OpenMinds

Confronting the Dual Challenge: Emerging Solutions

September 2023

An overview of OpenMinds and the Dual Challenge

The Dual Challenge

Affordable, reliable energy is the foundation upon which modern civilization rests. From the electricity used to light our homes to the fuels used in cars and planes to the energy needed to produce the fertilizer necessary to grow our food, energy is integral to everything we do. The massive expansion of primary energy supply since the nineteenth century has driven an unprecedented improvement in human longevity and prosperity. However, today, there is still considerable energy inequality: 2.4 billion people lack access to clean cooking fuels, and more than 700 million lack access to electricity. Future population growth will be overwhelmingly concentrated in these regions. The world needs more energy.

But our largest primary energy sources, fossil fuels, are also the largest sources of anthropogenic greenhouse gas emissions. Fossil fuels account for nearly 80% of our primary energy supply, and our reliance on them has not changed appreciably in 30 years. Rising greenhouse gas concentration in the atmosphere produced in large part by the combustion of fossil fuels is causing the planet to warm, and there is now widespread scientific evidence that adverse consequences to human prosperity and wellbeing will likely result if this warming trend continues.

The tension between energy supply and climate change presents a "Dual Challenge" for the 21st century. How do we affordably and reliably supply ever more energy while simultaneously reducing greenhouse gas emissions to limit future warming?

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OpenMinds is an association of business, academic, and political leaders from a range of backgrounds, geographies, and political affiliations.

The group was originally established by David Baldwin and Jeff Katz in 2018 to convene small, diverse groups of critical-thinking experts, with open minds, to discuss and debate in a non-partisan manner solutions to society's biggest challenges and opportunities.

We began work on the Dual Challenge in 2021. Our efforts in 2021 and 2022 culminated in the creation of a balanced, pragmatic definition of the challenge, supported by a detailed fact base.

This year, our focus is on solutions. We are seeking to create a realistic and actionable plan that optimizes for both energy and emissions, and we are collaborating with Bain & Company to develop that work.

OpenMinds' 2022–2023 Mission

We will convene a diverse team of climate and energy experts to create, debate, and refine in a non-partisan way the best combination of policies, practices, innovations, communications, and capital flows to expand energy access and by "203X" accelerate the reduction of anthropogenic greenhouse emissions without unduly limiting global economic growth and development

Our deliverables will be:

i. **Definition:** A data set which supports a balanced and clear understanding of the global "Dual Energy & Climate Challenge".

ii. **Solutions:** An integrated set of recommendations drawing from the experience and knowledge of our experts for successfully addressing the "Dual Challenge", including proposed actions for both (a) medium term (2030), and (b) longer term (2050) success.

iii. **Communications:** An array of communication tools and channels intended to reach and influence a broad audience towards strategic action.

A note on these materials

Click to access more information about the Dual Challenge

Focus of this deck

The purpose of this document is to outline our approach to developing and prioritizing solutions to the Dual Challenge. Please reference our definitions deck for further background detail on the Dual Challenge. **Our intent is for this to be accessible to anyone**, even those with no prior knowledge of energy or climate change.

In preparing these materials, **we drew from a range of sources**, including the IPCC's Sixth Assessment Report, the International Energy Agency, BP's Statistical Review of World Energy, the Global Carbon Project, and others.

We assessed possible solutions through a comprehensive framework that considers measures of technological and economic readiness, along with a range of other factors. Feasibility at a regional level was also a fundamental consideration.

Section 1 (Approach) and **Section 2 (Framework)** cover the approach to identify and prioritize possible solutions and ultimately select our top 10 global solutions.

Section 3 (Top 10 overview) and **Section 5 & 6 (Appendix A & B)** provide an overview on the top 10 prioritized solutions and offer additional detail on the current state and opportunities.

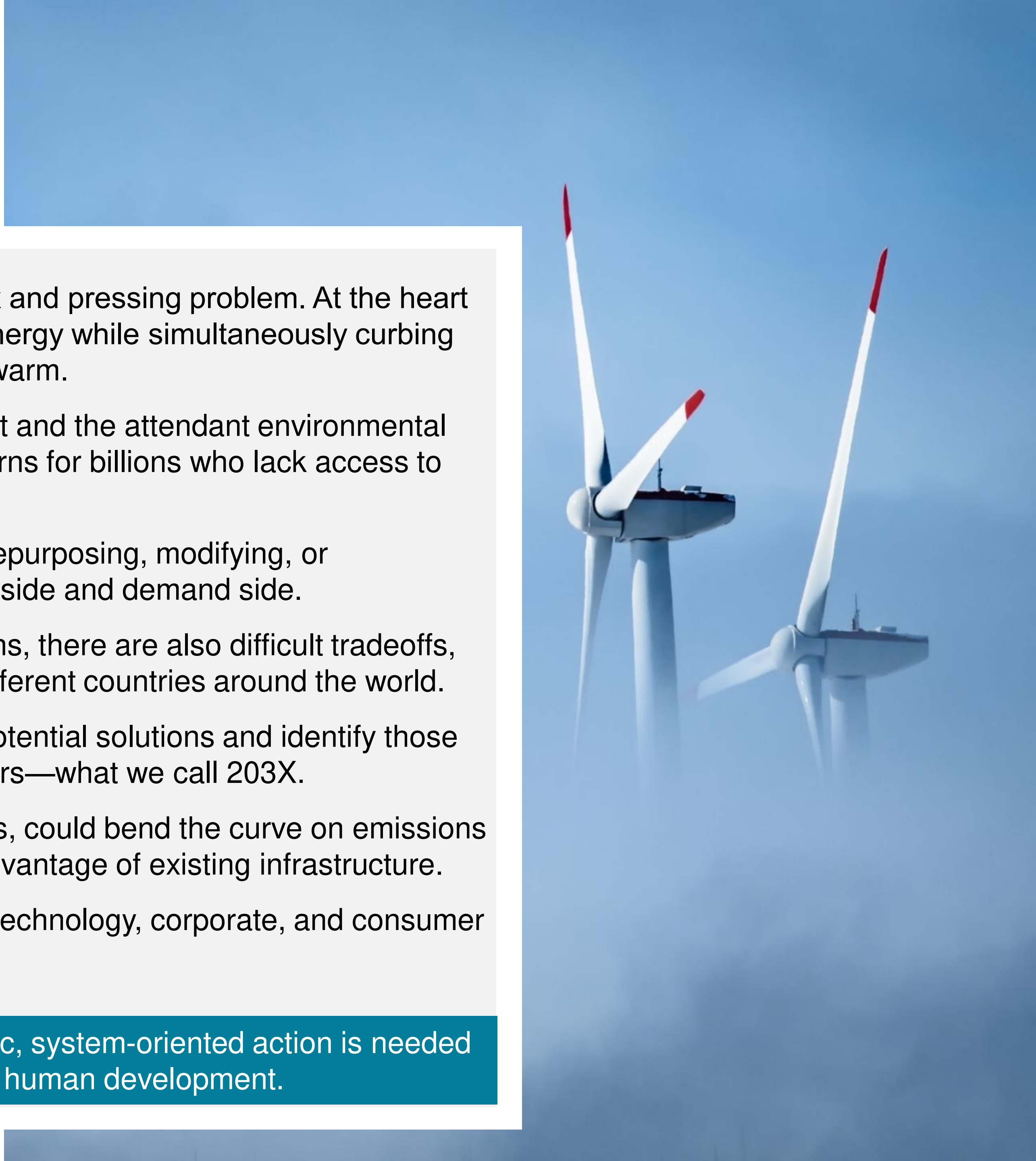
Section 4 (Country archetypes) details differences in how countries make decisions with respect to climate and energy and how that impacts potential solutions.

It will take a global, "all of us" effort to address the Dual Challenge. **We hope these materials convey the importance of attending to the physical realities of both energy and climate, alongside the world's economic and development needs, as we seek solutions.**

Executive Summary

- The Dual Challenge of energy & climate is the world's most complex and pressing problem. At the heart of it: we need to increase the world's supply of affordable, reliable energy while simultaneously curbing energy-related greenhouse emissions that are causing the earth to warm.
- The cost of failure in either direction is high: a rapidly warming planet and the attendant environmental risks; or stifled economic progress and lingering quality-of-life concerns for billions who lack access to modern energy services.
- Fundamentally, addressing the Dual Challenge involves replacing, repurposing, modifying, or augmenting huge portions of our energy system, on both the supply side and demand side.
- We need to act with urgency. While there are many potential solutions, there are also difficult tradeoffs, and we must consider the resources, priorities, and challenges of different countries around the world.
- To that end, we developed a comprehensive framework to assess potential solutions and identify those with the highest impact potential globally through the next 10-15 years—what we call 203X.
- We believe these solutions, if adopted at realistic but aspiration rates, could bend the curve on emissions by 203X, while working with the grain of market forces and taking advantage of existing infrastructure.
- Accelerating adoption of these solutions will require a mix of policy, technology, corporate, and consumer actions and innovation.

Addressing the Dual Challenge will require an all-of-us effort. Pragmatic, system-oriented action is needed to curb emissions while expanding energy supply to support continued human development.



