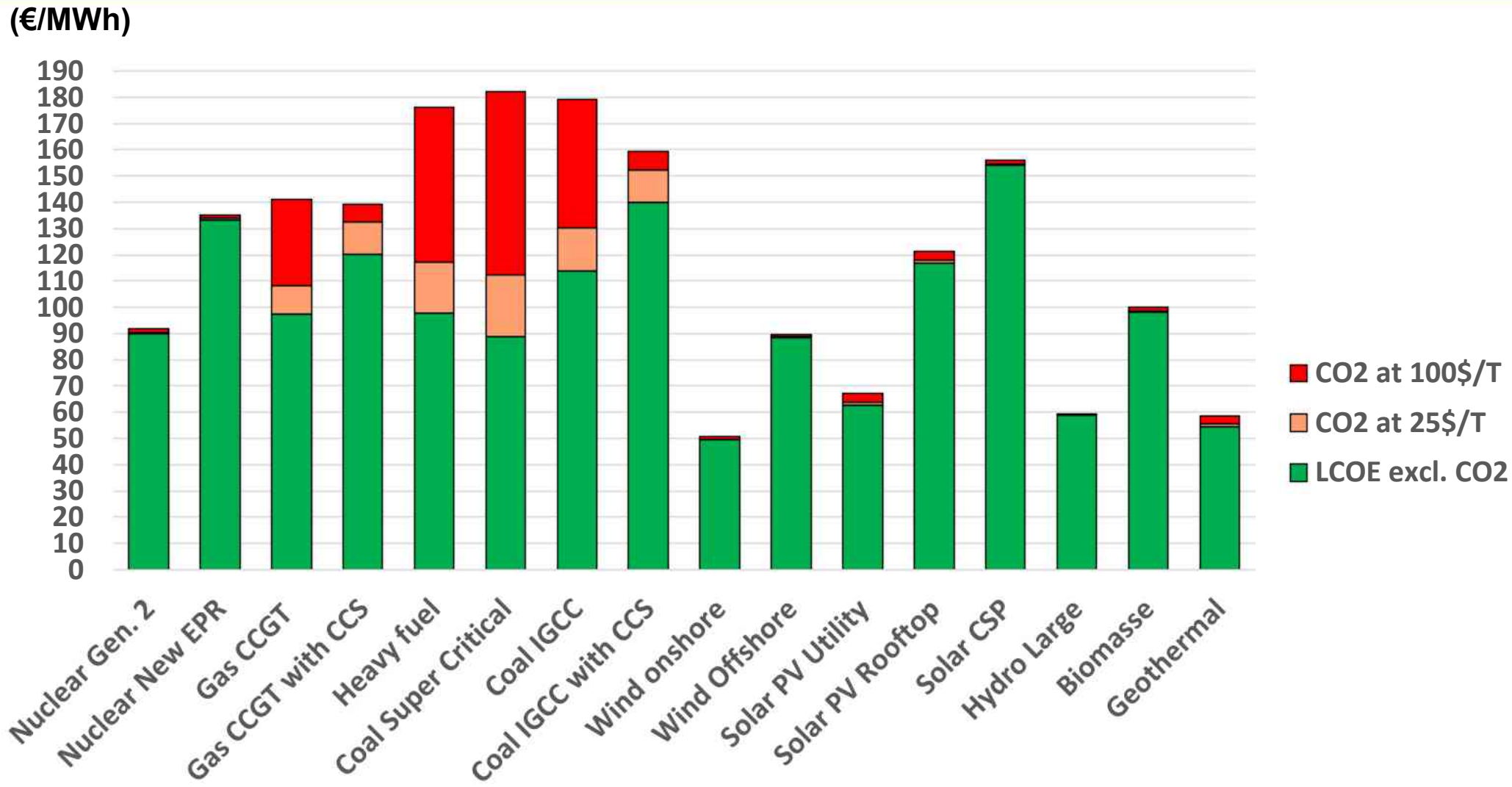
"Let us make sustainability the most powerful lobby… **Become advocates** for an effective, well-functioning carbon market… We must **place a true value on the cost of carbon** to our economies and our future. I urge you to work with Governments on this issue."

— Ban Ki-Moon
United Nations Secretary-General



See Book 3 - GHG for Carbon Pricing

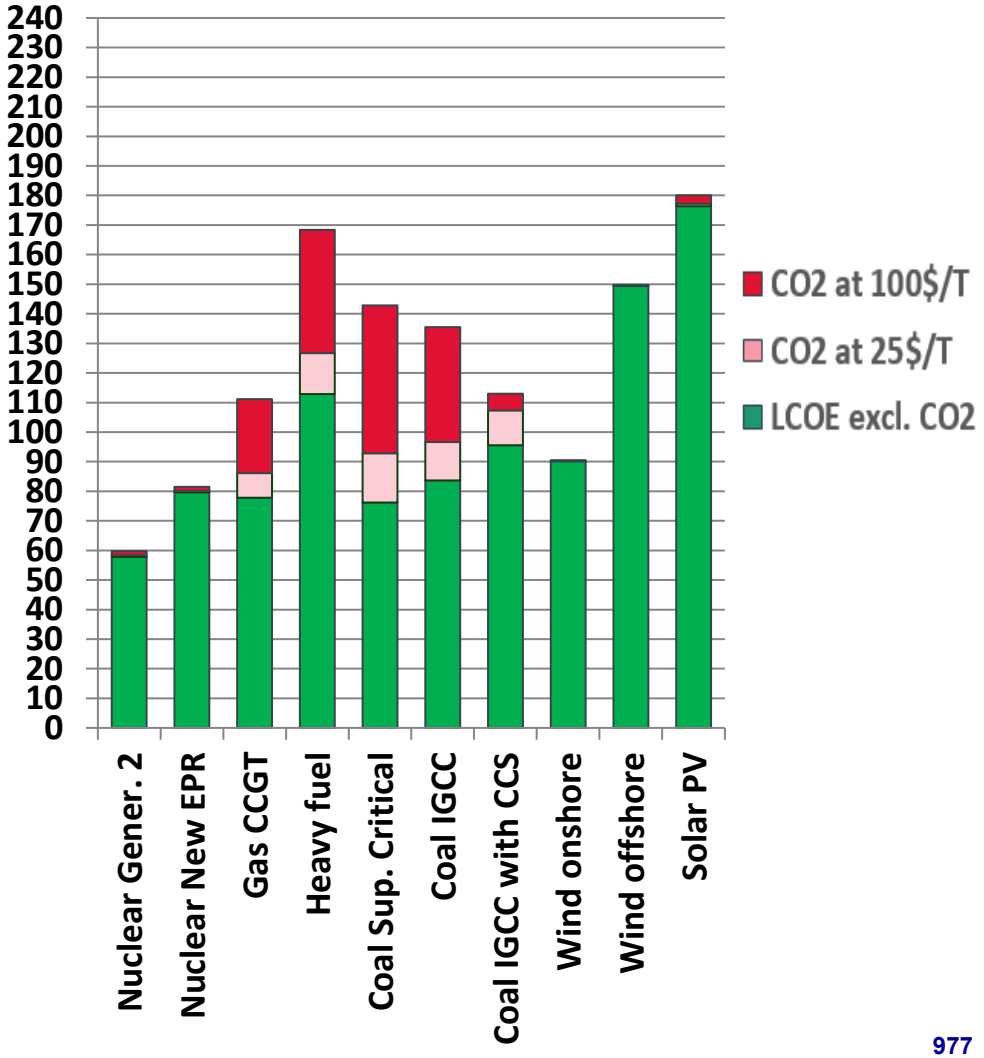
Cost price of Electricity produced by the various types of Power Plants @ 5% including CO_2 price (**2023/2024** Environm., European/OECD sites, **Mean values**)



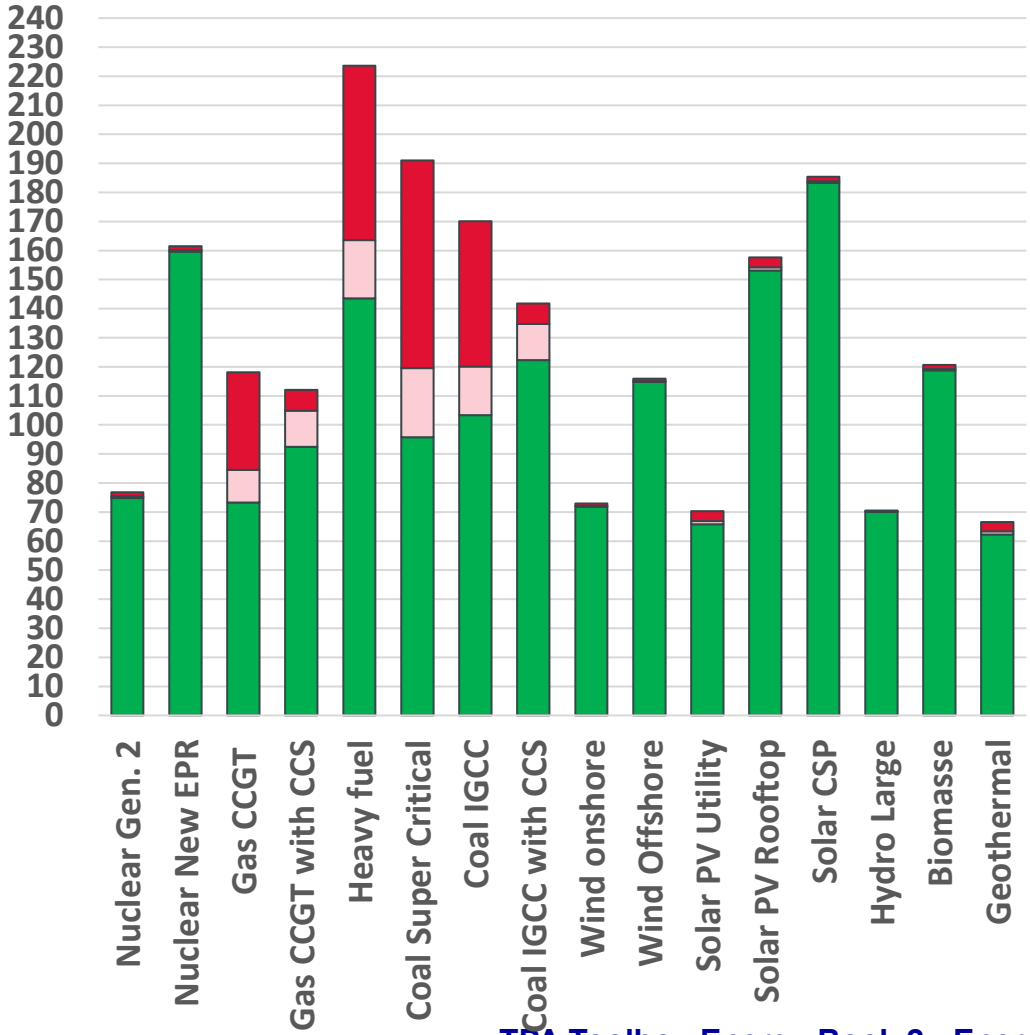
Source: Ch.Guéritte - Data on technical costs from IEA, IRENA, Lazard, ATB NREL, Fraunhofer, DBEIS UK…

Reminder - LCOE Variations (Including CO_2 Prices) (€/MWh)

2012/2014 Environment @ 8%



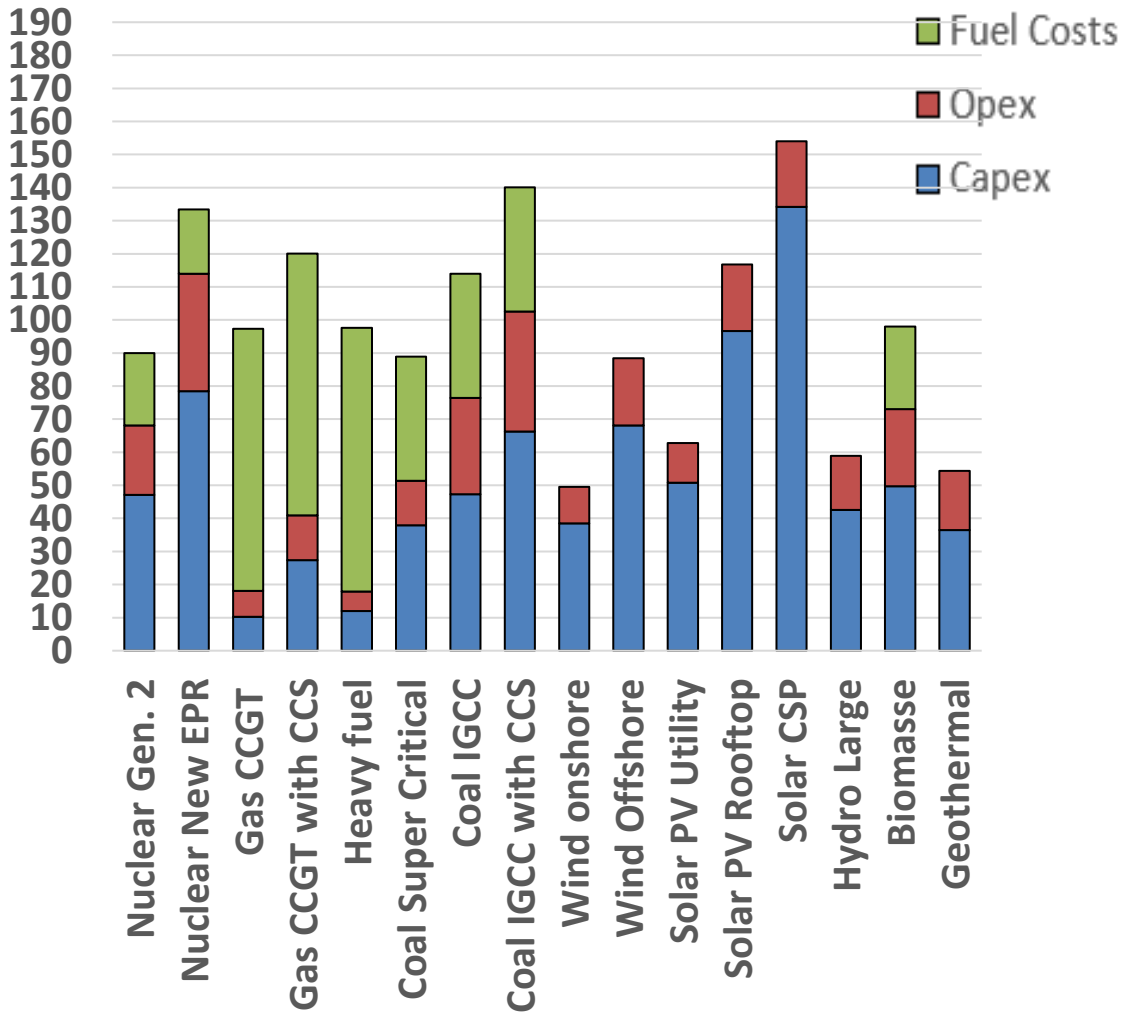
2021/2022 Environment @ 8%



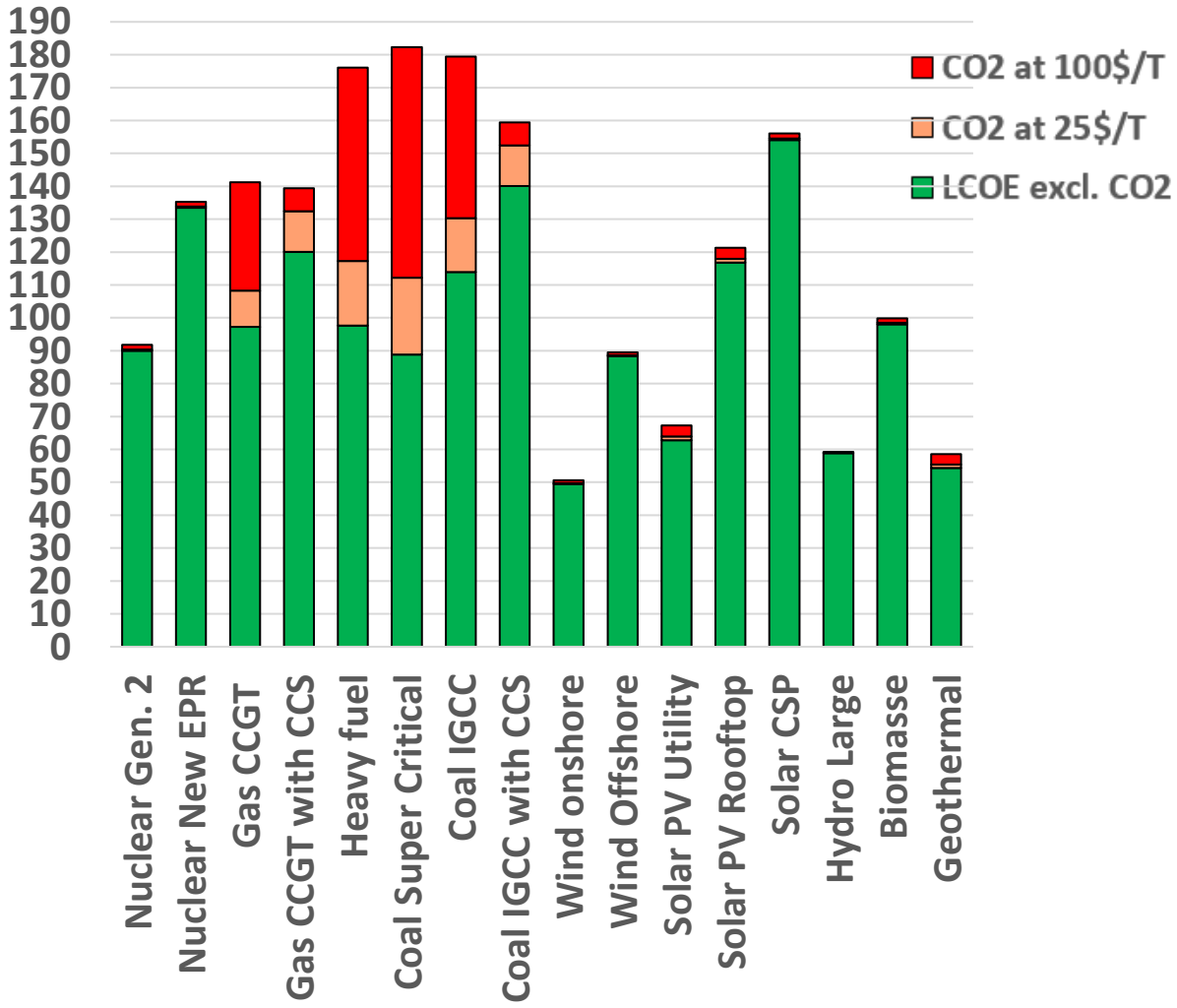
Source: Ch.Guéritte

LCOE 2023/2024 Environment @ 5% (excluding & including CO_2 Penalty) (€/MWh)

Excluding CO2 penalty



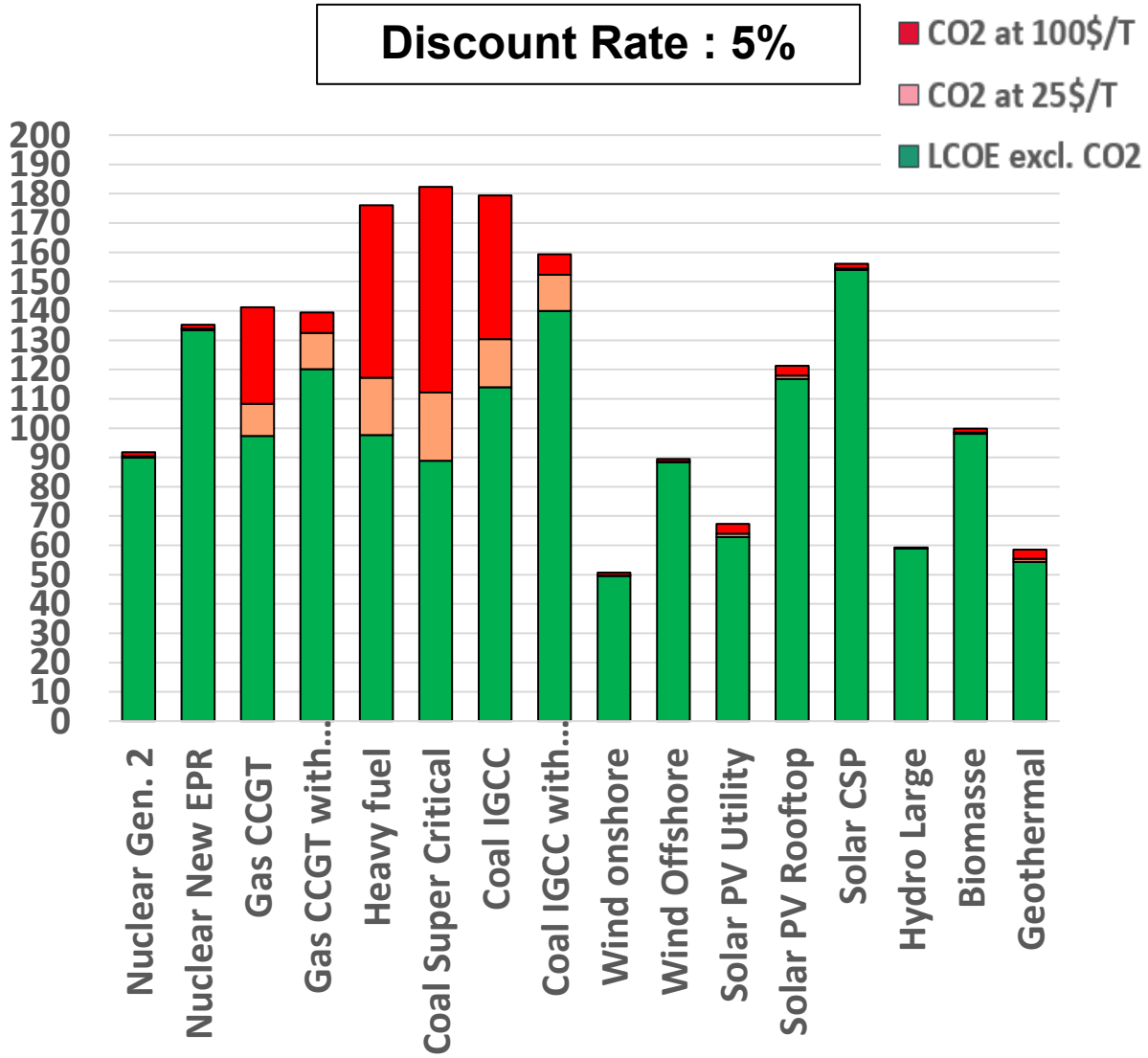
Including CO2 penalty



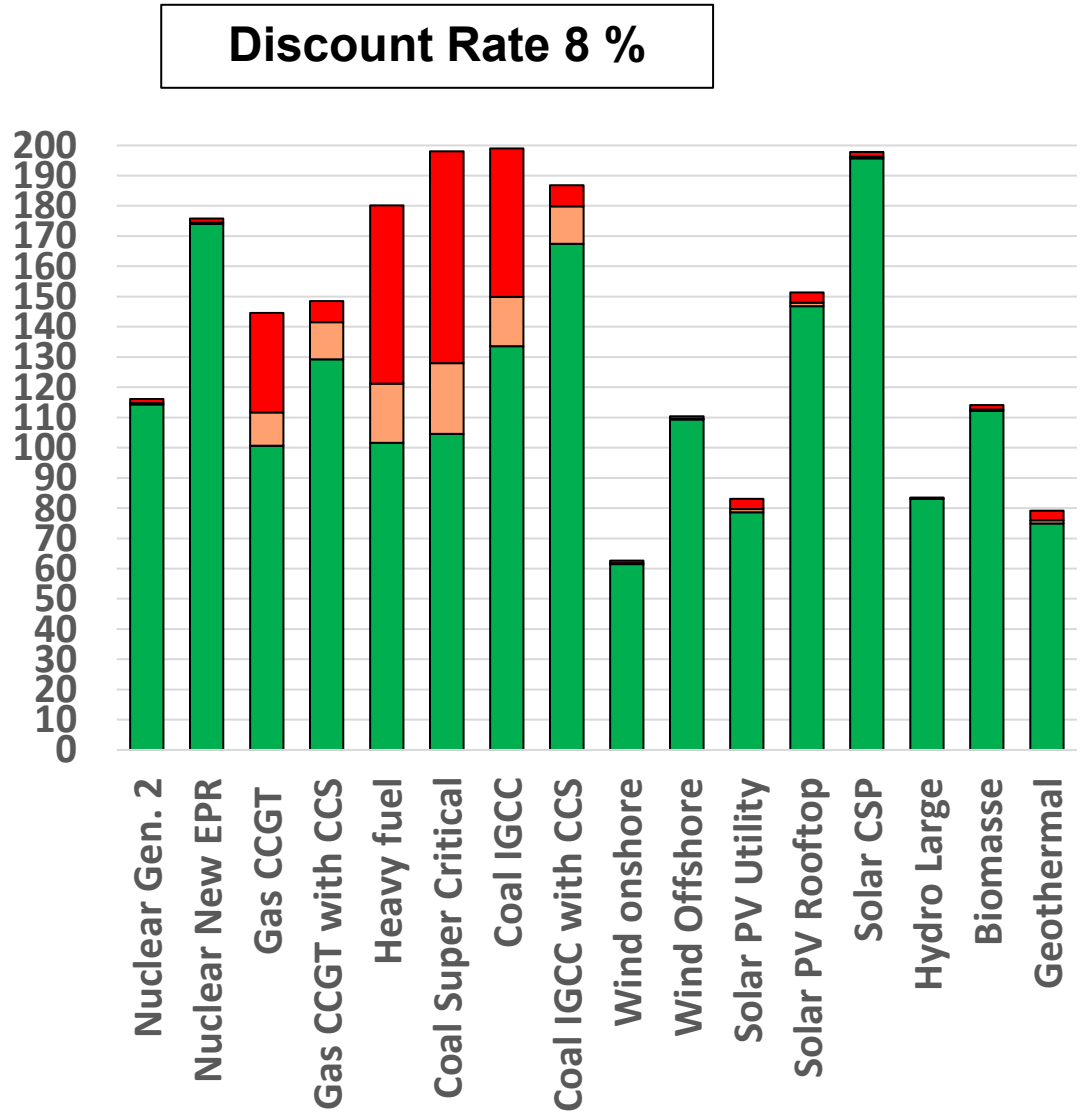
Source: Ch.Guéritte

LCOE including CO_2 Prices 2023/2024 Environment
Impact of the Discount Rate (€/MWh)

Discount Rate : 5%



Discount Rate 8 %



Source: Ch.Guéritte

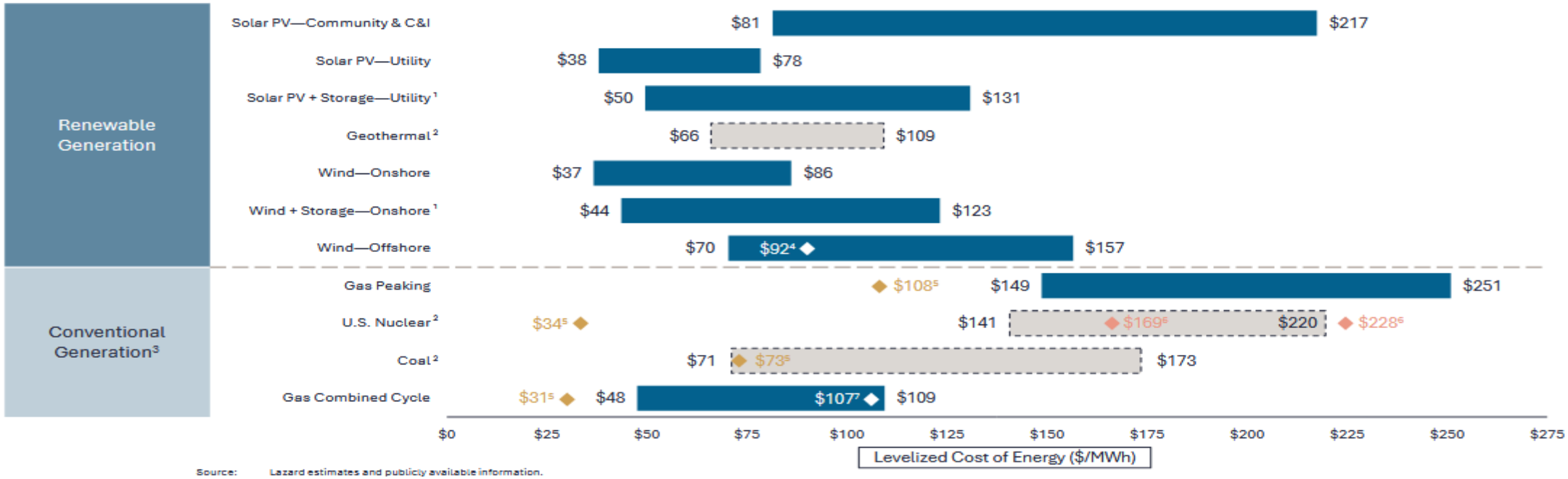
Different visions for the LCOE estimates for the next decades!
They depend upon assumptions on Costs of New Developments/Technologies, Prices of Oil, Gas and Coal, Uranium, Cost of CO_2 penalty….

LCOE by Lazard

LCOE by Lazard

Levelized Cost of Energy Comparison—Version 18.0

Selected renewable energy generation technologies remain cost-competitive with conventional generation technologies under certain circumstances



Source: Lazard estimates and publicly available information.

Note: Here and throughout this analysis, unless otherwise indicated, the analysis assumes 60% debt at an 8% interest rate and 40% equity at a 12% cost. See page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities.

1 Reflects the LCOE for a system composed of standalone generation plus standalone storage less the combined system-level synergies (assumed to be 10% of storage capital costs and 25% of inverter costs). The synergies capture potential cost reductions or efficiency gains from integrating generation and storage, such as shared interconnection infrastructure, improved energy dispatch, enhanced capacity utilization and operational efficiencies.

2 Given the limited public and/or observable data available for new-build geothermal, coal and nuclear projects, the LCOE presented herein reflects Lazard's LCOE v14.0 results adjusted for inflation and, for nuclear, are based on then-estimated costs of the Vogtle Plant. Coal LCOE does not include cost of transportation and storage.

3 The fuel cost assumptions for Lazard's LCOE analysis of gas-fired generation, coal-fired generation and nuclear generation resources are $3.45/MMBTU, $1.47/MMBTU and $0.85/MMBTU, respectively, for year-over-year comparison purposes. See page titled "Levelized Cost of Energy Comparison—Sensitivity to Fuel Prices" for fuel price sensitivities.

4 Represents the illustrative midpoint LCOE for Dominion's Coastal Virginia Offshore Wind ("CVOW") project, based on the publicly disclosed capital cost of ~$8.7 billion (excluding onshore transmission costs) and offshore wind estimates from Lazard. Dominion's projected LCOE for CVOW as of February 2025 is $91/MWh in 2027 dollars, with an expected COD in 4Q 2026.

5 Reflects the average of the high and low LCOE marginal cost of operating fully depreciated gas peaking, gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard's research. See page titled "Levelized Cost of Energy Comparison—New Build Renewable Generation vs. Marginal Cost of Conventional Generation" for additional details.

6 Represents illustrative LCOE values for Vogtle nuclear plant's units 3 and 4. The analysis is based on publicly available estimates and suggestions from selected industry experts, indicating a cost "learning curve" of ~30% between Vogtle units 3 and 4. Analysis assumes total operating capacity of ~2.2 GW, total capital cost of ~$32.3 billion, capacity factor of ~97%, operating life of 70 years and other operating parameters estimated by Lazard's LCOE v14.0 results, adjusted for inflation.

7 Illustrative high case reflects elevated capital costs ($2,400/kW – $2,600/kW) based on recently observed market quotes for CCGT projects in early stages of development (post-2028 COD).

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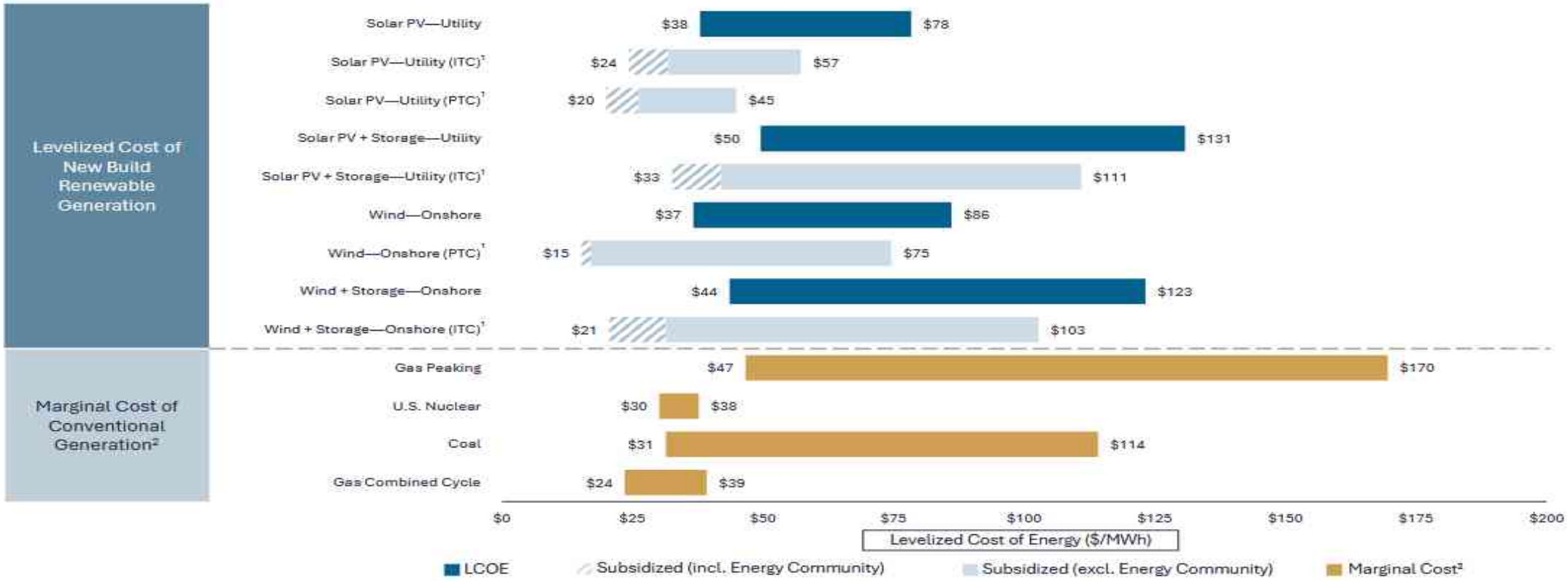
TPA Sharing Experience

Source: Lazard LCOE June 2025

LCOE New built Renewables vs marginal costs of conventional technologies by Lazard

Levelized Cost of Energy Comparison—New Build Renewable Generation vs. Marginal Cost of Conventional Generation

Certain renewable energy generation technologies have an LCOE that is competitive with the marginal cost of selected conventional generation technologies—notably, as incremental, intermittent renewable energy capacity is deployed and baseload gas-fired generation utilization rates increase, this gap closes, particularly in low gas pricing and high energy demand environments



Source: Lazard estimates and publicly available information.
Note: Unless otherwise noted, the assumptions used in this sensitivity correspond to those used on page titled "Levelized Cost of Energy Comparison—Version 18.0".
1 See page titled "Levelized Cost of Energy Comparison—Sensitivity to U.S. Federal Tax Subsidies" for additional details.
2 Reflects the marginal cost of operating fully depreciated gas, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed O&M are based on upper- and lower-quartile estimates derived from Lazard's research.

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Historical LCOE by Lazard

Levelized Cost of Energy Comparison—Historical LCOE Comparison

Lazard's LCOE analysis indicates significant historical cost declines for utility-scale renewable energy generation technologies, which has begun to level out and even slightly increase in recent years

Selected Historical Average LCOE Values[1]



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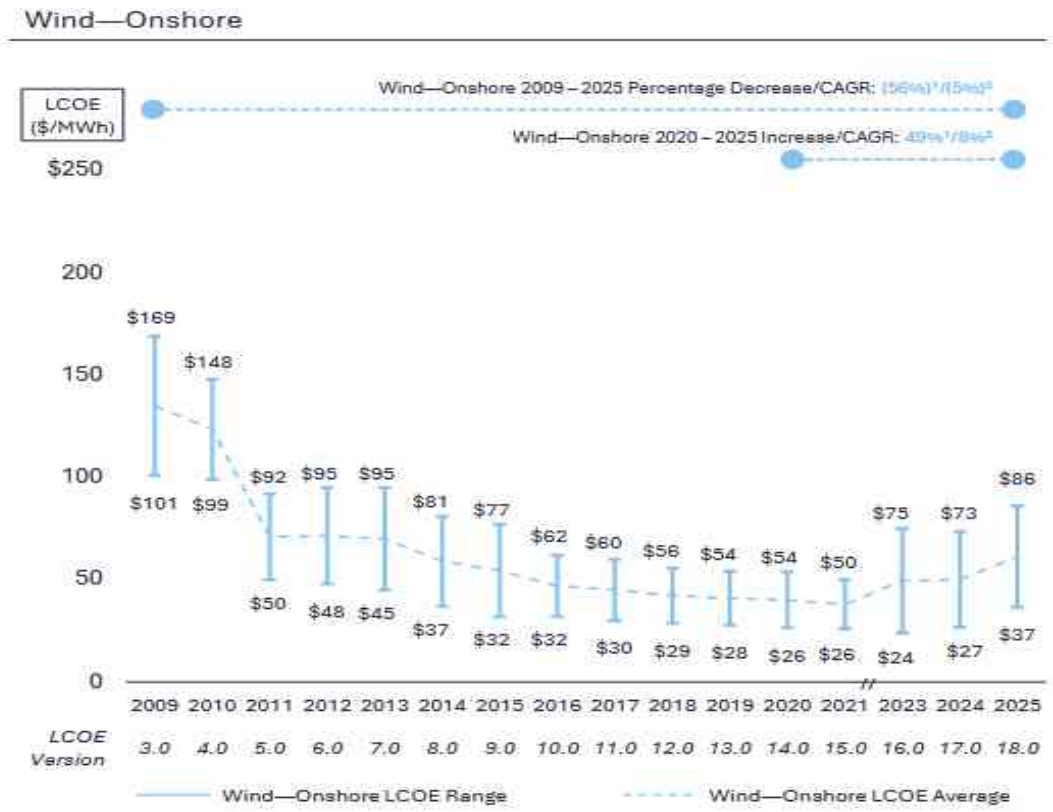
Source: Lazard estimates and publicly available information.
1 Reflects the average of the high and low LCOE for each respective technology in each respective year. Percentages represent the total change in the average LCOE since Lazard's LCOE v3.0 and LCOE v17.0, respectively.
2 Given the limited public and/or observable data available for new-build nuclear projects, the LCOE presented herein reflects Lazard's LCOE v14.0 results adjusted for inflation and are based on then-estimated costs of the Vogtle Plant.

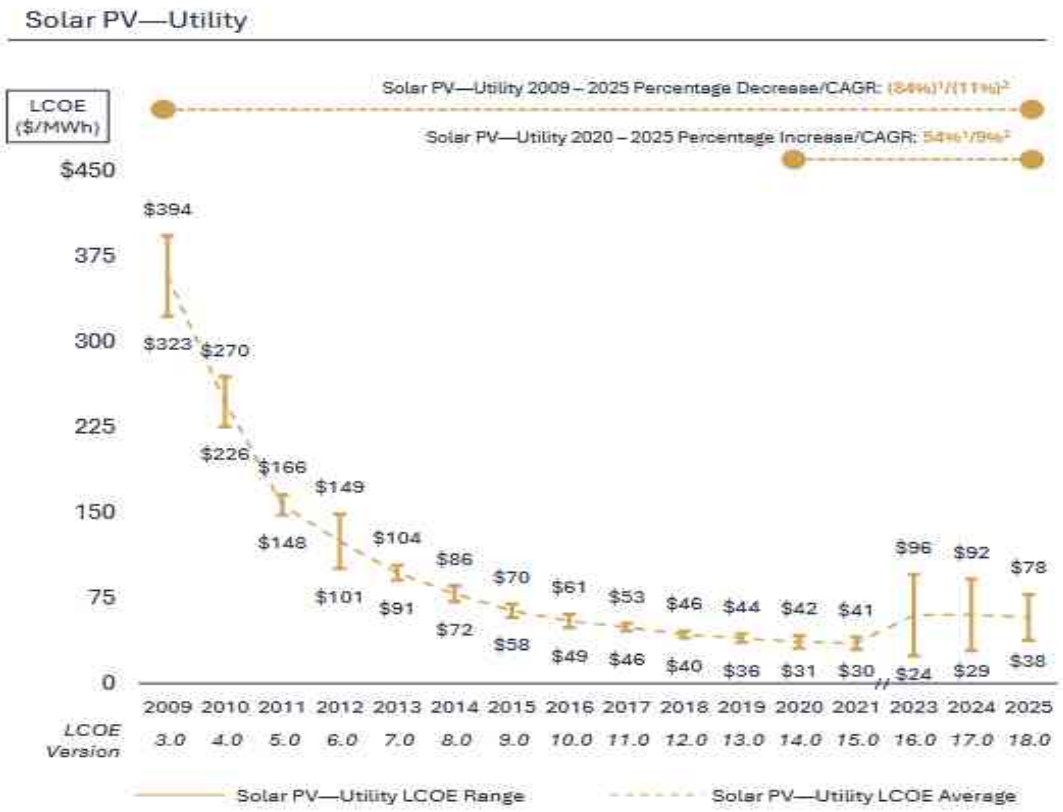
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Historical LCOE Wind & Solar by Lazard

Levelized Cost of Energy Comparison—Historical Renewable Energy LCOE

This year's analysis shows a divergence in trends between wind and solar with solar costs declining slightly and wind costs increasing, likely reflecting the difference in supply chain conditions across each technology





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Source: Lazard estimates and publicly available information.
1 Reflects the average percentage increase/(decrease) of the high end and low end of the LCOE range.
2 Reflects the average compounded annual growth rate of the high end and low end of the LCOE range.

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LCOE by IEA

Technological costs in specific regions by IEA WEO 2025 - STEPS

Economic assumptions are important when defining LCOE

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2, O&M (USD/MWh)			LCOE (USD/MWh)			VALCOE (USD/MWh)		
	2024	2035	2050	2024	2035	2050	2024	2035	2050	2024	2035	2050	2024	2035	2050
United States															
Nuclear	5 000	4 700	4 500	90	90	90	30	30	30	110	110	105	110	110	105
Coal	2 100	2 100	2 100	40	30	20	30	25	25	100	120	190	100	110	180
Gas CCGT	1 000	1 100	1 100	65	55	35	30	35	40	50	60	80	50	55	70
Geothermal*	15 000	9 000	6 600	75	75	80	50	25	20	330	195	135	330	195	135
Solar PV	1 060	660	530	20	23	23	10	10	10	55	35	25	65	50	50
Wind onshore	1 570	1 510	1 460	42	44	44	10	10	10	40	40	35	45	45	40
Wind offshore	4 060	2 860	2 340	41	46	49	35	30	25	125	85	65	130	90	70
Electricity generation costs										65	65	70			
European Union															
Nuclear	6 600	5 000	4 500	75	75	80	35	35	35	165	135	120	160	120	105
Coal	2 000	2 000	2 000	20	n.a.	n.a.	120	n.a.	n.a.	280	n.a.	n.a.	235	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	15	10	10	110	110	135	200	230	290	145	150	150
Geothermal*	21 630	18 130	16 730	75	75	80	55	45	45	455	380	330	450	365	325
Solar PV	760	470	390	14	14	14	10	10	10	50	35	30	60	65	70
Wind onshore	1 620	1 540	1 510	29	30	30	15	15	15	60	55	55	70	75	75
Wind offshore	3 460	2 300	1 980	50	54	55	15	10	10	75	50	40	75	65	60
Electricity generation costs										125	100	85			

	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2, O&M (USD/MWh)			LCOE (USD/MWh)			VALCOE (USD/MWh)		
	2024	2035	2050	2024	2035	2050	2024	2035	2050	2024	2035	2050	2024	2035	2050
China															
Nuclear	2 800	2 700	2 500	75	70	70	25	25	25	70	75	70	70	75	70
Coal	800	800	800	50	25	20	40	35	35	65	80	90	60	70	70
Gas CCGT	560	560	560	25	15	15	70	65	70	100	115	125	90	90	95
Geothermal*	16 050	11 050	9 050	75	75	80	55	30	25	320	215	165	320	215	165
Solar PV	590	350	280	12	12	12	10	10	10	45	30	25	65	65	70
Wind onshore	860	800	790	23	24	24	10	10	10	40	35	35	45	45	55
Wind offshore	1 520	1 020	880	30	32	32	15	10	10	60	40	35	65	50	55
Electricity generation costs										75	75	80			
India															
Nuclear	2 800	2 800	2 800	80	85	90	30	30	30	75	70	70	75	70	70
Coal	1 200	1 200	1 200	70	70	65	40	45	50	60	65	70	60	65	65
Gas CCGT	700	700	700	30	35	45	60	70	75	90	95	95	85	90	85
Geothermal*	19 500	15 000	13 200	75	75	80	75	55	45	400	305	250	400	305	250
Solar PV	530	310	250	20	21	22	5	5	5	30	20	15	35	30	45
Wind onshore	1 110	1 040	1 010	27	29	30	15	10	10	55	45	45	60	50	55
Wind offshore	2 620	1 760	1 460	34	38	39	25	15	15	110	70	55	110	75	65
Electricity generation costs										75	65	50			

Source: IEA WEO 2025 – Cost of CO_2 is included in Opex

*Next-generation geothermal.

Sources: IEA analysis; IRENA (2025).

Technological costs in specific regions by IEA WEO 2025 - NZE

Economic assumptions are important when defining LCOE

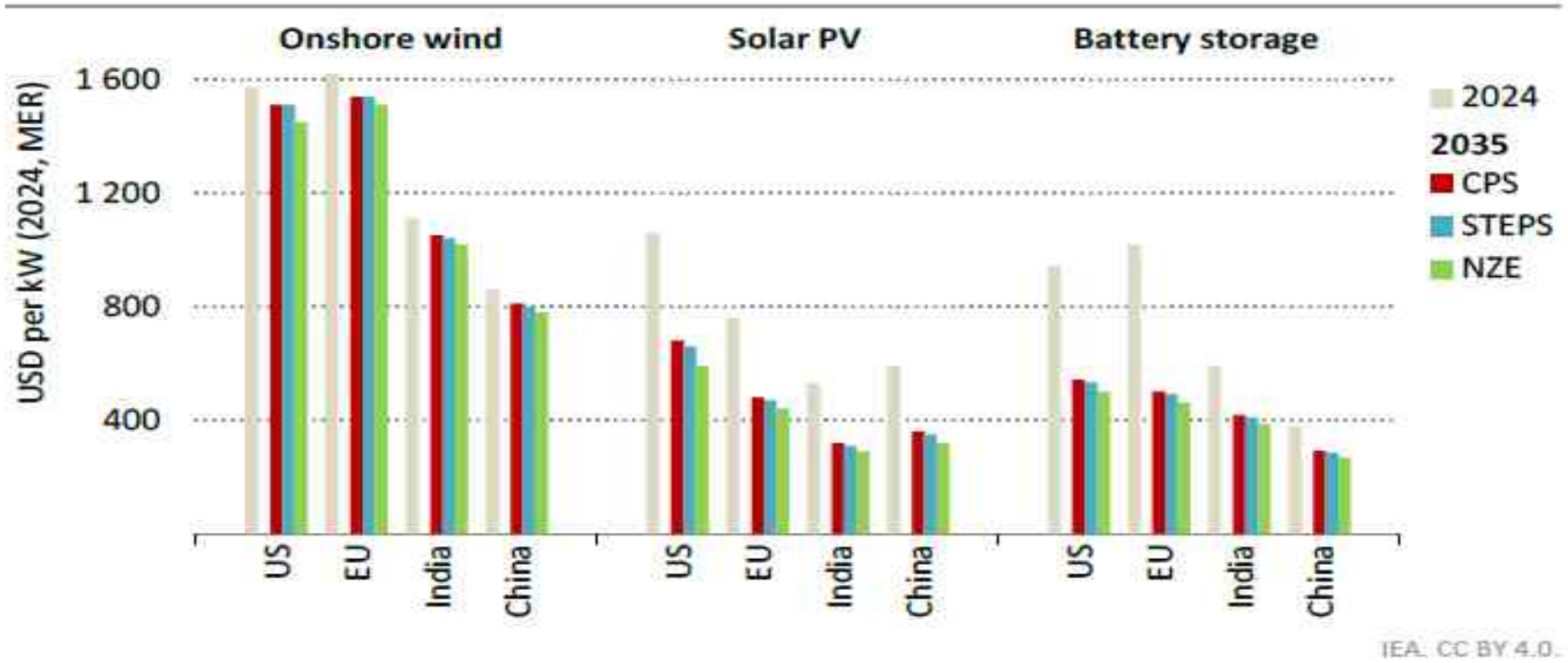
	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2, O&M (USD/MWh)			LCOE (USD/MWh)		
	2024	2035	2050	2024	2035	2050	2024	2035	2050	2024	2035	2050
United States												
Nuclear	5 000	4 700	4 500	90	85	85	30	30	30	110	115	115
Coal	2 100	2 100	2 100	25	n.a.	n.a.	95	n.a.	n.a.	210	n.a.	n.a.
Gas CCGT	1 000	1 100	1 100	40	10	n.a.	55	90	n.a.	85	265	n.a.
Geothermal*	15 000	6 600	3 560	75	75	80	50	20	10	330	140	70
Solar PV	1 060	590	480	20	23	23	10	10	10	55	30	25
Wind onshore	1 570	1 450	1 400	42	44	44	10	10	10	40	35	35
Wind offshore	4 060	2 380	1 980	41	46	49	35	20	15	125	70	55
Electricity generation costs										65	80	70
European Union												
Nuclear	6 600	5 000	4 500	75	70	65	35	35	35	165	140	135
Coal	2 000	2 000	2 000	15	n.a.	n.a.	150	n.a.	n.a.	330	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	15	n.a.	n.a.	115	n.a.	n.a.	215	n.a.	n.a.
Geothermal*	21 630	16 030	14 000	75	75	80	55	40	35	455	335	280
Solar PV	760	440	370	14	14	14	10	10	10	50	35	30
Wind onshore	1 620	1 510	1 460	29	30	30	15	15	15	60	55	50
Wind offshore	3 460	2 180	1 800	50	54	55	15	10	10	75	45	35
Electricity generation costs										125	95	80
China												
Nuclear	2 800	2 700	2 500	80	75	75	25	25	25	70	70	70
Coal	800	800	800	40	n.a.	n.a.	80	n.a.	n.a.	105	n.a.	n.a.
Gas CCGT	560	560	560	40	30	n.a.	85	100	n.a.	100	120	n.a.
Geothermal*	16 050	8 050	5 150	75	75	80	55	25	15	320	160	95
Solar PV	590	320	260	12	12	12	10	10	5	45	30	25
Wind onshore	860	780	750	23	24	24	10	10	10	40	35	35
Wind offshore	1 520	900	760	30	32	32	15	10	10	60	35	30
Electricity generation costs										75	80	75
India												
Nuclear	2 800	2 800	2 800	80	85	85	30	30	30	75	70	70
Coal	1 200	1 200	1 200	60	25	n.a.	35	135	n.a.	60	195	n.a.
Gas CCGT	700	700	700	30	30	n.a.	50	80	n.a.	80	110	n.a.
Geothermal*	19 500	12 300	9 690	75	75	80	75	45	35	400	250	185
Solar PV	530	290	220	20	21	22	5	5	5	30	15	15
Wind onshore	1 110	1 020	970	26	29	29	15	10	10	55	45	45
Wind offshore	2 620	1 600	1 280	34	38	39	25	15	10	110	65	50
Electricity generation costs										75	75	40

*Next-generation geothermal.
Sources: IEA analysis; IRENA (2025).

Source: IEA WEO 2025

Technological costs in specific regions by IEA WEO 2025 for Scenarios

Economic assumptions are important when defining LCOE



Installed costs decline to 2035 for onshore wind, solar PV and utility-scale battery storage across scenarios

Notes: kW= kilowatt; MER = market exchange rate; US = United States; EU = European Union. CPS = Current Policies Scenario; STEPS = Stated Policies Scenario; NZE = Net Zero Emissions by 2050 Scenario. Battery storage is based on four-hour storage.

Source: IEA WEO 2025

Capital Costs for selected Technologies IEA WEO 2025 by Scenarios

		Current Policies Scenario		Stated Policies Scenario		Net Zero Emissions by 2050 Scenario	
	2024	2035	2050	2035	2050	2035	2050
Levelised cost of iron-based steel production (USD/t)							
Conventional							
Lower range	470	460	460	450	450	560	690
Upper range	570	570	620	530	530	780	810
Innovative							
Lower range	N/A	790	750	710	690	700	700
Upper range	N/A	870	810	850	840	810	850
Vehicles (USD/vehicle)							
Hybrid cars	17 800	16 300	16 200	16 200	16 200	16 000	15 900
Battery electric cars	19 500	16 200	15 500	16 000	15 100	15 500	14 700
Batteries and hydrogen							
Hydrogen electrolysers							
Lower range (USD/kW)	600	440	390	420	390	330	310
Upper range (USD/kW)	2 600	1 680	1 460	1 650	1 450	1 310	1 180
Fuel cells							
Trucks (USD/kW)	370	230	190	210	190	150	80
Utility-scale stationary batteries (USD/kWh)	150	100	90	100	90	100	80

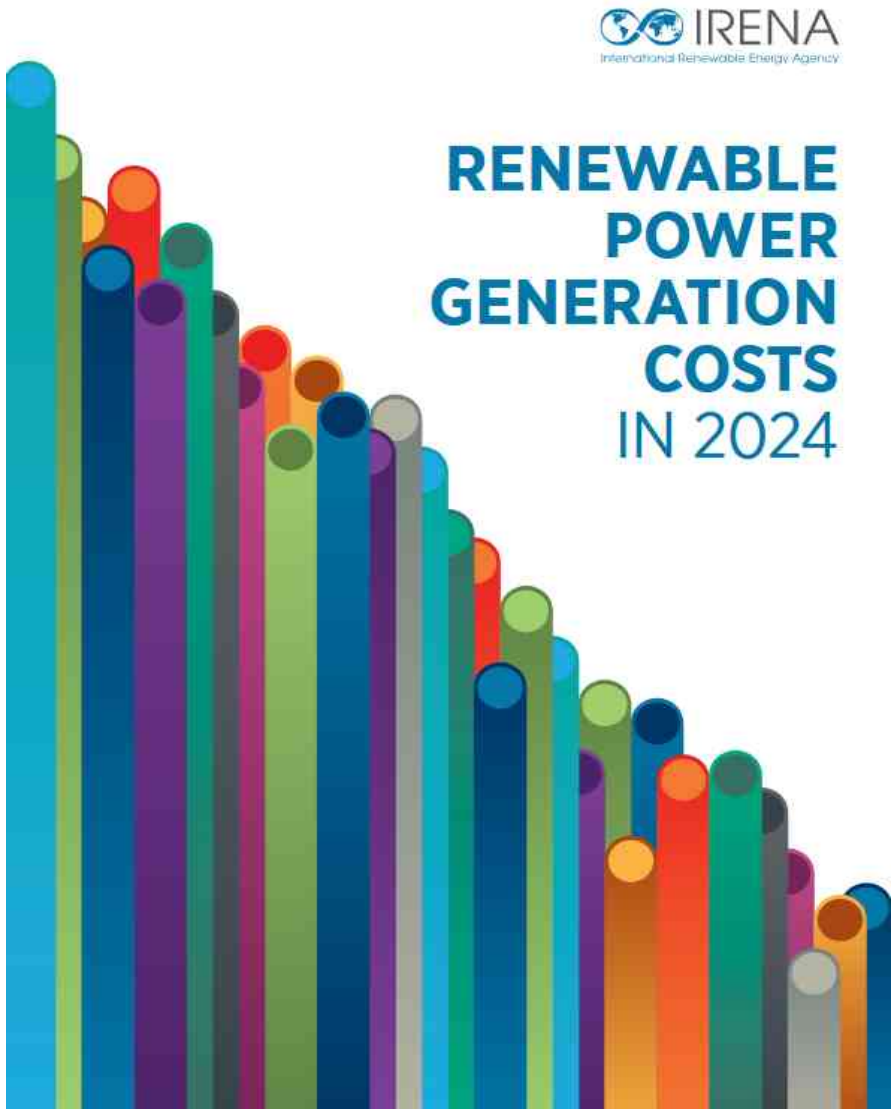
Notes: t = tonnes; kW = kilowatt; kWh = kilowatt-hour. All values are in USD (2024).

Sources: IEA analysis; BNEF (2025); Cole et al. (2021); Financial Times (2020); JATO (2021); S&P Global Mobility (2024); Tsiropoulos et al. (2018).

Source: IEA WEO 2025

LCOE IRENA Estimates for Renewables

LCOE Estimates by IRENA



Source: IRENA November 2025

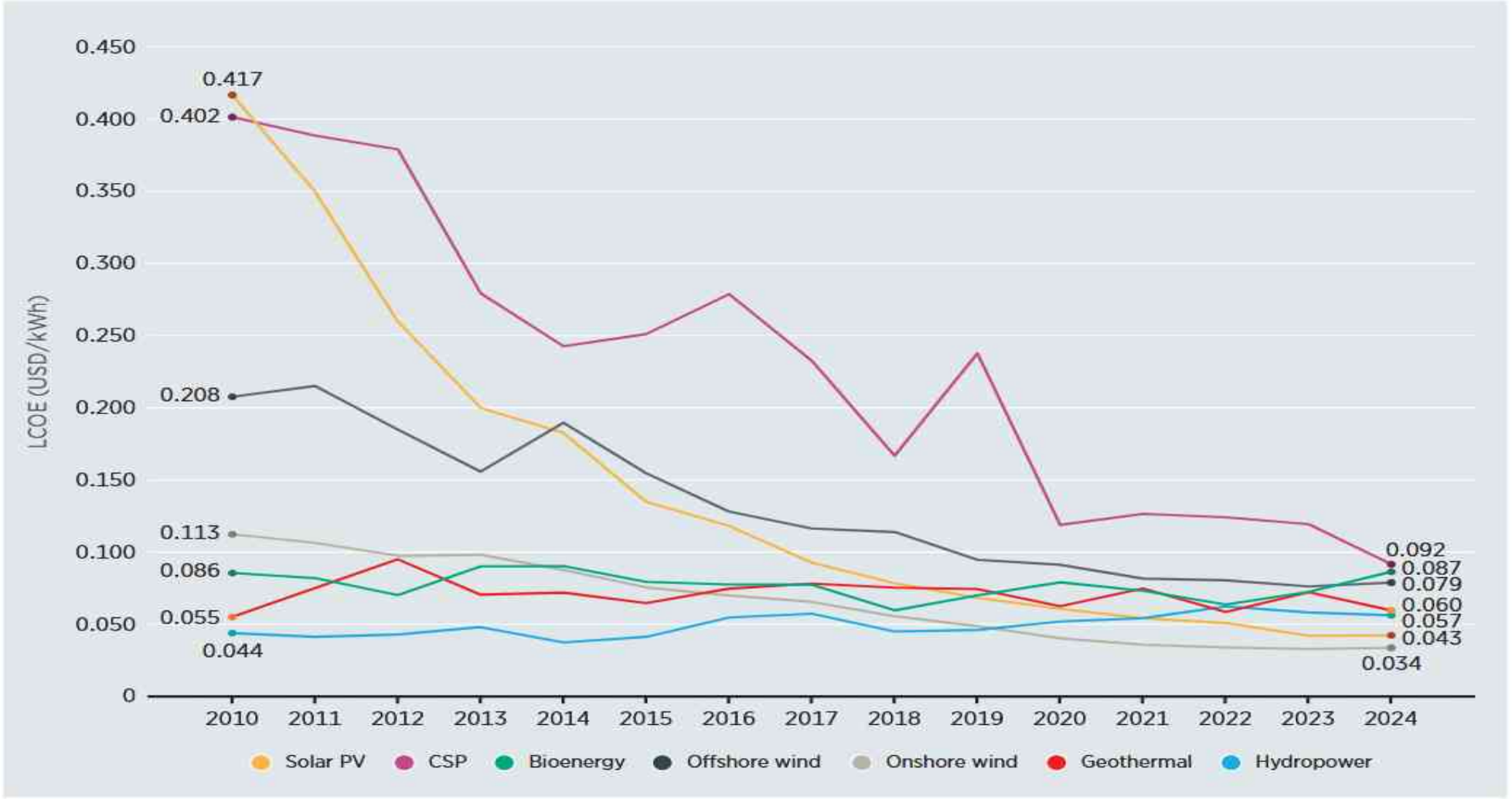
LCOE Estimates by IRENA

	Total installed costs (2024 USD/kW)			Capacity factor (%)			Levelised cost of electricity (2024 USD/kWh)		
	2010	2024	Percent change	2010	2024	Percent change	2010	2024	Percent change
Bioenergy	3 082	3 242	5%	72	73	1%	0.086	0.087	1%
Geothermal	3 083	4 015	30%	87	88	1%	0.055	0.060	9%
Hydropower	1 494	2 267	52%	44	48	9%	0.044	0.057	30%
Solar PV	5 283	691	-87%	15	17	13%	0.417	0.043	-90%
CSP	10 703	3 677	-66%	30	41	37%	0.402	0.092	-77%
Onshore wind	2 324	1 041	-55%	27	34	26%	0.113	0.034	-70%
Offshore wind	5 518	2 852	-48%	38	42	11%	0.208	0.079	-62%

Notes: CSP = concentrated solar power; kW = kilowatt; kWh = kilowatt hour; USD= United States dollars.

Source: IRENA November 2025

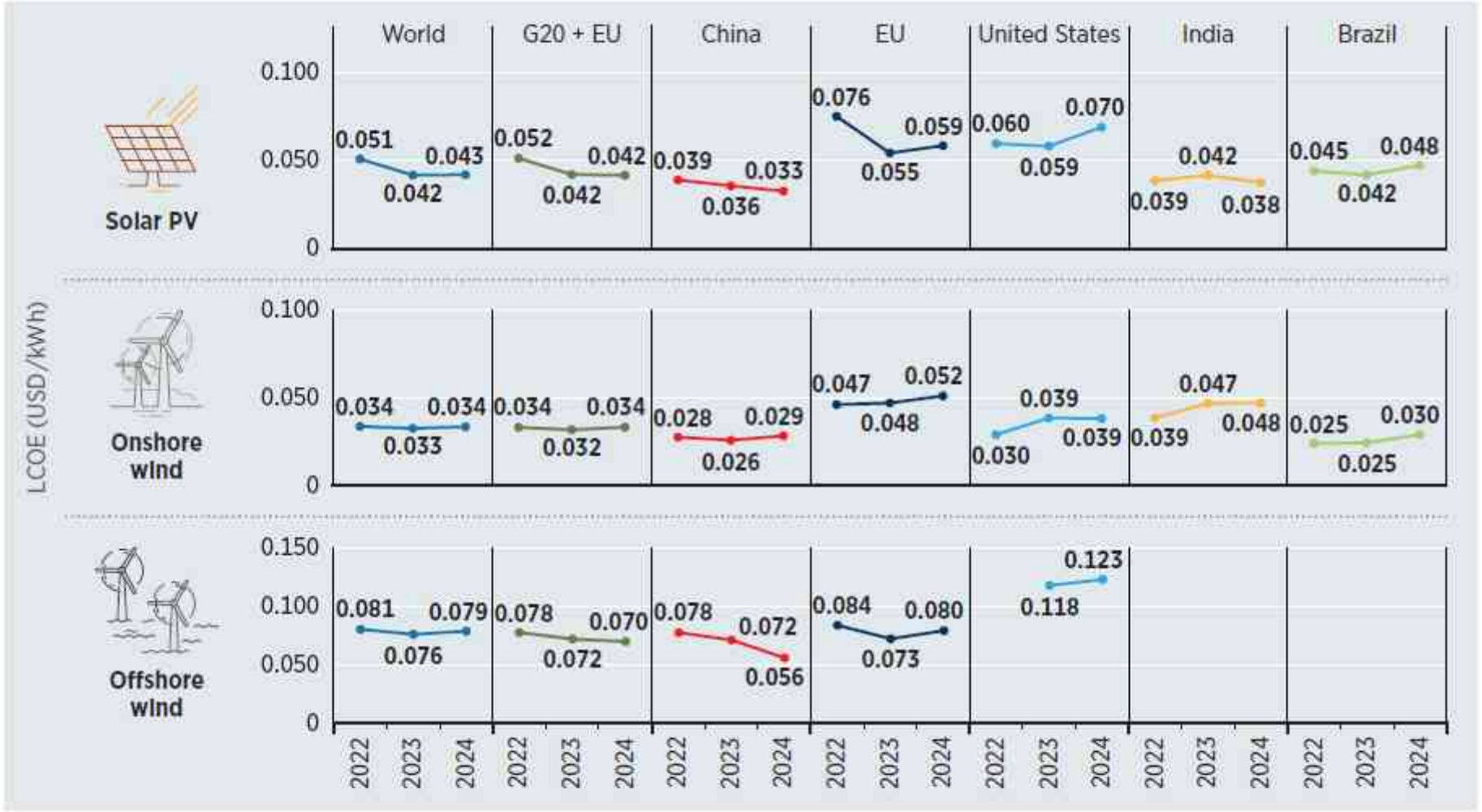
LCOE Estimates by IRENA



Notes: CSP = concentrated solar power; kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; USD = United States dollar.

Source: IRENA November 2025

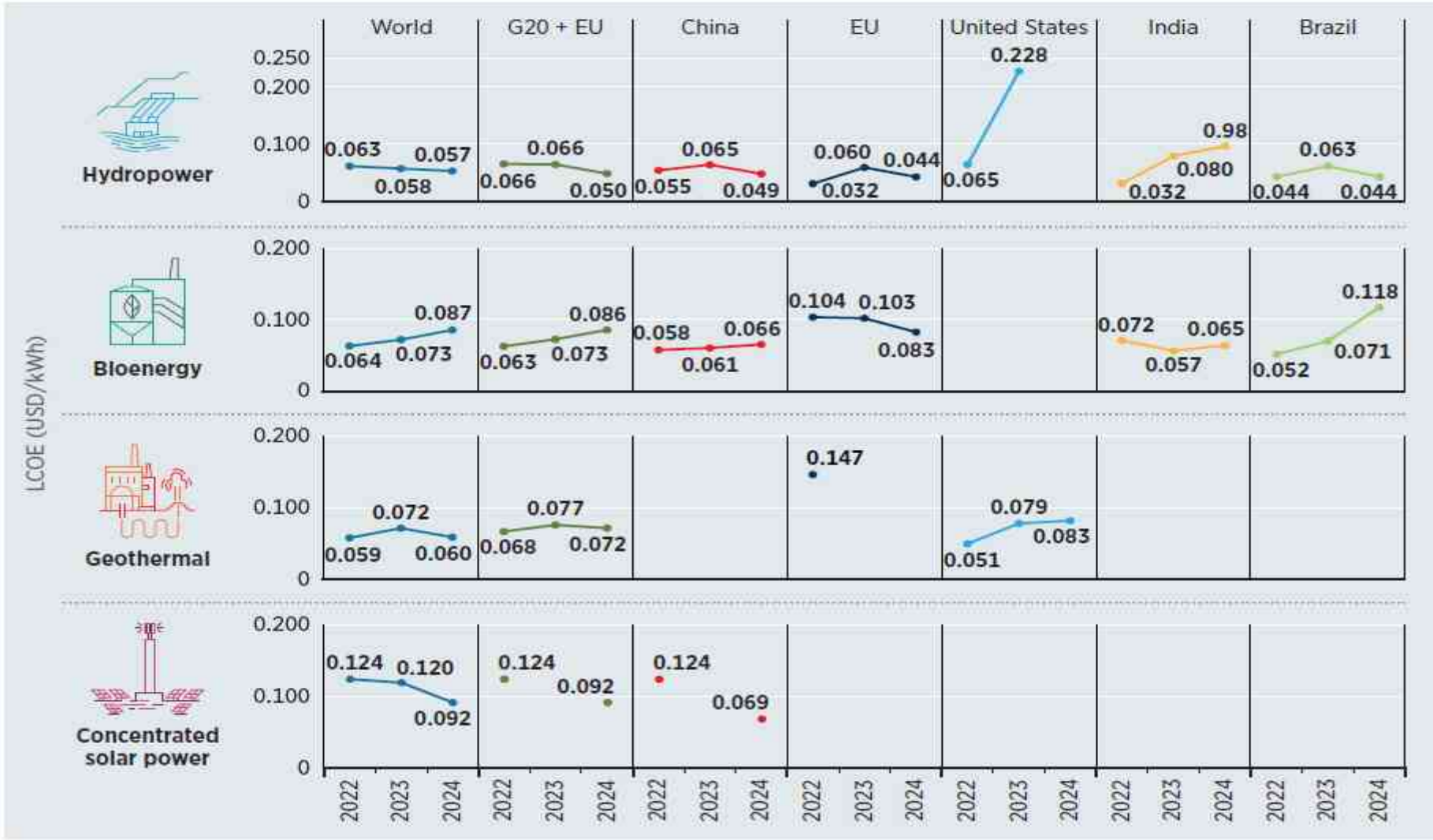
LCOE by Regions 2022 - 2024 by IRENA



Notes: EU = European Union; G20 = Group of 20; kWh = kilowatt hour; PV = photovoltaic; LCOE = levelised cost of electricity; USD = United States dollar.

Source: IRENA November 2025

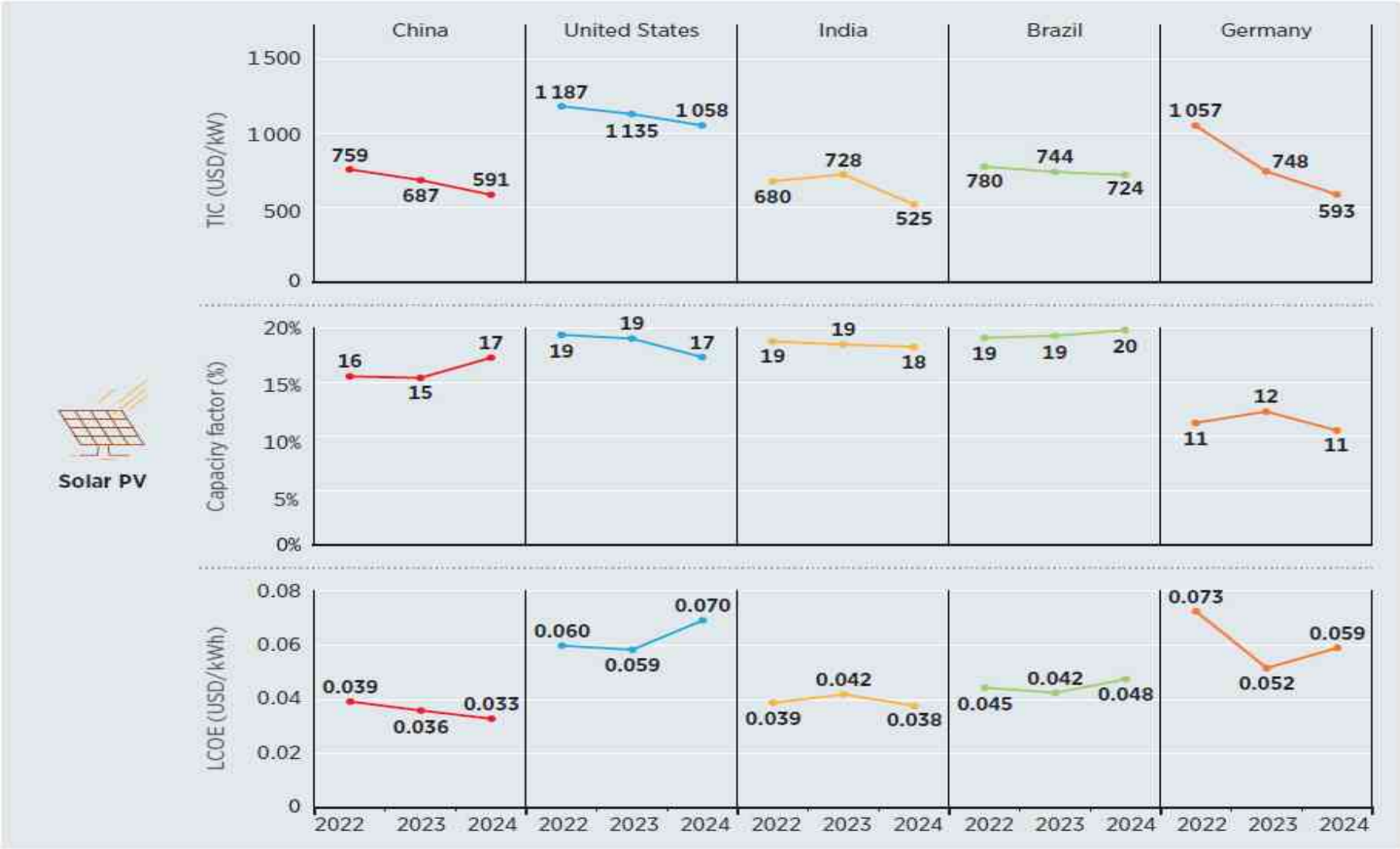
LCOE by Regions 2022 - 2024 by IRENA



Notes: EU = European Union; G20 = Group of 20; kWh = kilowatt hour; LCOE = levelised cost of electricity; USD = United States dollar.

Source: IRENA November 2025

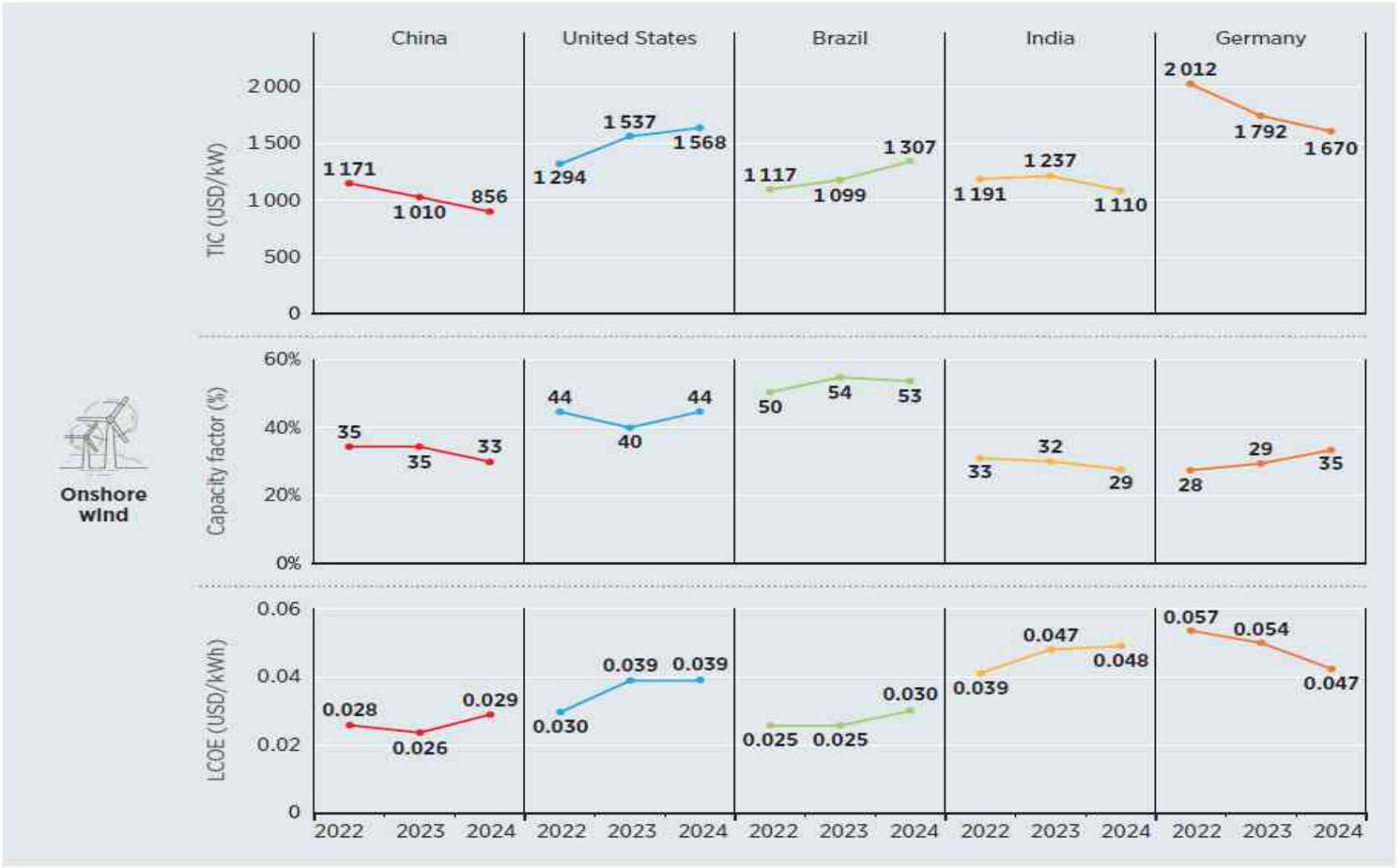
Installed costs, Capacity factor & LCOE for Solar PV



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; TIC = total installed cost; USD = United States dollar.

Source: IRENA November 2025

Installed costs, Capacity factor & LCOE for Onshore Wind



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; TIC = total installed costs; USD = United States dollar.

Source: IRENA November 2025

Installed costs, Capacity factor & LCOE for Hydropower



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; TIC = total installed costs; USD = United States dollar.

Source: IRENA November 2025

Installed costs, Capacity factor & LCOE for Geothermal



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; TIC = total installed costs; USD = United States dollar.

Source: IRENA November 2025

Installed costs, Capacity factor & LCOE for Bioenergy



Notes: kWh = kilowatt hour; LCOE = levelised cost of electricity; TIC = total installed costs; USD = United States dollar.

Source: IRENA November 2025

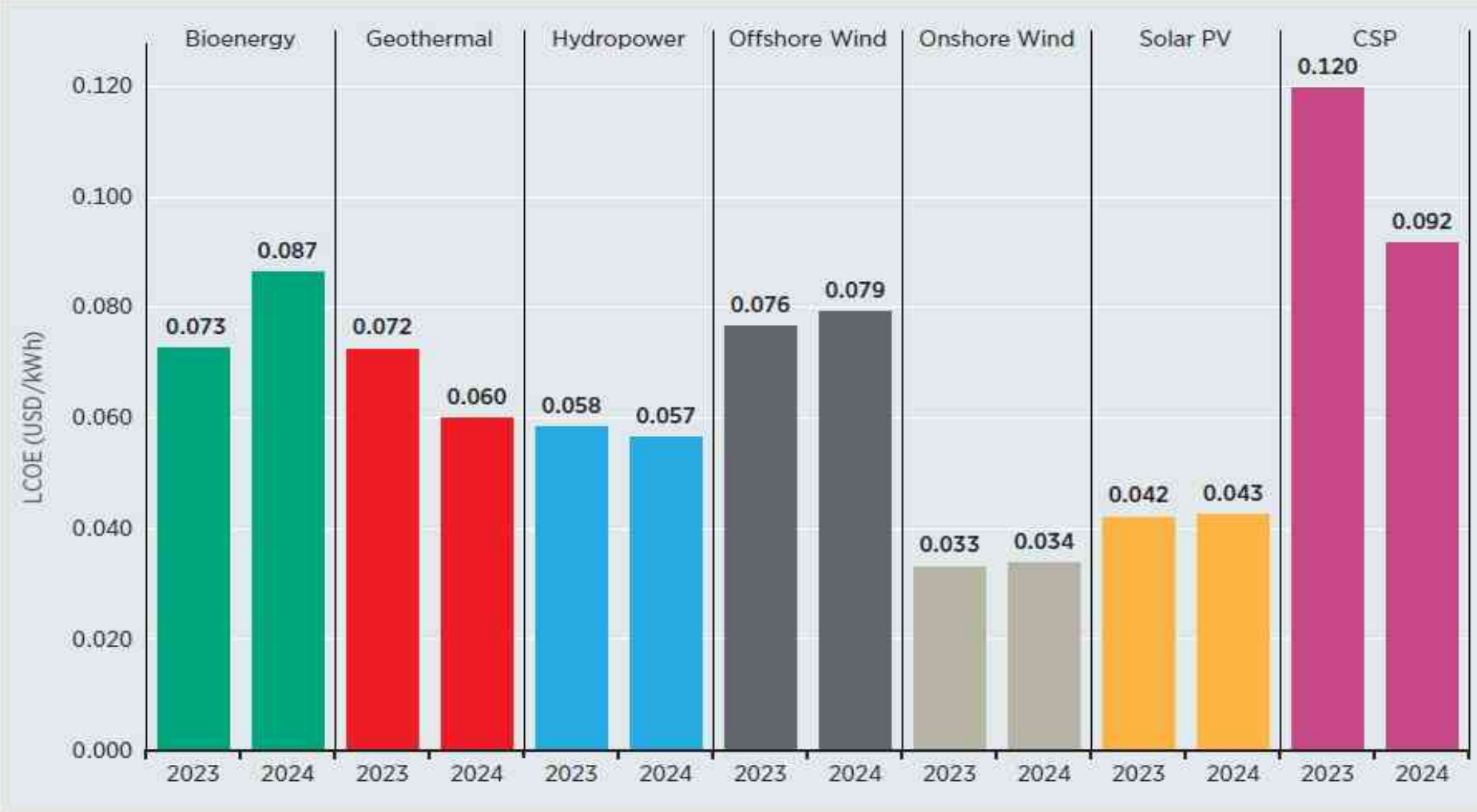
Total Installed Costs Solar PV & Wind Energy



Notes: TIC = total installed cost; USD = United States dollar; kW = kilowatt.

Source: IRENA November 2025

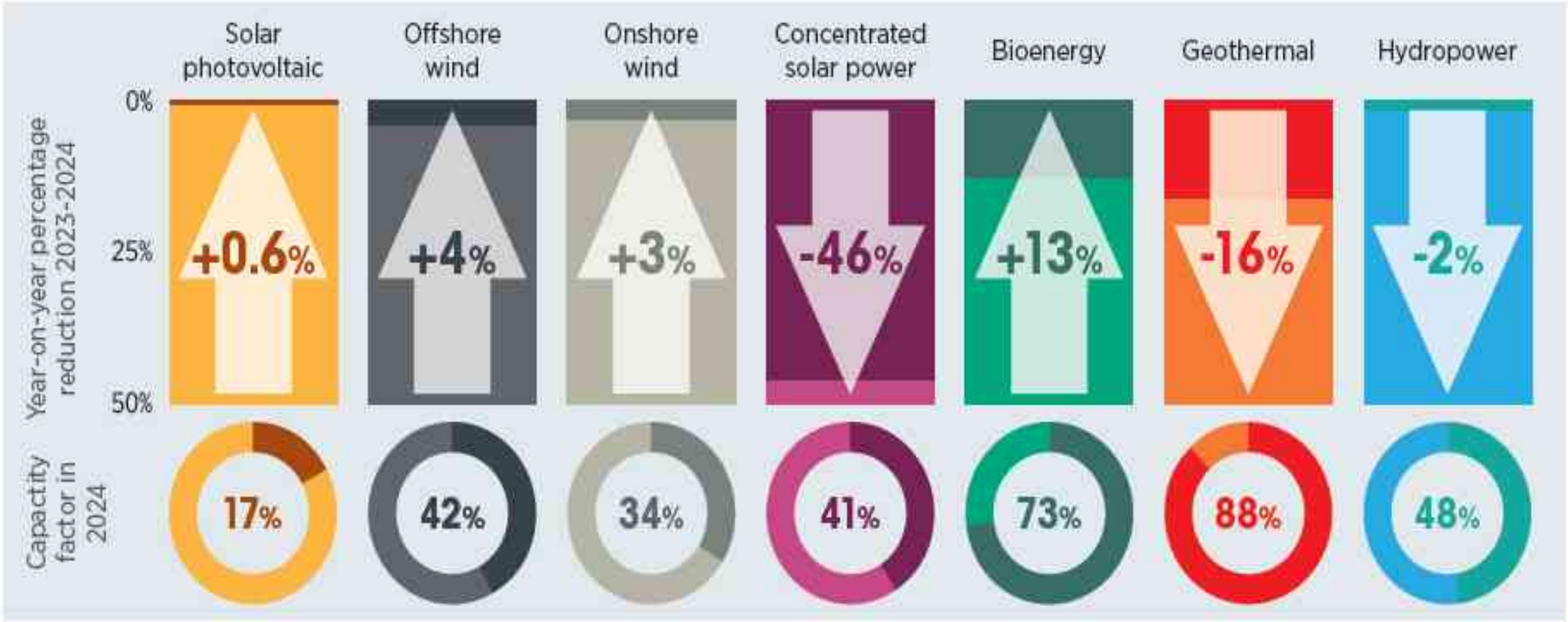
Global weighted average LCOE Estimates by IRENA



Notes: CSP = concentrating solar power; kWh = kilowatt hour; LCOE = levelised cost of electricity; PV = photovoltaic; USD = United States dollar.

Source: IRENA 2025

LCOE Estimates by IRENA

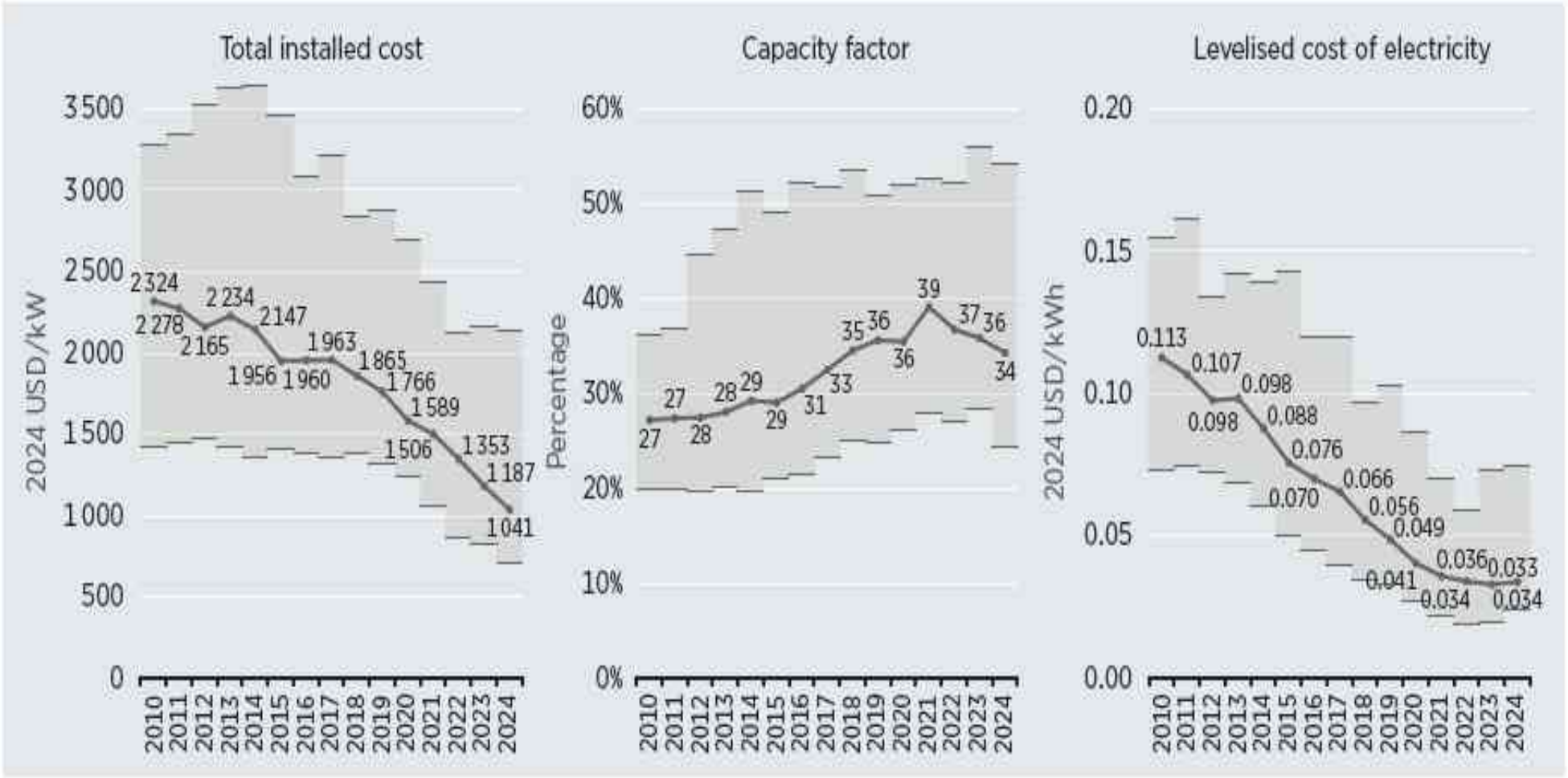


Note: The colour shading indicates the year-on-year percentage LCOE reduction (increase or decrease), starting from top (0%) to bottom (50%).

Source: IRENA November 2025

Onshore Wind Projects – IRENA 2025

LCOE Estimates by IRENA
Installed costs, Capacity factor, LCOE for Onshore Wind Projects



Notes: kW = kilowatt; kWh = kilowatt hours; USD = United States dollar.

Source: IRENA November 2025

LCOE for Onshore Wind Projects by Regions



	2010			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2024 USD/kWh)					
Africa	0.077	**0.077**	0.077	0.043	**0.051**	0.058
Central America and the Caribbean	0.101	**0.101**	0.101	0.081	**0.081**	0.081
Eurasia	0.142	**0.142**	0.142	0.050	**0.070**	0.101
Europe	0.094	**0.144**	0.216	0.034	**0.051**	0.075
Oceania	0.127	**0.144**	0.156	0.037	**0.041**	0.044
Other Asia	0.118	**0.162**	0.177	0.037	**0.072**	0.159
Other North America	0.088	**0.120**	0.145	0.032	**0.035**	0.037
Other South America*	0.071	**0.107**	0.344	0.038	**0.064**	0.100
Brazil	0.122	**0.122**	0.122	0.024	**0.030**	0.037
China	0.074	**0.092**	0.115	0.023	**0.029**	0.048
India	0.061	**0.100**	0.125	0.043	**0.048**	0.053
United States	0.071	**0.114**	0.157	0.026	**0.039**	0.052

Notes: * Regions where data was only available for projects commissioned in 2012, not 2010; see Annex III for regional country groupings.

Source: IRENA November 2025

Installed costs for Onshore Wind Projects by Regions



	2010			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2024 USD/kW)					
Africa	1 834	**1 834**	1 834	1 238	**1 333**	1 435
Central America and the Caribbean*	3 153	**3 153**	3 153	2 108	**2 108**	2 108
Eurasia	2 878	**2 878**	2 878	960	**1 425**	1 977
Europe	2 080	**2 859**	4 170	1 211	**1 659**	2 232
Oceania	3 608	**4 143**	4 555	1 143	**1 363**	1 704
Other Asia	2 181	**2 960**	3 249	1 277	**1 912**	3 764
Other North America	2 464	**3 245**	3 781	1 012	**1 238**	1 544
Other South America*	1 698	**2 521**	3 945	1 088	**1 492**	1 960
Brazil	3 106	**3 106**	3 106	1 015	**1 307**	1 628
China	1 489	**1 765**	2 066	626	**856**	1 315
India	1 053	**1 607**	1 900	984	**1 110**	1 270
Unitad States	2 201	**2 850**	3 863	950	**1 568**	1 902

Notes: * Regions where data was only available for projects commissioned in 2012, not 2010; See Annex III for regional country groupings.

Source: IRENA November 2025

Capacity factors for Onshore Wind Projects by Regions

	2010	2023	2024
	%		
China	25	35	33
United States	33	40	44
Brazil	36	54	56
India	25	32	39
Germany	24	29	35
Australia	34	36	35
France	26	33	30
Finland*	36	31	34
Canada	32	39	39
Türkiye	26	33	34
Sweden	29	37	34
Spain	37	33	34
United Kingdom	30	42	41
Poland	22	34	35
Italy	25	30	29

* Countries where data was only available for projects commissioned in 2013, not 2010.

Source: IRENA November 2025

Capacity factors for Onshore Wind Projects by Regions

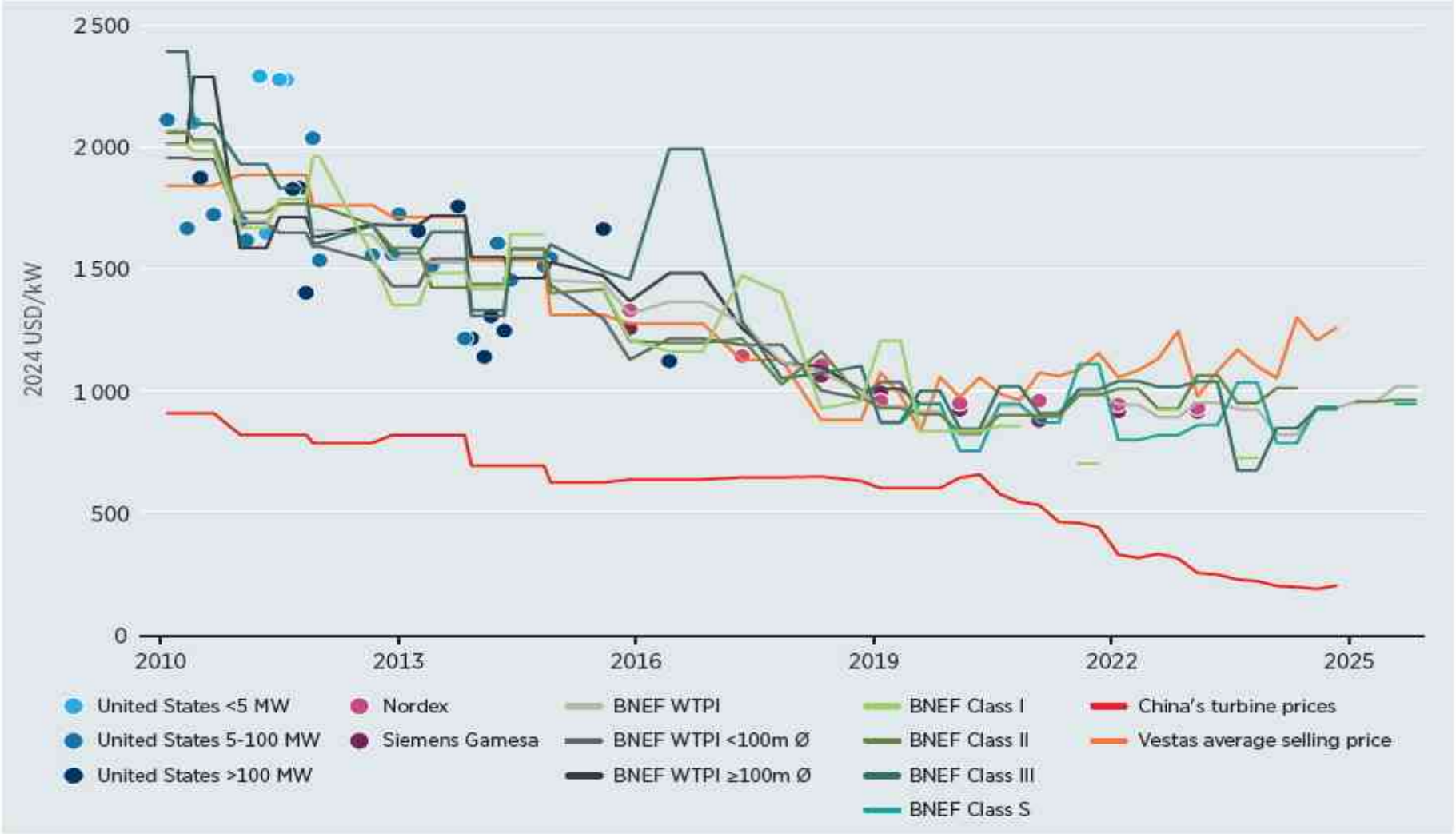


	2010			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	Capacity factor (%)					
Africa	38	**38**	38	41	**44**	47
Central America and the Caribbean	45	**45**	45	35	**35**	35
Eurasia	26	**26**	26	28	**34**	37
Europe	18	**26**	33	25	**34**	43
Oceania	34	**34**	34	32	**35**	43
Other Asia	22	**26**	32	24	**39**	47
Other North America	29	**34**	49	35	**39**	42
Other South America*	19	**32**	46	36	**45**	51

Notes: * Regions where data was only available for projects commissioned in 2012, not 2010; see Annex III for regional country groupings.