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Our approach to solutions development is systematic and focused on identifying pragmatic actions

1 Identify largest opportunity zones

Understand energy sources, consumption patterns, and emissions to spot crucial action areas

2 Evaluate potential solutions

Identify and systematically evaluate a long list of potential technical solutions

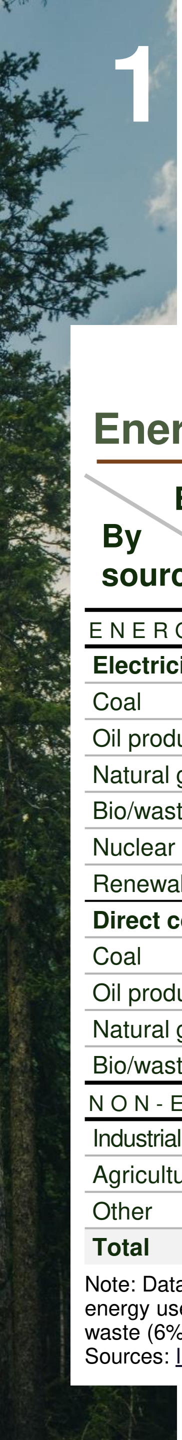
3 Determine the top 10 global solutions

Identify the solutions with the highest potential for impact through 203X and actions required to drive adoption

4 Incorporate regional context

Assess solution feasibility at a country-level, based on varying resources and priorities, to calibrate deployment rates

Accelerate progress against the Dual Challenge by 203X



We first identify the largest opportunity areas based on emissions and energy consumption analysis

Energy and Emissions

By end use / By source	Industry: Iron/steel, (petro)chemical, machinery, construction, etc.			Transport: Road, aviation rail and pipeline			Buildings: Residencial and commercial buildings			Agriculture: Agriculture and fishing			Other: Non-specified and non-energy sources			Total	
	Energy	Emission	En/Em	Energy	Emission	En/Em	Energy	Emission	En/Em	Energy	Emission	En/Em	Energy	Emission	En/Em	Energy	Emission
ENERGY																	
Electricity/heat	**18%**	**12%**	**-**	**<1%**	**0%**	**-**	**20%**	**12%**	**-**	**1%**	**1%**	**-**	**2%[1]**	**7%[2]**	**-**	**42%**	**32%**
Coal	8%	8%	● Low	<1%	0%	● Low	9%	8%	● Low	<1%	<1%	● Low	<1%	5%	● Low	18%	21%
Oil products and oil	<1%	<1%	● Moderate	-	-	-	<1%	<1%	● Moderate	-	-	-	-	-	-	<1%	1%
Natural gas	4%	3%	● Moderate	-	-	-	5%	3%	● Moderate	-	-	-	<1%	1%	● Moderate	10%	7%
Bio/waste[6]	<1%	<1%	● Low	-	-	-	1%	<1%	● Low	-	-	-	-	-	-	2%	2%
Nuclear	3%	<1%	● Moderate	-	-	-	3%	<1%	● High	-	-	-	-	-	-	6%	<1%
Renewables[7]	2%	<1%	● Moderate	-	-	-	2%	<1%	● High	-	-	-	<1%	<1%	● High	5%	<1%
Direct combustion	**14%**	**13%**	**-**	**22%**	**17%**	**-**	**14%**	**6%**	**-**	**<1%**	**<1%**	**-**	**8%[3]**	**7%[4]**	**-**	**58%**	**44%**
Coal	6%	6%	● Low	-	-	-	1%	<1%	● Moderate	-	-	-	<1%	1%	● Low	7%	7%
Oil products and oil	2%	2%	● Low	20%	16%	● Moderate	2%	1%	● Moderate	<1%	<1%	● Low	6%	5%	● Moderate	31%	24%
Natural gas	5%	3%	● Moderate	<1%	<1%	● Low	5%	2%	● Moderate	-	-	-	1%	1%	● Low	12%	6%
Bio/waste	1%	2%	● Low	<1%	1%	● Low	6%	3%	● Moderate	-	-	-	-	-	-	8%	6%
NON-ENERGY																	
Industrial processes	-	6%	N/A	-	-	N/A	-	-	N/A	-	-	N/A	-	-	N/A	N/A	6%
Agriculture	-	-	N/A	-	-	N/A	-	-	N/A	-	12%	N/A	-	-	N/A	N/A	12%
Other	-	-	N/A	-	-	N/A	-	-	N/A	-	-	N/A	-	7%[5]	N/A	N/A	7%
Total	**32%**	**31%**		**22%**	**17%**		**34%**	**18%**		**2%**	**13%**		**10%**	**21%**		**100%**	**100%**

Note: Data reflected above is for 2019. Energy data reflects primary energy and emissions data reflects greenhouse gas emissions in terms of CO_2 equivalent. 1: Electricity/heat going to non-specified and non-energy uses, 2: Unallocated fuel combustion for electricity, 3: Energy going to non-specified and non-energy uses, 4: Emissions from energy production and fugitive emissions, 5: Emissions from LUCF and food waste (6%), 6: Includes traditional biomass and animal materials/waste 7: Includes geothermal, solar/tide/wind, and hydro, CO_2 equivalent includes methane and nitrous oxide emissions. **Figures are directional.**

Sources: IEA, WRI , Climate Watch, German Environment Agency; EIA

Key impact areas

- (A) **Electricity** generation from **fossil fuels**
- (B) Oil and oil products for **transportation**
- (C) Energy usage in **buildings**
- (D) **Fugitive emissions**
- (E) **Industrial processes**
- (F) **Energy supply needs to expand in a lower carbon manner to support economic growth in the developing world**

Legend:

- ☐ Key impact areas
- ● High Energy/Emissions ratio
- ● Moderate Energy/Emissions ratio
- ● Low Energy/Emissions ratio

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We then map solutions to each of those opportunity areas

Across end uses, there is a common set of high-level technical decarbonization levers

Category	Technical lever
Change fuels	Clean up existing fuels
	Switch to new fuels (compatible with existing equipment)
Change equipment	Switch to new fuels (requires new equipment)
	Electrify
Change consumption	Improve technical efficiency
	Improve material efficiency
	Change behavior
Capture	Capture emissions

Example: Impact area - oil and oil products for transportation (light duty vehicles)

End use	Transport
Sector	Passenger Transport
Equipment and device	ICE Car
Fuel	Oil
Emissions	CO_2

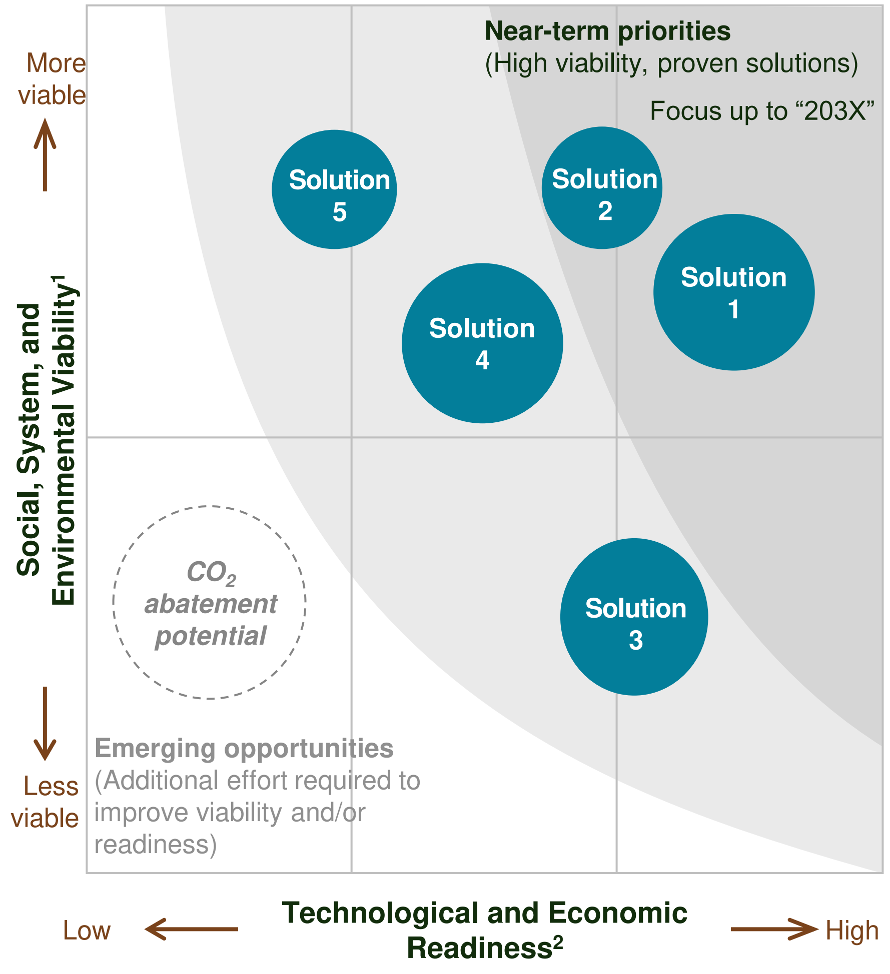
Possible technical solutions

- **Change behavior**: Switch to smaller vehicles
- **Change behavior:** Increase use of public transport and/or ride sharing
- **Electrify:** Switch to EVs over ICE vehicles
- **Improve technical efficiency:** Increase fuel economy standards
- **Switch to new fuels** (existing equipment): Low-carbon biofuels blending
- **Clean up existing fuels:** Reduce emissions intensity of oil production; abate methane
- **Capture:** DACCS or nature-based solutions

Overview of solution assessment framework

Criteria overview

Criteria	Description
CO_2 abatement potential	**Carbon abatement:** What is the realistic medium-term CO_2 emissions abatement potential of the solution?
Technological and economic readiness *"Could we scale this to have an impact quickly?"*	**Technology and resources:** What is the degree of technological development of the solution? Are there sufficient resources to deploy at scale? **Economics and affordability:** What is the marginal abatement cost of the technology relative to other solutions? Is the solution cost-competitive with existing or incumbent technologies? Is it aligned with consumer preferences?
Social, System, and Environmental Viability *"Should we scale this given the social, system, environmental and political considerations?"*	**Reliability and security:** Is the solution reliable? Does it have any impact on system reliability? Is the solution aligned with national security objectives and social priorities? **Fair and equitable:** Does the solution have a fair and equitable distributional impact? **Upstream and downstream environmental impact:** To what degree are there negative environmental consequences associated with the solution?



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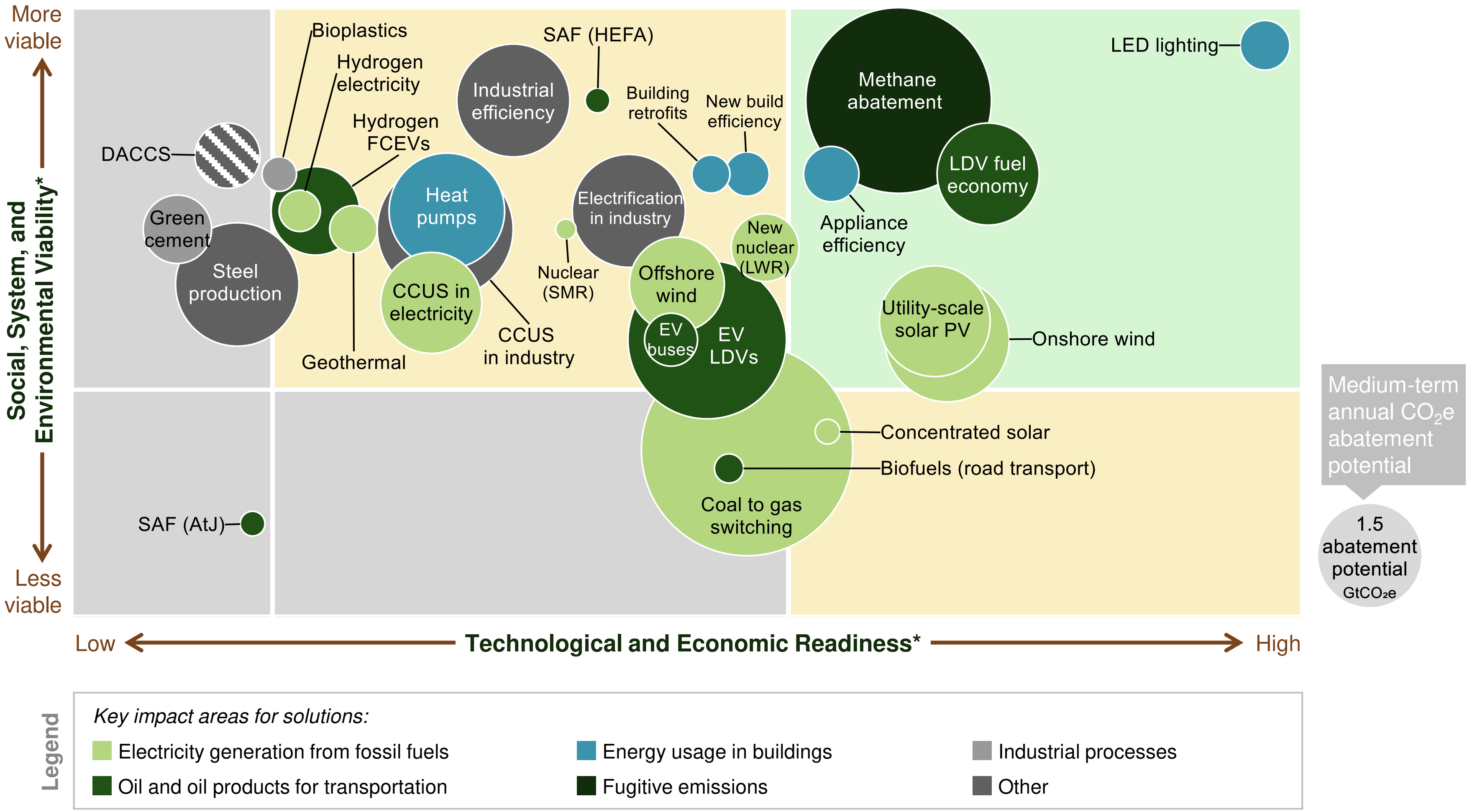
Evaluation of long list of solutions showed large spread with regards to impact by 203X



*Social, System, and Environmental Viability:

- Impact on system reliability
- Environmental impact
- Distributional effects/impact on communities
- National security and social priority alignment

*Technological and Economic Readiness:

- Technological Readiness
- Marginal cost of abatement
- Cost relative to alternatives
- Resource availability
- Consumer preferences

Note: Abatement potential refers to medium-term annual CO_2e emissions reduction; building efficiency and retrofits refers to insulation and HVAC only; DACCS abatement potential virtually infinite; industrial efficiency includes solutions such as waste to heat recovery; renewable solutions include battery component in cost and abatement potential; geothermal represents enhanced geothermal systems; assumes methane has global warming potential 30 times that of CO_2

Source: IEA; IRENA; Goldman Sachs; Project Drawdown; OpenMinds research and lit. scan

The 10 highest potential solutions are shortlisted for additional exploration

Our preliminary shortlist of solutions

Clean up traditional energy
- Abate methane emissions from energy
- Coal-to-gas switching
- CCUS in electricity and industry

Low-carbon electricity
- Renewables (i.e., solar and wind)
- New and existing nuclear

Efficiency and electrification
- Transportation energy efficiency
- Transport electrification
- Industrial efficiency and electrification
- Buildings efficiency
- Heat pumps

We assess our top 10 as having the highest impact potential, but there are a range of other important solutions

‘Top 10’ solutions

Prioritized set of solutions with high viability and sufficient technological and economic readiness to “bend the curve” by 203X

- Abating methane emissions from energy
- Transportation on energy efficiency
- Coal-to-gas switching
- Electric LDVs
- CCUS in electricity and industry
- Industrial efficiency and electrification
- Renewables (i.e., solar and wind)
- Heat pumps
- New and existing nuclear
- Buildings efficiency

Other important solutions

Solutions that **may be critically important** but are assessed as having less overall impact potential by 203X relative to our list of ‘top 10’ solutions

- Behavioral change
- Adaptation

We are considering whether and how to incorporate these more fully into our efforts

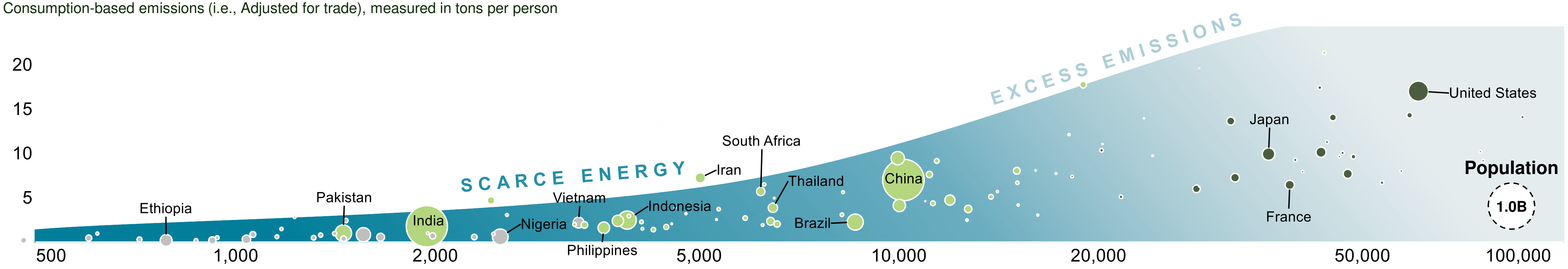
- Distributed generation
- Green steel and cement
- Nature-based solutions
- Hydrogen
- LED lighting
- Direct air capture
- Geothermal
- Circular economy

But not every country has the same starting point — we need to account for this as we work toward specific actions

~3 billion people	~3.5 billion people	~1 billion people
Birth rate: ~25/1,000 people	Birth rate: ~15/1,000 people	Birth rate: ~11/1,000 people

CO_2 emissions per capita, 2019

Consumption-based emissions (i.e., Adjusted for trade), measured in tons per person



GDP per capita, 2019

Measured in constant 2015 USD; logarithmic axis

Low-income developing countries
How do we lift countries out of energy poverty in a low-carbon way without erecting barriers to economic development? (i.e., without following the previous trajectory of the Advanced countries)

Emerging countries
How do we support countries in industrialization and accessing low cost clean energy?

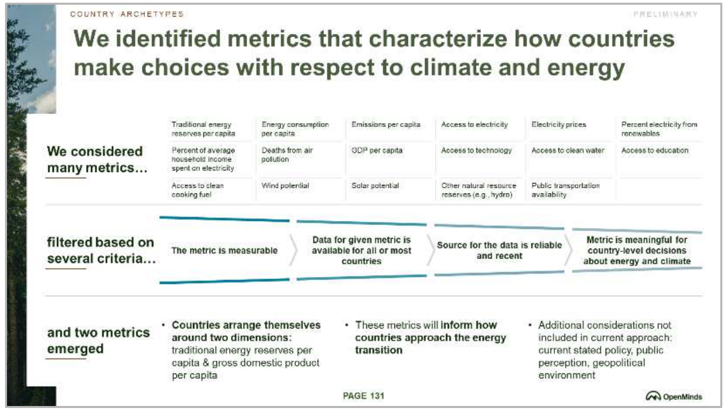
Advanced countries
How do we reduce emissions while maintaining high quality of life and growth?

Note: GDP is adjusted for purchasing power parity
Source: Bain & Company analysis; Max Roser, "The world's energy problem", Our World in Data; Switch On (2020); World Bank; Global Carbon Project; IMF; UN World Population Prospects 2019

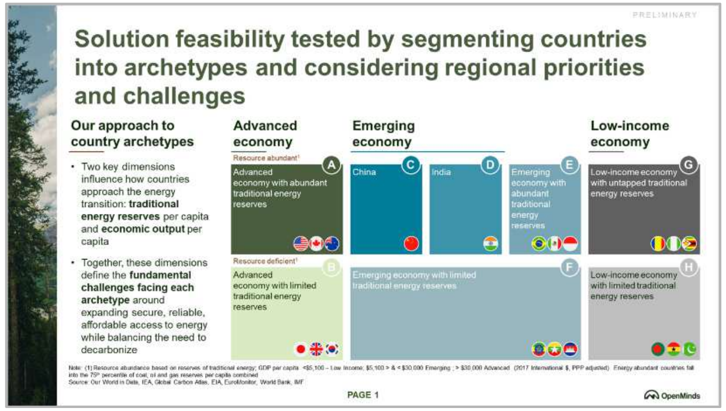
1

For that reason, we segment the world into eight archetypes to understand solution applicability

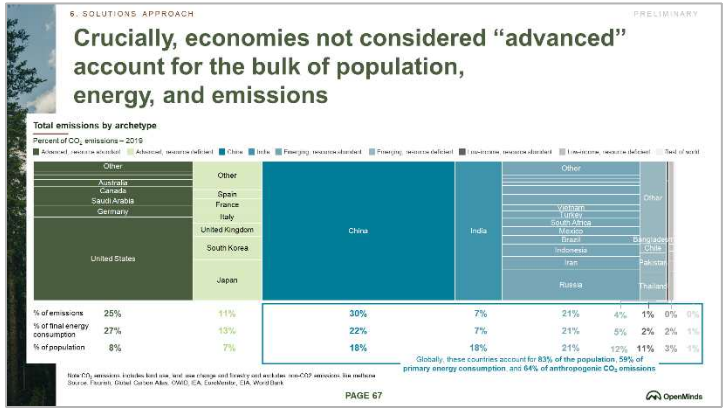
Country archetypes inform applicability of a given solution at a regional level



We identified a list of **unique metrics that influence energy and emissions** and for which high quality and reliable data is available across geographies



We found that **segmenting countries into archetypes along two dimensions – traditional fuel reserves and GDP**, enables a better understanding of how the shared attributes within each archetype informs their approach to the Dual Challenge



We looked at emissions by archetype across a range of categories to **identify most impactful solutions**

Note: Further detail can be found in the appendix

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Solution feasibility tested by segmenting countries into archetypes and considering regional priorities and challenges

Our approach to country archetypes

- Two key dimensions influence how countries approach the energy transition: **traditional energy reserves** per capita and **economic output** per capita
- Together, these dimensions define the **fundamental challenges facing each archetype** around expanding secure, reliable, affordable access to energy while balancing the need to decarbonize