Source: IRENA November 2025

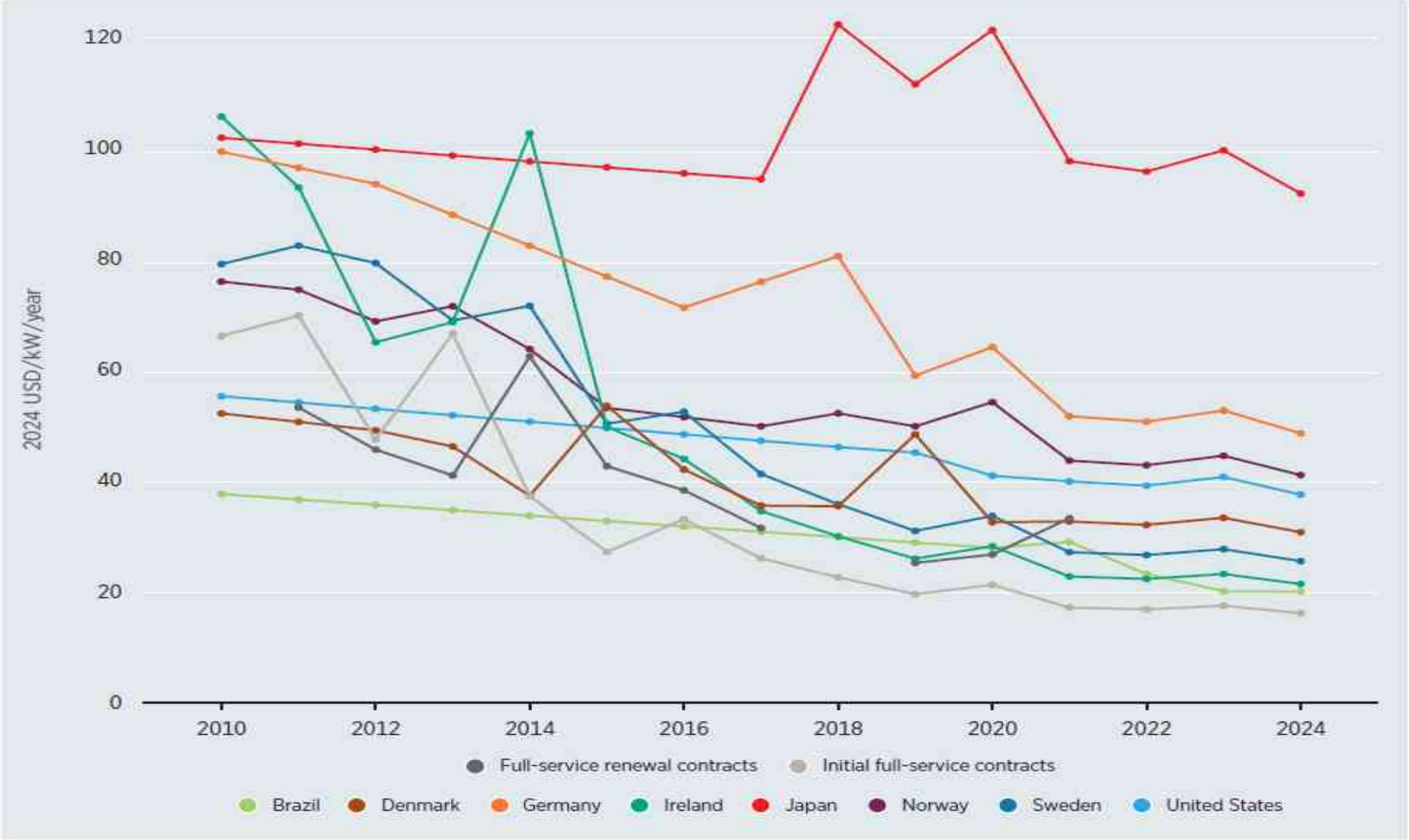
Wind turbine prices



Source: (BNEF, 2024a; Vestas, 2024; Wiser *et al.*, 2025).
Notes: kW = kilowatt; USD = United States dollar.

Source: IRENA November 2025

O&M Costs for Onshore Wind Projects by Regions

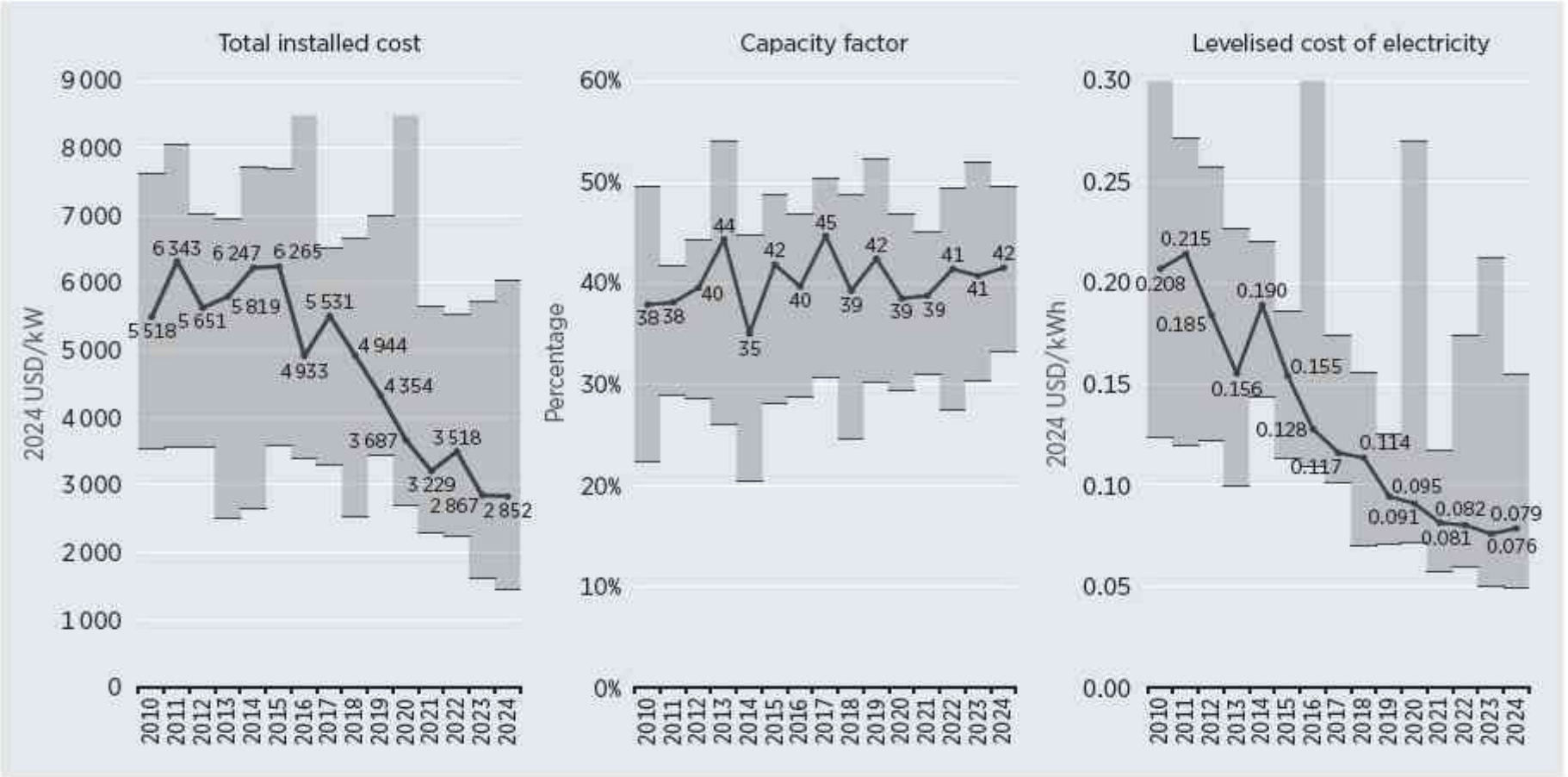


Source: (BNEF, 2025; IEA Wind, 2023; Wood Mackenzie, 2025d).
Notes: kW = kilowatt; USD = United States dollar.

Source: IRENA November 2025

Offshore Wind Projects – IRENA 2025

LCOE Estimates by IRENA
Installed costs, Capacity factor, LCOE for Offshore Wind Projects



Notes: kW = kilowatt; kWh = kilowatt hour; USD = United States dollar.

[56] *Given the limited number of operational floating projects to date, this chapter has focused on fixed-bottom offshore wind developments.*

Source: IRENA November 2025

Technical features for Offshore Wind Projects in China & Europe

The average offshore wind farm in China and Europe		2010	2024
Project size (MW)	China	67	339
	Europe	155	415
Distance from shore (km)	China	12	24
	Europe	18	20
Water depth (m)	China	9	29
	Europe	21	38
Hub height (m)	China	80	138
	Europe	83	114
Rotor diameter (m)	China	90	235
	Europe	112	177
Nameplate capacity (MW)	China	2.8	10.1
	Europe	3.1	9.2

Based on: (Wood Mackenzie, 2025j; and inputs from WindEurope and GWEC).

Source: IRENA November 2025

LCOE for Offshore Wind Projects by Regions

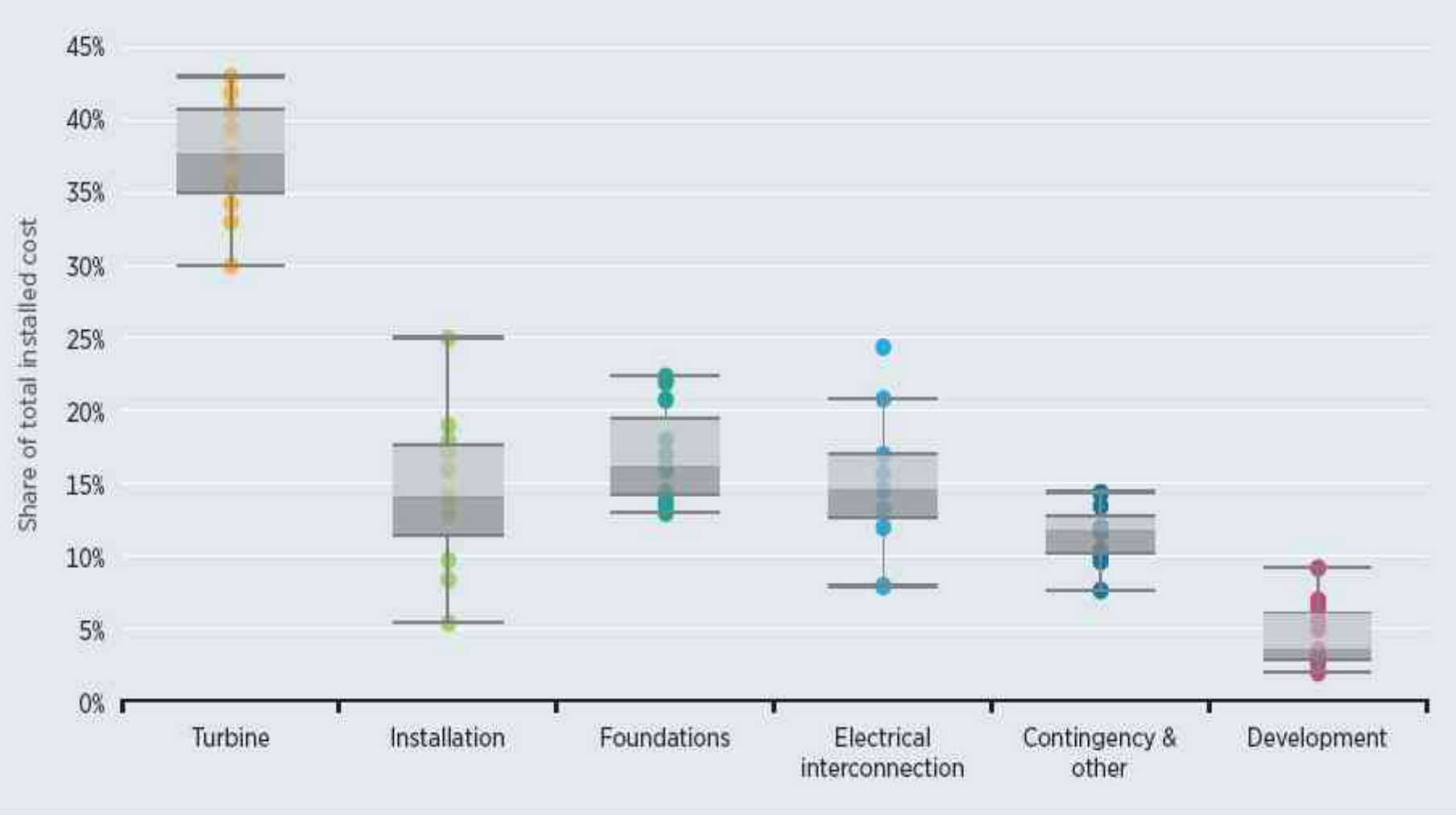


	2010			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2024 USD/kWh)					
Asia	0.135	**0.201**	0.222	0.047	**0.078**	0.164
China	0.133	**0.200**	0.220	0.046	**0.056**	0.063
Japan	0.212	**0.212**	0.212	0.181	**0.181**	0.181
Europe	0.142	**0.208**	0.246	0.056	**0.080**	0.125
Denmark	0.119	**0.119**	0.119	0.053	**0.053**	0.053
France	n.a.	**n.a.**	n.a.	0.123	**0.123**	0.126
Germany	0.195	**0.198**	0.205	0.070	**0.069**	0.094
The Netherlands*	0.115	**0.115**	0.115	0.066	**0.066**	0.066
United Kingdom**	0.218	**0.228**	0.237	0.057	**0.059**	0.063

Notes: * Countries where data were only available for projects commissioned in 2015, not 2010; ** countries where data were only available for projects commissioned in 2023, not 2024; see Annex III for regional country groupings; n.a. = not available.

Source: IRENA November 2025

Costs breakdown for Offshore Wind Projects



Sources: (Alsubal *et al.*, 2021; IRENA, 2016; Lacal-Arántegui *et al.*, 2018; MAKE Consulting, 2016; Musial, 2018; Noonan *et al.*, 2018; ORE Catapult, 2019; Smart *et al.*, 2016; Stehly *et al.*, 2020).

Source: IRENA November 2025

Installed costs for Offshore Wind Projects by Regions



	2010			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2024 USD/kW)					
Asia	3 386	**5 316**	5 952	1 449	**2 467**	6 052
China	3 307	**5 268**	5 852	1 434	**1 520**	1 869
Japan	5 808	**5 808**	5 808	5 684	**5 684**	5 684
Europe	4 183	**5 547**	7 655	2 713	**3 389**	5 250
Denmark	3 888	**3 888**	3 888	2 987	**2 987**	2 987
France	n.a.	**n.a.**	n.a.	4 911	**4 991**	5 347
Germany	7 655	**7 655**	7 655	3 061	**3 000**	4 611
The Netherlands*	4 883	**4 883**	4 883	2 626	**2 626**	2 626
United Kingdom**	4 799	**5 399**	5 761	3 362	**3 514**	3 743

Notes: * Countries where data were only available for projects commissioned in 2015, not 2010; ** countries where data were only available for projects commissioned in 2023, not 2024; see Annex III for regional country groupings; n.a. = not available.

Source: IRENA November 2025

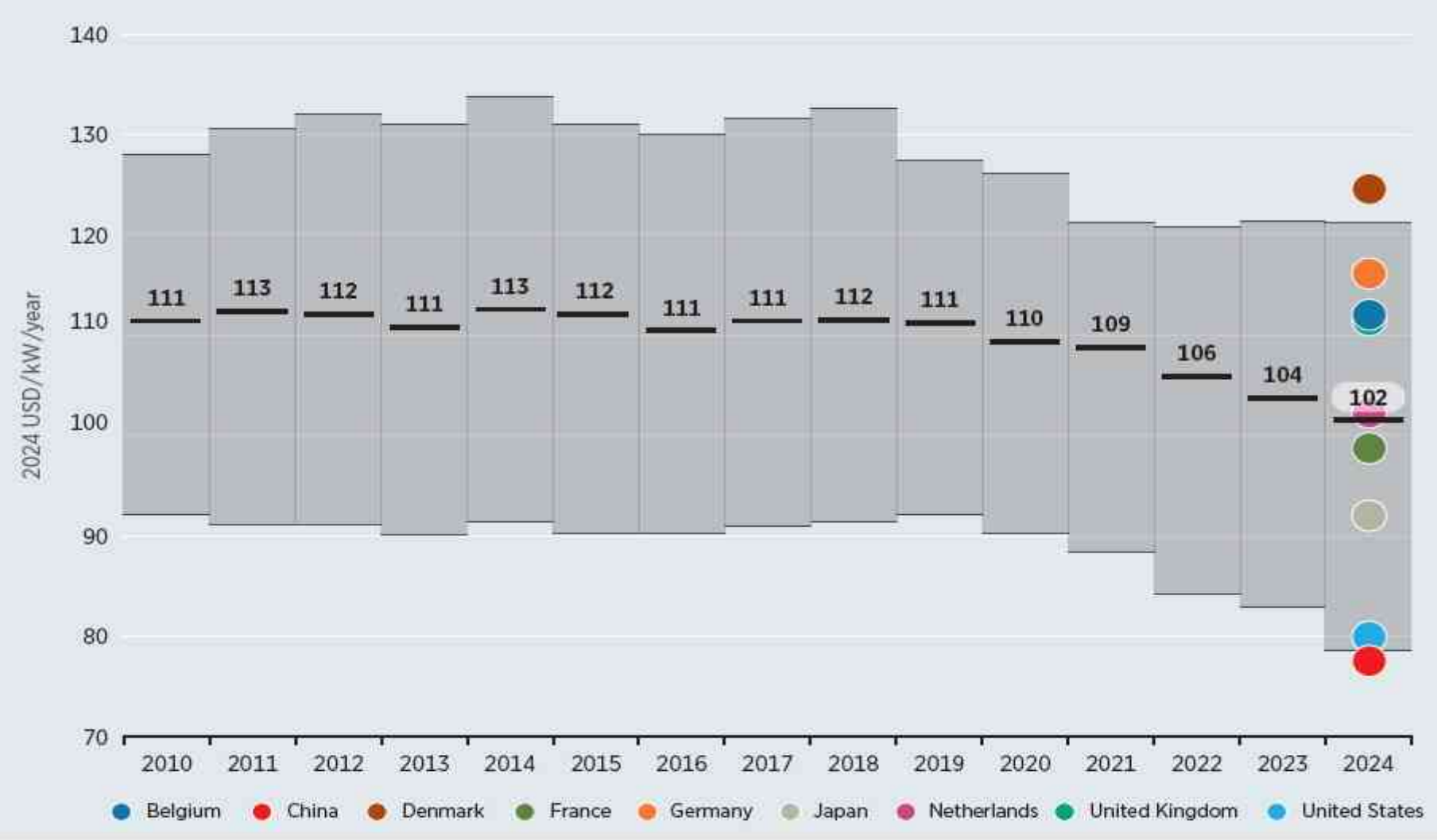
Capacity factors for Offshore Wind Projects by Regions

	2010	2024	Percentage change 2010-2024
	%		
China	30	37	↑ 23%
Denmark	44	52	↑ 18%
France	n.a	44	n.a.
Germany	50	46	↓ 8%
Japan	28	37	↑ 32%
The Netherlands*	48	49	↑ 2%
United Kingdom**	36	52	↑ 44%

Notes: * Countries where data were only available for projects commissioned in 2015, not 2010; ** countries where data were only available for projects commissioned in 2023, not 2024; see Annex III for regional country groupings; n.a. = not available.

Source: IRENA November 2025

Average fixed O&M Costs for Offshore Wind Projects by Regions



Source: (Wood Mackenzie, 2024c).

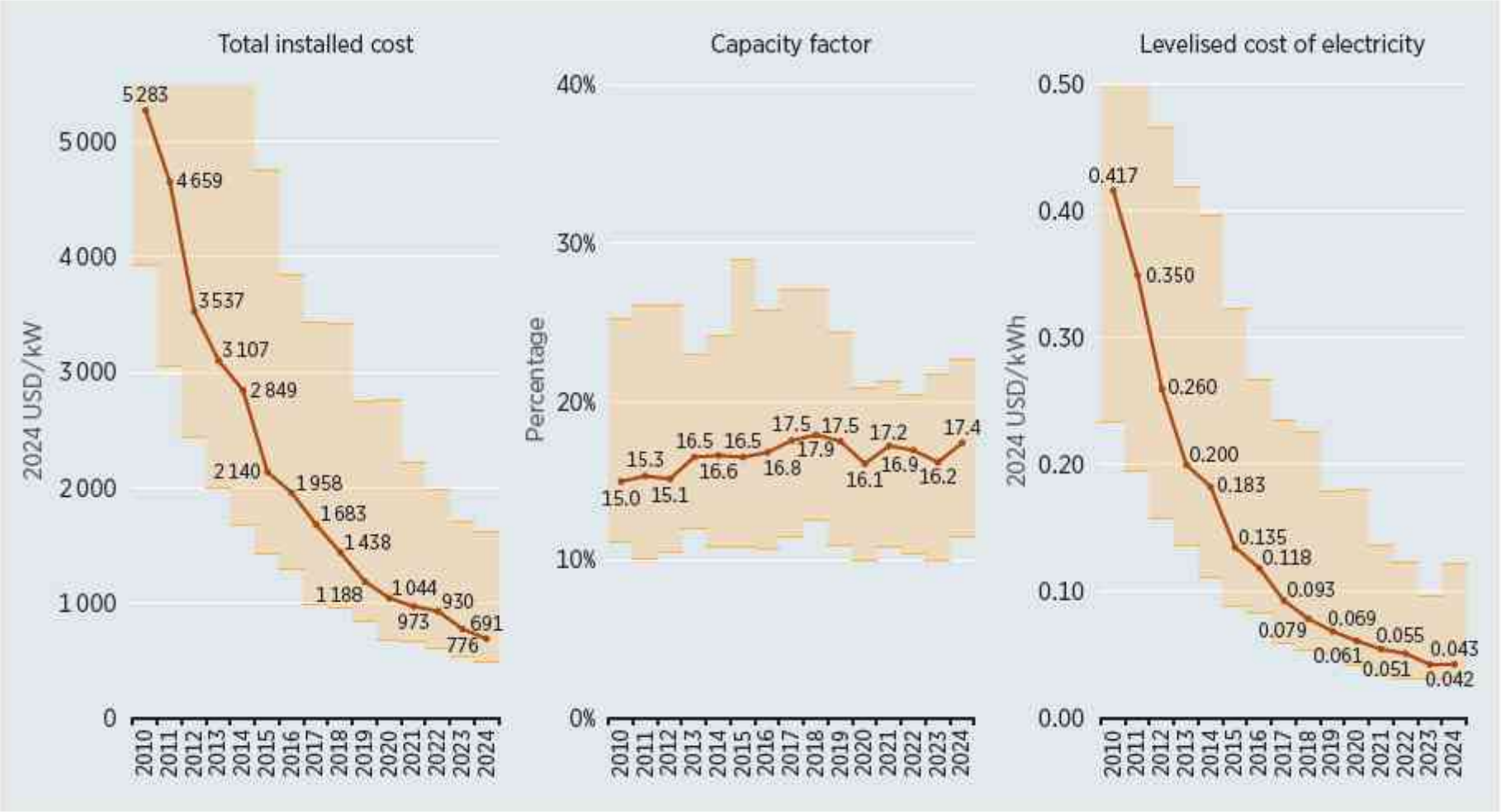
Notes: kW = kilowatt

Source: IRENA November 2025

Solar PV Projects – IRENA 2025

LCOE Estimates by IRENA

Weighted average of Installed costs, Capacity Factor & LCOE for Solar PV Projects



Notes: kW = kilowatt; kWh = kilowatt hour; USD = United States dollar.

Source: IRENA November 2025

LCOE for Solar PV Utility scale Projects by Regions

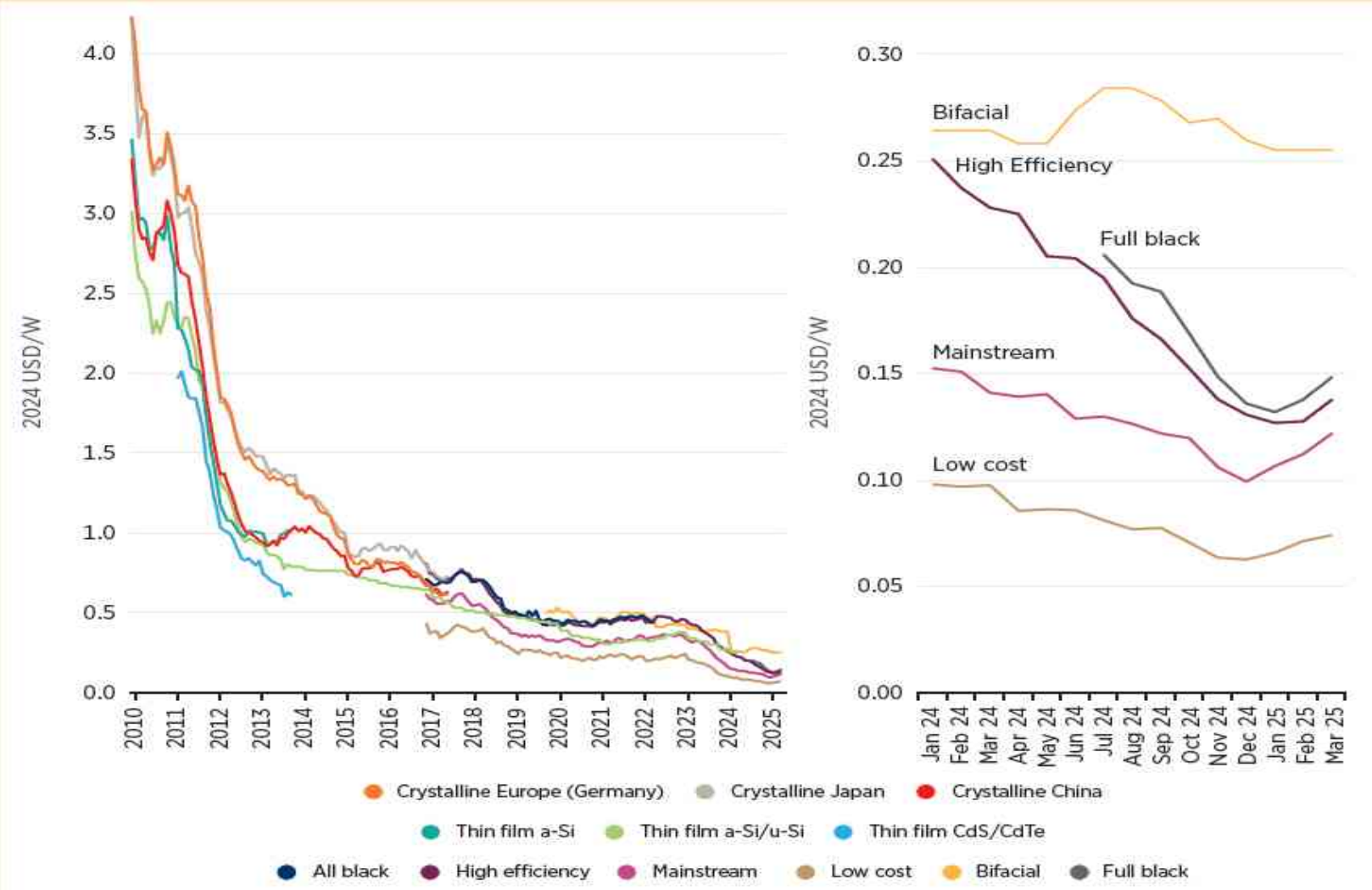


	2015			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2024 USD/kWh)					
Africa	0.100	**0.225**	0.356	0.049	**0.074**	0.186
Central America and the Caribbean	0.117	**0.154**	0.258	0.070	**0.091**	0.152
Eurasia	0.247	**0.338**	0.439	0.068	**0.087**	0.256
Europe	0.081	**0.150**	0.182	0.041	**0.060**	0.103
Oceania	0.106	**0.119**	0.122	0.033	**0.049**	0.065
Other Asia	0.101	**0.181**	0.378	0.035	**0.070**	0.146
Other North America	0.091	**0.163**	0.425	0.062	**0.094**	0.147
Other South America	0.091	**0.122**	0.192	0.040	**0.063**	0.126
Brazil	0.144	**0.180**	0.193	0.036	**0.048**	0.077
China	0.104	**0.097**	0.186	0.028	**0.033**	0.052
India	0.073	**0.091**	0.178	0.032	**0.038**	0.059
United States	0.093	**0.160**	0.302	0.049	**0.070**	0.141

Note: See Annex III for regional country groupings.

Source: IRENA November 2025

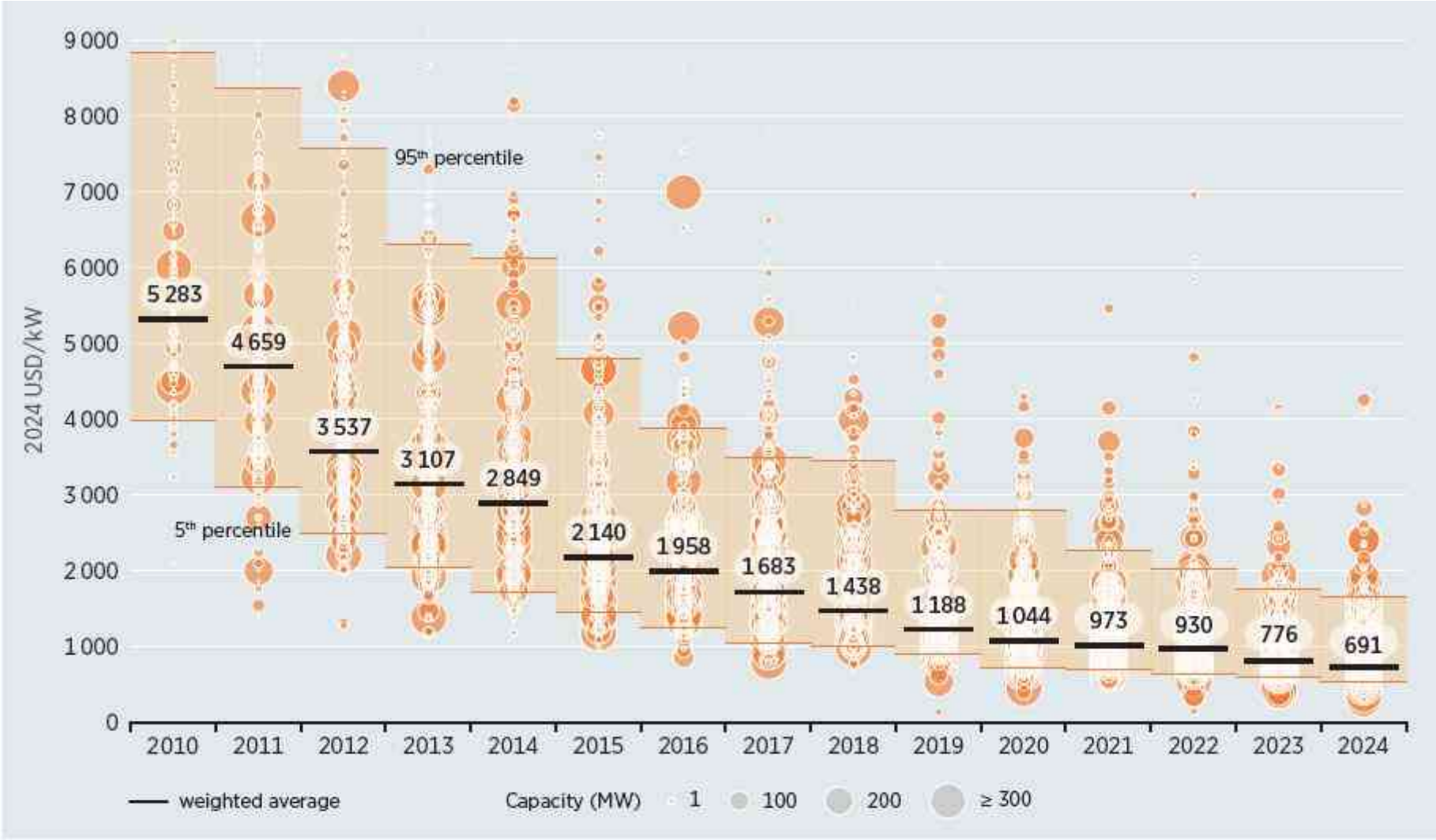
Solar PV Modules Prices by technology & manufacturing countries



Source: (pvXchange, 2025; Wood Mackenzie, 2025e).
Notes: W = watt; USD = United States dollar.

Source: IRENA November 2025

Installed costs for Solar PV Utility scale Projects & weighted average



Notes: kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Installed costs for Solar PV Utility scale Projects by Regions



	2015			2024		
	5th percentile	Weighted average	95th percentile	5th percentile	Weighted average	95th percentile
	(2024 USD/kW)					
Africa	1 591	**3 437**	5 091	861	**1 093**	1 630
Central America and the Caribbean	2 042	**2 612**	3 956	939	**1 375**	2 288
Eurasia	2 481	**3 438**	4 509	671	**1 030**	2 861
Europe	1 339	**1 759**	3 552	524	**779**	1 312
Oceania	2 160	**2 663**	2 787	598	**944**	1 385
Other Asia	1 819	**2 652**	4 929	502	**1 133**	2 585
Other North America	1 986	**2 642**	6 007	807	**1 206**	1 689
Other South America	2 234	**3 202**	5 440	596	**1 048**	1 634
Brazil	2 088	**2 498**	2 633	503	**724**	1 152
China	1 523	**1 623**	2 767	438	**591**	867
India	1 090	**1 548**	2 515	415	**525**	831
United States	1 932	**3 062**	4 835	771	**1 058**	2 308

Notes: Costs are total installed costs (TIC); see Annex III for regional country groupings.

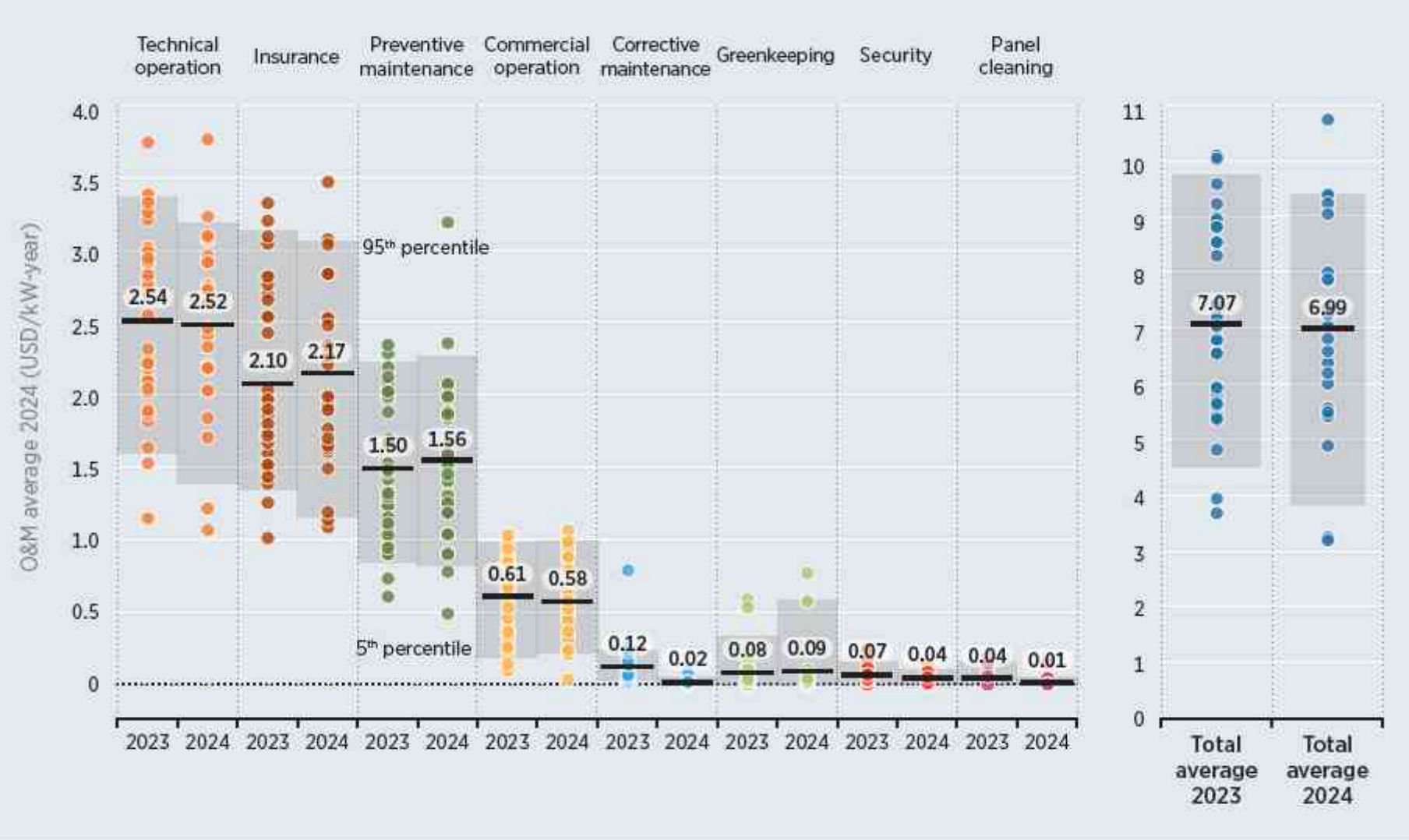
Source: IRENA November 2025

Capacity factors for Solar PV Utility scale Projects by Regions

Year	5th percentile	Weighted average	95th percentile
2010	11.1%	15.0%	25.2%
2011	10.1%	15.3%	26.0%
2012	10.5%	15.1%	25.9%
2013	11.9%	16.5%	23.0%
2014	10.8%	16.6%	24.4%
2015	10.8%	16.5%	29.0%
2016	10.7%	16.8%	25.7%
2017	11.4%	17.5%	27.0%
2018	12.5%	17.9%	27.0%
2019	10.9%	17.5%	24.3%
2020	9.9%	16.1%	20.8%
2021	10.8%	17.2%	21.3%
2022	10.4%	16.9%	20.4%
2023	10.0%	16.2%	21.7%
2024	11.5%	17.4%	22.6%

Source: IRENA November 2025

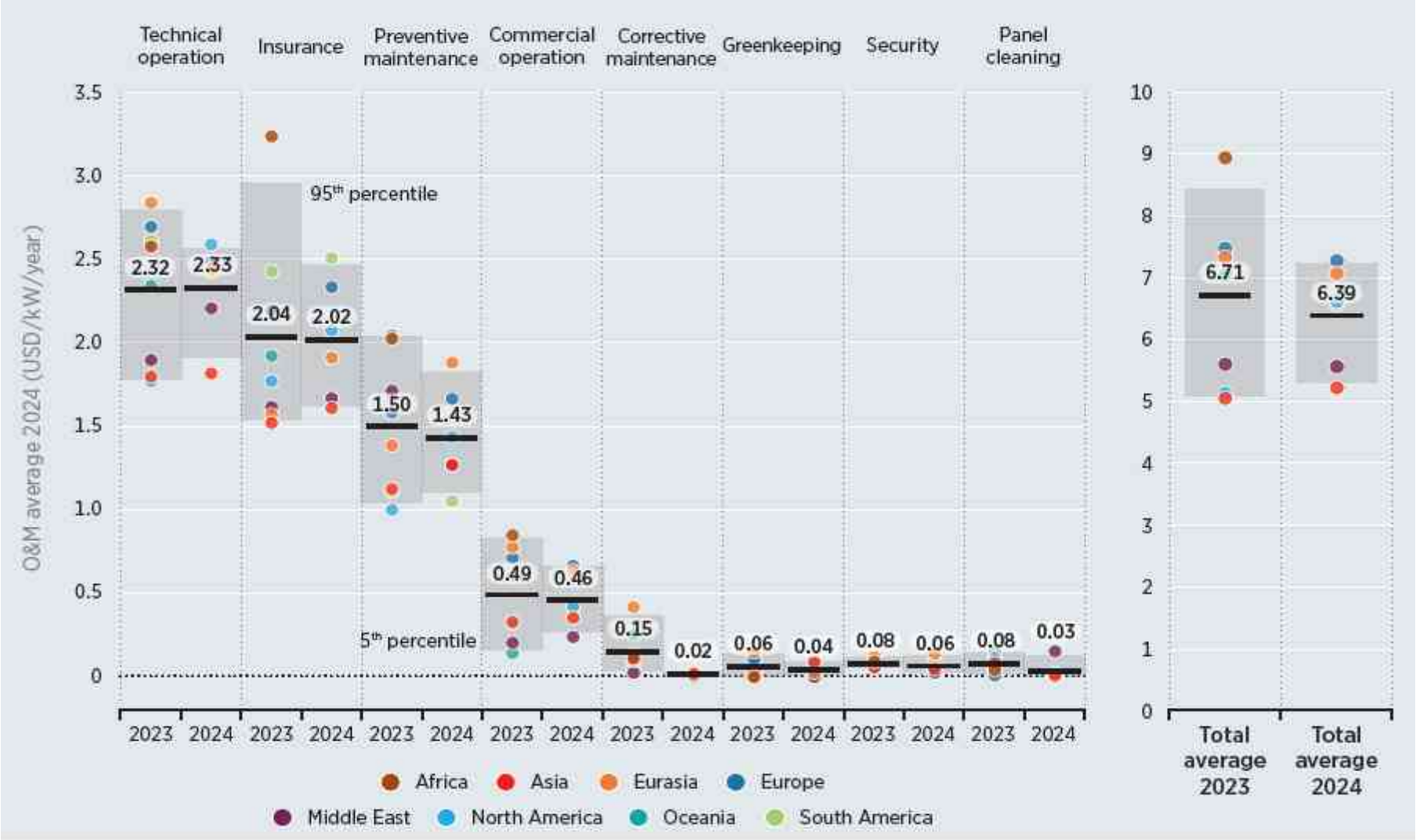
O&M Costs for Solar PV Utility scale Projects by Cost categories



Notes: kW = kilowatt; O&M = operation and maintenance; USD = United States dollar.

Source: IRENA November 2025

O&M Costs for Solar PV Utility scale Projects by Cost categories & Regions



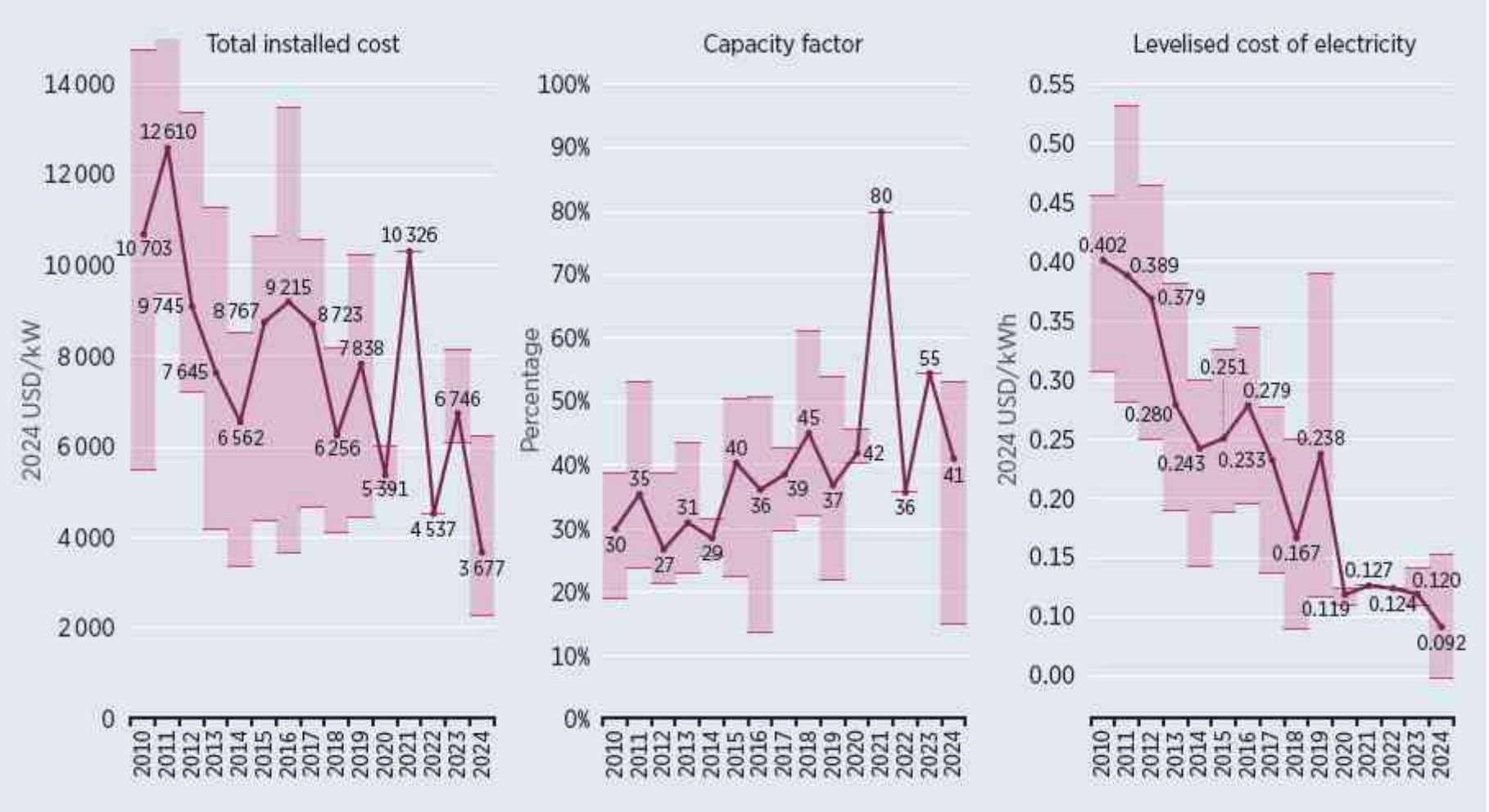
Notes: See Annex III for regional country groupings; kW = kilowatt; O&M = operation and maintenance; USD = United States dollar.

Source: IRENA November 2025

Solar CSP Projects – IRENA 2025

LCOE Estimates by IRENA

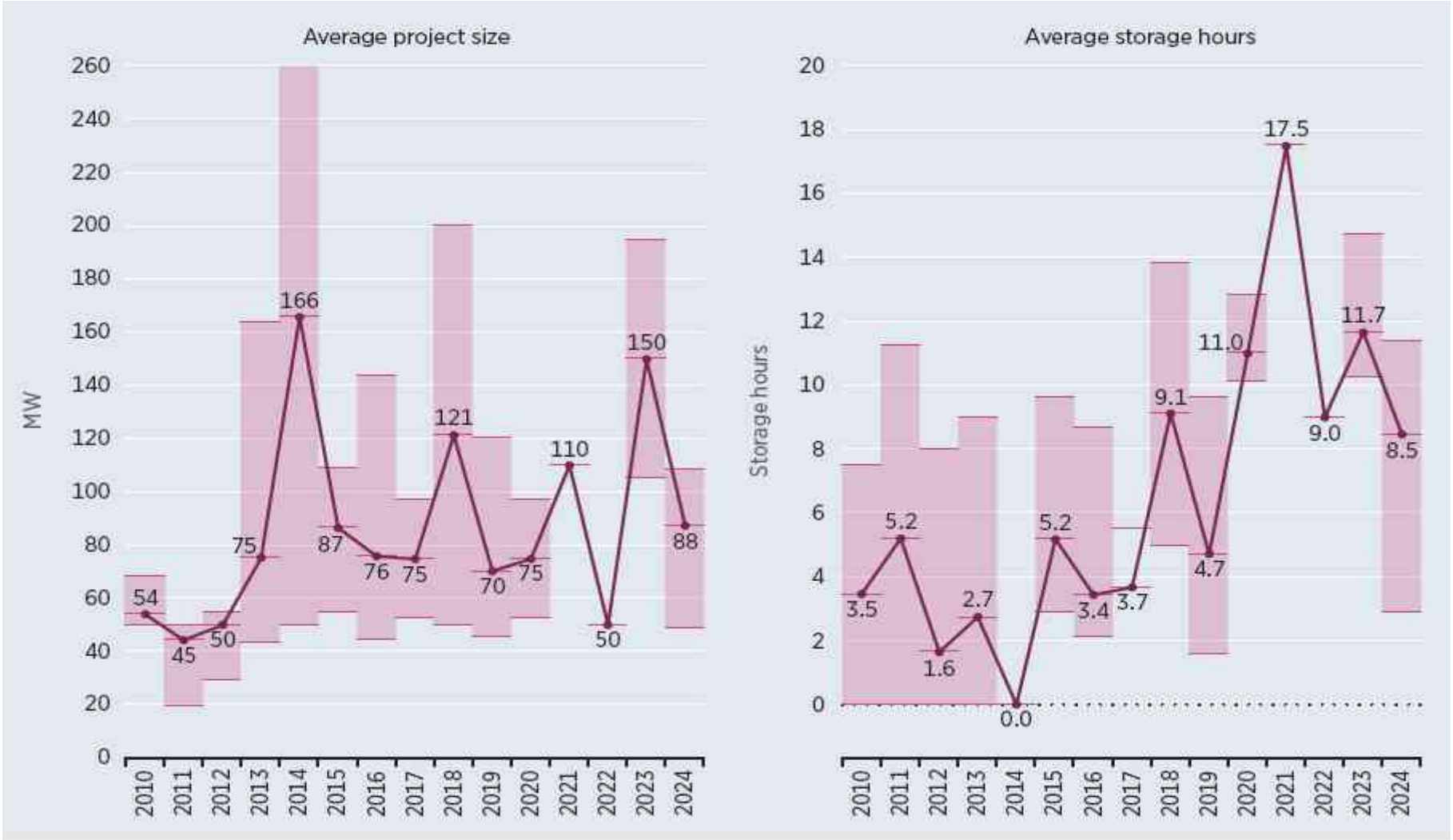
Weighted average of Installed costs, Capacity Factor & LCOE for Solar CSP Projects



Notes: kW = kilowatt; kWh = kilowatt hour; USD = United States dollar.

Source: IRENA November 2025

Solar CSP Projects – Technical features



Note: MW = megawatt.

Source: IRENA November 2025

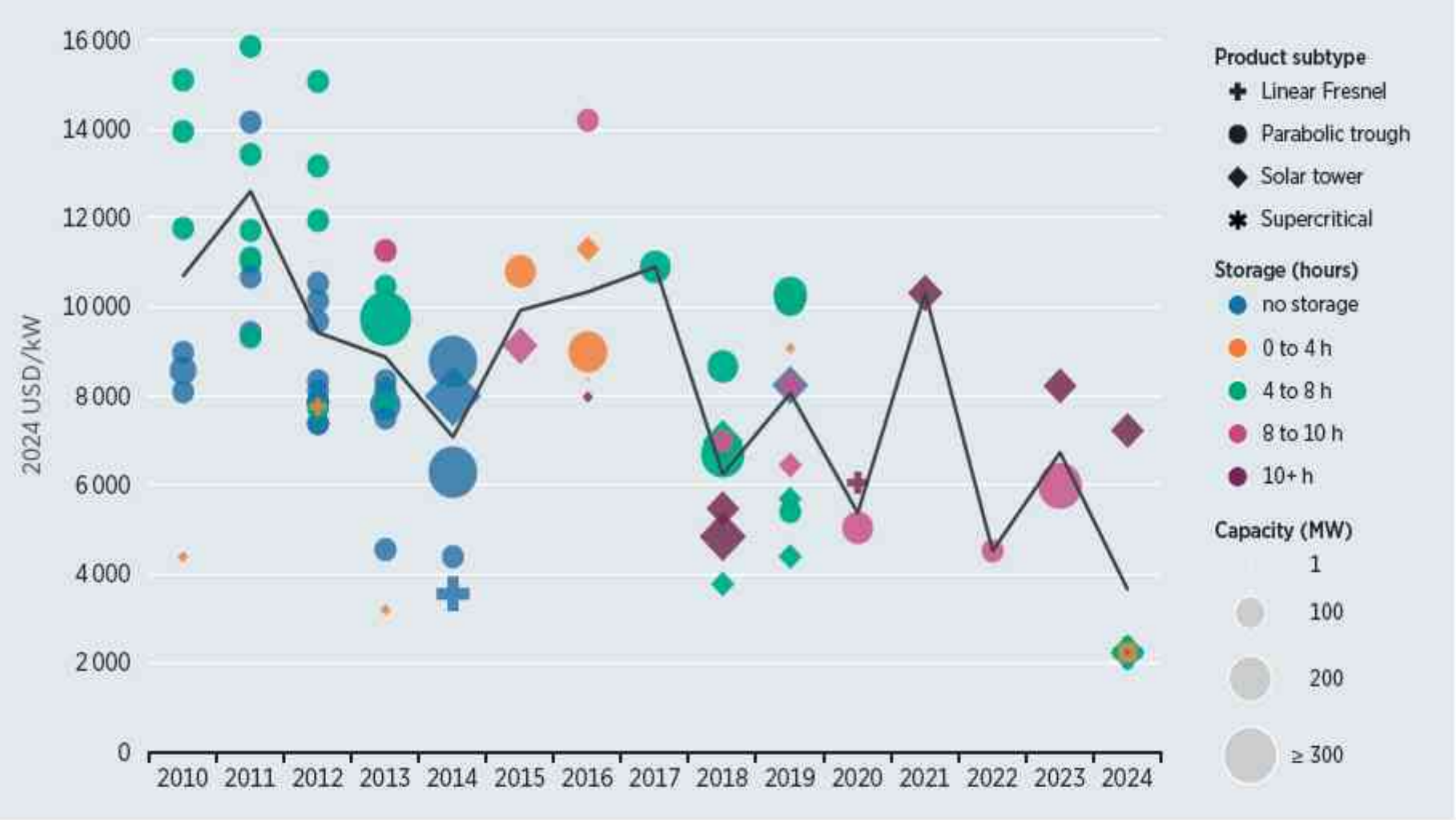
LCOE for Solar CSP Projects



Notes: kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

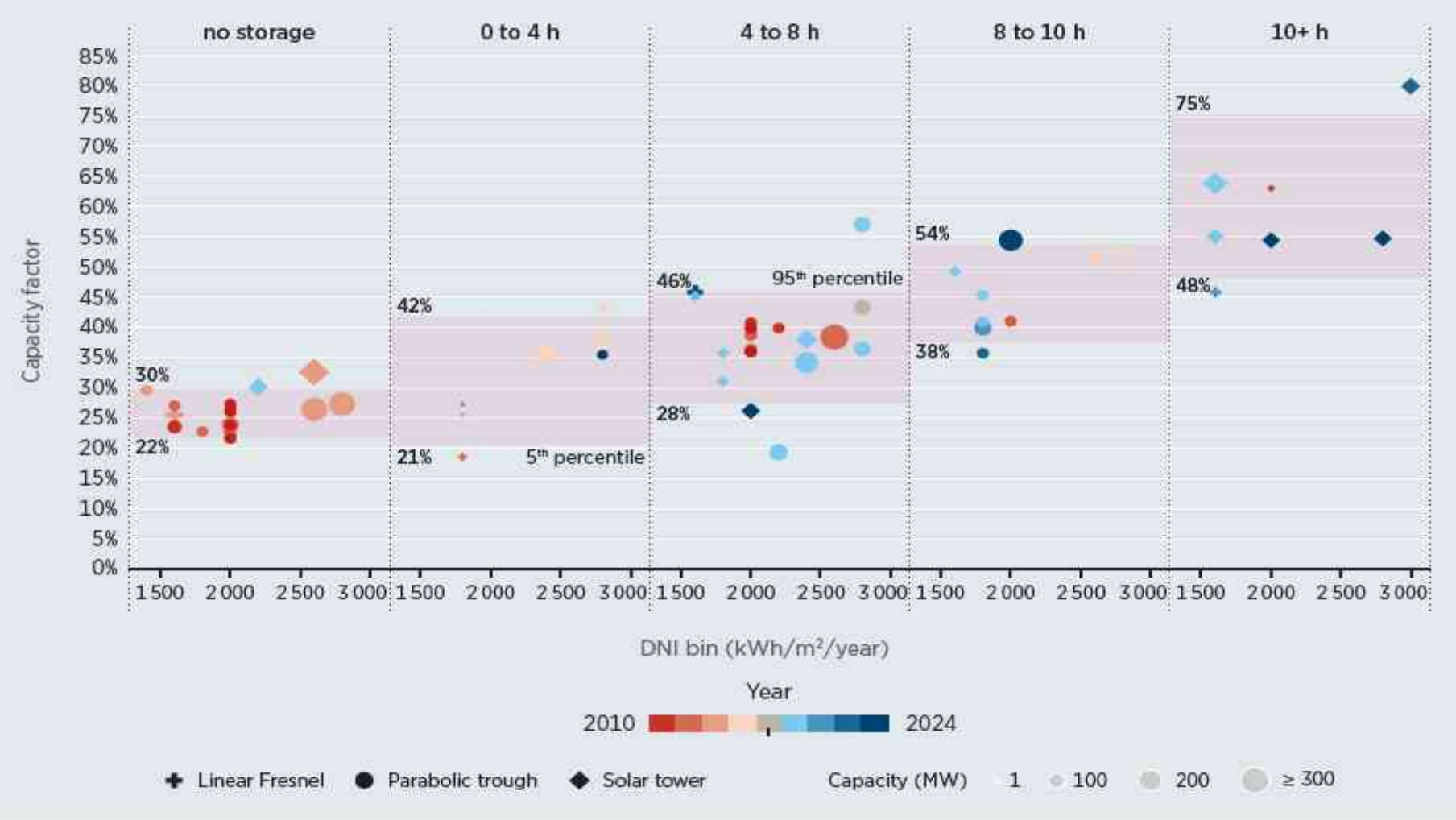
Installed costs for Solar CSP Projects



Notes: Only projects in the database with information available for all the variables displayed are shown. Data can therefore diverge from the global dataset; h = hour; kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Capacity factors for Solar CSP Projects by DNI & Storage duration



Source: (CSP.guru, 2025; World Bank Group *et al.*, 2025).

Notes: DNI = direct normal irradiance; h = hour; kW = kilowatt; kWh = kilowatt hour; MW = megawatt; m^2 = square metre; USD = United States dollar.

Source: IRENA November 2025

O&M for Solar CSP Projects by countries

	Parabolic trough collectors (2024 USD/kWh)	Solar tower (2024 USD/kWh)
Argentina	0.029	0.027
China	0.025	0.021
South Africa	0.015	0.014
OECD countries	0.028	0.025
Non-OECD countries	0.021	0.020

Note: OECD = Organisation for Economic Co-operation and Development.

Source: IRENA November 2025

LCOE for Solar CSP Projects



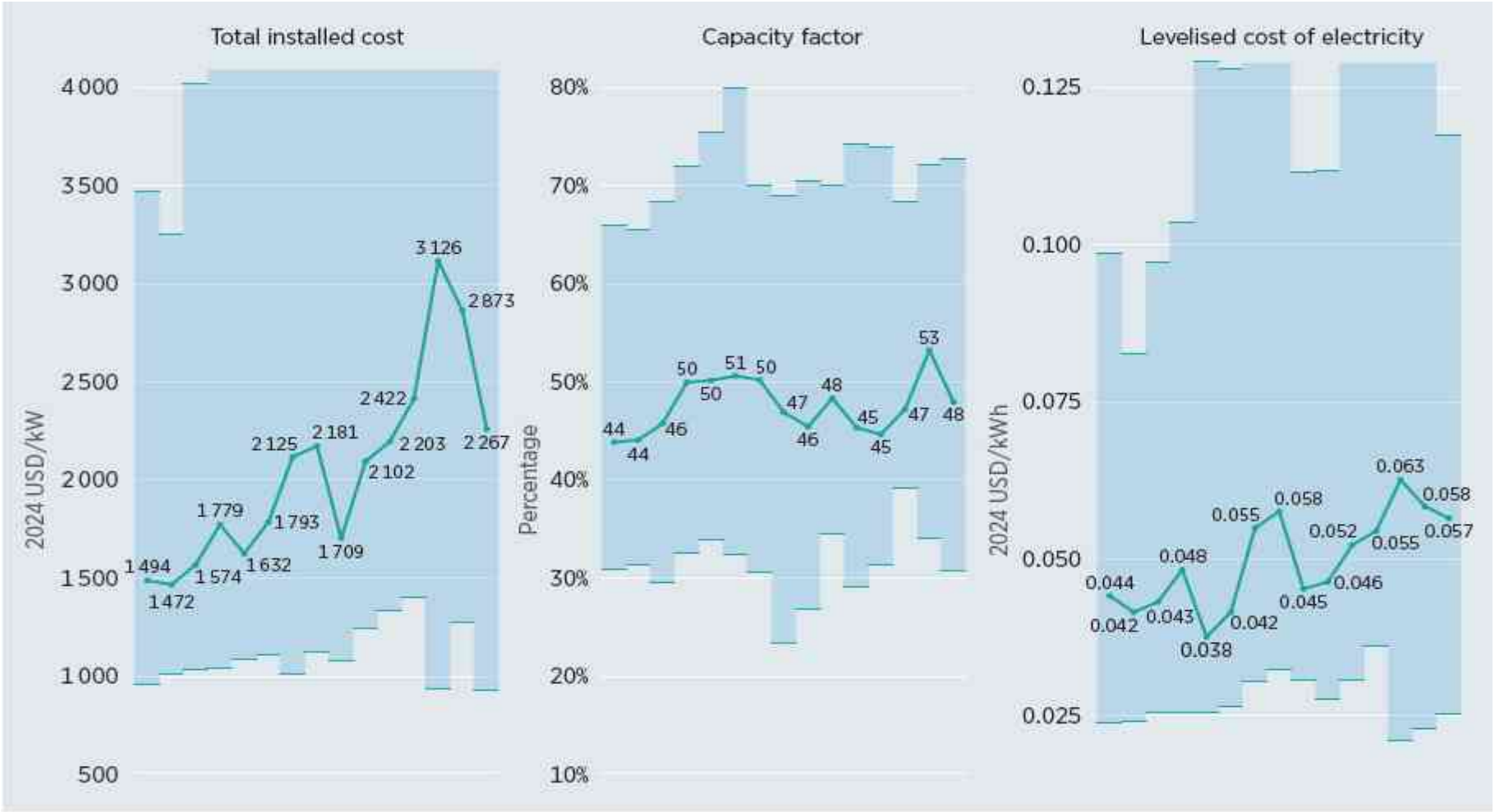
Notes: kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Hydropower Projects – IRENA 2025

LCOE Estimates by IRENA

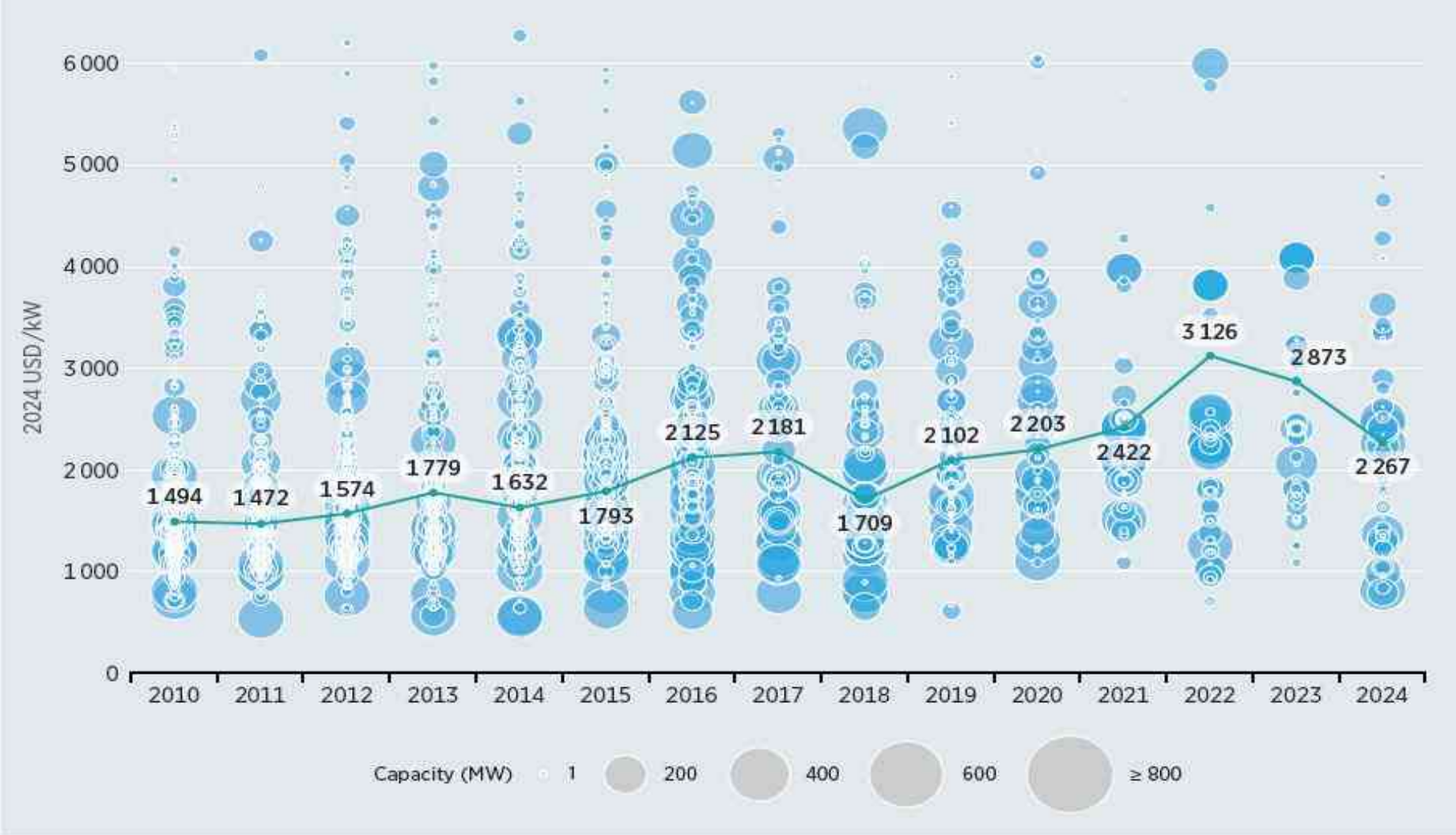
Weighted average of Installed costs, Capacity Factor & LCOE for Hydropower



Notes: kW = kilowatt; kWh = kilowatt hour; USD = United States dollar.

Source: IRENA November 2025

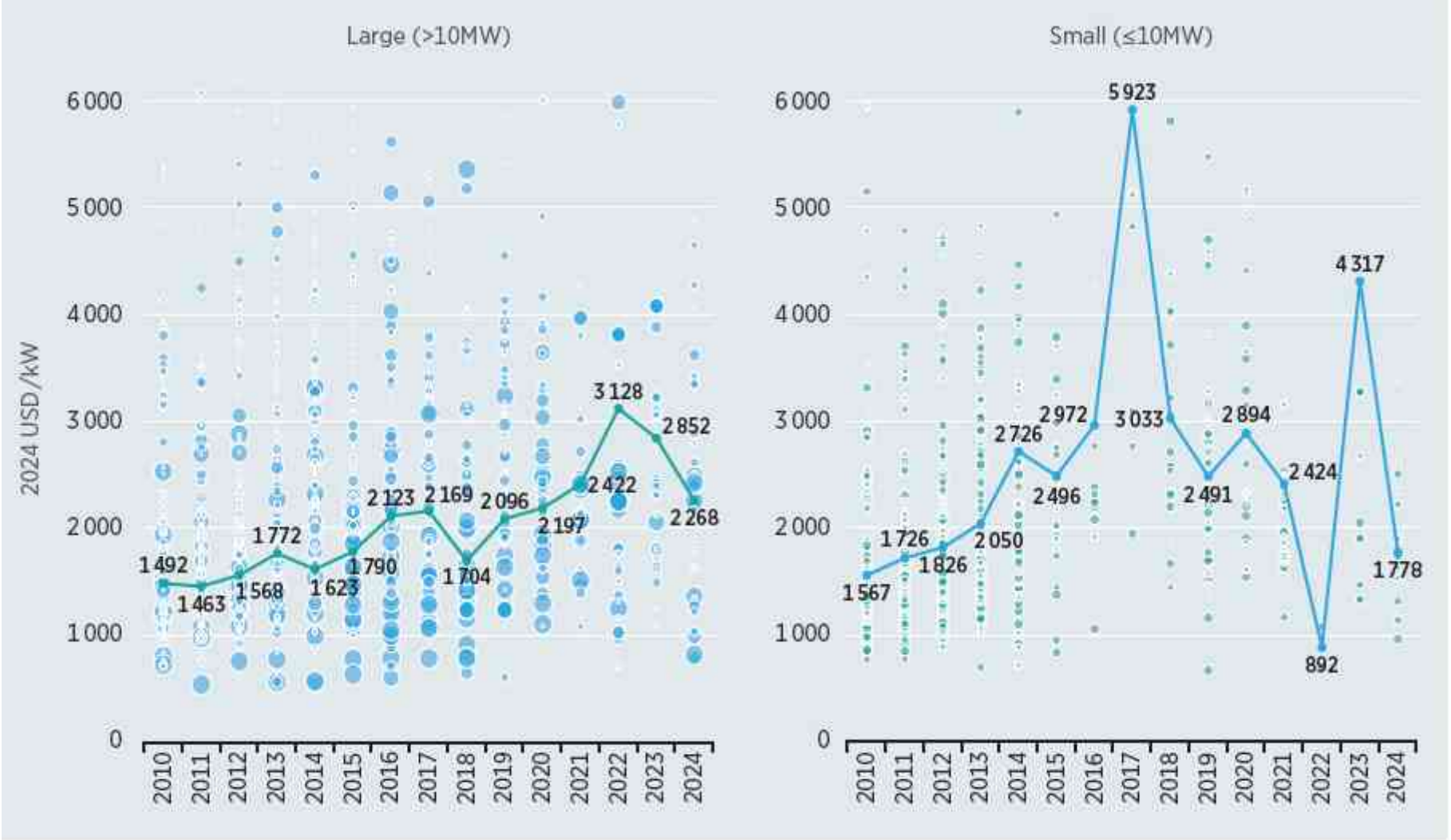
Installed costs for Hydropower & weighted average



Notes: kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2024

Installed costs for small & large Hydropower Projects & weighted average



Notes: kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

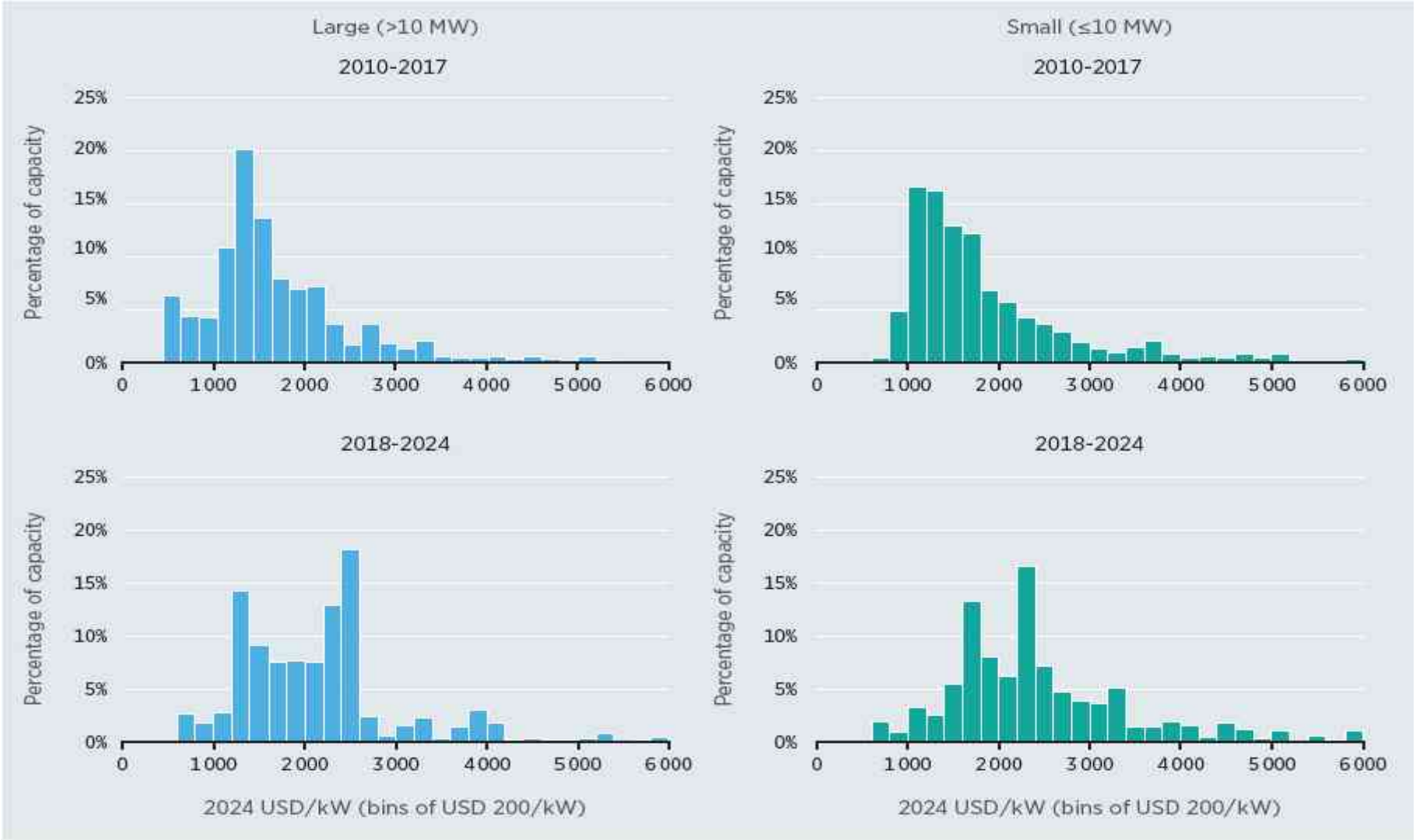
Installed costs for small & large Hydropower Projects & weighted average

2010-2024			
Capacity (MW)	5th percentile (2024 USD/kW)	Weighted average (2024 USD/kW)	95th percentile (2024 USD/kW)
0-50	1 011	2 067	4 407
51-100	1 038	2 261	4 998
101-150	1 097	2 117	4 276
151-200	1 049	2 089	3 616
201-250	1 161	2 376	4 130
251-300	1 050	2 478	4 457
301-350	1 056	2 318	5 100
351-400	782	1 804	3 083
401-450	1 361	2 288	3 459
451-500	1 166	1 773	2 804
501-550	1 294	3 036	5 138
551-600	1 540	2 084	2 945
601-650	1 203	1 686	3 885
651-700	2 265	2 577	2 710
701-750	1 103	1 792	2 454
751-800	1 217	1 789	2 523
801-850	992	3 801	12 048
851-900	1 373	1 947	2 198
901-950	810	1 295	1 521
951-1000	2 533	2 533	2 533

Notes: kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Distribution of Installed costs for small & large Hydropower Projects by Capacity



Notes: kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Capacity Factors for large Hydropower Projects by countries



	2010-2017			2018-2024		
	5th percentile (%)	Weighted average (%)	95th percentile (%)	5th percentile (%)	Weighted average (%)	95th percentile (%)
Africa	29	**51**	68	33	**48**	81
Central America	27	**50**	62	37	**46**	53
Eurasia	28	**44**	64	29	**41**	68
Europe	16	**36**	68	23	**38**	66
North America	24	**44**	78	39	**64**	73
Oceania	25	**38**	47	n.a.	**n.a.**	n.a.
Other Asia	37	**47**	68	37	**48**	69
Other South America	46	**61**	84	45	**60**	70
Brazil	51	**61**	80	39	**41**	61
China	31	**46**	57	37	**47**	63
India	27	**44**	62	29	**50**	63

Notes: See Annex III for regional country groupings; n.a. = not available.

Source: IRENA November 2025

Capacity Factors for small Hydropower Projects by countries



	2010-2017			2018-2024		
	5th percentile (%)	Weighted average (%)	95th percentile (%)	5th percentile (%)	Weighted average (%)	95th percentile (%)
Africa	38	**56**	68	50	**55**	66
Central America	45	**59**	75	n.a.	**n.a.**	n.a.
Eurasia	45	**60**	75	38	**57**	69
Europe	24	**48**	70	28	**41**	64
Oceania	45	**45**	45	n.a.	**n.a.**	n.a.
Other Asia	37	**50**	78	37	**59**	79
Other South America	43	**65**	82	n.a.	**n.a.**	n.a.
Brazil	43	**62**	88	49	**54**	59
China	33	**46**	60	38	**40**	43
India	28	**51**	70	34	**37**	45

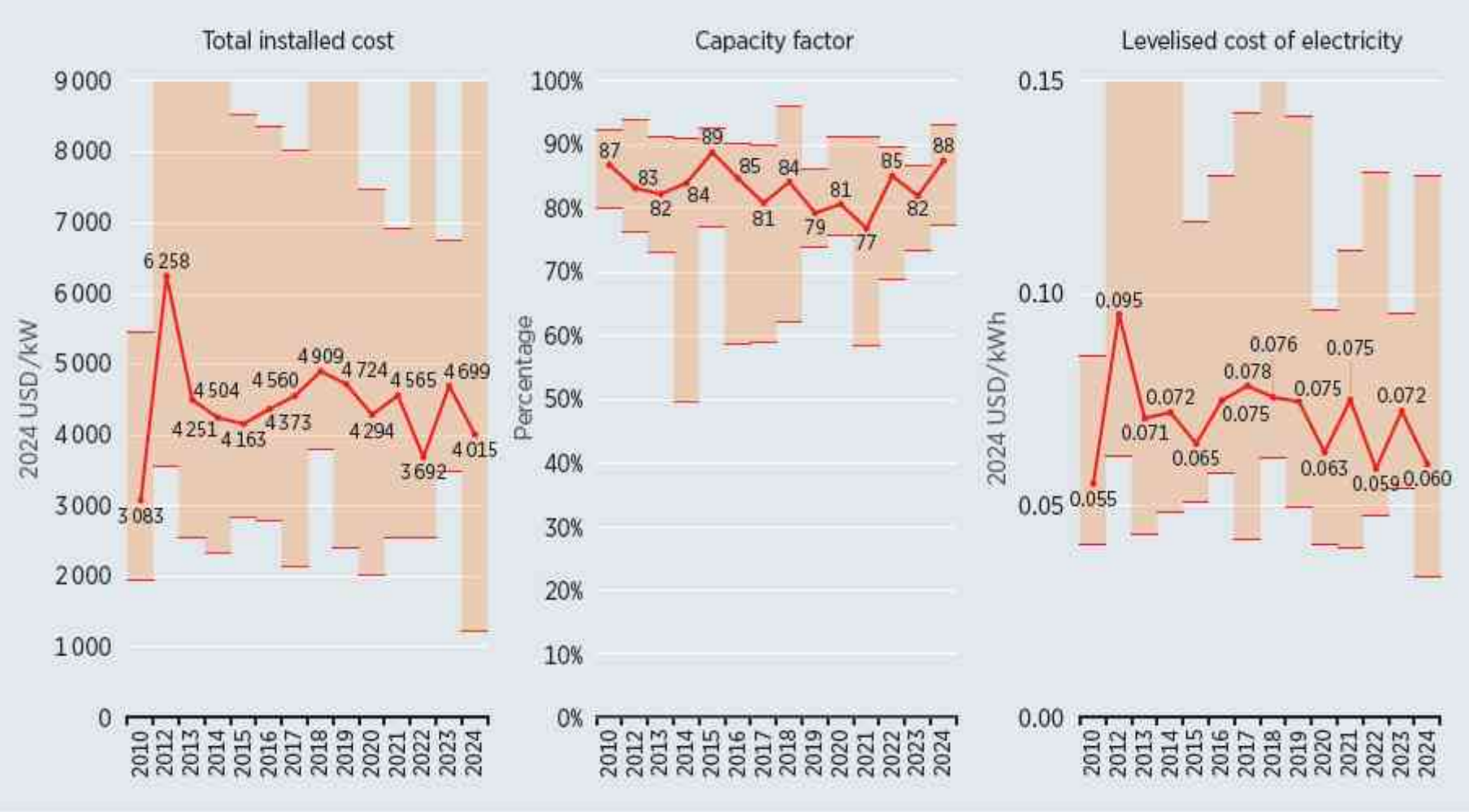
Notes: See Annex III for regional country groupings; n.a. = not available.

Source: IRENA November 2025

Geothermal Projects – IRENA 2025

LCOE Estimates by IRENA

Weighted average of Installed costs, Capacity Factor & LCOE for Geothermal



Notes: kW = kilowatt; kWh = kilowatt hour; USD = United States dollar.

Source: IRENA November 2025

LCOE for Geothermal Projects



Notes: kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

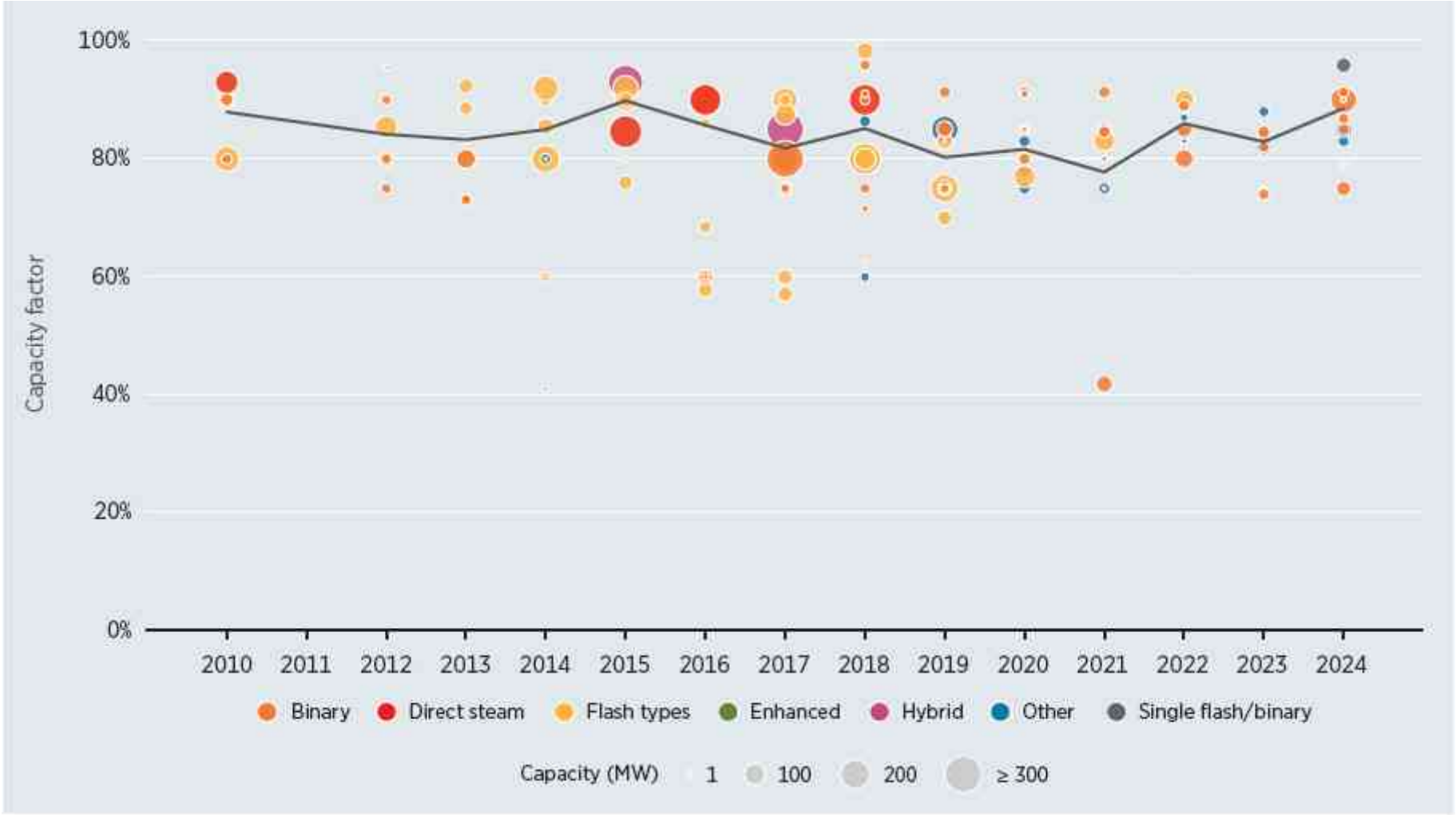
Installed costs for Geothermal Projects



Notes: kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Capacity factors for Geothermal Projects



Note: MW = megawatt.

Source: IRENA November 2025

O&M for Geothermal Projects

O&M costs for geothermal projects are high relative to onshore wind and solar PV. In particular, this is because over time the reservoir pressure around the production well declines, leading to poorer flow rates. The productivity of the well therefore deteriorates over time. Eventually, power generation production also falls, if remedial measures are not taken.

To maintain production at the designed capacity factor, the reservoir and production profile of the geothermal power plant therefore require agile management. This will also typically include the need to incorporate additional production wells over the lifetime of the plant.

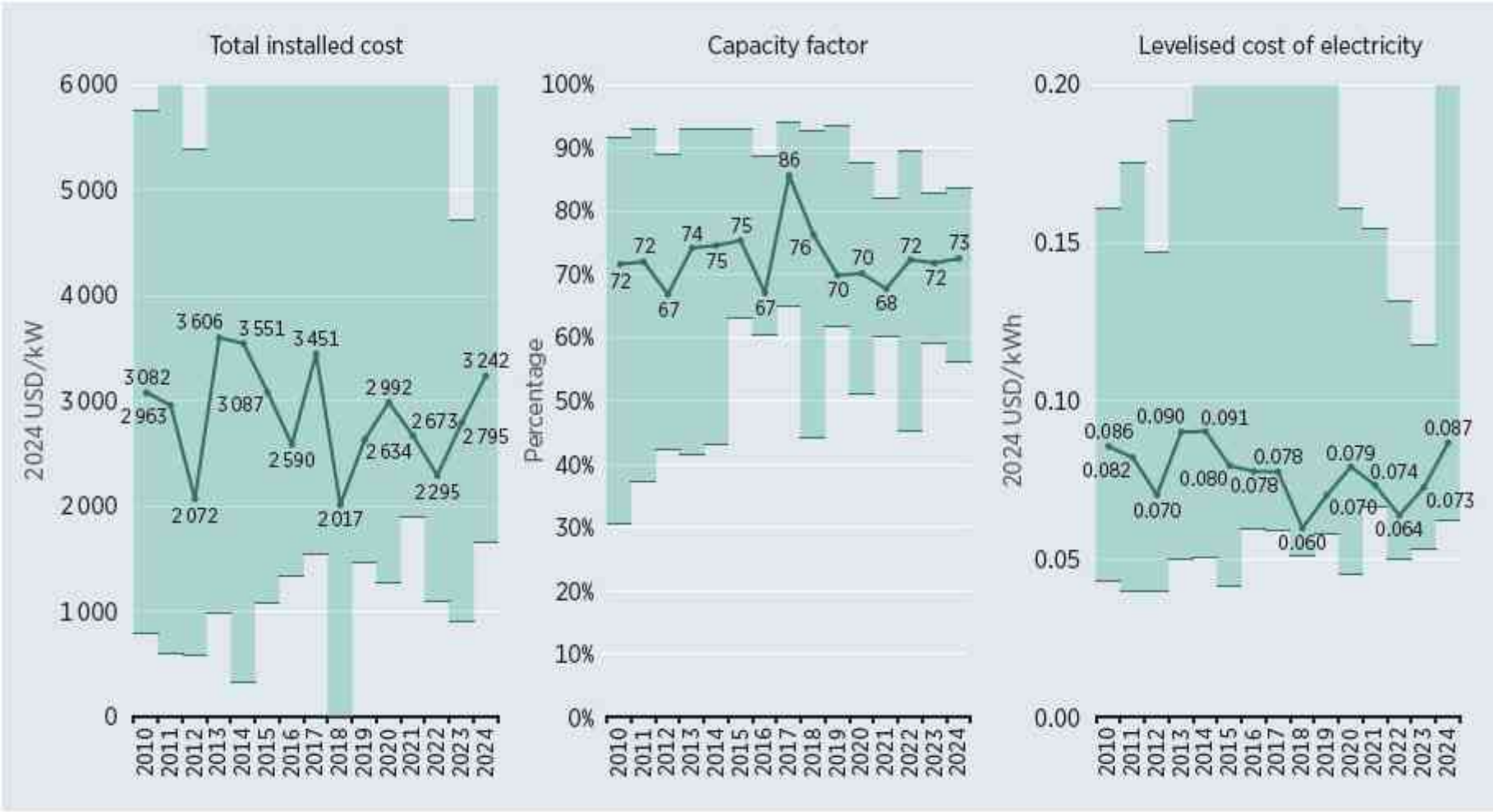
The O&M cost assumption applied for projects commissioned in 2024 was USD 125/kW per year and USD 110/kW per year for projects deployed between 2010 and 2023. Those values include two sets of wells for makeup and reinjection – necessary to maintain performance over the 25-year life of the project.

Source: IRENA November 2025

Bioenergy Projects – IRENA 2025

LCOE Estimates by IRENA

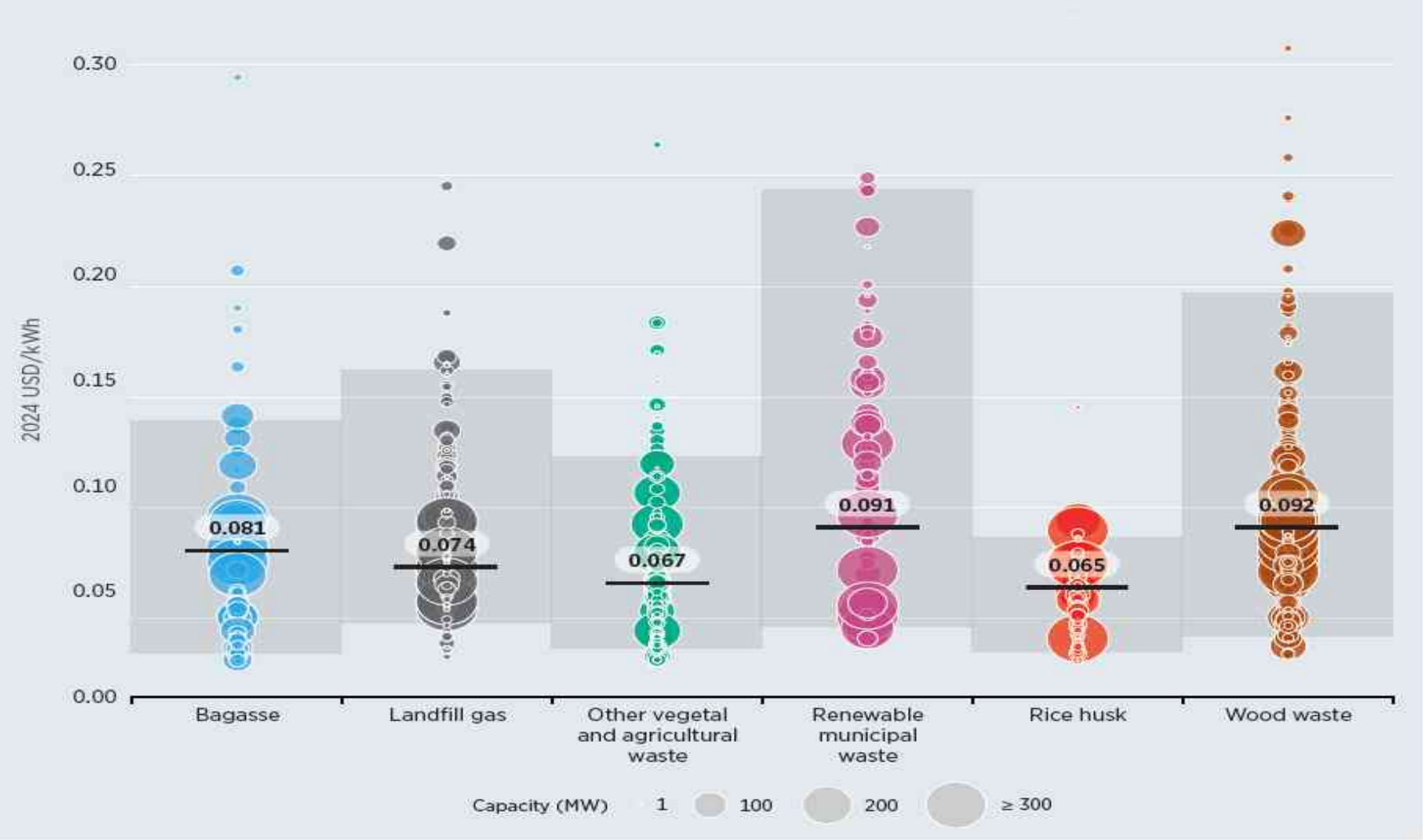
Weighted average of Installed costs, Capacity Factor & LCOE for Bioenergy



Notes: kW = kilowatt; kWh = kilowatt hour; USD = United States dollar.