	Advanced economy	Emerging economy			Low-income economy
Resource abundant[1]	**A** Advanced economy with abundant traditional energy reserves	**C** China	**D** India	**E** Emerging economy with abundant traditional energy reserves	**G** Low-income economy with untapped traditional energy reserves
Resource deficient[1]	**B** Advanced economy with limited traditional energy reserves	**F** Emerging economy with limited traditional energy reserves			**H** Low-income economy with limited traditional energy reserves

Note: (1) Resource abundance based on reserves of traditional energy; GDP per capita <$5,100 – Low Income; $5,100 > & < $30,000 Emerging ; > $30,000 Advanced (2017 International $, PPP adjusted). Energy abundant countries fall into the 75th percentile of coal, oil and gas reserves per capita combined
Source: Our World in Data, IEA, Global Carbon Atlas, EIA, EuroMonitor, World Bank, IMF

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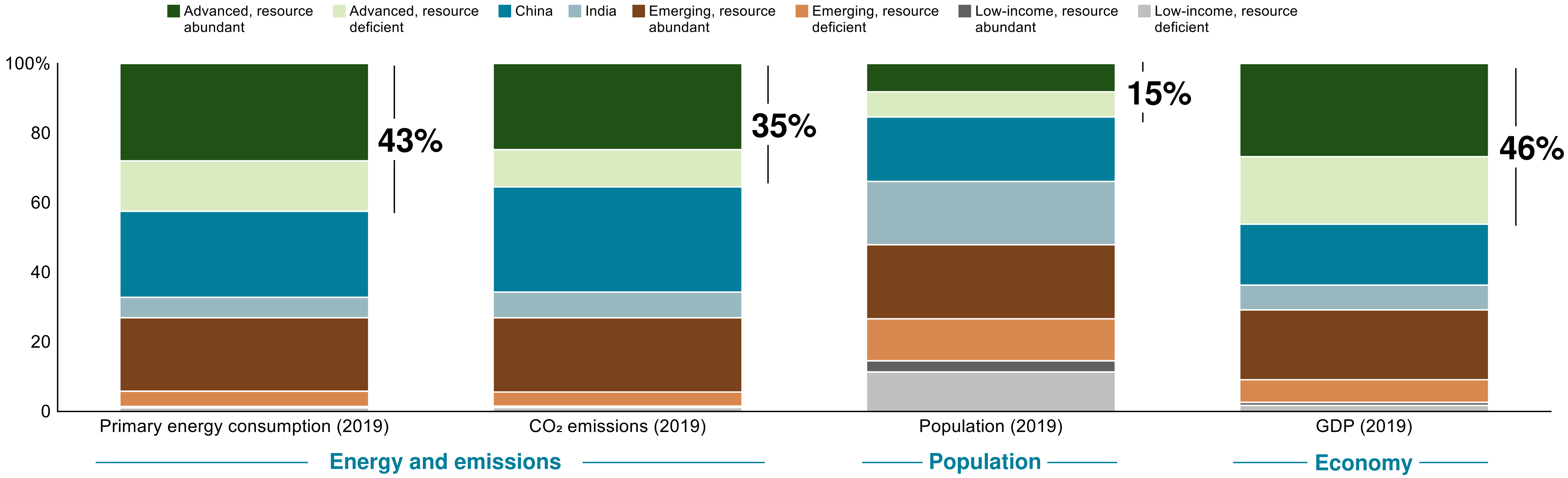
Energy, emissions, and GDP skew toward advanced economies relative to population

Energy, population, and economic indicators by archetype (%)



Note: GDP per capita <$5,100 – Low Income; $5,100 > & < $30,000 Emerging ; > $30,000 Advanced (2017 International $, PPP adjusted); Energy abundant countries fall into the 75th percentile of coal, oil and gas reserves per capita combined; CO_2 emissions includes land use, land use change and forestry and excludes non-CO2 emissions like methane; 2019 population comes from World Bank; Population projection uses UN Medium Fertility Scenario; GDP uses 2017 International $, PPP adjusted

Source: Our World in Data, Global Carbon Atlas, World Bank, UN

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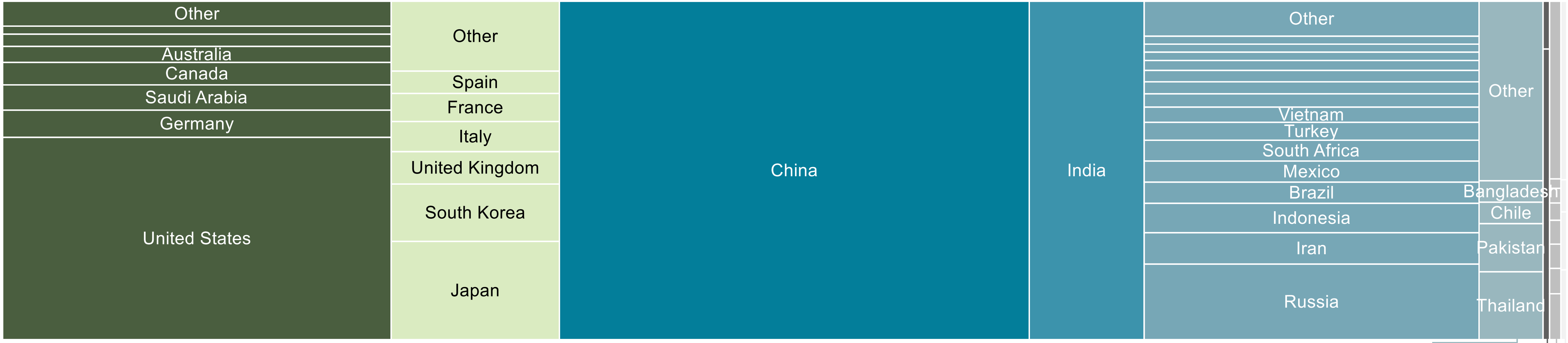
Crucially, economies not considered “advanced” account for the bulk of population, energy, and emissions

Total emissions by archetype

Percent of CO_2 emissions – 2019

Advanced, resource abundant | Advanced, resource deficient | China | India | Emerging, resource abundant | Emerging, resource deficient | Low-income, resource abundant | Low-income, resource deficient | Rest of world



	Advanced, resource abundant	Advanced, resource deficient	China	India	Emerging, resource abundant	Emerging, resource deficient	Low-income, resource abundant	Low-income, resource deficient	Rest of world
% of emissions	25%	11%	30%	7%	21%	4%	1%	0%	0%
% of final energy consumption	27%	13%	22%	7%	21%	5%	2%	2%	1%
% of population	8%	7%	18%	18%	21%	12%	11%	3%	1%

Globally, these countries account for **83% of the population**, **59% of primary energy consumption**, and **64% of anthropogenic CO_2 emissions**

Note: CO_2 emissions includes land use, land use change and forestry and excludes non-CO2 emissions like methane
Source: Flourish, Global Carbon Atlas, OWID, IEA, EuroMonitor, EIA, World Bank

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These archetypes provide important perspective on where solutions need to be deployed

	Characteristics		CO2 emissions by fuel (2019)[1]					Greenhouse gas emissions by sector (2019)[3]								
	GDP[5]	Pop.	Coal	Oil	Gas	Other[2]	Total	Electricity & heat	Transport	Mfr'ing. & Constr.	Other industry	Agri-culture	Buildings	Fugitive emissions	All other sources[4]	Total
A Advanced, resource abundant	27%	8%	5%	11%	8%	1%	**25%**	7%	5%	2%	1%	2%	2%	1%	1%	**21%**
B Advanced, resource deficient	19%	7%	3%	5%	3%	0%	**11%**	3%	2%	1%	1%	1%	1%	0%	1%	**10%**
C China	18%	19%	21%	4%	2%	3%	**30%**	11%	2%	6%	2%	1%	1%	1%	0%	**25%**
D India	7%	18%	5%	2%	0%	0%	**7%**	3%	1%	1%	0%	1%	0%	0%	0%	**7%**
E Emerging. resource abundant	20%	21%	6%	7%	7%	2%	**21%**	6%	3%	2%	1%	3%	2%	3%	4%	**25%**
F Emerging. resource deficient	6%	12%	1%	2%	1%	0%	**4%**	1%	1%	0%	0%	1%	0%	0%	1%	**6%**
G Low income, resource abundant	1%	3%	0%	0%	0%	0%	**<1%**	0%	0%	0%	0%	0%	0%	0%	0%	**<1%**
H Low income, resource deficient	2%	11%	0%	0%	0%	0%	**<1%**	0%	0%	0%	0%	2%	0%	0%	3%	**5%**
Total	**100%**	**100%**	**41%**	**31%**	**21%**	**7%**	**100%**	**32%**	**14%**	**13%**	**6%**	**12%**	**6%**	**7%**	**10%**	**100%**
Top 10 Solutions			Coal-to-gas switching; CCUS	Methane abatement	Methane abatement			Heat pumps; Building efficiency	Transportation efficiency and electrification	Industrial efficiency and electrification	Industrial efficiency and electrification		Building efficiency	Methane abatement		

Coal-to-gas switching | CCUS | Methane abatement | Heat pumps | Building efficiency | Transportation efficiency and electrification | Industrial efficiency and electrification | High impact areas

Note: (1) Share of global production-based CO2 emissions. Does not account for emissions embedded in traded goods. Excludes non-CO2 greenhouse gases like methane. Excludes land use change. (2) "Other" includes process emissions from cement manufacturing, flaring, and other industry process emissions. (3) Share of global greenhouse gas emissions, including non-CO2 GHG emissions like methane. Includes land use change. Does not include International Bunkers, which is 1,400 Mt of GHG (4) "All other sources" includes aviation/shipping, land use change and forestry, waste, and other fuel combustion. (5) % of global total
Source: Our World in Data; Climate Watch; Global Carbon Project; World Bank

And help pinpoint region-specific challenges to implementation of solutions

	Characteristics		CO2 emissions by fuel (2019)[1]						
	GDP[5]	Pop.	Coal	Oil	Gas	Other[2]	Total	Electricity & heat	Transpo
A Advanced, resource abundant	27%	8%	5%	11%	8%	1%	25%	7%	5%
B Advanced, resource deficient	19%	7%	3%	5%	3%	0%	11%	3%	2%
C China	18%	19%	21%	4%	2%	3%	30%	11%	2%
D India	7%	18%	5%	2%	0%	0%	7%	3%	1%
E Emerging. resource abundant	20%	21%	6%	7%	7%	2%	21%	6%	3%
F Emerging. resource deficient	6%	12%	1%	2%	1%	0%	4%	1%	1%
G Low income, resource abundant	1%	3%	0%	0%	0%	0%	<1%	0%	0%
H Low income, resource deficient	2%	11%	0%	0%	0%	0%	<1%	0%	0%
Total	100%	100%	41%	31%	21%	7%	100%	32%	14%
Top 10 Solutions									

Coal-to-gas switching · CCUS · Methane abatement · Heat pumps · Building efficiency · Transportation effic

Coal-to-Gas Switching

25% — **CO_2 emissions:** Emissions from coal power generation in China and India account for about one-quarter of global CO_2 emissions[1]

66% — **Power generation:** China and India together account for two-thirds of global coal power generation, and both are heavily reliant on coal for electricity (China 63%, India 74% of electricity generation)

Energy security: Both have abundant domestic coal production and reserves but limited production and reserves of other energy sources

Energy affordability: Average price of coal since 2010 is ~$3-5/Mbtu compared to gas which has ranged from ~$6-20/Mbtu

Jobs: The coal industry supports millions of jobs in both countries

13yr — **Age of fleet:** The average age of coal power plants in both India and China is only 13 years compared to 41 years in Russia and the U.S.