Source: IRENA November 2025

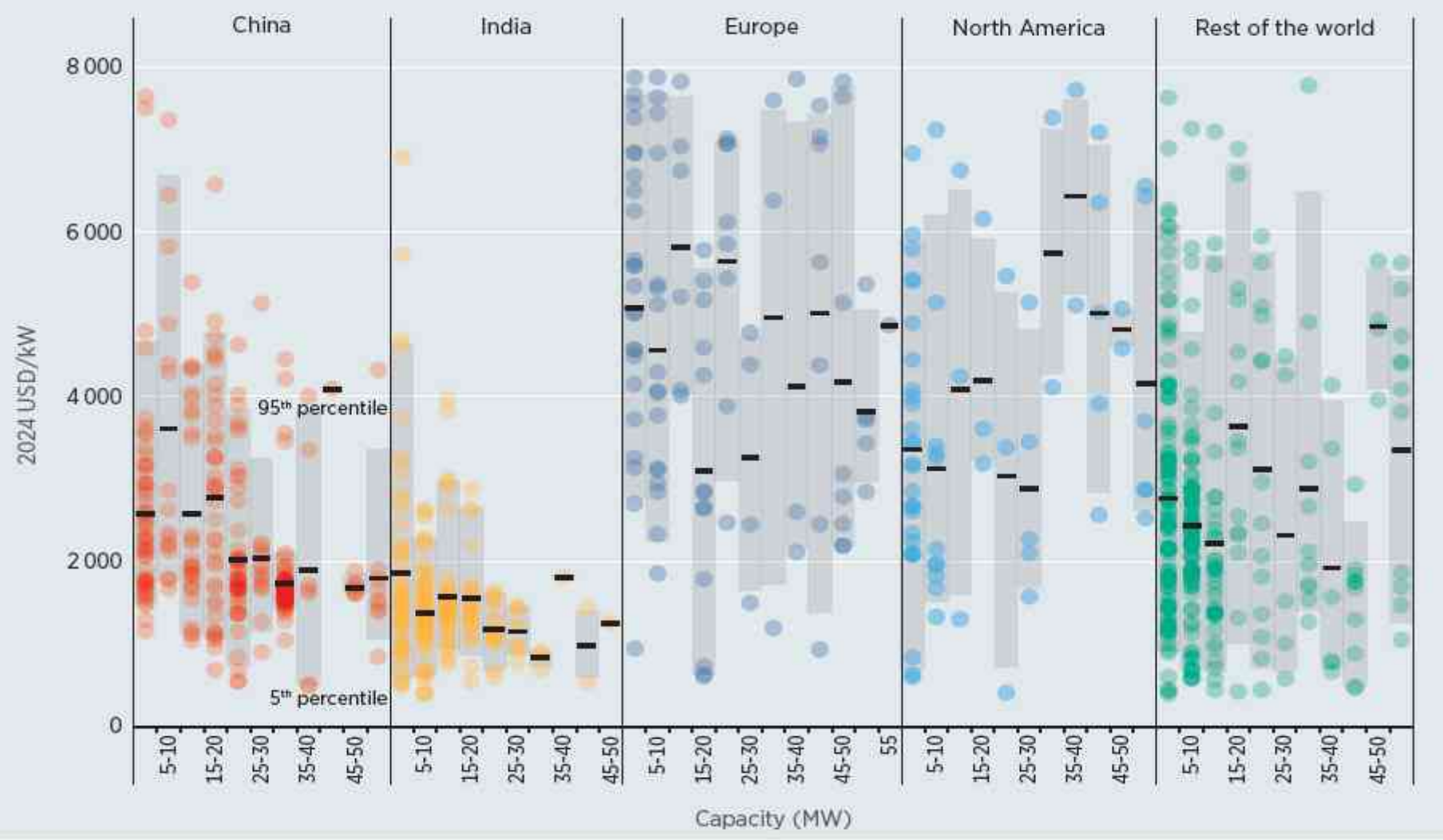
LCOE for Bioenergy Projects



Notes: kW = kilowatt; kWh = kilowatt hour; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

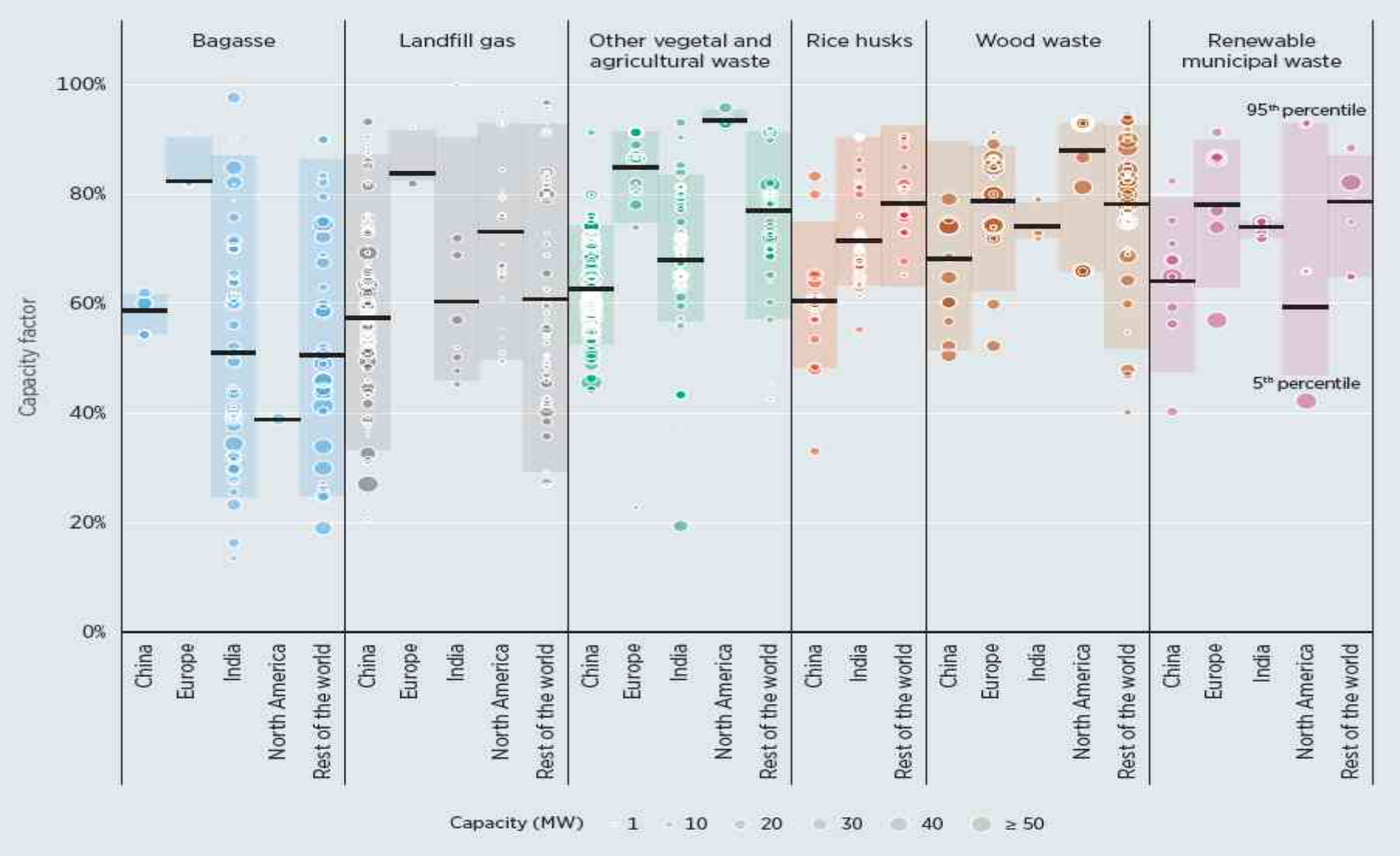
Installed costs for Bioenergy Projects



Note: See Annex III for regional country groupings; kW = kilowatt; MW = megawatt; USD = United States dollar.

Source: IRENA November 2025

Capacity factors for Bioenergy Projects by selected feedstocks



Source: IRENA November 2025

Capacity factors for Bioenergy fired power generation Projects



	2000-2024		
	5th percentile (%)	Weighted average (%)	95th percentile (%)
China	44	66	81
Europe	57	81	91
India	35	68	90
North America	50	85	93
Rest of the world	39	68	91

Source: IRENA November 2025

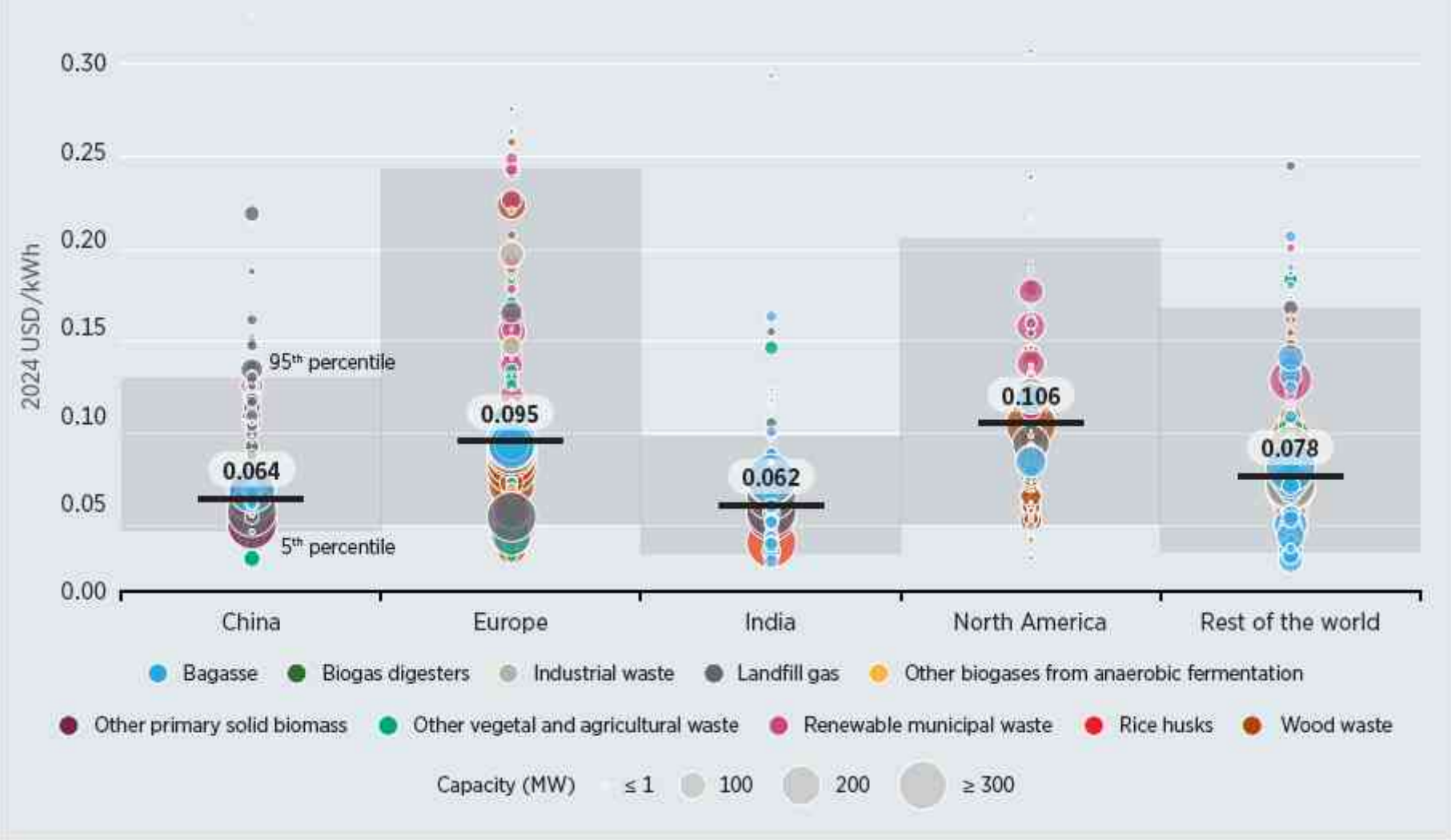
O&M costs for Bioenergy Projects

Fixed O&M costs include expenses related to labour, insurance and scheduled maintenance. They also include routine replacement of plant components, such as boilers and gasifiers, feedstock handling equipment and other associated costs. Generally, these costs constitute between 2% and 6% of the TICs per year. Larger bioenergy power plants typically have lower fixed O&M costs per kW, due to economies of scale.

Variable O&M costs for bioenergy power plants are generally lower than fixed O&M costs, averaging around USD 0.004/kWh. The primary components of variable O&M costs are replacement parts and incremental servicing costs, including non-biomass fuel expenses such as ash disposal. Due to project specific variations and limited available data, this report combines variable O&M and fixed O&M costs.

Source: IRENA November 2025

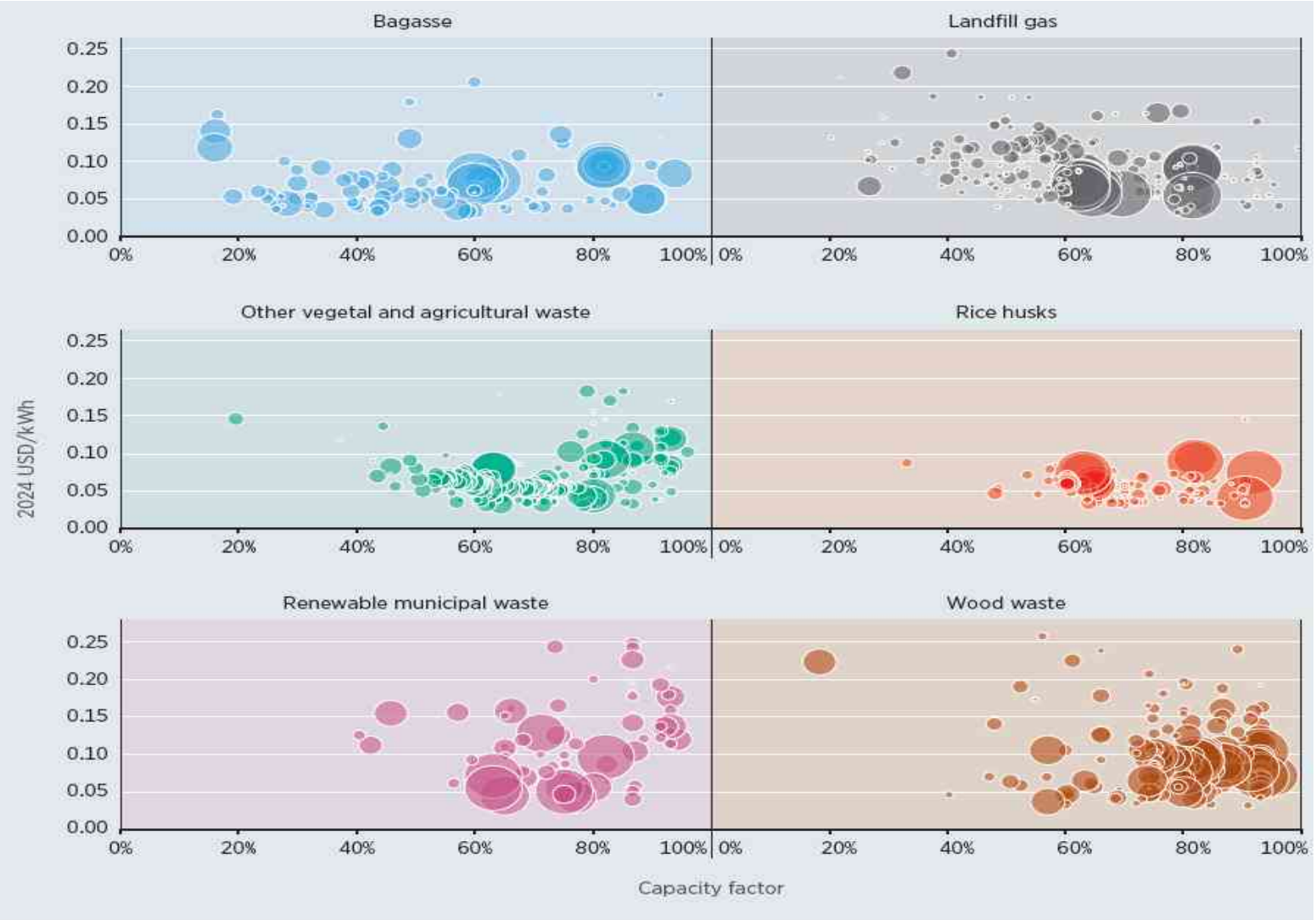
LCOE for Bioenergy Power Generation Projects by feedstock & country



Notes: See Annex III for regional country groupings.; kWh = kilowatt hour; MW = megawatt.

Source: IRENA November 2025

LCOE & Capacity factors for Bioenergy Power Generation Projects by feedstock



Note: kWh = kilowatt hour; USD = United States dollar.

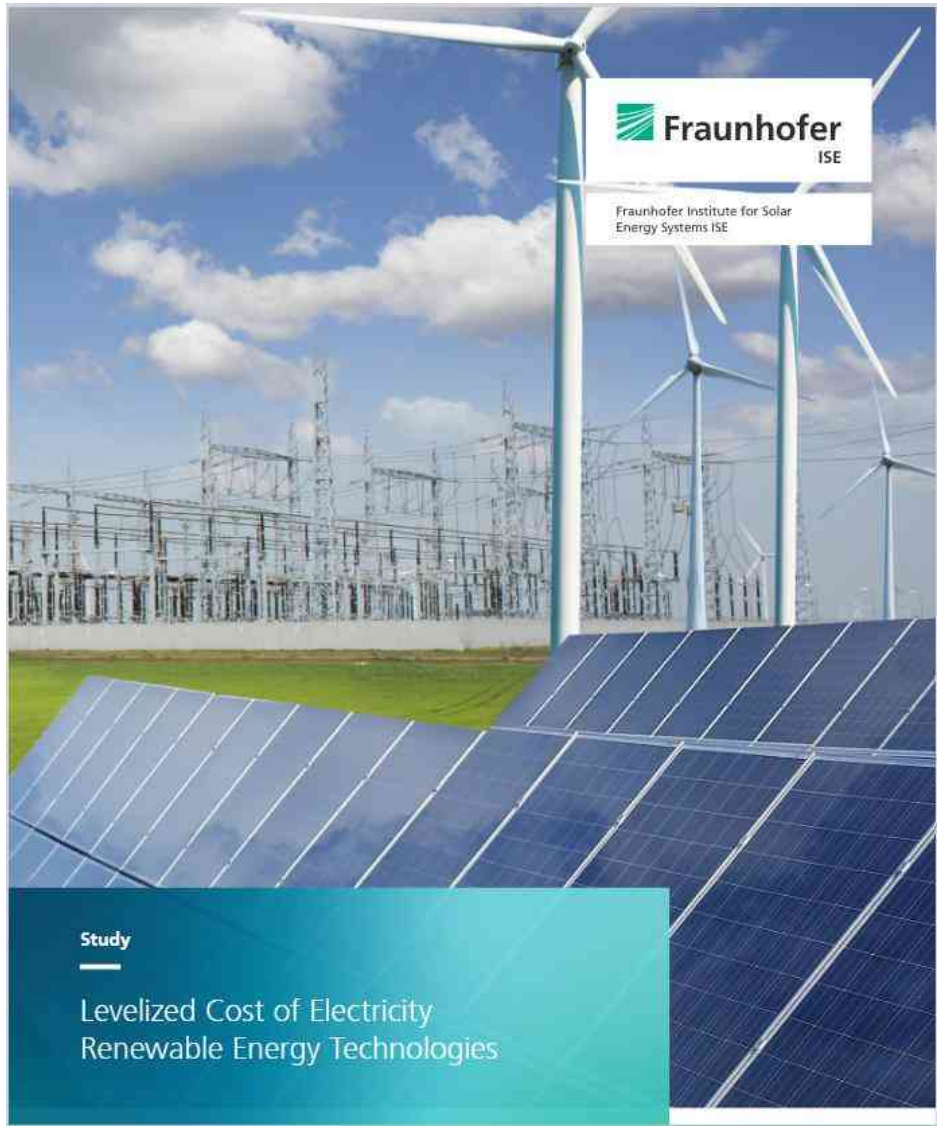
Source: IRENA November 2025

LCOE Estimates by IRENA
Standard assumptions for LCOE calculations

Technology	Economic life (years)	Weighted average cost of capital (real)	
		OECD and China	Rest of the world
Wind power	25	7.5% in 2010 falling to 5% in 2020	10% in 2010 falling to 7.5% in 2020
Solar PV	25		
CSP	25		
Hydropower	30		
Biomass for power	20		
Geothermal	25		

Source: IRENA November 2024

LCOE by Fraunhofer ISE



LCOE for Various Technologies by Fraunhofer ISE

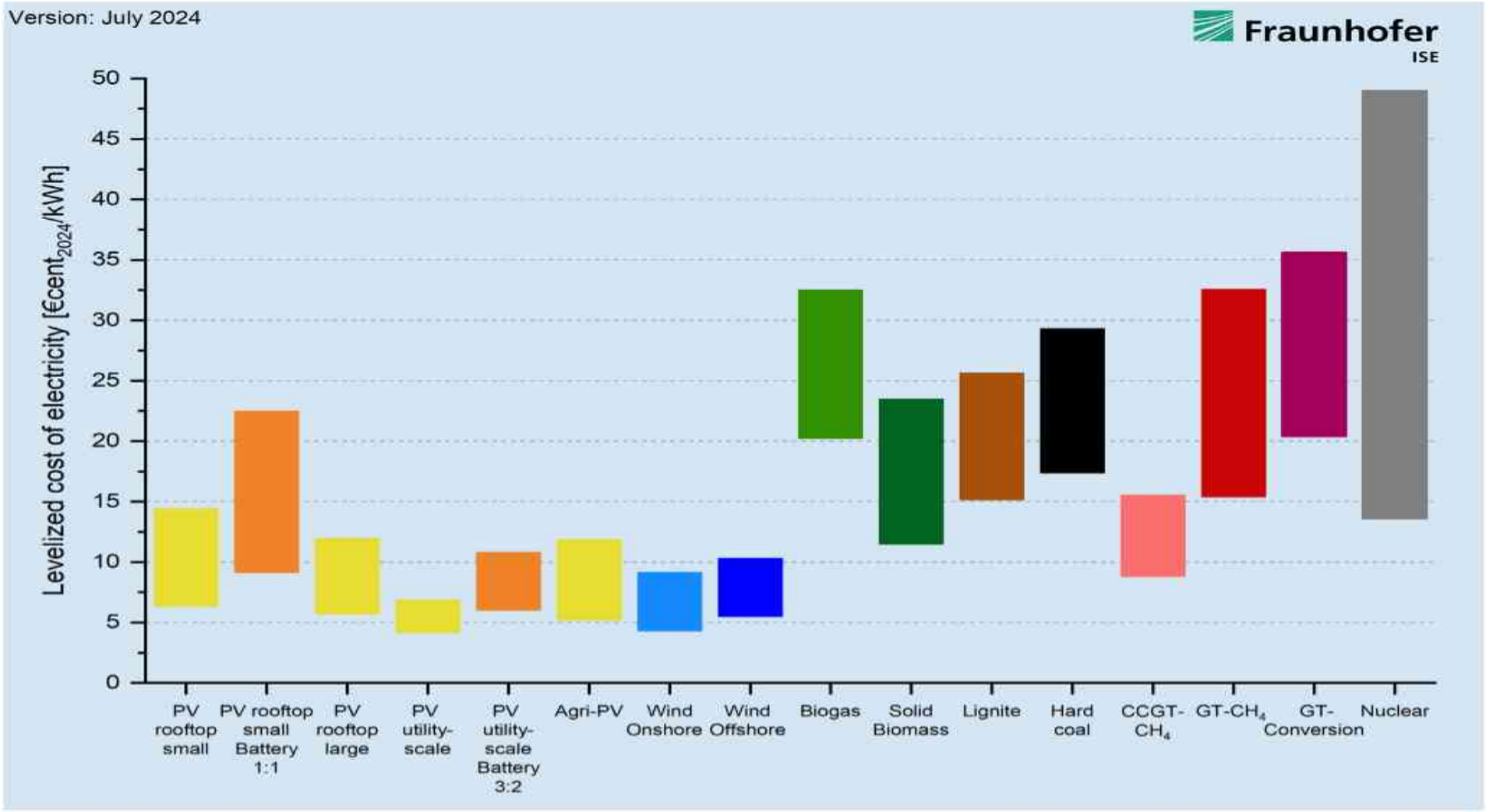


Figure 1: LCOE of renewable energy technologies and conventional power plants at locations in Germany in 2024. Specific investments are considered using a minimum and maximum value for each technology.

Source: Fraunhofer July 2024

LCOE for Various Technologies by Fraunhofer ISE

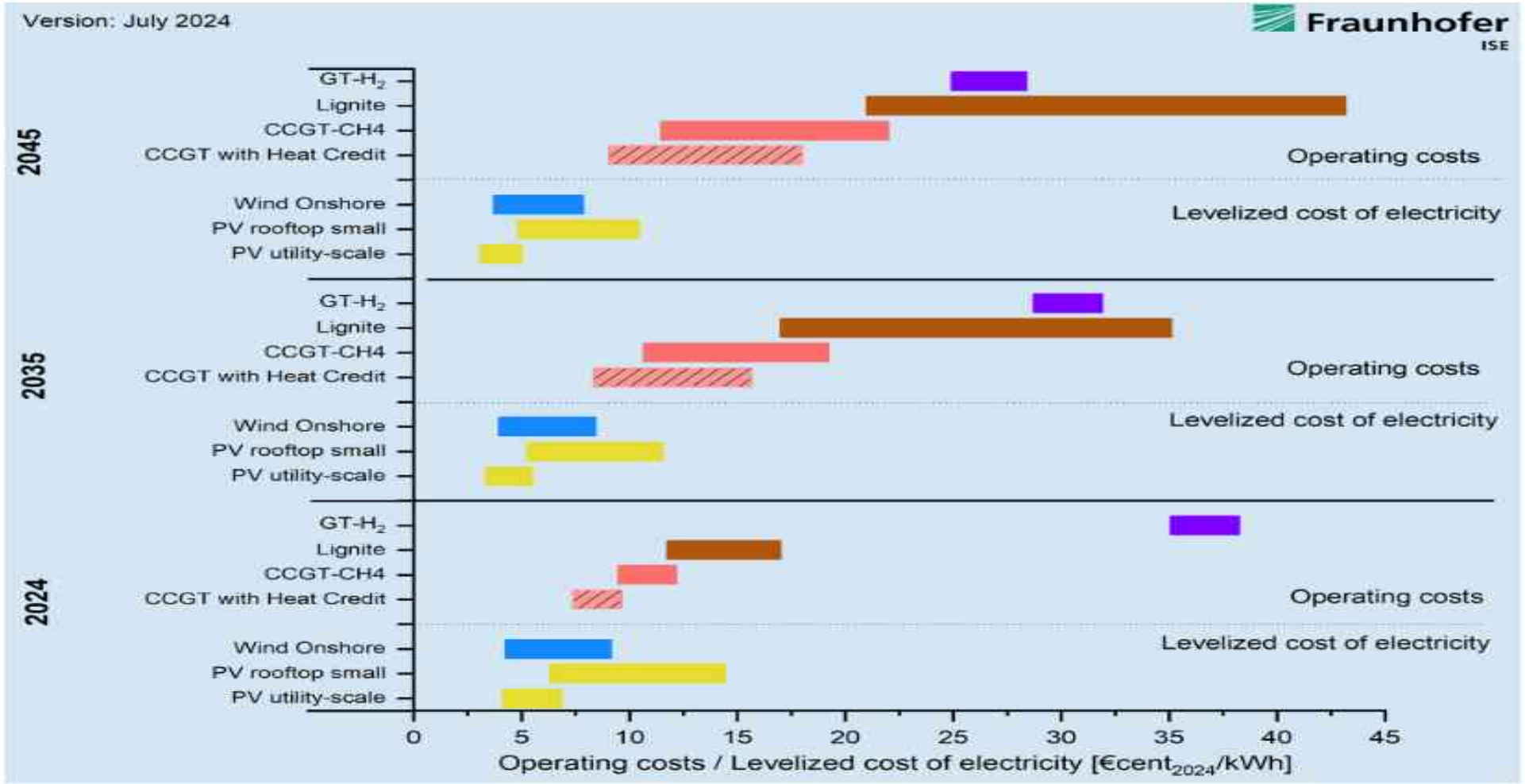


Figure 3: Comparison of LCOE of renewables with operating costs of existing conventional fossil-fuel power plants in 2024, 2035, and 2045

Source: Fraunhofer July 2024

LCOE for Various Technologies by Fraunhofer ISE

CAPEX [EUR/kW]	Wind Onshore	Wind Offshore	Biogas	Solid Biomass	Lignite	Hard coal	CCGT	Gas turbine	H2 Gasturbine	H2 CCGT	Fuel cell	Nu-clear
Investment 2024 low	1300	2200	2894	3473	1850	1700	900	450	550	1100	5000	6000
Investment 2024 high	1900	3400	5788	5788	2550	2300	1300	700	1200	2400	8000	16000

CAPEX [EUR/kW]	PV rooftop small (<= 30 kW_p)	PV rooftop large (>30 kW_p)	PV utility-scale(> 1 MW_p)	Agri-PV (0.5-2 MW_p)	PV rooftop small incl. battery storage (<= 30 kW_p, PV output to battery capacity 1:1)	PV rooftop large incl. battery storage (> 30 kWp – 1 MW_p, PV-output to battery capacity 2:1)	PV utility-scale incl.battery storage (> 1 MW_p, PV output to battery capacity 3:2)
Unit	[EUR/kW_p]	[EUR/kW_p]	[EUR/kW_p]	[EUR/kW_p]	[EUR/kWh]	[EUR/kWh]	[EUR/kWh]
Investment 2024 low	1000	900	700	900	500	450	400
Investment 2024 high	2000	1600	900	1700	1000	800	600

Table 1: Specific CAPEX in EUR/kW or EUR/kWh for current plants in 2024 (Source: Fraunhofer ISE intern, Lazard 2024)

Source: Fraunhofer July 2024

LCOE for Various Technologies by Fraunhofer ISE

	Wind onshore	Wind offs-hore	Biogas	Solid Biomas-se	Lignite	Hard coal	CCGT	GT	CCGT H2	GT H2	Fuel cell	Nu-clear
Lifetime in years	25	25	25	25	40	30	30	30	30	30	12	45
Share of debt [%]	80	70	80	80	60	60	60	60	60	60	60	60
Share of equity [%]	20	30	20	20	40	40	40	40	40	40	40	40
Interest rate on debt [%]	5.5	7.0	5.5	5.5	7.0	7.0	7.0	7.0	7.0	7.0	8.0	8.0
Return on equity [%]	7.0	10.0	8.0	8.0	11.0	11.0	10.0	10.0	11.3	11.3	12.0	12.0
WACC nominal [%]	5.8	7.9	6.0	6.0	8.6	8.6	8.2	8.2	8.7	8.7	9.6	9.6
WACC real [%]	3.9	6.0	4.2	4.2	6.8	6.8	6.4	6.4	6.9	6.9	7.8	7.8
OPEX fix [EUR/kW]	32	39	4% von CAPEX	4% von CAPEX	42	37	20	23	25	23	30	100
OPEX var [EUR/kWh]	0.007	0.008	0.004	0.004	0.005	0.005	0.005	0.004	0.005	0.005	0.016	0.007
Annual degra-dation	0	0	0	0	0	0	0	0	0	0	0	0

Source: Fraunhofer July 2024

LCOE for Various Technologies by Fraunhofer ISE

	PV rooftop small (≤ 30 kW_p)	PV rooftop large (> 30 kW_p)	PV utility-scale (> 1 MW_p)	Agri-PV (0,5-2 MW_p)	PV rooftop small incl. battery (≤ 30 kW_p, 1:1)	PV rooftop large incl. battery (> 30 kW_p, 2:1)	PV utility-scale incl. battery (> 1 MW_p, 3:2)
Lifetime in years	30	30	30	30	15	15	15
Share of debt	80%	80%	80%	80%	80%	80%	80%
Share of equity	20%	20%	20%	20%	20%	20%	20%
Interest rate on debt	5.0%	5.0%	5.0%	5.0%	3.0%	3.0%	3.0%
Return on equity	5.0%	6.5%	6.5%	6.5%	5.0%	6.5%	6.5%
WACC nominal	5.0%	5.3%	5.3%	5.3%	3.4%	3.7%	3.7%
WACC real	3.2%	3.5%	3.5%	3.5%	2.2%	2.5%	2.5%
OPEX fix [EUR/kW]	26	21.5	13.3	13.3	0	4.5-8.0*	5.3-8.0*
OPEX var [EUR/kWh]	0	0	0	0	0	0	0
Annual degradation	0.25%	0.25%	0.25%	0.25%	0	0	0
Battery replacement costs	-	-	-	-	40-50% of initial investment	35% of initial investment	30% of initial investment
Efficiency	-	-	-	-	90%	90%	90%
Annual charge cycles	-	-	-	-	200	100-300**	100-300**

Table 2: Input parameter for LCOE calculation. The real WACC is calculated with an inflation rate of 1.8% (Source: Fraunhofer ISE intern)

** related to the PV system power output (corresponds to 2% of the battery investment costs)*

** Since the battery lifetime is assumed to be fixed, the annual charge cycles only have an influence on the value of the battery storage loss. A high number of cycles (high losses) is used for the upper limit of the LCOE, a low number of cycles (low losses) is used to calculate the lower limit of the LCOE.*

Source: Fraunhofer July 2024

LCOE for Various Technologies by Fraunhofer ISE

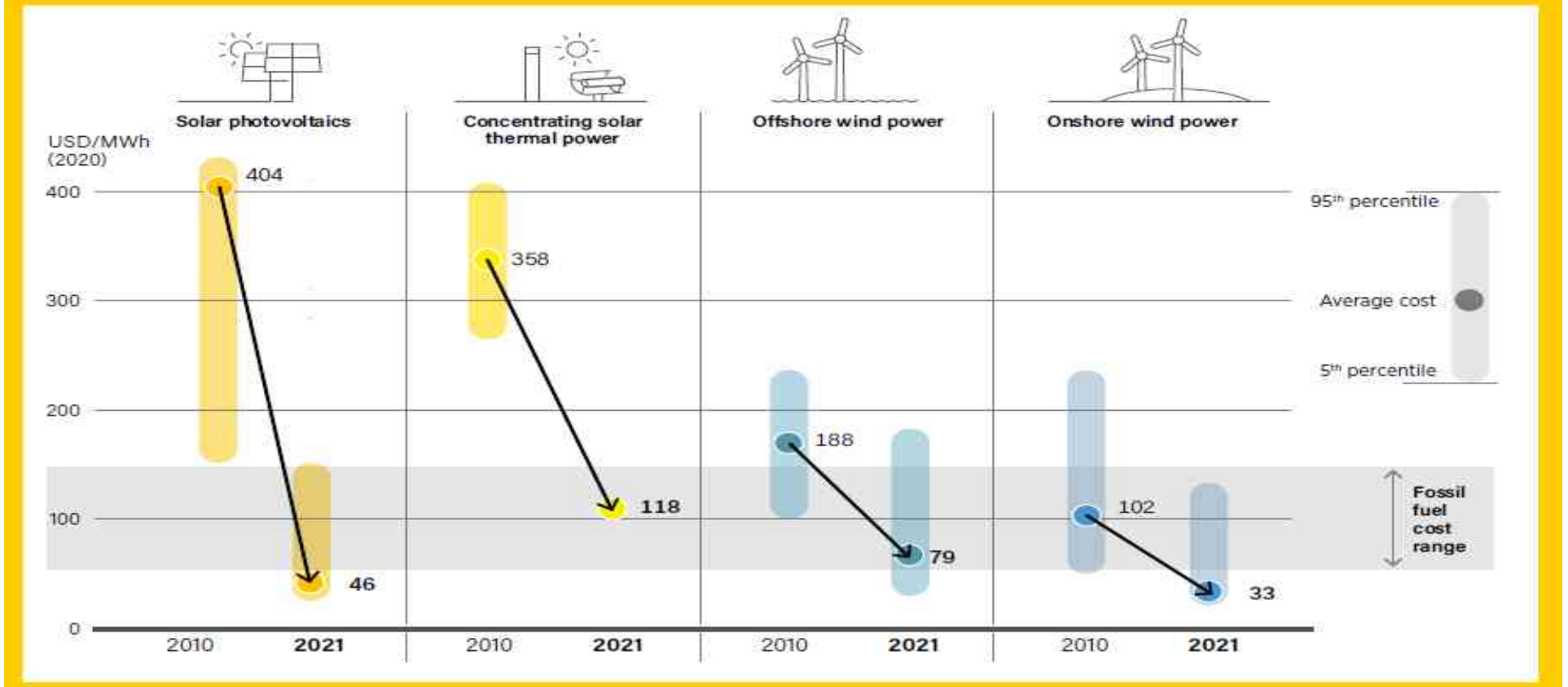
Fuel Prices [EUR/MWh]	2024	2030	2035	2040	2045
Lignite	2.3	2.3	2.3	2.3	2.3
Hard Coal	11.6	11.6	11.6	11.6	11.6
Natural Gas	38.0	27.0	27.0	27.0	27.0
Green Hydro-gen	150	150	129	111	100
Uranium	8.0	8.0	8.0	8.0	8.0
Substrate Biogas	87.5	99.6	103.3	106.7	110.2
Substrate Solid Biomass	23.8	25.5	26.4	27.3	28.2

Source: Fraunhofer July 2024

LCOE REN21 Estimates for Renewables

LCOE Estimates by REN21

Global Weighted-Average LCOEs from Newly Commissioned, Utility-scale Renewable Power Generation Technologies, 2010-2021



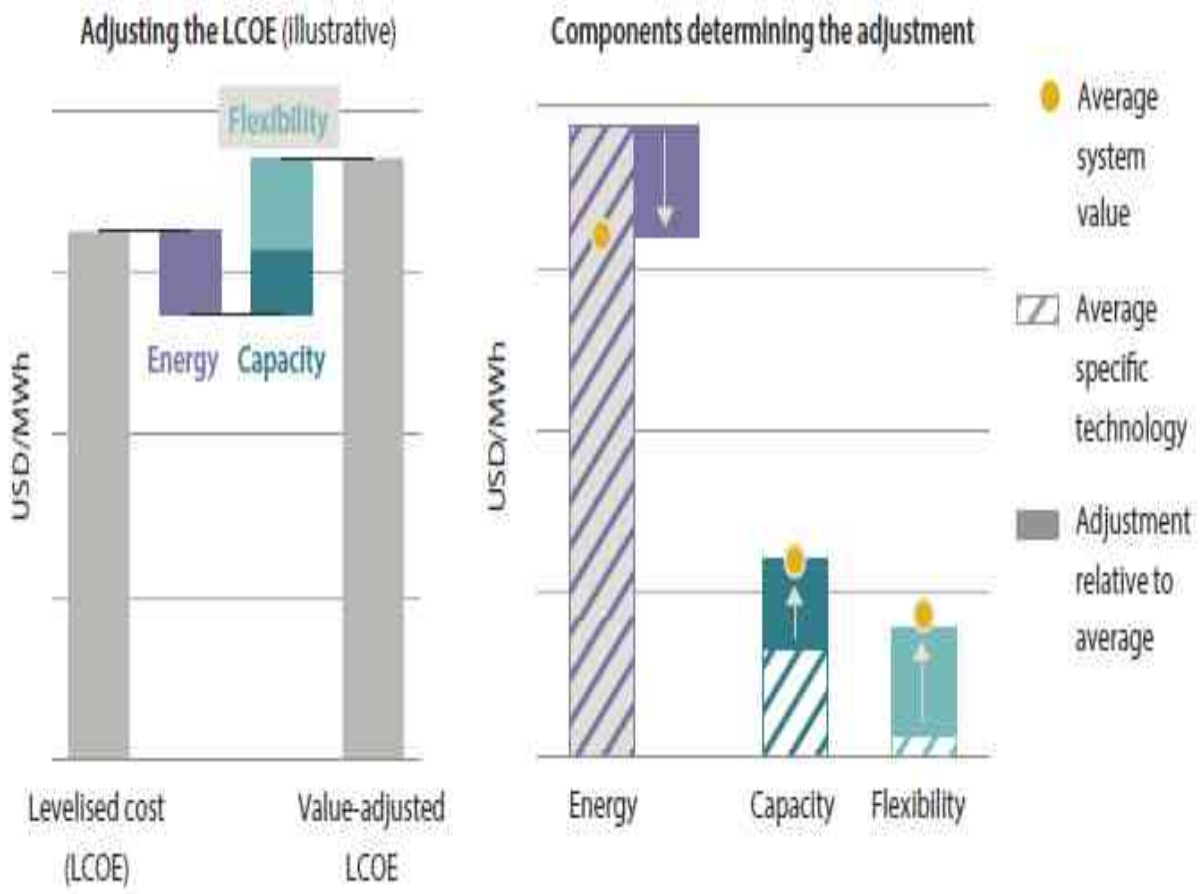
Note: These data are for the year of commissioning. The thick lines are the global weighted-average LCOE value derived from the individual plants commissioned in each year. The LCOE is calculated with project-specific installed costs and capacity factors, while the other assumptions are detailed in the *Power Generation Costs 2021* report from IRENA. The single band represents the fossil fuel-fired power generation cost range, while the bands for each technology and year represent the 5th and 95th percentile bands for renewable projects. No price range was available for CSP. In 2021 there was only one CSP plant comissioned, as many projects have been delayed.

Source: IRENA Renewable Cost Database.

Source: REN21 2022

A New Concept: Value-Adjusted LCOE VALCOE

A New Concept: Value-Adjusted LCOE (VALCOE)



Combining costs and value provides a more robust basis for evaluating competitiveness across technologies than costs alone.

Some Energy Sources do not render the same services, quality and flexibility services. Example: Renewable Energy is intermittent.

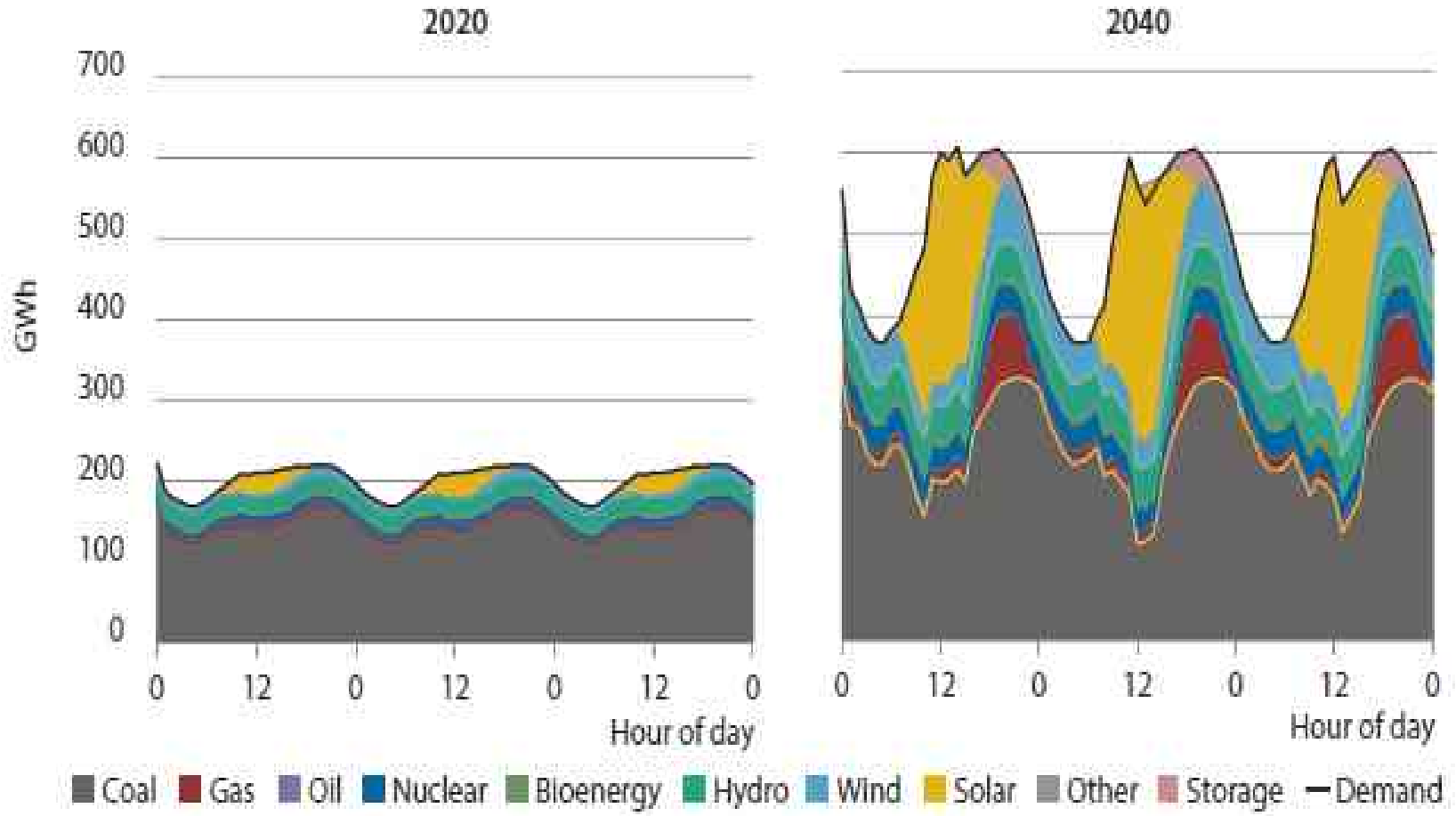
VALCOE corrects the LCOE by including 3 elements of value:

Energy
Capacity
Flexibility

It varies by technologies depending upon operating conditions, system-specific conditions, dispatchability of the energy source.

Source: IEA Projected Costs of Electricity Production 2020

A New Concept: Value-Adjusted LCOE (VALCOE)
Example of flexibility needed in India 2020 & 2040
IEA STEPS Scenario



Source: IEA Projected Costs of Electricity Production 2020

Levelized Cost of Storage
LCOS

Introduction to Levelized Cost of Storage (LCOS)
One criteria

$$LCOS = \sum_{k=0}^{k=n} \frac{C_k + Ok + TCCk}{(1+i)^k} \Big/ \sum_{k=0}^{k=n} \frac{QD_k}{(1+i)^k}$$

- *QD : Quantity of Electricity Discharged*
- *C : Capital Expenditures*
- *O : Operating Expenses*
- *TCC : Total Cost of Electricity used for Charging*
- *n : Economic Storage Device Life*
- *i : Discount Rate*

Introduction to Levelized Cost of Storage (LCOS)
One criteria

$$ACC = \sum_{k=0}^{k=n} \frac{TCC_k}{(1+i)^k} \Big/ \sum_{k=0}^{k=n} \frac{QC_k}{(1+i)^k}$$

$$ACC = 1/\rho \sum_{k=0}^{k=n} \frac{TCC_k}{(1+i)^k} \Big/ \sum_{k=0}^{k=n} \frac{QD_k}{(1+i)^k}$$

- *ACC: Weighted Average Cost during the Charging Period*
- *QC : Quantity of Electricity Charged*
- *TCC : Total Cost of Electricity used for Charging*
- *n : Economic Storage Device Life*
- *i : Discount Rate*
- *$\rho = QD_k/QC_k$, Device efficiency*

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Energy, safety and air pollution challenges

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Energy and Safety

Table 1.SF.2. Summary of Severe Accidents in the Energy Sector, 1970–2008

	OECD		Non-OECD	
Energy Chain	Accidents	Immediate Fatalities	Accidents	Immediate Fatalities
Coal	87	2,259	2,394	38,672
Oil	187	3,495	358	19,516
Natural gas	109	1,258	78	1,556
Liquefied petroleum gas	58	1,856	70	2,789
Hydro	1	14	9	30,069
Nuclear	–	–	1	31
Biofuel	–	–	–	–
Biogas	–	–	2	18
Geothermal	–	–	1	21

Source: Burgherr and Hirschberg 2014.
Note: Accidents with more than five fatalities are considered severe. Accidents in Organisation for Economic Co-operation and Development (OECD) countries from hydro power refer to the U.S. Teton Dam failure in 1976. For nuclear accidents, only immediate fatalities of the Chernobyl accident are shown. – = negligible.

Source: World Economic Outlook IMF 2016

EXAMPLES OF MAJOR HSE EVENTS THAT HAVE GREATLY IMPACTED THE INDUSTRY

1988



COMPANY	EVENT	YEAR	PEOPLE	ENVIRONMENT	ASSETS	FINANCE	REPUTATION	OTHER IMPACTS
OCCIDENTAL PETROLEUM	PIPER ALPHA DISASTER	1988	XXX (167)	X	XX	XX (3.5G$)	XX (UK)	Changed UK Legislation

EXAMPLES OF MAJOR HSE EVENTS THAT HAVE GREATLY IMPACTED THE INDUSTRY

2010



COMPANY	EVENT	YEAR	PEOPLE	ENVIRONMENT	ASSETS	FINANCE	REPUTATION	OTHER IMPACTS
BP	MACONDO DISASTER (Deepwater Horizon)	2010	XX (11)	XXX (GoM)	X	XXX (200G$+)	XXX (World)	O&G Industry game changer (major risks, drilling)

EXAMPLES OF MAJOR HSE EVENTS THAT HAVE GREATLY IMPACTED THE INDUSTRY

2011



COMPANY	EVENT	YEAR	PEOPLE	ENVIRONMENT	ASSETS	FINANCE	REPUTATION	OTHER IMPACTS
TEPCO	FUKUSHIMA CATASTROPHY	2011	XXX (1 direct, 20000 indirect)	XXX (Japan+, population displacement)	XXX	XXX (200 G$+)	XXX (World)	Changed Nuclear Industry Legislation

Air Pollution

- **Air pollution is the fourth largest human health risk**
  - *3.5 million premature deaths are linked to energy poverty due to the use of biomass for cooking and kerosene for lighting*
  - *3 million premature deaths are linked to outdoor air pollution, mostly in cities*
- **Many of its root causes – and cures – are in the energy sector**
  - *The majority of air pollutant emissions comes from the energy sector, mainly from fuel combustion*
  - *Currently only 8% of global energy production is combustion free: more than half of the rest has no effective technology in place to control emissions*
  - *No country in the world has solved the air pollution problem completely, but many are taking important policy steps*

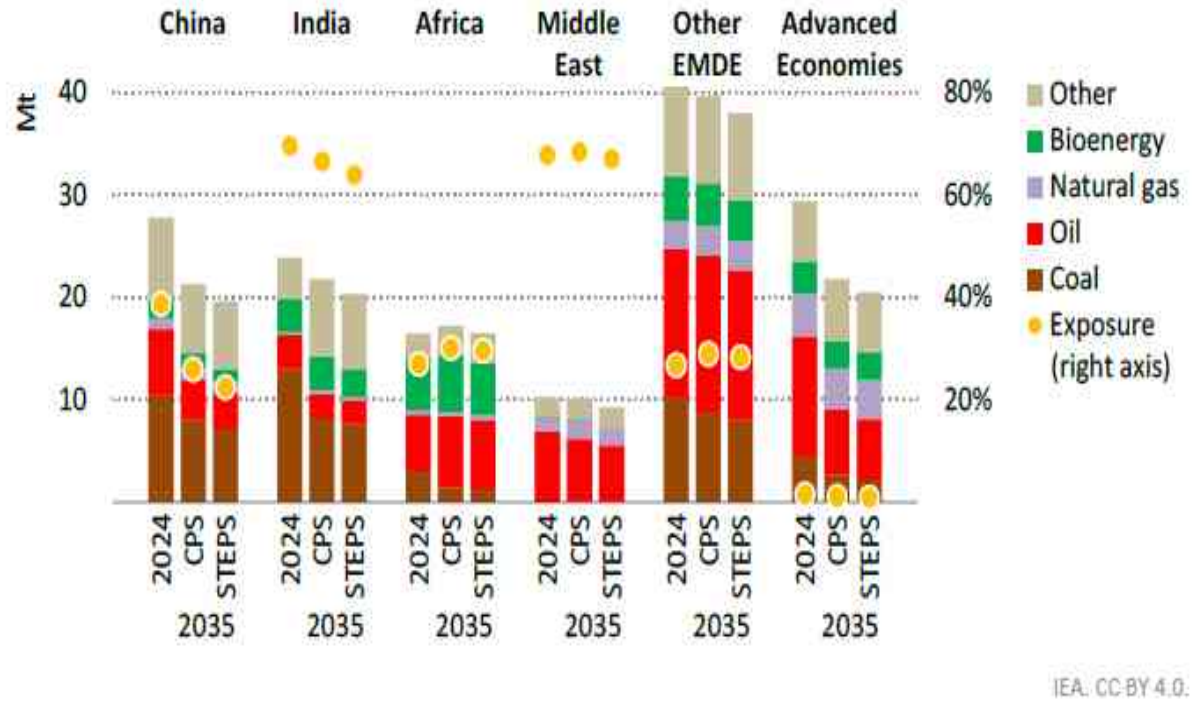
Source: IEA June 2016 – Special Report Energy and Air Pollution

Contribution of GHG and pollutants by sectors of activity
Among the fossil fuels, Gas is the less polluter



Source: NETL, EEA, OIES, BCG analysis

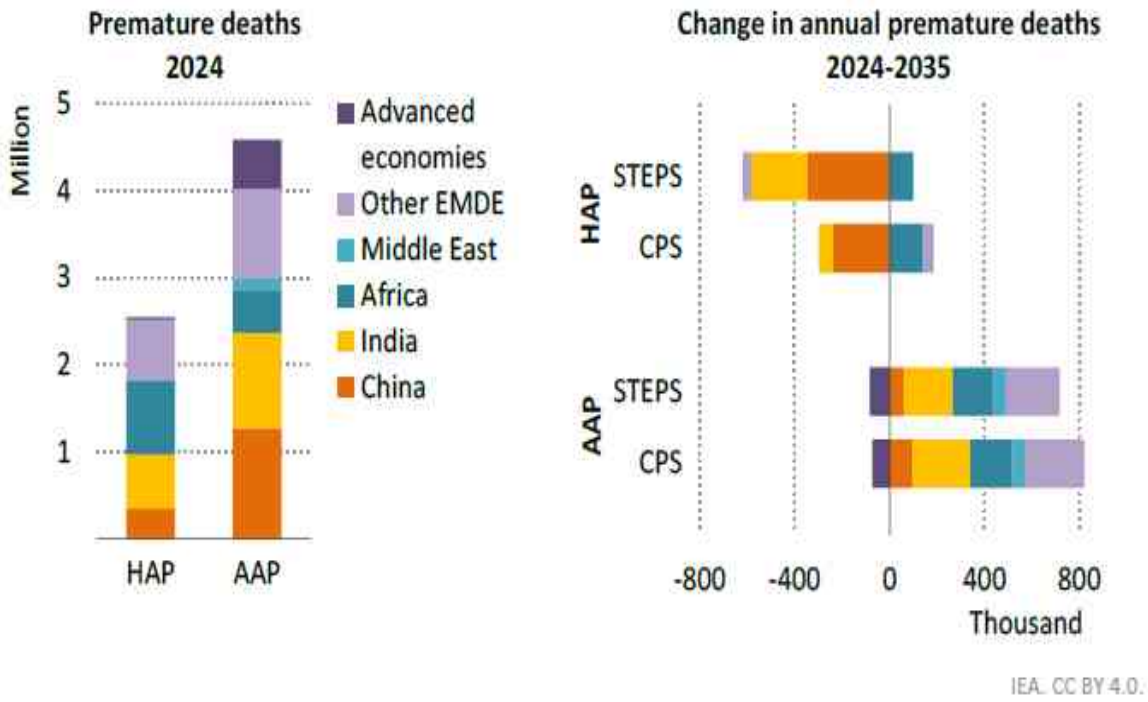
Impact of Air pollutants and premature deaths vs Scenarios by IEA 2025



Air pollution emissions and exposure to heavily polluted air decline in advanced economies and China, but see little or no improvement in other parts of the world

Notes: Total air pollution = sulphur dioxide (SO_2), nitrogen oxides (NO_x) and fine particulate matter ($PM_{2.5}$). Other = process emissions and combustion emissions from other fuels. Mt = million tonnes. Heavily polluted air corresponds to having a $PM_{2.5}$ density more than 35 microgrammes per cubic metre, in accordance with the World Health Organisation Interim Target 1 (WHO, 2021).

Source: IEA analysis based on International Institute for Applied Systems Analysis (IIASA).



Premature deaths from household air pollution were around 2.5 million in 2024 and decline in both scenarios; those from ambient air pollution rise in both scenarios, but more so in CPS

Note: HAP = household air pollution; AAP = ambient air pollution; STEPS = Stated Policies Scenario; CPS = Current Policies Scenario; EMDE = emerging market and developing economies.

Source: IEA analysis based on IIASA modelling.

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A Reminder: the 2008 - 2009 economic crisis & the 2020 Covid-19 sanitary crisis

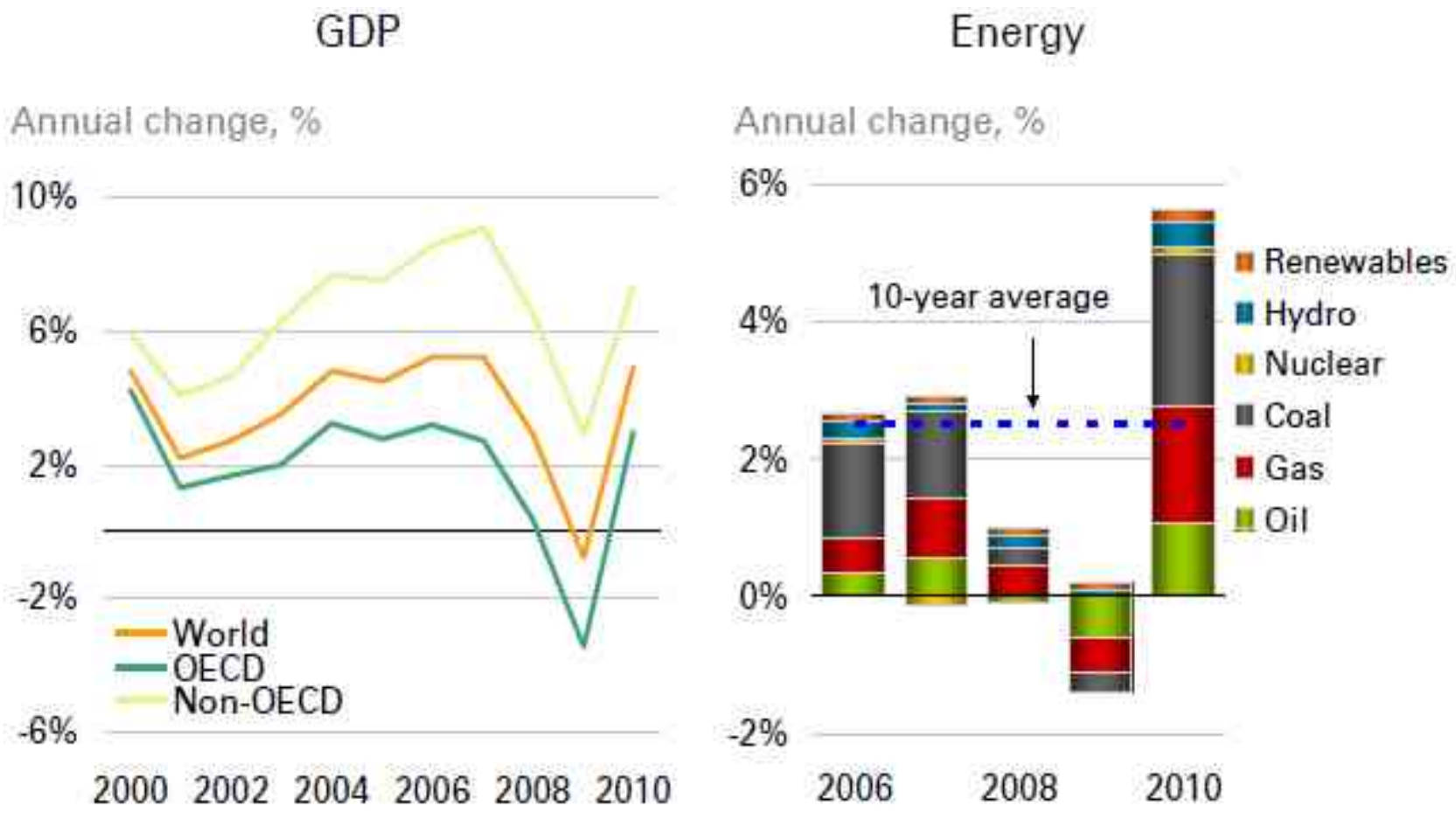
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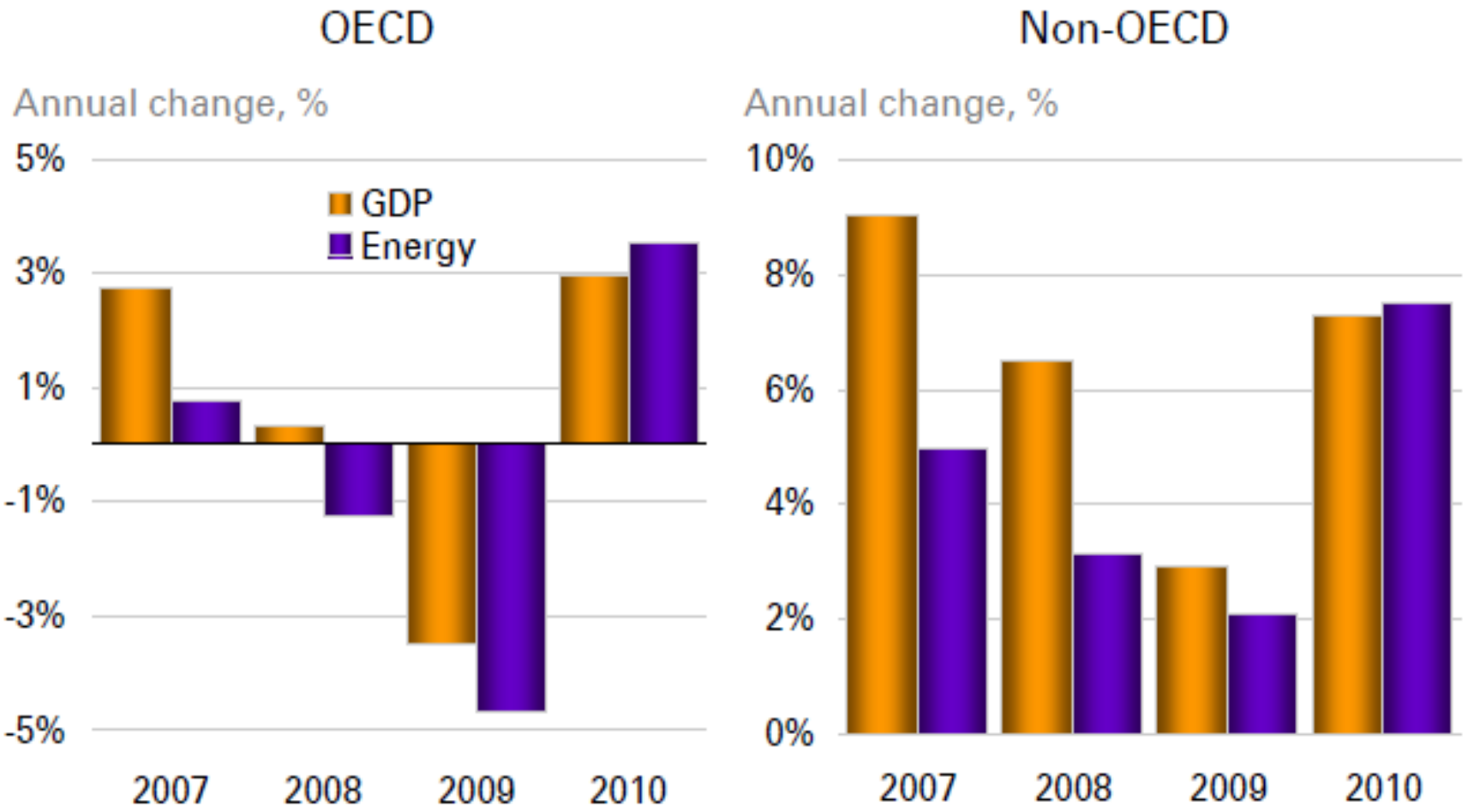
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Global Economy and Energy Demand
Lessons from the last World Economic Crisis



Source: BP Statistical Review 2011/Rühl

GDP and Energy Growth – OECD vs non-OECD



Source: BP Statistical Review 2011/Rühl

THE SHORT TERM IMPACT OF THE 2008 ECONOMIC CRISIS ENERGY IN 2009: FROM RECESSION TO RECOVERY……. ENERGY IN 2010: A STRONG REBOUND AND NOW?

GLOBAL PRIMARY ENERGY CONSUMPTION: - 1.1 % in 2009, +5.6% in 2010

CHINA'S SHARE OF ENERGY CONSUMPTION: 20.3% in 2010

NATURAL GAS CONSUMPTION: +7.4% in 2010

COAL SHARE OF WORLD ENERGY CONSUMPTION: 29.6% in 2010

CHINESE SHARE OF COAL CONSUMPTION: 48.2% in 2010

STRONG REBOUND IN 2010, BUT SLOW GROWTH IN OECD SINCE THEN…..ALSO, DECLINING GROWTH IN CHINA…….

SLOW DEMAND, OIL SHALES PRODUCTION IN THE US → BRENT OIL PRICE DOWN TO 80 $/b IN NOVEMBER 2014, 60 $/b AFTER OPEC MEETING (OPEC PRODUCTION CEILING UNCHANGED AT 30 MB/D), 37 $/b END DECEMBER 2015 ! 55 $/b JANUARY 2017, # 80 $/b IN OCTOBER 2018, # 66 $/b IN DECEMBER 2019…….

The 2020 Covid-19 Sanitary Crisis and its impact on the World Economy

The Covid - 19 Crisis and the economic potential consequences – The history

- Starting in China, the Covid-19 crisis has upset the world economic activity during more than 18 months.
  - Confinement in China has been slowed down and partially stopped the economic activity in this country since january 2020, with huge detrimental consequences on the world trade.
  - The extension of the epidemia to many other countries in the world including Europe and US has accentuated the economic crisis.
  - From late January to May 2020, more than 3 billion people confined. A second wave and a third wave of the pandemia have been progressing.
  - A global world programme for vaccination has been put in place.
- World economic activity partially or entirely stopped during several months.

→ World GDP: # - 5% in 2020 vs 2019.

Recovery: at which rythm? Estimates show an important potential rebound in 2021.

Decrease of Primary Energy consumption: # - 5% in 2020 vs 2019.

Decrease of CO2 emissions: # - 6% in 2020 vs 2019. An important rebound is expected in 2021.

Substantial change of people behaviour and way of life?

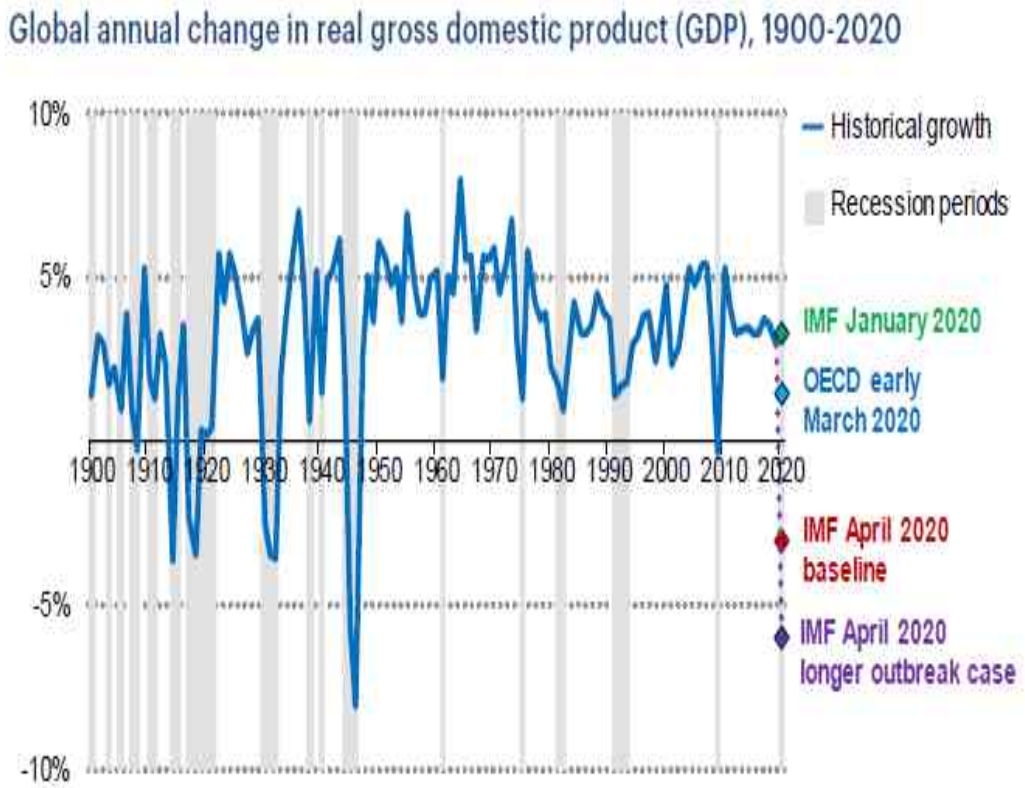
The Covid - 19 Crisis and the economic potential consequences – The History

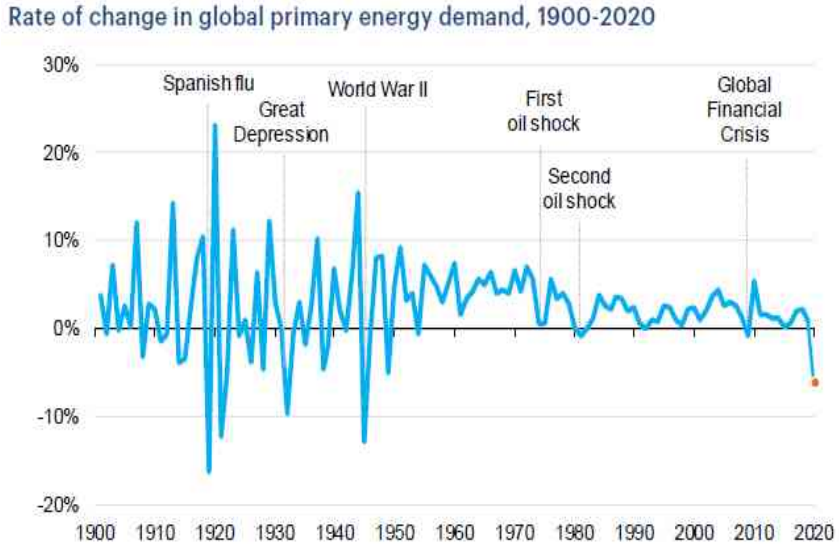
- The immediate effect of Covid-19 crisis was a drop in the Energy demand and consequently in the Oil demand.
- In first half of 2020,the OPEC countries together with Russia discussed a possible decrease of production to limit an oil price fall, but Russia refuses to do so, and Saudi Arabia reacted by increasing its own production up to 12 Mb/d. The overall consequence was an over-supply of the market by at least 10 Mb/d!
- As a result, crude oil prices decreased from 70/60 $/b down to 25/20 $/b...then increase up to 42 $/b begining September 2020.
- Following the sanitary measures applied in the world and the vaccination campaign, confidence in the Economy and the Energy world has been regained. The crude oil price increased up to # 70 $/b in June 2021. The OPEC countries are under discussions to stabilize the market.
- Oil price is an important marker for the World Economy. Its future evolution will have a strong impact too on Energy Transition.

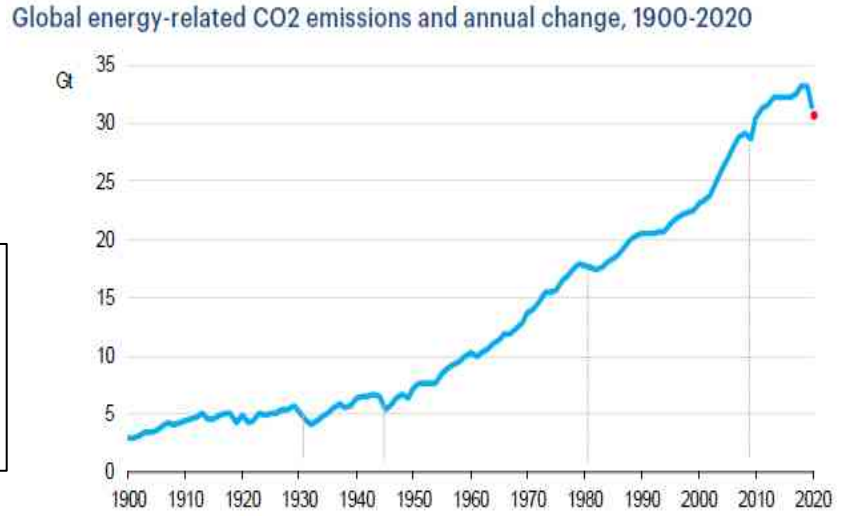
→ In 2020, drastic fall for Investments in the Energy sector (except for Solar Energy), delays in Energy transition developments, rebalance of energy sources competitiveness have been experienced.

→ The impacts and consequences of this crisis are estimated in the scenarios presented hereafter. They could give arguments to promote the IEA Sustainable Development Scenario (SDS)

A vision by IEA April 2020



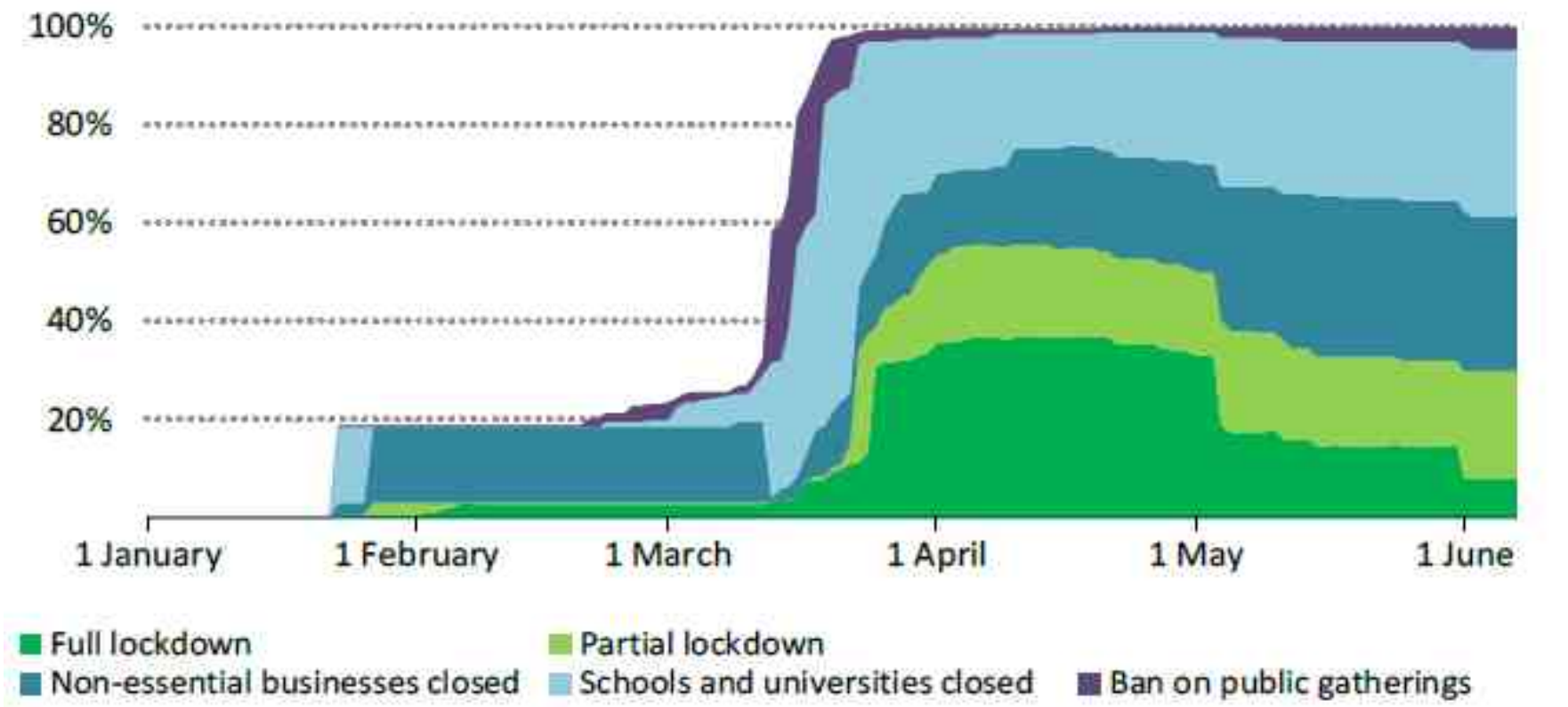




The final impact of Covid-19 on year 2020 might evolve depending upon the development of the pandemia

Source: IEA April 2020
Global Energy Review 2020

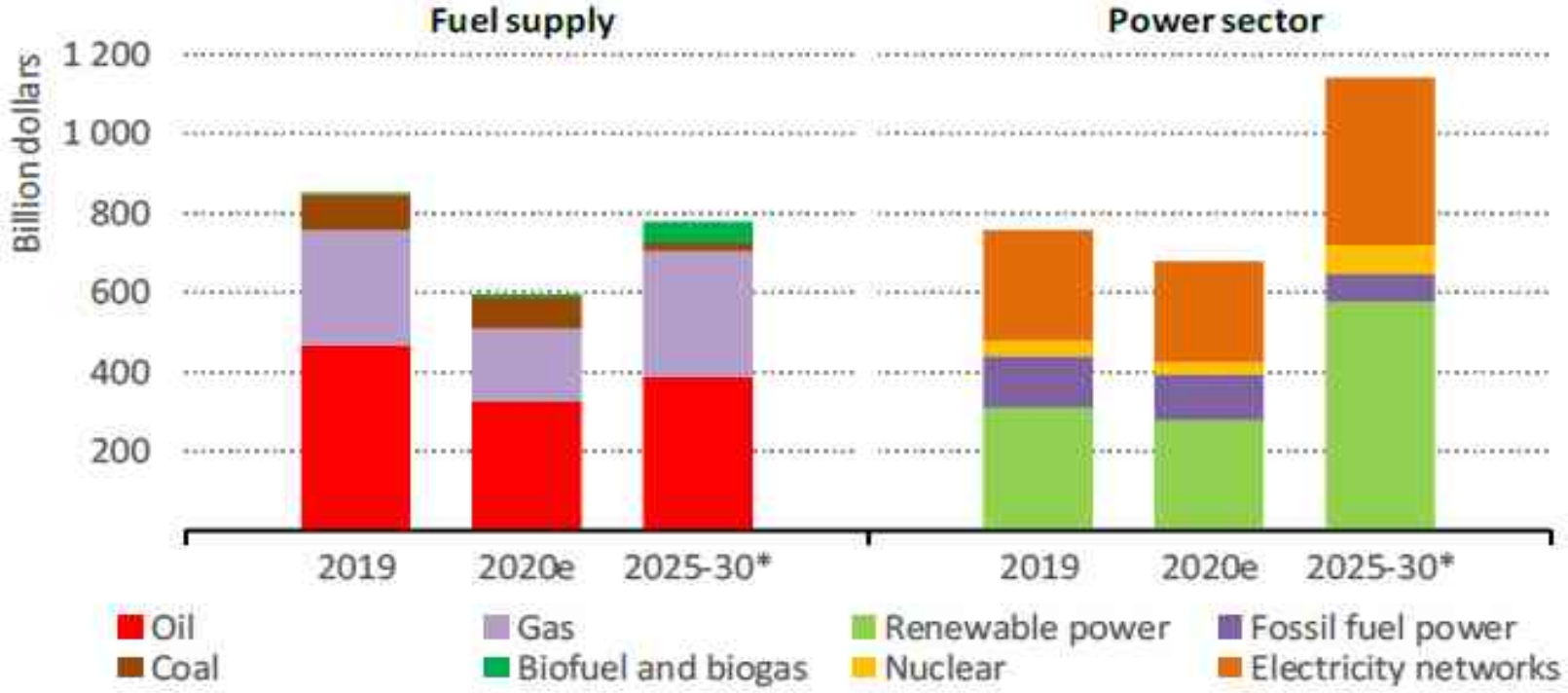
Global Population under Containement Measures



Measures to contain the spread of the pandemic started at the end of January. In mid-May, around one-third of the global population remained under full or partial lockdown.

Source: IEA/IMF Sustainable Recovery June 2020
World Energy Outlook Special Report

Energy Sector Investment and Projections (SDS)
Impact of the Covid-19 in 2020



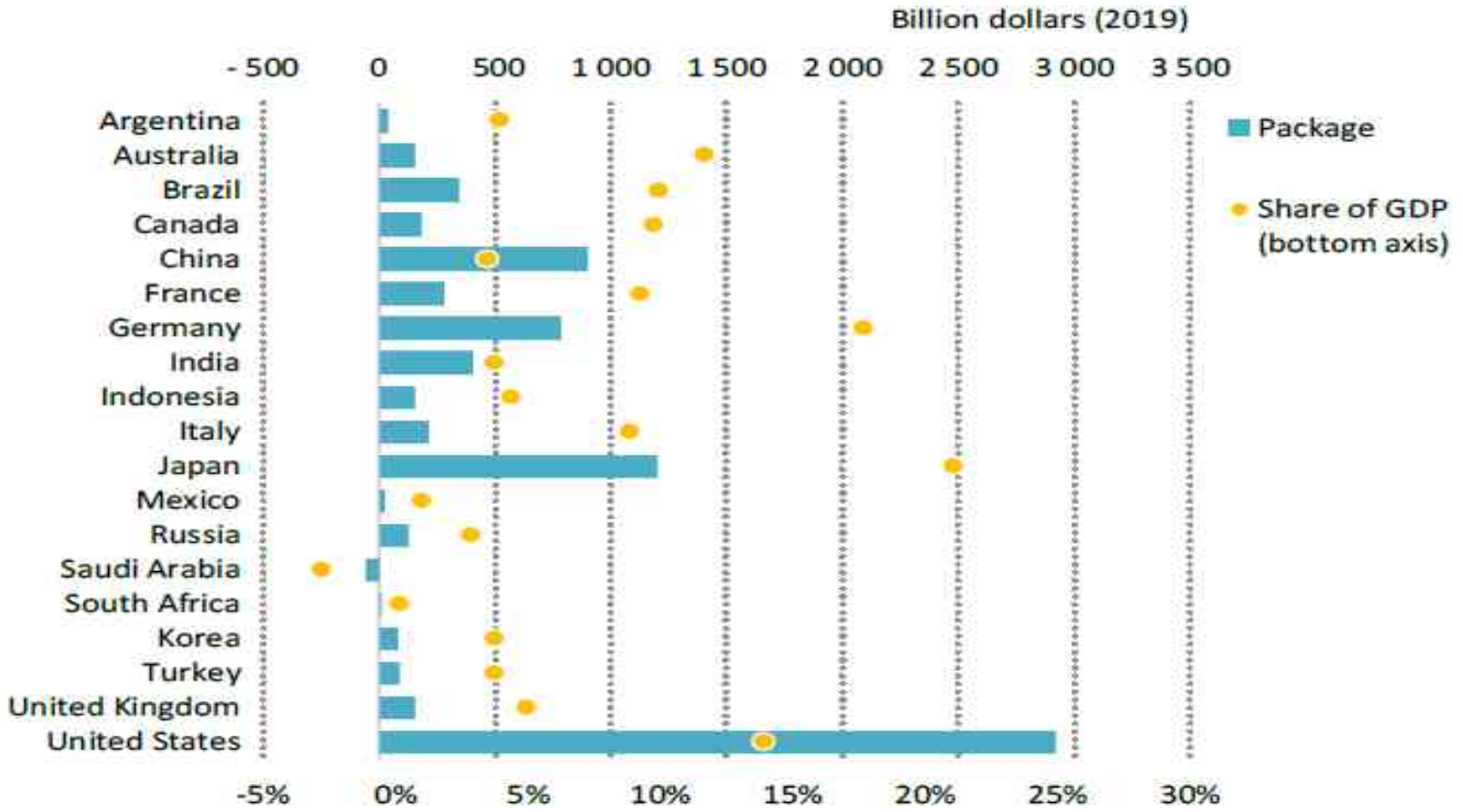
Investment levels have dropped across the board, especially in oil and gas. Power sector investments are at half the levels seen in the Sustainable Development Scenario.

* Annual average in the Sustainable Development Scenario. Note: 2020e = estimated values for 2020.

Source: IEA (2020d).

Source: IEA/IMF Sustainable Recovery June 2020
World Energy Outlook Special Report

Emergency Fiscal Measures - Covid 19
G20 Countries

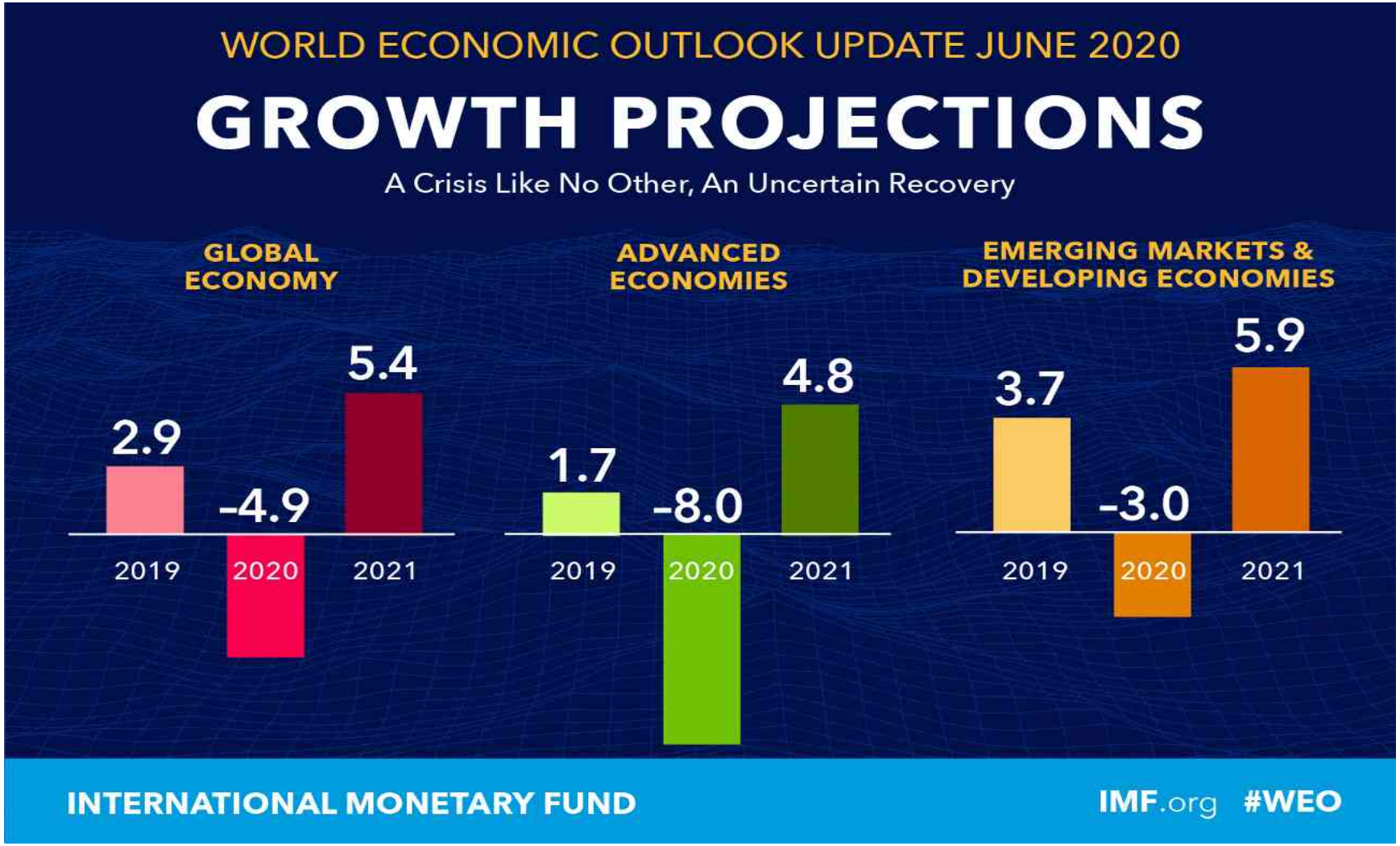


In G20 countries, emergency fiscal measures vary between -3% and 21% of GDP – similar to the large variation of final recovery plans after the 2008-09 financial crisis.

Source: IEA/IMF Sustainable Recovery June 2020
World Energy Outlook Special Report

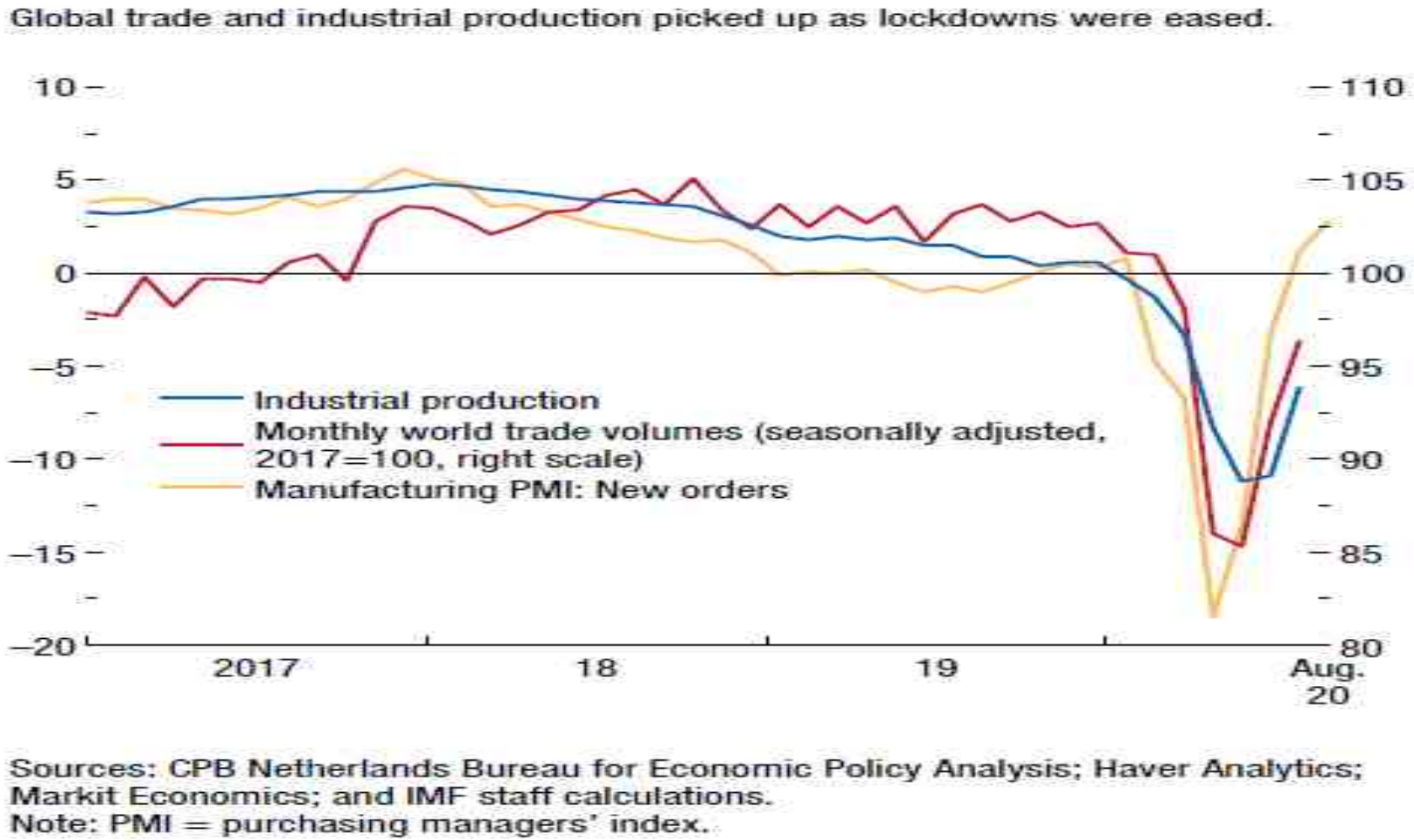
The Global Economic Vision
by IMF World Economic Outlook 2020/2021
The Covid-19 Impact

Covid-19/IMF June 2020 Growth Projections



Source: IMF WEO Update June 2020

Global Trade and Production Indicators
Impact of the Covid-19 according to IMF June 2020

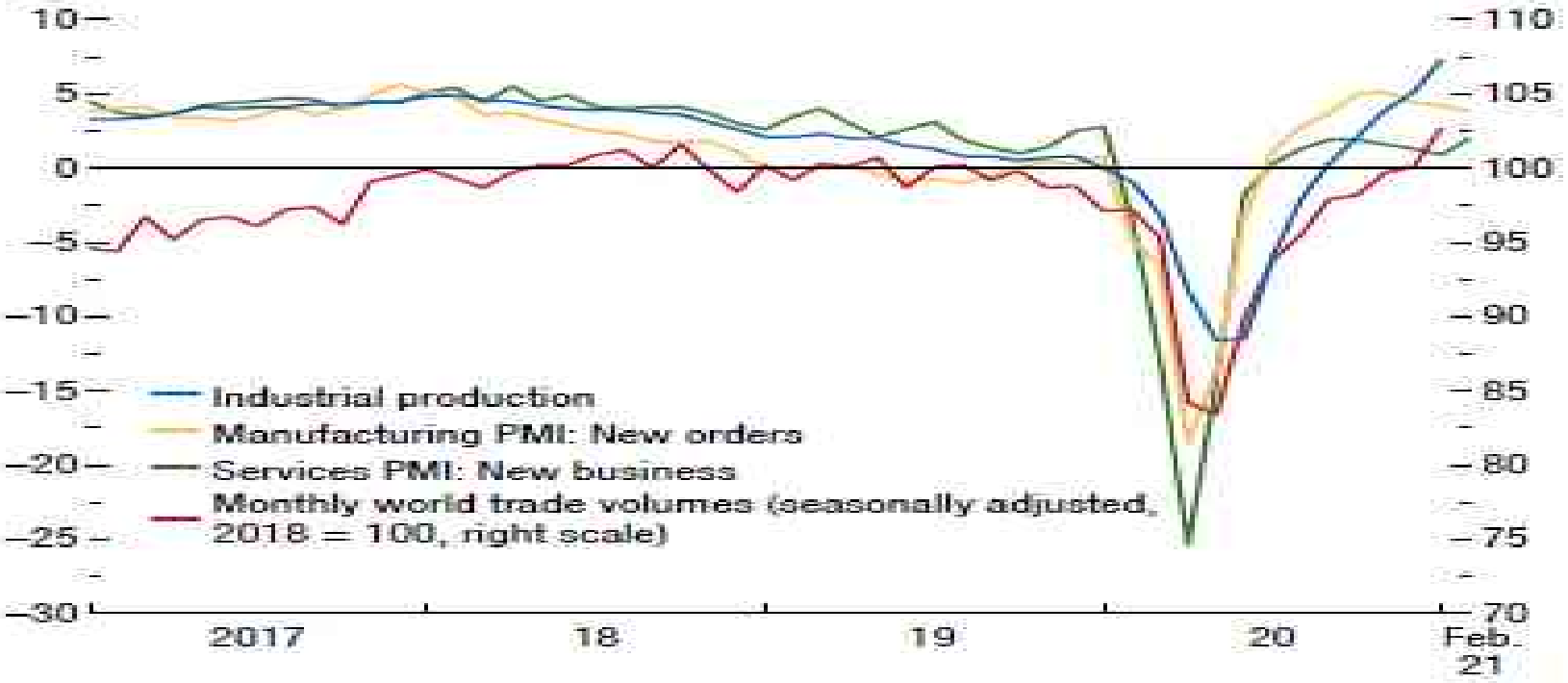


Source: IMF 2020 – World Economic Outlook
Note: PMI : Purchasing Managers' Index

Global Trade and Production Indicators
Impact of the Covid-19 according to IMF April 2021

(Three-month moving average, annualized percent change; deviations from 50 for PMI, unless noted otherwise)

High-frequency indicators suggest that manufacturing and trade are back to pre-pandemic levels, but there is still some way to go in the services sector.



Sources: CPB Netherlands Bureau for Economic Policy Analysis; Haver Analytics; Markit Economics; and IMF staff calculations.
Note: PMI = purchasing managers' index.

Source: IMF WEO Update April 2021

GDP Growth according to IMF April 2021
Base case (% per annum)

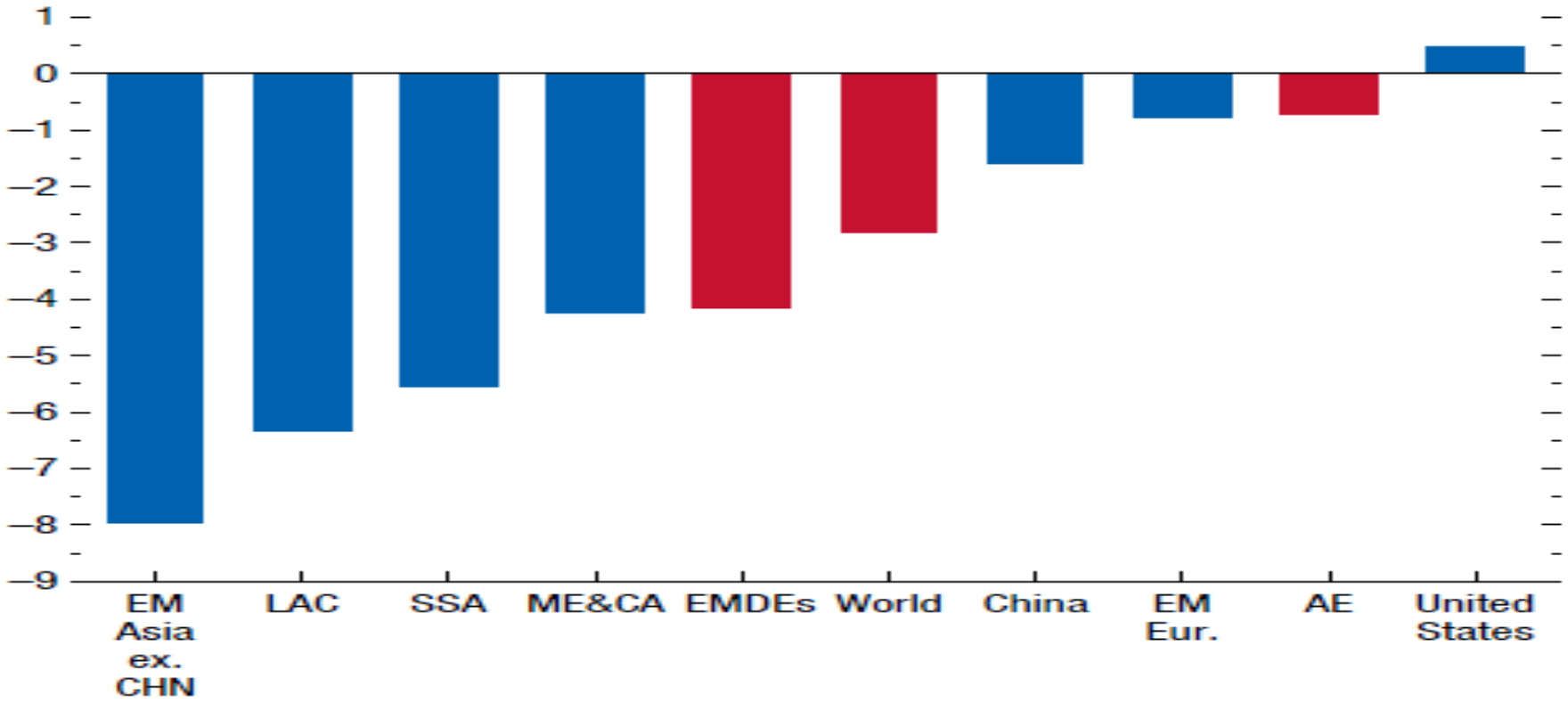
GDP at Market Exchange Rate

		Projections	
	2020	2021	2022
World Output	**–3.6**	**5.8**	**4.1**
Advanced Economies	**–4.7**	**5.2**	**3.6**
Emerging Market and Developing Economies	**–2.0**	**6.6**	**4.9**
Emerging and Developing Asia	–0.1	8.4	5.8
Emerging and Developing Europe	–2.3	4.3	4.0
Latin America and the Caribbean	–7.0	4.5	3.1
Middle East and Central Asia	–4.1	3.6	3.6
Sub-Saharan Africa	–2.5	3.4	3.8
Memorandum			
European Union	–6.2	4.3	3.8
Middle East and North Africa	–4.7	3.8	3.5
Emerging Market and Middle-Income Economies	–2.1	6.8	4.9
Low-Income Developing Countries	–0.3	4.3	5.1

Source: IMF staff estimates.

Note: The aggregate growth rates are calculated as a weighted average, in which a moving average of nominal GDP in US dollars for the preceding three years is used as the weight. WEO = *World Economic Outlook*.

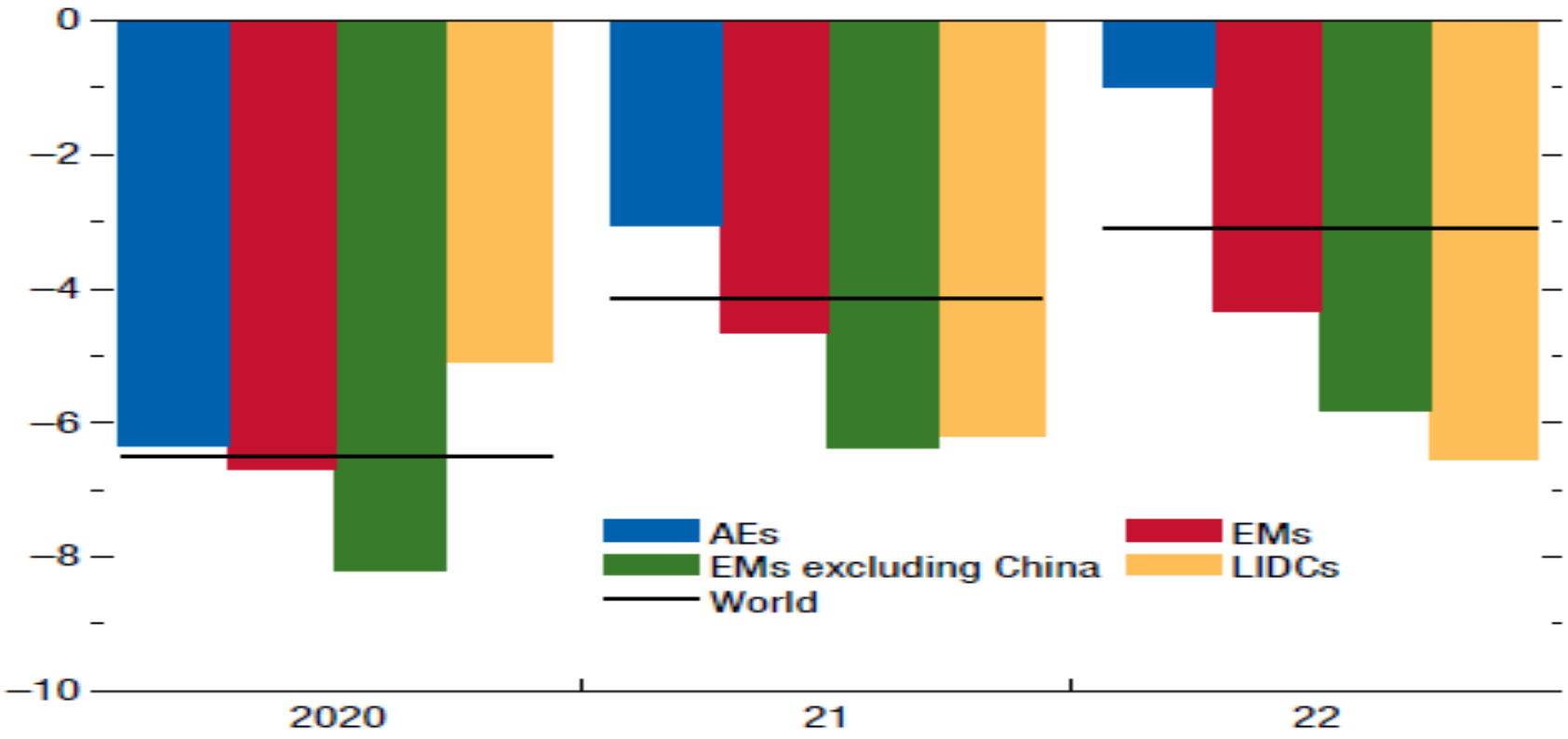
GDP expected cumulated Growth in 2024 vs pre-pandemic forecasted trends according to IMF April 2021 (%)



Source: IMF staff estimates.
Note: AE = advanced economies; EM Asia ex. CHN = emerging and developing Asia excluding China; EM Eur. = emerging and developing Europe; EMDEs = emerging market and developing economies; LAC = Latin America and the Caribbean; ME&CA = Middle East and Central Asia; SSA = sub-Saharan Africa.

Source: IMF WEO April 2021

GDP per Capita Cumulative Growth 2019 - 2021
Impact of the Covid-19 by IMF April 2021 (%)

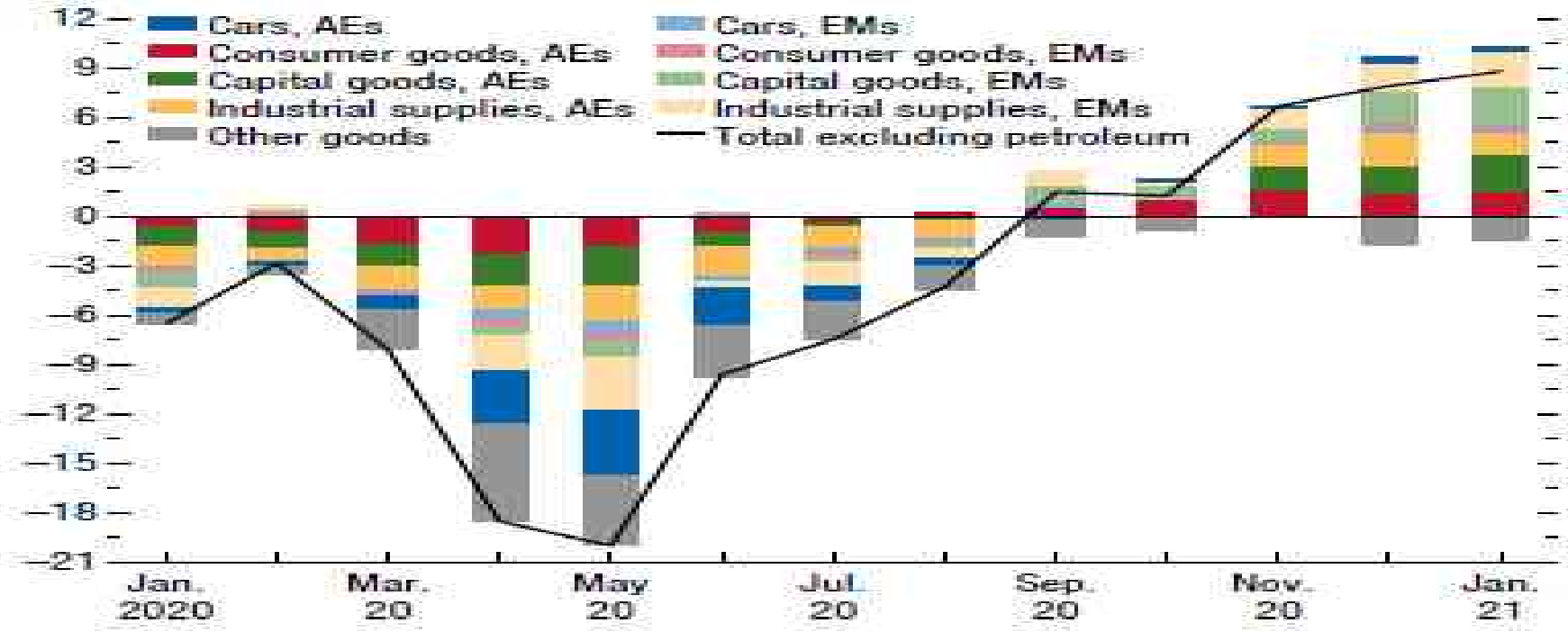


Source: IMF staff estimates.
Note: Per capita real GDP (2017 purchasing-power-parity dollars) is used in the calculations. AEs = advanced economies; EMs = emerging market economies; LIDCs = low-income developing countries; WEO = *World Economic Outlook*.

Source: IMF WEO April 2021

Global Imports – Contributions by Types and Regions Impact of the Covid-19 by IMF April 2021 (%)

The sharp rebound in international trade in the second half of 2020 reflects pent-up demand for consumer durables (cars) from advanced economies and resumption of supply chains in emerging markets.

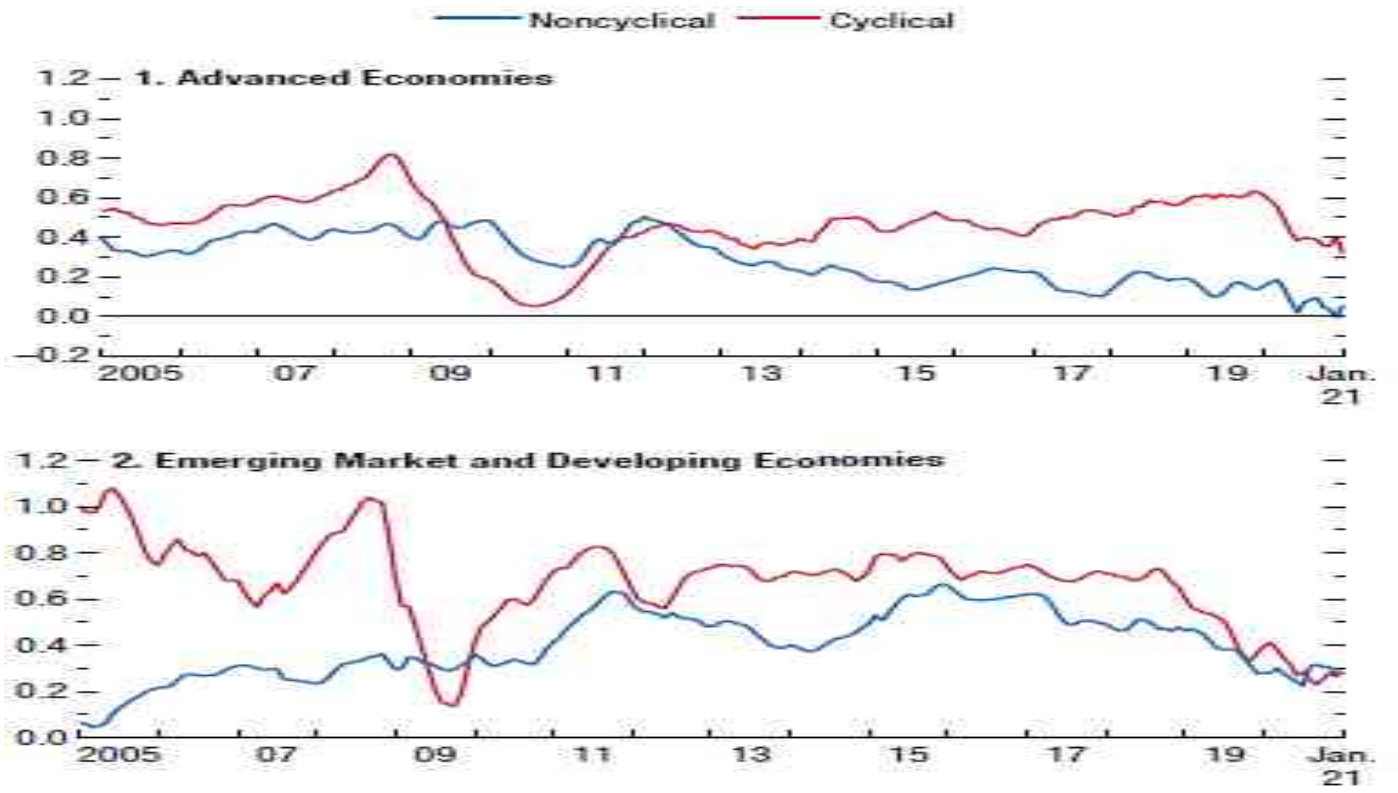


Sources: Haver Analytics; and IMF staff calculations.
Note: Advanced economies (AEs) comprise Australia, Canada, Denmark, euro area, Hong Kong SAR, Israel, Japan, Korea, New Zealand, Sweden, Taiwan Province of China, United Kingdom, and United States. Emerging market economies (EMs) comprise Argentina, Brazil, Chile, China, Colombia, Hungary, India, Malaysia, Mexico, Peru, Philippines, Poland, Russia, South Africa, Thailand, and Turkey.

Source: IMF WEO April 2021

Headline Inflation according to IMF April 2021 (%)

Price inflation (excluding food and energy) has dropped in sectors usually sensitive to fluctuations in aggregate demand (cyclical) and those that are not.



Sources: Eurostat; Haver Analytics; Organisation for Economic Co-operation and Development; and IMF staff calculations.
Note: The figure plots the time fixed effects of regressions in which three-month trailing averages of contributions to headline inflation are regressed on country and time fixed effects, with the weights being the GDP in purchasing-power-parity terms. The contribution of a component is defined as its year-over-year price change multiplied by its weight in the headline consumer price index basket.

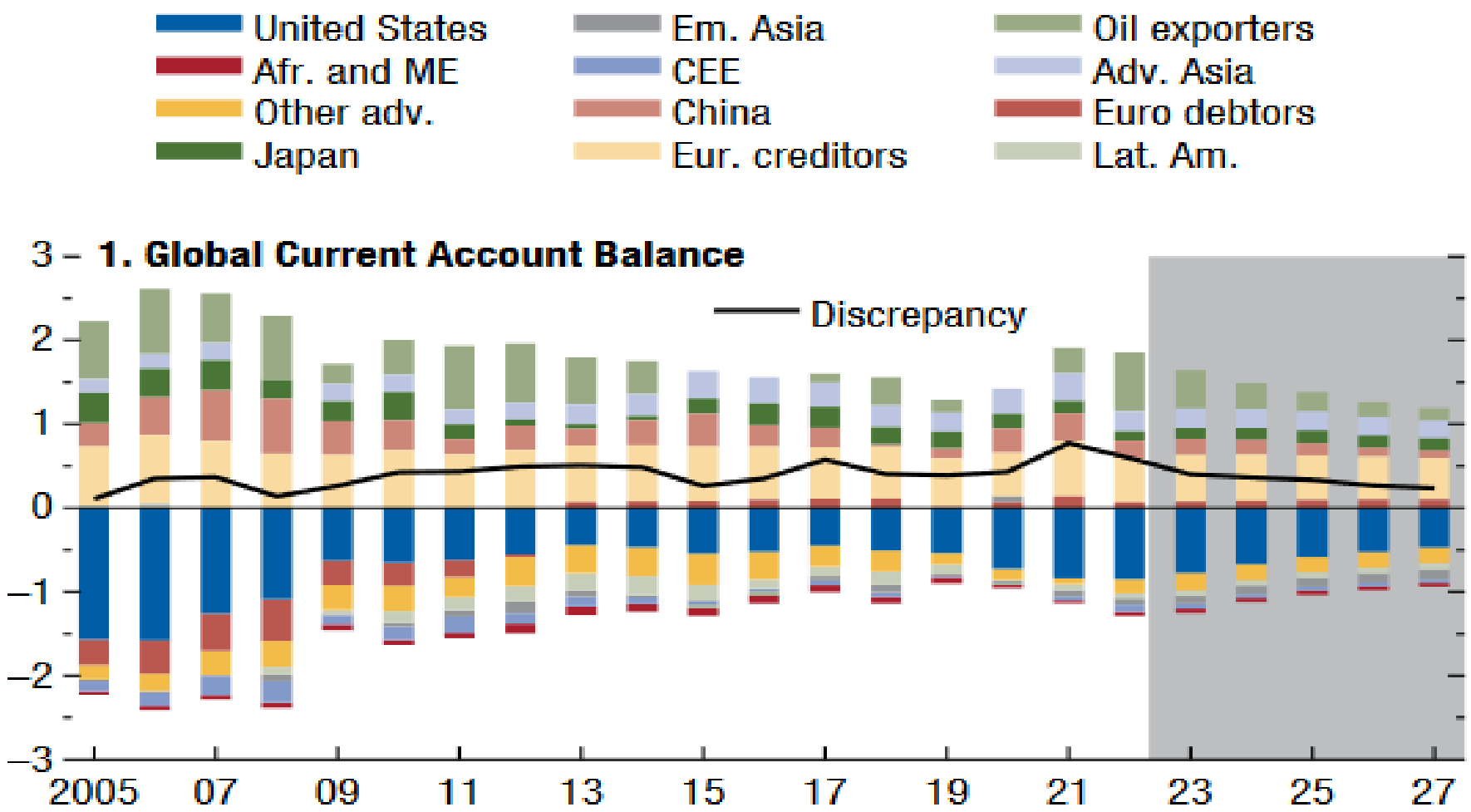
Nota:

Cyclical components include furnishing, household equipment and routine household maintenance, housing (excluding utilities whenever the data permit), recreation and culture, and restaurants and hotels.

Noncyclical components include clothing and footwear, communication, education, health, and miscellaneous goods and services.

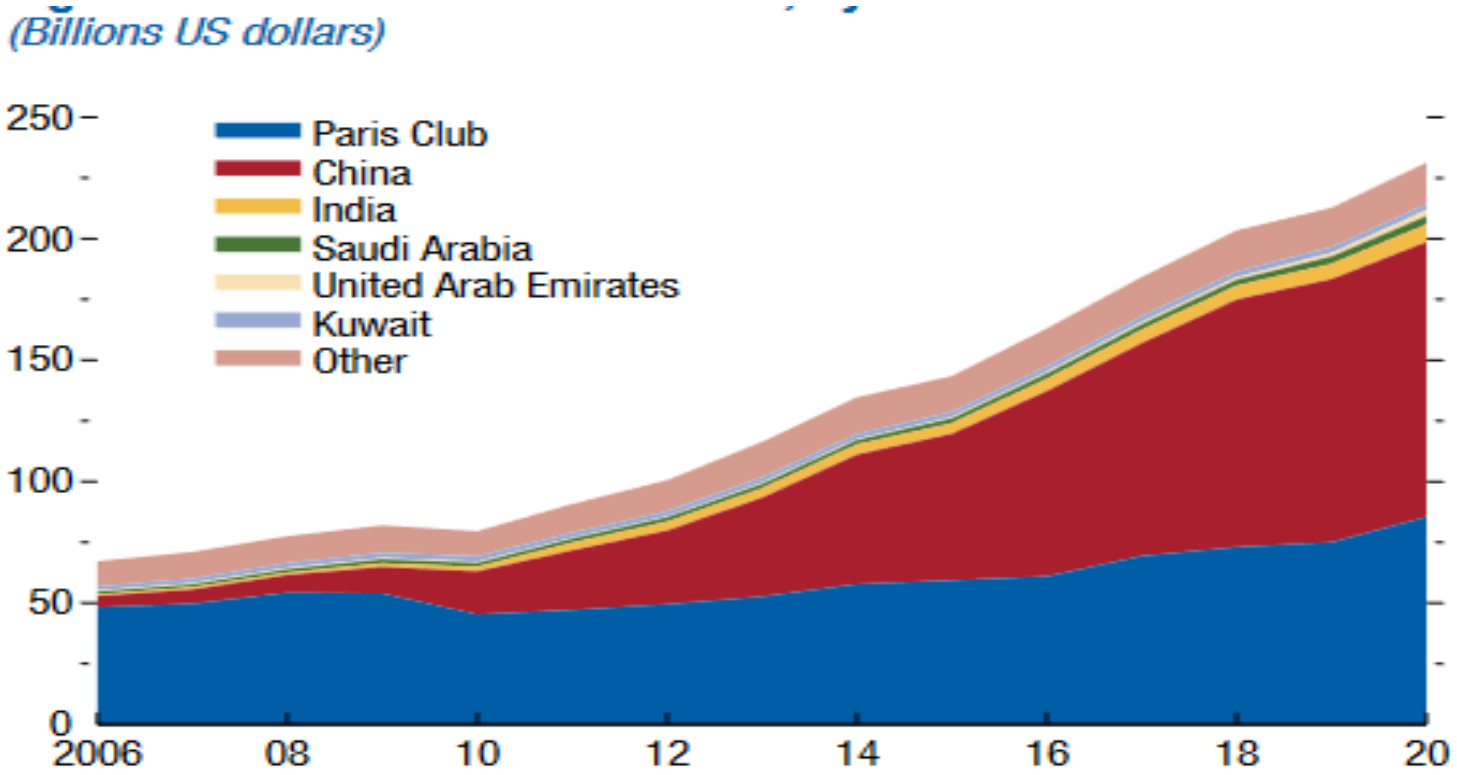
Source: IMF WEO April 2021

Global Current Account Balance according to IMF April 2022 (% of World GDP)



Source: IMF WEO 2022

Public External Debt



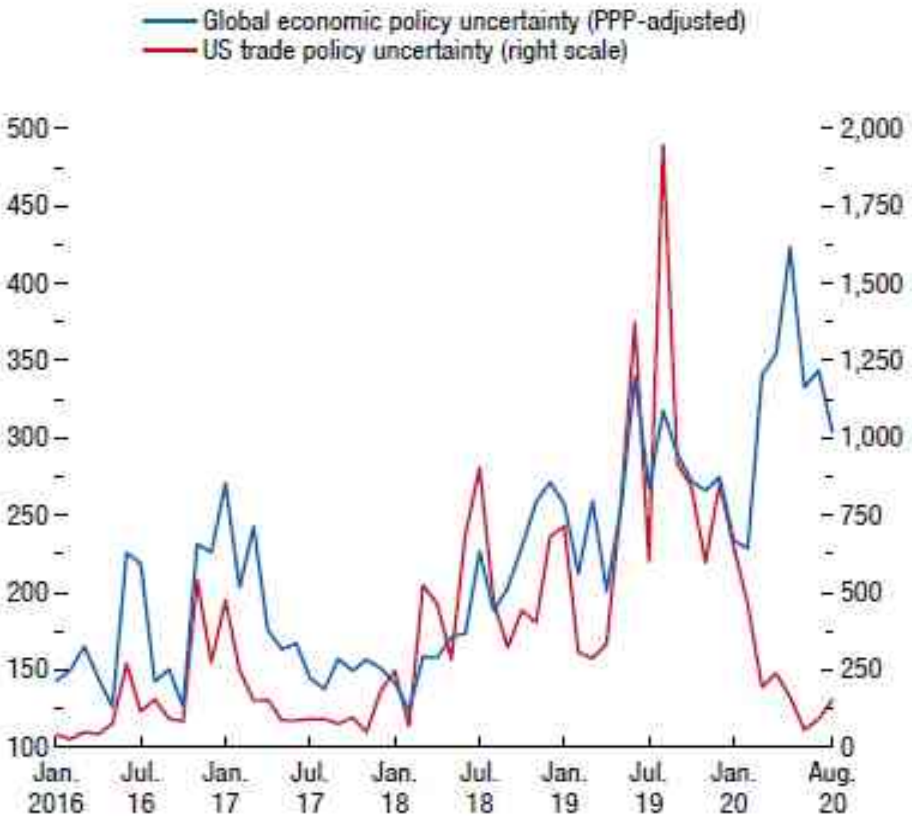
Source: World Bank, International Debt Statistics.
Note: The figure shows public and privately guaranteed debt of countries eligible for the Debt Service Suspension Initiative. In terms of International Organization for Standardization (ISO) country codes, the Paris Club is composed of AUS, AUT, BEL, BRA, CAN, CHE, DEU, DNK, ESP, FIN, FRA, GBR, IRL, ISR, ITA, JPN, KOR, NLD, NOR, RUS, SWE, USA.

Source: IMF WEO April 2022

Global Economic Policy remains uncertain and Geopolitical Risk remains high – IMF 2020 (Index)*

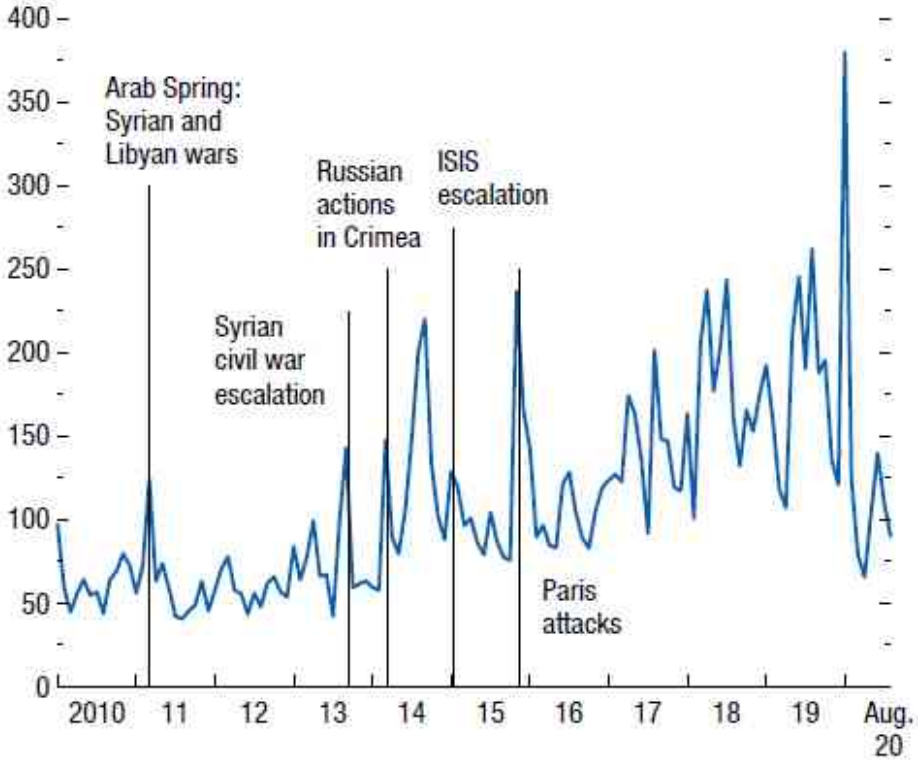
In 2022, a new worrying event: the russian invasion of Ukraine

Trade policy uncertainty has declined recently, but trade tensions remain elevated.



Source: Baker, Bloom, and Davis 2016.

Geopolitical tensions seemed to de-escalate during the pandemic but could again flare up.



Source: Caldara and Iacoviello 2018.

Source: IMF 2020 - World Economic Outlook
*See Indexes definition in next slide

Global Economic Policy remains uncertain and Geopolitical Risk remains high – IMF 2020 (Index) Definition of Indexes

Note: The Baker Bloom Davis Index of Global Economic Policy Uncertainty (GEPU) is a GDP-weighted average of national EPU indices for 20 countries: Australia, Brazil, Canada, Chile, China, France, Germany, Greece, India, Ireland, Italy, Japan, Korea, Mexico, the Netherlands, Russia, Spain, Sweden, the United Kingdom, and the United States. Mean GEPU from 1997 to 2015 = 100; mean US trade policy uncertainty index from 1985 to 2010 = 100. PPP = purchasing power parity.

Note: The Caldara and Iacoviello Geopolitical Risk index reflects automated text-search results of the electronic archives of 11 national and international newspapers. The index is calculated by counting the number of articles related to geopolitical risk in each newspaper for each month (as a share of the total number of news articles) and normalized to average a value of 100 over the 2000–09 decade. ISIS = Islamic State.

Source: IMF 2020 - World Economic Outlook

20

Some geopolitical considerations – Impact of Ukraine invasion by Russia & geopolitical events

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- 7. Global Energy Growth – Scenarios from various organizations
- 8. Global Energy Growth – Mobility/Transport
- 9. Global Energy Growth – A zoom on Hydrogen
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- 11. Global Energy Growth – Electricity storage
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- 20. Some geopolitical considerations – Impact of Ukraine invasion by Russia & geopolitical events – Iran/Israel/US war
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The World of Energy and Global Economy
The impact of geopolitical events



A zoom on the Energy crisis and the Russia invasion of Ukraine

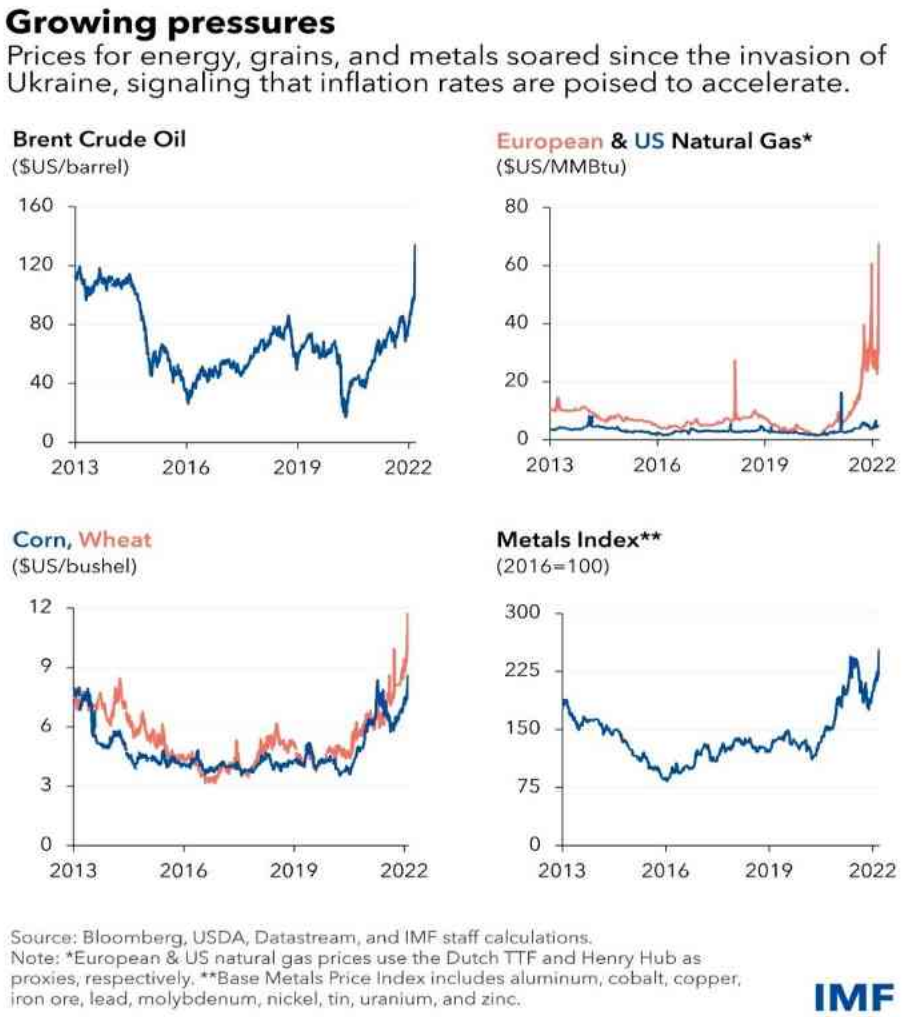
February 2022: Russia attacks Ukraine
How the 2022 Energy crisis could have been anticipated and is exacerbated by the Russia – Ukraine crisis

A picture of the situation & perspectives evaluated in 2022/2023

Russia – Ukraine War - 2022
Major Impact on World Economy and Energy Markets



Source: Harvard University – International Monetary Fund

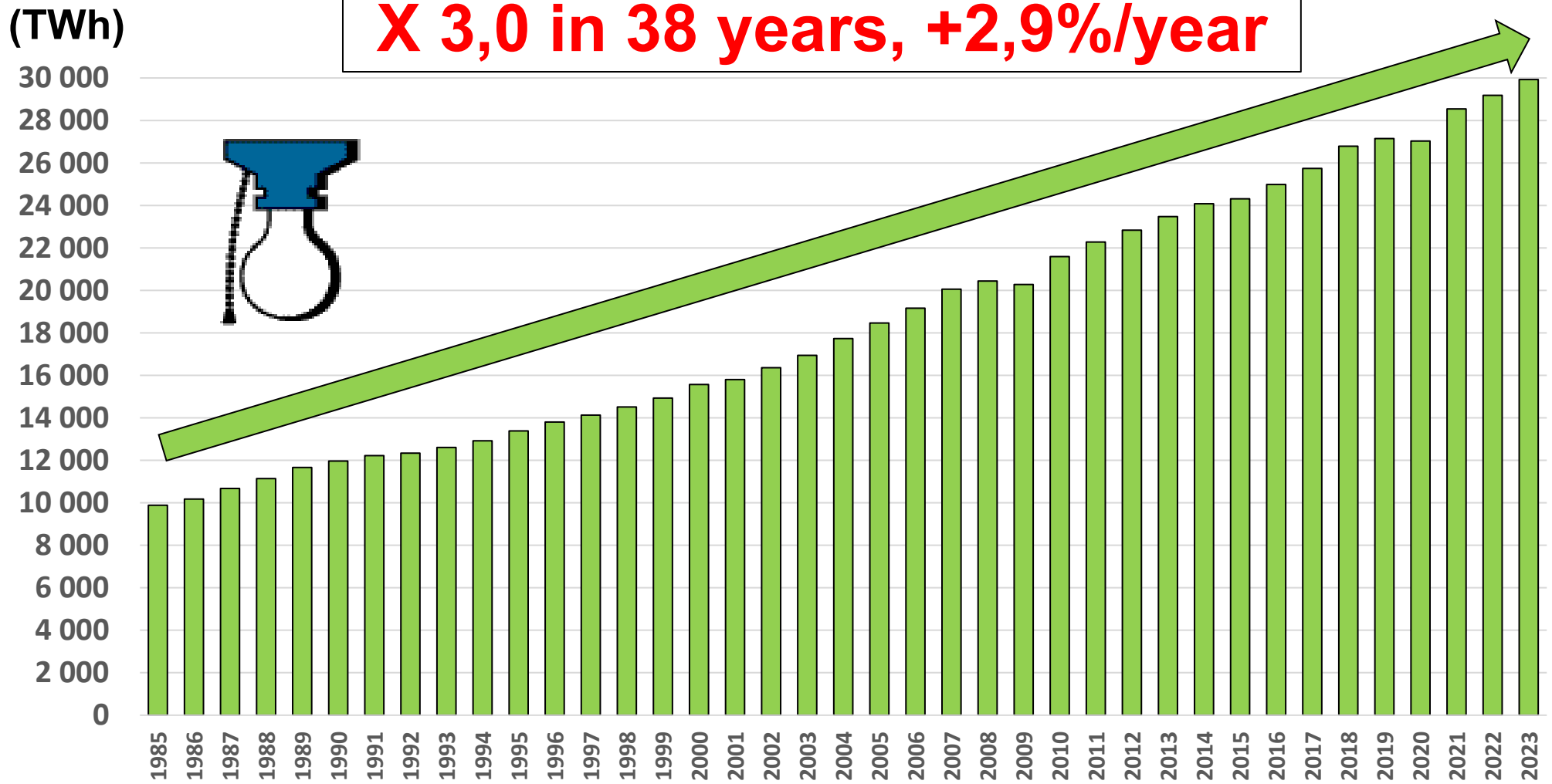


THE 2022 ENERGY CRISIS COULD HAVE BEEN ANTICIPATED

- During the last 35 years, Electricity Generation in the World has grown by 3% per year.
- In line with Energy Transition, Electricity Demand will continue to grow substantially fed by Gas-fired power plants and Renewables.
- In the recent past, important increase of Investments for Renewables, lack of Investments in Oil & Gas as well as in Nuclear characterized the Energy sector financing.
- With the increasing Demand for Natural Gas in Europe, including anticipation for back-up needs for Renewables, the lack of new investments led to a sharp increase of Gas and Electricity prices.
- This phenomena has been exacerbated by the Ukraine/Russia crisis.

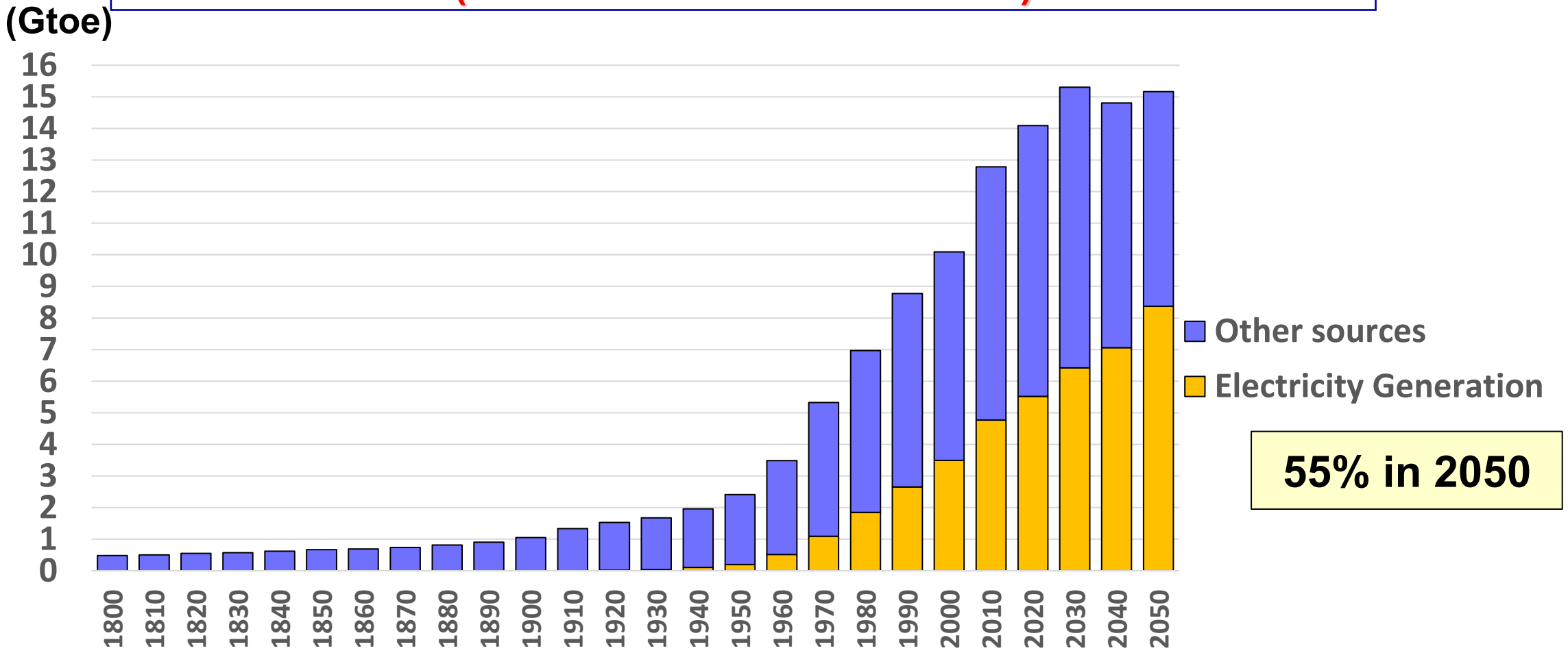
World Electricity Generation 1985 - 2023

Constant Electricity Generation Growth
From 10000 TWh in 1985 to # 30000 TWh in 2023
X 3,0 in 38 years, +2,9%/year



Source: Data from EI Stat. Review 2024

In terms of Primary Energy equivalent demand, electricity is taking more and more importance in the Energy mix (2020 – 2050: IEA 2024 APS)



Source; Ch.Guéritte Nota: 1 Mtoe = 11632 Gwhe. Data from IEA WEO 2024
1 Gwhe # 2,6 GWh eq. Primary Energy in 2010
2,4 GWh eq. Primary Energy in 2020
1,5 GWh eq. Primary Energy in 2040
1,4 GWh eq. Primary Energy in 2050

Various Electricity Generation Sources











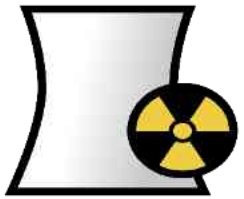








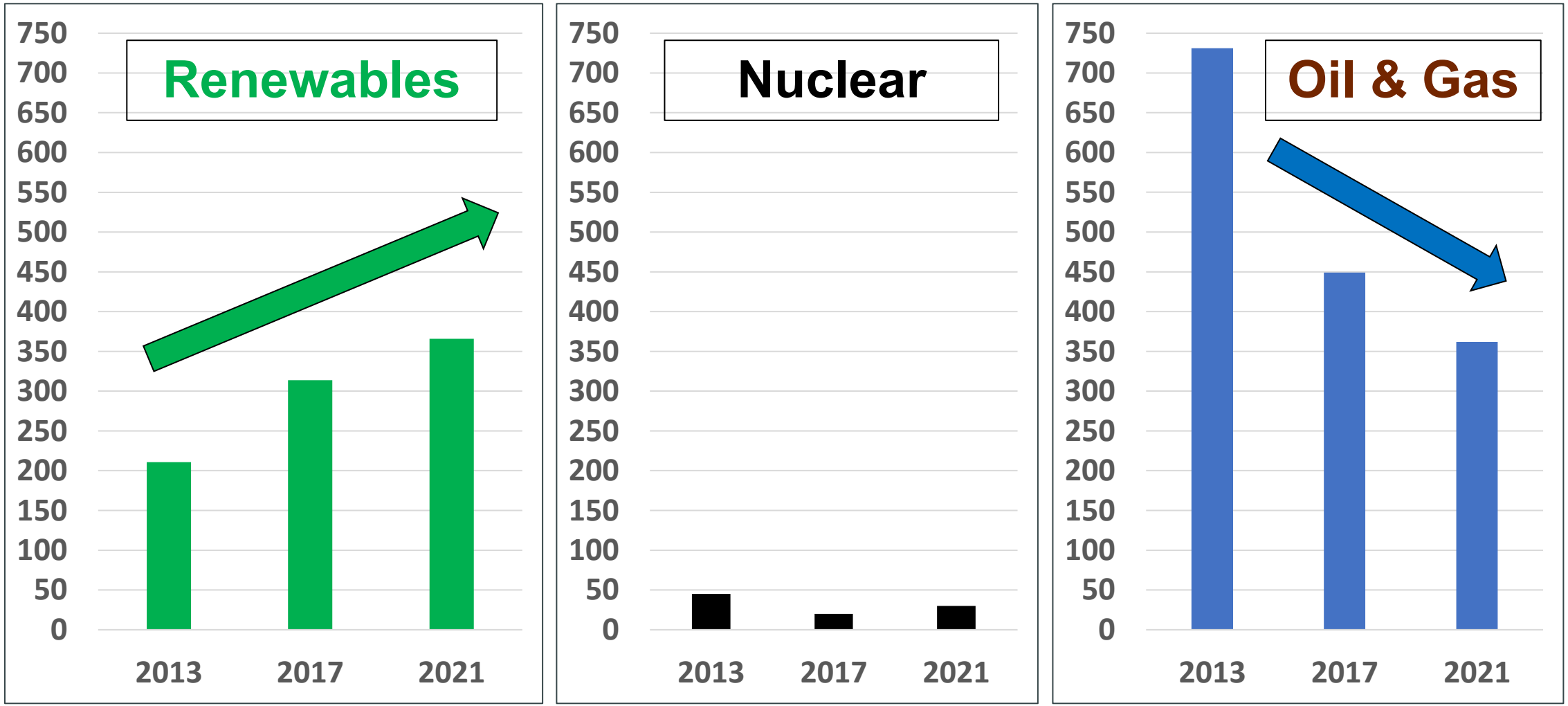






World Energy Investments from 2013 to 2021 (G$)

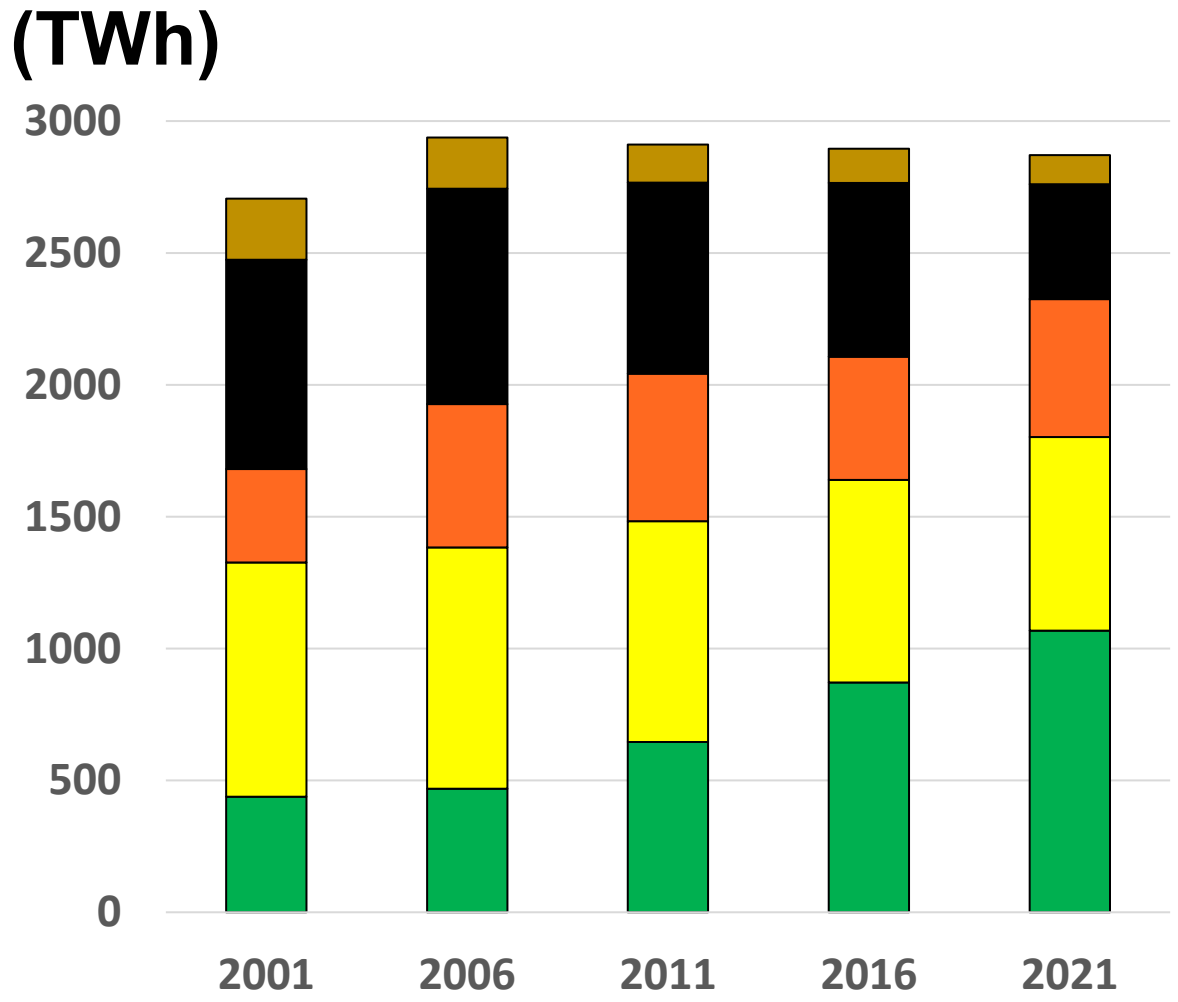
Constant Growth for Renewables – Decline for Oil & Gas – Low levels for Nuclear



Source: Data from REN21 2022/Mycle Schneider 2022/IEA/Rystad

EU Electricity Generation by Sources

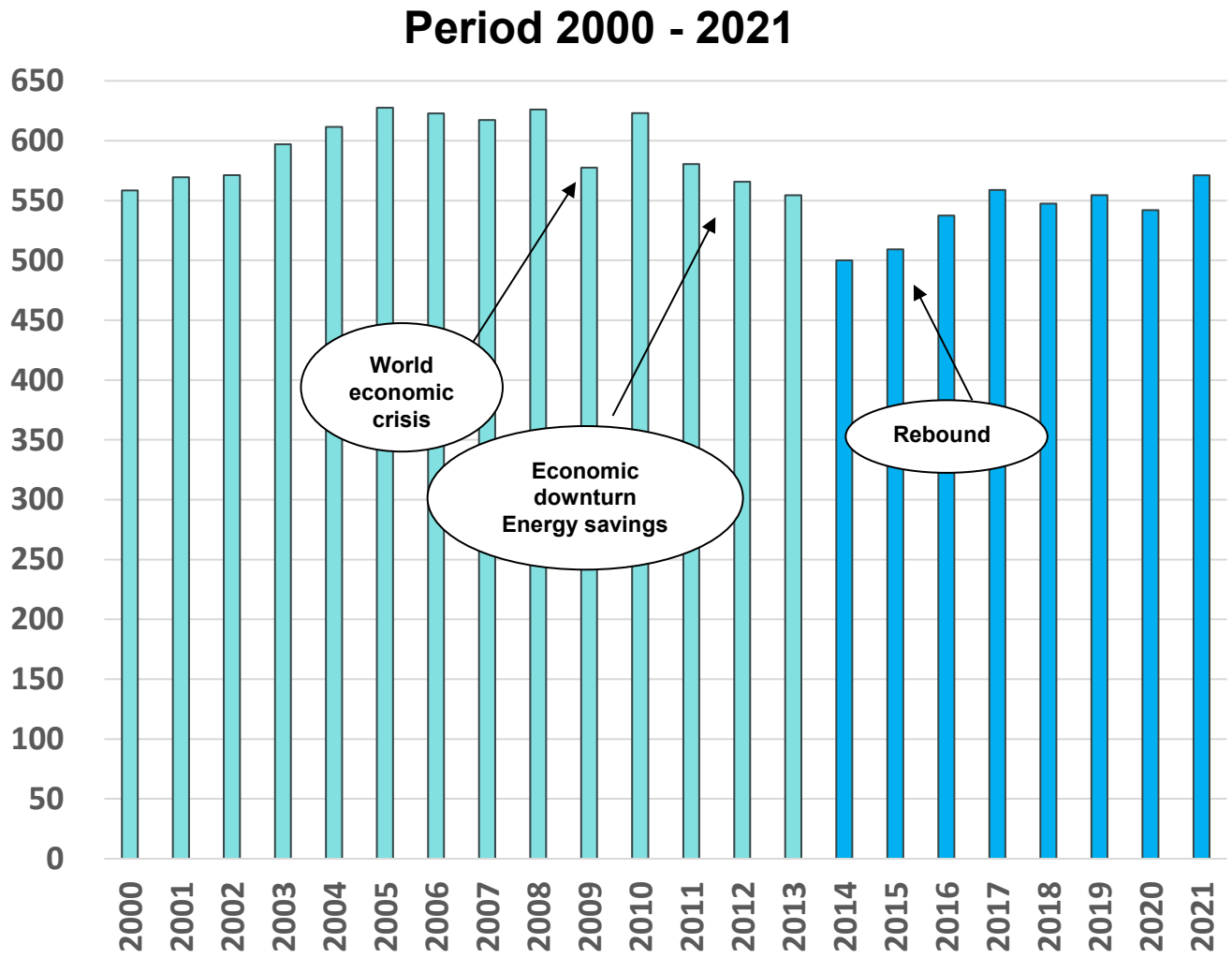
In 20 years, massive growth of Renewables, substantial growth of Gas, decline of Coal

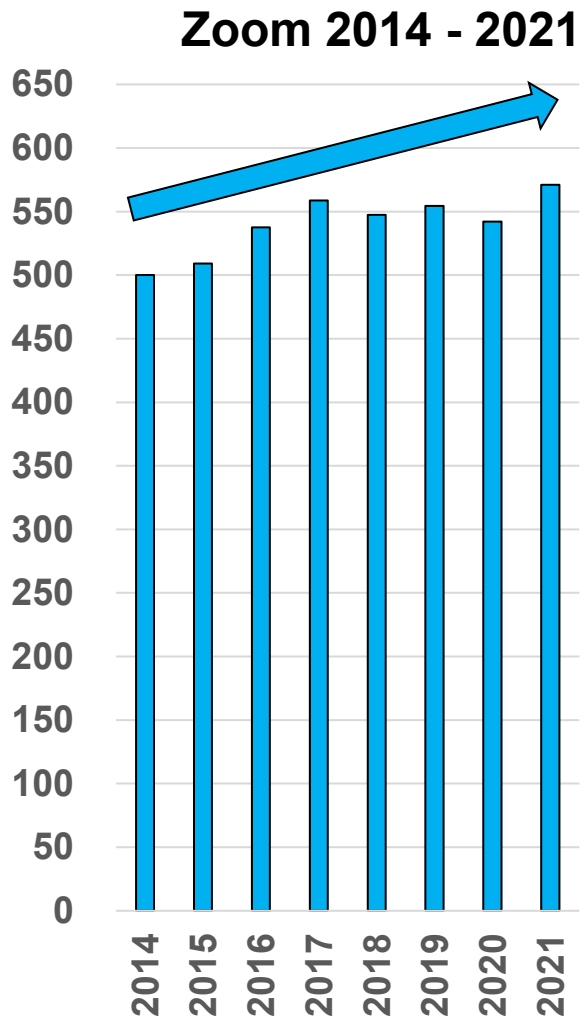


Evolution 2021 vs 2001
- 53%
- 45%
+ 48%
- 17%
X 2,4

Source: Data from IEA/BP

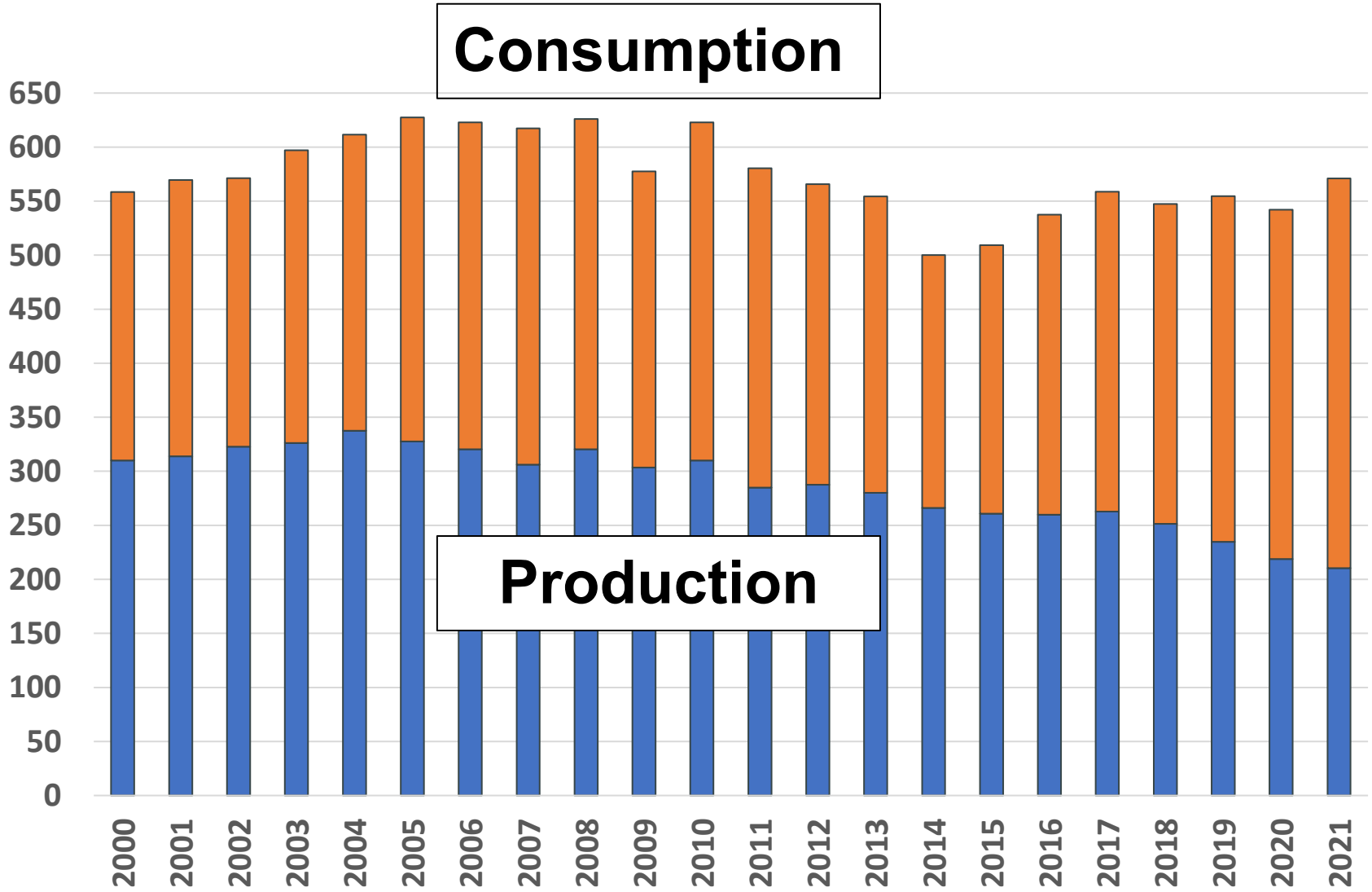
History of Natural Gas Consumption in Europe (Gm3)
A constant increase of Demand since 2014





Source: Data from BP Stat. Review 2022

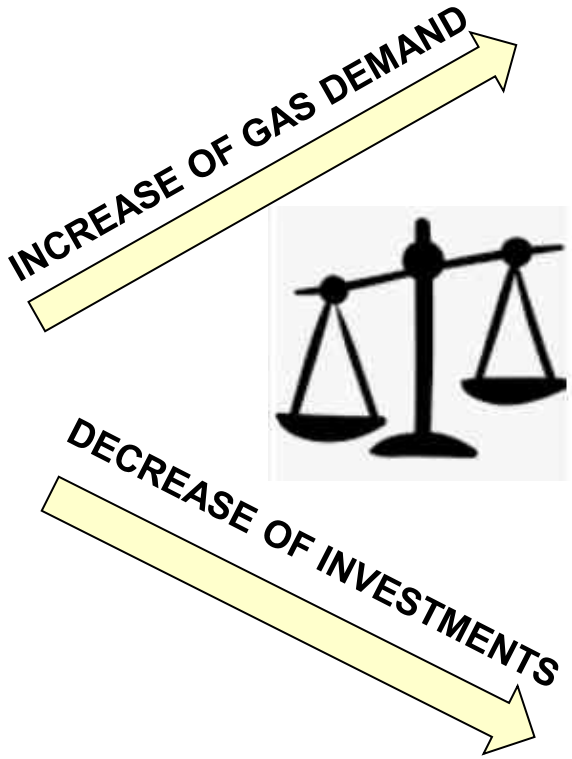
History of Natural Gas Consumption & Production in Europe (Gm3)
2000 – 2021 Production: - 40% from 2004 to 2021

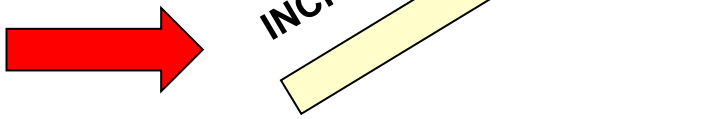


The increasing gap between Consumption and indigenous Production leads to increased imports of Natural Gas

Source: Data from BP Stat. Review 2022

During the last 7 years, increase of Gas Demand combined with lack of Oil & Gas Investment and anticipation of back-up needs for Renewables Intermittency leads to a sharp increase of Gas Price, phenomena exacerbated by the Russia/Ukraine conflict





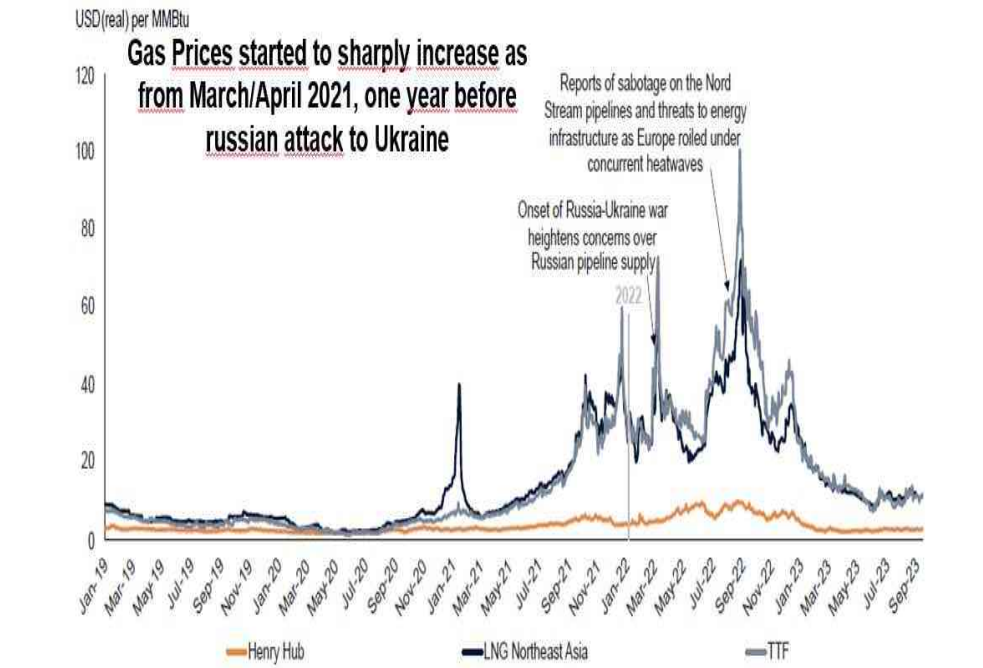
INCREASE OF GAS PRICE

Gas Prices started to substantially increase as from April 2021, one year before russian attack to Ukraine

(except for US Henry Hub)

Natural Gas Pricing Jan. 2019 – Sept. 2023

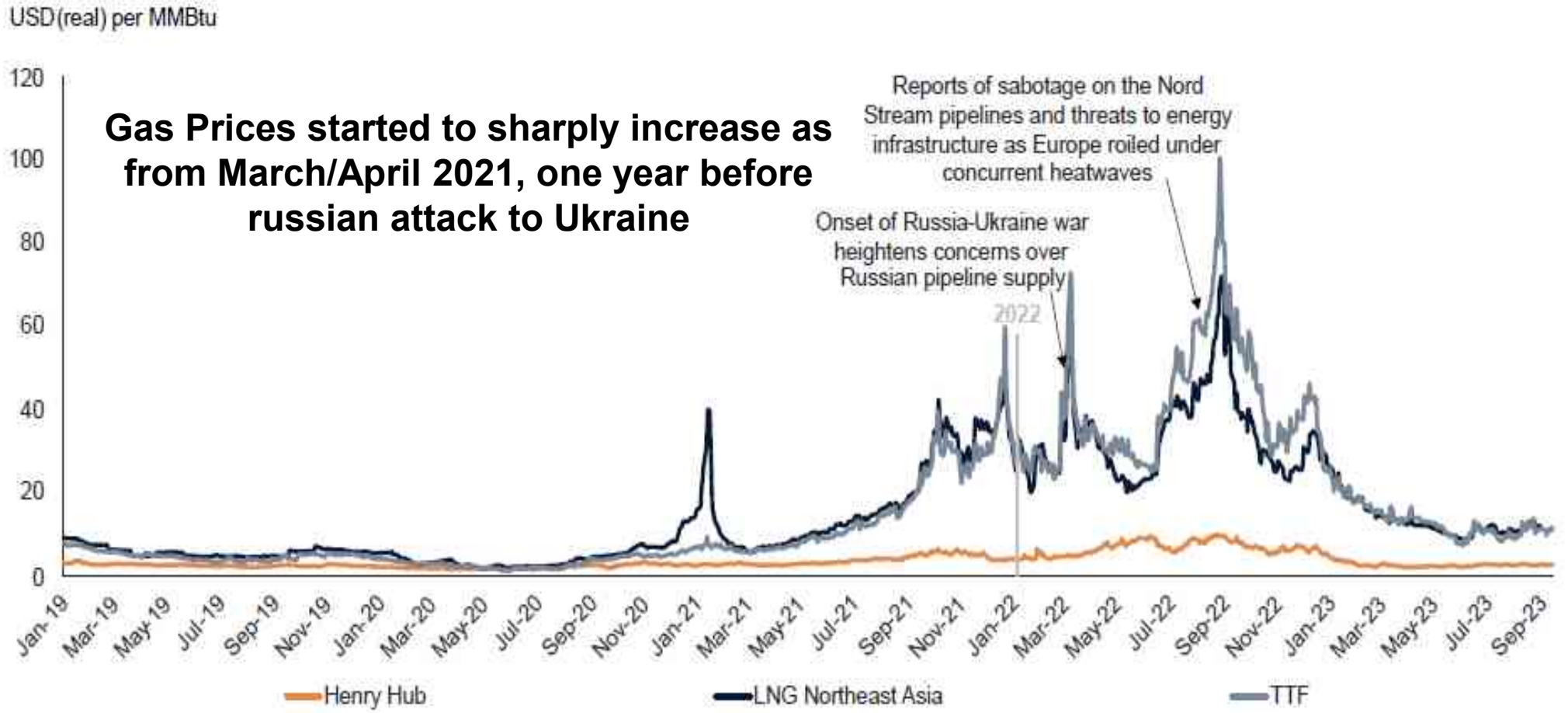
For LNG & TTF, record lows in 2020 due to Covid. Peak in Sept.2022: 100 $/Mbtu # 600 $/b!, down to # 15 $/Mbtu in 2023 # 90 $/MBtu



Note: TTF MA = Title Transfer Facility month-ahead prices; LNG = liquefied natural gas

Natural Gas Pricing Jan. 2019 – Sept. 2023

For LNG & TTF, record lows in 2020 due to Covid. Peak in Sept.2022: 100 $/Mbtu # 600 $/b!, down to # 15 $/Mbtu in 2023 # 90 $/MBtu

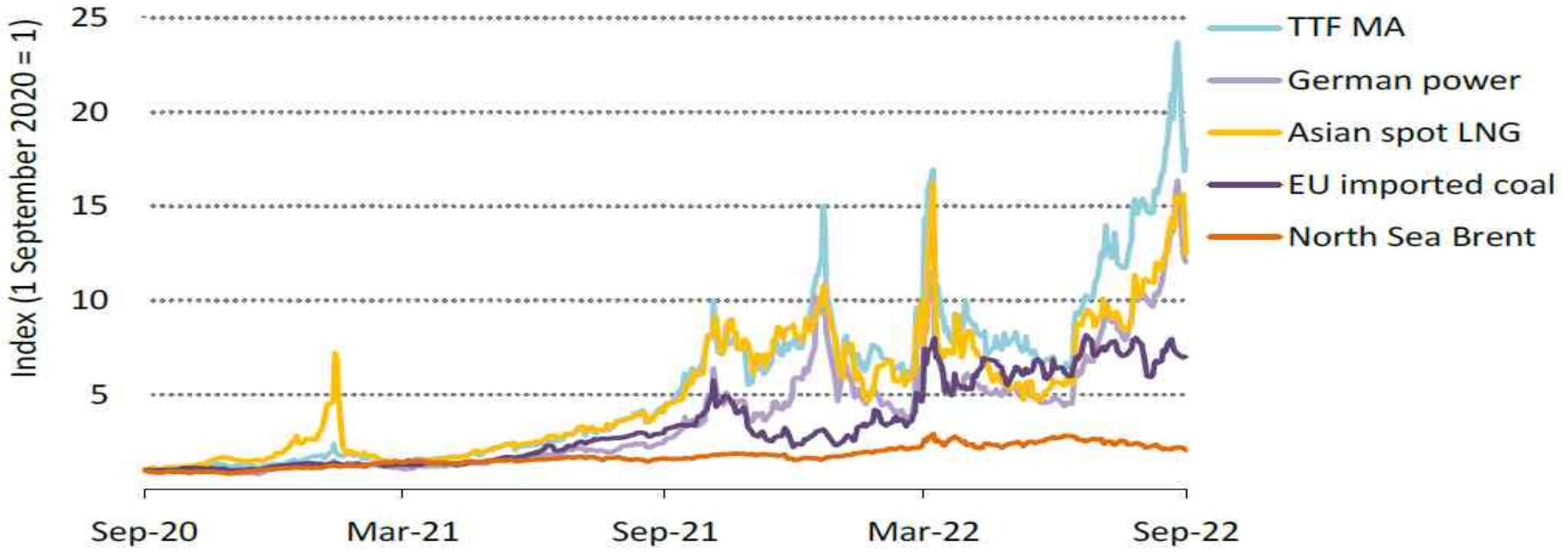


Note: TTF MA = Title Transfer Facility month-ahead prices; LNG = liquefied natural gas

Source: Rystad Energy; Argus (LNG Northeast Asia)

Source: IGU 2023 Global Gas Report

Reminder: Energy Prices indicators Sept. 2020 – Sept. 2022
Major turbulences - European TTF x 24



This has been a period of extraordinary turbulence in energy markets, intensified by Russia's invasion of Ukraine in February 2022

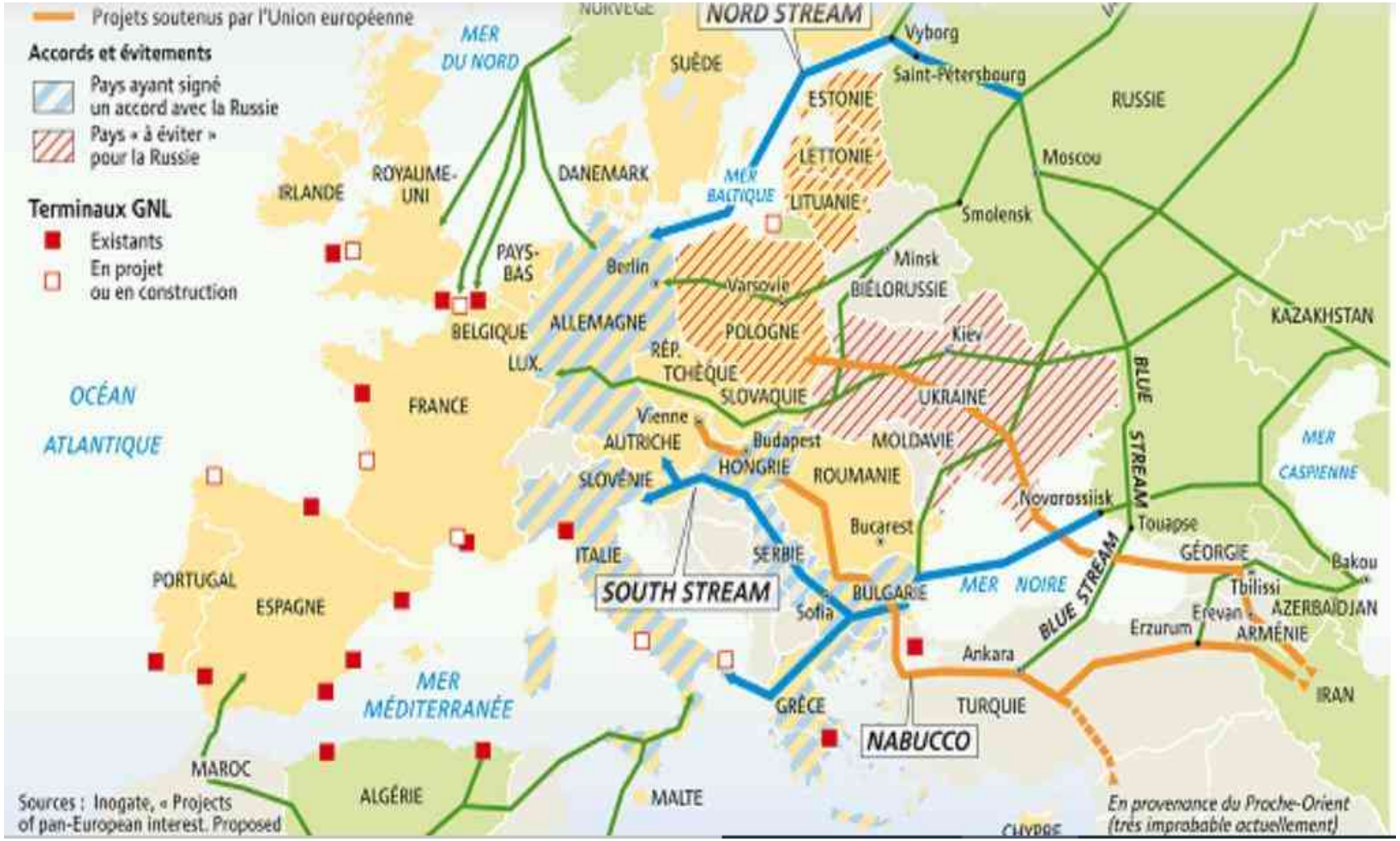
Note: TTF MA = Title Transfer Facility month-ahead prices; LNG = liquefied natural gas; Brent = Brent crude oil benchmark.

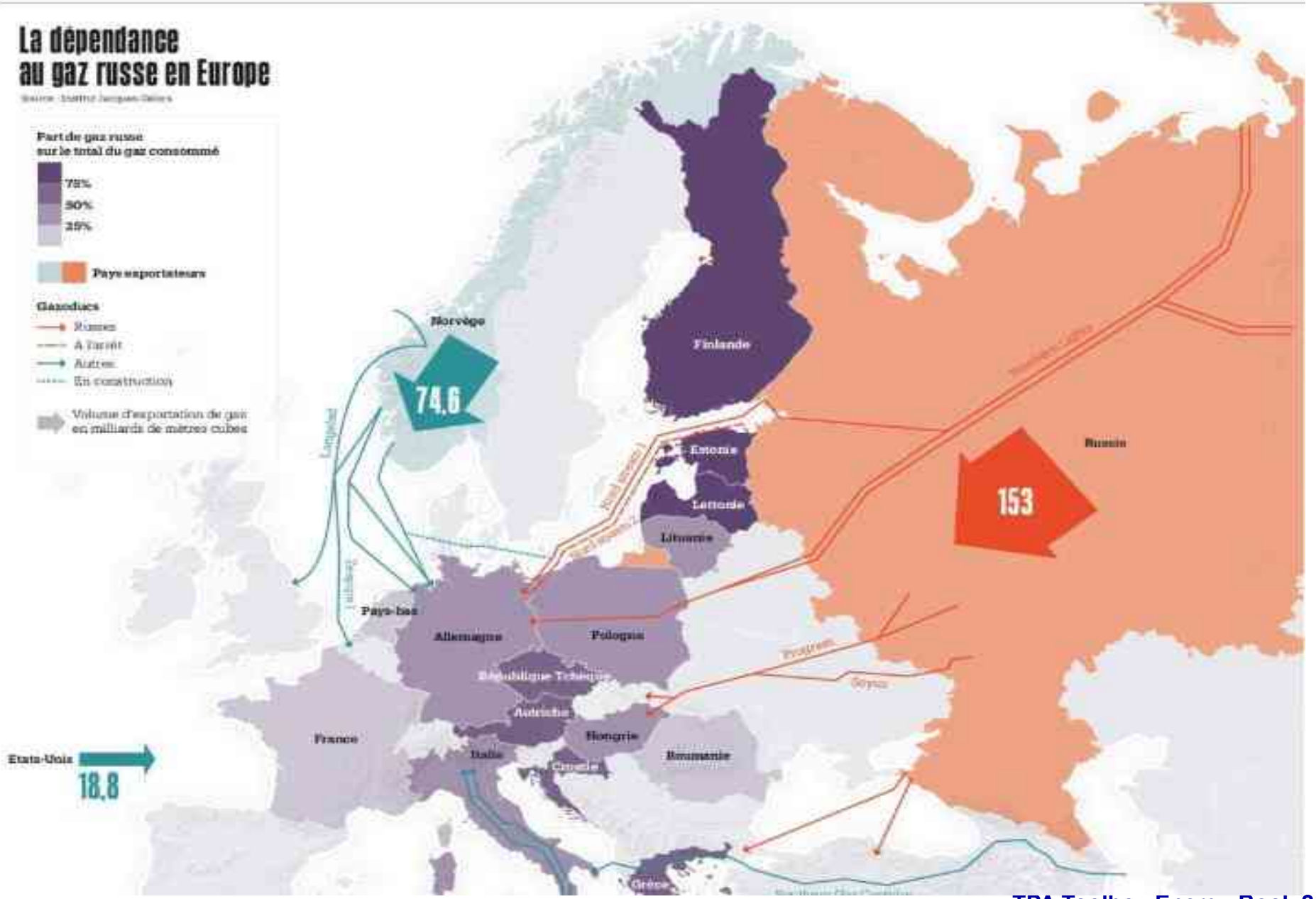
Sources: IEA analysis based on Argus Media (2022); ICIS (2022); BNEF (2022).

Source: IEA World Energy Outlook 2022

Specific impact on Europe & European Union (EU)
See also Book 5 - Gas

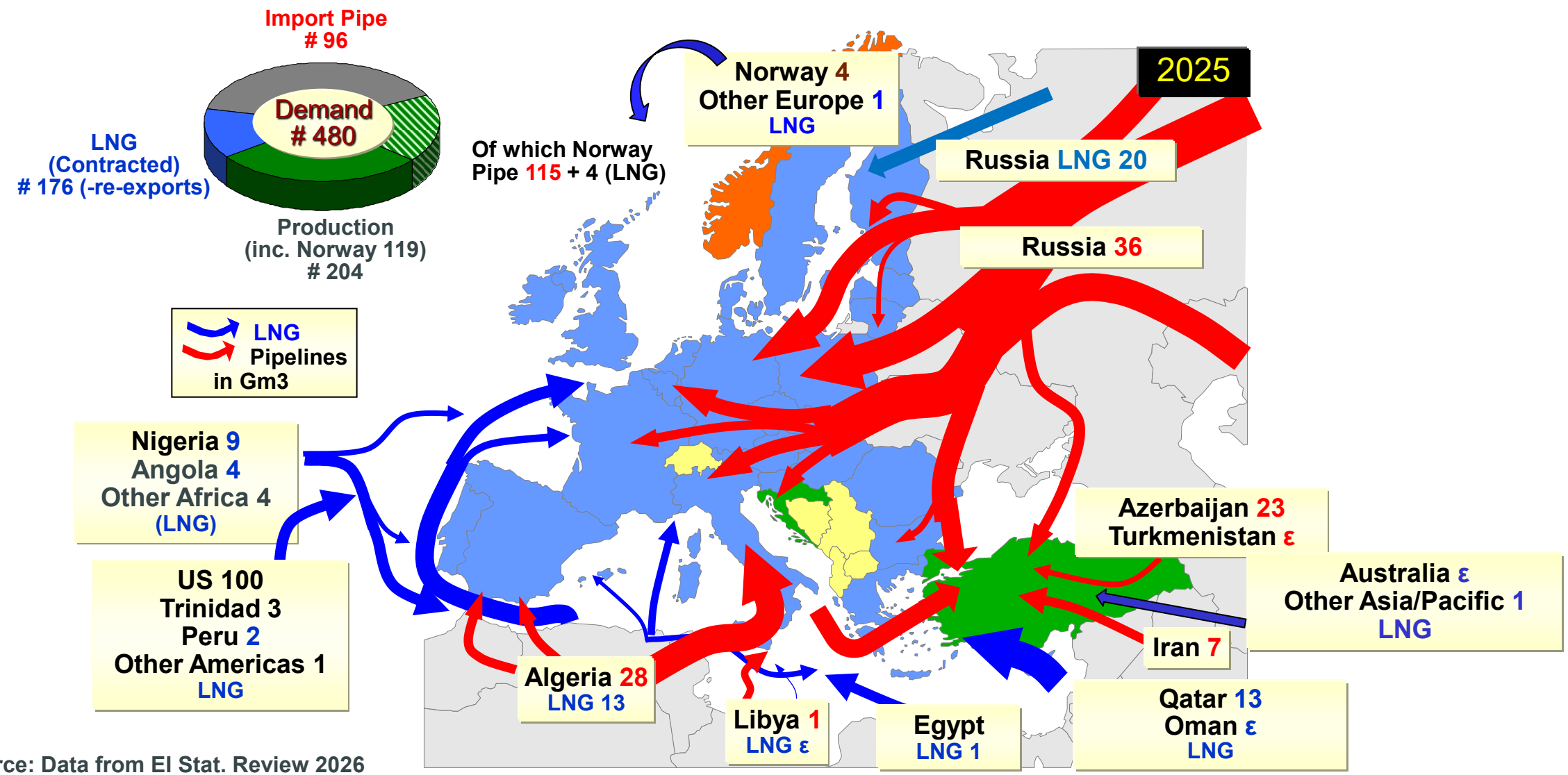
Gas Pipes and Import Terminals




La dépendance
au gaz russe en Europe
Part de gaz russe
sur le total du gaz consommé
75%
50%
25%
Pays exportateurs
Gazoducs
Russes
A l'avenir
Autres
En construction
Volume d'exportation de gaz
en milliards de mètres cubes
Norvège
74,6
Finlande
Russie
153
Estonie
Lettonie
Lituanie
Pays-bas
Allemagne
Pologne
France
Etats-Unis
18,8
Hongrie
Roumanie
Grèce

Europe Gas Supply & Demand in 2025 (G.m3)

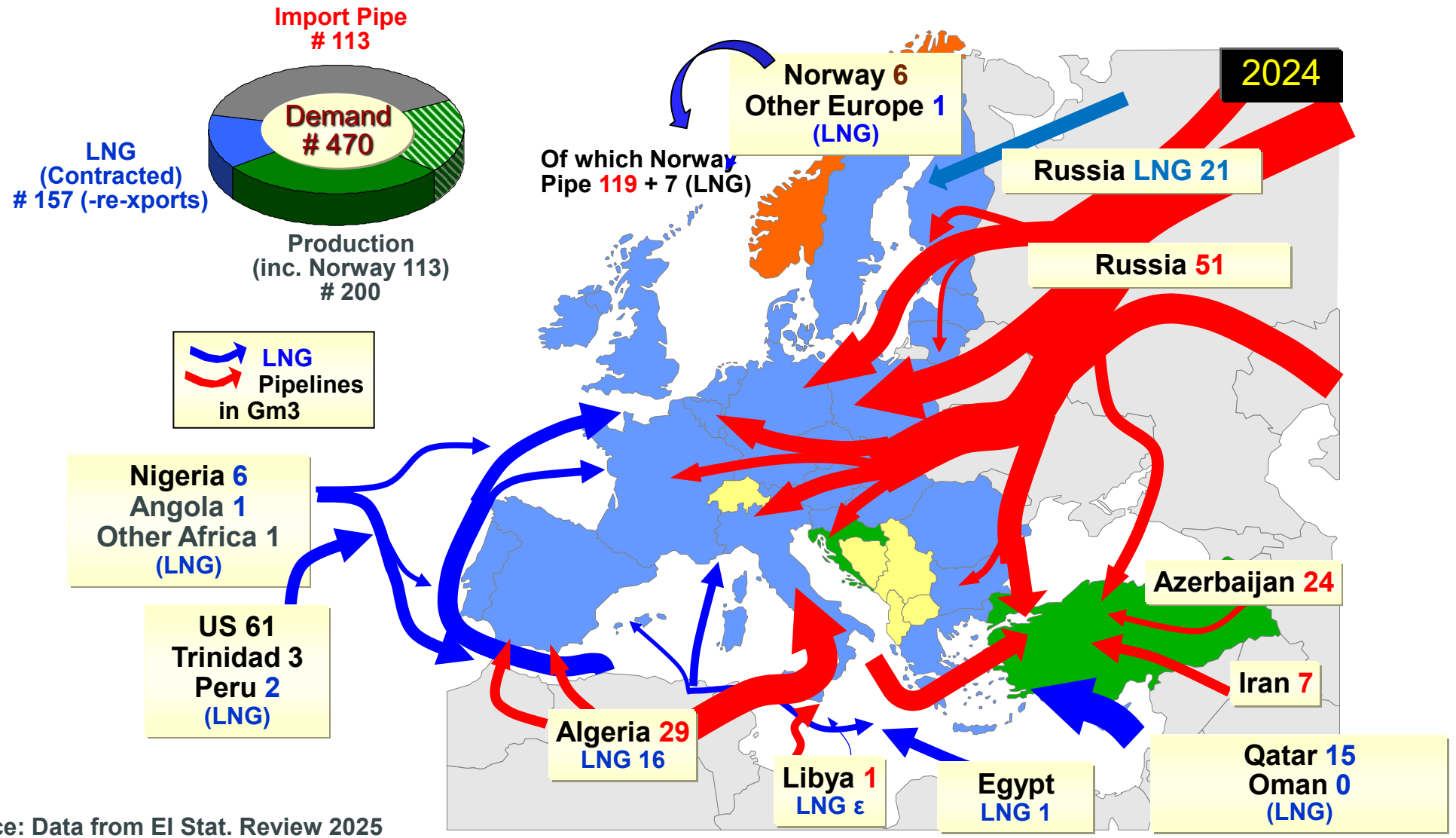
Russian pipe exports to Europe: 152 G.m3 in 2021 down to 36 G.m^3 in 2025 (4 G.m3 to UE)



Source: Data from EI Stat. Review 2026
All countries in Europe including Turkey. EU: European Union
Arrows not at scale

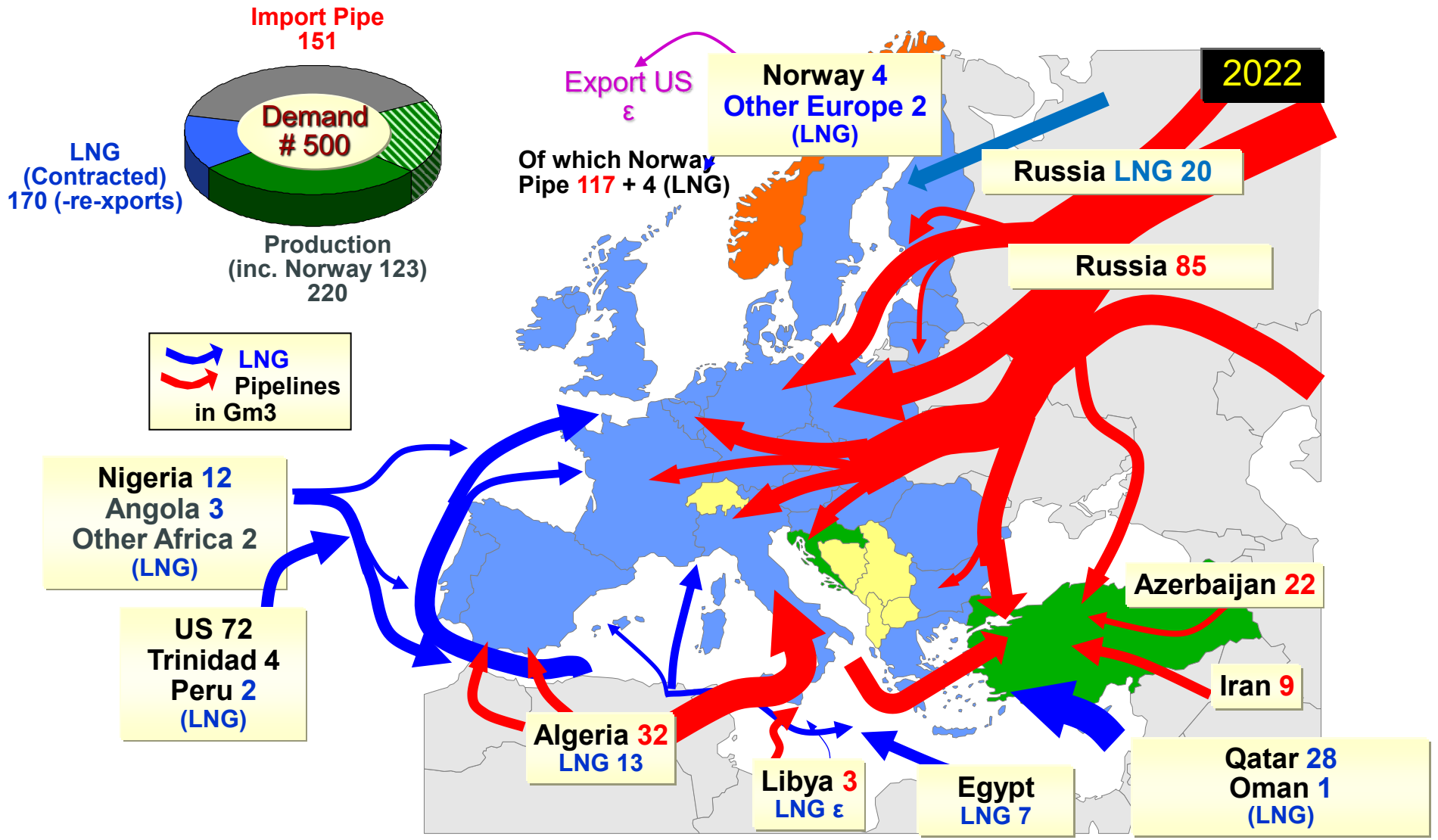
Europe Gas Supply & Demand in 2024 (G.m3)

Russian pipe exports to Europe: 152 G.m3 in 2021 down to 51 G.m^3 in 2024 (27 G.m3 to EU)



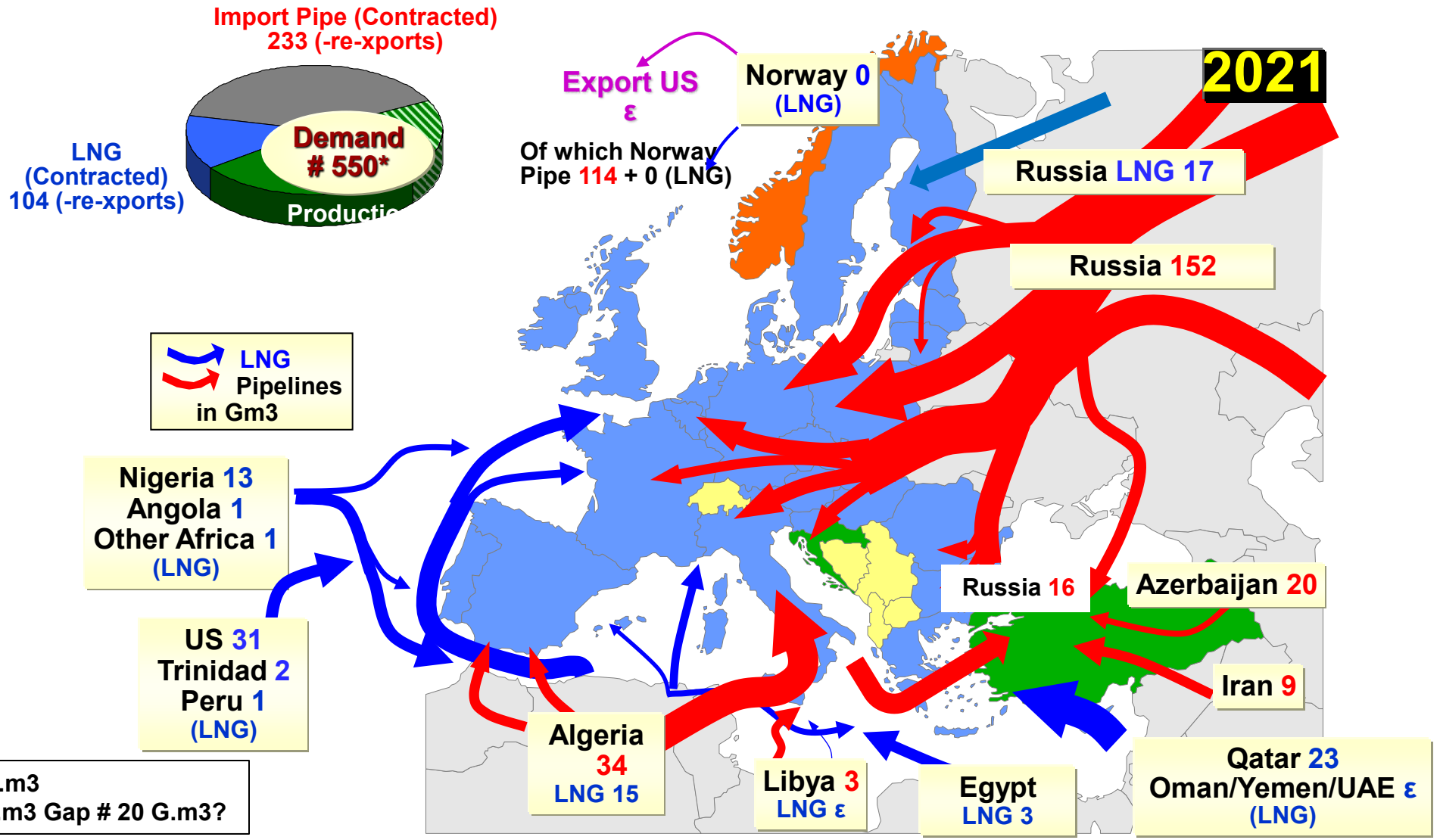
Source: Data from EI Stat. Review 2025
All countries in Europe including Turkey. EU: European Union
Arrows not at scale

Europe Gas Supply & Demand in 2022 (G.m3)
Russian exports: 152 G.m3 down to 85 G.m3 in 2022 vs 2021



Source: Data from EI Stat. Review 2023
All countries in Europe including Turkey

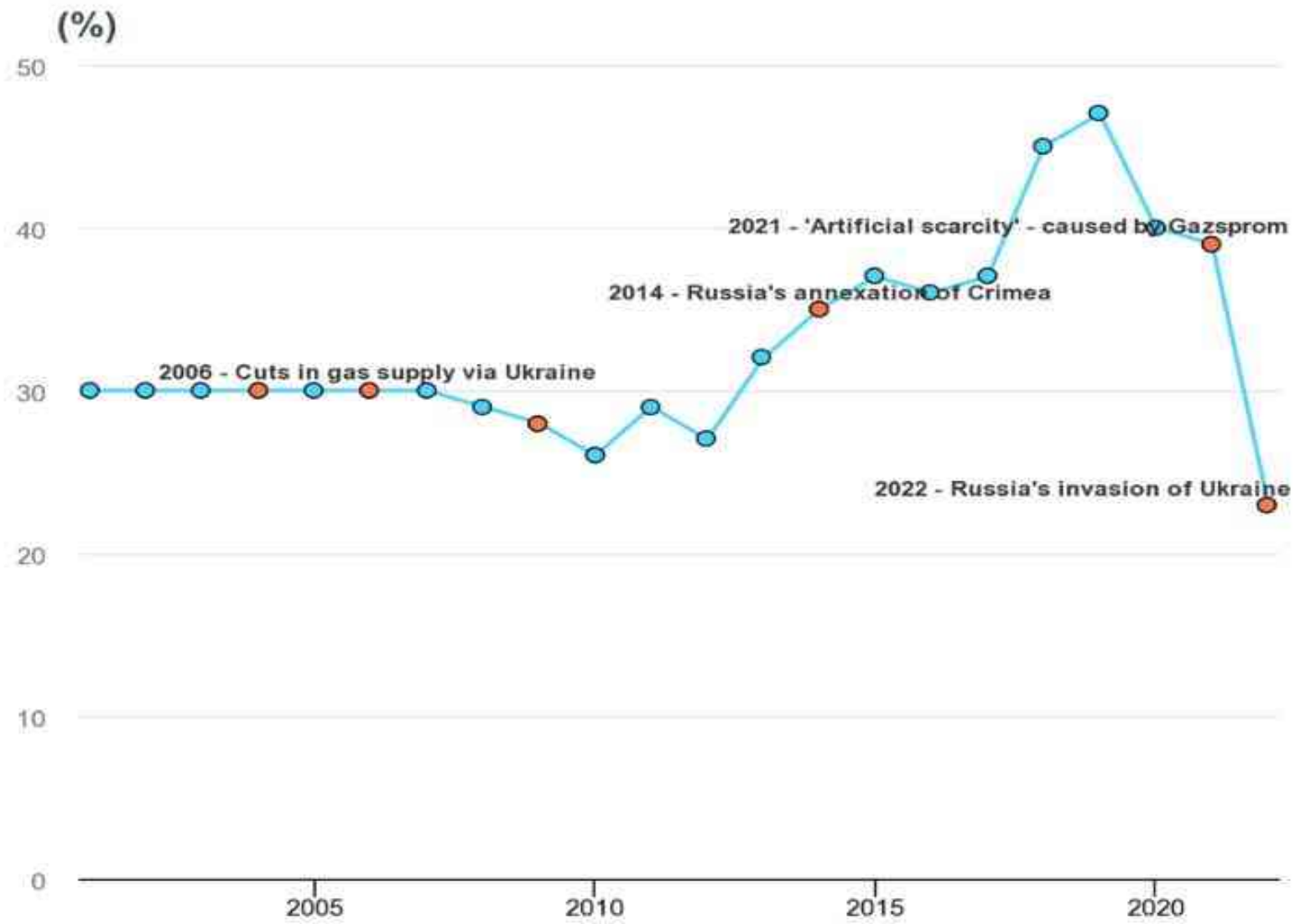
Europe Gas Supply & Demand in 2021 (G.m3)

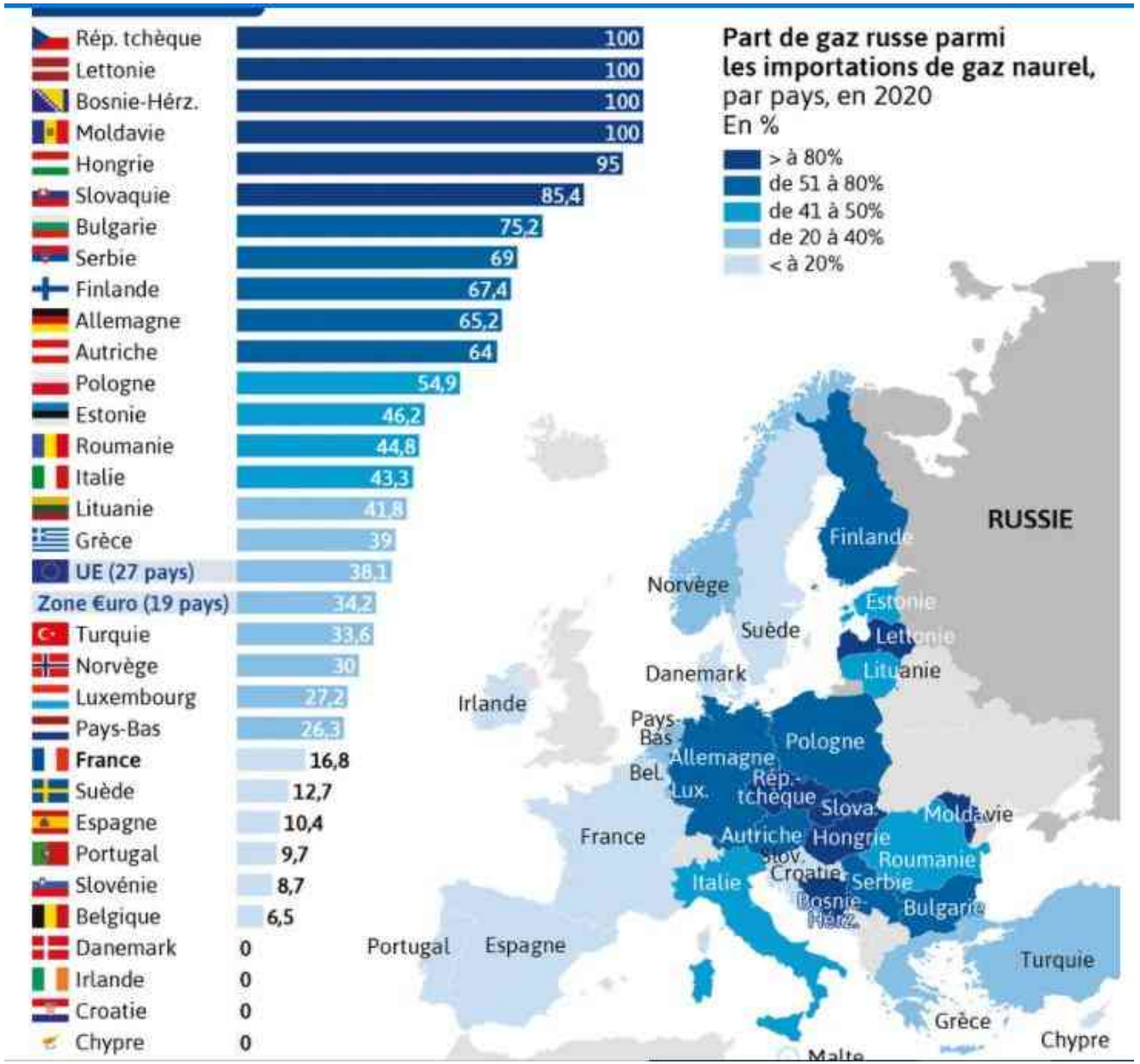


- IGU: 550 G.m3
- BP : 570 G.m3 Gap # 20 G.m3?