For these reasons and others, moving these countries away from coal will be challenging

Note: (1) CO_2 emissions from fossil fuels and land use change, excludes non-CO2 emissions like methane
Source: IEA; Reuters; S&P; Our World in Data

Considering solution feasibility around the globe, the rates of deployment are tuned to be aspirational but realistic

01 Methane abatement
Global energy sector methane emissions reduction, 2021-2030

- IEA APS & OM: ~25%
- IEA NZE: ~75%

02 Coal-to-gas switching
Change in primary energy from natural gas, 2021-2030 (% p.a.)

- IEA APS: -0.9%
- IEA STEPS: +0.4%
- IEEJ Adv: +0.9%
- OM: +1.3%

03 CCUS in electricity and industry[1]
Global electricity generation, coal and NG, % CCUS, 2021-40 (TWh)

- 2021: ~0%
- IEA STEPS: ~1%
- IEA APS: ~9%
- OM: ~10%

04[a] Solar
Global installed solar capacity, 2021-2030 (GW)

- 2021: 892
- IEEJ Adv: 1,990
- OM: 2,986
- IEA STEPS: 3,020
- IEA APS: 3,498

04[b] Wind
Global installed wind capacity, 2021-2030 (GW)

- 2021: 832
- IEA STEPS: 1,830
- IEEJ Adv: 1,982
- IEA APS: 2,251
- OM: 2,333

05 Nuclear
Significant acceleration in nuclear after 2030

Global installed nuclear capacity, 2021-2040 (GW)

- 2021: 413
- IEA STEPS: 545
- IEA APS: 622
- IEEJ Adv and OM: 659

06 LDV fuel economy
Avg rated fuel consumption, new ICE vehicles[2], 2021-2030 (km/L)

- 2021: ~15
- IEA STEPS: ~18
- OM and IEA APS: ~20

07 Electric LDVs
EV share of passenger vehicle stock, 2021-2030 (%)

- 2021: 1.3%
- IEEJ Adv: 8%
- OM: 12%
- IEA STEPS: 14%
- IEA APS: 15%

08 09 Electrification
Electricity share of TFC[3] in industry and buildings, 2021-2030 (%)

- 2021: ~27%
- IEA STEPS and OM: ~30%
- IEA APS: ~33%

08 10 Efficiency
YOY improvement, energy intensity of GDP, 2021-2030

- 2000-19: 1.6%
- OM: 1.9%
- IEEJ Adv: 2.3%
- IEA STEPS: 2.4%
- IEA APS: 3.0%

Note: (1) CCUS evaluated for potential in the power sector only; (2) ICE vehicles include hybrid electric; (3) TFC = total final consumption; IEEJ does not provide data for methane emissions, sector-specific data on electricity share of TFC, or new ICE vehicle rated fuel consumption; IEEJ energy intensity and change in primary energy show 2020-30 change; OM energy intensity is for 2019-30; IEA STEPS is the Stated Policies Scenario; IEA APS is the Announced Pledges Scenario; IEEJ Adv is the Advanced Technologies Scenario; OM shows the impact of the 'top 10 solutions' only and does not consider the impact of additional policies or solutions
Source: IEA; IEEJ; Climate Interactive

Putting it all together, a picture emerges of where these solutions need to be deployed at a regional level to drive 203X impact

Top 10 Solutions

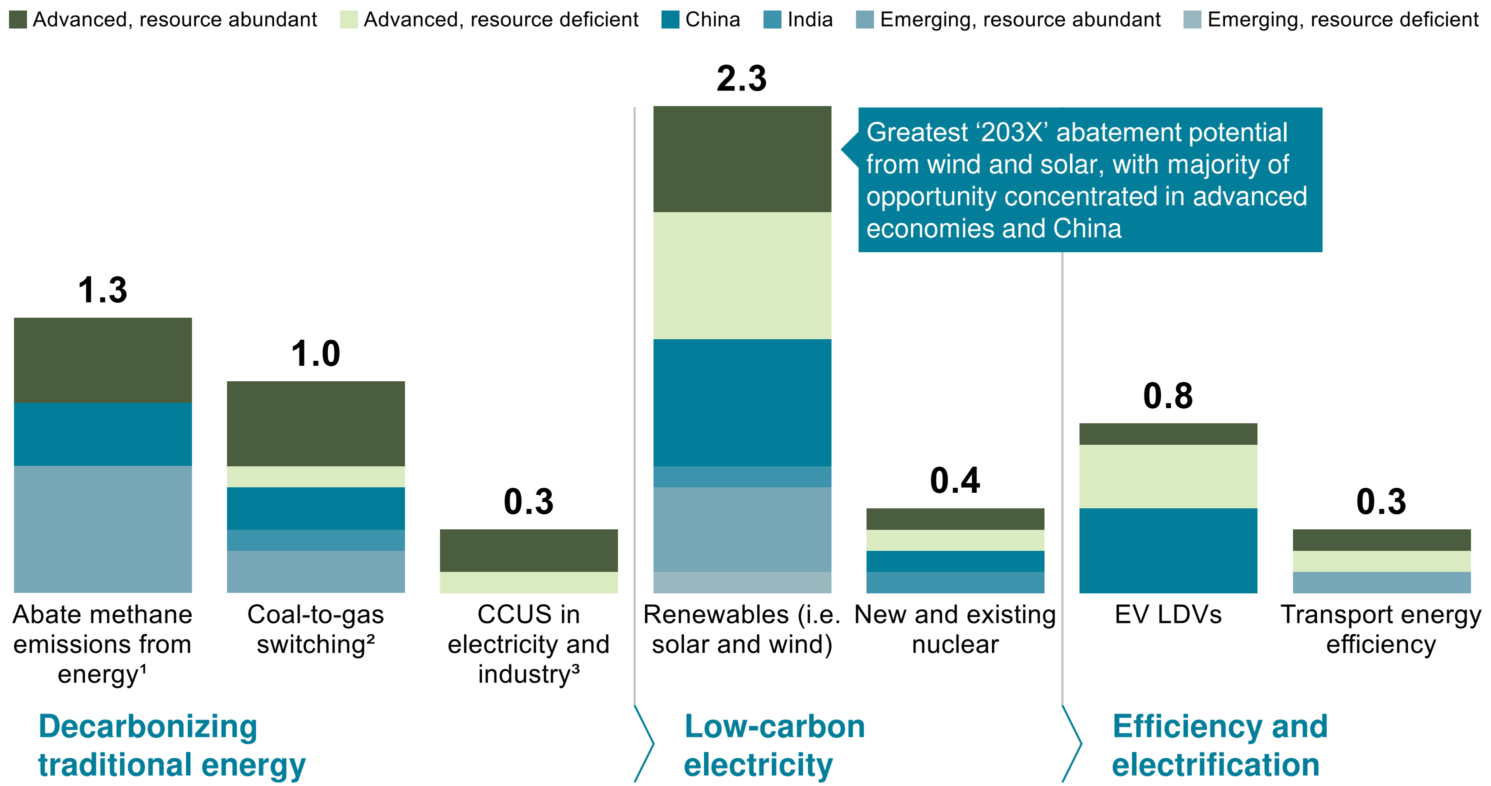
- Abate methane emissions from energy
- Coal-to-gas switching
- Transportation energy efficiency
- Electric LDVs
- Renewables (i.e., solar and wind)
- CCUS in electricity and industry
- New and existing nuclear

Not reflected in the chart

- Industrial efficiency and electrification
- Heat pumps
- Buildings efficiency

Projected greenhouse gas abatement by solution in 2035

GIGATONS OF CO_2-EQUIVALENT



1: Methane converted to CO2-equivalent using a GWP-100 factor of 30, **2:** Projected solution abatement potential by 2035 reflects net emissions reduction on switching from coal to gas. **3:** CCUS evaluated for potential in the power sector only
Source: Our World in Data, IEA, Ember, Lit search; GEM

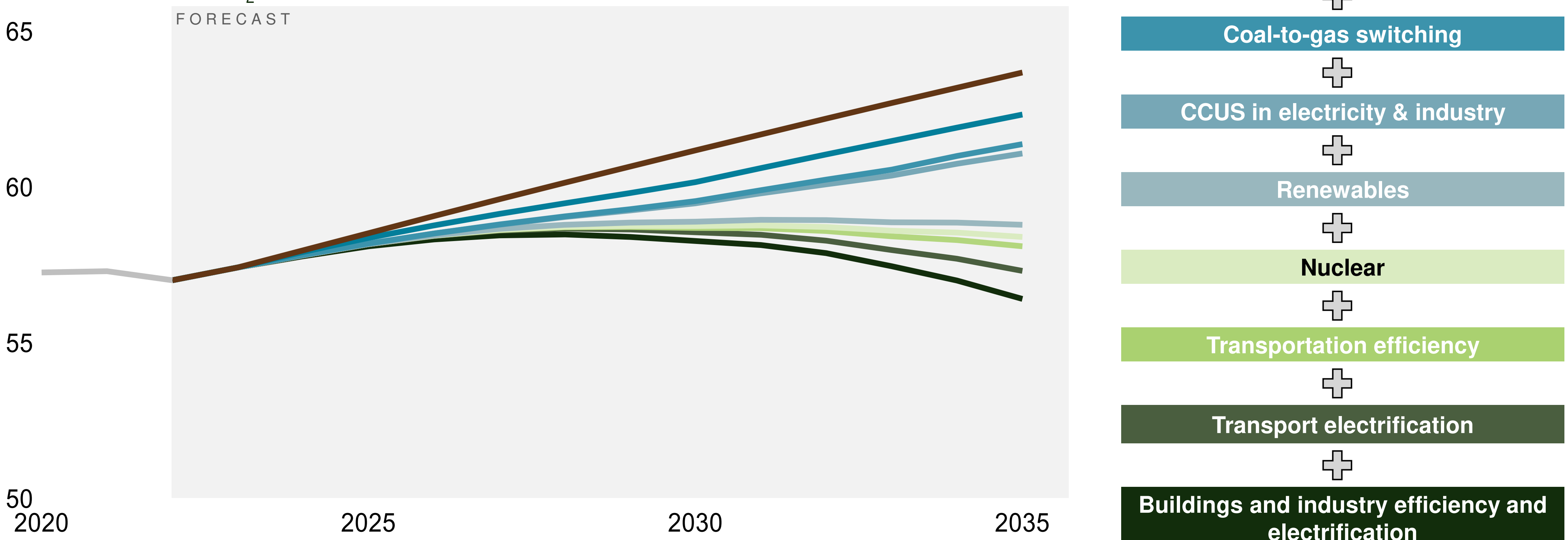
1

Early analysis indicates the collective implementation of these solutions could be enough to “bend the curve” by 203X

Projected emissions impact

Global annual net GHG emissions

GIGATONS OF CO_2E PER YEAR



Source: Climate Interactive

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Multiple enablers required across each solution in order to achieve '203X' impact (1 of 2)

Abating methane emissions

- Enhance **international policy support** for the Global Methane Pledge
- Apply **technology standards, bans on venting**, and stricter standards on flaring
- Energy companies implement **positive ROI projects** using LDAR, new devices, etc.
- **Invest in midstream infrastructure** necessary to capture fugitive emissions

Coal-to-gas switching

- **Ensure stable natural gas availability and price** to support economics
- **Support for natural gas** as an important ongoing source of energy
- **Implement policies** supporting the shift away from coal (e.g., coal phase-out)
- Establish a robust and transparent **market for liquified natural gas**

CCUS in electricity and industry

- **Improve technology and project economics** for lower-purity CO_2 streams
- **Introduce carbon markets** or other forms of carbon pricing
- Significantly **scale existing CO_2 transport systems** to meet expected demand
- **Improve permitting processes** and timelines for injection wells

Renewables

i.e., solar and wind

- Expand electrical **grid with increased transmission capacity** and reliability
- Expand **electrical storage capacity to address variability** in generation
- **Ensure diversified supply chains for critical minerals** for batteries and components
- **Incentivize backup generation capacity** to meet peak demand

New and existing nuclear

- **Develop policy environment** favorable to lifetime extensions for existing plants
- **Provide policy support** for construction of **new plants** (e.g., regulatory reform)
- Deliver new projects **on-time and on-budget**
- Establish fuel supply chain and disposal **infrastructure and labor force**

Source: IEA; U.S. Department of Energy; OpenMinds research and lit. scan

Legend: Technology Markets Policy

NOT EXHAUSTIVE

Multiple enablers required across each solution in order to achieve ‘203X’ impact (2 of 2)

Transportation energy efficiency

- **Implement and strengthen fuel economy standards** for new vehicles
- **Shift vehicle attributes** toward lighter, smaller models and away from SUVs
- **Provide subsidies to support sales** of fuel-efficient vehicles and cleaner fuels
- Increase **penetration of hybrid electric vehicles** in new car sales

Electric LDVs

- **Ensure sufficient supply of critical minerals** needed for batteries and other key inputs
- **Provide subsidies to support** electric vehicle production and sales
- **Develop widespread charging infrastructure** network for electric vehicles
- Improve EV **range, charging time, and upfront cost** to consumers

Industrial efficiency and electrification

- **Substitute electricity** for fossil fuels in low- and medium-heat processes
- **Subsidize development and commercialize** high efficiency heavy industrial technology
- **Integrate smart technologies** (e.g., AI, monitoring) to enhance productivity
- **Improve recovery of energy** (e.g., waste heat, carbon capture) where possible

Heat pumps

- Improve cost **competitiveness and awareness** of heat pumps relative to alternatives
- **Commercialize cold climate** air-source heat pumps supported by gas furnaces
- **Scale up supply chains** for HP expansion (manufacturers and contractors)
- Adopt regulations and building codes **promoting heat pumps over fossil fuels**

Buildings efficiency

residential and commercial

- **Adopt and expand building codes** with energy efficiency requirements
- **Provide incentives for retrofitting** existing buildings to increase energy efficiency
- Update and enforce **minimum energy performance standards** for new appliances
- Develop and improve **key energy efficient technologies** for buildings

Source: IEA; OpenMinds research and lit. scan

Legend: Technology Markets Policy

OpenMinds

Agenda

01	**02**	03	04	05	06
Solutions approach	**Solution assessment framework**	Top 10 solutions overview	Country archetypes	Appendix A: Detail on Top 10 solutions	Appendix B: Background on methane

Overview of solution assessment framework

Criteria overview

CO_2 abatement potential

Carbon abatement: What is the realistic medium-term CO_2 emissions abatement potential of the solution?

Technological and economic readiness
"Could we scale this to have an impact quickly?"

Technology and resources: What is the degree of technological development of the solution? Are there sufficient resources to deploy at scale?

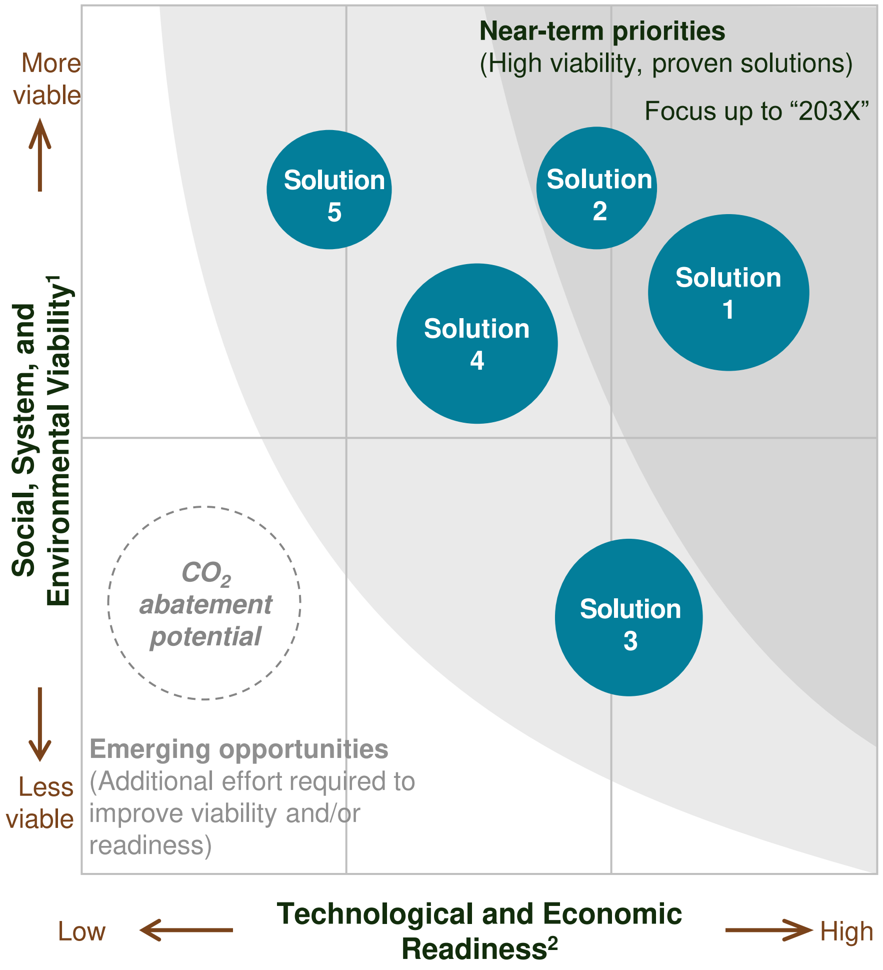
Economics and affordability: What is the marginal abatement cost of the technology relative to other solutions? Is the solution cost-competitive with existing or incumbent technologies? Is it aligned with consumer preferences?

Social, System, and Environmental Viability
"Should we scale this given the social, system, environmental and political considerations?"

Reliability and security: Is the solution reliable? Does it have any impact on system reliability? Is the solution aligned with national security objectives and social priorities?

Fair and equitable: Does the solution have a fair and equitable distributional impact?

Upstream and downstream environmental impact: To what degree are there negative environmental consequences associated with the solution?



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Tech and economic readiness: Five 'readiness' criteria evaluated to determine ability to scale the solution quickly

	Technological readiness	Marginal cost of abatement	Cost relative to alternatives	Resource availability	Consumer preferences
Description	Degree of technological maturity of the solution	Relative cost per ton of carbon abated by the solution	Cost of the solution to consumers relative to the existing technology	Material resource sufficiency to deploy at scale (e.g., metals, biofuel feedstocks, etc.)	Alignment of the solution with consumer behavior and choice
Weighting	25%	25%	25%	15%	10%
Scale (5 → 1)	Mature ↓ Early adoption ↓ Demonstration ↓ Large prototype ↓ Small prototype ↓ Concept	-\$120 per tn CO_2e ↓ \$1,000 per tn CO_2e	Least-cost option ↓ Cost-competitive ↓ Not cost-competitive	Sufficient ↓ Potentially sufficient (minimal investment) ↓ Potentially sufficient (moderate investment) ↓ Potentially sufficient (significant investment) ↓ Not sufficient	Aligned ↓ Somewhat aligned ↓ Not aligned
Sources	IEA	IEA, Goldman Sachs	OM research and lit. scan	OM research and lit. scan	OM research and lit. scan

Social, System, and Environmental Viability: Four criteria evaluated to determine if a solution should be implemented

	Impact on system reliability	Environmental impact	Distributional effects / impact on communities	National security and social priority alignment
Description	Reliability of the solution and potential impact, if any, on broader system reliability	Presence of any negative environmental externalities beyond CO_2 emissions	Fairness of the solution and impact on local communities (e.g., job losses, displacement)	Alignment of the solution with national security objectives and social priorities
Weighting	30%	30%	20%	20%
Scale 5	Significantly expands	None	Minimal	Aligned
4	Somewhat expands	Minimal		
3	Maintains	Slight	Moderate	Moderately aligned
2	Somewhat negatively impacts	Moderate		
1	Negatively impacts	Substantial	Substantial	Misaligned
Sources	OM research and lit. scan	OM research and lit. scan	OM research and lit. scan	OM research and lit. scan