Source: Data from BP Stat. Review 2022
All countries in Europe including Turkey

Share of EU Gas Demand met by Russian Supply 2001 - 2022




Part de gaz russe parmi les importations de gaz naurel, par pays, en 2020
En %
> à 80%
de 51 à 80%
de 41 à 50%
de 20 à 40%
< à 20%
Rép. tchèque 100
Lettonie 100
Bosnie-Hérz. 100
Moldavie 100
Hongrie 95
Slovaquie 85,4
Bulgarie 75,2
Serbie 69
Finlande 67,4
Allemagne 65,2
Autriche 64
Pologne 54,9
Estonie 46,2
Roumanie 44,8
Italie 43,3
Lituanie 41,8
Grèce 39
UE (27 pays) 38,1
Zone €uro (19 pays) 34,2
Turquie 33,6
Norvège 30
Luxembourg 27,2
Pays-Bas 26,3
France 16,8
Suède 12,7
Espagne 10,4
Portugal 9,7
Slovénie 8,7
Belgique 6,5
Danemark 0
Irlande 0
Croatie 0
Chypre 0
RUSSIE
Finlande
Norvège
Suède
Estonie
Lettonie
Lituanie
Danemark
Irlande
Pays-Bas
Pologne
Allemagne
Bel.
Lux.
Rép. tchèque
Slova.
Moldavie
France
Autriche
Hongrie
Slov.
Croatie
Roumanie
Italie
Serbie
Bosnie-Hérz.
Bulgarie
Portugal
Espagne
Turquie
Grèce
Chypre
Malte

European Gas dependancy – From 2010 to 2021

For EU 27, dependancy vs russian Gas is # 37% in 2021 representing # 150 G.m^3

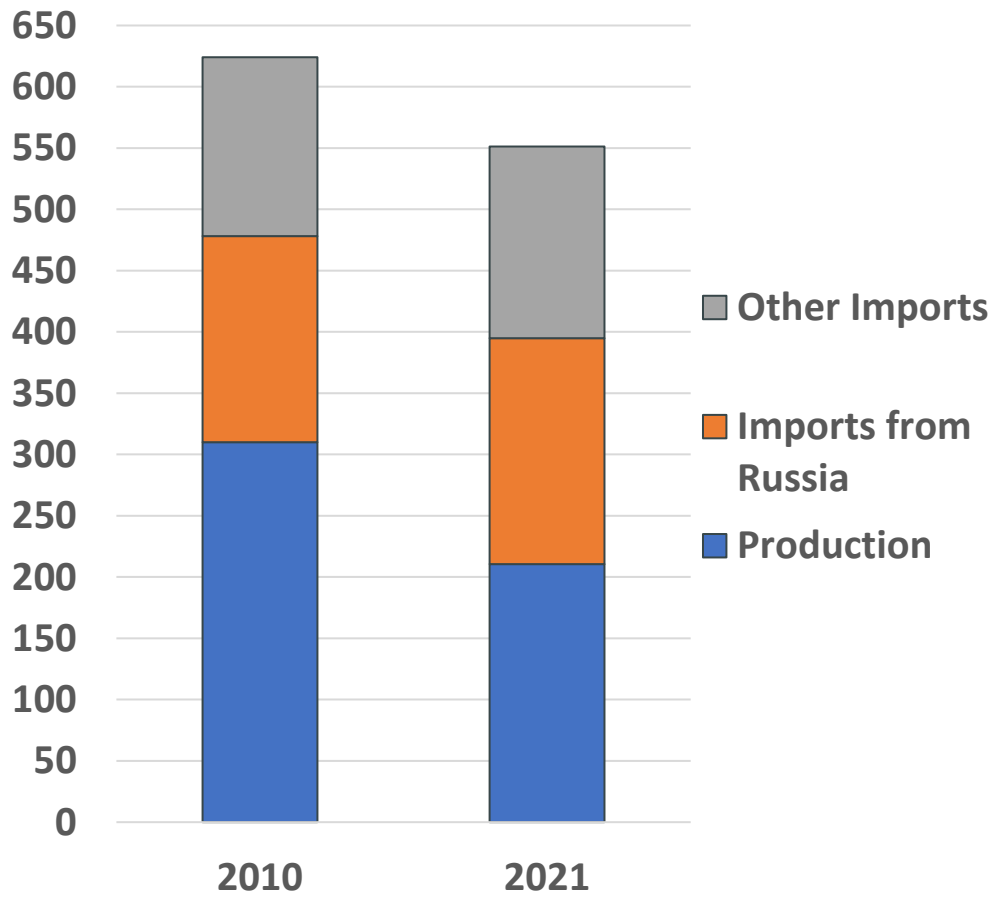
Year 2021 (G.m3)	All Europe 2010	All Europe 2021	European Union (EU 27) 2010	European Union (EU 27) 2021	France 2021	Germany 2021
Natural Gas Consumption	623	570	423	396	43	91
Natural Gas Production	310	210	117	40	0	5
% Technical Dependancy	50%	63%	72%	90%	100%	95%
Total Gas Imports (Gas pipe + LNG)	314	341	315	349	43	90
% Dependancy vs total Imports	50%	60%	74%	87%	100%	100%
Imports from Russia (Gas pipe + LNG)	168	184	112	147	9	50
% Dependancy vs Russia	27%	32%	26%	37%	20%	55%
Share of Russian Gas in total imports	54%	54%	36%	42%	20%	56%

Nota: Europe = EU 27 + Norway + UK + Switzerland + Turkey + Ukraine + other Europe
Various sources, BP, Agora Energiewende, .., rounded figures

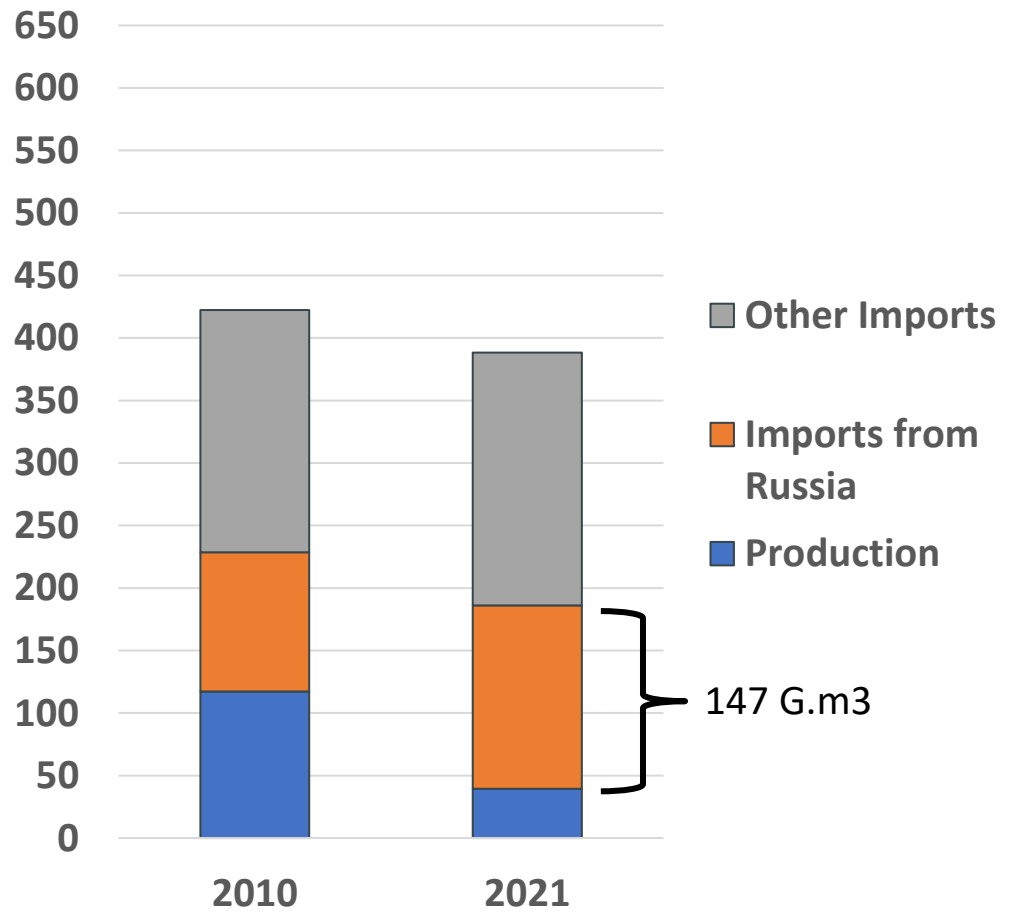
European Gas dependancy – From 2010 to 2021

For EU 27, dependancy vs russian Gas is # 37% in 2021 representing # 150 Gm^3

Sources of Gas Consumption - All Europe



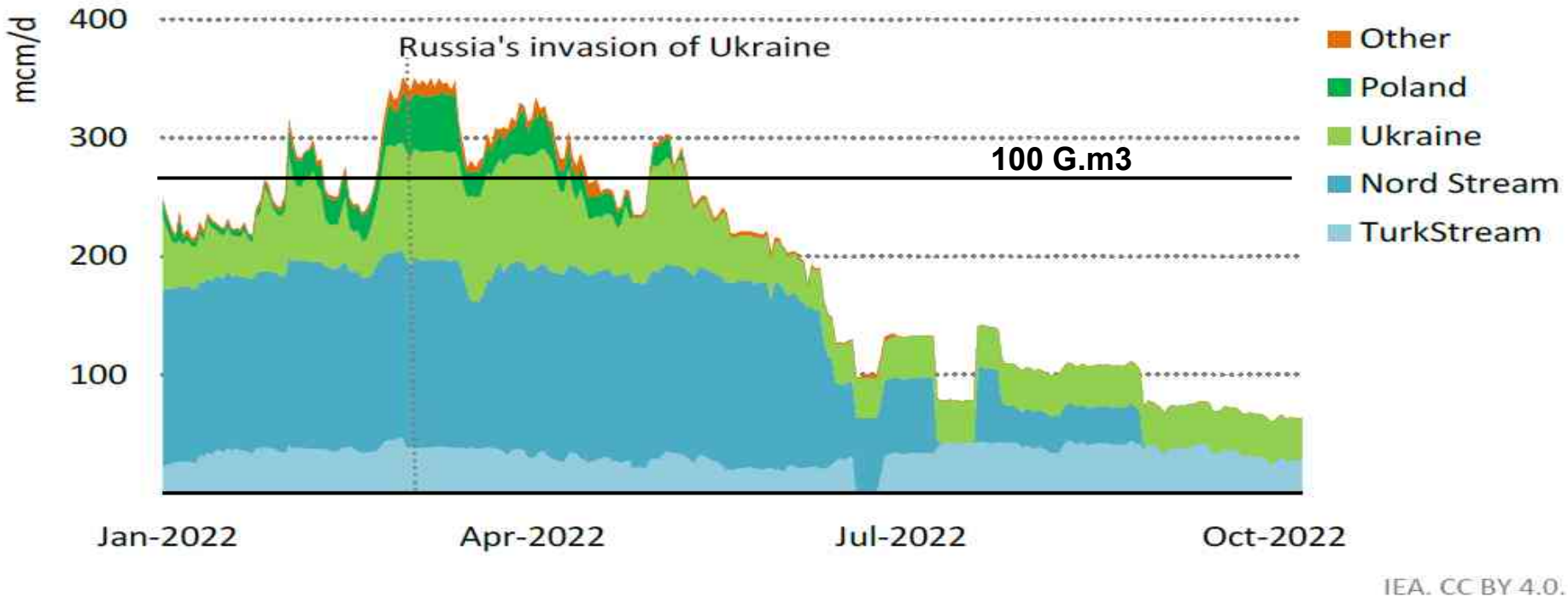
Sources of gas Consumption - EU 27



Nota: Europe = EU 27 + Norway + UK + Switzerland + Turkey + Ukraine + other Europe
Various sources, BP, Agora Energiewende, .., rounded figures

Russia attacks Ukraine: A zoom on Year 2022

Russia has cut its Natural Gas pipeline flows to EU by 80%, Nordstream 1 & 2 non operational



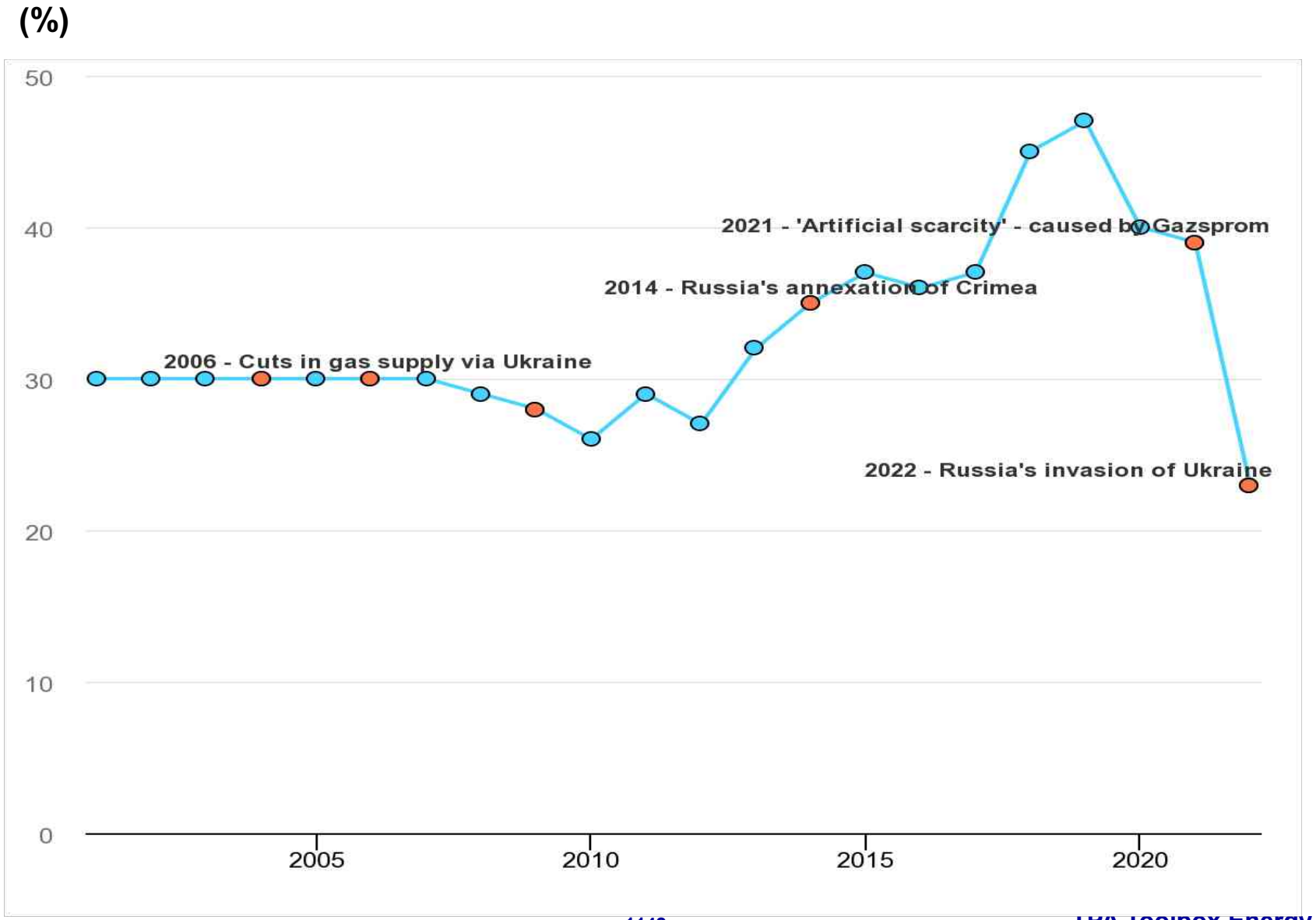
Between May and October 2022, daily pipeline flows from Russia to the European Union dropped by around 80%

Note: mcm/d = million cubic metres per day.

Source: IEA analysis based on ENTSOG Transparency Platform (2022).

Source: IEA World Energy Outlook 2022

Share of EU Gas Demand met by Russian Supply – 2001 - 2022



History of Nord Stream Project

Nord Stream
Secure gas supply for Europe







History of Nord Stream Project – Nord Stream 1

2006: Gazprom, E.ON Ruhrgas AG and BASF SE/Wintershall Holding GmbH, established an independent project company in order to advance the planning and realisation of an additional reliable supply of energy from the vast Russian gas fields to European end consumers.

2012: Completion of the project. Nord Stream 1 will be providing Europe with a reliable supply of Russian natural gas for at least the next 50 years.

The Nord Stream 1 twin pipeline system through the Baltic Sea runs from Vyborg, Russia to Lubmin near Greifswald, Germany. The pipelines were built and are operated by Nord Stream AG.
The Nord Stream 1 route crosses the Exclusive Economic Zones of Russia, Finland, Sweden, Denmark and Germany, as well as the territorial waters of Russia, Denmark, and Germany.

The two 1,224-kilometre offshore pipelines are the most direct connection between the vast gas reserves in Russia and energy markets in the European Union. Combined, the twin pipelines have the capacity to transport a combined total of 55 billion cubic metres (bcm) of gas a year to businesses and households in the EU for at least 50 years. As the project strengthens the EU energy market and reinforces security of supply, the project has been designated as being of "European interest" by the European Parliament and Council.

Construction of Line 1 of the twin pipeline system began in April 2010, and was completed in June 2011. Transportation of gas through Line 1 began in mid November 2011. Construction of Line 2, which runs parallel to Line 1, began in May 2011 and it was completed in April 2012. Gas transport through the second line began in October 2012. Each line has a transport capacity of roughly 27.5 bcm of natural gas per annum.

TPA Sharing Experience

Source: Nord Stream AG

History of Nord Stream Project



History of Nord Stream Project – then Nord Stream 2

Nord Stream 1 (NS1) runs from Vyborg, in northwestern Russia near Finland, and entered service in 2011. It is composed of 2 pipelines. It is operated by Nord Stream AG.

Nord Stream 2 (NS2) runs from Ust-Luga in northwestern Russia near Estonia. The pipeline was built in order to increase gas exports towards Europe, aiming to double annual capacity. The project is composed of 2 pipelines and was completed in 2021, but has not yet entered service, because Germany withheld opening permission on February 22, 2022 due to Russia declaring that further parts of Ukraine Territory belonged to breakaway republics, in line with a previous joint warning made with US president Joe Biden on February 7, 2022 to kill the project if Russia tried to invade Ukraine.
Following Ukraine invasion and European countries reactions, Russia decides to cut supply of gas to Europe.

On 26 September 2022, news broke of three explosions at the Nord Stream 1 and 2 natural gas pipelines. The blasts rendered three of the four lines inoperable and released vast quantities of gas into the Baltic Sea.

None of the four pipes is currently operational, bringing the Nord Stream project to an effective standstill. Russia has confirmed one of the two Nord Stream 2 pipes is operable.

History of Nord Stream Project – then Nord Stream 2



History of Nord Stream Project – then Nord Stream 2



Source: Al Jazeera, Reuters

History of Nord Stream Project – then Nord Stream 2



EU Energy Supply challenge for the future

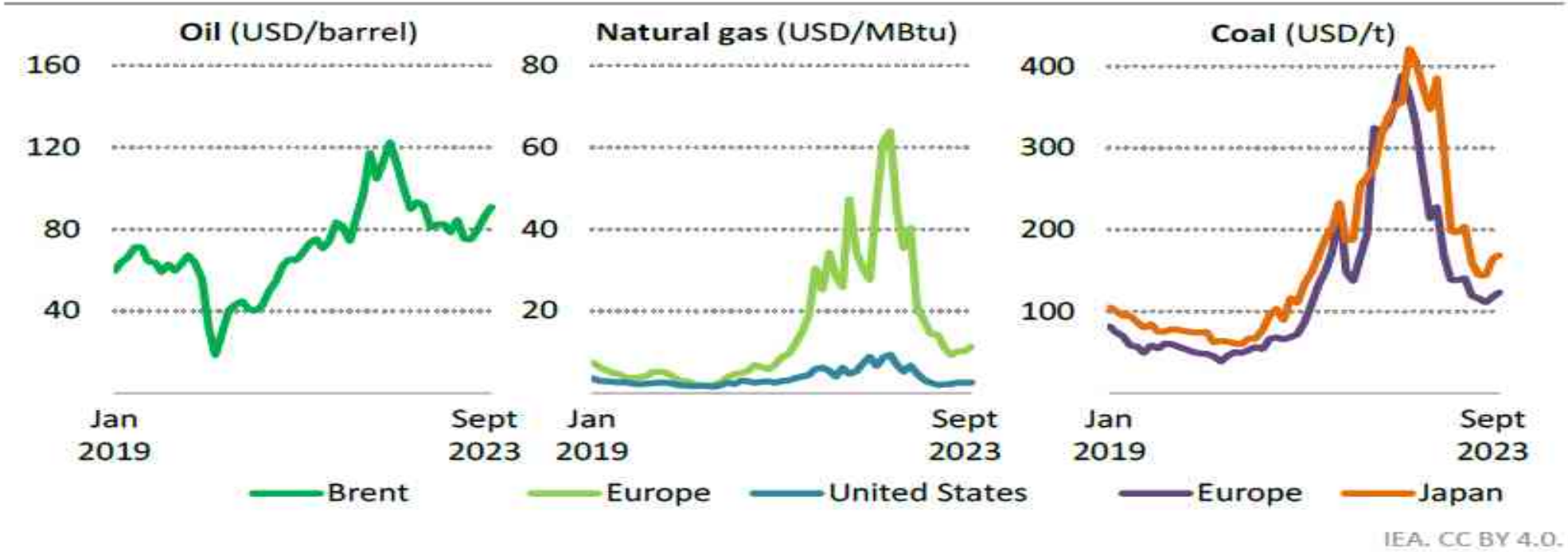
How to replace # 150 G.m^3 of russian Gas for the supply of EU?

- **By increasing the access to new LNG supply (Current World Production today : 480 G.m^3)**
- **By increasing Gas storage capacities**
- **By reducing Gas Consumption**

Specific impact on European Gas & Electricity prices

Russia/Ukraine War - 2022

Major Impact on World Economy and Energy Markets. After a peak, commodities prices have been declining importantly but will not reach pre-crisis levels



Fossil fuel prices spiked in 2022, before moderating back towards pre-crisis levels in recent months

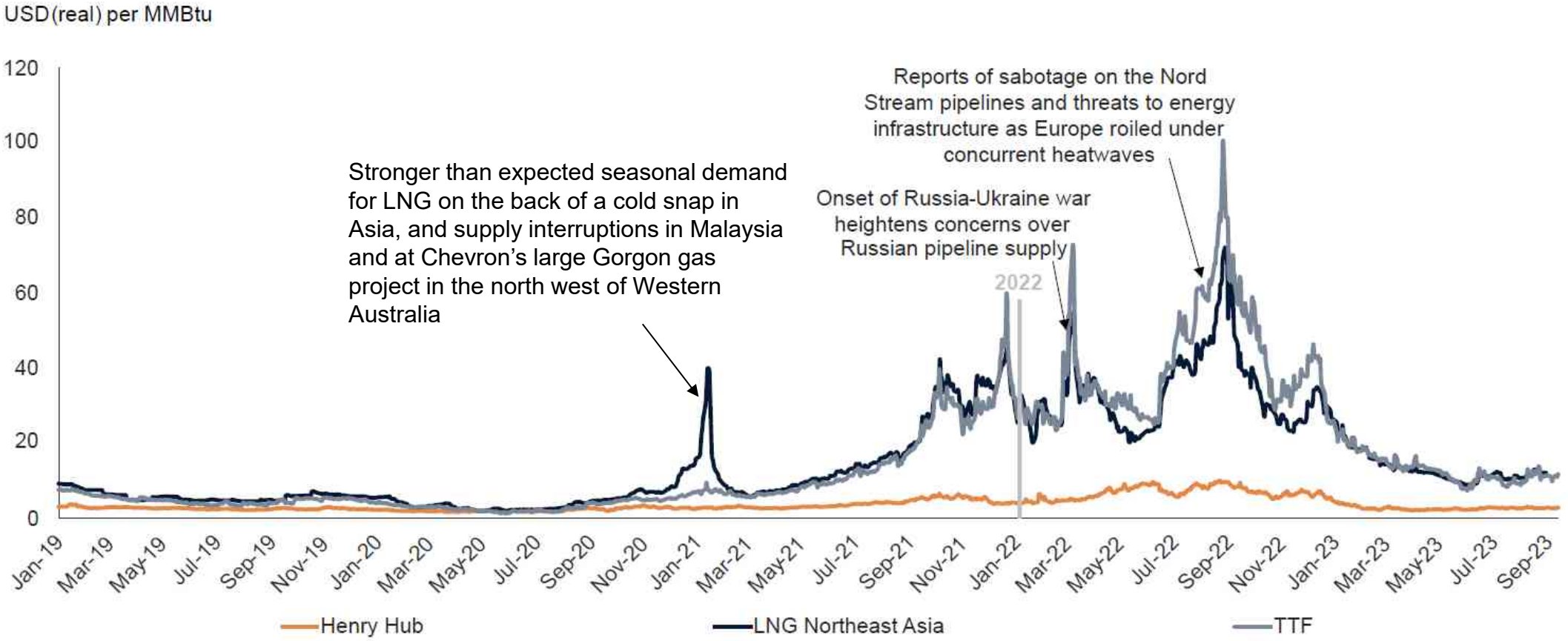
Notes: MBtu = million British thermal units; USD/t = US dollars per tonne. Europe natural gas price = natural gas TTF index; US natural gas price = natural gas Henry Hub index; Europe coal price = northwest Europe CIF ARA; Japan coal price = Japan CIF marker. Nominal prices.

Sources: US EIA (2023); Argus (2023); McCloskey (2023).

Source: IEA WEO 2023

Russia/Ukraine War - 2022

Major Impact on World Economy and Energy Markets. A zoom on the Gas Price

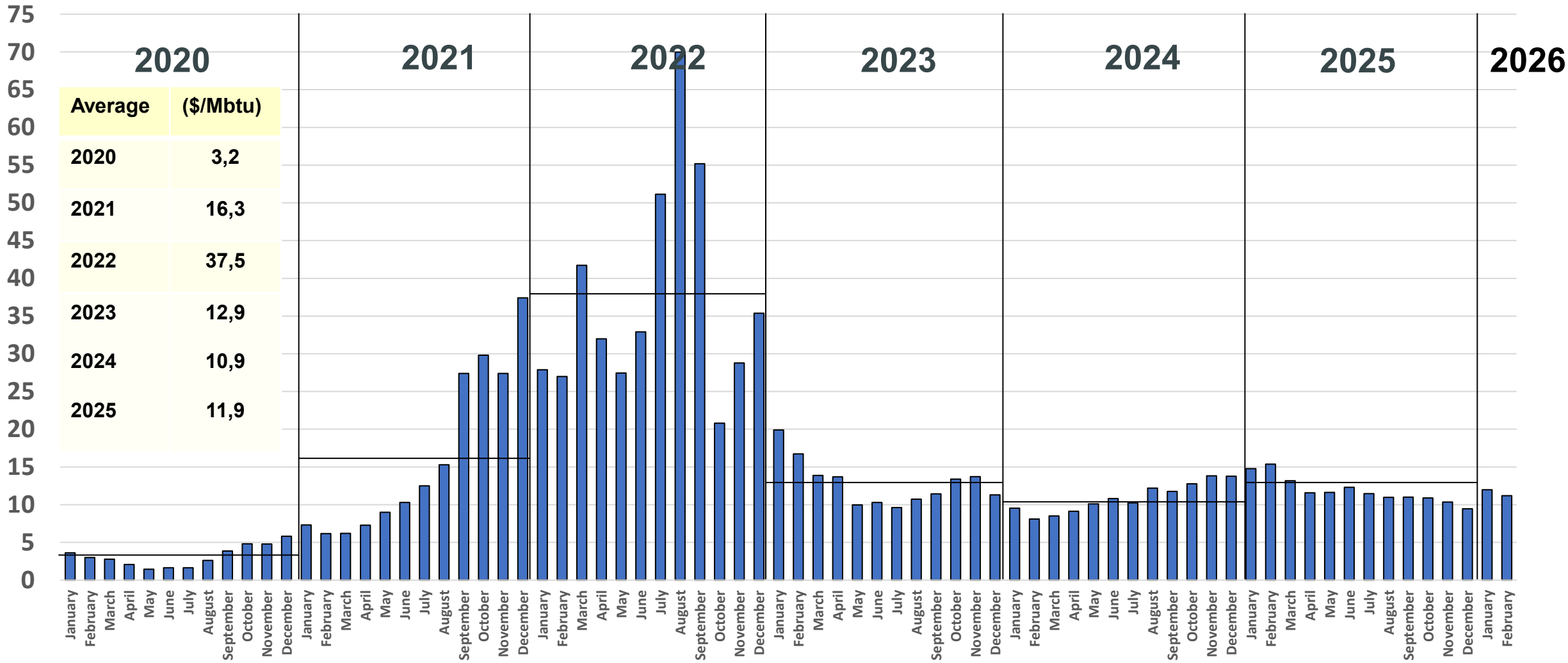


Source: Rystad Energy; Argus (LNG Northeast Asia)

Note: TTF MA = Title Transfer Facility month-ahead prices; LNG = liquefied natural gas

Source: International Gas Union (IGU) Global Gas Report 2023/Rystad Energy

Monthly German Border Gas Prices Evolution 2020 – 2025 ($/Mbtu)
The impacts of economic & geopolitical turmoils are great

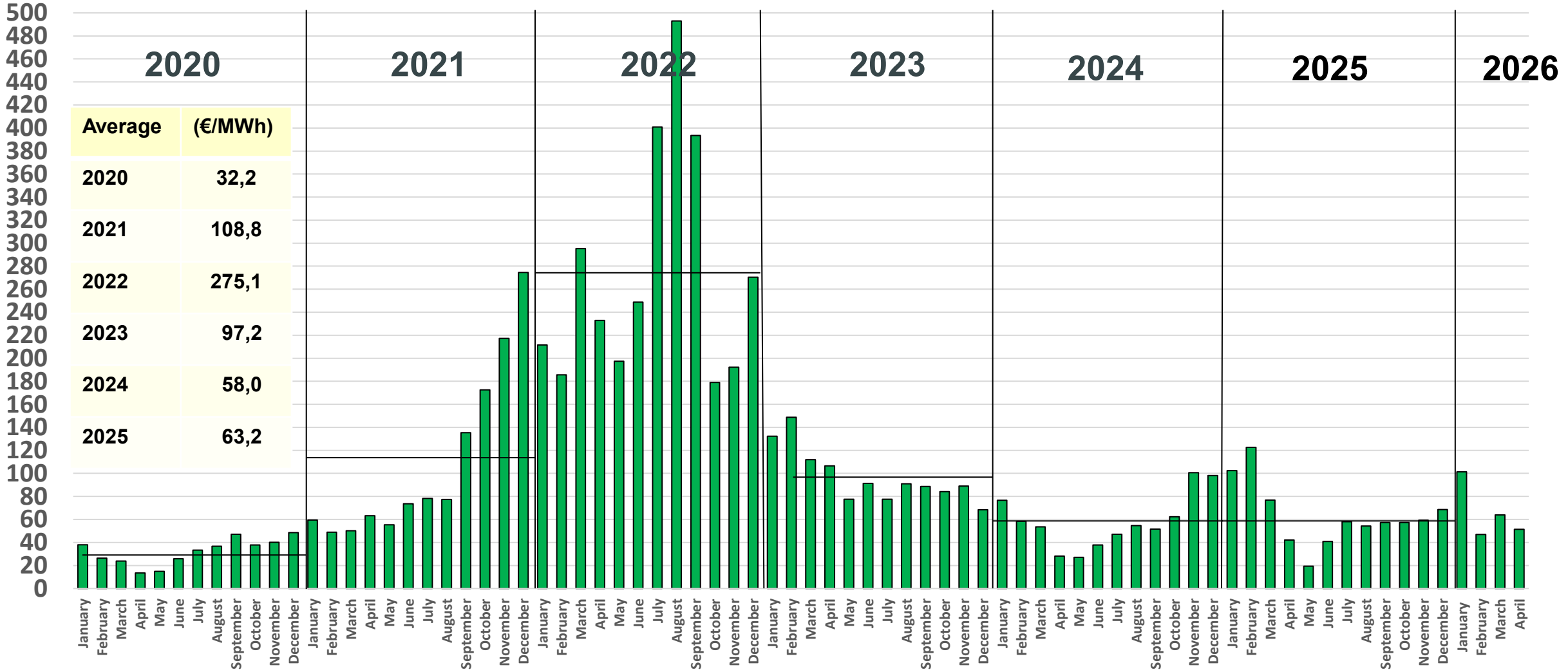


Average	($/Mbtu)
2020	3,2
2021	16,3
2022	37,5
2023	12,9
2024	10,9
2025	11,9

Source: Ch.Guéritte/Data from IMF Primary Commodity Prices

Monthly Wholesale Electricity Prices France 2020 – 2025 (€/MWh)

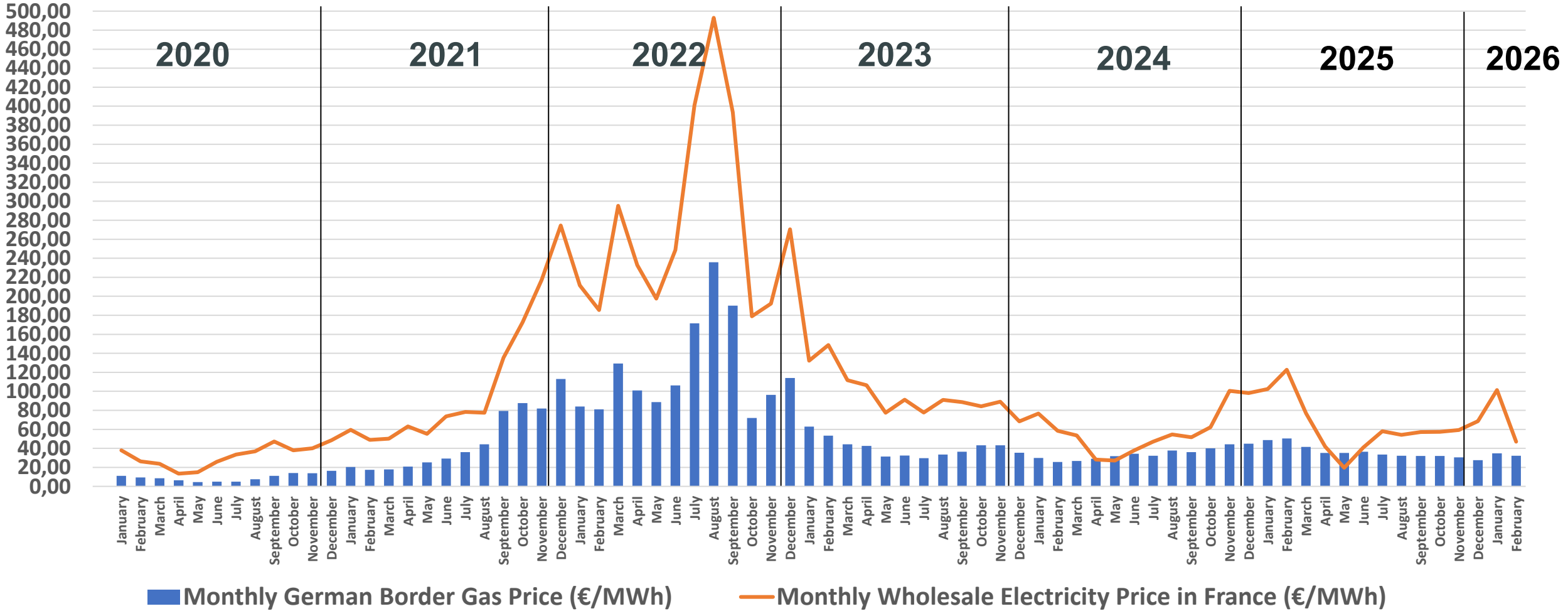
The impacts of economic & geopolitical turmoils are great



Average	(€/MWh)
2020	32,2
2021	108,8
2022	275,1
2023	97,2
2024	58,0
2025	63,2

Source: Ch.Guéritte/Data from Ember

Strong correlation Electricity Price/ Gas Price in Europe (€/MWh)
The impacts of economic & geopolitical turmoils are great

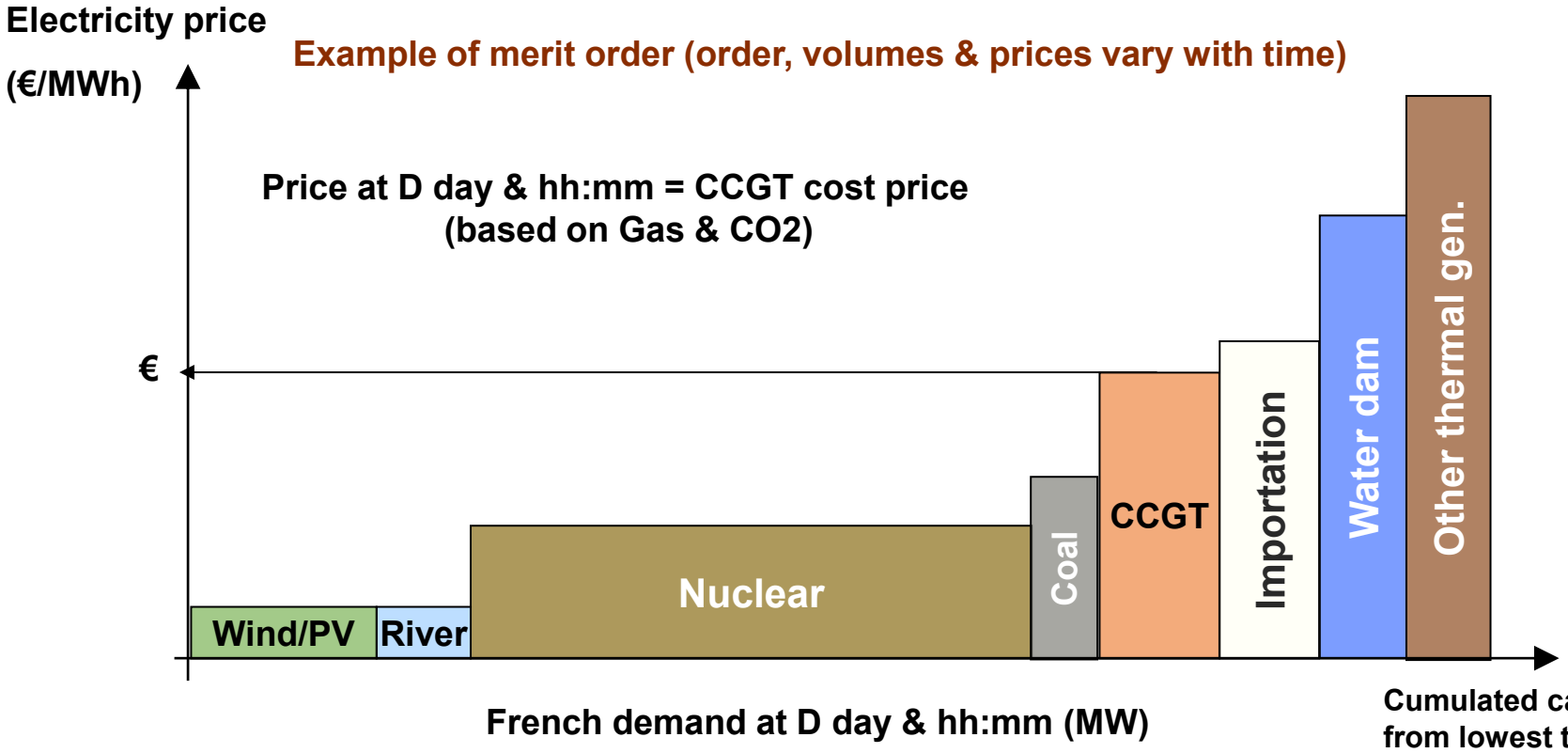


Source: Ch.Guéritte/Data from Ember, IMF
Exchange Rate: FRED, US Fed. Reserve system

Energy management / Electricity pricing in Europe

In Europe, electricity pricing is the result of offer and demand.

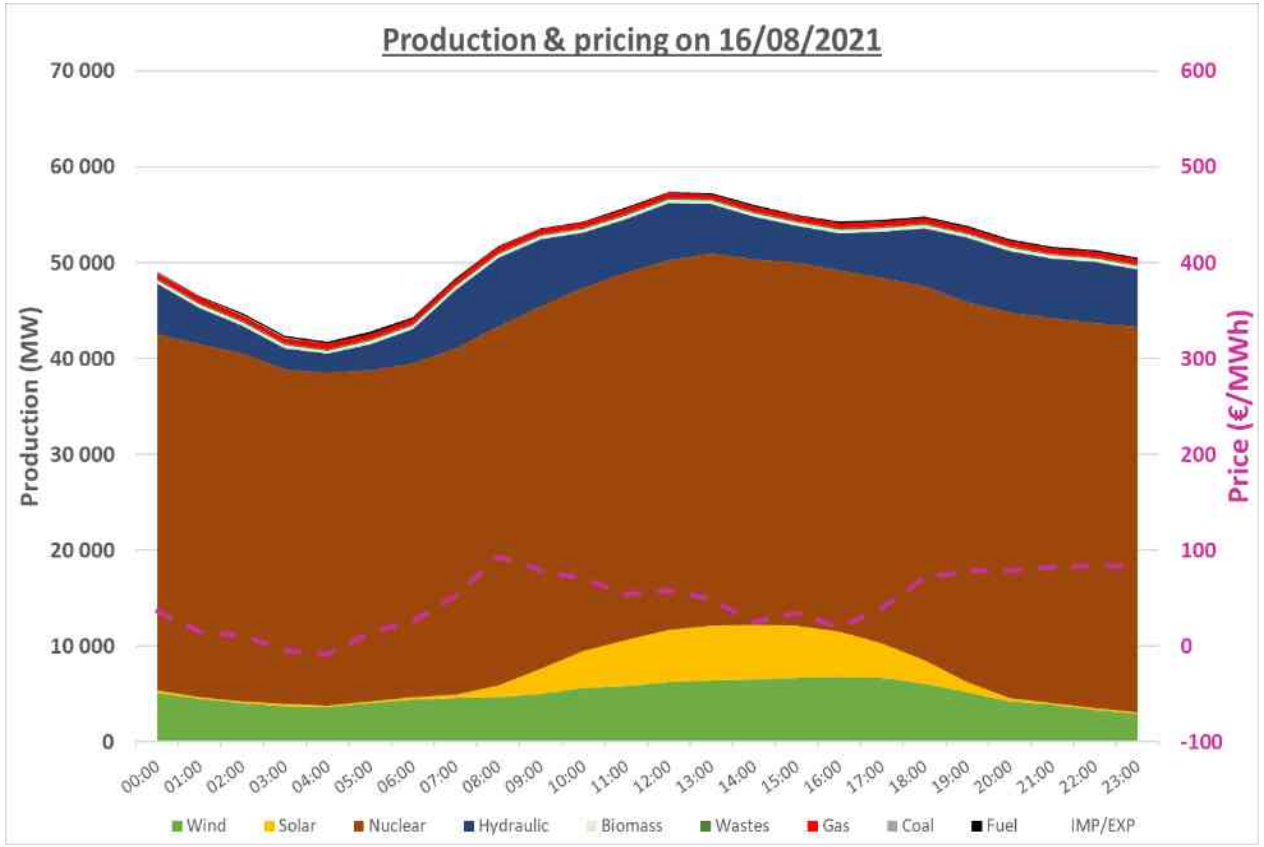
Production means are ranked by merit order based on production costs. Price of electricity is set by the most expensive plant required to serve demand ("marginal pricing")

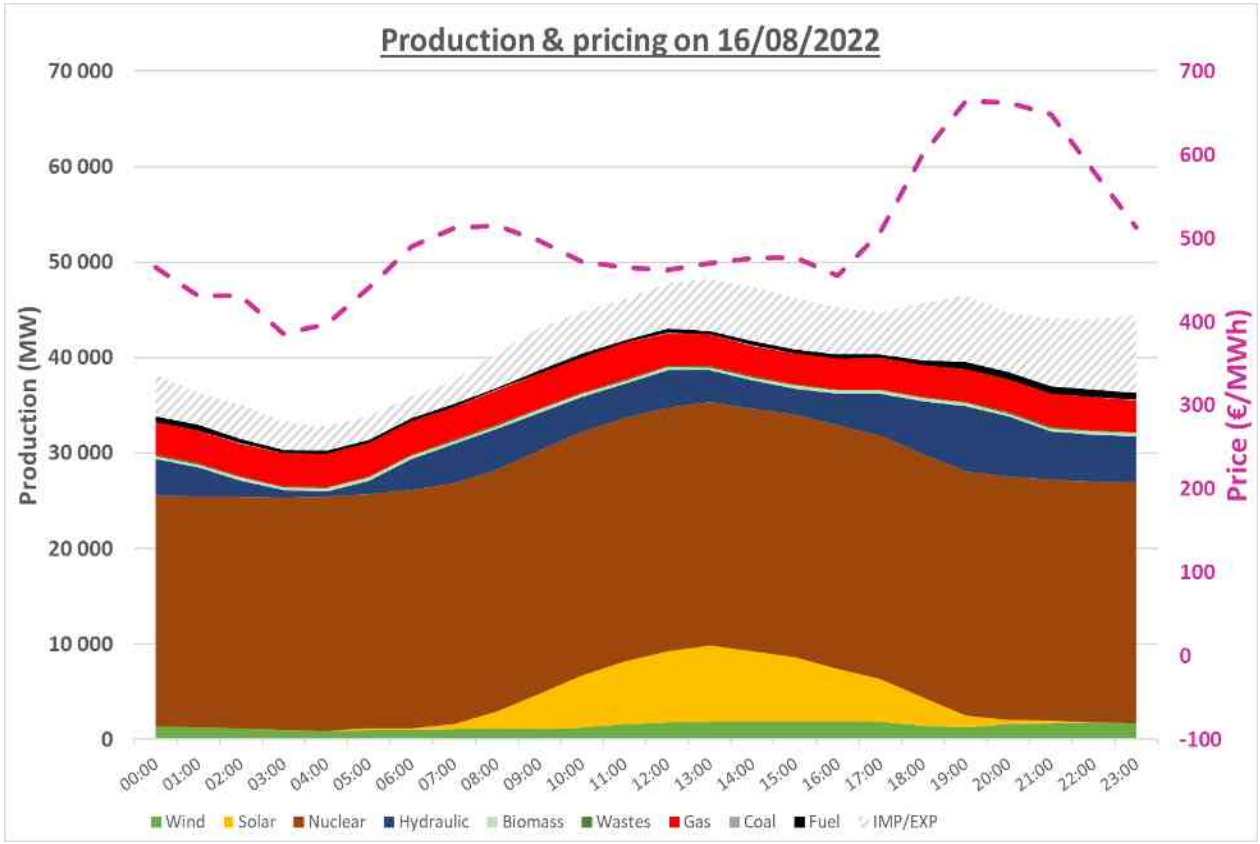


	Cost variability	Production Variability
Wind / PV	Low	High
River dam	Low	Medium
Nuclear	Low	Medium
Coal	High (CO2, coal)	On demand
CCGT	High (CO2, gas)	On demand
Importation	High	High
Water dam	Medium (water)	On demand

Energy management / electricity pricing in Europe

Same day, 2 different years / 2 opposite contexts:





High nuclear (37GW), high wind (6GW), high export (-10GW) => CCGTs OFF	**Low nuclear (25GW), low wind (1GW), high import (+5GW) => CCGTs ON (4GW)**
Average price = 50 €/MWh	**Average price = 500 €/MWh**
CO_2 = 55€/t, Gas = 45€/MWh	**CO_2 = 90€/t, Gas = 150€/MWh**

The formation of Electricity Prices in France

- **Electricity price in France depends upon:**

1) the price deriving from the supply/demand balance at european level. Wholesale Electricity price is indexed on the european Gas price, which reached recently mid-2022 very high levels, due to the gas crisis following russian invasion of Ukraine. Since the 4th quarter 2022, the Wholesale price for Gas & Electricity has then substantially decreased.

2) the price regulated according to the french legislation.

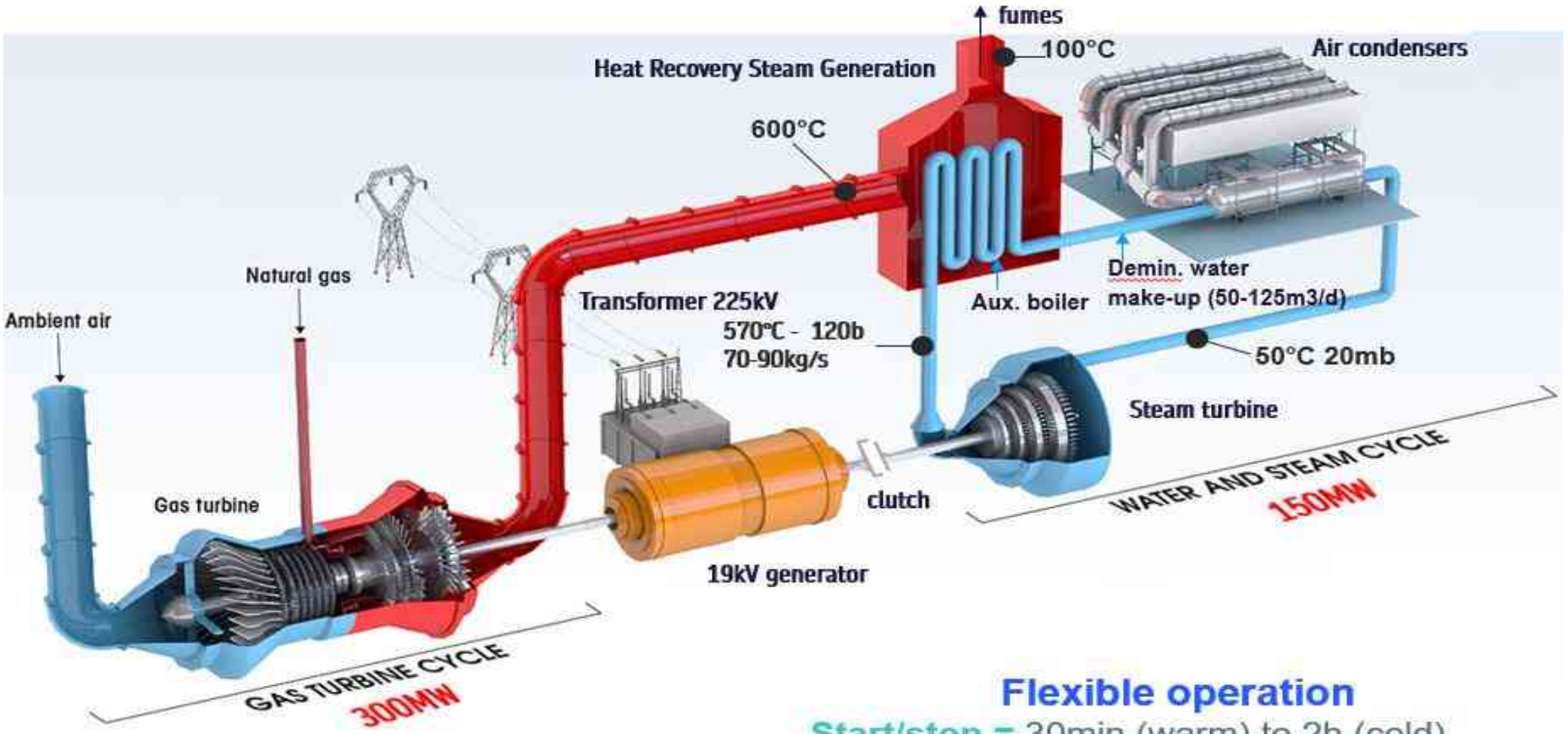
- **The final Electricity price for the french consumer takes into account several elements: the imported price of Electricity, the cost price of Electricity from nuclear power, hydroelectricity, wind and solar power, it also includes different level of taxes (VAT, Accise, CFCE, TCFE)**

- **In order to limit the price increase following the Russia/Ukraine war, the french government decided to limit or cancel certain taxes on Electricity (CFCE, TCFE)**

- **Since the end of year 2023, Electricity production capacities have increased thanks to nuclear reactors to power-up following refurbishment, high water level in hydraulic dams, higher performance of wind farms. Combined with a lower demand, the effect was an decrease of average production price of Electricity.**

- **Nevertheless, compared to the pre-crisis level, Electricity price in France will continue to grow, also in view of the resettlement of taxes on Electricity.**

Energy Management - Combined Cycle Gas Turbine (CCGT)
A good tool for production variability



Flexible operation

Start/stop = 30min (warm) to 2h (cold)

Power management = 200 to 450 MW

US Focus - Impact of US elections – Trump's investiture
Which consequences on World Economy and Energy?

Why focusing on the US when talking Energy & Climate

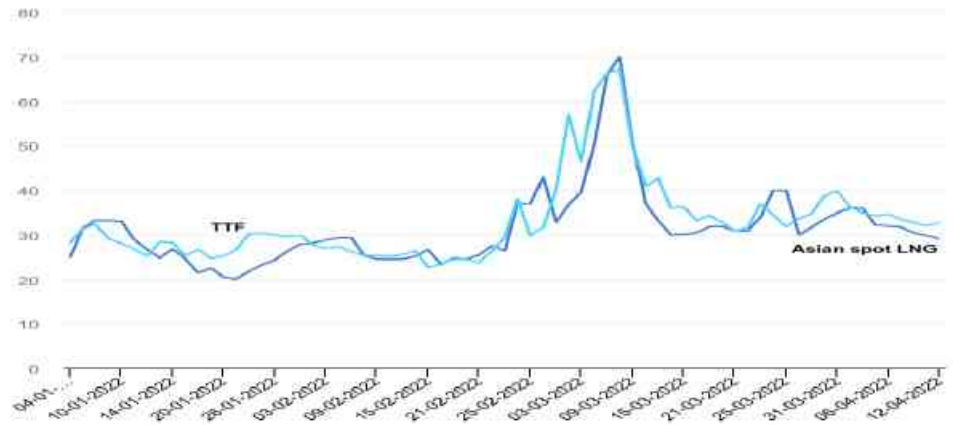
- As the largest economy in the world, the U.S. leads the way and has a global impact
- As the first oil, natural gas and nuclear power producer WW, the U.S. has a specific impact on global energy trade and balance
- Energy and geopolitics are increasingly interwined today with recent U.S. actions
- As Climate is a global issue at the heart of all current debates, the U.S.'s position is crucial for the planet future

Source: Ladislas Paszkiewicz –TPA webinar Feb4, 2026

US priorities

U.S. priority N°1: Build on economic competitive advantage provided by cheap and abundant domestic energy

- Job creation boosted by the shale revolution (O&G > 2M direct jobs (est.) – X10 indirect)
- Affordable energy is a key competitive advantage:
  - Oil market is global but NG market is still local
    - Eg:TTF & JKM prices after Ukraine invasion by Russia (HH remained below $8/Mbtu)



But radically different approaches between D and R on the « how »

Source: Ladislas Paszkiewicz –TPA webinar Feb4, 2026

US priorities

Priority N°2: Ensuring security of supply and using energy as a geopolitical lever

Historic attempts at cooperation…..

- Saoud-Roosevelt on USS Quincy (1945)
- GATT (1947) and WTO (1994)
- Atoms for peace 1953 → AIEA 1957
- IEA 1974 (created by OECD following first oil shock 1973)
- UNFCCC 1992, COP since 1995 X
- U.S. joined IRENA in 2010 X

…followed by withdrawals and energy leverage…

- U.S. sanctions on Russia's two largest oil Cies
- Threats of tariffs against India if it did not cease Russian oil purchases
- Pressure on Europe to buy U.S. LNG
- Venezuela oil blockade, NOPEC bill, …

...and a shift from market led approaches toward state capitalism

- State equity stakes in energy projects
- State involvment to reduce supply chain dependency
- State pressure towards private sector (Venezuela – « $B100's to be invested »)

Source: Ladislas Paszkiewicz –TPA webinar Feb4, 2026

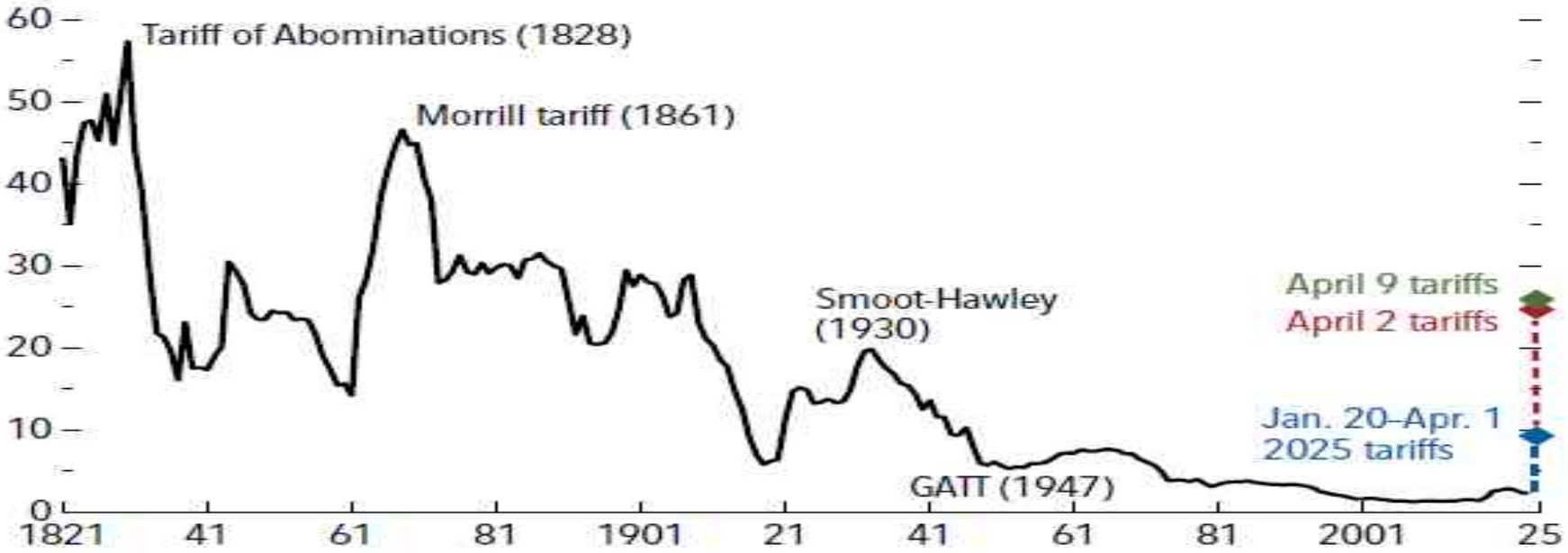
US priorities

Priority N°3 (or not a priority at all) - Climate



Source: Ladislas Paszkiewicz –TPA webinar Feb4, 2026

Tariff & Trade: Historical evolution: Up's and Down's! – The Trump's effect for 2025
US Effective Tariff Rates on All Imports (%)



Sources: US Bureau of the Census, *Historical Statistics of the United States, 1789–1945*; US International Trade Commission; and IMF staff calculations.

Note: The Jan. 20–Apr. 1 tariffs in 2025 include 20 percent tariffs on China; 25 percent tariffs on steel and aluminum; 25 percent tariffs on Mexico and Canada; and a 10 percent tariff on Canadian energy imports. A United States–Mexico–Canada Agreement (USMCA) carve-out is assumed to halve the effective tariff increase for Canada and Mexico. The April 2 tariffs include auto sector tariffs and country-specific tariffs, applying exemptions provided in Annex II of the Executive Order per IMF staff judgment. The April 9 tariffs include an increase in the tariffs on China to 145 percent and a reduction in other country-specific tariffs to 10 percent. It also includes exemptions on some electronic products announced on April 11. GATT = General Agreement on Tariffs and Trade.

Source: IMF World Economic Outlook April 2025
A critical Juncture amid Policy Shifts

Tariff & Trade: Historical evolution - Some specific events

Tariff of Abominations:

The bill was passed in the US Congress in 1828. The goal was to protect the US factories by taxing imports from Europe. But the law was vehemently contested by the South arguing that the tariffs enhanced the interests of the North at their detriment. The tariffs were replaced in 1833.

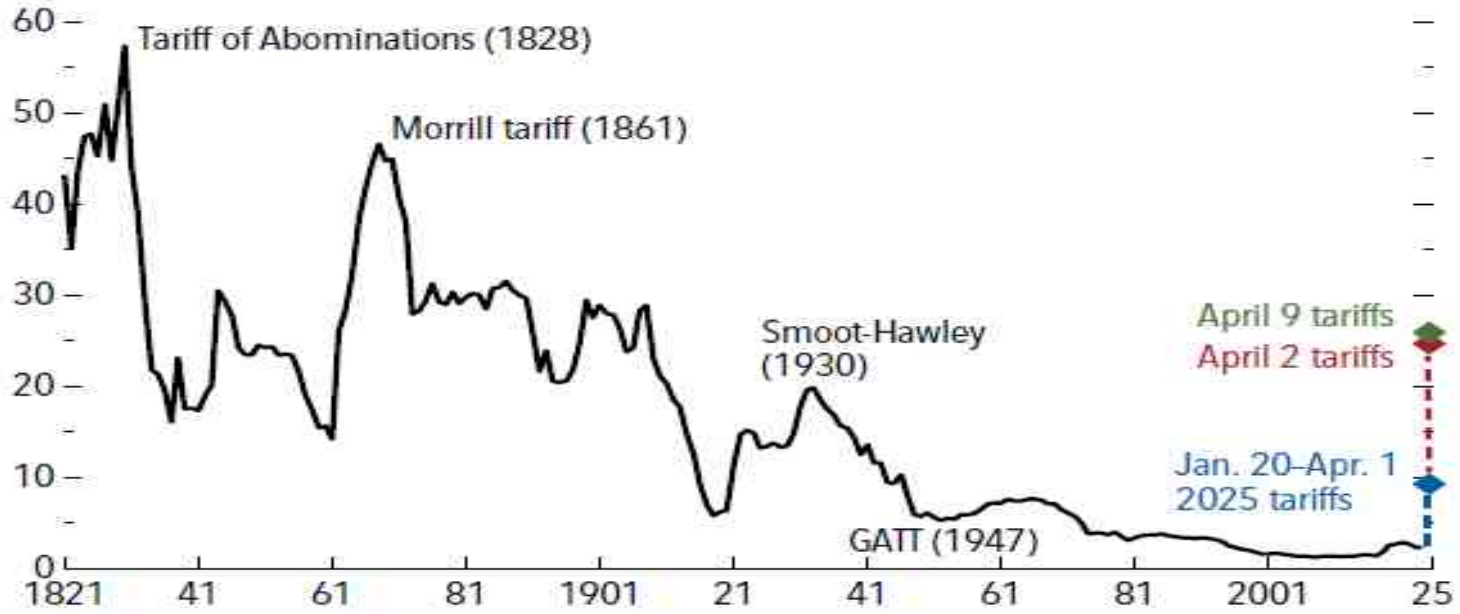
Morrill tariff:

An increased import tariff promoted by Justin Smith Morrill adopted in March 1861 during the presidency of the Democrat James Buchanan. It was put in place for the benefit of industrialists and factory workers to implement a rapid industrial growth.

Smoot-Hawley tariff:

A protectionist measure signed into law in June 1930 under the presidency of Herbert Hoover, in order to shield American industries from foreign competition during the onset of the Great Depression.

Tariff & Trade: Historical evolution: Up's and Down's! – The Trump's effect for 2025
February 2026: US Supreme Court invalidates Trump's Tariffs & Trades 2025 decrets



Sources: US Bureau of the Census, *Historical Statistics of the United States, 1789–1945*; US International Trade Commission; and IMF staff calculations.

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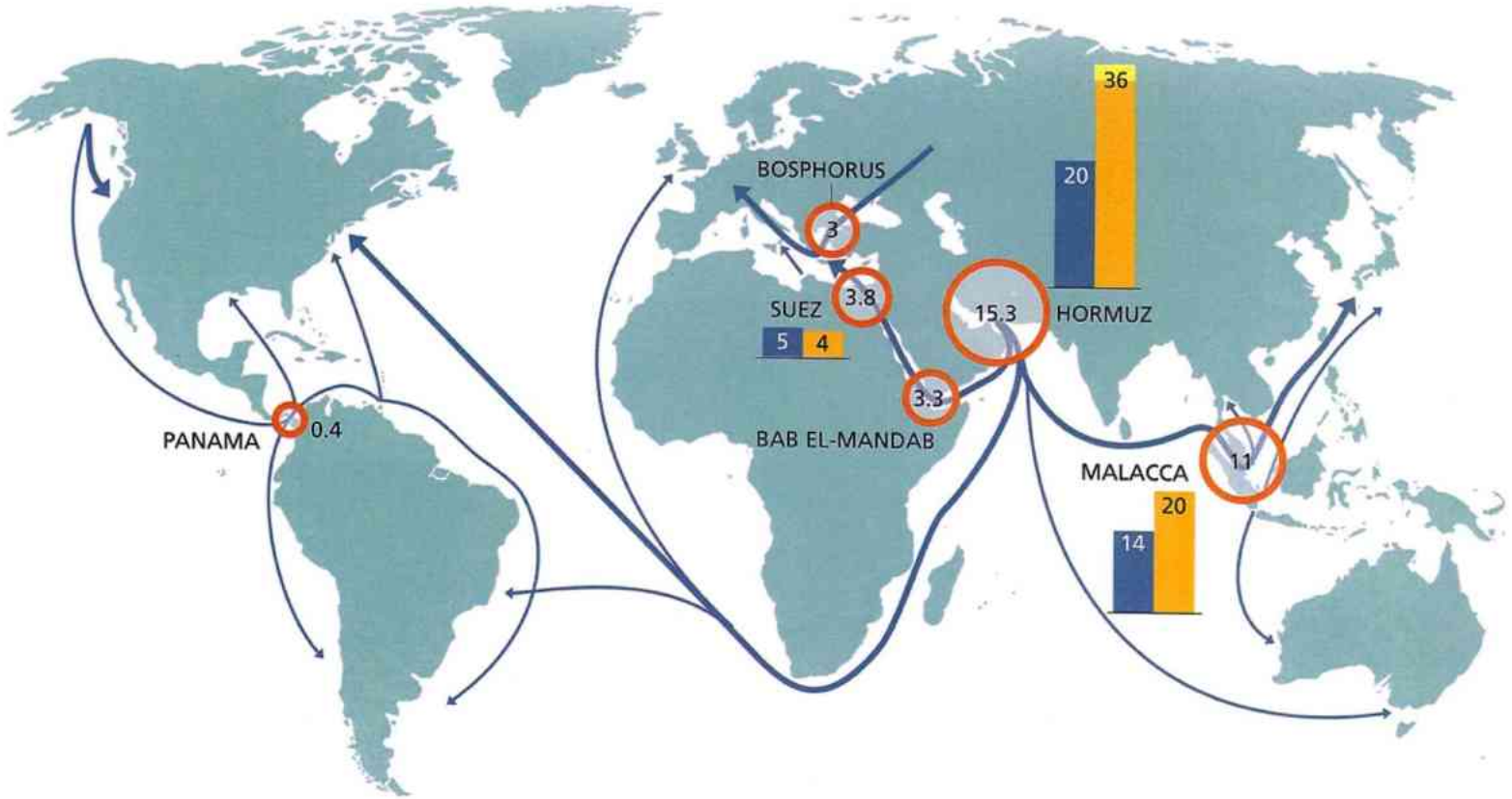
February 2026:

US Supreme Court invalidates Trump's Tariffs & Trades as illegal ➡ Important conséquences for the World Trading Business

Source: IMF World Economic Outlook April 2025
A critical Juncture amid Policy Shifts

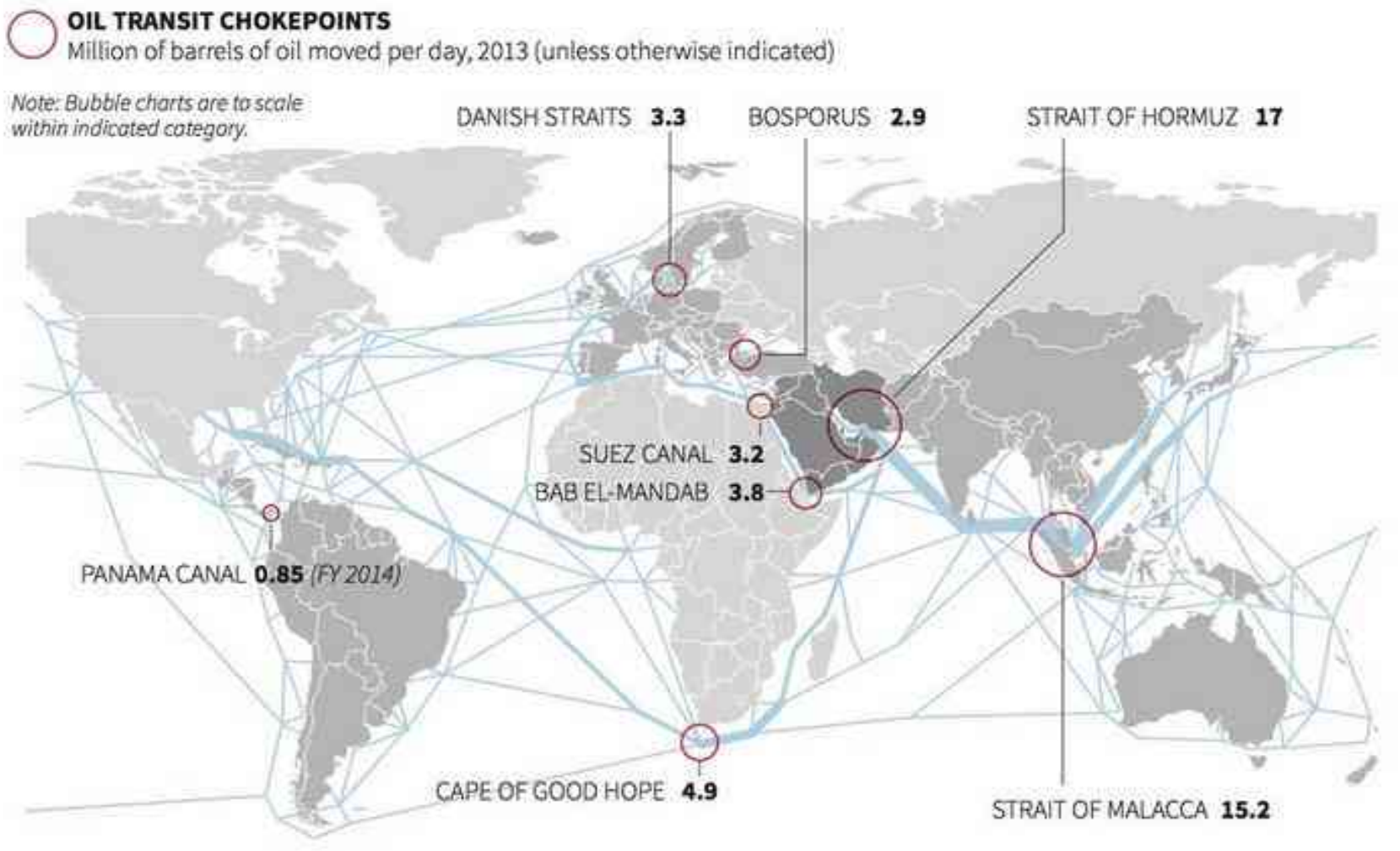
Geopolitical hotspots
Tensions/Wars in the Middle East

Oil major geopolitical hot points



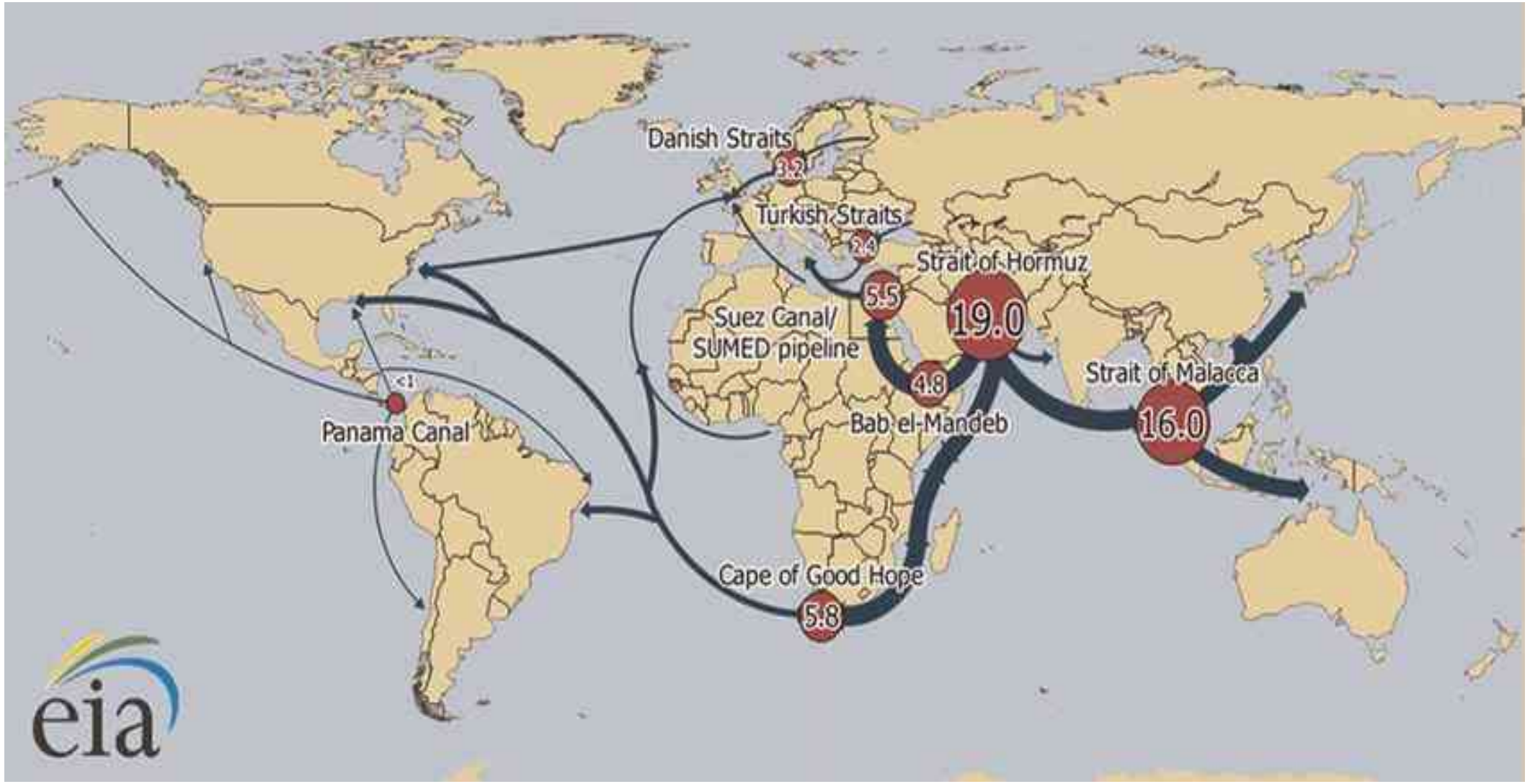
Source: International Energy Agency, *World Energy Outlook 2004.*

Oil major geopolitical hot points
Situation 2013



Source: US EIA

Oil major geopolitical hot points
Situation 2024 (Figures in Mb/d)



Tensions in the Middle East….. 2017



Courrier International 15 juin 2017



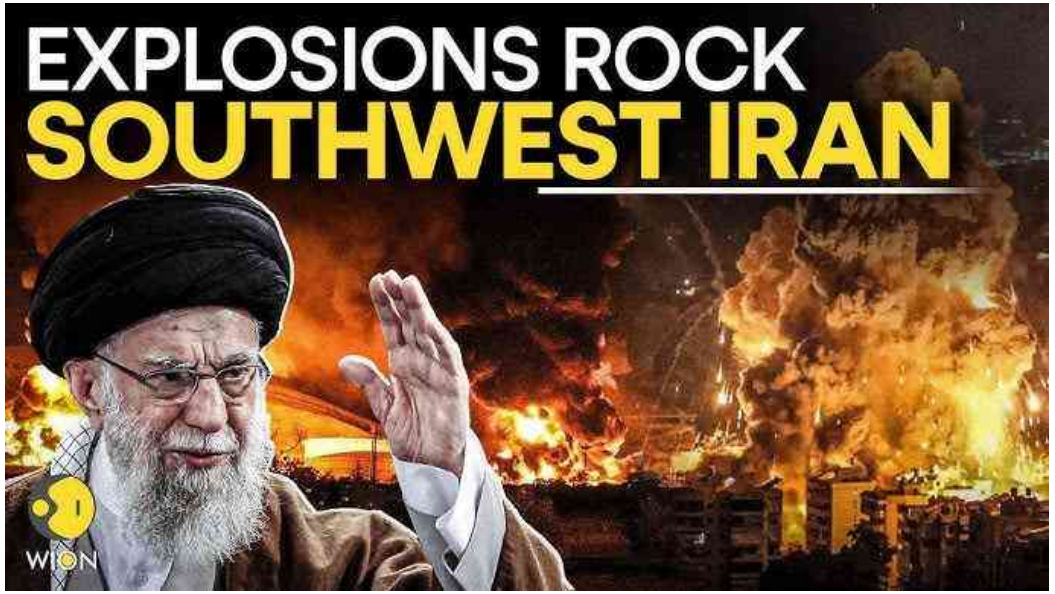
Courrier International 16 novembre 2017

Tensions in the Middle East
Oman Sea - June 2019



Source: News Agency - ISNA/AP

June 2025/Israel – Iran – US war - Threats on Hormuz strait







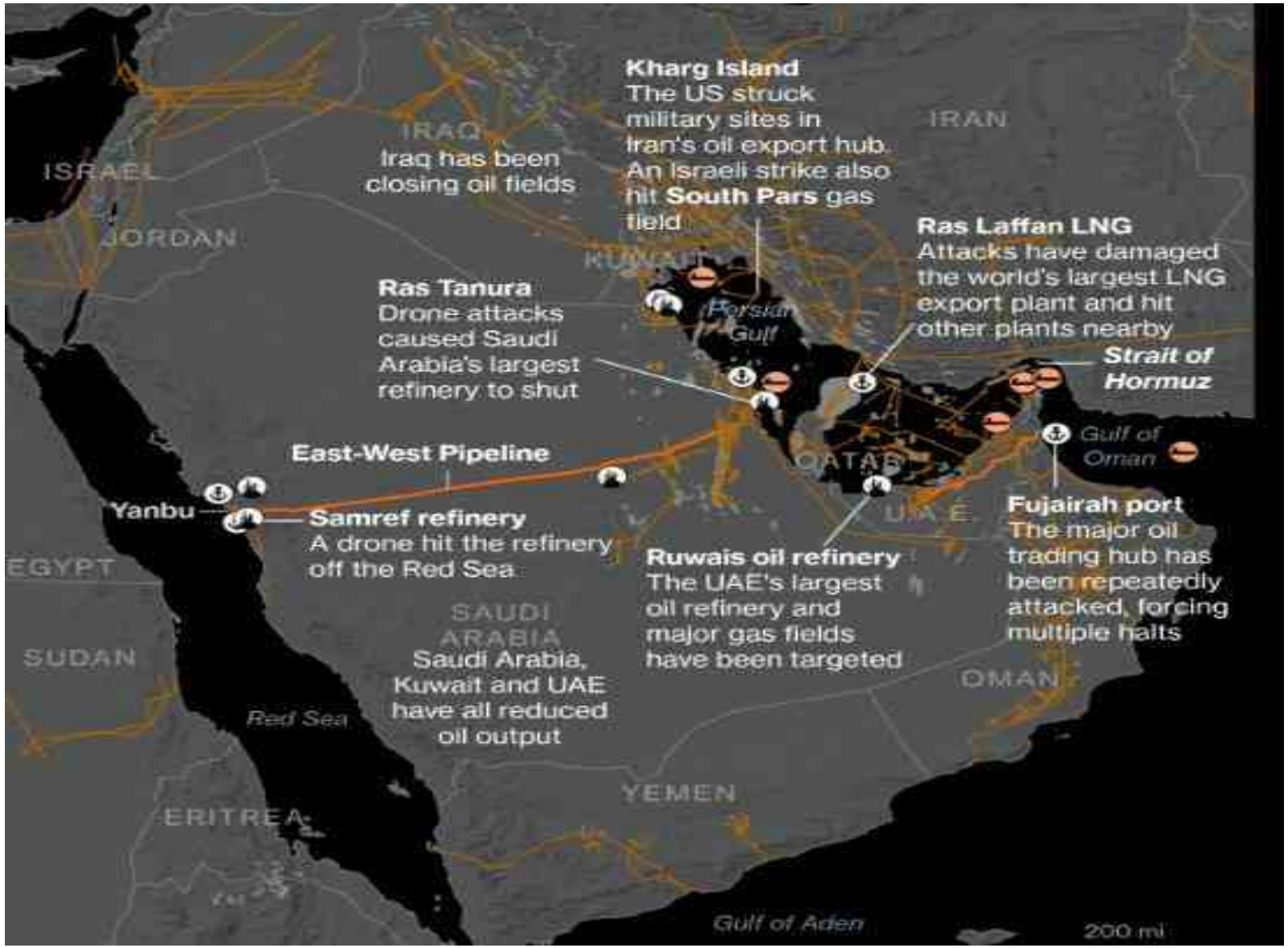


March 2026/Israel – Iran – US war - Threats on Hormuz strait



Téhéran – 1st March 2026

March 2026/Israel – Iran – US war – Oil & Gas Facilities damages



March 2026/Israel – Iran – US war - Threats on Hormuz strait

Oil

20 mb/d, around 25% world seaborne oil trade, transits the Strait – 80% destined for Asia.

3.5 to 5.5 mb/d of pipeline capacity with the potential to re-direct crude flows to avoid the Strait.

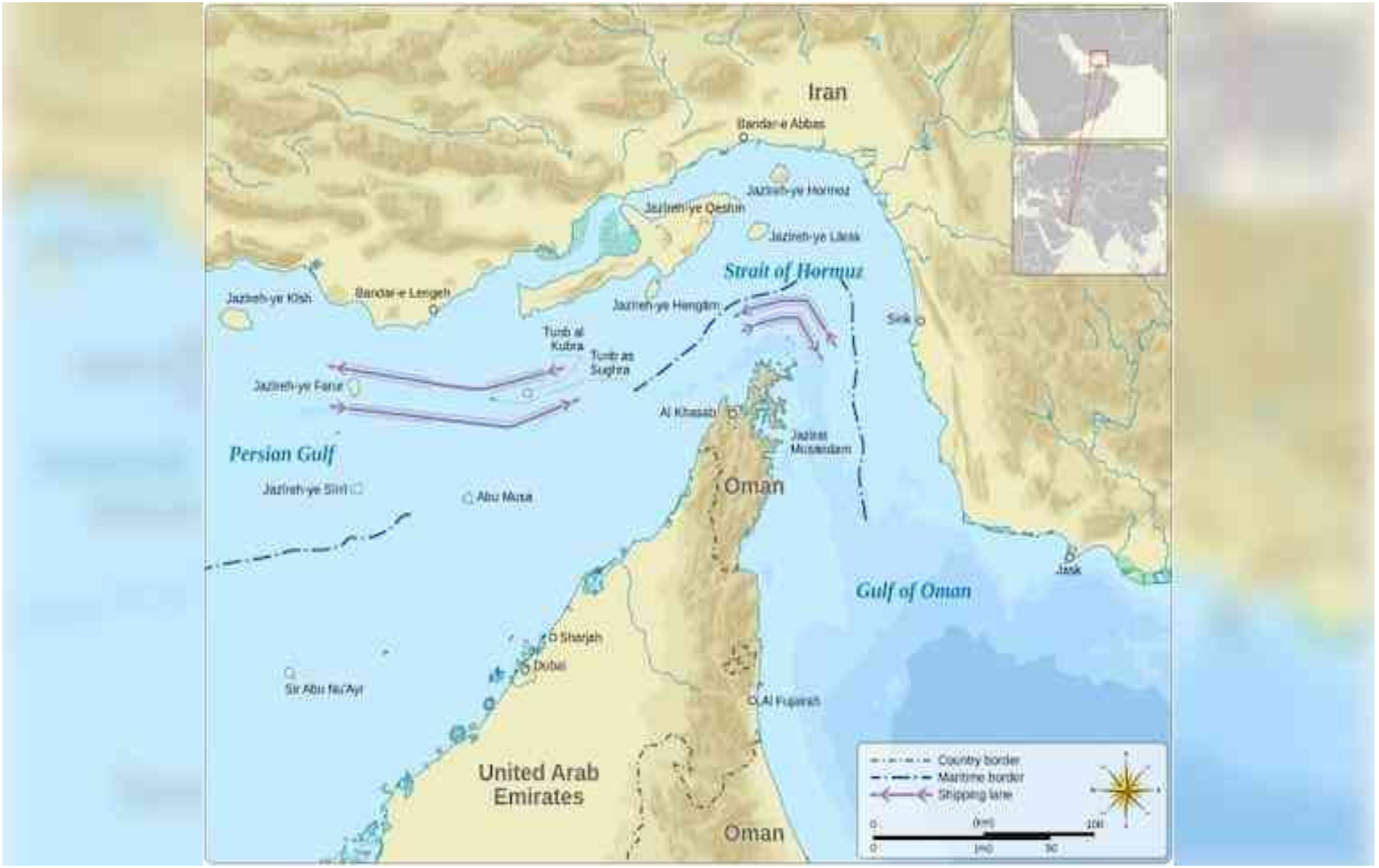
Lasting disruptions unlikely, but even if short-lived would have significant impact on oil markets.

Natural gas

About 93% of Qatar's and 96% of the UAE's LNG exports transit through the Strait, representing 19% of global LNG trade.

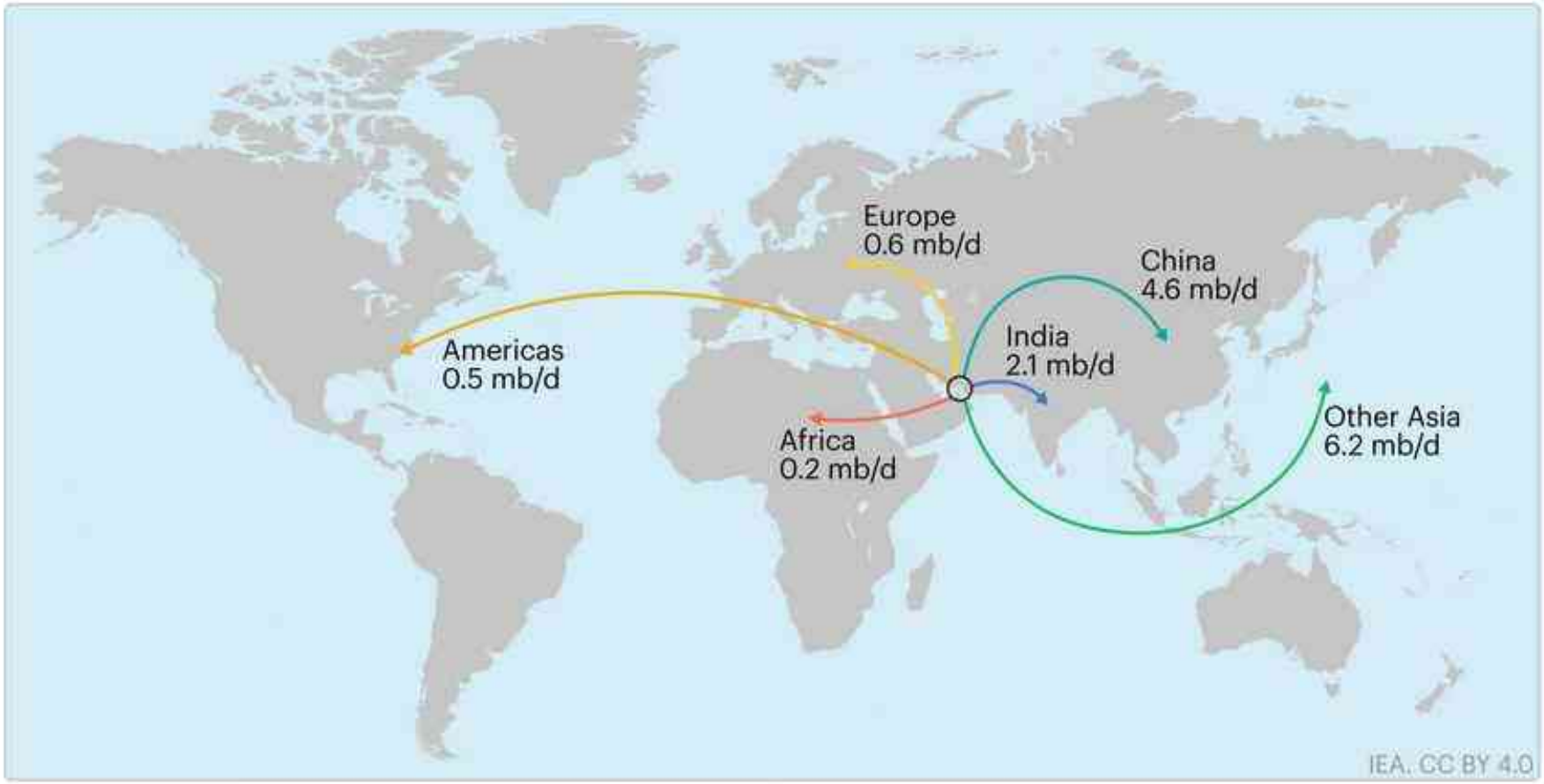
Source – IEA March 2026

March 2026/Israel – Iran – US war - Threats on Hormuz strait



March 2026/Israel – Iran – US war - Threats on Hormuz strait

Crude oil exports transiting the Strait of Hormuz by destination (2025)

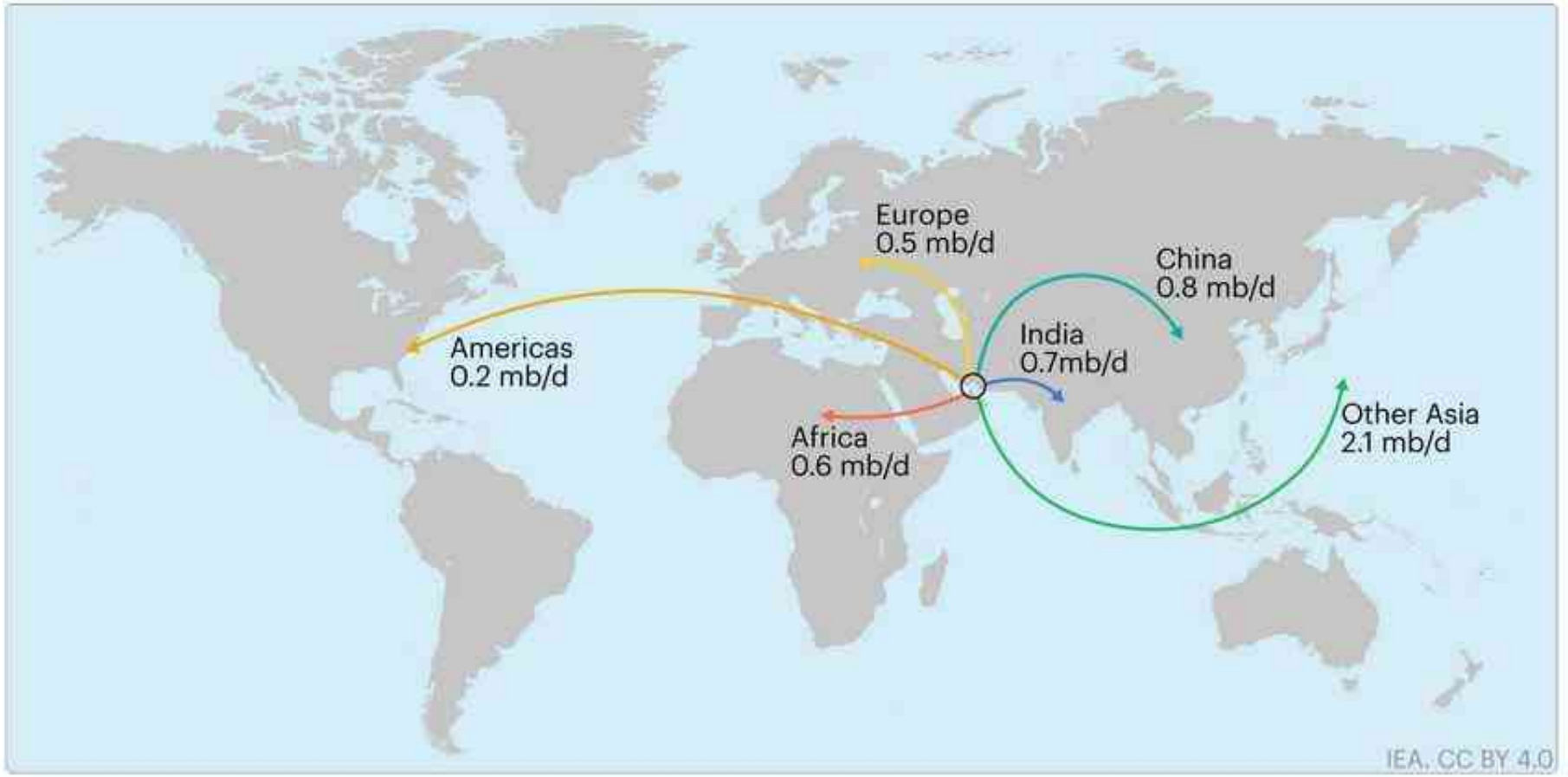


Total does not match sum of adding individual numbers due to destinations not indicated. Source: IEA analysis based on Kpler.

Source – IEA March 2026

March 2026/Israel – Iran – US war - Threats on Hormuz strait

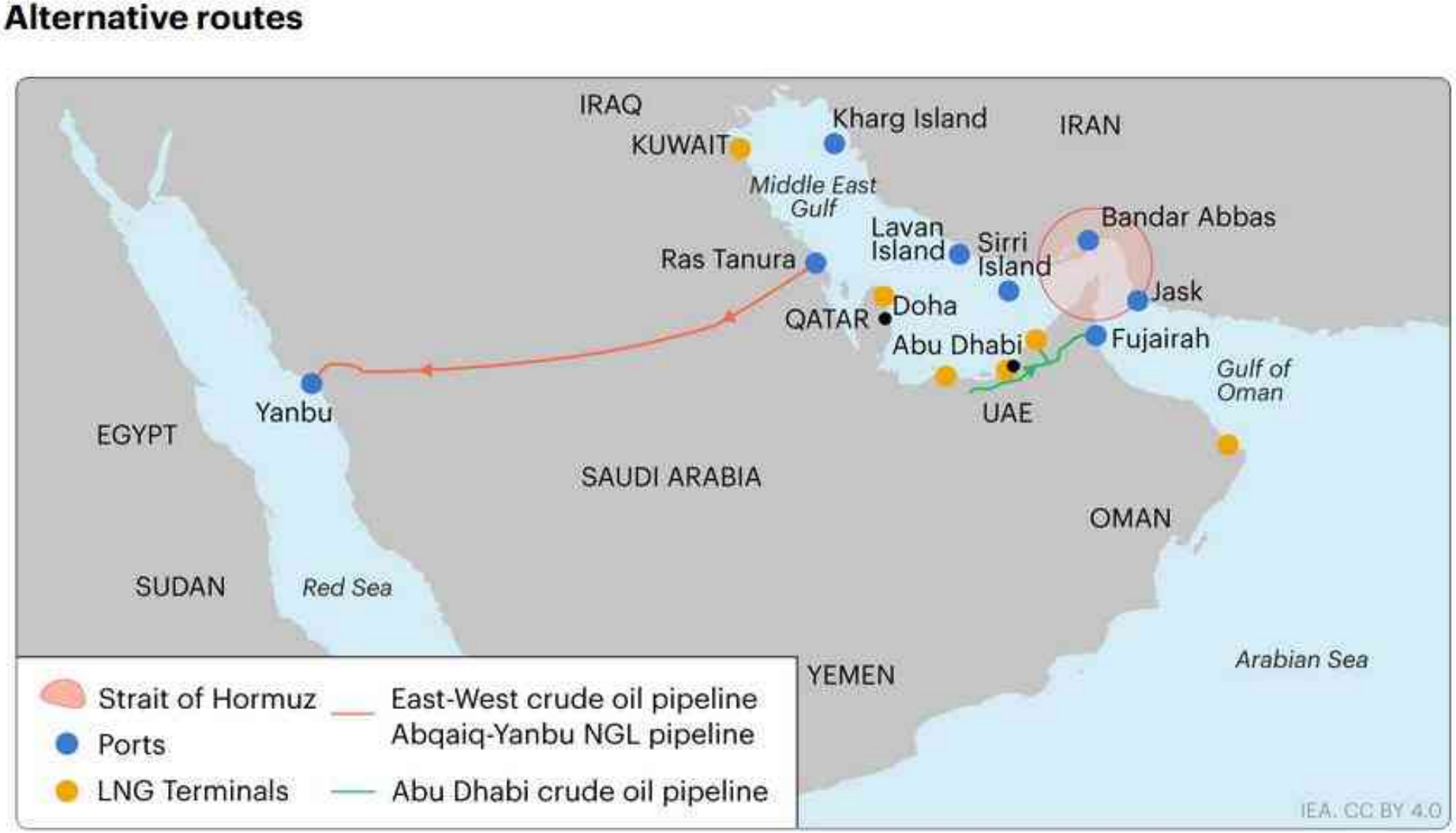
Oil product exports transiting the Strait of Hormuz by destination (2025)



Total does not match sum of adding individual numbers due to destinations not indicated. Source: IEA analysis based on Kpler.

Source – IEA March 2026

March 2026/Israel – Iran – US war - Threats on Hormuz strait

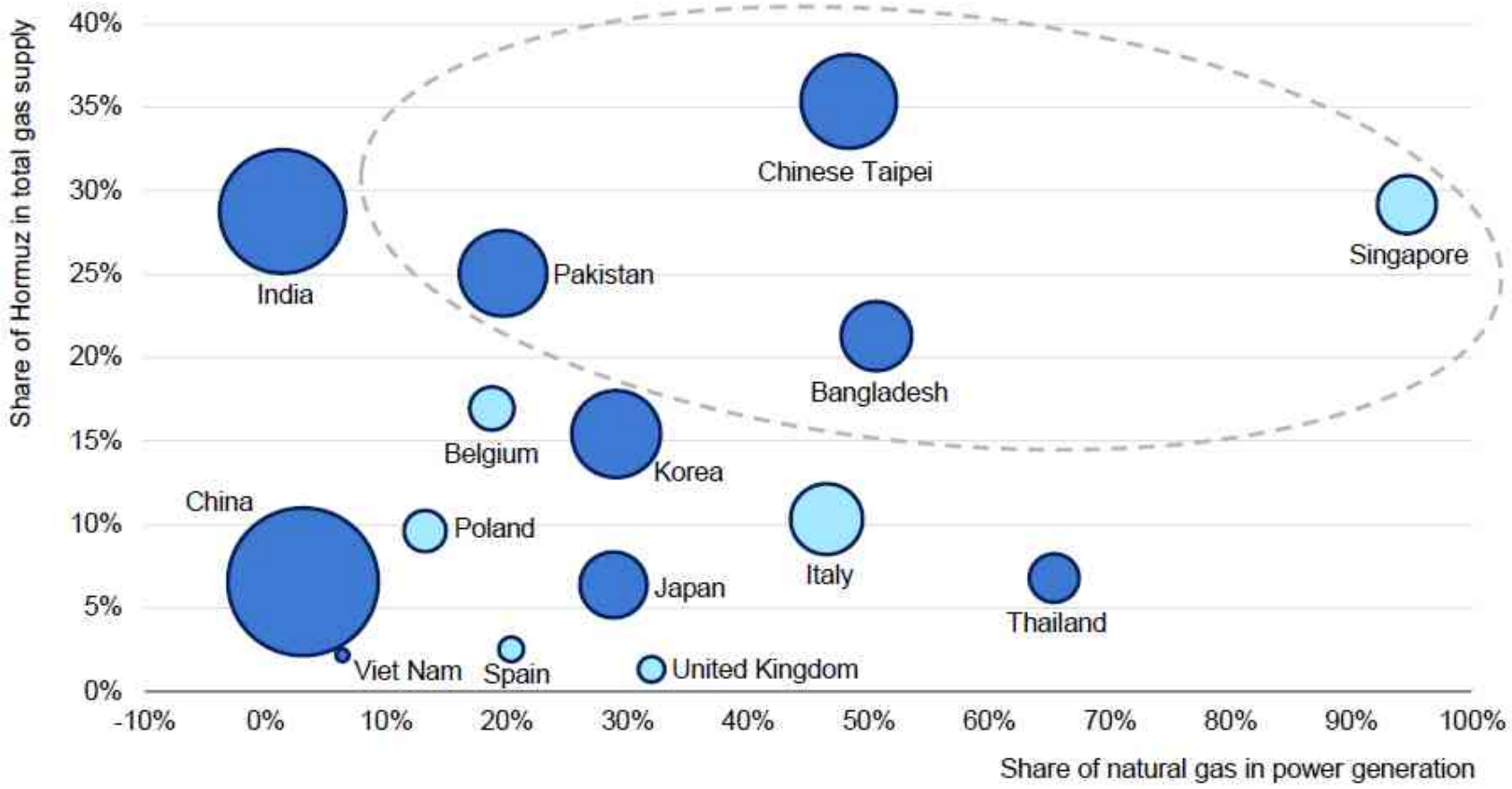


Source – IEA March 2026

March 2026/Israel – Iran – US war - Threats on Hormuz strait

Asian markets are more directly exposed to the LNG supply disruption via the Strait of Hormuz

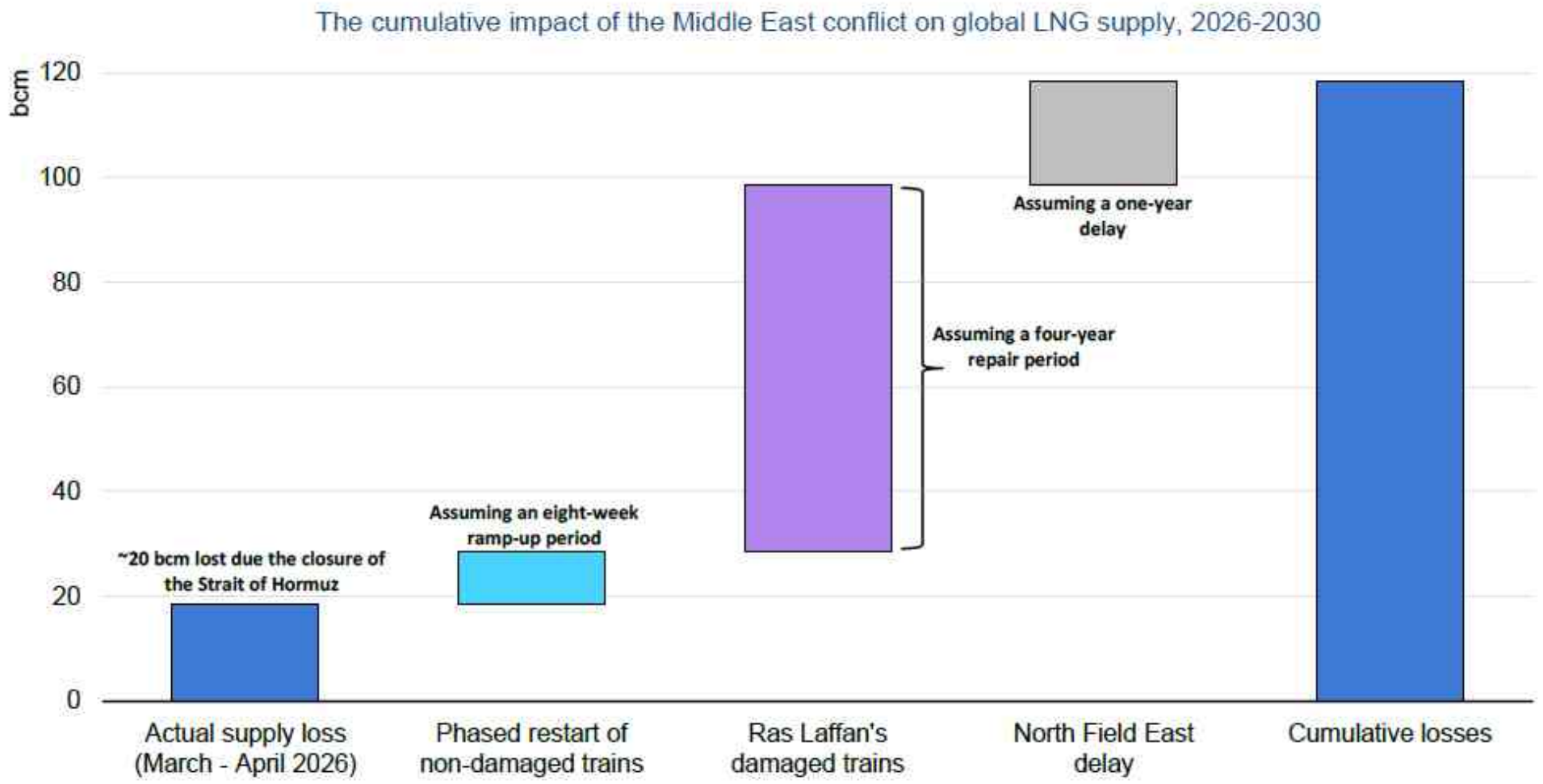
LNG supplied via Strait of Hormuz as a share of natural gas demand in key import markets and the share of gas-fired power generation in their power mix in 2025



Source: IEA-Gas report 2026-Q1

March 2026/Israel – Iran – US war - Threats on Hormuz strait

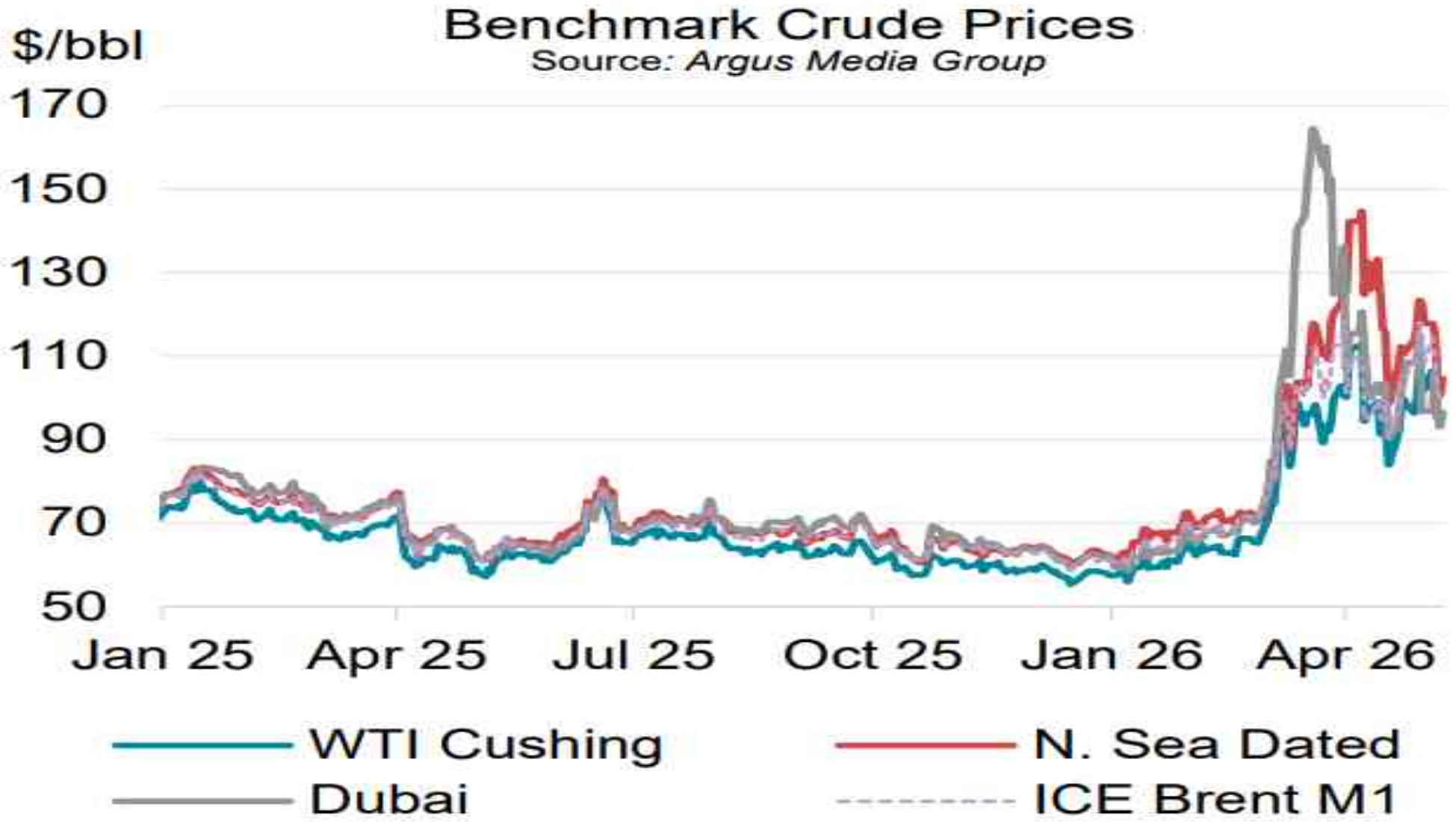
The Middle East conflict leads to a loss of over 120 bcm of cumulative LNG supply in the 2026-2030 period



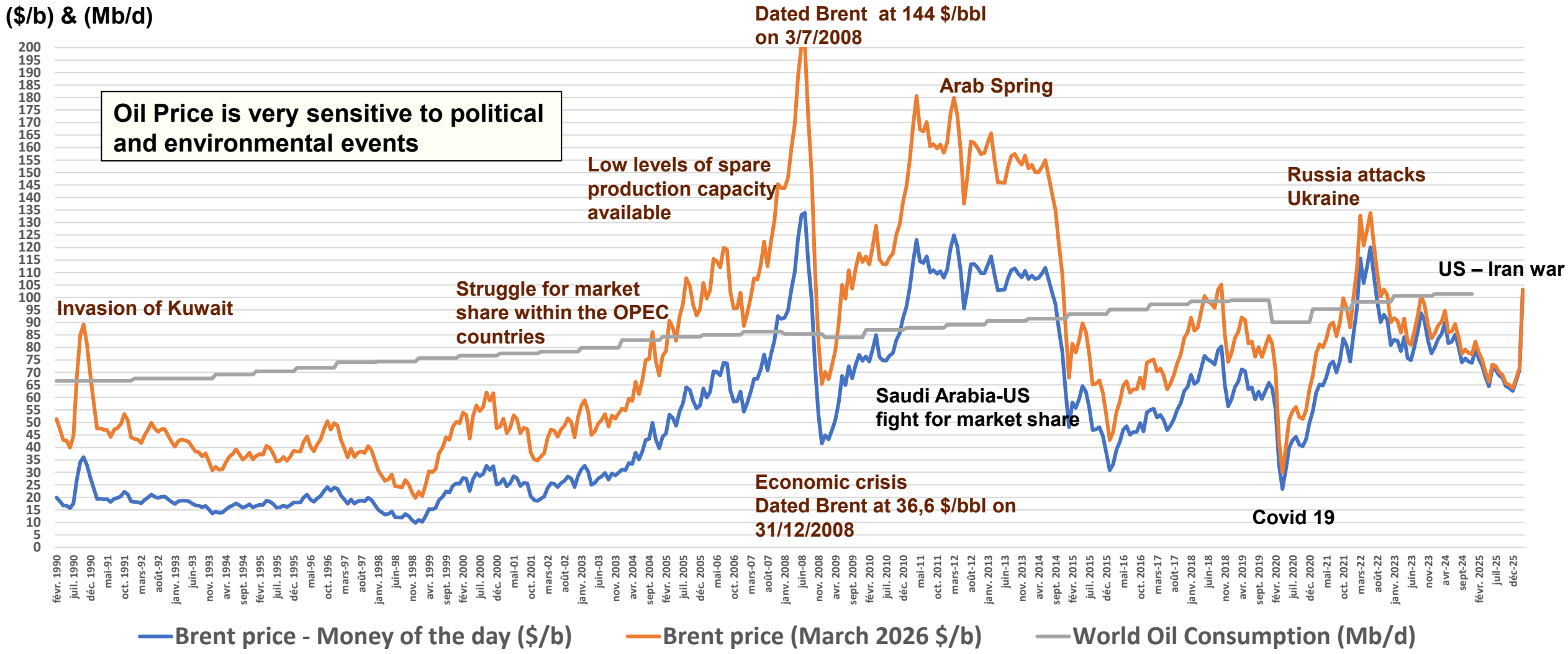
Source: IEA-Gas report 2026-Q1

Impact on Crude Oil and Gas Prices

Oil Prices in 2025-2026: Iran war effect



Crude Oil Price and Oil Consumption since 1990 till March 2026
(Monthly Average - Prices are fluctuating within a month)

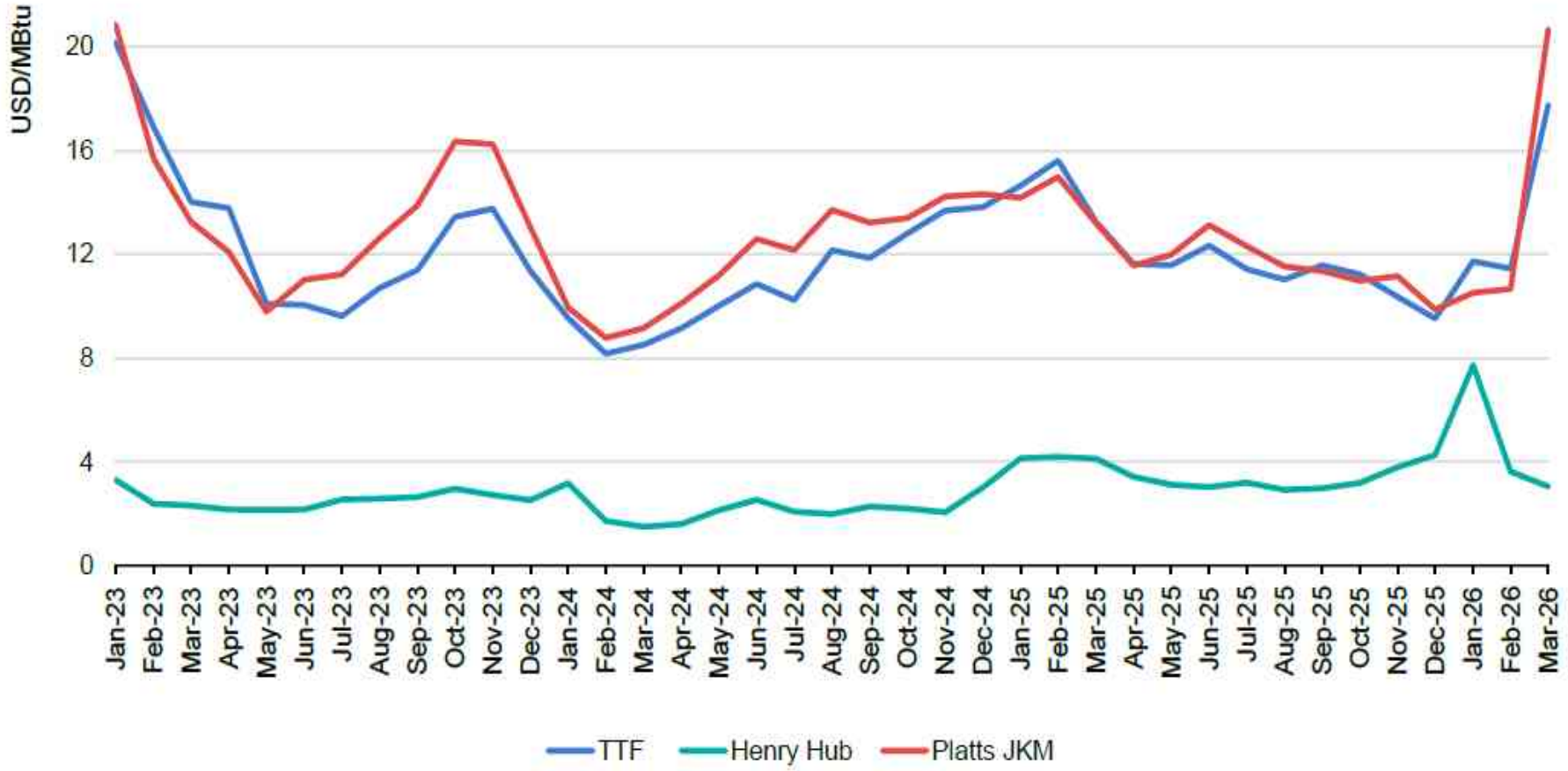


Source: ChG/Price: Data from EIA Index Mundi – US CPI: Bur. of Labor Statistics
Oil Consumption: EI Stat. Review 2025

LNG Prices

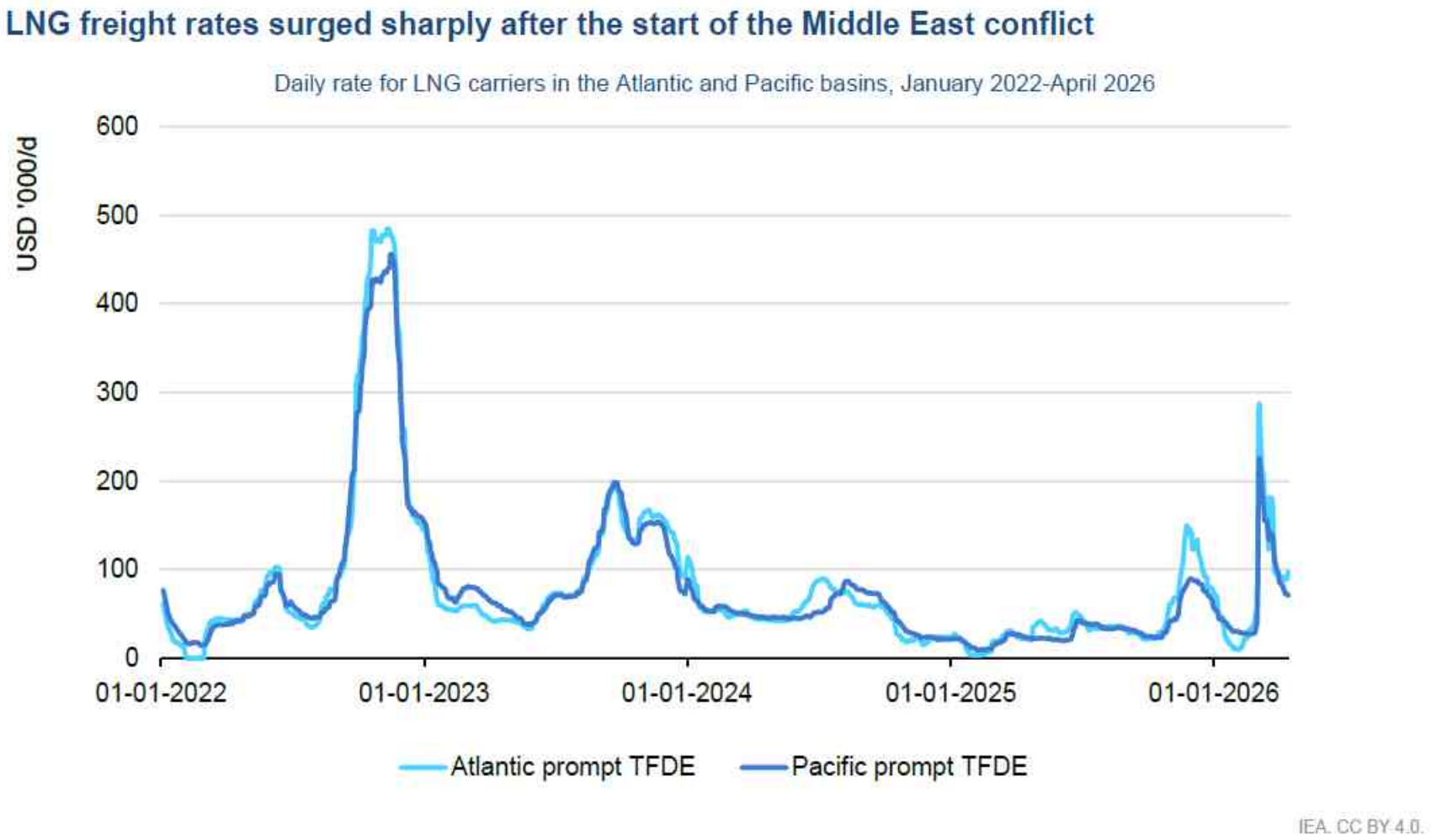
Asian spot LNG prices traded well above European hub prices in March 2026

Main spot and forward natural gas prices, January 2023-March 2026



Source: IEA Gas Market Report Q2 2026

LNG freight rates

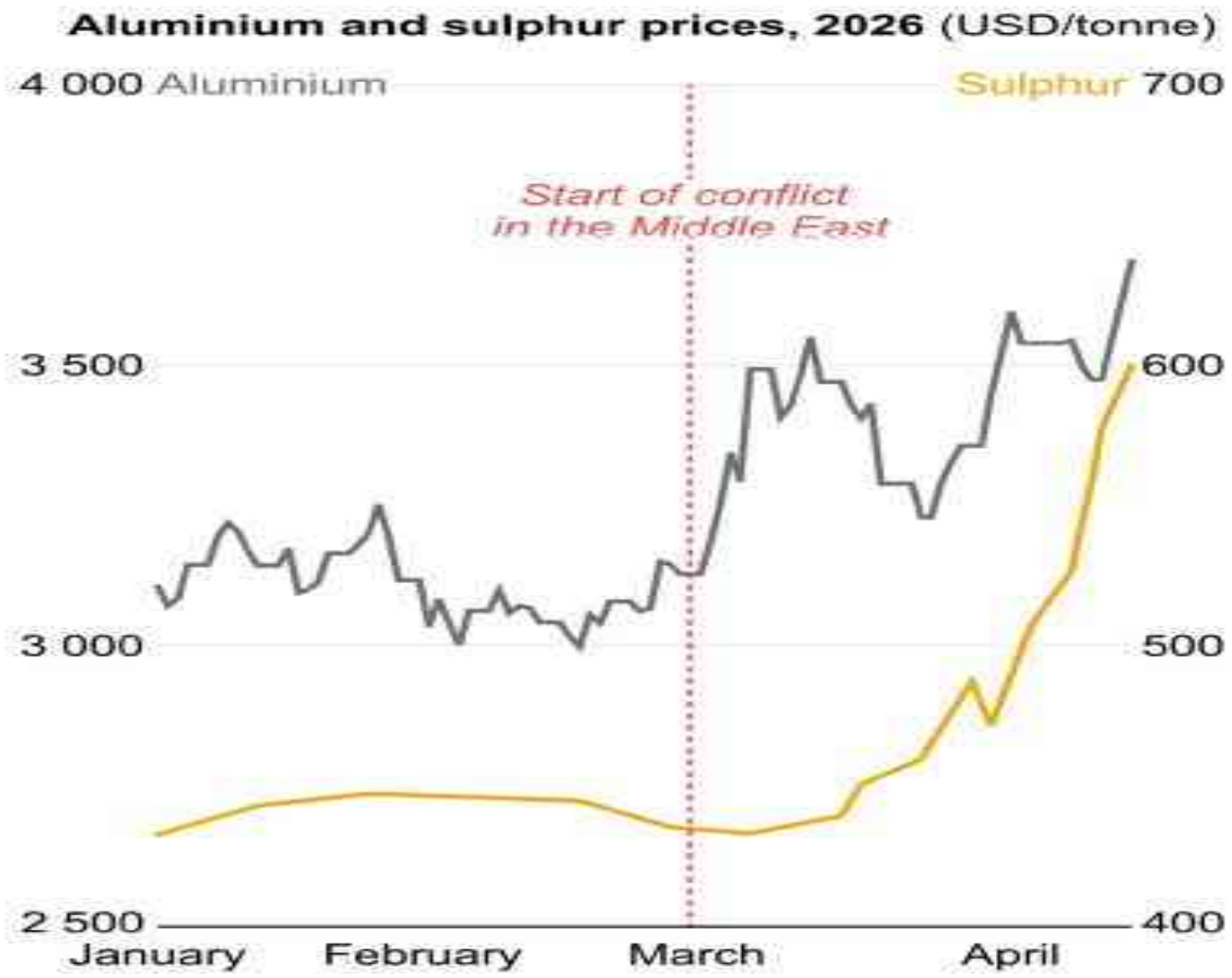


Note: TFDE = tri-fuel diesel electric vessel.
Source: IEA analysis based on Spark Commodities, as of 15 April 2026.

Source: IEA Gas Report Q2 2026

Impact on Critical Minerals Prices

Aluminium & Sulphur Prices 2026

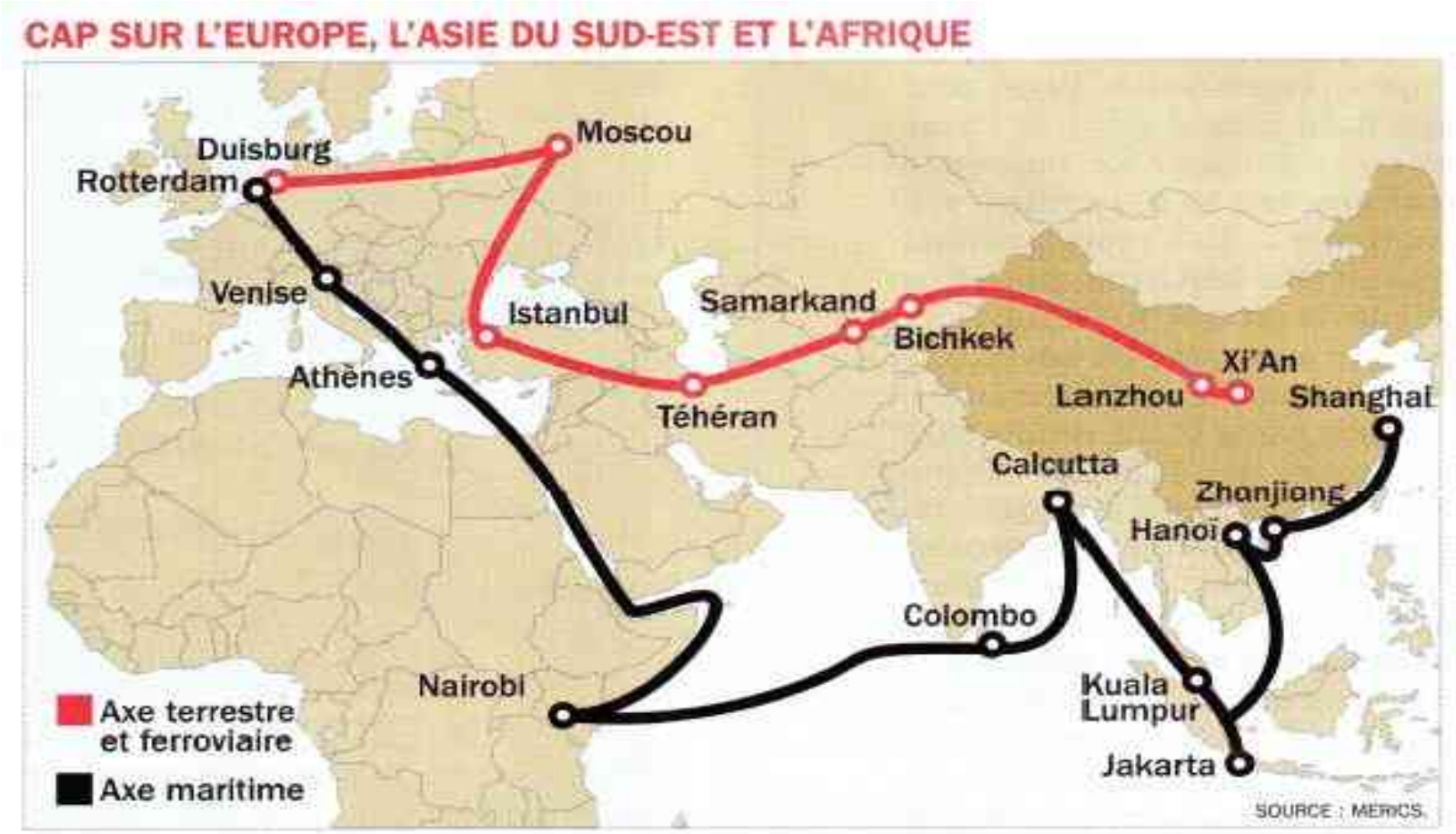


Source: IEA Global Critical Minerals Outlook – July 2026

A few geopolitical considerations and the case of China

China
Global Positioning - Economy/Energy

China Ambitions – One Example
The Belt and Road Initiative



Les Chinois l'appellent «Belt and Road Initiative», les Français «Nouvelles routes de la soie» : le projet lancé par Xi en 2013 vise à tisser un vaste réseau d'infrastructures. Il n'existe aucune carte définitive.

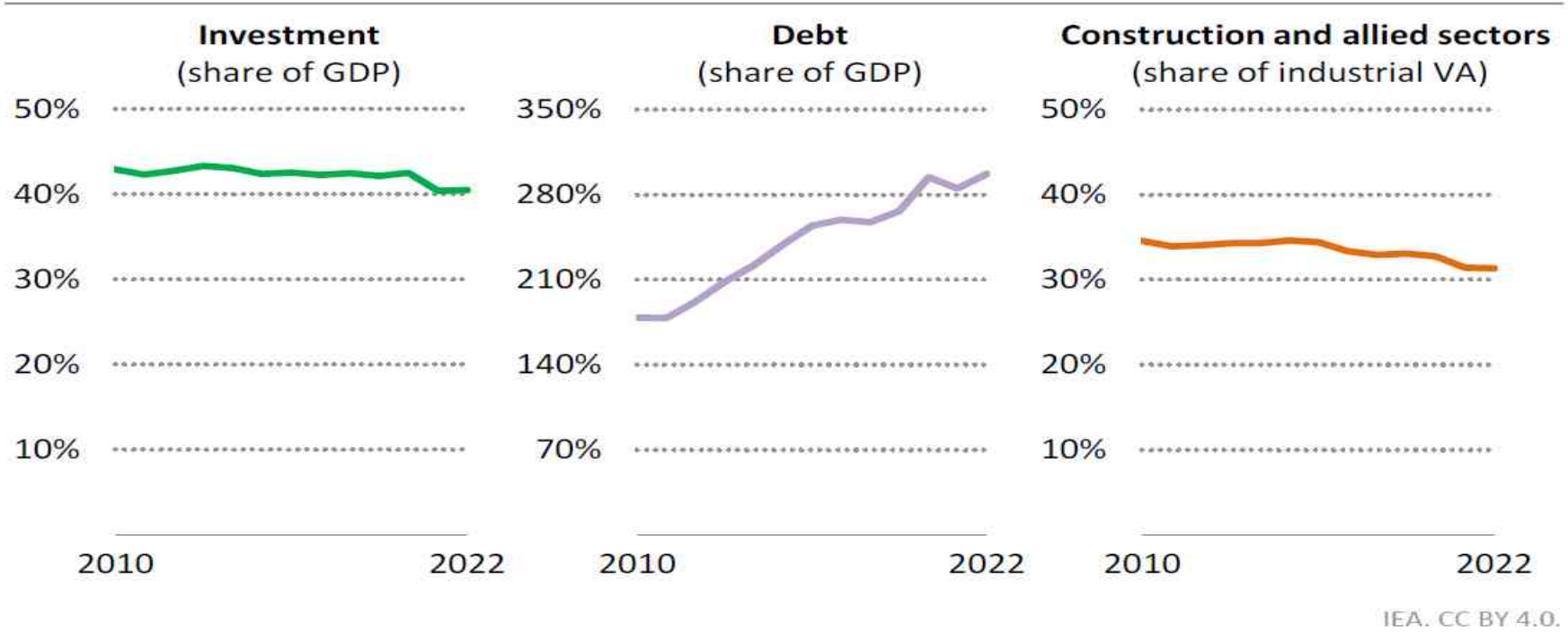
Source: Challenges – Novembre 2018

Reminder - China
A World Leader in the Energy Sector

Country	Company	Turnover (G€)
China	State Grid of China	271
Italy	Enel	75
France	EDF	70
Korea	Kepco	48
Japan	Tepco	48

Source: Challenges – Novembre 2018

China
Global Positioning - Economy/Energy

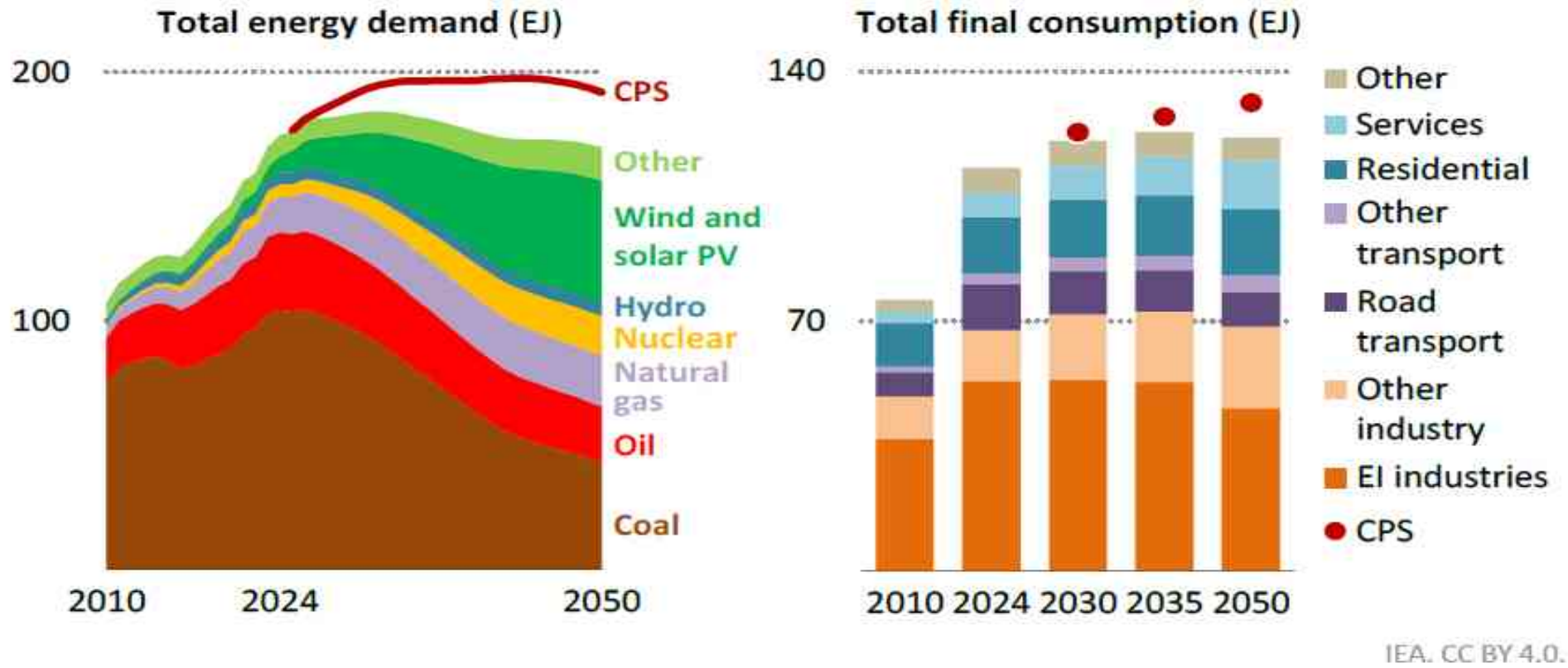


Rebalancing of China's economy still has a long way to go with investment, debt-to-GDP ratio, and share of the construction sector in GDP remaining high

Notes: GDP is expressed in market exchange rate terms. VA = value added. Allied sectors are basic chemicals and fertilisers, basic metals, non-metallic minerals, pulp and paper, wood and wood products excluding furniture. Debt refers to total outstanding credit to the non-financial sector from all lending sectors, expressed as a percent of GDP.

Source: IEA September 2023

China - Total Energy Demand & Final Consumption
IEA STEPS Scenario

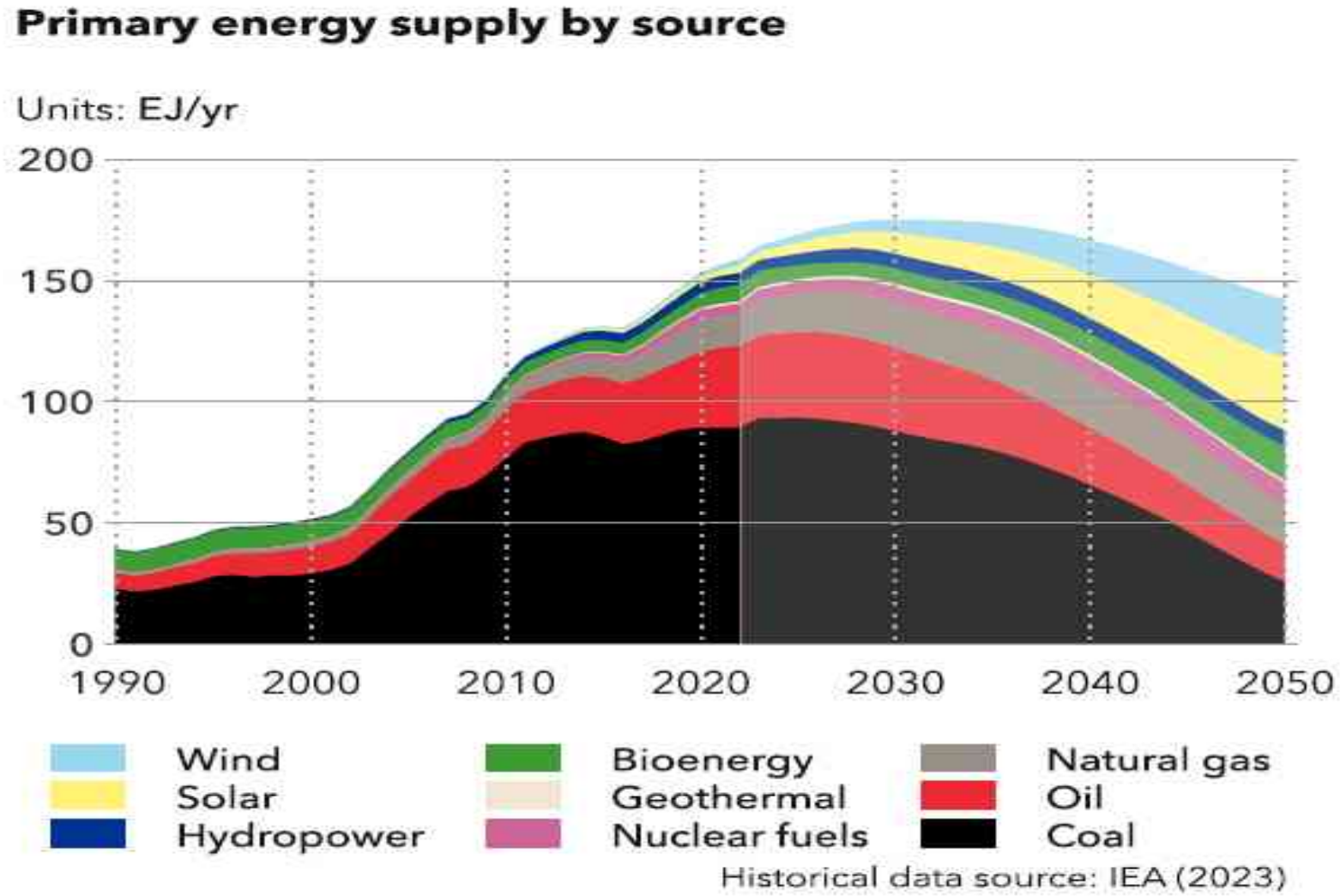


After years of rapid growth, energy consumption is set to peak and plateau in the next few years, driven by structural economic change, electrification and efficiency

Note: EJ = exajoule; CPS = Current Policies Scenario; EI industries = energy-intensive industries.

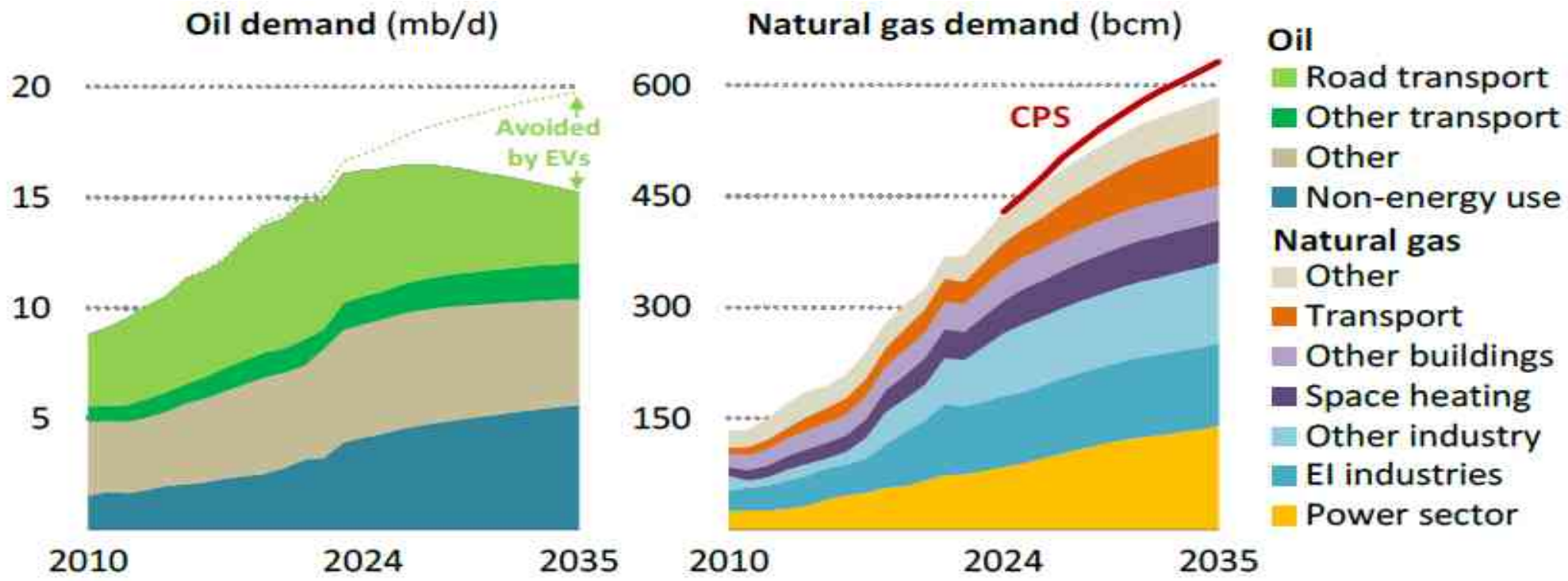
Source: IEA WEO 2025
1TJ= 23,88 toe

Primary Energy Supply in China by DNV 1990 - 2050



Source: DNV China 2024
1TJ = 23,88 toe

China - Oil & Natural Gas Demand
IEA STEPS Scenario



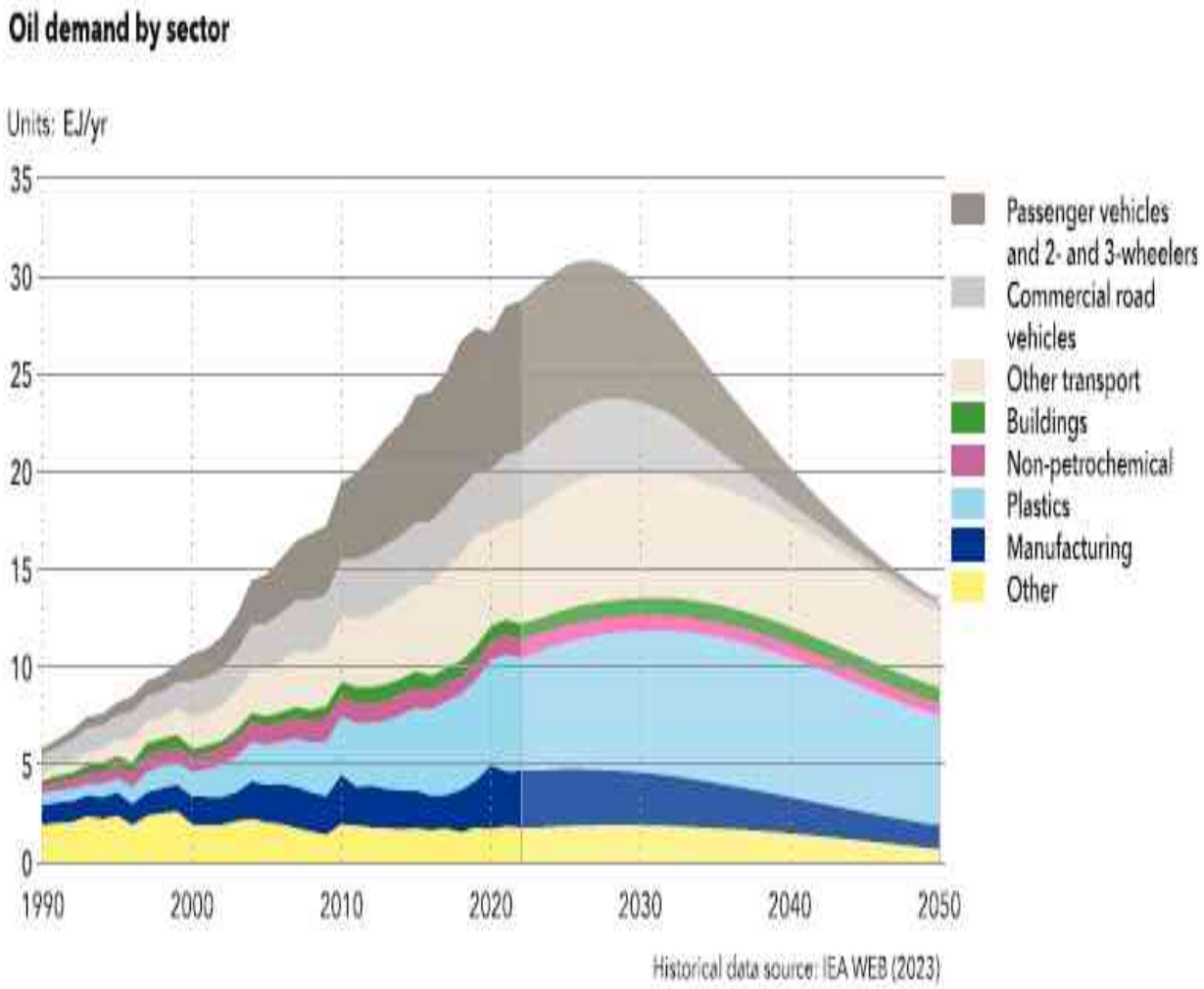
IEA. CC BY 4.0.

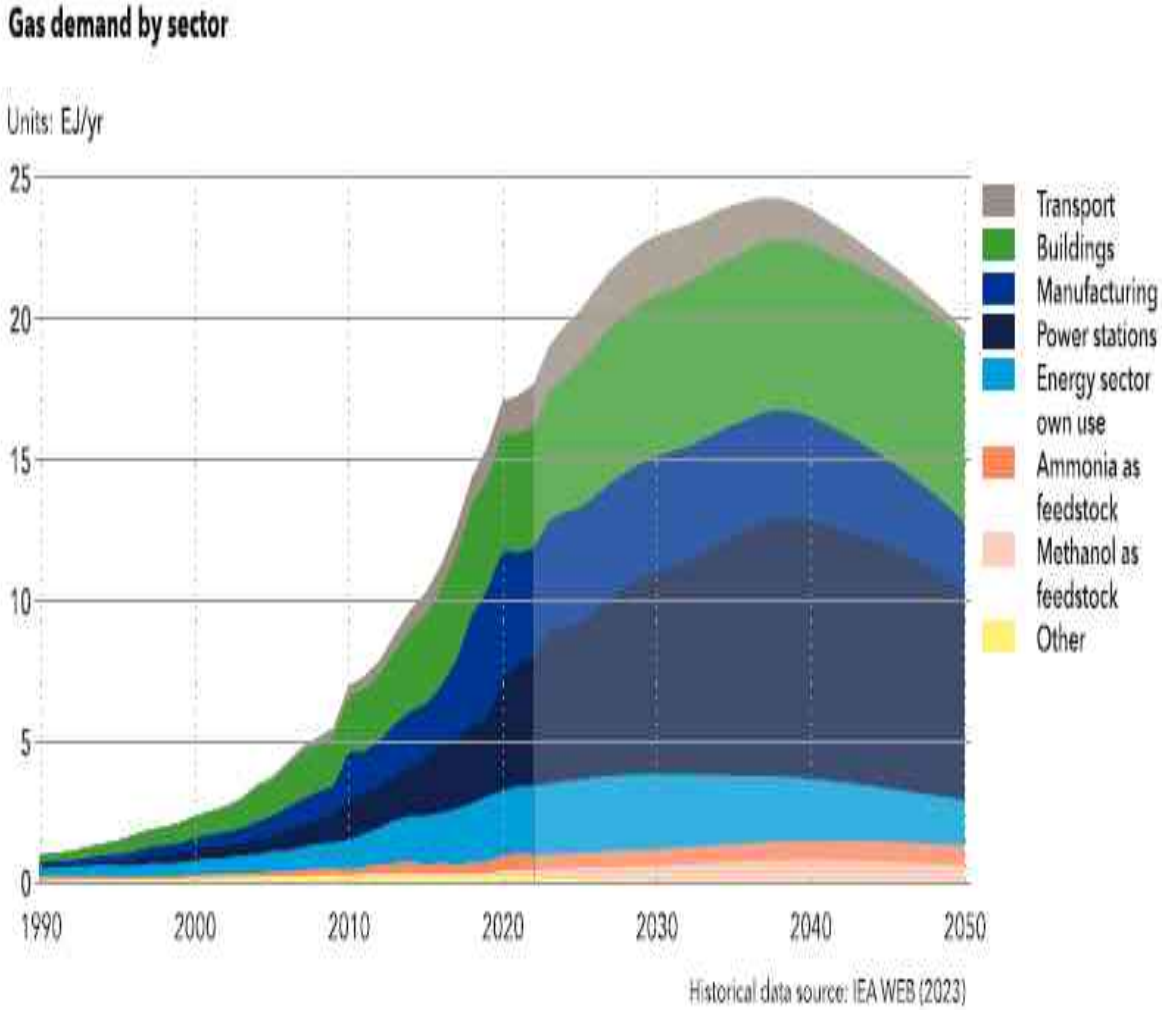
Oil demand peaks before 2030, curbed by EVs; gas demand rises, but electrification and energy efficiency limit the upside in key end-use sectors

Note: mb/d = million barrels per day; bcm = billion cubic metres; CPS = Current Policies Scenario; EI industries = energy-intensive industries.

Source: IEA WEO 2025

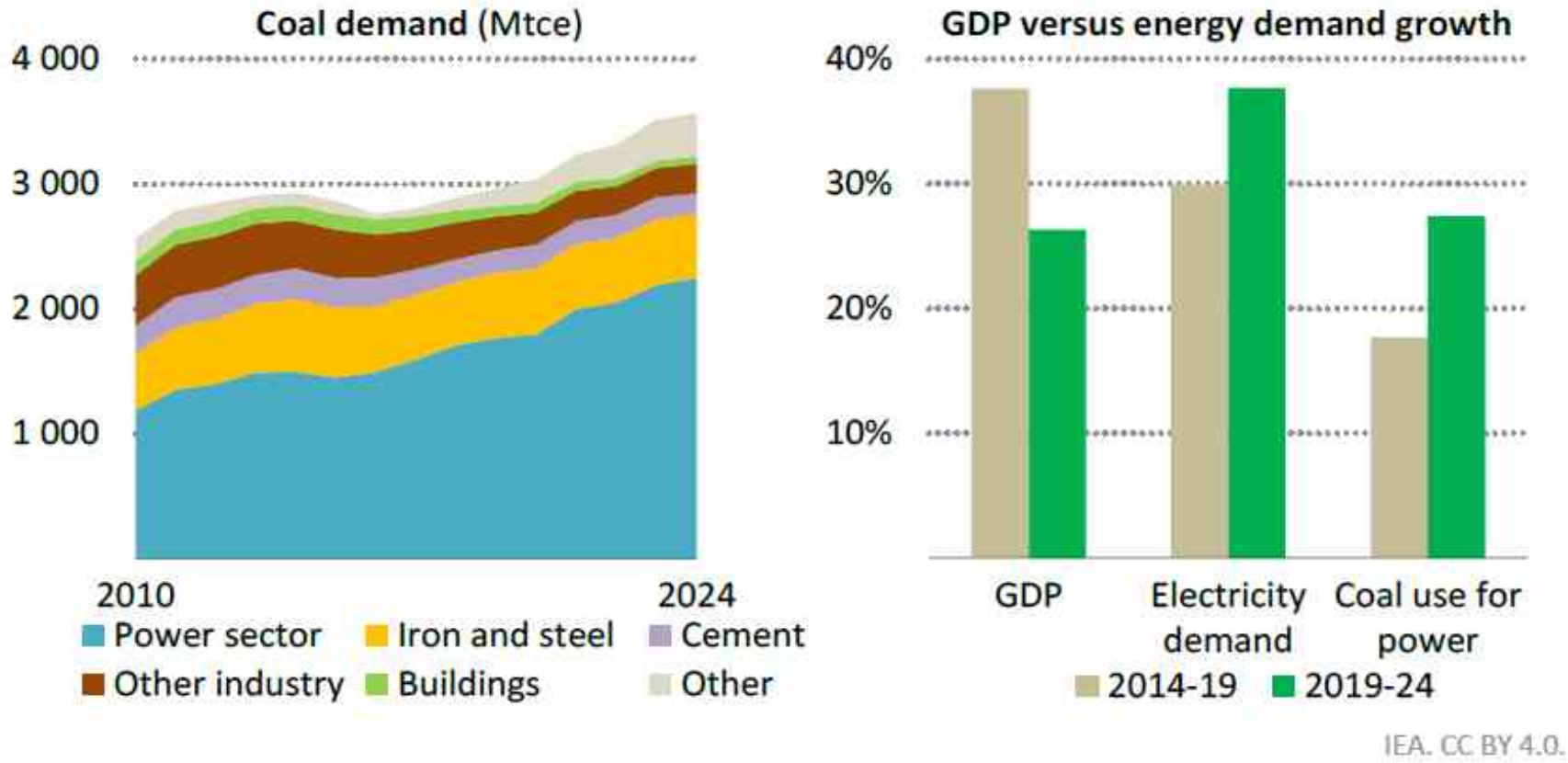
China - Oil & Natural Gas Demand by DNV 1990 - 2050





Source: DNV China 2024
1TJ = 23,88 toe

China – Coal Demand & GDP vs Energy Demand Growth
IEA STEPS Scenario

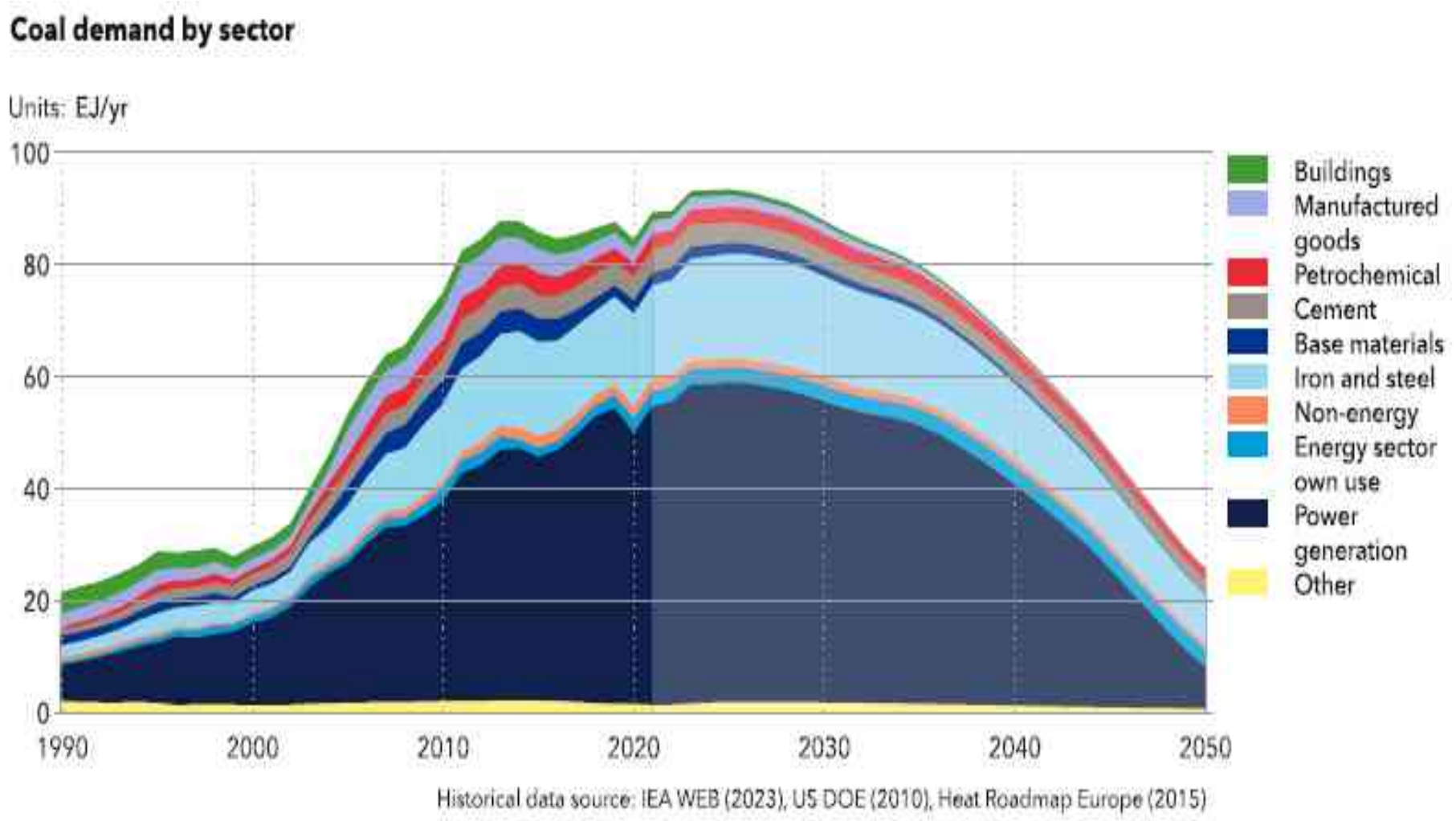


From 2010 to 2024, the share of electricity generation in China's coal demand increased from 45 to 65%, driven by strong electricity demand growth

Note: Mtce = million tonnes of coal equivalent; GDP = gross domestic product.

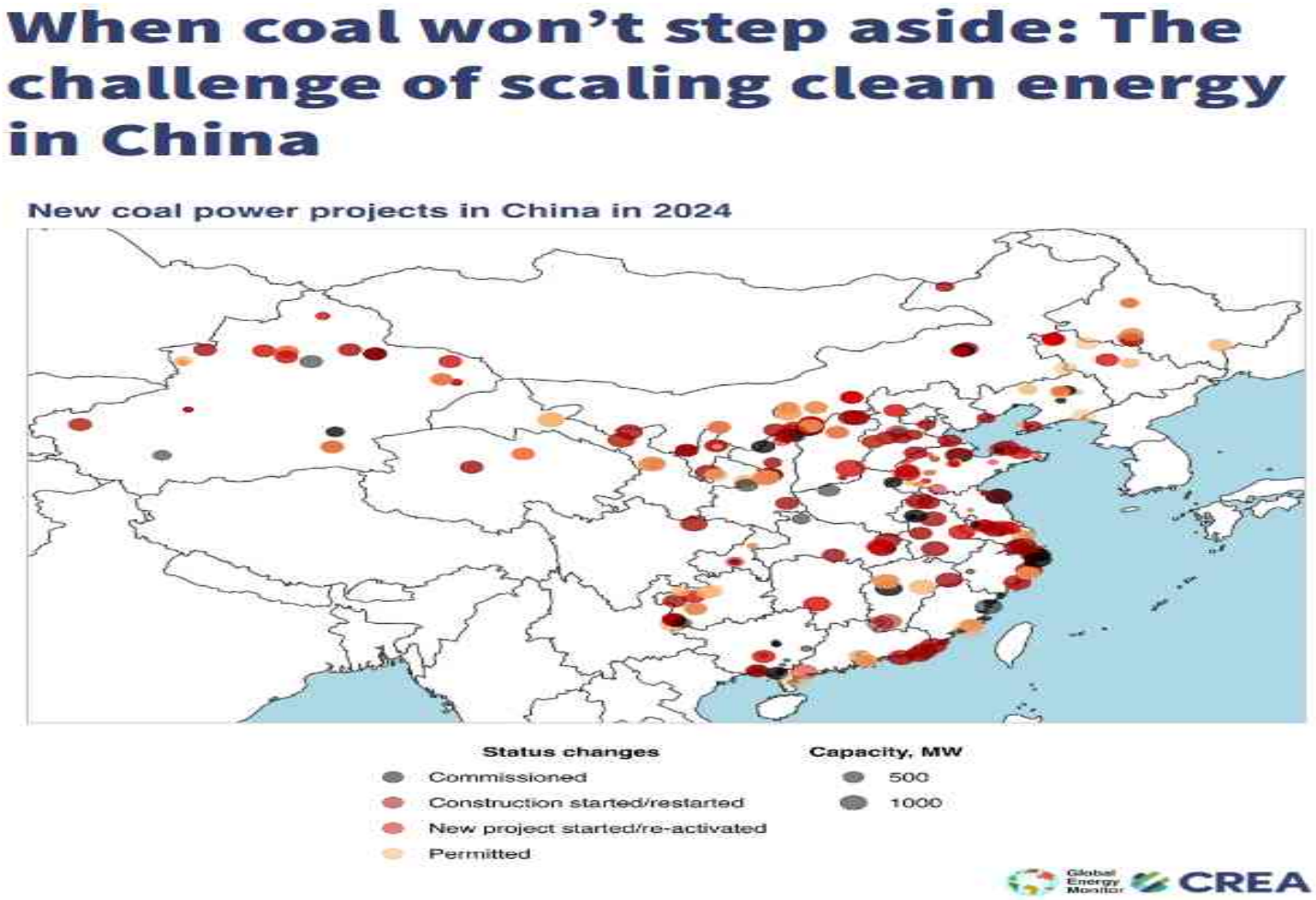
Source: IEA WEO 2025

Coal Demand by Sectors in China by DNV 1990 - 2050



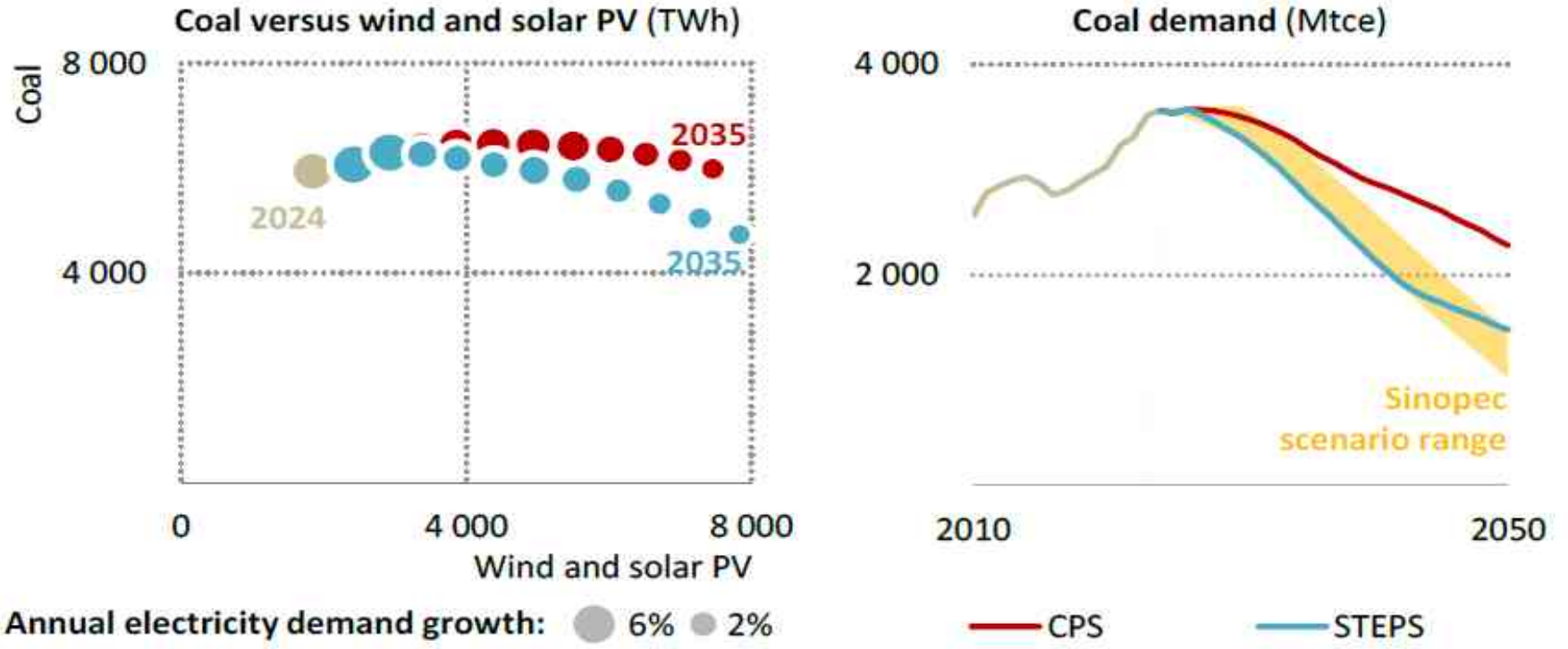
Source: DNV China 2024
1TJ = 23,88 toe

New Coal Projects in China
Conflicts with Energy Transition goals?



Source: Center for Research on Energy and Clean Air (CREA) February 2025

China – Electricity: Renewables contribution will increase drastically vs Coal - IEA 2025 Scenarios

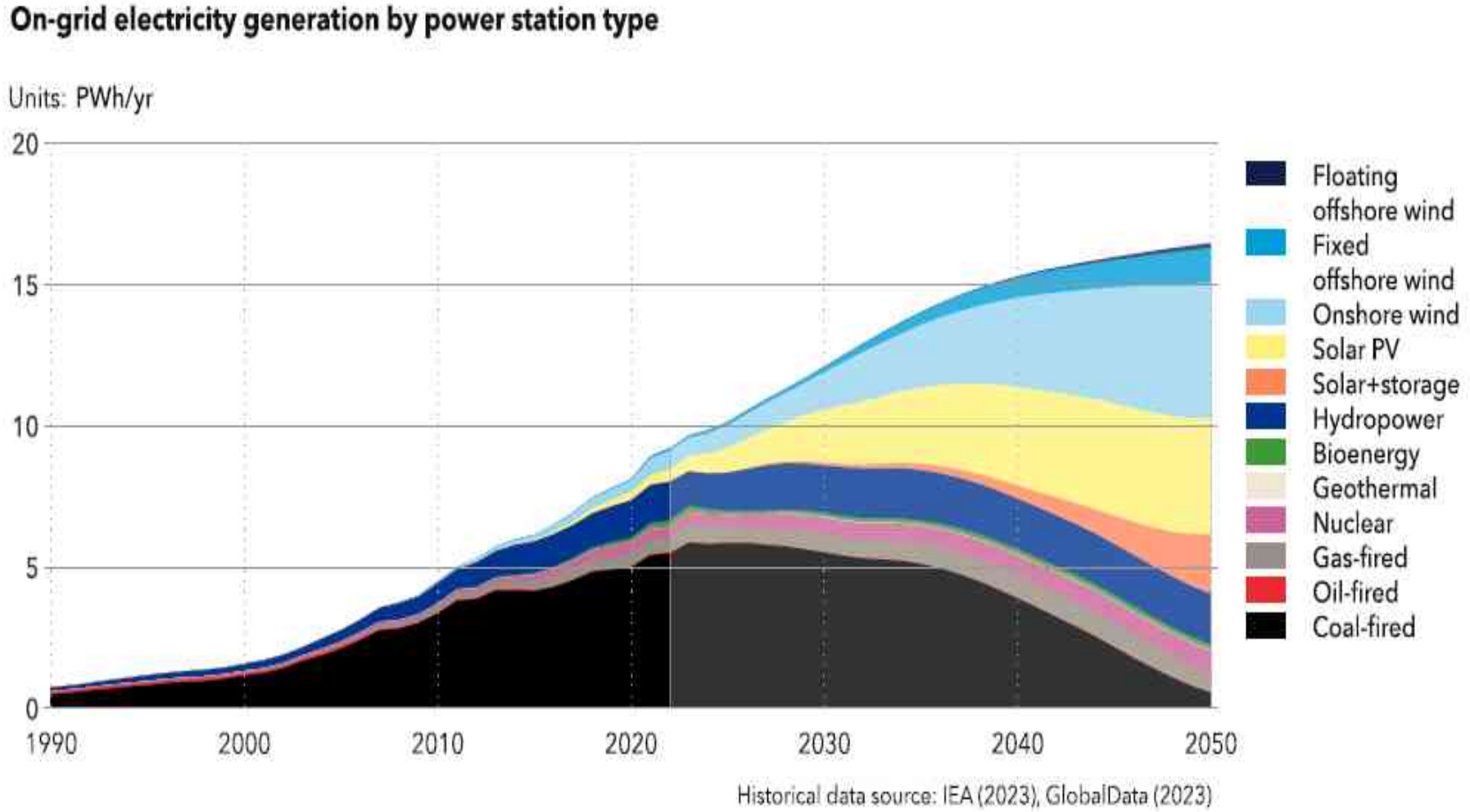


Coal demand peaks and declines by 20% in the STEPS, led by declines in coal-fired power generation; in the CPS, higher demand and lower renewables keep coal higher for longer

Notes: TWh = terawatt-hour; Mtce = million tonnes of coal equivalent. Sinopec scenario results are from China Energy Outlook 2060 (Sinopec EDRI, 2025).

Source: IEA WEO 2025

Electricity Generation and Mix in China by DNV 1990 - 2050



Source: DNV China 2024
1TJ = 23,88 toe

A Roadmap to Carbon Neutrality in China



Source: IEA September 2021
An Energy Sector Roadmap to Carbon Neutrality in China

2025: China N°1 in the World for Installed Capacity for Solar and Wind Energy (See Book 7 – Renewables)

21

Reminder: Basic Thermodynamics

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- 6. Demography: A key element
- 7. Global Energy Growth – Scenarios from various organizations
- 8. Global Energy Growth – Mobility/Transport
- 9. Global Energy Growth – A zoom on Hydrogen
- 10. Global Energy Growth – Electricity Demand & Generation
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- 17. Energy sources competitivity - LCOE
- 18. Energy, safety and air pollution challenges
- 19. Reminder - The 2008/2009 economic crisis, the 2020 Covid-19 sanitary crisis
- 20. Some geopolitical considerations – Impact of Ukraine invasion by Russia & geopolitical events – Iran/Israel/US war
- 21. Reminder: Basic Thermodynamics
- 22.Equivalences and conversion factors

Basic Concepts in Thermodynamics
Energy, Entropy, Exergy

Reminder:
What is Energy?

When there is a change of state in a « system » in the world around us, a certain amount of Energy is required.

For example :

Change of temperature, of velocity, of chemical composition, solid state to liquid or gas, or vice versa ….

The measure of Energy (also defined as the capacity to perform a Work) expresses the degree of transformation of this system.

Energy is the unit of account of the transformation of the world.

Energy: Some basic reminder



1 cal: Calorific Energy needed to increase 1g of water by 1°C (From 14,5 °C to 15,5 °C at atmospheric pressure)

The Human Body needs Energy

For the Nutritionists, 1 Cal (Large calorie or Food calorie) = 1 kcal = 1 000 cal (Small calorie)

1 cal = 4,186 Joule (International System)

Where Energy flows start in the operation of our own body

Daily Energy needs for the body of an active person, transformed into Heat, metabolism:



- **2 500 Cal # 10 460 kJ # 2 900 Wh for 1 day**
- **Corresponding Power # 120 W (= 10 460 kJ/86 400 s)**

Energy developed to climb 3 floors by a healthy person for 30 seconds:



- **75 kg x 9,81 m/s^{-2} x 10 m # 7 400 J**
- **Corresponding Power = 7 400 J/30 s # 250 W**

Power developed by a modern agricultural tractor # 150 kW



Power developed by a rolling mill # 5 000 kW



Human Beings available Energy is very small compared to Energy produced by Industrial Machines.