2

Example: Detailed solutions scoring analysis for methane abatement

Methane abatement

The energy sector contributes ~**40% of human methane emissions**, primarily from fossil fuel operations and leaks from end-use equipment

Many existing technologies could be **deployed at minimal (or even negative) cost** to minimize methane emissions

Technological and economic readiness

Criteria	Score	Detail
Technological readiness (25%)	4.5	Integration needed at scale Majority of potential solutions already in practice
Marginal cost of abatement (25%)	4.2	Cost of abatement is competitive with many other technologies
Cost relative to alternatives (25%)	3.0	~25% of fossil fuel emissions could be avoided in a profitable way
Resource availability (15%)	5.0	Limited to no resource constraints present
Consumer preferences (10%)	3.0	Dependent on company willingness to make long-term investments
Composite score	**4.0**	

Social, System, and Environmental Viability

Criteria	Score	Detail
Impact on system reliability (30%)	4.0	Investments in infrastructure could improve or expand system reliability
Environmental impact (30%)	5.0	Significant positive environmental impact
Distributional effects / impact on communities (20%)	5.0	No distributional effects anticipated
National security and social priority alignment (20%)	5.0	Generally aligned with national security objectives and social priorities
Composite score	**4.7**	

Low readiness / viability 1 2 3 4 5 High readiness / viability

Source: IEA; Project Drawdown; Goldman Sachs; lit. search

Agenda

01 Solutions approach

02 Solution assessment framework

03 **Top 10 solutions overview**

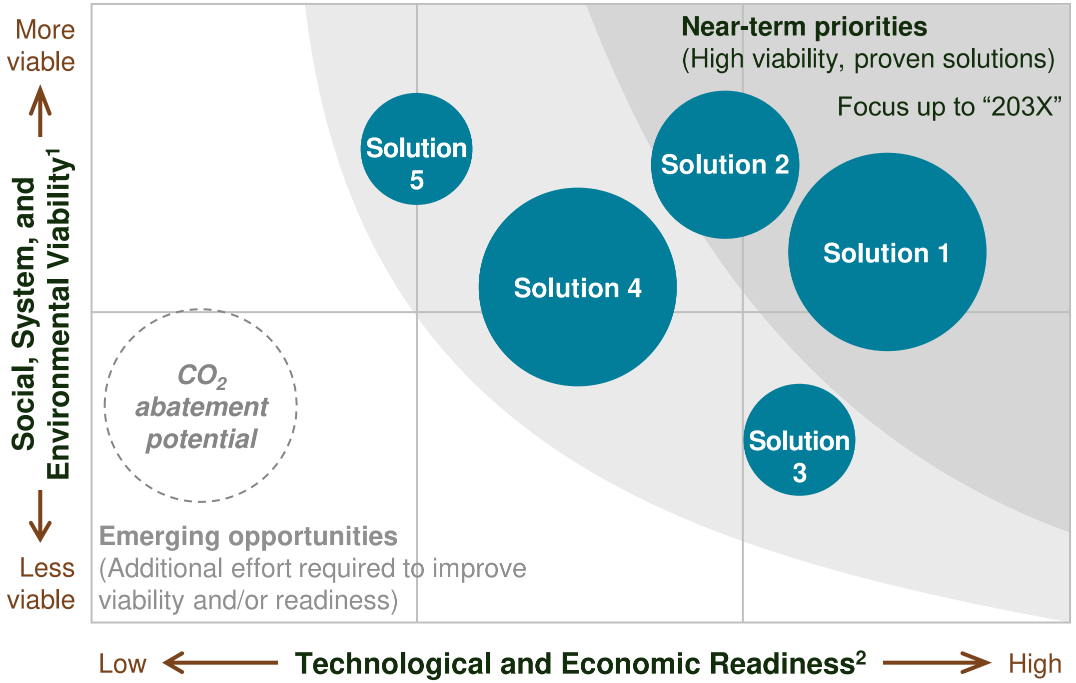
04 Country archetypes

05 Appendix A: Detail on Top 10 solutions

06 Appendix B: Background on methane

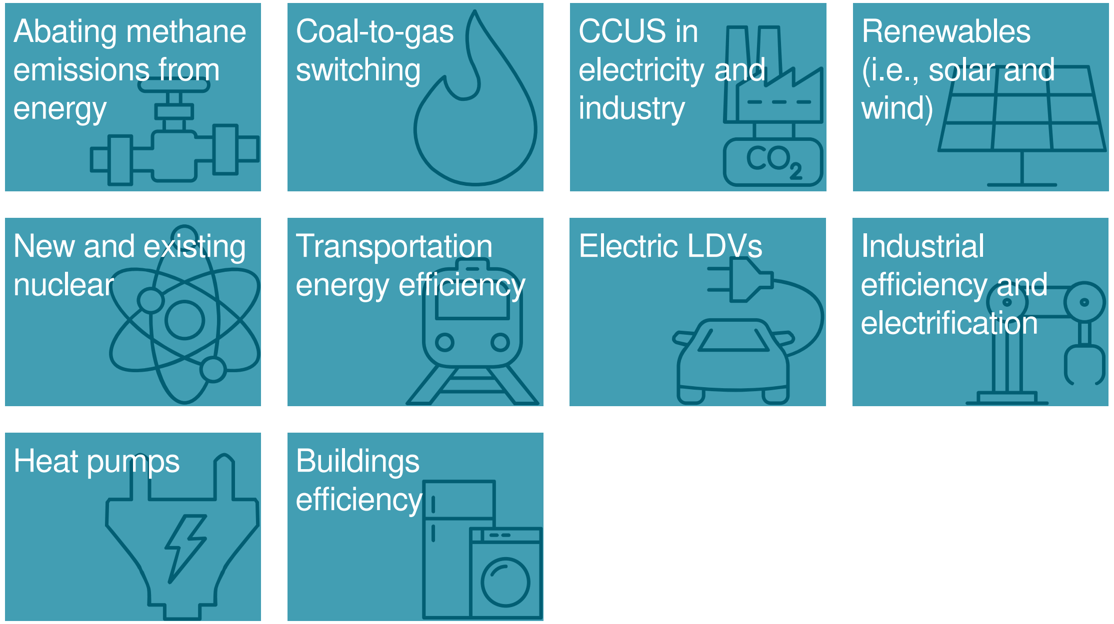
We shortlisted 10 high potential solutions with the collective potential to “bend the curve” by 203X

Solutions evaluated based on readiness, viability, and emissions abatement potential



Near-term priorities

Ten high potential solutions with sufficient degree of technological and economic readiness and viability prioritized based on ability to deliver results by “203X”

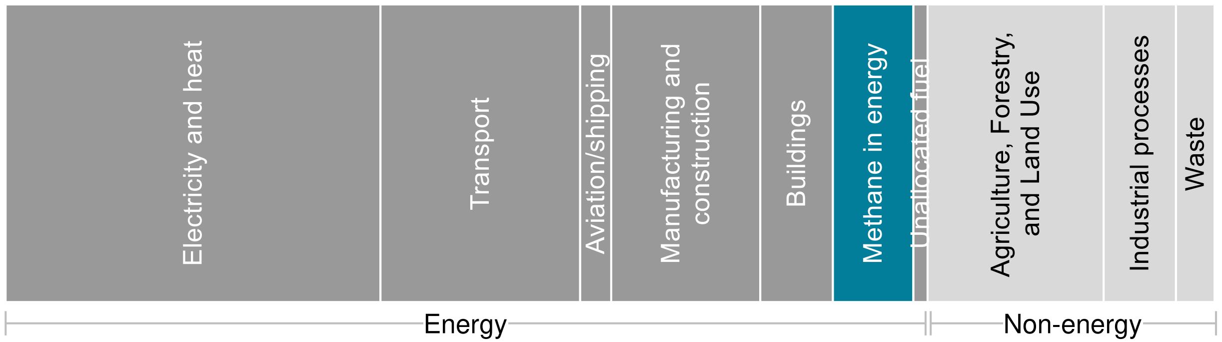


Note: (1) Includes impact on system reliability, environmental impact, distribautional effects, and national security and social priority alignment; (2) Includes technological maturity, marginal cost of abatement, cost relative to alternatives, resource availability, and consumer preferences. Additional detail on approach is included in the appendix.

Energy-related methane emissions are significant but cost-effectively addressable

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- Since COP26 in 2021, more than 150 countries have signed onto the Global Methane Pledge, **committing to reduce methane emissions by 30% by 2030** relative to 2020 levels
- Meeting the Global Methane Pledge target has the **potential to reduce end-of-century warming by 0.2°C**
- Many countries already have at least some oil & gas methane emissions regulations in place, **but more action is needed**

Background

- Methane is an extremely potent greenhouse gas: its **global warming potential is >80X** that of CO_2 over a 20-year period
- Global **energy-related methane emissions account for ~7%** of anthropogenic GHG on a CO2-equivalent basis
- **Oil & gas accounts for ~62% of energy-related methane** emissions, either through venting, fugitive emissions, or incomplete flaring

Solution details

- Given that methane can be captured and sold, many abatement opportunities can be **achieved at low or even negative net cost by leveraging existing technologies**
- Potential solutions include **leak detection and repair** (LDAR), installation of **new devices** (e.g., vapor recovery units), **replacement of existing devices**, and reductions in non-emergency flaring

Source: Climate Watch; Our Word in Data; IEA; EIA

Methane abatement could reduce emissions by ~1.3 Gt CO_2e in 2035, with majority of potential achieved through policy

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent

Abate methane emissions from energy[2]

Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	Other
Markets	• Build infrastructure for recovered methane	• Adopt coal mine methane utilization	• Include methane in CBAM[5] to increase cost of carbon and incentivize abatement
Technology	• Use satellite tracking to identify and prioritize opportunities	• Improve thermal or catalytic oxidation technologies for ventilation air methane oxidation	• Use satellite tracking to identify and prioritize opportunities
Policy	• Adopt LDAR[3] and technology standards • Implement zero venting and flaring policies • Include small producers in policy development	• Adopt the Global Methane Pledge and Zero Routine Flaring Initiative • Institute reporting requirements and monitoring programs	• Adopt LDAR[3] and technology standards • NOCs[4] comply with national methane reduction pledges • Reduce flaring in select countries