Reminder:
Don't confuse Energy/Work and Power

- **Force expressed in Newton (N) (F = mγ = mass x acceleration)**

1 N = 1 kg x m x s^{-2} (1 kilogramme x metre x $second^{-2}$)

Dimension: MLT^{-2}

- **Energy = Work expressed in Joule (J) or Watthour (Wh)**

1 J = 1 N x m (1 Newton x meter)

1 Wh = 1 N x m x s^{-1} x 3 600 seconds = 3 600 J

Wh/year = 1 Wh x 24 hours x 365 days = 31,5 10^6 J

Dimension: ML^2T^{-2}

- **Power expressed in Watt (W) = Energy delivered in 1 second**

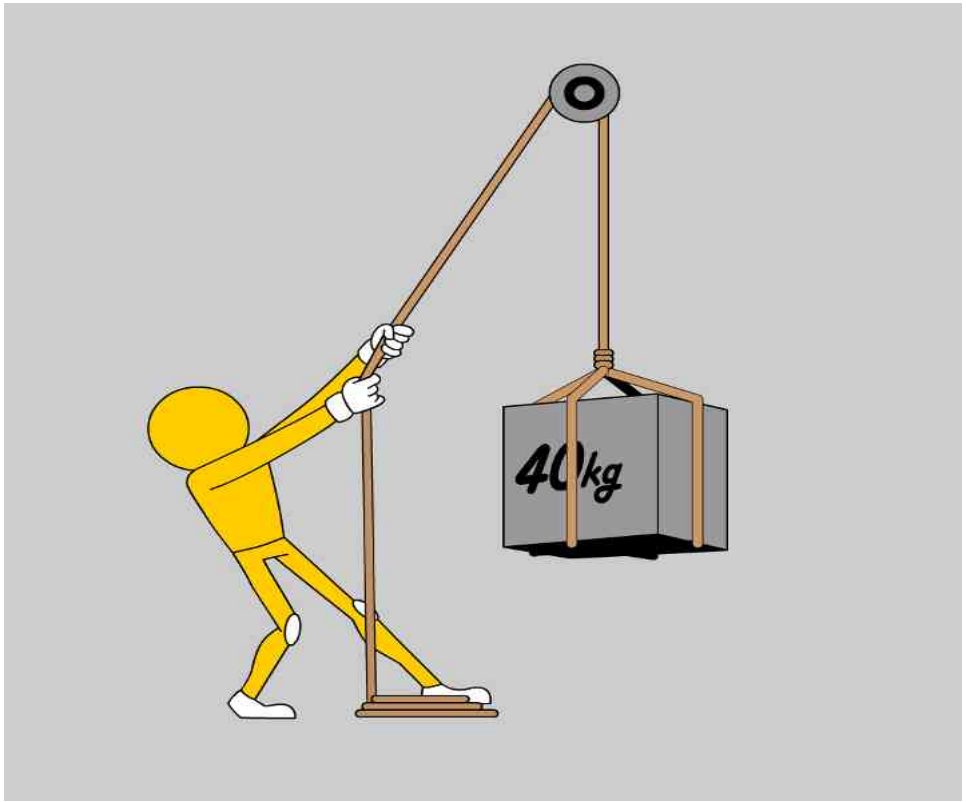
1 W = 1 N x m x s^{-1} (1 Newton x metre x $second^{-1}$)

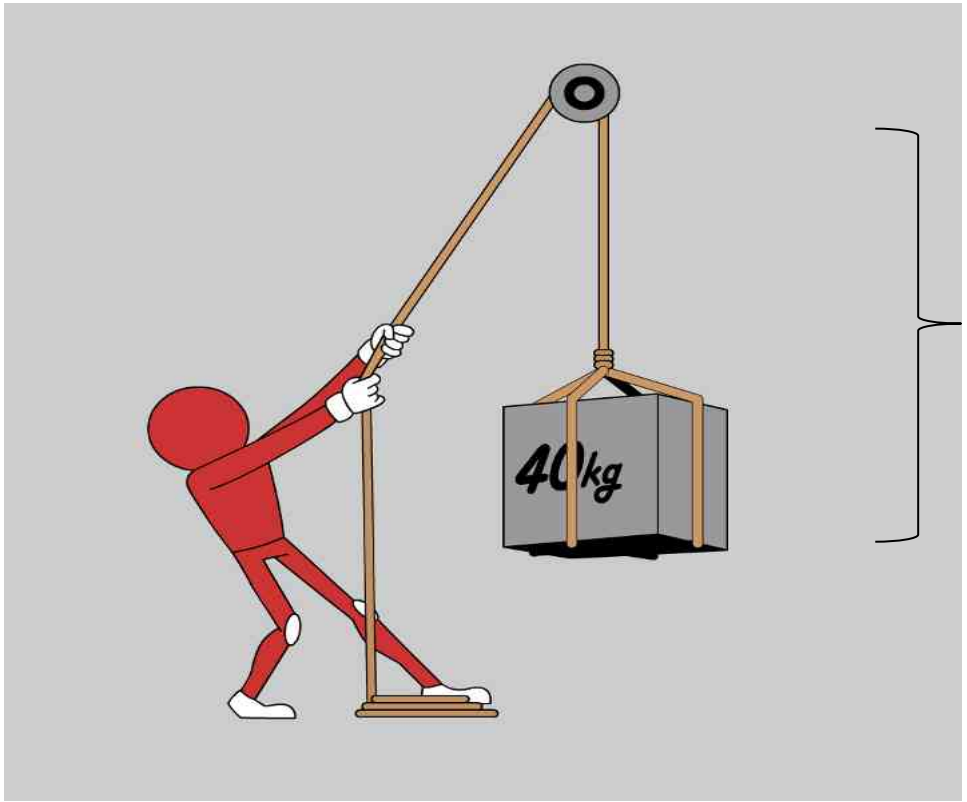
Dimension: ML^2T^{-3}

Force, Energy, Power

Force = F = Mγ
= 40 kg x 9,8 ms^{-2}
= 392 N (Newton)

Displacement (l) = 1 m during 2 s
Energy = Fl = 392 N x 1 m = 392 J (Joule)
Power = 392 J/2 s = 196 W (Watt)





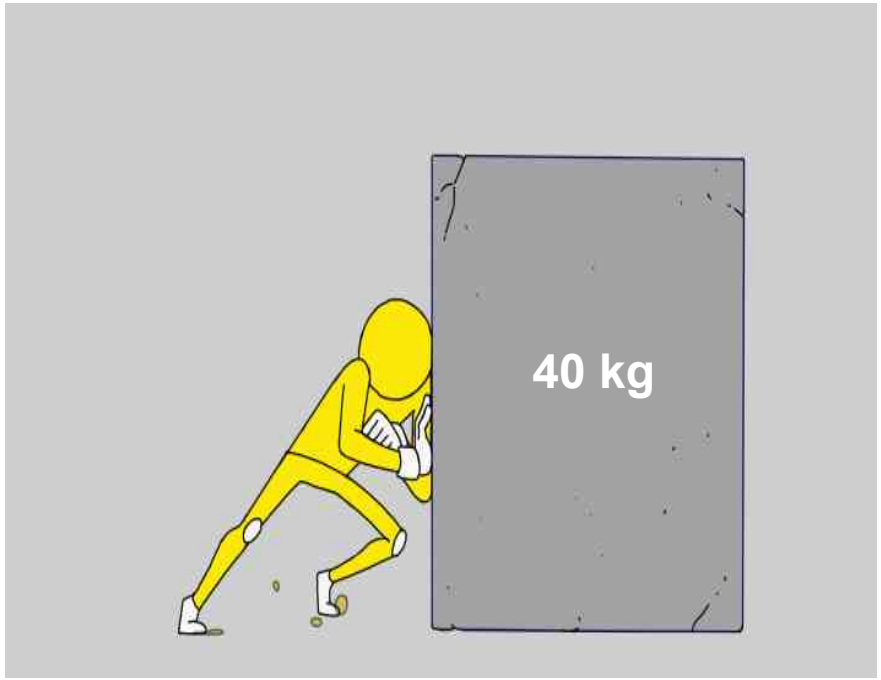
Animation:
Matthieu Guéritte

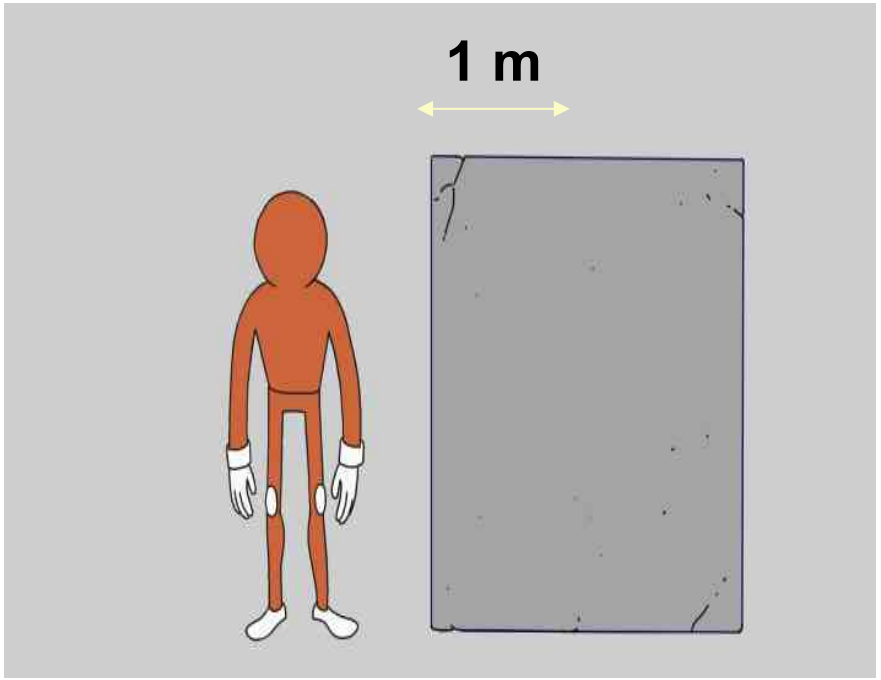
Energy = Work = Power x time

Force, Energy, Power

Force = F = Mγ
= 40 kg x 9,8 ms^{-2}
= 392 N (Newton)

Displacement (l) = 1 m during 2 s
Energy = Fl = 392 N x 1 m = 392 J (Joule)
Power = 392 J/2 s = 196 W (Watt)





MG/ChG

Hypothesis: Friction coefficient = 1

Energy = Work = Power x time

Equivalences

- **Energy = Work expressed in Joule (J)**

1 J = 1 N x m (1 Newton x meter)

1 Calorie = 4,186 J

1 KWh = 3,60 MJ

1 eV (Electronvolt) = 1,602 x 10^{-19} J

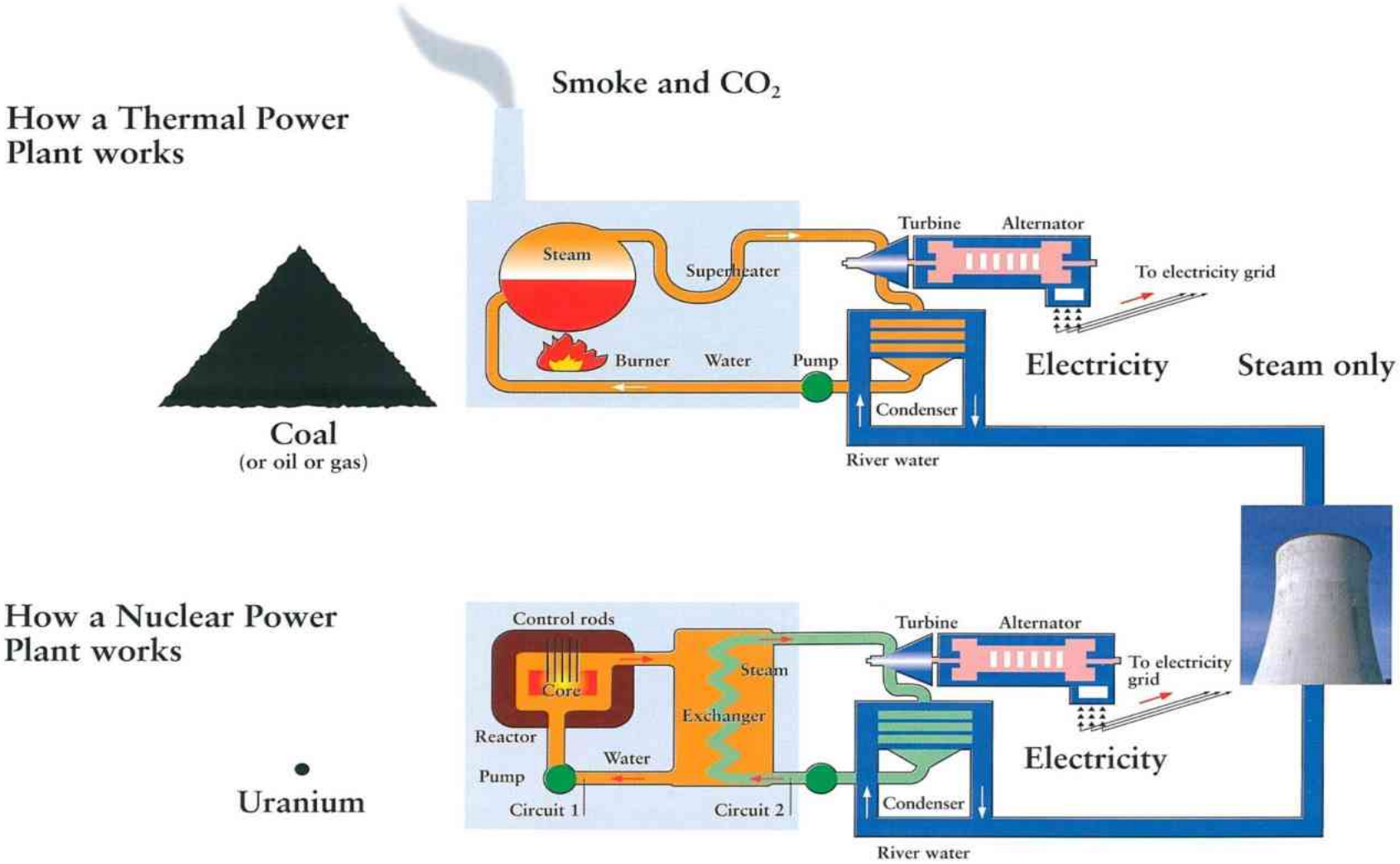
- **Power expressed in Watt**

1 W = 1 N x m x s^{-1} (1 Newton x metre x $second^{-1}$)

1 HP (Horse Power) = 746 W

Energy is produced worldwide by Power Plants, Steam Turbines, Gas Turbines, Nuclear Reactors…..
All these facilities and related equipments are operating on the basis of Thermodynamics principles

Example of a Power Plant



Thermodynamics: The Science that deals with Heat and Work and those properties of matter that relate to Heat and Work

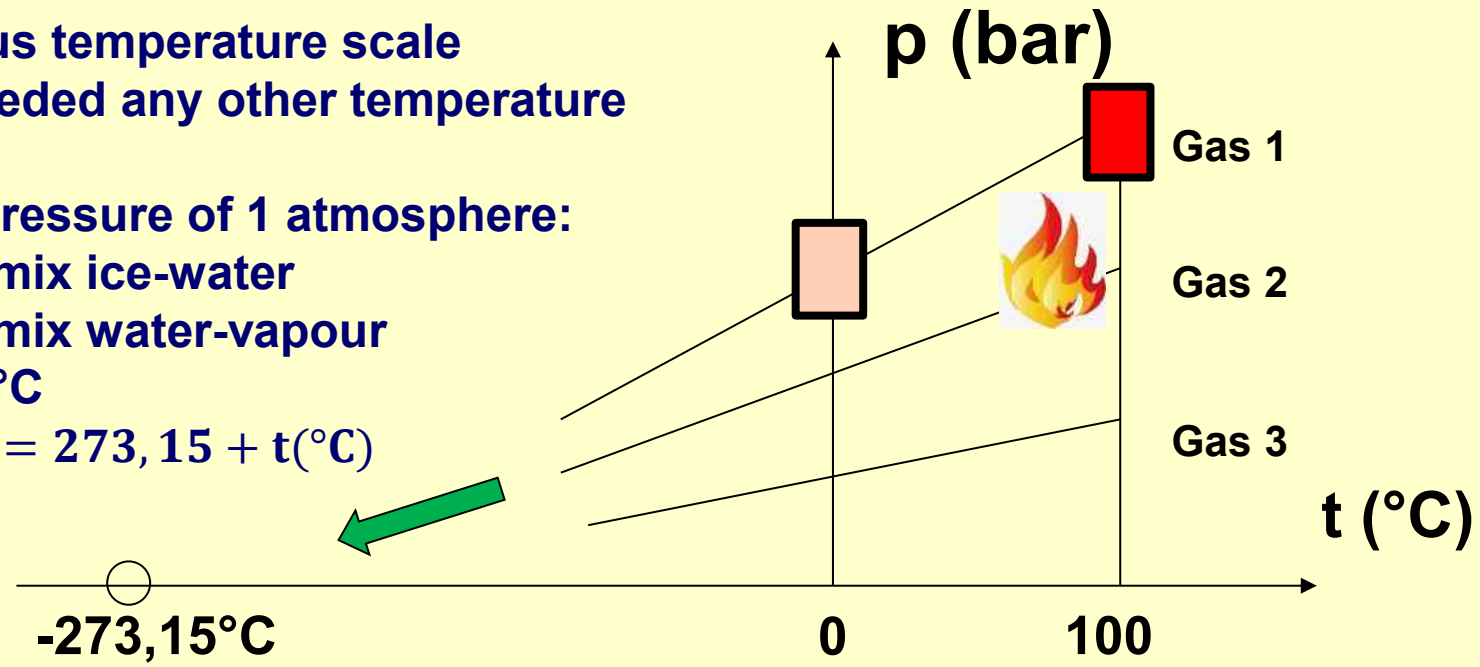
Thermodynamic Temperature

Thermodynamic Temperature

Experience: Let's consider a gas in a defined closed volume at a given pressure. When this system is subject to an increase of temperature from 0°C to 100°C, the gas pressure increases. Therefore, there should exist a temperature corresponding to a pressure of 0 bar.

Celsius temperature scale preceeded any other temperature scale:
At a pressure of 1 atmosphere:
0 : mix ice-water
100 : mix water-vapour
Unit: °C

$$T(°K) = 273,15 + t(°C)$$



The Scientists - Chronology of Energy Sciences

- **17th and 18th centuries: Classical Mechanics**

Galiléo Galiléi, Isaac Newton,….

- **18th and beginning 19th centuries: Heat Science:**

Daniel Bernoulli, Anders Celsius, James Watt, Nicolas Léonard Sadi Carnot,….

- **19th and beginning 20th centuries: Thermodynamics, Electricity, Magnetism, Electromagnetism, Wave optics**

James Prescott Joule, Hermann Helmholtz, Rudolph Clausius, William Thomson (Lord Kelvin), James Clerk Maxwell, Josiah Willard Gibbs, Ludwig Boltzmann, Walter Hermann Nernst,….

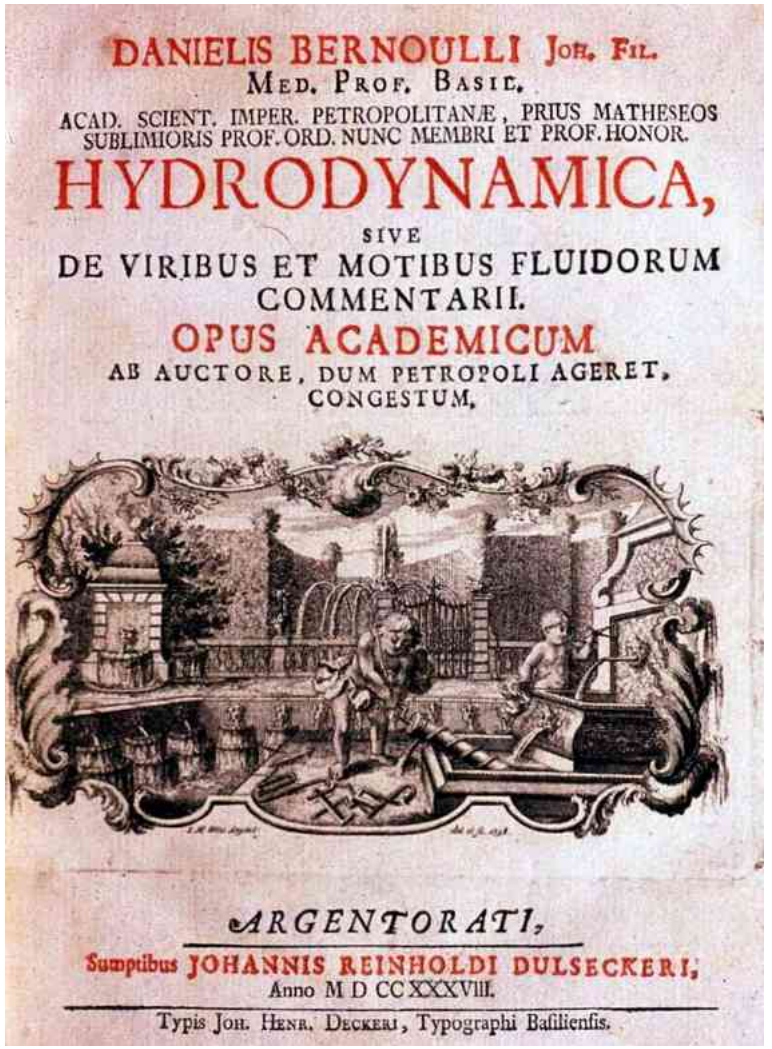
- **20th century: General Relativity, Special Relativity, Nuclear Energy,…..**

- ***Max Planck, Albert Einstein, Otto Hahn,…***

Daniel Bernoulli (Switzerland) (Kinetic Theory of Gases)



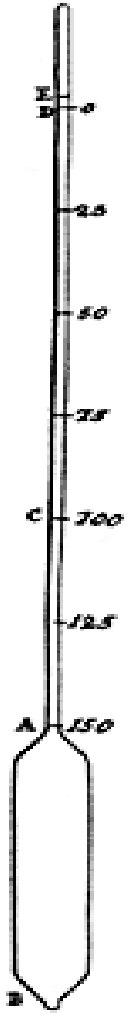
Daniel Bernouilli
(1700 – 1782)


DANIELIS BERNOULLI JOH. FIL.
MED. PROF. BASIL.
ACAD. SCIENT. IMPER. PETROPOLITANÆ, PRIUS MATHESEOS SUBLIMIORIS PROF. ORD. NUNC MEMBRI ET PROF. HONOR.
HYDRODYNAMICA,
SIVE
DE VIRIBUS ET MOTIBUS FLUIDORUM COMMENTARII.
OPUS ACADEMICUM
AB AUCTORE, DUM PETROPOLI AGERET, CONGESTUM.
ARGENTORATI,
Sumptibus JOHANNIS REINHOLDI DULSECKERI,
Anno M D CC XXXVIII.
Typis JOH. HENR. DECKERI, Typographi Basilienſis.

Anders Celsius (Sweden) and his Thermometer



Anders Celsius
(1701 – 1744)



James Watt (Scotland) and his Steam Engine



James Watt
(1736 – 1819)

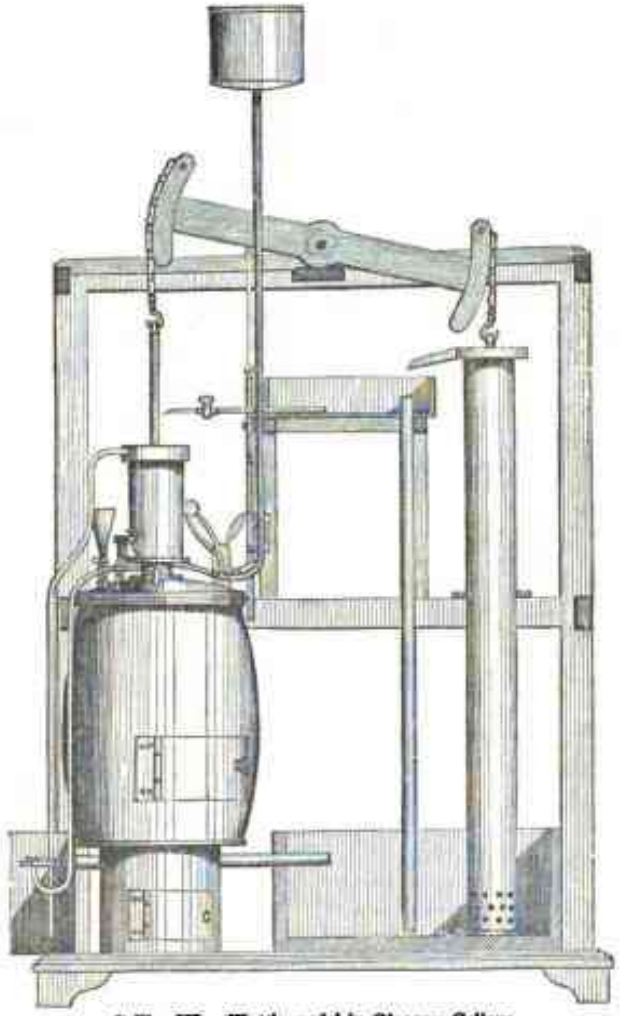
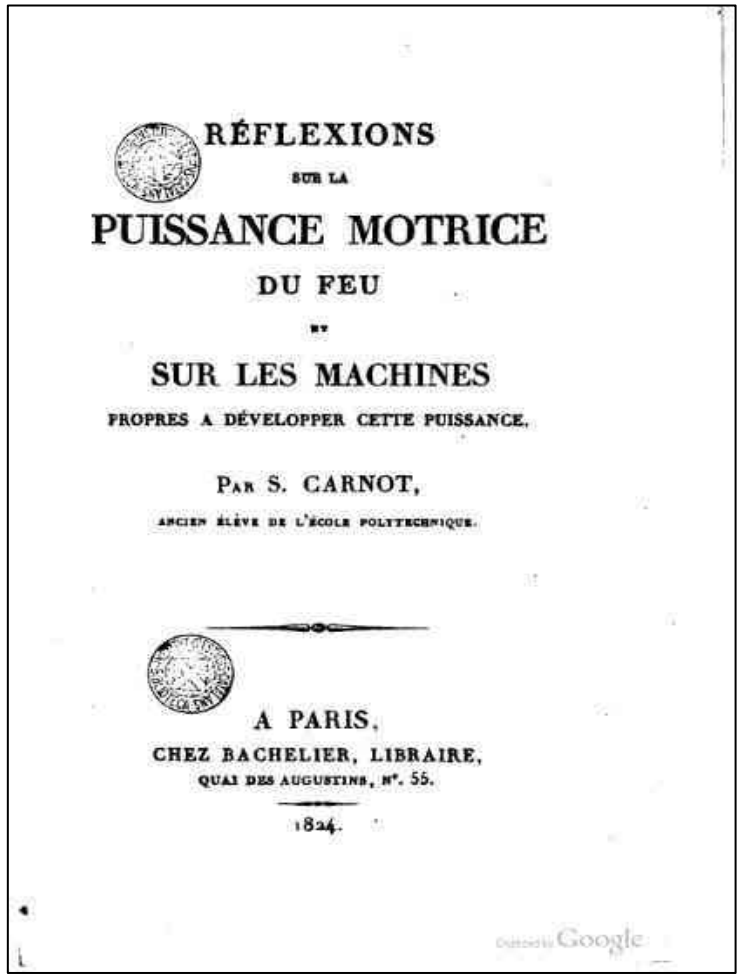


Fig. IV.—Watt's model in Glasgow College.

Carnot (France)



Nicolas Leonard Sadi Carnot
(1796 – 1832)



RÉFLEXIONS
SUR LA
PUISSANCE MOTRICE
DU FEU
ET
SUR LES MACHINES
PROPRES A DÉVELOPPER CETTE PUISSANCE.

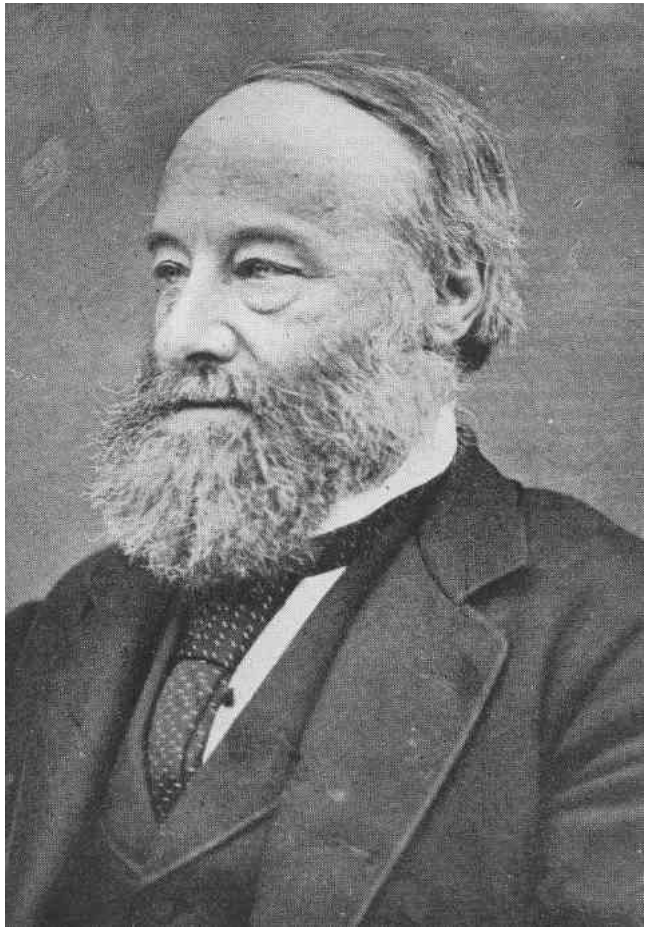
PAR S. CARNOT,
ANCIEN ÉLÈVE DE L'ÉCOLE POLYTECHNIQUE.

A PARIS,
CHEZ BACHELIER, LIBRAIRE,
QUAI DES AUGUSTINS, N°. 55.
1824.

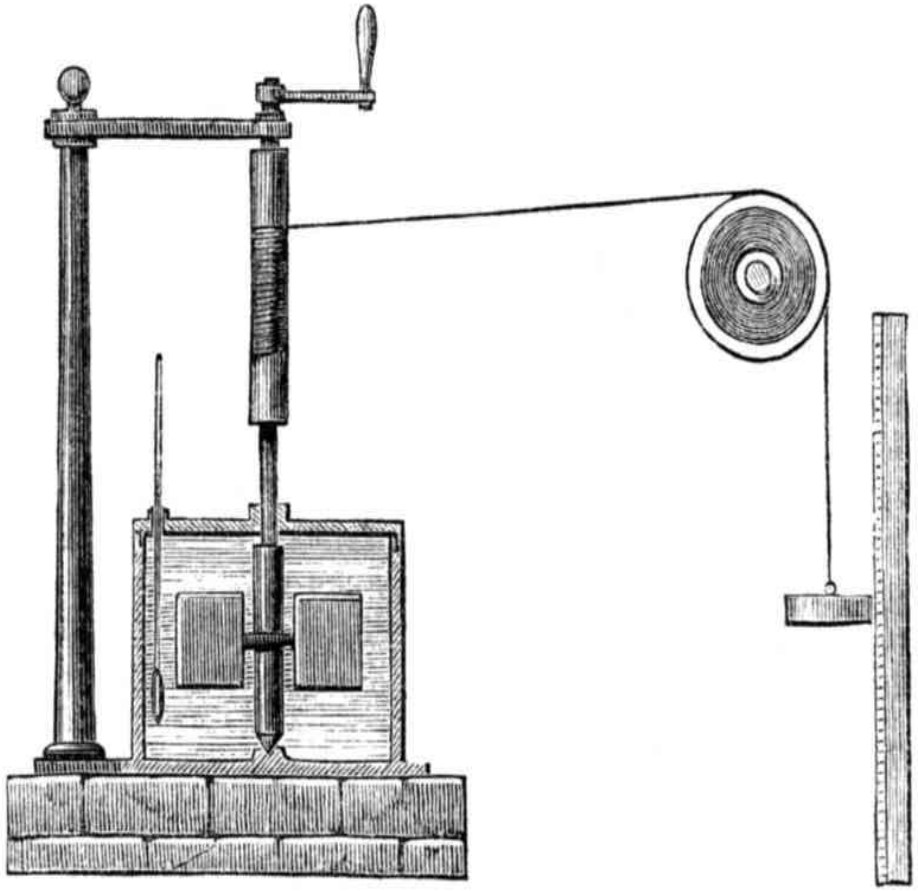
Digitized by Google

Son of Lazare Carnot (1753 – 1823), mathematician, physician & politician.
Uncle of Marie-François Sadi Carnot (1837 – 1894), president of French Republic (1887 – 1894)

James Prescott Joule (England)



James Prescott Joule
(1818 – 1889)

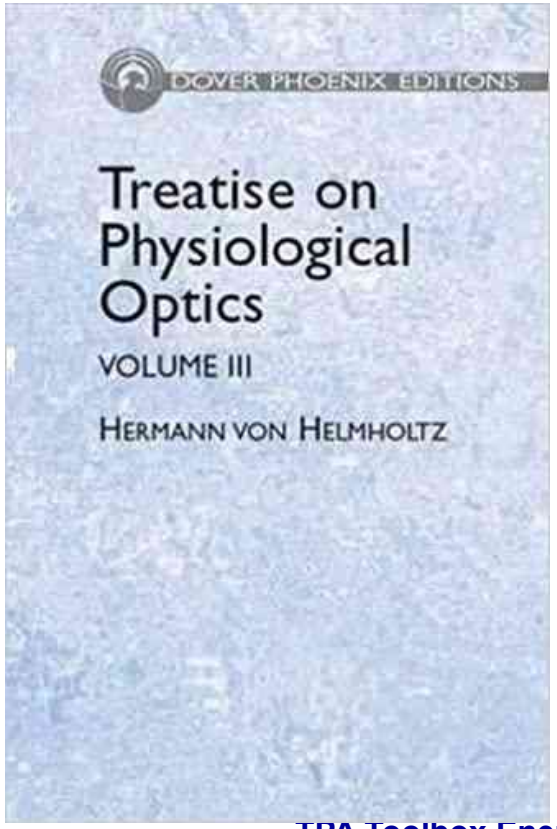


Hermann von Helmholtz (Germany)



Hermann von Helmholtz
(1821 – 1894)

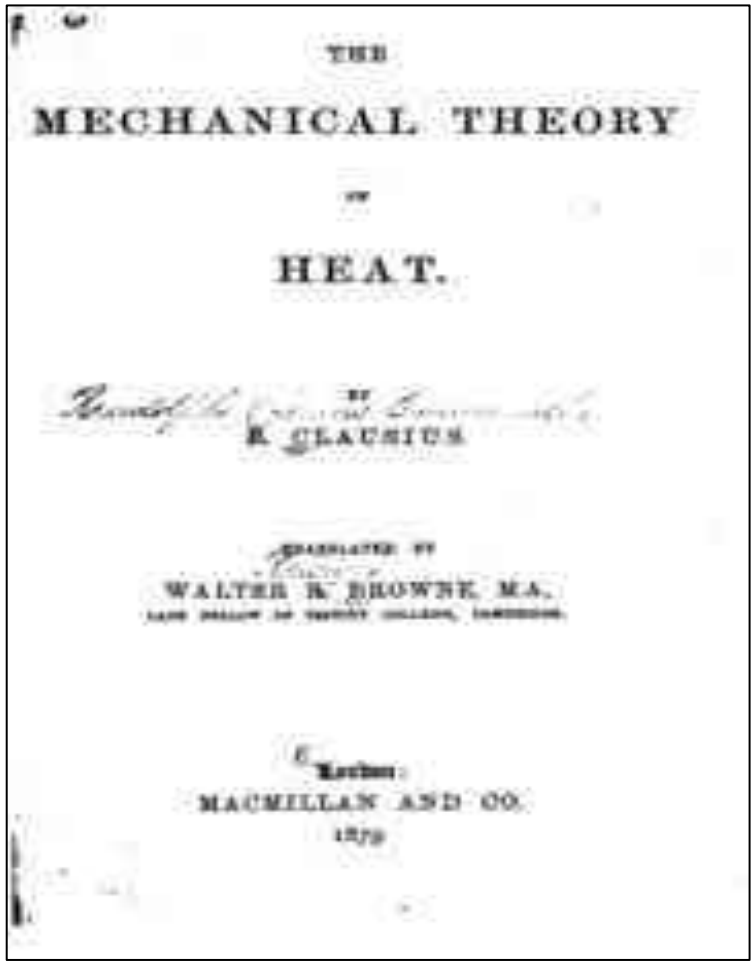
Helmholtz Free Energy
F = U - TS



Rudolph Clausius (Germany)



Rudolph Clausius
(1822 – 1888)



THE

MECHANICAL THEORY

OF

HEAT.

BY

R. CLAUSIUS.

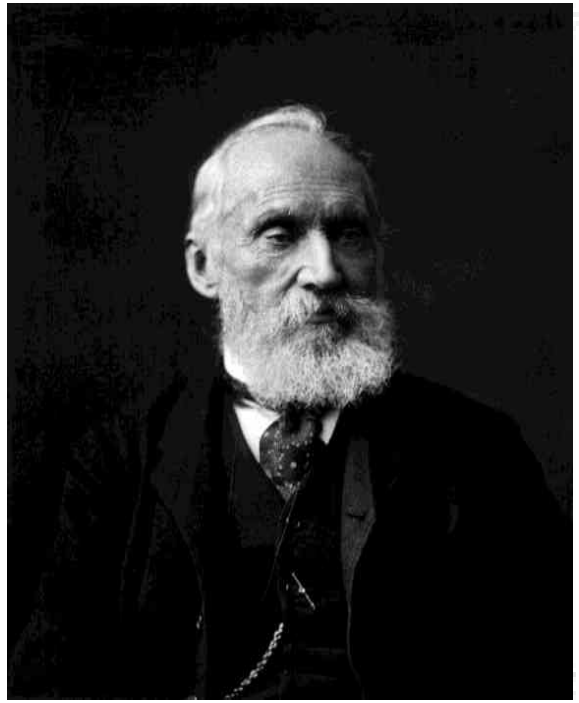
TRANSLATED BY

WALTER R. BROWNE, M.A.

MACMILLAN AND CO.

1879

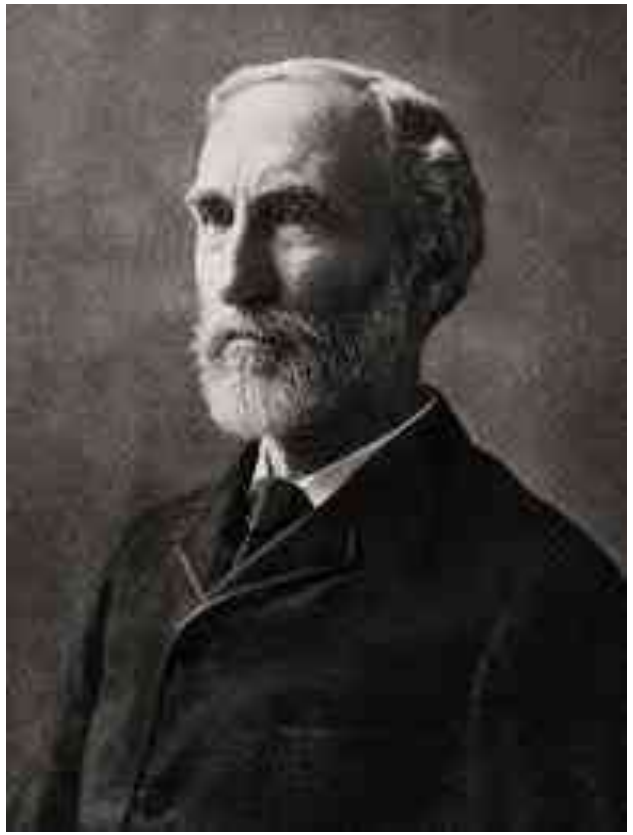
William Thomson (Lord Kelvin) (England)



William Thomson (Lord Kelvin)
(1824 – 1907)

12. A *perfect* thermo-dynamic engine of any kind, is a machine by means of which the greatest possible amount of mechanical effect can be obtained from a given thermal agency; and, therefore, if in any manner we can construct or imagine a perfect engine which may be applied for the transference of a given quantity of heat from a body at any given temperature, to another body, at a lower given temperature, and if we can evaluate the mechanical effect thus obtained, we shall be able to answer the question at present under consideration, and so to complete the theory of the motive power of heat.

Josiah Willard Gibbs (US)

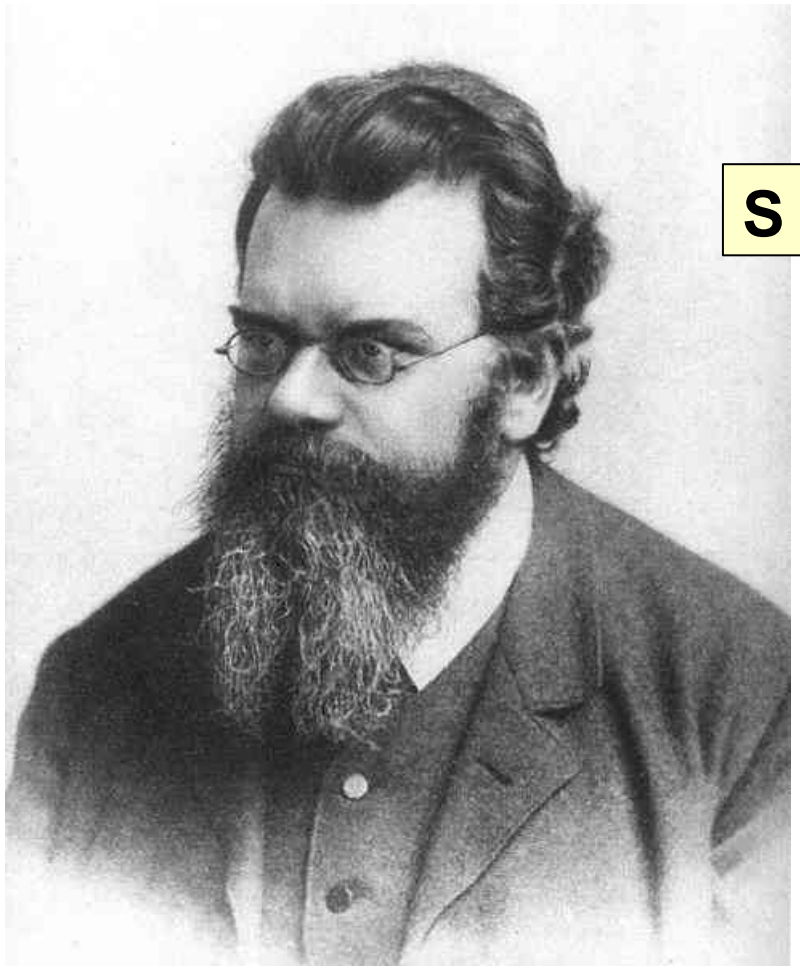


Josiah Willard Gibbs
(1839 – 1903)

« Any method involving the notion of Entropy, the very existence of which depends on the second law of Thermodynamics, will doutless seem to many far-fetched, and may repel beginners as obscure and difficult of comprehension »

Josiah Willard Gibbs

Ludwig Boltzmann (Austria)



Ludwig Boltzmann
(1844 – 1906)

$S = k_B \mathrm{Log} W$



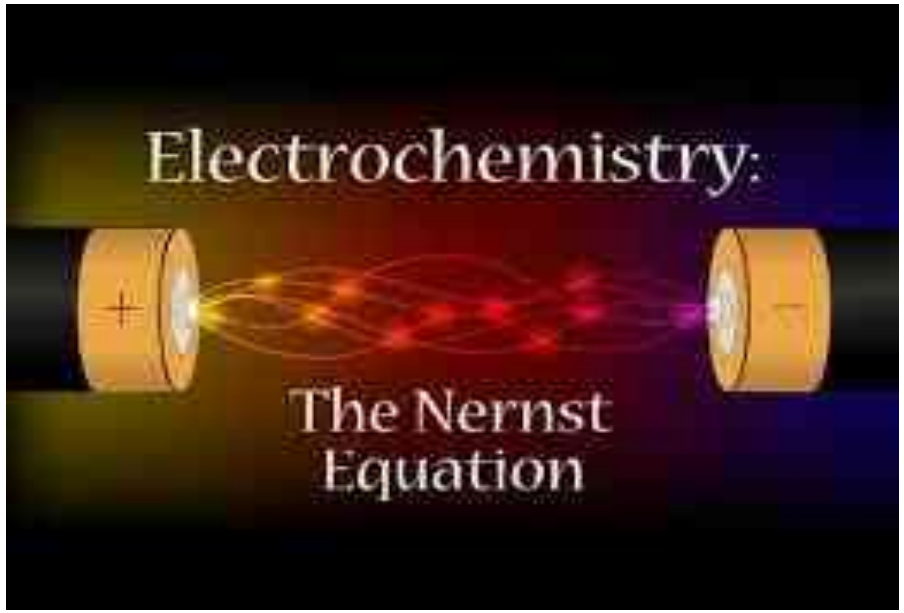
L. Boltzmann grave in Vienna

Walter Hermann Nernst (Germany)



Walter Hermann Nernst
(1864 – 1941)

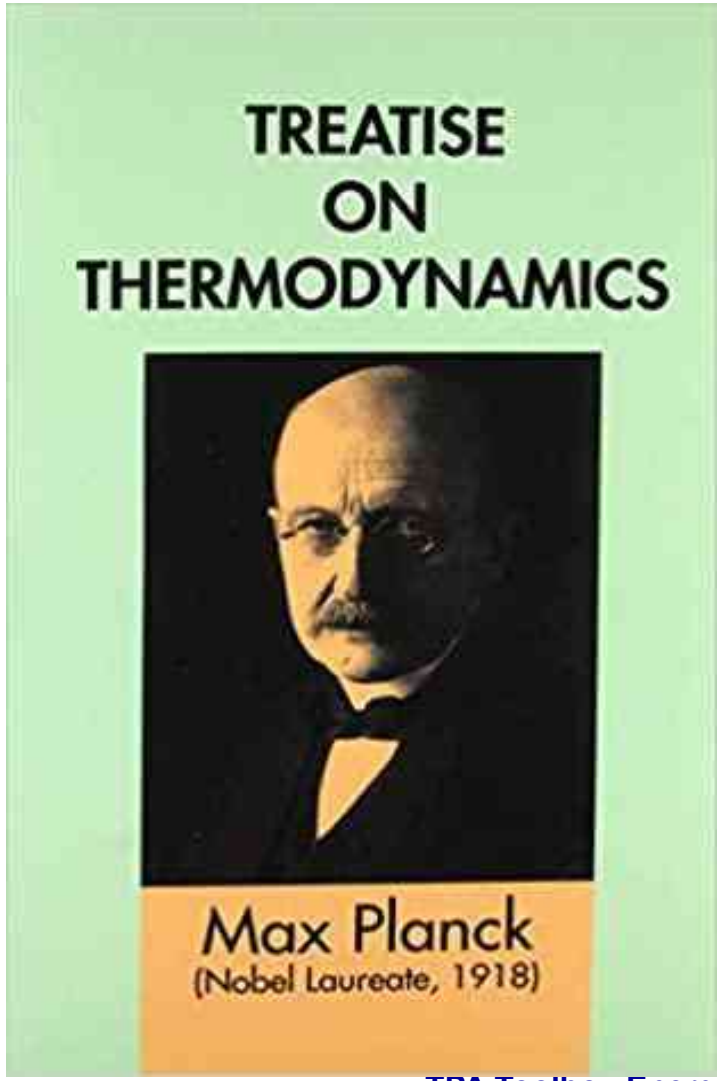
$$S = k_B \text{Log} W$$



Max Planck (Germany)



Max Karl Ernst Ludwig Planck
(1858 – 1947)



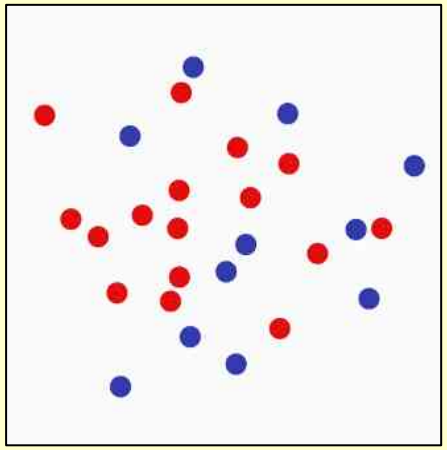
Thermodynamics

Two different approaches:

- Classical Thermodynamics, based on macroscopic features



- Statistical Thermodynamics, based on microscopic features



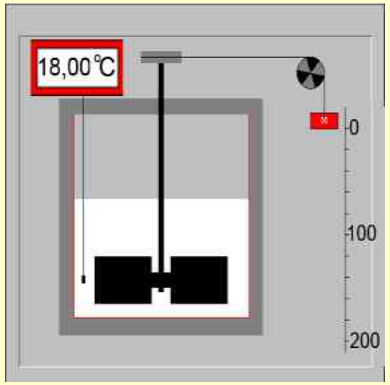
Classical Thermodynamics

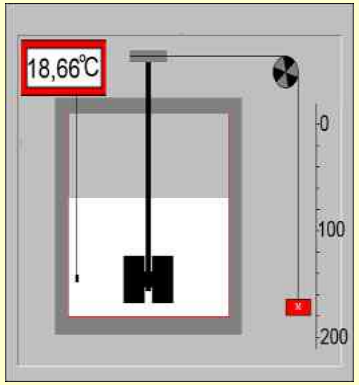
Thermodynamics

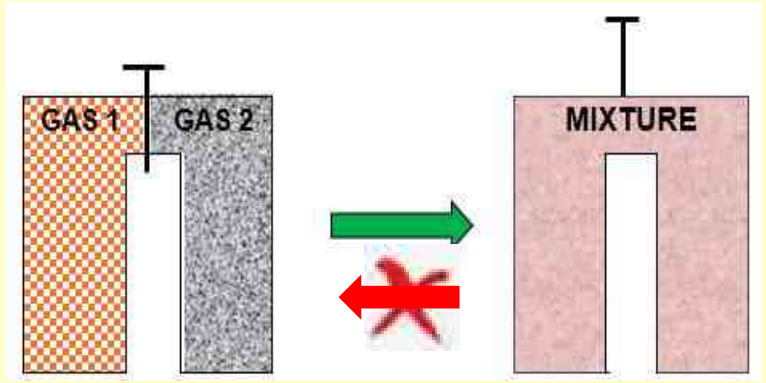
Classical Thermodynamics is developped of the basis of two principles:

1st principle which characterized Energy transformation phenomena on a quantitative viewpoint (Equivalence principle)

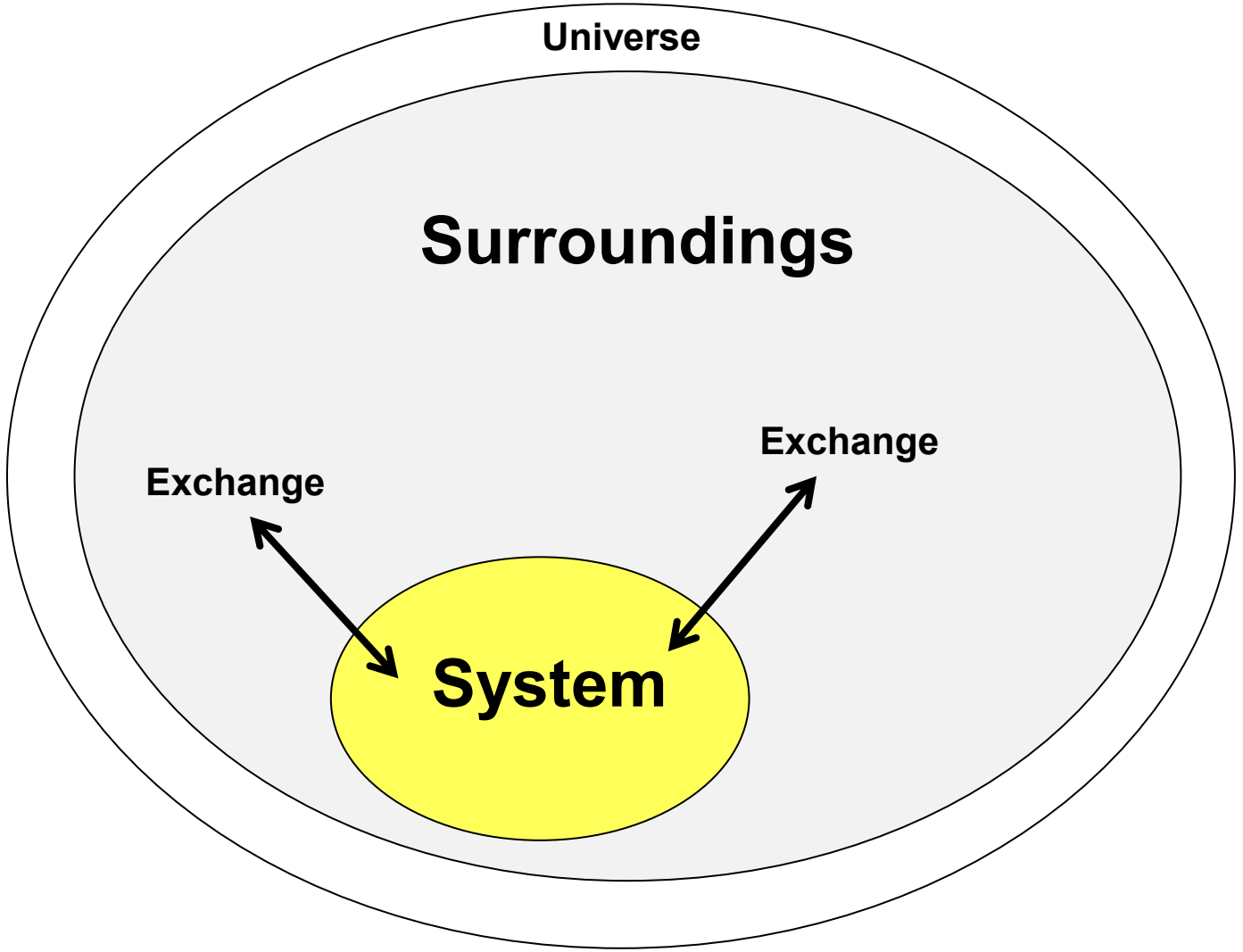
2nd principle which determines the direction of transformations evolution (Evolution principle)







Thermodynamics
System, Surroundings, Universe



Thermodynamics
Work & Heat

In the following, we suppose that only Work (W = Mechanical Energy) and Heat (Q = Calorific Energy) will intervene in the exchanges between the System and the Surroundings

By convention, Energy received by the System is positive:

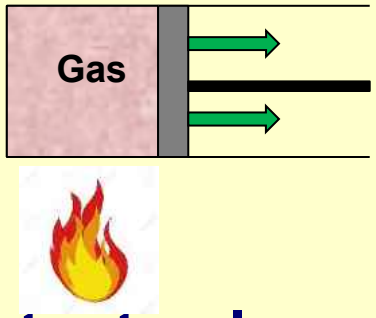
W > 0 & Q > 0 : Energy received by the System

W < 0 & Q < 0 : Energy delivered by the System

Thermodynamics
Work & Heat

Example: Warming of a Gas

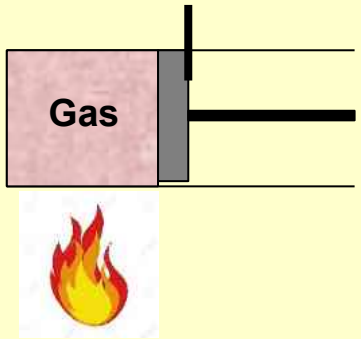
At constant pressure:



Heat → Volume variation

→ Work (W) + Heat (Q)

At constant volume:

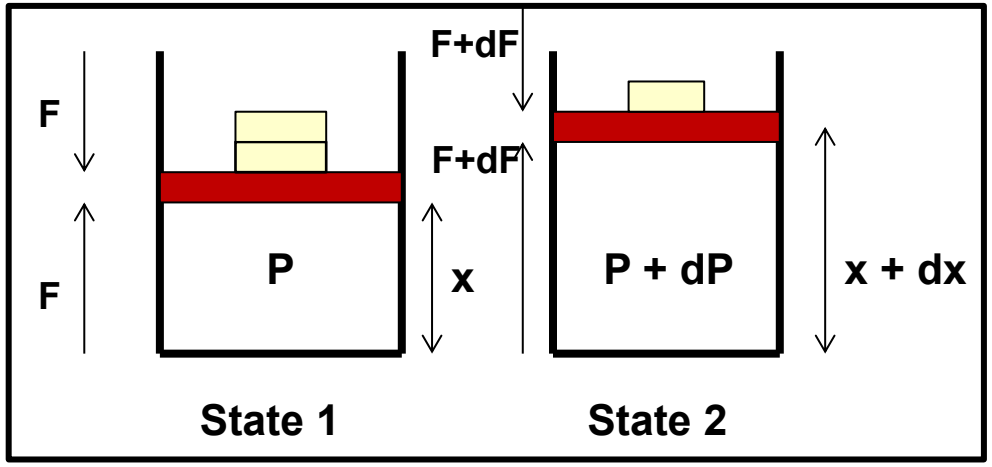


Heat → Constant volume

→ Work (W) = 0 + Heat (Q)

Work (Mechanical Energy)

In a closed system, without exchange of Heat



By convention, Energy received by the system is >0

$$\delta W = -PdV$$

$$\Delta W = \int_1^2 -PdV$$

Work is path-dependant

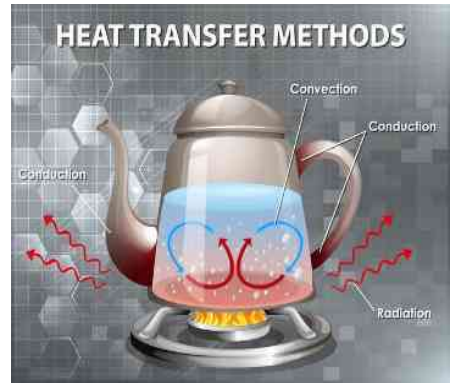
A : Area of the piston-cylinder
F : Weight Force
P : Pressure
V : Volume
x : Height

W : Work

δW = Fdx
State 1 : F = PA
State 2 : F+dF = (P + dP)A
F # ½ (PA + (P + dP)A)
F # PA + ½ AdP
δW # Fdx # PAdx = PdV

Heat (Calorific Energy)

- **Heat : A form of Energy transferred across the boundary of a system at a given temperature to another system or the surroundings at a different temperature by virtue of the temperature difference between the two.**



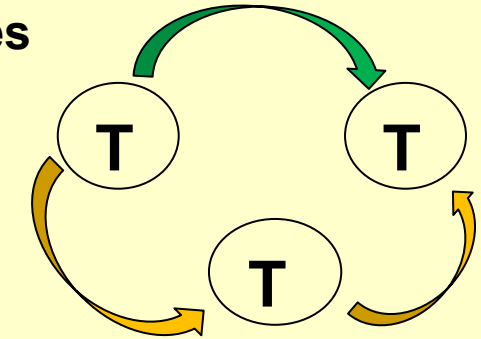
- **When two bodies have the same temperature, there is no Heat transfer between the two bodies.**

  $Q = f(\Delta T)$

- **Thermal machines use Heat to produce Work. Therefore, Heat is a certain form of Energy. Heat and Work can be expressed in the same unit (Joule).** $W = JQ \quad J = 4{,}1852\ J.cal^{-1}$

Thermodynamics
0th & 1st laws

- **Zeroth law of Thermodynamics**: When two bodies have equality of temperature with a third body, then they have equality of temperature.



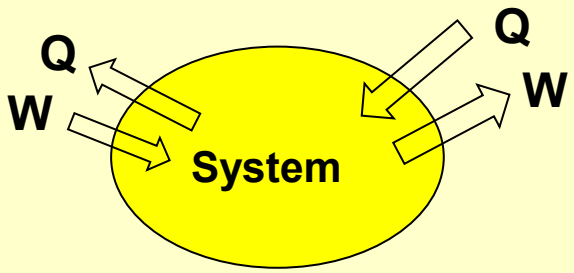
- **First law of Thermodynamics**:

  - 1st statement: in a closed cycle, if the system receives Work (W), then it supplies Heat (Q) to the environment, if it receives Heat (Q), then it supplies Work (W) to the environment.

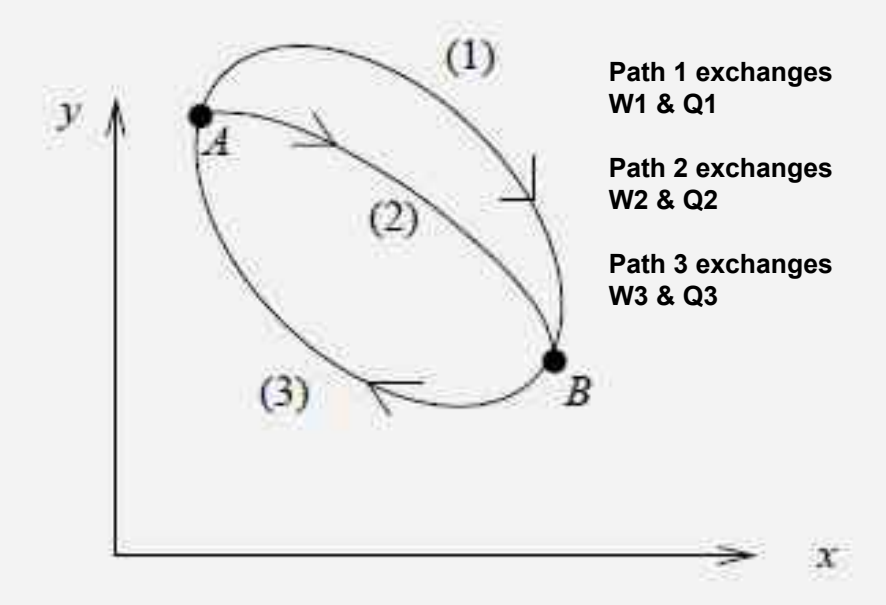
  - 2nd statement: In a closed cycle, with only exchanges of Heat (Q) and Work (W), the algebric sum of mechanic and calorific energy received or supplied is equal to 0.

  - $W + Q = 0 \; or \; \oint(W + Q) = 0$

  - $(W + Q)_{sys.} + (W + Q)_{surr.} = 0$



Internal Energy: U = W + Q
W+Q only depends of initial and final states of a system



U = Internal Energy

$\Delta U_{AB} = U_B - U_A = W+Q$

For an ideal gas, U depends only upon Temperature (Joule – Gay-Lussac)

$\Delta U_{AB} = nc_V (T_B - T_A)$

A: Initial state

B: Final state

Application of 1st law:

Path 1, then 3:

$W_1+Q_1+W_3+Q_3=0$

Path 2, then 3:

$W_2+Q_2+W_3+Q_3=0$

Therefore,

$W_1+Q_1=W_2+Q_2$

W+Q is path-independant

U is a State Function

Thermodynamics
2nd law

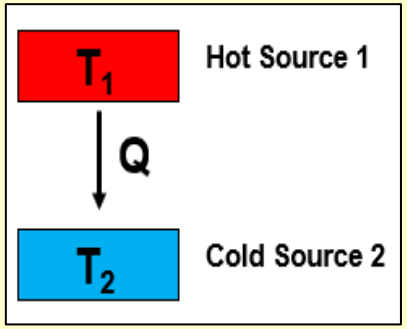
- **Second law of Thermodynamics**:

- **Clausius statement: Heat cannot, of itself, pass from a colder to a hotter body. Heat transfer can only occur spontaneously in the direction of temperature decrease.**

- **Kelvin-Planck statement: It is impossible for any System to operate in a thermodynamic cycle and deliver a net amount of Work to its surroundings while receiving an energy transfer by Heat from a single thermal reservoir. It is impossible for any System to receive a given amount of Heat from a high-temperature reservoir and provide an equal amount of Work output.**

The Second law defines an entity which values characterize the direction of the evolution, based on a time order relation. So, the Second law takes the form of an inequality (except for reversible machines)

- $\sum \frac{Q}{T} < 0 \; for \; irreversible \; machines \; (Losses \; during \; processes)$
  Clausius Inequality
- $\sum \frac{Q}{T} = 0 \; for \; reversible \; machines \; (Carnot \; principle)$



Thermodynamics
3rd law

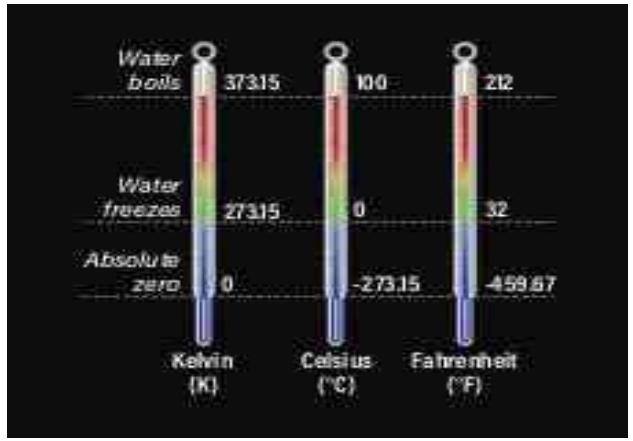
- **Third law of Thermodynamics**:

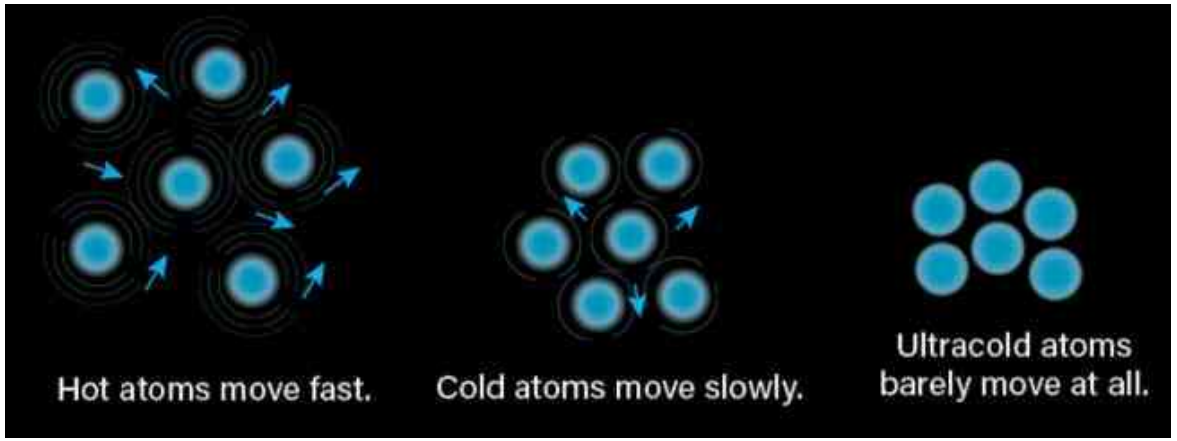
- ***Entropy: A thermodynamic property which provides a quantitative measure of the disorder of a given thermodynamic state within the System (See following chapters)***

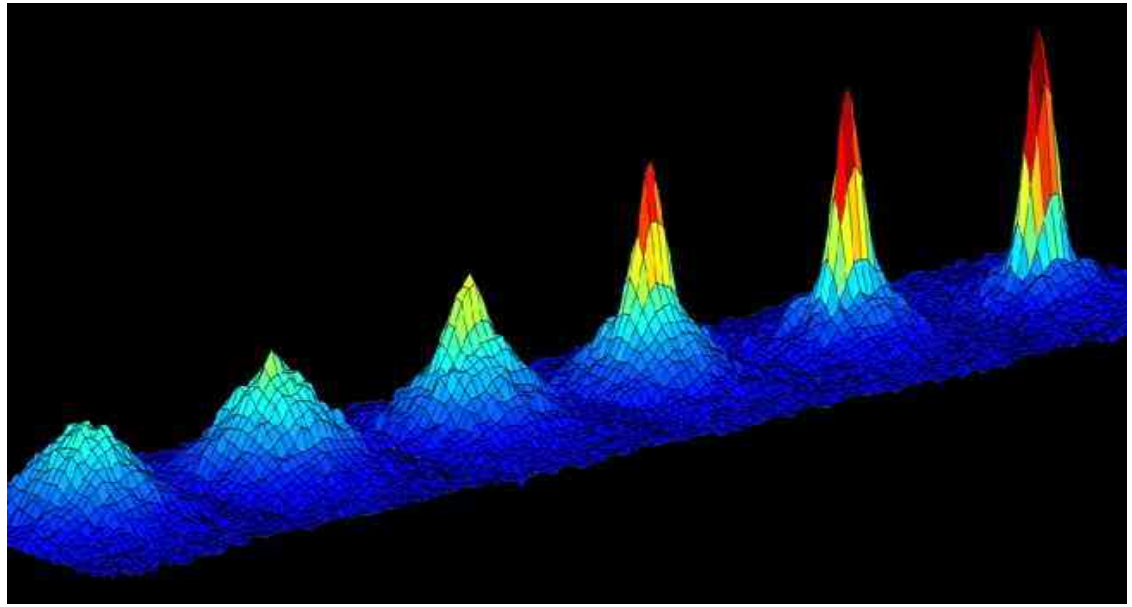
- **The Entropy of a perfect crystal at absolute 0°K temperature is equal to zero.**

- **Nernst statement: The Entropy change associated with any condensed System undergoing a reversible isothermal process approaches zero as the temperature at which it is performed approaches 0°K.**

Thermodynamics
3rd law







Atoms density increases when they get colder and colder.
When Absolute Zero is almost reached, individual atoms overlap very much in a kind of ultra dense matter where they tend to behave as a single coalesced entity.
This phenomena, the Bose-Einstein Condensate (BEC) has been observed at University of Colorado – Boulder in 1995.
In this extreme environment, Entropy is 0.

Source: NASA/Caltech

Thermodynamics : Some basic reminders (1)

U = Internal Energy of the thermodynamic system (State function)
The Energy balance between the System and the Surroundings is 0 (1st principle).

$$dUsyst + dUsurr = 0$$

Let's consider a System subject to a state change:

$dU_{syst} = \delta W + \delta Q$ **(Work and Heat received by the System)**
$dU_{surr} = -\delta W - \delta Q$

System and Surroundings constitute a closed global system:

$dV_{syst} + dVsurr = 0 \Longrightarrow \delta W = -PdVsyst \; _{=} \; PdVs_{urr} = -\delta W_{surr}$

Work received by Surroundings is opposite to the Work received by the System, the same for Heat.

Thermodynamics : Some basic reminders (2)

For a thermodynamic system,

$dU = \delta W + \delta Q = -PdV + \delta Q$ **(δW and δQ Work & Heat received by the System)**

Q only depends upon T. Let's define: $\delta Q = TdS$

$dU = -PdV + TdS$

S is defined as Entropy, a state function (See below: chapter on Entropy). The System is subject to state transformations, not the Surroundings. For the Surroundings:

$dUsurr = -pdVsurr + TdSsurr = -\delta W - \delta Q \Rightarrow \quad dS_{surr} = -\delta Q/T$

For a reversible transformation within the global system, Entropy creation is 0:

$dS_{syst} + dSsurr = 0 \Rightarrow \quad dS_{syst} = \delta Q_{rev}/T$

For a irreversible transformation, Entropy creation is > 0:

$dS_{syst} + dSsurr > 0 \Rightarrow \quad dS_{syst} > \delta Q_{irrev}/T$

Transformation state 1 to state 2 (with reversible and irreversible process) :

$S2 - S1 = Qrev/T \qquad S2 - S1 > Qirrev/T \qquad Q_{rev} > Qirrev$

$U2 - U1 = Wrev + Qrev = Wirrev + Qirrev \qquad W_{rev} < Wirrev \Rightarrow$ **$|W_{rev}| > |W_{irrev}|$**

Conclusion: the Work received by Surroundings (generated by the System) is greater when the transformation is reversible than when it is irreversible.

Thermodynamics : Some basic reminders (3)

E = Total Energy of a System
U = Internal Energy (due to the internal structure of the matter)
KE = Kinetic Energy (due to motion, macroscopic form of Energy)
PE = Potential Energy (due to gravity, macroscopic form of Energy)
H = Enthalpy

$$E = KE + PE + U \quad E: State\ Function$$
$$\Delta U = UB - UA = \oint (W + Q) = W + Q \quad U: State\ Function$$

Let's define:

$$H = U + PV \quad H: State\ Function$$
$$\Delta H = \Delta U + P\Delta V + V\Delta P = -P\Delta V + Q + P\Delta V + V\Delta P = Q + V\Delta P$$

In the case of isobaric process:

$$\Delta H = Q + V\Delta P = Q$$

Thermodynamics : Some reminders (4)

n moles

Specific Heat = $c = 1/n \times \delta Q/dT$

At constant volume: $c_v = 1/n \times \delta Q_v/dT$

At constant pressure: $c_p = 1/n \times \delta Q_p/dT$

At constant volume: $dU = \delta Q_v = nc_v dT$ $\quad c_v = (\partial U/\partial T)_v$

At constant pressure: $dH = \delta Q_p = nc_p dT$ $\quad c_p = (\partial H/\partial T)_p$

Ideal Gas: $PV = nRT$

$dH = dU + d(PV) = dU + nRdT$

$\Rightarrow \quad nc_p dT = nc_v dT + nRdT$

$c_p - c_v = R$ (R = Ideal Gas constant = 8,32 $JK^{-1}mole^{-1}$)

Thermodynamics : Some reminders (5)

For ideal gas, PV = nRT

Isochoric Transformation:

V = cst: $W = \int_A^B -PdV = 0$ and $\delta Q_v = nc_v dT$

Isobaric Transformation

P = cst: $W = \int_A^B -PdV = -PO(VB - VA)$ and $\delta Q_p = nc_p dT$

Isothermal Transformation

T = cst: $W = \int_A^B -PdV = -nRT_0 \int_A^B \frac{dV}{V} = nRT_0 Log(\frac{VA}{VB})$

and $\Delta U_{AB} = 0 \Rightarrow W + Q = 0 \Rightarrow Q = -W = -nRT_0 Log(\frac{VA}{VB})$

Adiabatic Transformation

$dU = nc_v\, dT = \delta Q + \delta W = \delta W = -PdV = -nRTdV/V \Rightarrow$

$dT/T + R/c_v \times dV/V = 0$ With $c_p - c_v = R$ and $\gamma = c_p/c_v$

$R/c_v = \gamma - 1$ $Log(T/T_0) + (\gamma-1)Log(V/V_0) = Cst$

$\Rightarrow TV^{\gamma-1} = Cst$ and $PV^{\gamma} = Cst$

Thermodynamics
Some famous words

Antoine Lavoisier (1743 – 1794):



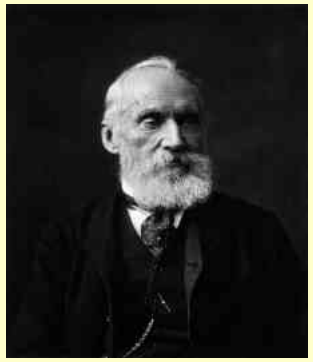
« Rien ne se perd, rien ne se crée »

Paul Langevin (1872 – 1946):



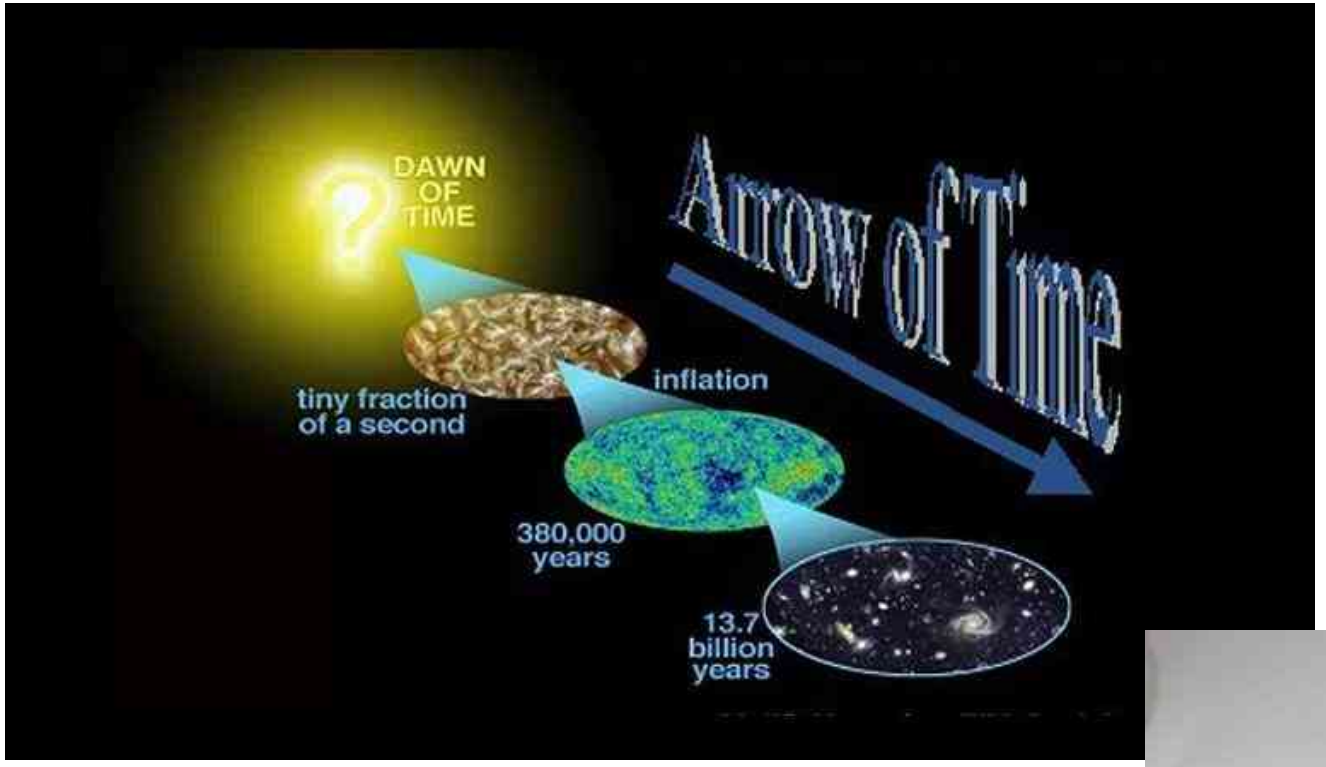
« Si un changement est spontanément réalisable, le changement inverse ne l'est pas »

Kelvin (1824 – 1907):



« La nature ne peut revenir en arrière »

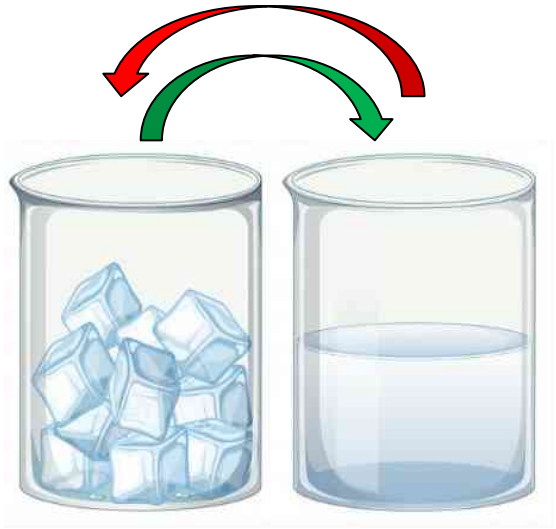
Thermodynamics and The Arrow of Time





Thermodynamics and The Arrow of Time







« The increase of disorder or Entropy with time is one example of what is called an Arrow of Time, something that distinguishes the past from the future, giving a direction to time. »
Stephen Hawking
(1942 – 2018)

Sir Arthur Stanley Eddinton (UK)
(1882 – 1944)

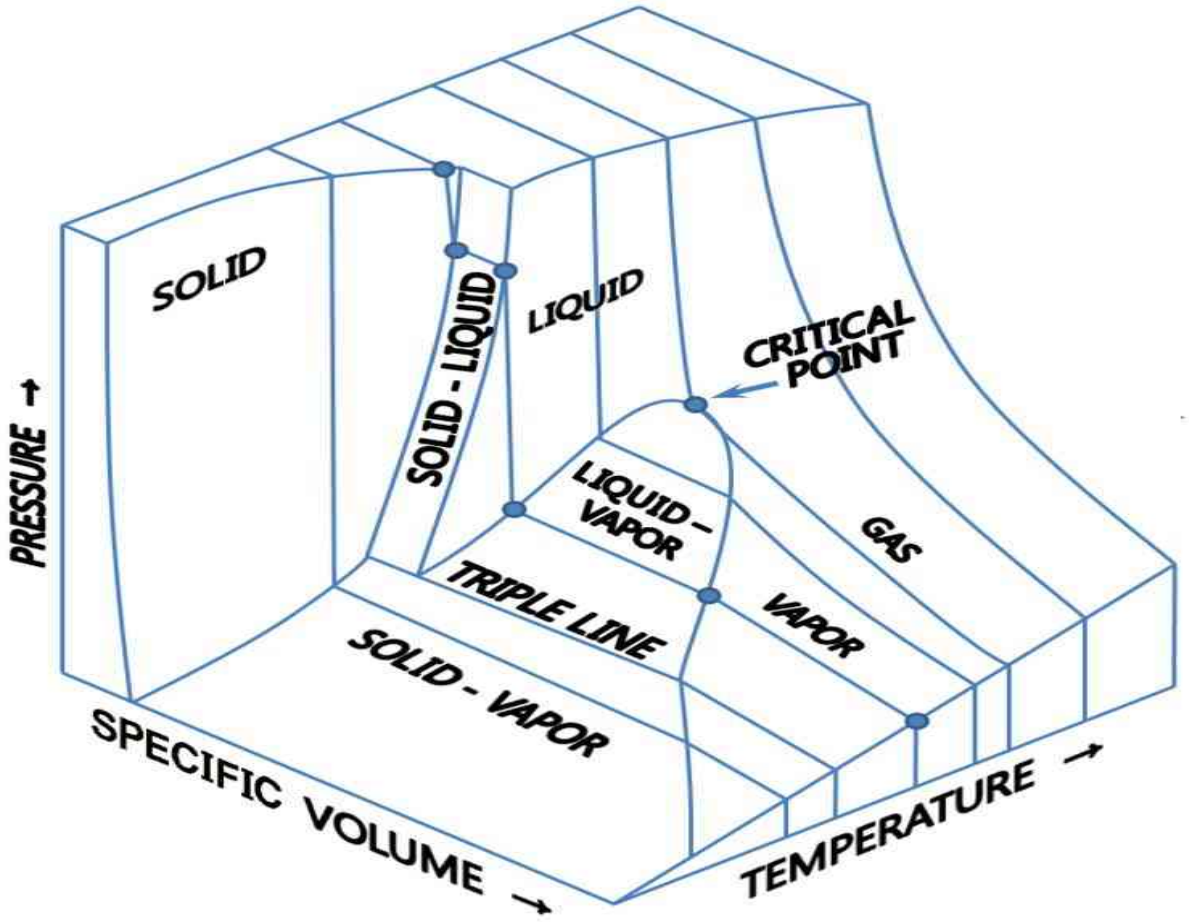
Carnot



Nicolas Leonard Sadi Carnot
(1796 – 1832)

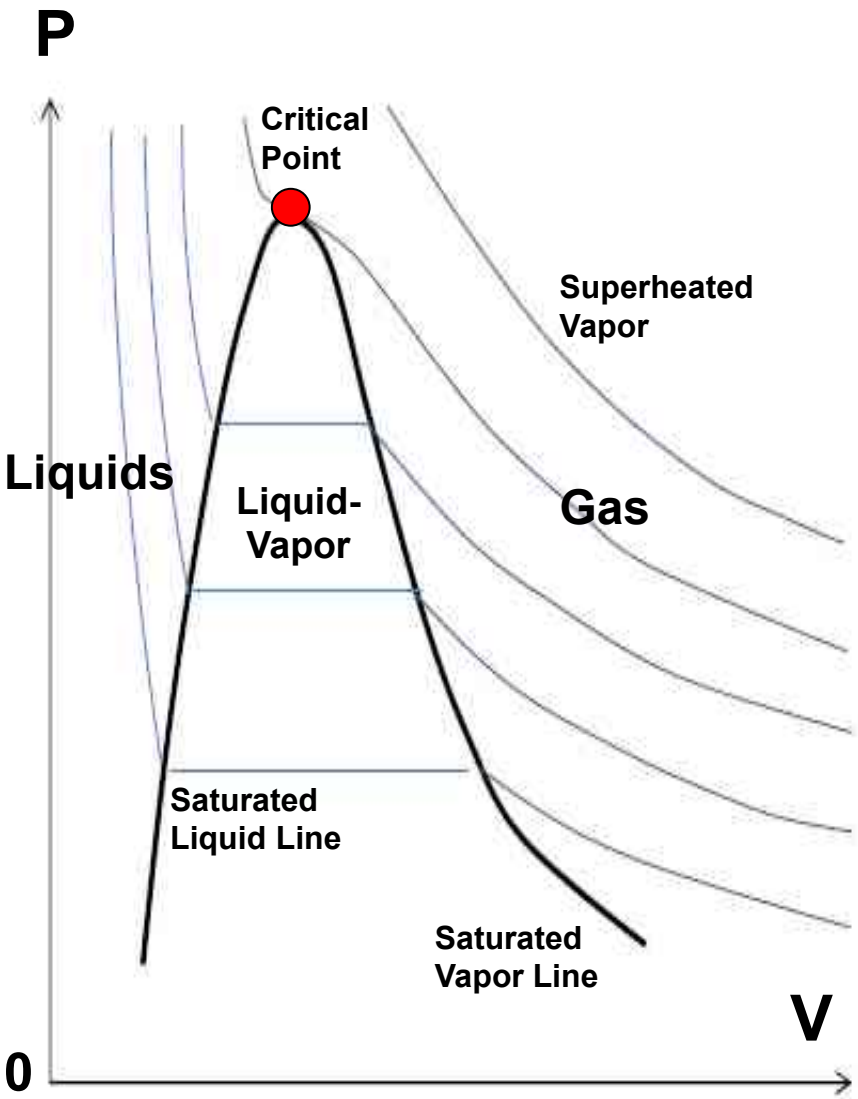
Son of Lazare Carnot (1753 – 1823), mathematician, physician & politician.
Uncle of Marie-François Sadi Carnot (1837 – 1894), president of French Republic (1887 – 1894)

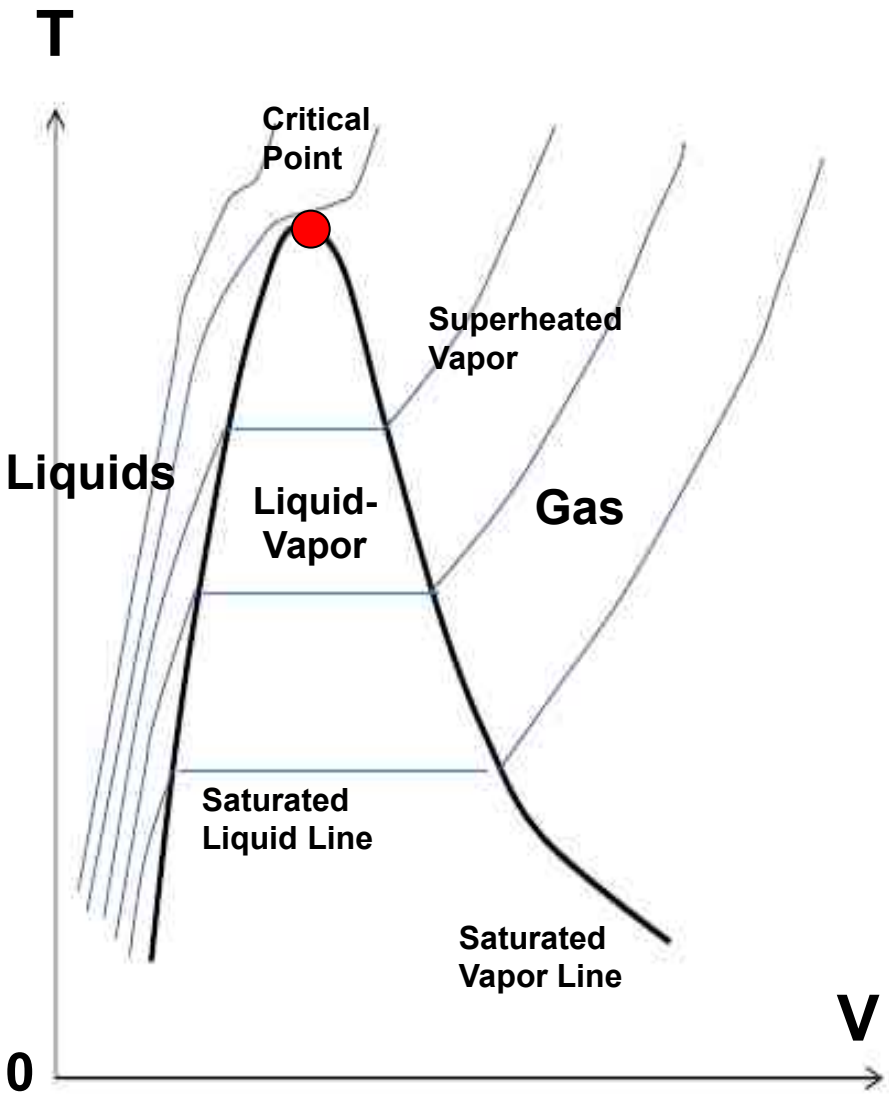
Phase Diagram for pure material



Source: by Donald L. Smith

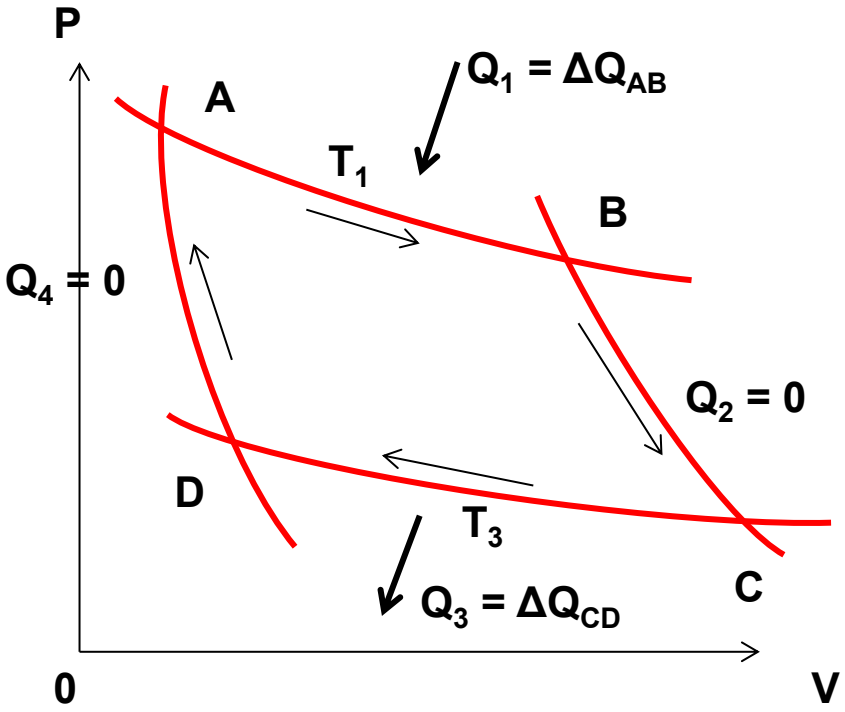
Water Vapour State Diagram (P,V) & (T,V)





Carnot Cycle (PV Diagram)

Carnot Cycle is a reversible process. No change in Entropy



For Ideal Gas

$PV = nRT \quad P = nRT/V$

$\gamma = C_P/C_V$

Adiabatic transform. : $PV^{\gamma} = Cst$

$TV^{\gamma-1} = Cst$

AB: Isothermal T_1

BC: Adiabatic

CD: Isothermal T_2

DA: Adiabatic

$dU_{AB} = 0 = -PdV + \delta Q_{AB}$

$\delta Q_{AB} = PdV = nRT_1 dV/V$

$\Delta Q_{AB} = Q_1 = nRT_1 Log(V_B/V_A) \quad Q_1 = \Delta Q_{AB} > 0$

$Q_2 = \Delta Q_{BC} = 0 \quad T_1 V_B^{\gamma-1} = T_3 V_C^{\gamma-1}$

$dU_{CD} = 0 = -PdV + \delta Q_{CD}$

$\delta Q_{CD} = PdV = nRT_3 dV/V$

$\Delta Q_{CD} = Q_3 = nRT_3 Log(V_D/V_C) \quad Q_3 = \Delta Q_{CD} < 0$

$Q_4 = \Delta Q_{DA} = 0 \quad T_1 V_A^{\gamma-1} = T_3 V_D^{\gamma-1}$

$\Rightarrow \quad V_B/V_A = V_C/V_D$

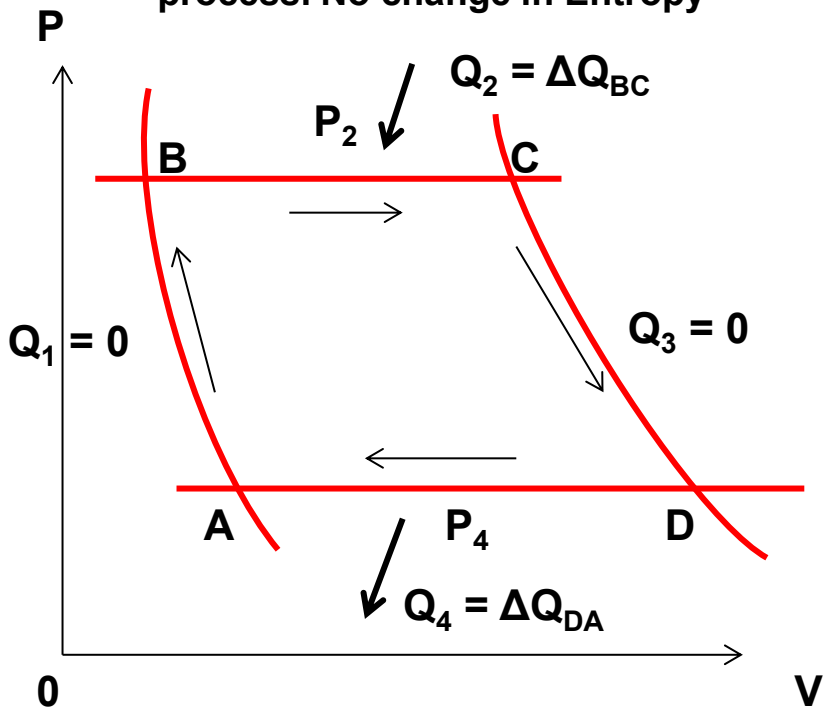
$\Rightarrow \quad Q_1/T_1 + Q_3/T_3 = 0$

Efficiency Ratio: $\eta = 1 - |Q_3/Q_1|$

$\eta = 1 - T_3/T_1$

Rankine Cycle (PV Diagram)
Application to a Gas Turbine

Rankine Cycle is a reversible process. No change in Entropy



For Ideal Gas

$PV = nRT \quad P = nRT/V$

$\gamma = C_P/C_V$

Adiabatic transform. : $PV^{\gamma} = Cst$

$TV^{\gamma-1} = Cst$

AB: Adiabatic Compression
BC: Isobaric Vaporisation
CD: Adiabatic Expansion
DA: Isobaric Liquefaction

$Q_2 = nc_p(T_C - T_B)$
$Q_4 = nc_p(T_A - T_D)$

$T_A V_A^{\gamma-1} = T_B V_B^{\gamma-1} = k_1$
$T_C V_C^{\gamma-1} = T_D V_D^{\gamma-1} = k_3$

$P_2V_B = nRT_B \quad \& \quad P_2V_C = nRT_C$
$P_4V_A = nRT_A \quad \& \quad P_4V_D = nRT_D$

$T_A = k_1 P_4^{(\gamma-1)/\gamma} \quad \& \quad T_B = k_1 P_2^{(\gamma-1)/\gamma}$
$T_C = k_3 P_2^{(\gamma-1)/\gamma} \quad \& \quad T_D = k_3 P_4^{(\gamma-1)/\gamma}$

Efficiency Ratio: $\eta = 1 - |Q_4/Q_2|$

$\eta = 1 - |(T_A - T_D)/(T_C - T_B)|$

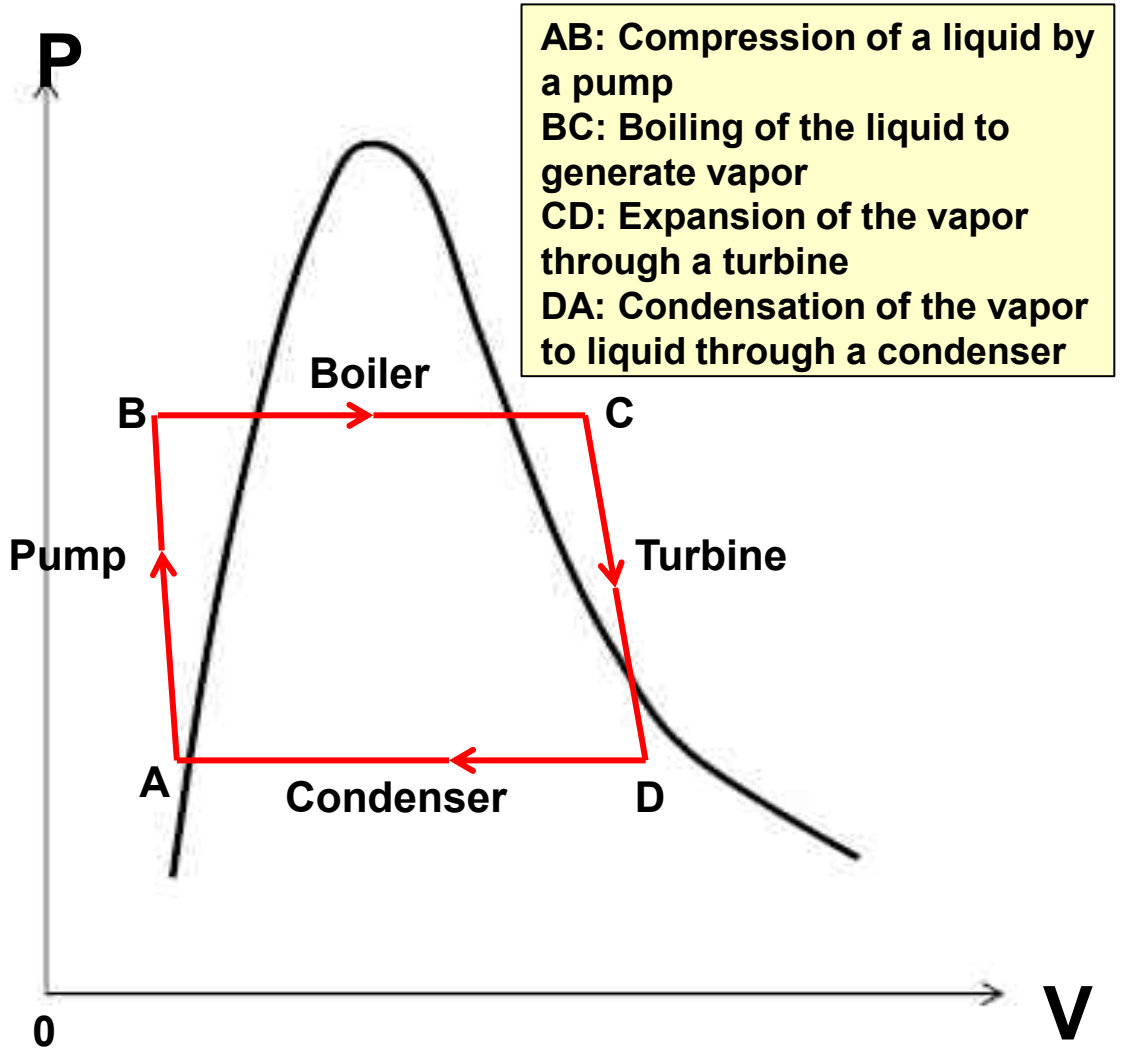
$\eta = 1 - (T_D - T_A)/(T_C - T_B)$

$\eta = 1 - P_4/P_2^{(\gamma-1)/\gamma}$

Rankine Cycle (PV Diagram)
Application to Steam Power Plant

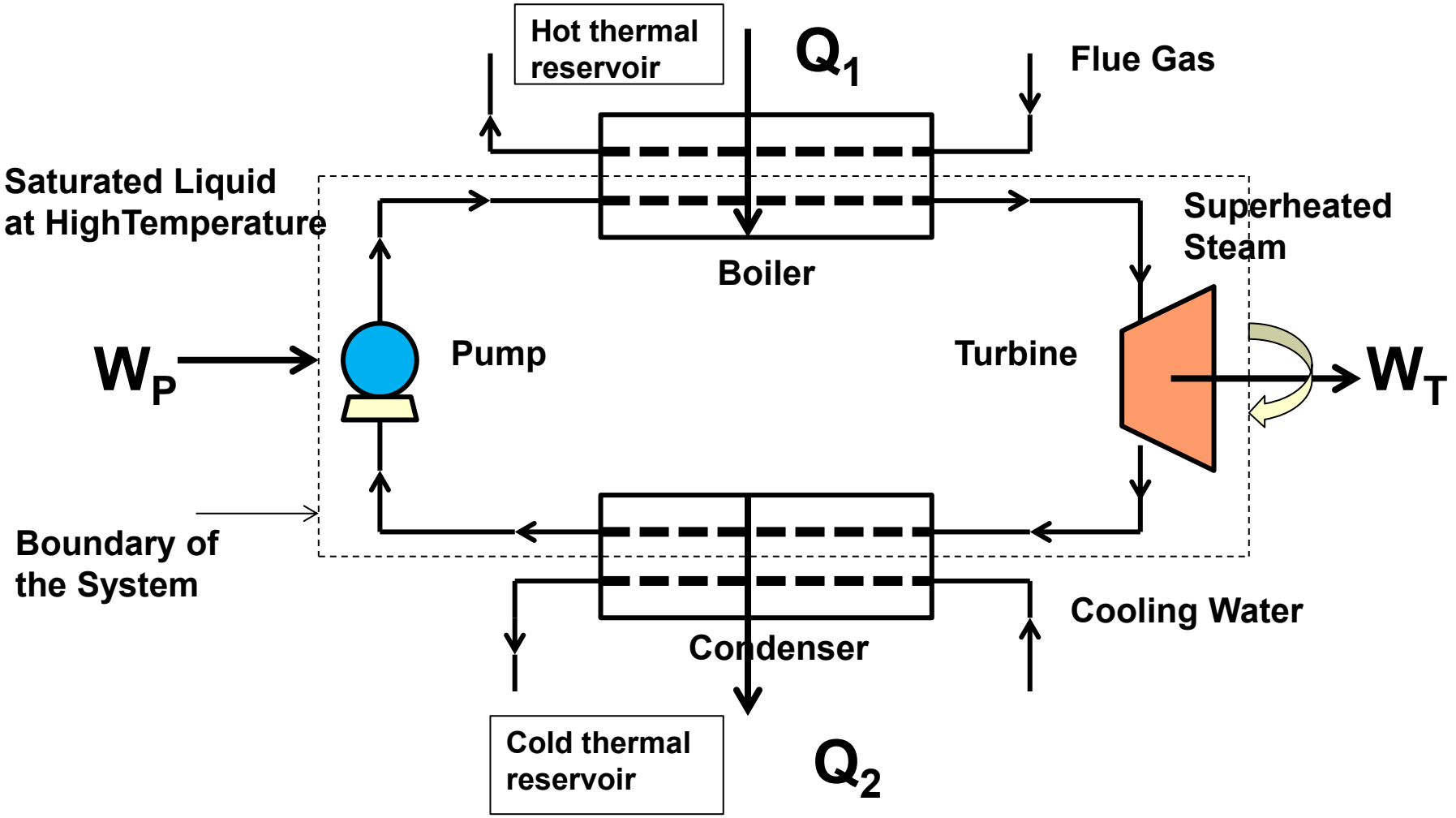


William John Maquorn Rankine
(1820 – 1872)



AB: Compression of a liquid by a pump
BC: Boiling of the liquid to generate vapor
CD: Expansion of the vapor through a turbine
DA: Condensation of the vapor to liquid through a condenser

Heat Engine (Thermal Power Plant)



Thermal Efficiency Heat Engine

Net Work delivered = $W_T - W_P$
Energy absorbed as Heat by the System = Q_1
Energy rejected as Heat by the System = Q_2

First law (Absolute values): $W_T - W_P = Q_1 - Q_2$

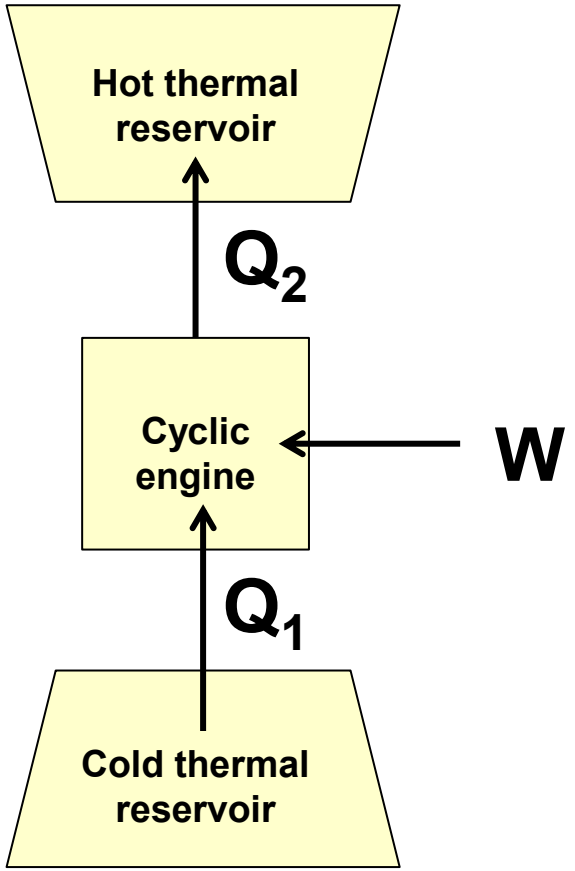
Thermal Efficiency = $\eta = (W_T - W_P)/Q_1$

or $\eta = 1 - Q_2/Q_1$

Any reversible engine operating between the same thermal reservoirs must have the same Efficiency. So, the Thermal Efficiency depends only on the characteristics of these reservoirs: ⟶ $\eta = f(T_1, T_2)$

That means: $\eta = 1 - T_2/T_1$ $T_2 < T_1$ ⟶ $\eta < 1$

Heat Pump


Hot thermal reservoir
Q_2
Cyclic engine
W
Q_1
Cold thermal reservoir

Thermal Efficiency Heat Pump

Heat delivered = Q_2
Heat absorbed by the System = Q_1
Work absorbed by the System = W

First law (Absolute values): $Q_2 - Q_1 = W$

Thermal Efficiency = $\eta = Q_2/W$

or $\eta = 1 + Q_1/W = 1/(1-Q_1/Q_2)$

Any reversible engine operating between the same thermal reservoirs must have the same Efficiency. So, the Thermal Efficiency depends only on the characteristics of these reservoirs: $\eta = f(T_1,T_2)$

That means: $\eta = 1/(1-T_1/T_2)$ $T_1<T_2$ ⇒ $\eta > 1$

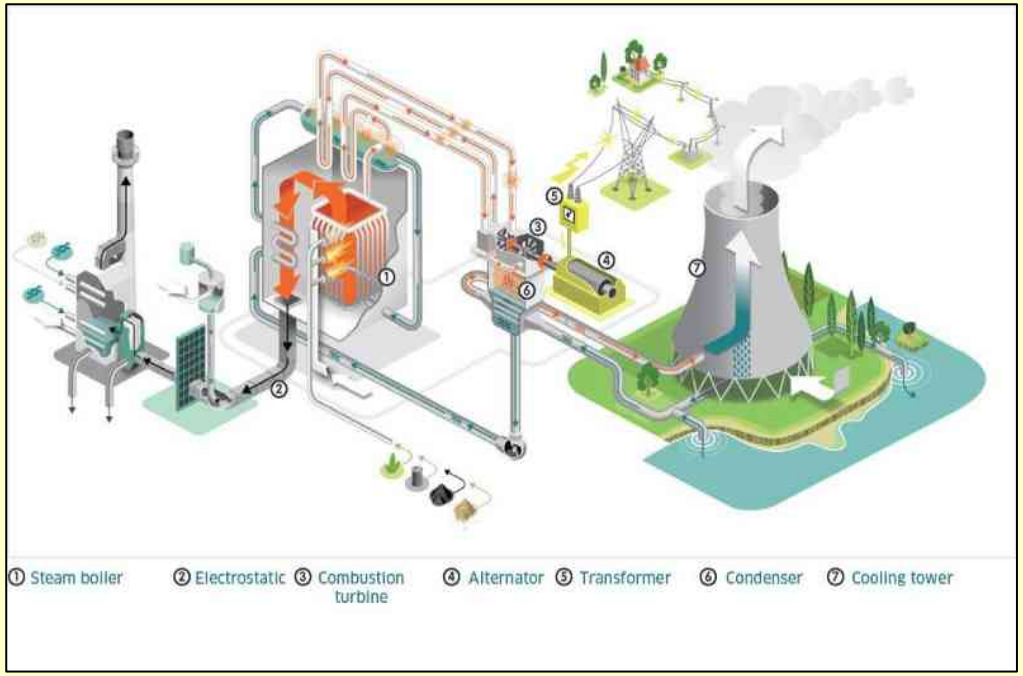
Thermodynamical Cycles

- Thermodynamical machines (Power plants, car engines, heat pumps) operate with successive transformations which form a cycle.

- During a cycle, Energy & Entropy are state functions, that depends only on the current equilibrium thermodynamic state ot the system, not on the path taken by the system to reach its current state.

- In practice, these transformations are not reversible (Frictions, losses during processes)

- Reversible transformations characterize ideal machines.



Thermodynamical Cycles

- **Reversible** transformations characterize ideal machines.

- Thermal **reversible** machines must satisfy the 2 principles of Thermodynamics:

  1st principle: $W + Q_1 + Q_2 = 0$

  2nd principle: $Q_1/T_1 + Q_2/T_2 = 0$

Thermodynamical Cycles

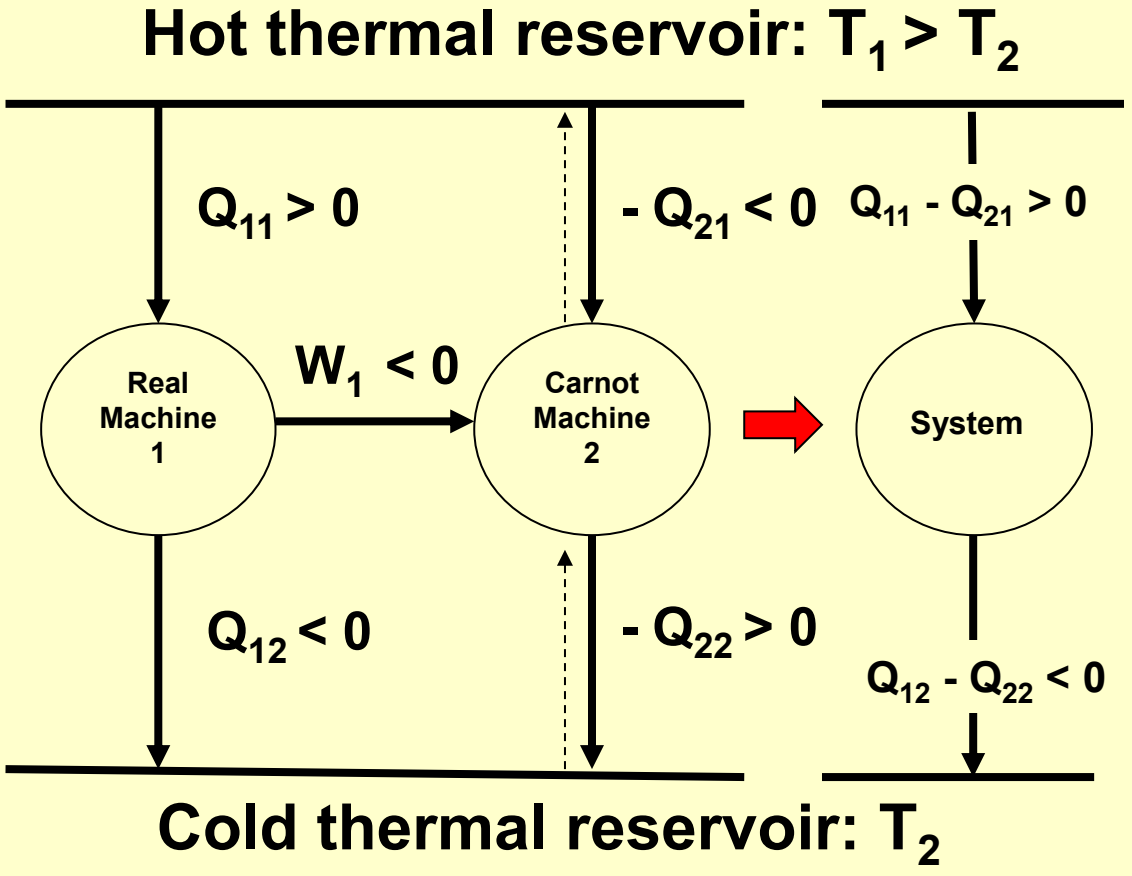
- **In practice, real transformations are not reversible (Losses during processes)**
- **Examples of internal irreversibilities: frictions, chemical reactions, combustion, mixture of two different products, magnetic hysteresis, …..**
- **Examples of external irreversibilities: Heat exchange between two sources (Heat transfer from a cold reservoir to a hot reservoir is only possible with a source of Work),…..**
- **Irreversible (Real) thermal machines efficiency is lower than reversible thermal machines efficiency.**







Thermodynamical Cycles
Carnot theorem and Clausius Inequality



Machines 1 & 2 delivers the same Work W from exchange between hot and cold thermal reservoirs.

$\eta_1 = |W|/Q_{11} = (Q_{11} + Q_{12})/Q_{11}$
$\eta_2 = |W|/Q_{21} = (Q_{21} + Q_{22})/Q_{21}$

Let's reverse the Carnot cycle, by considering Machine 2 as a frigorific machine and combining Machines 1 & 2.

The resulting system doesn't generate any Work.

Heat > 0 or < 0: $Q_{11} > Q_{21}$
Energy conservation:
$\Delta U = 0 = Q_{11} - Q_{21} + Q_{12} - Q_{22}$
$Q_{21} + Q_{22} = Q_{11} + Q_{12}$

$\Rightarrow \eta_2 > \eta_1$

Thermodynamical Cycles
Carnot theorem and Clausius Inequality

Irreversible thermal machine Efficiency:

$$\eta_{irr.} = 1+Q_2/Q_1 \quad (Q_1>0,\ Q_2<0)$$

Reversible machine Efficiency:

$$\eta_{rev.} = 1-T_2/T_1 \quad \text{(Carnot principle)}$$

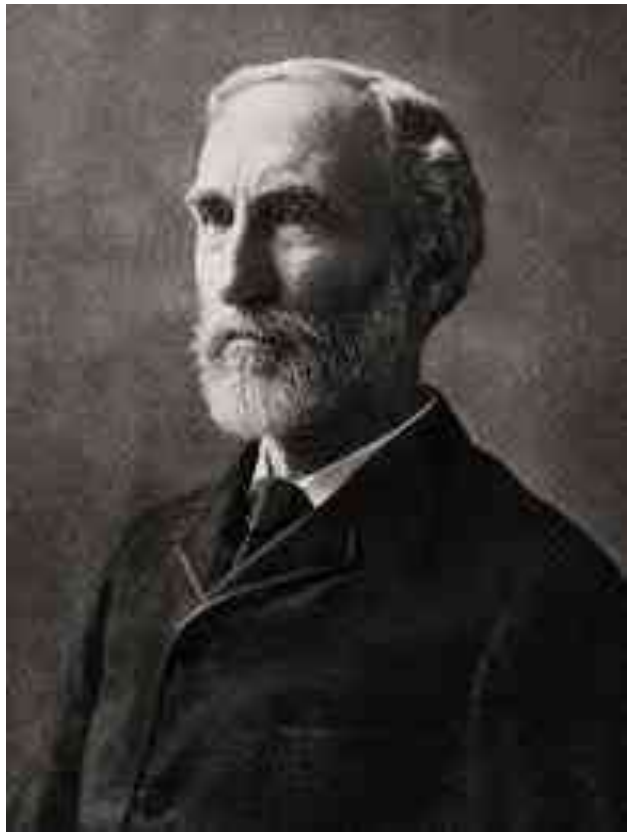
$$\eta_{irr.} < \eta_{rev.} \Rightarrow 1+Q_2/Q_1 < 1-T_2/T_1 \Rightarrow Q_1/T_1 + Q_2/T_2 < 0$$

Can be written: $\oint \frac{\delta Q_1}{T_1} + \oint \frac{\delta Q_2}{T_2} < 0$ **for irreversible machines**

Can be written: $\oint \frac{\delta Q_1}{T_1} + \oint \frac{\delta Q_2}{T_2} = 0$ **for reversible machines**

Entropy

Entropy



« Any method involving the notion of Entropy, the very existence of which depends on the second law of Thermodynamics, will doutless seem to many far-fetched, and may repel beginners as obscure and difficult of comprehension »

Josiah Willard Gibbs (1839-1903)

Entropy

- Can be defined by the behaviour of a thermodynamic system through a macroscopic or microscopic viewpoint.
- A thermodynamic property which provides a quantitative measure of the disorder of a given thermodynamic state within the System.
- The higher is the Entropy, the higher is the disorder of its components, the greater is the part of usable Energy to generate a Work.
- Real transformations are irreversible. Energy lost by a System in the form of Heat contributes to increase the global disorder in the form of Entropy.
- A System can only generate, not destroy Entropy.
- The Entropy of a System can be increased or decreased by energy transports across the System boundaries.

Entropy

- $dU = \delta W + \delta Q$
- $\delta W = -PdV$
- Q depends only upon T
- By analogy, let's define: $\delta Q = TdS$
- ⟶ $dU = -PdV + TdS$

Entropy
Carnot theorem and Clausius inequality

Irreversible thermal machine Efficiency:

$$\eta_{irr.} = 1+Q_2/Q_1 \quad (Q_1>0,\ Q_2<0)$$

Reversible machine Efficiency:

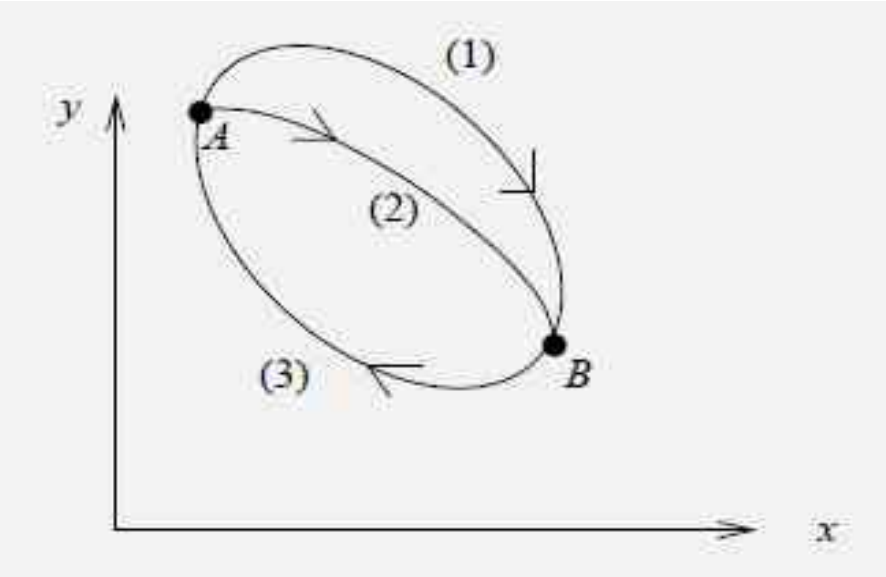
$$\eta_{rev.} = 1-T_2/T_1$$

$$\eta_{irr.} < \eta_{rev.} \Rightarrow 1+Q_2/Q_1 < 1-T_2/T_1 \Rightarrow Q_1/T_1 + Q_2/T_2 <0$$

Can be written: $\oint \frac{\delta Q_1}{T_1} + \oint \frac{\delta Q_2}{T_2} < 0$ for irreversible machines

Can be written: $\oint \frac{\delta Q_1}{T_1} + \oint \frac{\delta Q_2}{T_2} = 0$ for reversible machines

Entropy: S
S only depends of initial and final states of a system



S = Entropy

$$dS = \frac{\delta Q}{T}$$

$$\Delta S = SB - SA = \oint \left(\frac{\delta Q}{T}\right)_{rev.}$$

$$\Delta S = SB - SA > \oint \left(\frac{\delta Q}{T}\right)_{irr.}$$

A: Initial state

B: Final state

Path 1, then 3:

$$\int_A^B \left(\frac{\delta Q}{T}\right)_{Path1} + \int_B^A \left(\frac{\delta Q}{T}\right)_{Path3} = 0$$

Path 2, then 3:

$$\int_A^B \left(\frac{\delta Q}{T}\right)_{Path2} + \int_B^A \left(\frac{\delta Q}{T}\right)_{Path3} = 0$$

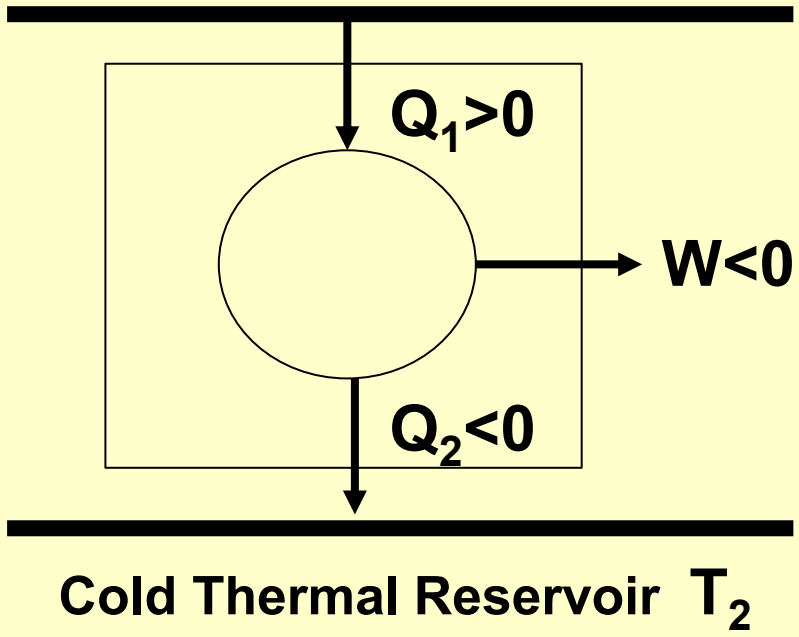
Therefore,

$$\int_A^B \left(\frac{\delta Q}{T}\right)_{Path1} = \int_B^A \left(\frac{\delta Q}{T}\right)_{Path2}$$

S is path-independant

S is a State Function

Entropy
Case of a Thermal Machine



U State function:

$\Delta U = Q_1+Q_2+W = 0$

$\eta = - W/Q_1 = 1 - |Q_2/Q_1|$

S:State function + Entropy creation:

$\Delta S_{syst} = S_{exchange} + S_{creation}$

$\Delta S_{syst} = 0$ and $S_{creation} > 0$

$S_{exchange} = Q_1/T_1 + Q_2/T_2$

$\eta = 1 - T_2/T_1 - T_2/Q_1 * S_{creation}$

$\eta_{rev} = 1 - T_2/T_1 < 1$

$\eta_{irrev} < \eta_{rev} < 1$

Entropy

- Any thermal exchange equalizes Temperatures and leads to a dissipation and degradation of Energy into Heat.
- Energy is subject to transformations and divisions.
- In all real transformations, the quality of Energy is degrading during the process, and tends to a situation of dissipation and disorder.
- Friction and diffusion phenomena lead to a loss of usable Energy in the form of Work.
- Real transformations are moving from the status of low Entropy (order) to a status of high Entropy (disorder).

Entropy
Clausius Inequality and Entropy variation

- The Clausius Inequality applies to any real engine cycle and implies a negative change in Entropy on the cycle.

- That is, the Entropy given to the environment during the cycle is larger than the Entropy transferred to the engine by heat from the hot reservoir.

Entropy
Clausius Inequality and Entropy variation

For the closed System,

$$S_{exchange} = \oint \frac{\delta Q}{T} \leq 0$$ **for real machines**

$S_{creation} = \Delta S_{syst} + \Delta S_{surr}$

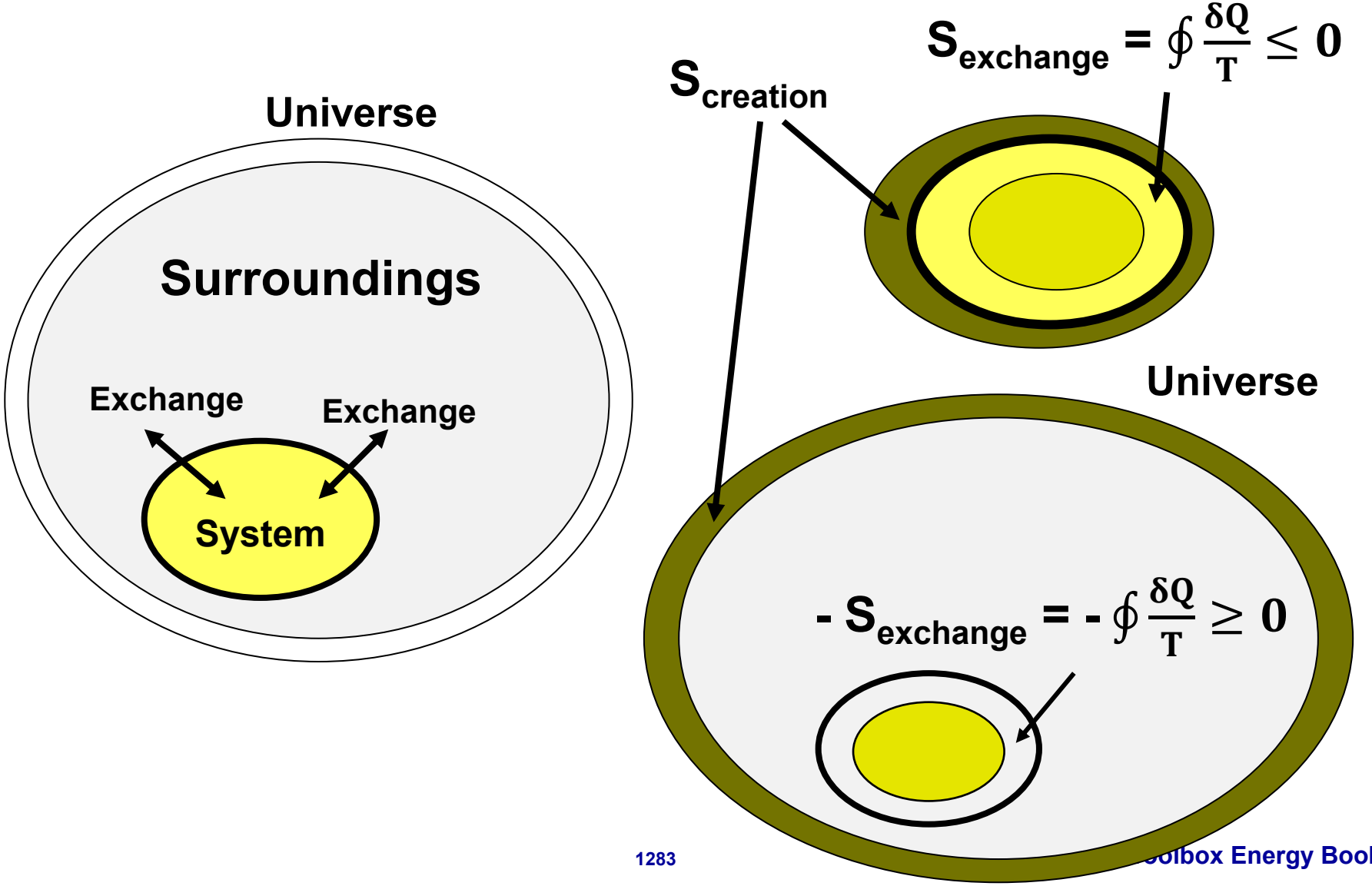
$\Delta S_{surr} = - S_{exchange} = -\oint \frac{\delta Q}{T} \geq 0$

$\Delta S_{syst} = 0$

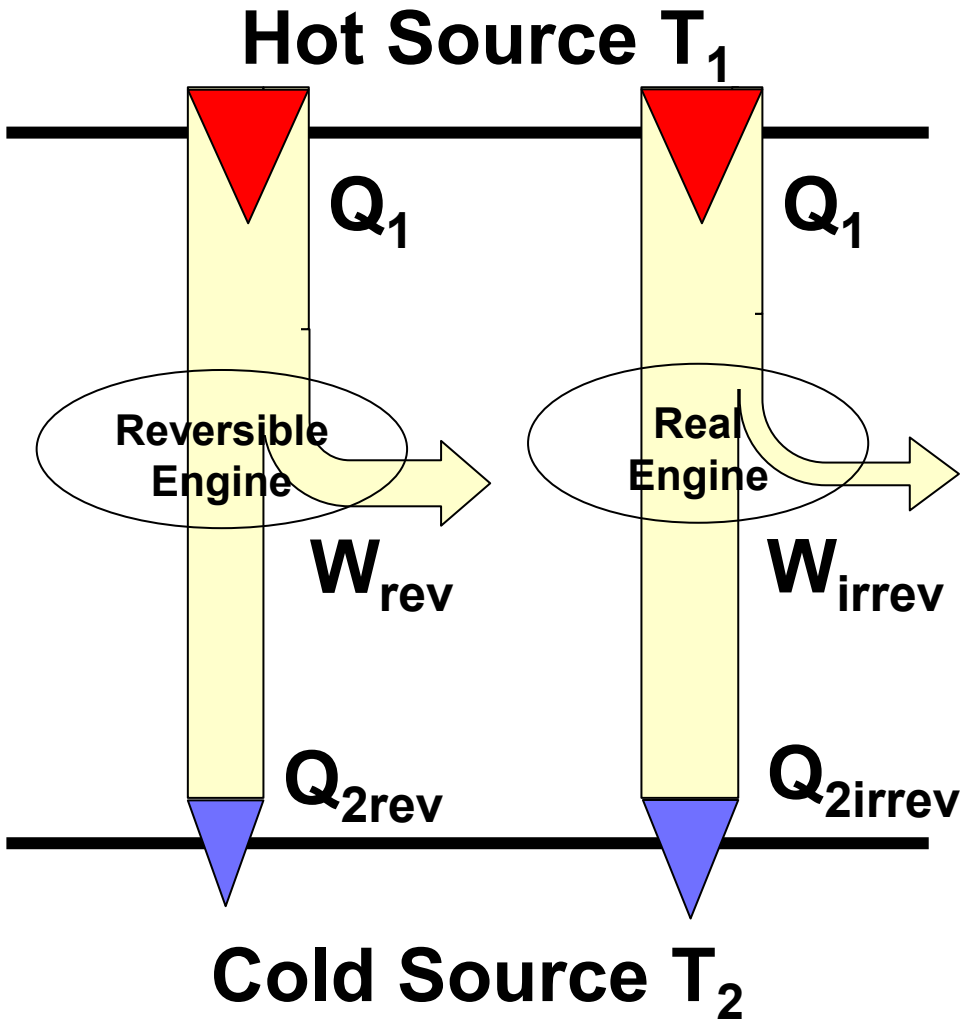
$S_{creation} = \Delta S_{surr} \geq 0$ ⟶ **Entropy creation**

$S_{creation} = 0$ **for reversible machines**

Entropy
Clausius Inequality and Entropy variation



Entropy
Clausius Inequality and Entropy variation



$|W_{rev}| = Q1 - |Q_{2rev}|$

$|W_{irrev}| = Q1 - |Q_{2irrev}|$

Reversible Engine:

$$\oint \frac{\delta Q}{T} = \frac{Q_1}{T1} - \frac{|Q_{2rev}|}{T2} = 0$$

Irreversible Engine:

$$\oint \frac{\delta Q}{T} = \frac{Q_1}{T1} - \left(\frac{|Q_{2rev}|}{T2} + \frac{|\Delta Q_2|}{T2}\right) < 0$$

The real (irreversible) Engine is less efficient than the reversible Engine ($W_{irrev} < W_{rev}$) because it rejects more Heat to the cold Source than the reversible Engine.

Entropy
Clausius statement

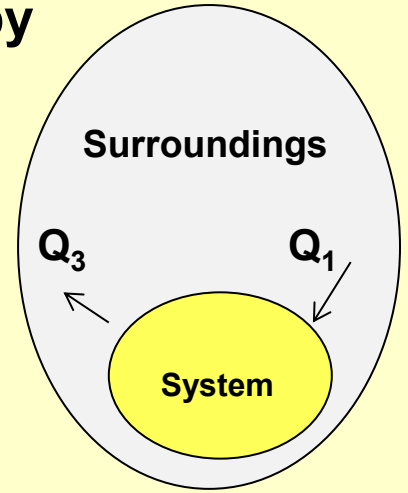
- The Energy of the Universe is constant
- The Entropy of the Universe tends to a maximum

Entropy of the Univers is always increasing

Total Entropy = System Entropy + Surroundings Entropy

$\Delta S_{tot.} = \Delta S_{syst.} + \Delta S_{surr.}$ = Created Entropy

$\Delta S_{syst.} = \Delta S_{AB} + \Delta S_{CD} = (Q_1/T_1)_{rev.} + (Q_3/T_3)_{rev.} = 0$
$\Delta S_{surr.} = \Delta S_{surr.AB} + \Delta S_{surr.CD} = -(Q_1/T_1)_{rev.} - (Q_3/T_3)_{rev.} = 0$

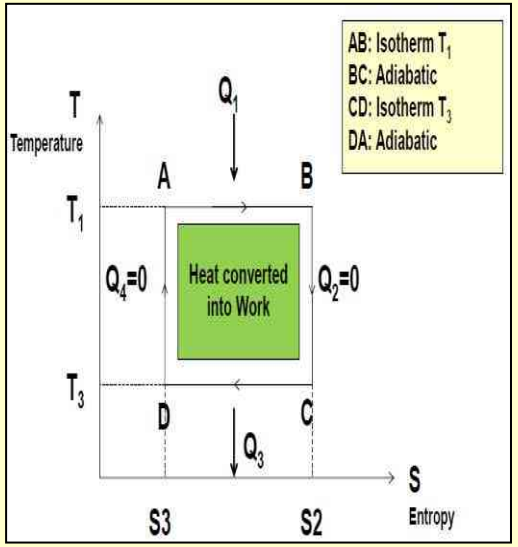


For a reversible Carnot cycle: $\Delta S_{tot.} = 0$

Suppose AB irreversible

$\Delta S_{syst.} = \Delta S_{AB} + \Delta S_{CD} = (Q_1/T_1)_{rev.} + (Q_3/T_3)_{rev.} = 0$
$\Delta S_{surr.} = \Delta S_{surr.AB} + \Delta S_{surr.CD} = -(Q_1/T_1)_{irr.} - (Q_3/T_3)_{rev.}$
$(Q_1/T_1)_{irr.} < (Q_1/T_1)_{rev.}$ (Clausius inequality)
Therefore, $\Delta S_{surr.} > 0$

For an irreversible cycle: $\Delta S_{tot.} > 0$



Entropy
The Entropy of the Universe tends to a maximum

- Inexorably, Nature should degenerate toward the state of greater disorder, greater Entropy.
- This seems contradictory with the observation of some phenomena in the current life, like the formation of galaxies, the existence of well organized systems, organisation of the human body metabolism, etc……
- Actually, Entropy can be lowered by external actions, like in a refrigerator in which temperature is lowered by means of thermodynamical equipment.
- But, this local increase in order is only possible at the expense of an Entropy increase in the surroundings, the global balance of Entropy being positive.

Entropy
Additional Formulas

$dU = \delta Q + \delta W = \delta Q - PdV$

$dS = \delta Q/T$

$dU = TdS - PdV$

For an Ideal Gas and for one mole: $PV = RT$

$TdS = dU + PdV = c_v dT + RTdV/V$

$dS = c_v dT/T + RdV/V \rightarrow S - S_0 = cv \int_{T_0}^{T} \frac{dT}{T} + R \int_{V_0}^{V} \frac{dV}{V} = cvLog(\frac{T}{T_0}) + RLog(\frac{V}{V_0})$

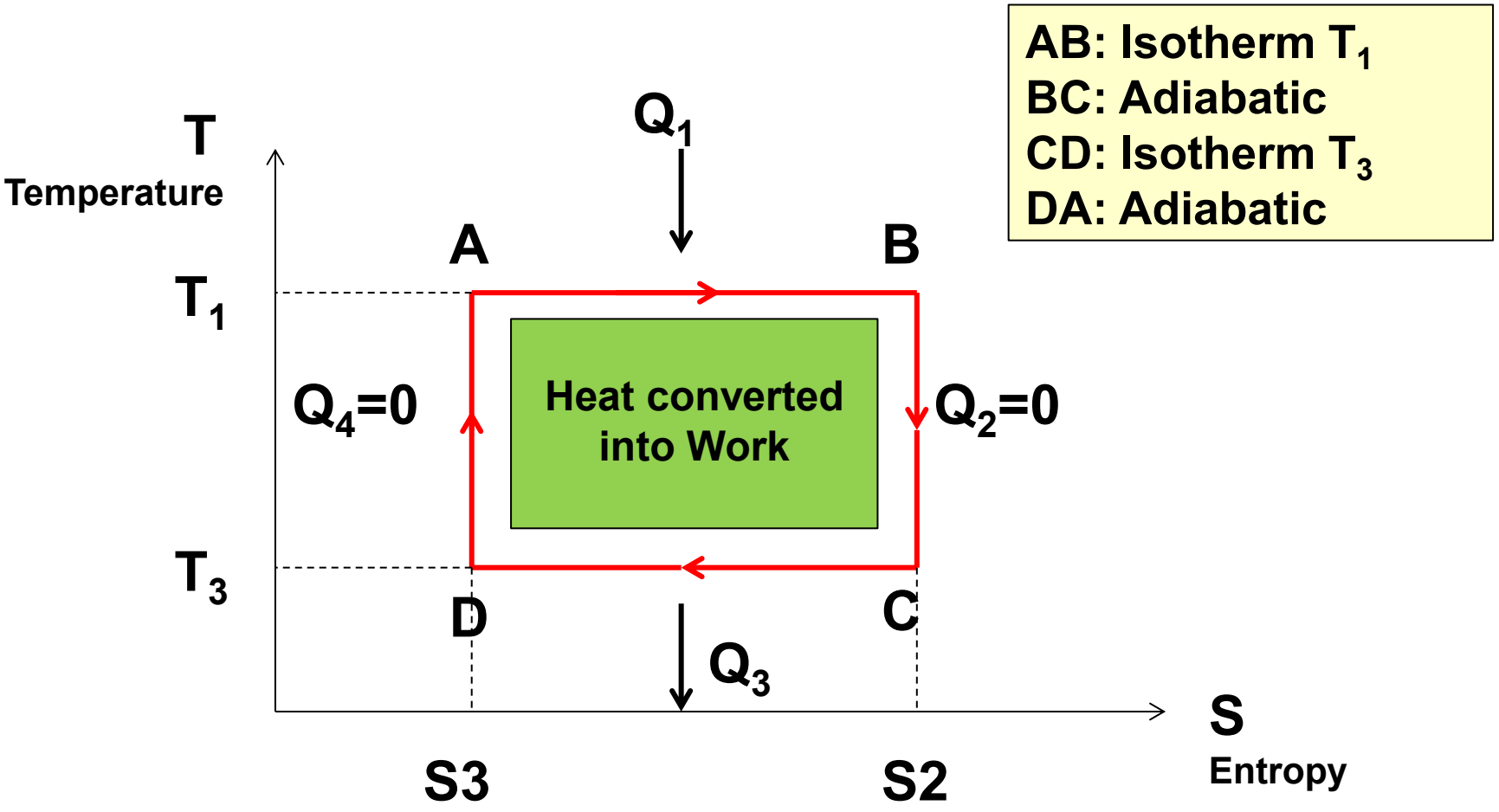
$dH = c_p dT = dU + PdV + VdP = TdS + RTdP/P$

$dS = c_p dT/T - RdP/P \rightarrow S - S_0 = cp \int_{T_0}^{T} \frac{dT}{T} - R \int_{P_0}^{P} \frac{dP}{P} = cpLog\left(\frac{T}{T_0}\right) - RLog(\frac{P}{P_0})$

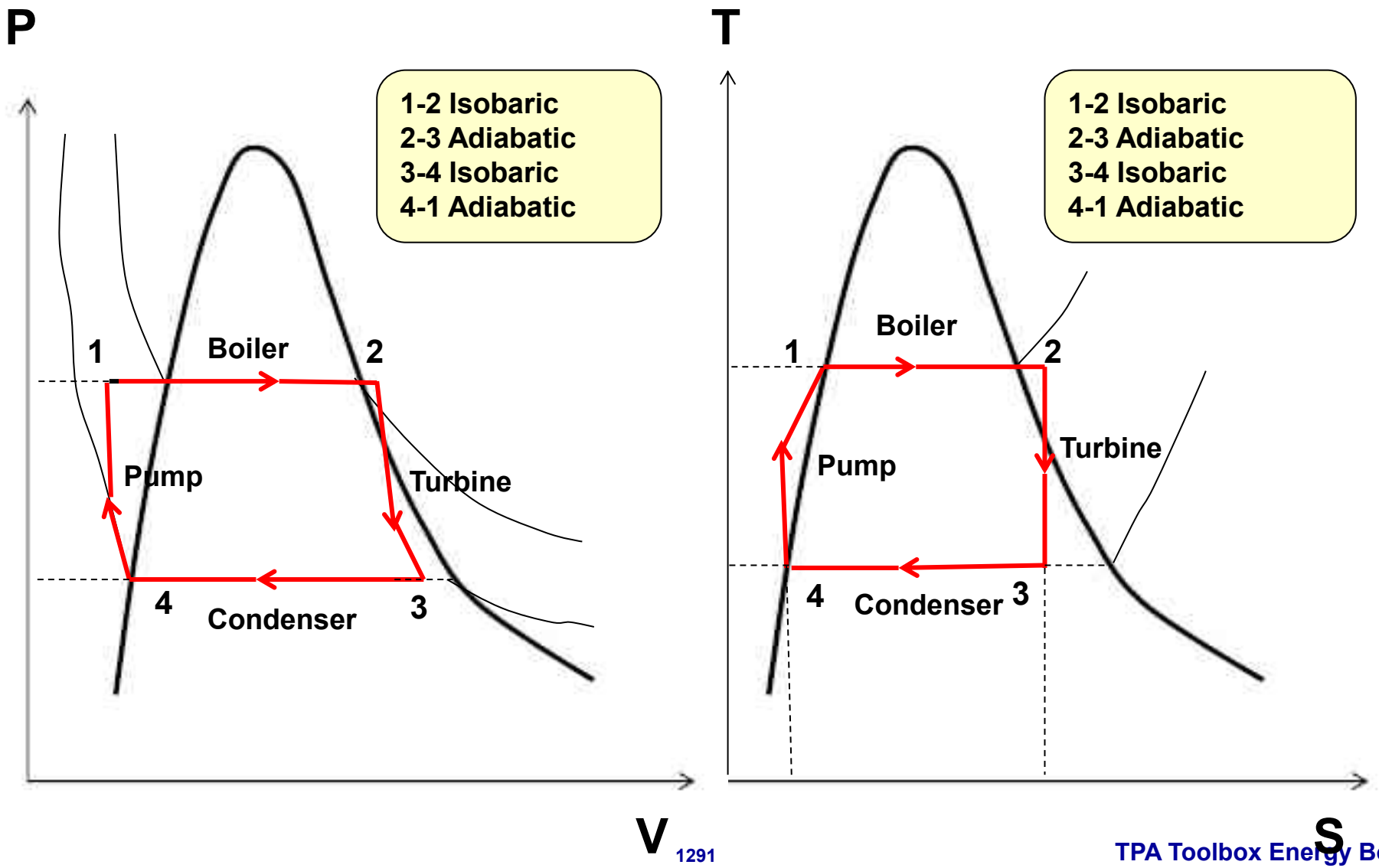
$dT/T = dP/P + dV/V \longrightarrow Log\left(\frac{T}{T_0}\right) = Log\left(\frac{P}{P_0}\right) + Log(\frac{V}{V_0})$

Thermodynamical Cycles can be expressed in PV ($W = - PdV$) and TS ($Q = TdS$) Diagrams

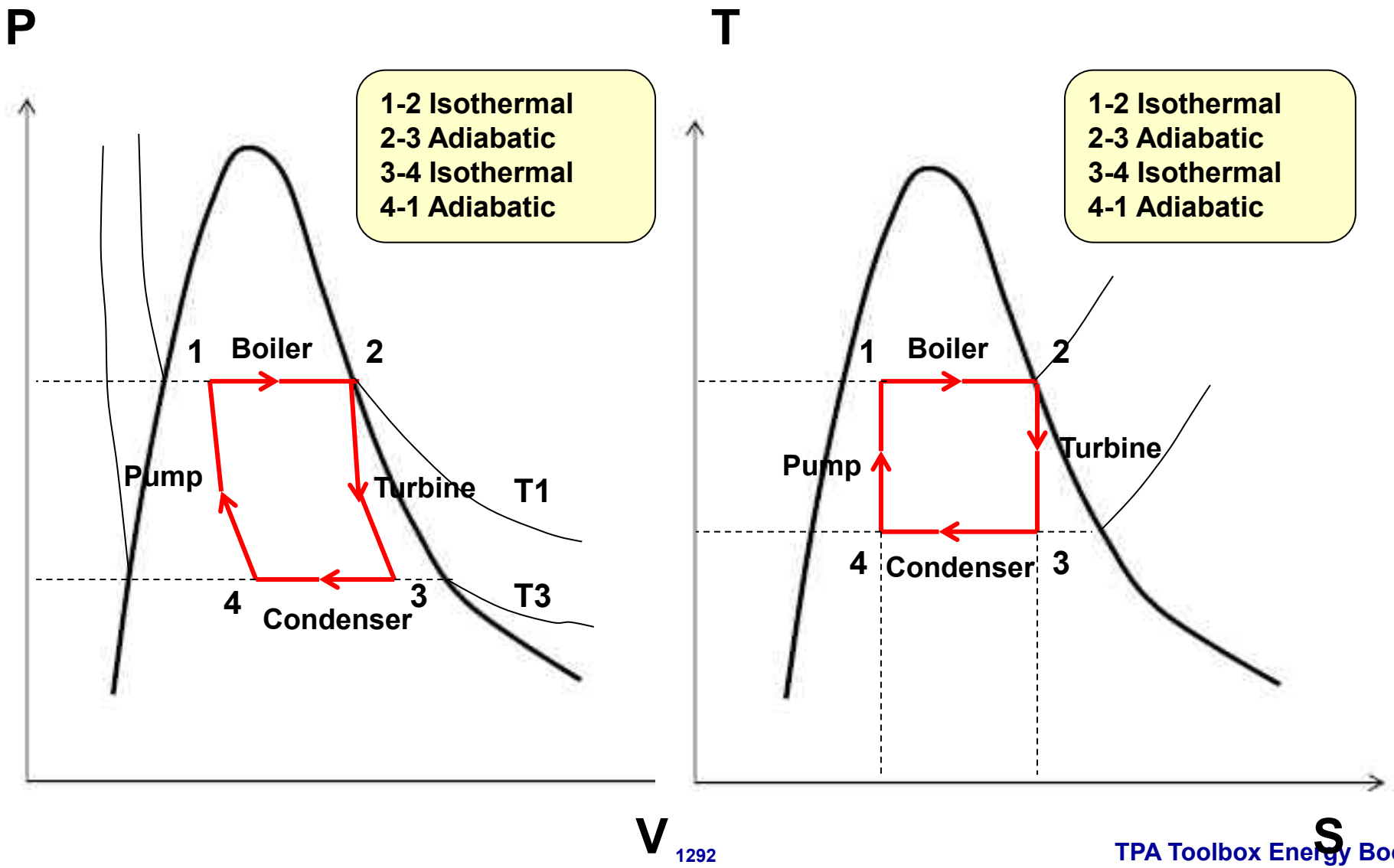
Carnot Cycle (TS Diagram)



Rankine Cycle in PV & TS Diagrams
Application to Steam Turbines



Carnot Cycle in PV & TS Diagrams
Application to Steam Turbines



Exergy

Exergy

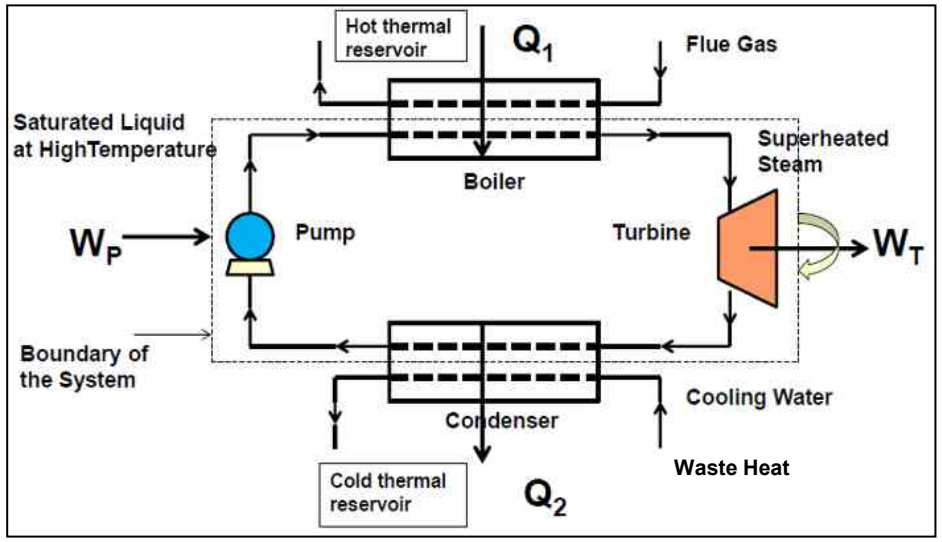
- 1st Law: Energy cannot be neither created nor destroyed. Any change of Energy of a System corresponds to a change of Energy of the Surroundings, so that the total Energy of the System plus the Surroundings remain constant.

- 2nd Law: In any transfer of conversion of Energy within a closed System, the Entropy of the System increases. The natural direction of Energy transfer or conversion is toward increasing Entropy, and all Energy transfers or conversions are irreversible. One has to differentiate quantity of Energy and quality or worth value of Energy.

- Exergy is the maximum usable energy or work in a System during a process that lead to an equilibrium with the System Surroundings.

- Exergy is the opposite of Entropy. A gain of Entropy corresponds to a loss of Exergy

Energy Flow vs Exergy Flow







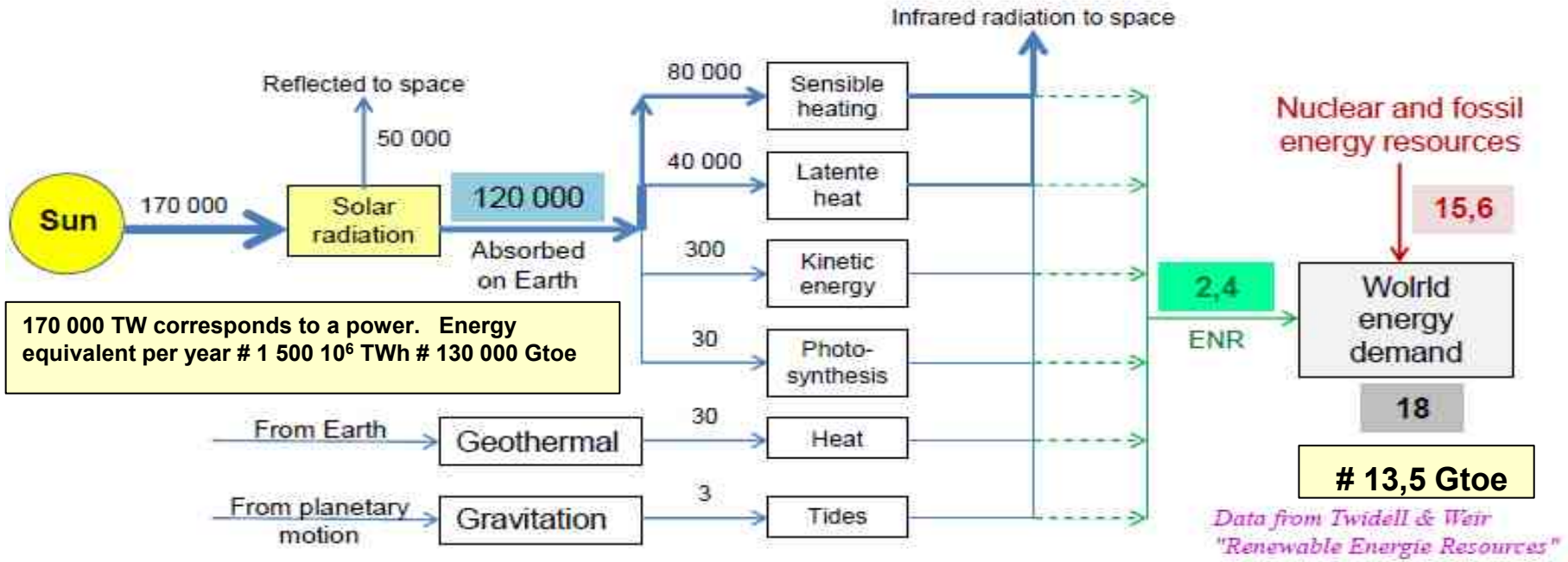


Exergy

Energy is abundant. Energy Efficiency could be greater improved

The Earth Energy balance, in terawatt

(1 terawatt = energy flux equal to the production of 1000 power stations of 1000 MW each and corresponds to about 750 Mtoe/year)



170 000 TW corresponds to a power. Energy equivalent per year # 1 500 10^6 TWh # 130 000 Gtoe

The concern about how to meet the world energy demand is not a matter of quantity available.
It results from a major discrepancy from a qualitative point of view
between energy as available and energy as needed.

Source: Jean-Bernard Sigaud 2017

Exergy

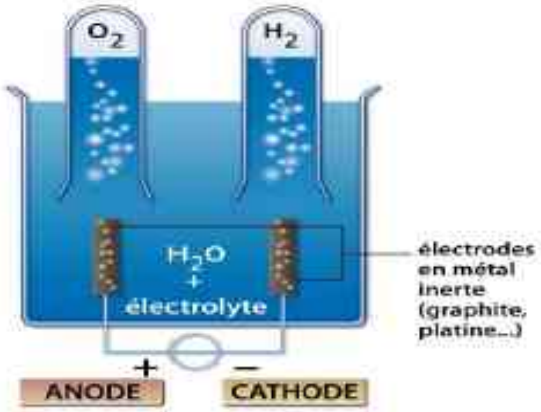
Any Energy conversion generates gain in Entropy and loss in Exergy

Any conversion of energy results in a drop of exergy

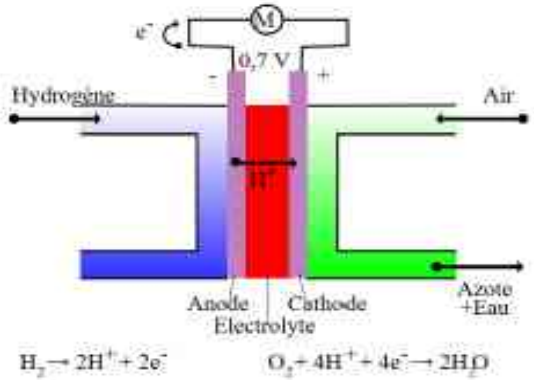
On the one hand, part of the initial amount of energy is released as heat

Examples :

"Energy loss" = 30 to 50 % in the case of electrolysis
(conversion of electricity into chemical energy as H_2)



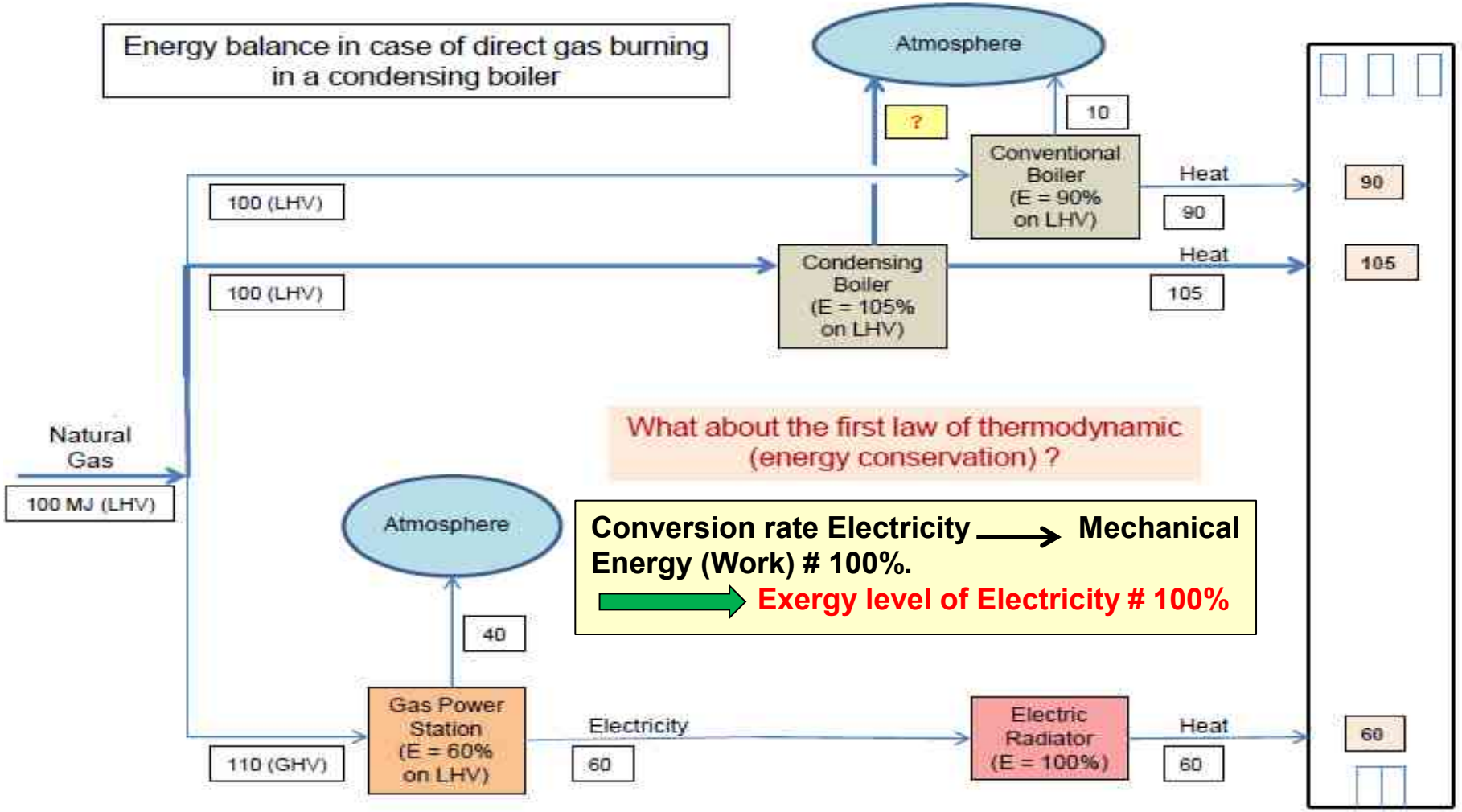
And 40 to 50 % in the case of a fuel cell
(reverse operation)



On the hother hand, it is impossible to convert entirely this heat into work *(Carnot law)*

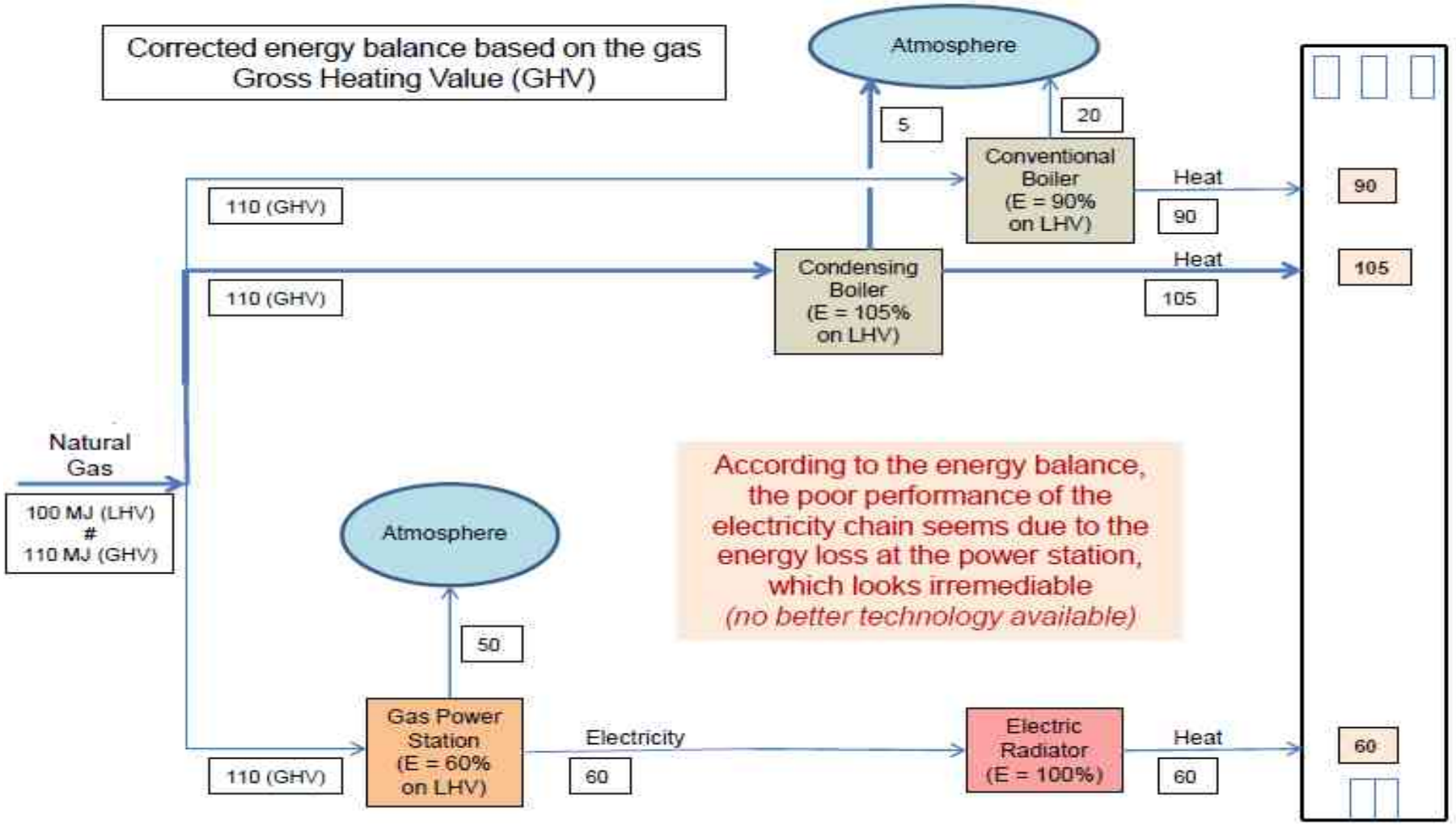
Exergy can be seen as the reverse of entropy
but with the advantage of being more easily usable in practice.

Exergy
Direct Heating with Gas better than Electricity



Source: Jean-Bernard Sigaud 2017

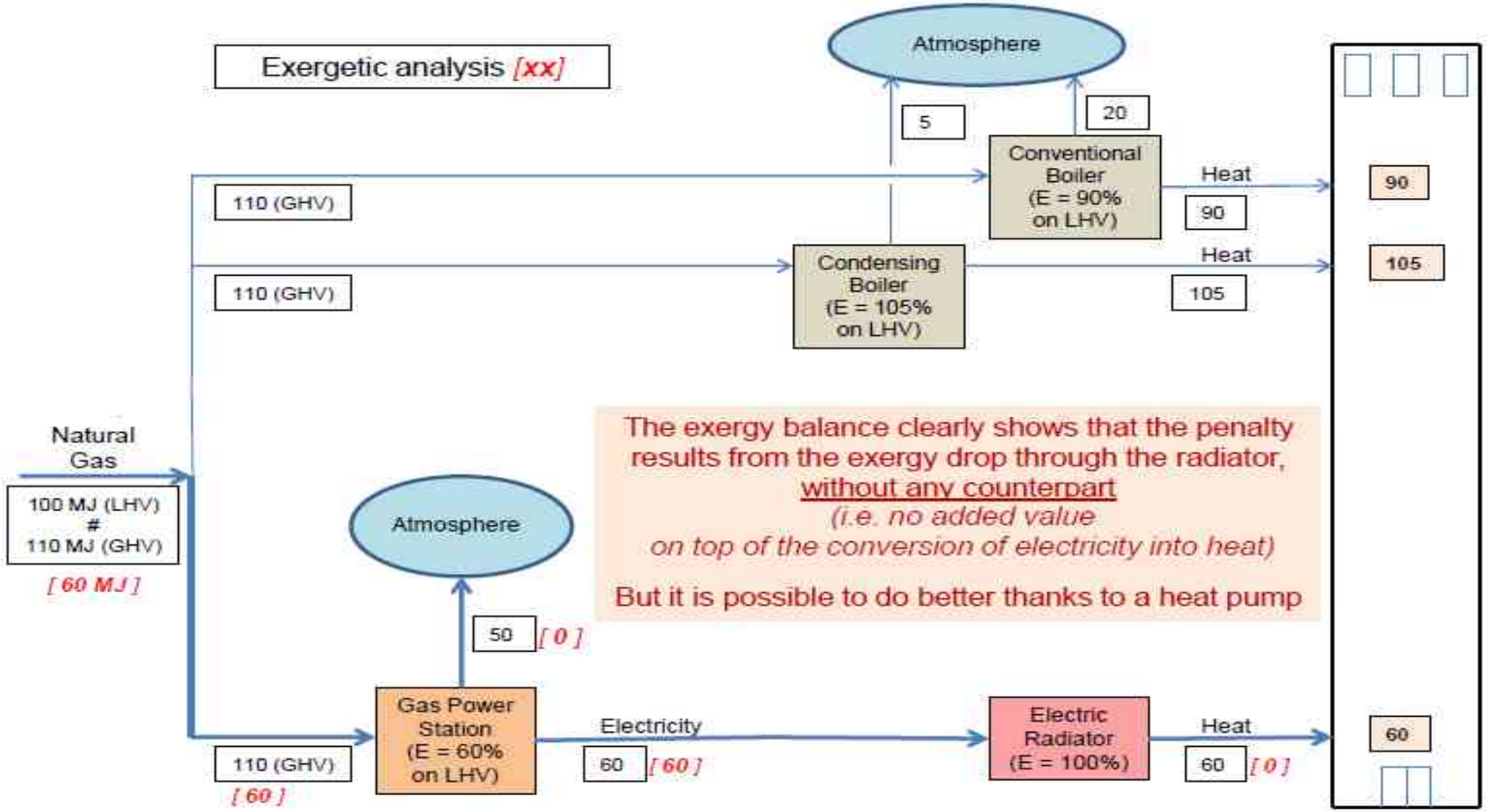
Exergy
Direct Heating with Gas better than Electricity



Source: Jean-Bernard Sigaud 2017

Exergy (Electricity → Heat)

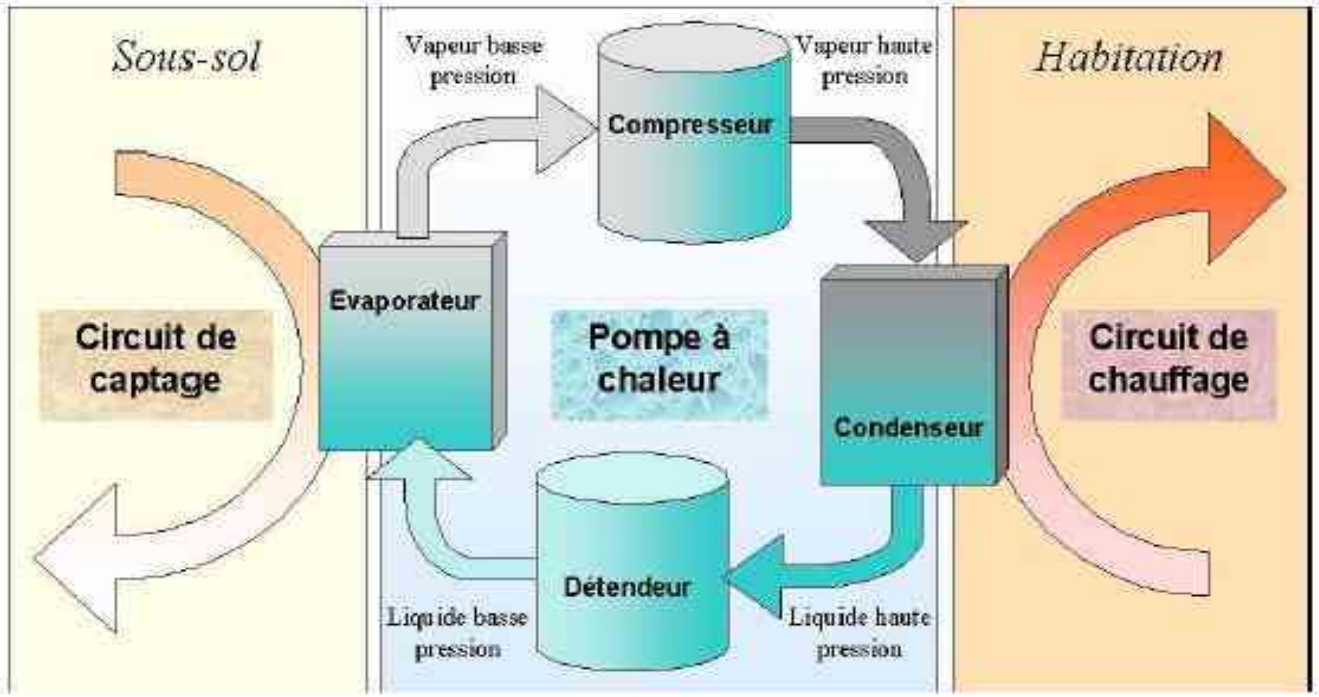
Exergy coming out from the Power Plant doesn't generate any work : Exergy is lost



Source: Jean-Bernard Sigaud 2017

Exergy
Interest of the Heat Pump – Thermal Efficiency > 1

Conceptual scheme of a Heat Pump
(based on the frigorific cycle principle)



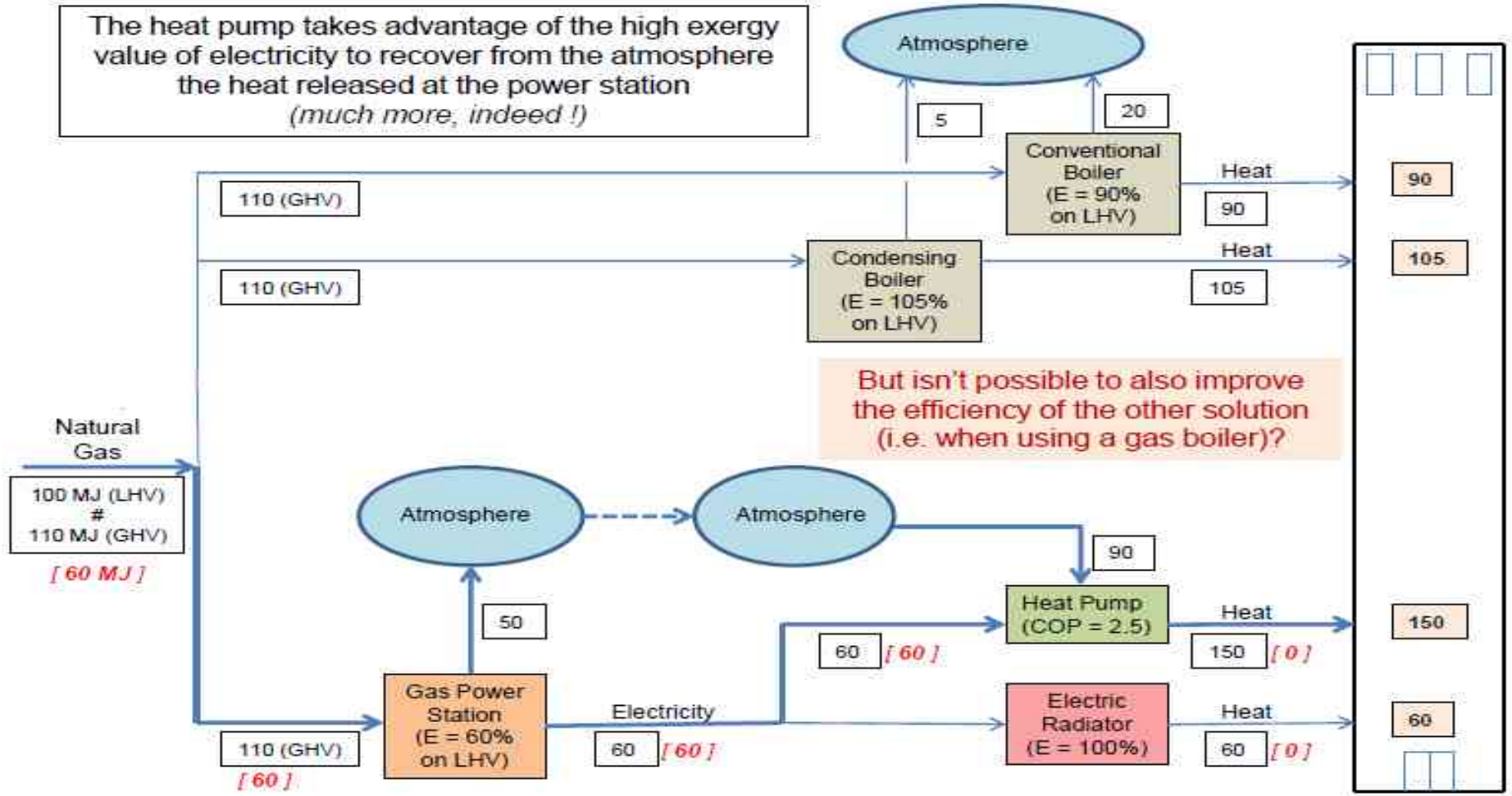
Source Wikipédia

A heat pump may release 2 to 3 kWh of heat par kWh of electricity under standard operating conditions

The ratio "heat released /electricity consumed" is called «Coefficient Of Performance» (COP)

Exergy

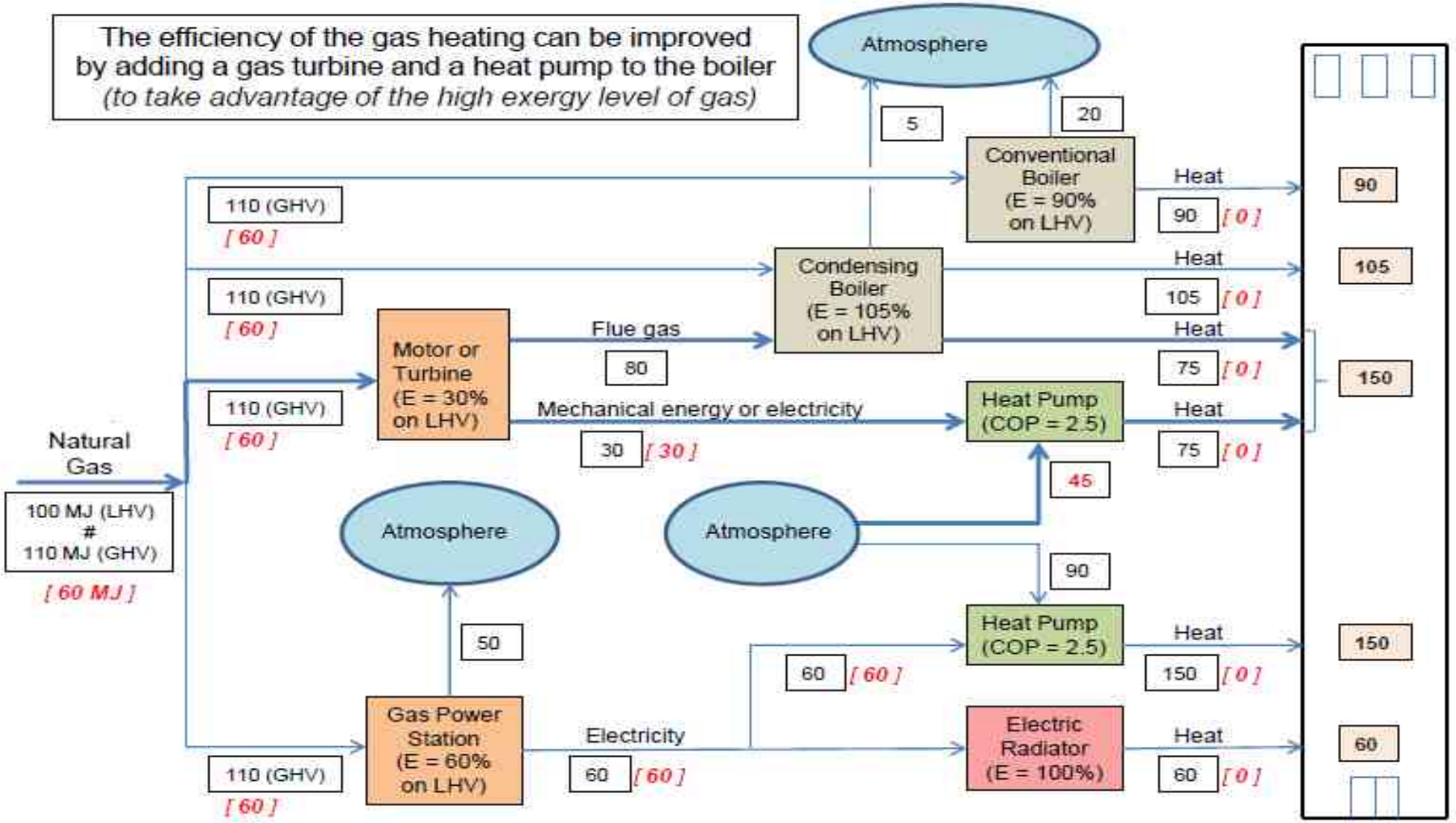
Coupling Electrical Heating with a Heat Pump improves significantly the Exergy Efficiency (Additional Work generated)



Source: Jean-Bernard Sigaud 2017

Exergy

Coupling Electrical Heating with relevant additional systems can improve significantly the Exergy Efficiency (Additional Work generated)



Source: Jean-Bernard Sigaud 2017

Exergy

- The Exergy (Quality of Energy) flow can be drastically improved in Energy production Systems by optimizing the components of the System.

- This consideration must be completed by an economic analysis regarding the profitability of the overall System (Benefits vs Costs)

22

Equivalences and conversion factors

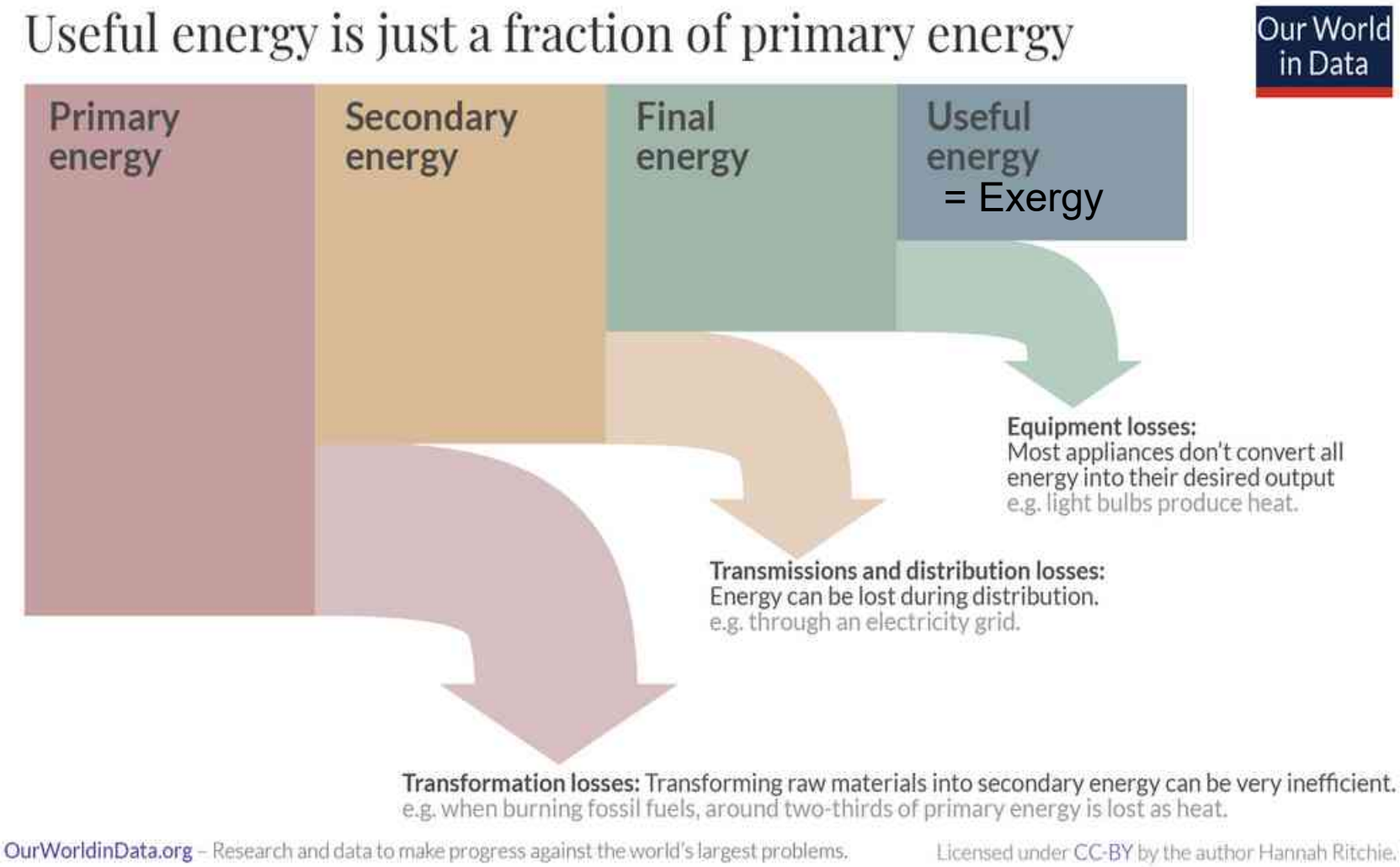
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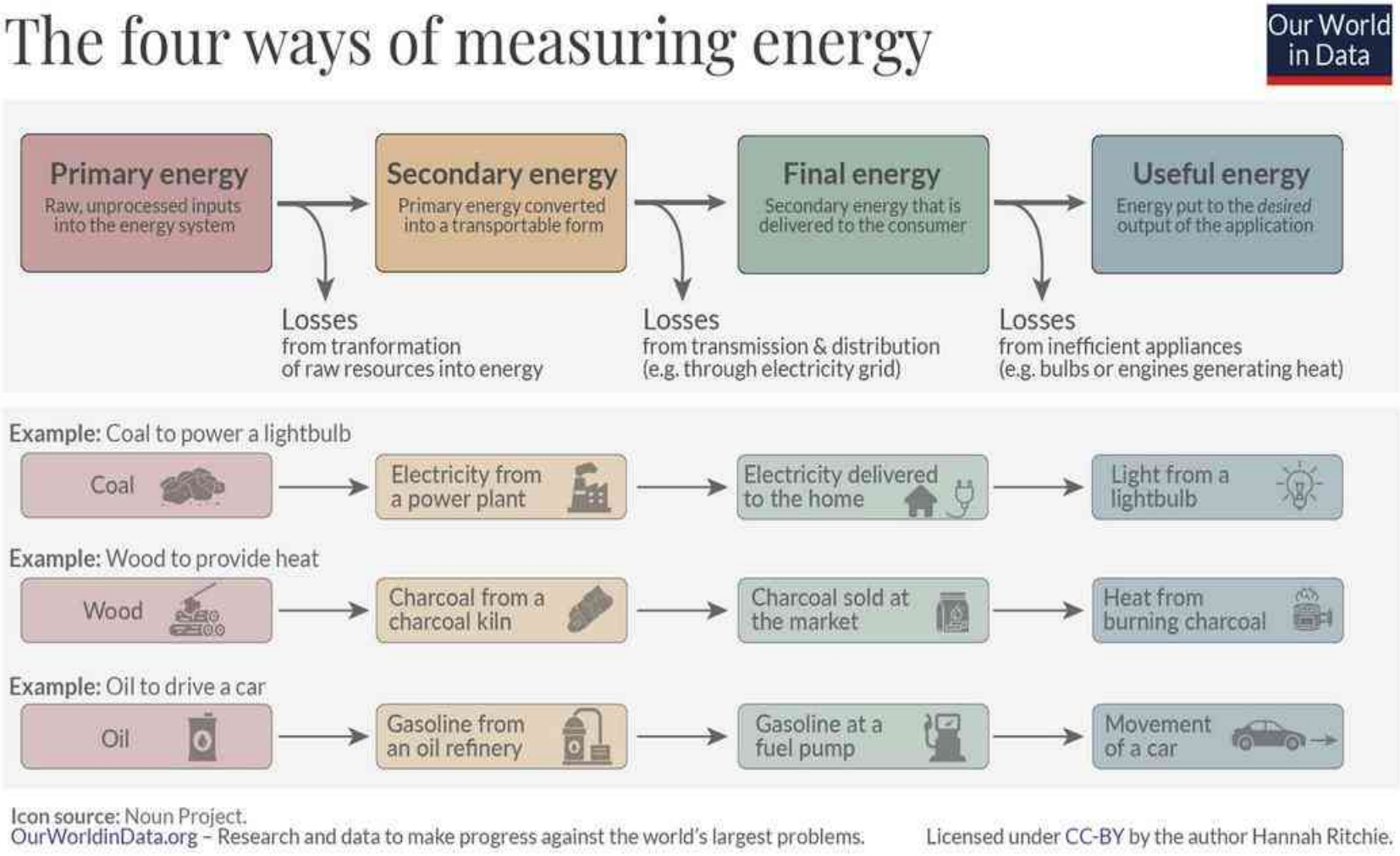
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Different ways of measuring Energy
Conversion factors for Energy may differ vs sources



Source: Our World in Data – Hannah Ritchie
https://ourworldindata.org/energy-substitution-method

Different ways of measuring Energy
Conversion factors for Energy may differ vs sources



Source: Our World in Data – Hannah Ritchie
https://ourworldindata.org/energy-substitution-method

Direct Primary Energy vs « Substitution Primary Energy »

Energy from fossil fuels - coal, oil and gas & uranium - are usually measured as Primary Energy. This represents the amount of energy that is generated when they are burned in their raw form in power plants. This a combustion process, a fission one for nuclear plants.
A large amount of this raw energy is wasted as heat. Typical fossil fuels fired power plants have an efficiency ratio of between 33% and 45%. Only between one-third and 45% generates electricity, and the other part is wasted as heat. The same applies for nuclear plants.
How to treat energy processes for non-fossil sources of energy & electricity?

One can apply the «Substitution method » . This tries to adjust non-fossil energy sources to the inputs that would be needed if it was generated from fossil fuels. It assumes that wind and solar electricity is as inefficient as coal, gas, or nuclear.
Non-fossil electricity generation could therefore be divided by a «thermal efficiency factor » , which is the average efficiency of fossil electricity. This factor can changed over time due to changes in the composition of the fossil fuel mix and efficiency improvements in power plants over time.

The «Substitution method » is used by Energy Institute (EI, which took over the works done previously by BP) in their yearly report « Statistical Review of World Energy » which various elements are reported in Our World in Data publications.
International Energy Agency (IEA) uses different methods for converting Renewable Energy electricity into Primary Energy (using in particular the Thermal equivalent by Joule effect) These methods are internationally recognized.

In the TPA Toolbox Energy, TPA is applying conversion factors and equivalences defined by International Energy Agency (IEA)

Basic Equivalences and Conversion Factors

M = Million = Mega = 10^6
B = Billion = G = Giga = 10^9
T = Trillion = Tera = 10^{12}
P = Quadrillion = Peta = 10^{15}
E = Quintillion = Exa = 10^{18}

1 barrel = 0,159 m^3 # 6 MBtu
1 cf (cubic feet) gas = 0,02832 m^3
1 cal (calorie) = 4,1868 J (Joule)
1 Btu (British thermal unit) = 1 055 J

1 toe (tonne oil equivalent) # 7,3 barrel
1 b/d # 50 t/year
1 toe # 41,868 GJ # 10 Gcal # 39,68 MBtu
1 000 m3 gas # 0,86 toe
1 t coal # 0,70 tce (tonne coal equivalent) # 0,49 toe
1 t bioethanol # 0,64 toe
1 t biodiesel # 0,86 toe

Power expressed in W (Watt) (International system)
Energy expressed in Wh (Watt x hour) (International system)

Nota: Large numbers expressed in Short Scale Values (SS)

Some conversion factors for the Gas Industry

- 1 cubic feet = 0,02832 m^3
- 1 Btu = 1 055 J
- 1m^3 # 38 000 Btu
- 1 boe # 6 Mbtu
- 1t LNG # 2220 m^3 LNG # 1360 sm^3 Natural Gas
- 1m^3 LNG # 615 sm^3 Natural Gas
- 1000 sm^3 Natural Gas # 0,86 toe

Conversion factors used by IEA – International conventions

General conversion factors for energy

		Multiplier to convert to:					
		EJ	Gcal	Mtoe	MBtu	bcme	GWh
Convert from:	EJ	1	2.388×10^{8}	23.88	9.478×10^{8}	27.78	2.778×10^{5}
	Gcal	4.1868×10^{-9}	1	10^{-7}	3.968	1.163×10^{-7}	1.163×10^{-3}
	Mtoe	4.1868×10^{-2}	10^{7}	1	3.968×10^{7}	1.163	11 630
	MBtu	1.0551×10^{-9}	0.252	2.52×10^{-8}	1	2.932×10^{-8}	2.931×10^{-4}
	bcme	0.036	8.60×10^{6}	0.86	3.41×10^{7}	1	9 999
	GWh	3.6×10^{-6}	860	8.6×10^{-5}	3 412	1×10^{-4}	1

Note: There is no generally accepted definition of barrel of oil equivalent (boe); typically the conversion factors used vary from 7.15 to 7.40 boe per tonne of oil equivalent. Natural gas is attributed a low heating value of 1 MJ per 44.1 kg. Conversions to and from billion cubic metres of natural gas equivalent (bcme) are given as representative multipliers but may differ from the average values obtained by converting natural gas volumes between IEA balances due to the use of country-specific energy densities. Lower heating values (LHV) are used throughout.

Conversion Factors for Energy (International conventions)

Conversion factor for energy based on LCV (Low Calorific Value)

	Oil	Heavy Fuel	Natural Gas	LNG	Hard Coal	Hard Coal Coke	Hard Coal Anthracite	Brown Coal Lignite	Wood				
	1 Mtoe	1Mt	1 Bm3	1 MtLNG	1 Mt	1Mt	1Mt	1Mt	1Mt	1 TJ	1 Gcal	1 MBtu	1 Gwh
1 Mtoe	1,00	1,05	1,16	0,91	1,61	1,50	1,31	1,55	2,30	41868	1,00E+07	3,97E+07	11632
1Mt Heavy Fuel	0,96	1,00	1,11	0,87	1,54	1,43	1,25	1,48	2,20	40000	9,56E+06	3,79E+07	11113
1 Bm3 Natural Gas	0,86	0,90	1,00	0,78	1,38	1,29	1,13	1,33	1,98	36000	8,60E+06	3,41E+07	10001
1 MtLNG	1,10	1,15	1,28	1,00	1,77	1,64	1,44	1,70	2,53	46000	1,10E+07	4,36E+07	12779
1Mt Hard Coal	0,62	0,65	0,72	0,57	1,00	0,93	0,81	0,96	1,43	26000	6,21E+06	2,46E+07	7223
1Mt Coke/Hard Coal	0,67	0,70	0,78	0,61	1,08	1,00	0,88	1,04	1,54	28000	6,69E+06	2,65E+07	7779
1Mt Anthracite/Hard Coal	0,76	0,80	0,89	0,70	1,23	1,14	1,00	1,19	1,76	32000	7,65E+06	3,03E+07	8890
1Mt Lignite/Brown Coal	0,64	0,68	0,75	0,59	1,04	0,96	0,84	1,00	1,48	27000	6,45E+06	2,56E+07	7501
1Mt Wood	0,43	0,46	0,51	0,40	0,70	0,65	0,57	0,67	1,00	18200	4,35E+06	1,73E+07	5056
1 TJ	2,39E-05	2,50E-05	2,78E-05	2,17E-05	3,85E-05	3,57E-05	3,13E-05	3,70E-05	5,49E-05	1,00	239	948	0,278
1 Gcal	1,00E-07	1,05E-07	1,16E-07	9,10E-08	1,61E-07	1,49E-07	1,31E-07	1,55E-07	2,30E-07	4,186E-03	1,00	3,967	1,16E-03
1 MBtu	2,52E-08	2,64E-08	2,93E-08	2,29E-08	4,06E-08	3,77E-08	3,30E-08	3,91E-08	5,80E-08	1,055E-03	0,252	1,00	2,93E-04
1 GWhtherm.	8,60E-05	9,00E-05	1,00E-04	7,83E-05	1,38E-04	1,29E-04	1,12E-04	1,33E-04	1,98E-04	3,60	860	3412	1,00
Electricity Vector													
1GWhe Hydro/Wind/PV	8,60E-05									3,60			
1GWhe Nuclear	2,61E-04									3,60			
1GWhe Geothermal	8,60E-04									3,60			

Conversion Factors for Electricity - MWh/toe (International conventions)

To evaluate primary energy generating electricity (Based on Net Calorific Value – NCV):

- For nuclear energy, one adopt the primary energy content at production using a power plant with an efficiency ratio of 33%.
  1 MWh = 0,260606 toe (0,086/0,33)

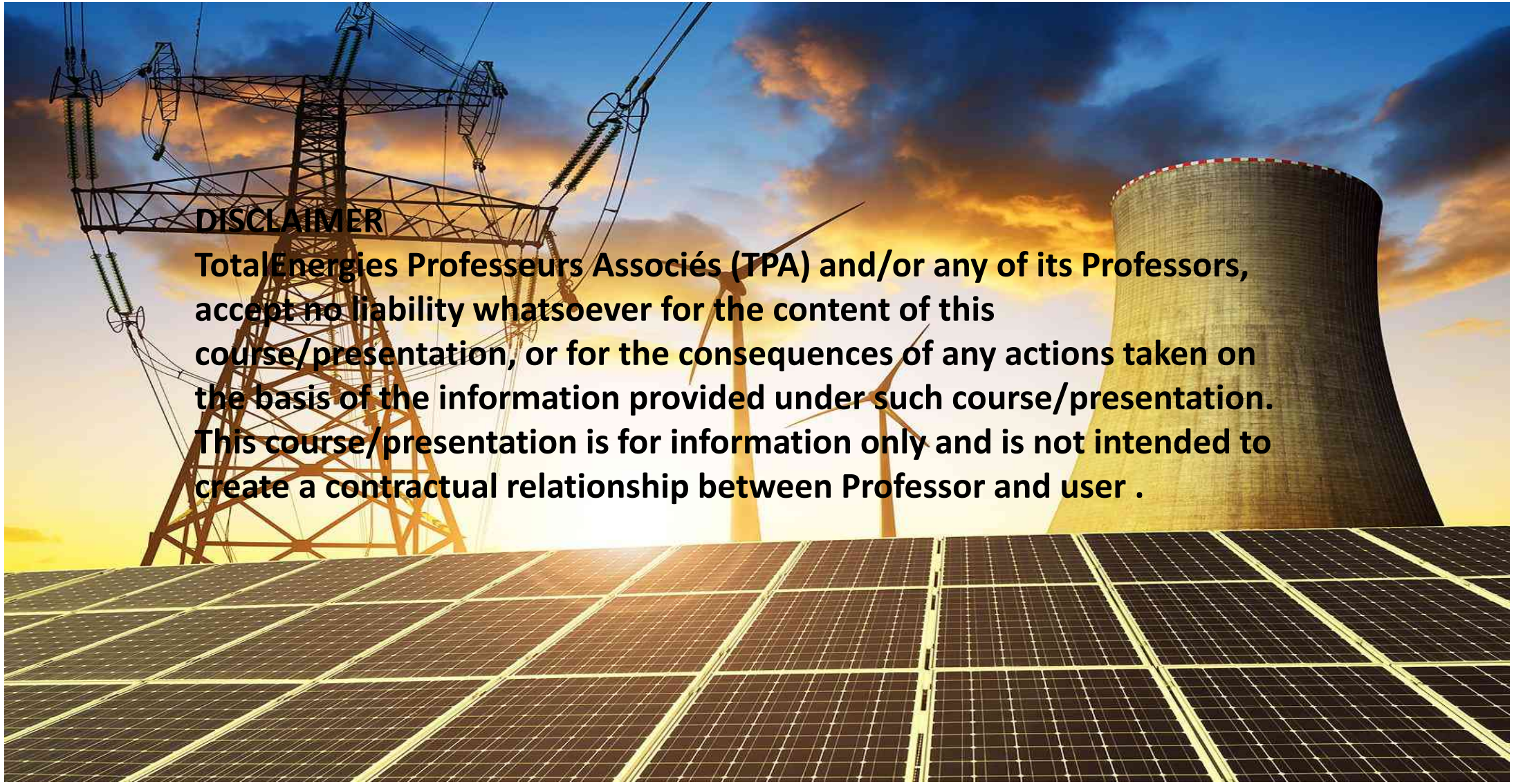
- For geothermal electricity, one adopt the primary energy content at production, with an efficiency ratio of 10%.
  1MWh = 0,86 toe (0,086/0,10)

- For geothermal heat, one adopt the primary energy content at production, with an efficiency ratio of 50%.
  1MWh = 0,172 toe (0,086/0,50)

- For renewable energies (Hydro, solar, wind, marine….) producing electricity without thermodynamic cycle, one adopt the energy content of the electricity (thermal equivalent by Joule effect)
  1 MWh = 0,086 toe

Electricity Generation: Equivalences for Primary Energy

	Primary Energy			Assumed average Conversion Efficiency & Final Consumption	
Oil	0,086 toe	1 MWh		33%	0,33 MWhe
Gas	0,100 toe	1 MWh		37%	0,37 MWhe
Coal	0,130 toe	1 MWh		33%	0,33 MWhe
Hydro	0,086 toe	1 MWh		100%	1,00 MWhe
Solar/Wind	0,086 toe	1 MWh		100%	1,00 MWhe
Nuclear	0,261 toe	3 MWh		33%	1,00 MWhe
Geothermal	0,860 toe	10 MWh		10%	1,00 MWhe



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