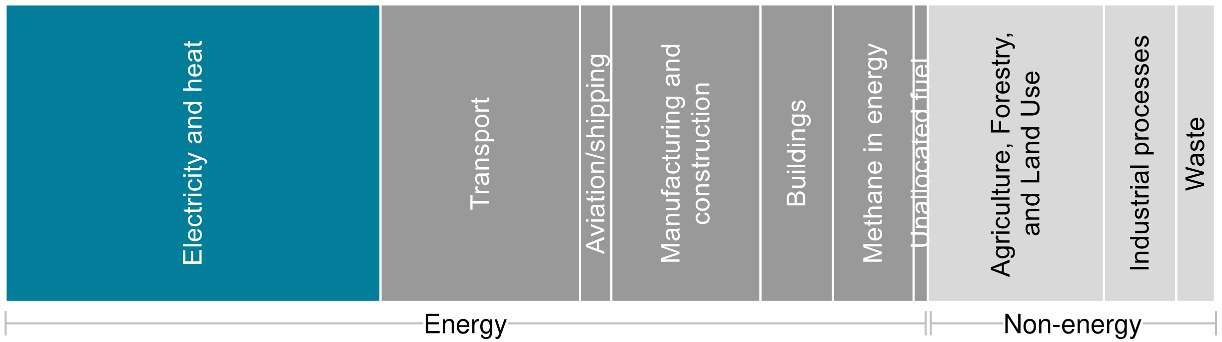
Note: (1) Data for 2019; (2) Methane converted to CO2-equivalent using a GWP-100 factor of 30; (3) Leak detection and repair; (4) National oil companies; (5) CBAM = carbon border adjustment mechanism
Source: Our World in Data; IEA; Columbia Center on Global Energy Policy; OpenMinds research and lit. scan

3

Switching fuels from coal to natural gas can significantly reduce power sector emissions

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- Between 2010 and 2018, **coal-to-gas switching saved ~500 Mt CO_2 globally**
- The majority of these savings were **concentrated in the U.S. and China**
- The **shale revolution drove fuel switching in the U.S.** as the economic case for switching improved
  - From 2011-2019, 103 coal-fired power plants were converted to or replaced by natural gas
- Fuel switching in China **driven primarily by air quality policies**

Background

- **Fuel switching from coal to natural gas** can significantly reduce power sector emissions
- **Natural gas emits half as much carbon dioxide** as coal to generate the same amount of electricity
- Coal-to-gas switching may also provide a path to emissions reduction in **high-heat industrial processes**
- Particularly when **coupled with methane abatement and CCUS**, coal-to-gas switching is an effective solution to the Dual Challenge

Source: Climate Watch; Our Word in Data; IEA; EIA

Solution details

- In many cases, coal-to-gas switching can occur by **leveraging existing infrastructure and converting coal-fired plants** to burn gas, significantly lowering switching costs
- Without policy support, **economics has historically functioned as the key driver**
- Broader **acceleration would require robust, liquid LNG markets with transparent hub-based pricing** to support adoption in countries lacking domestic gas reserves

Coal-to-gas switching

OpenMinds

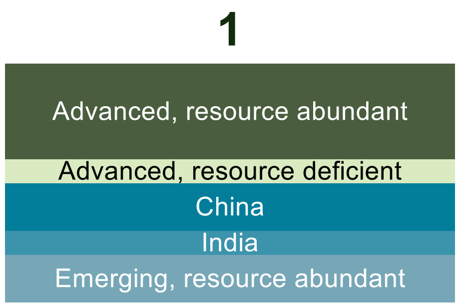
3

Coal-to-gas switching could reduce emissions by ~1.0 Gt CO_2 in 2035, with the largest opportunity in the U.S. and Europe

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Coal-to-gas switching[1]

Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	India	Other
Markets	• Invest in new LNG infrastructure in Europe • In the U.S., increase existing NGCC load factors	• Establish hub-priced LNG markets • Invest in new production, storage, and LNG infrastructure	• Establish hub-priced LNG markets • Invest in pipeline infrastructure	• Establish hub-priced LNG markets
Technology	• Scale up use of biomethane	• Expand biogas production		
Policy	• Adhere to coal phase-out pledges • Close coal mines at end of current operating licenses	• Replace industrial coal-fired boilers with gas • Replace coal for use in heating	• Improve permitting of gas networks • Replace industrial coal-fired boilers with gas	• Create and adhere to coal phase-out plan

Coal-to-gas switching

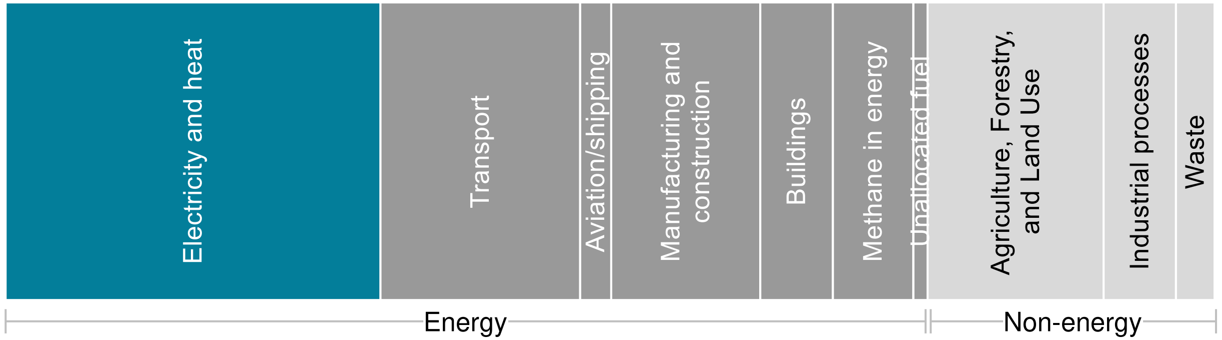
Note: (1) Projected solution abatement potential by 2035 reflects net emissions reduction on switching from coal to gas
Source: IEA; OpenMinds research and lit. scan

3

Point-source carbon capture in power and industry can help reduce emissions in difficult to abate sectors

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- CCUS is currently deployed primarily in **high-purity CO_2 streams in industrial applications** (primarily natural gas processing)
- A **large share of existing CCUS capacity is located in the U.S.** and stores captured CO_2 through enhanced oil recovery
- A **significant number of projects are in various stages of development**—both in the U.S. and internationally, with geological storage expected to expand

Background

- **Carbon capture, utilization, and storage (CCUS) is a three-step process** that involves the point-source capture of CO_2, its compression and transportation, and its use or storage
- CCUS can be **deployed in both the power and industrial sectors**, leveraging existing infrastructure and thereby limiting switching costs

Solution details

- Given its high cost relative to some alternatives, **government support will be required** in the form of grants, tax credits, or carbon pricing mechanisms
- **Technological improvements are also required** to improve the efficiency of carbon capture technologies
- Additional regulatory changes are required to **improve the permitting process for injection wells**

CCUS

Source: Climate Watch; Our Word in Data; IEA; U.S. Department of Energy

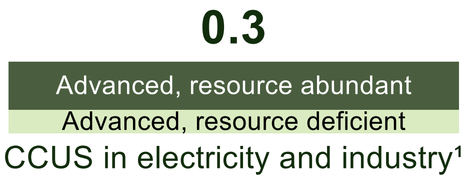
3

CCUS in electricity could reduce emissions by ~300 Mt CO_2e in 2035, with majority of opportunity in advanced economies

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Actions across archetypes to achieve abatement potential

Enabler	Advanced
Markets	• Significant scaling of existing CO_2 transport systems • Standardization of business models across the value chain
Technology	• Improved technology and project economics for lower-purity CO_2 streams
Policy	• Introduction of carbon markets or other forms of carbon pricing • Improved permitting processes and timelines for injection wells

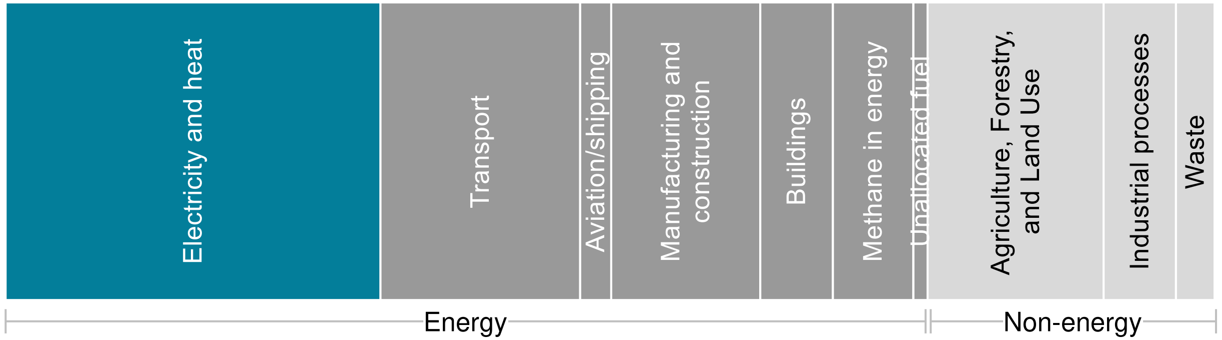
CCUS

Note: (1) CCUS evaluated for potential in the power sector only
Source: U.S. Department of Energy; OpenMinds research and lit. scan

Renewables are one of the most cost-effective solutions to decarbonize power, but present challenges

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- COP26 featured several pledges to accelerate the clean energy transition, including **phasing out coal by 2040**
- To achieve this goal, wind and solar capacity are **expected to continue growing steadily at ~9-12% p.a.** through 2030
- Utility-scale solar and onshore wind have **experienced >40% cost declines in the last decade**, making many projects cost competitive with conventional generation[1]

Background

- Global **fossil fuel electricity emissions account for ~30%** of anthropogenic GHG on a CO2-equivalent basis
- **Wind and solar have experienced significant capacity growth** over the past decade (~15% and ~33% p.a., respectively), supported by subsidies and improving economics
- However, the **share of fossil fuels in the energy mix has remained fairly stable** at ~80% of global primary energy supply

Note: (1) As measured based on levelized costs of energy
Source: Climate Watch; Our Word in Data; IEA; IRENA; Lazard; Lit. scan

Solution details

- Solar and wind projects are **expected to become increasingly cost competitive** over the coming years
- As these renewable sources increase their share of electricity generation, **solutions will need to address supply intermittency** with backup capacity or improved battery technology
- In addition, renewable supply chains will need to **achieve greater diversification of critical minerals** for batteries and other components

Renewables

OpenMinds

Renewables could reduce emissions by ~2.3 Gt CO_2e in 2035

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent

Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	India	Other
Markets	←	• Expansion of transmission lines to connect renewable generation	→	• Provide financing support to offset country risk premium
Technology	←	• Decrease manufacturing costs through efficiency and scale • Improve energy storage		→
Policy	• Improve permitting and grid interconnection process • Incentivize pairing of storage with new renewables	• Meet renewables energy generation targets • Continue incentivizing renewable development (e.g., tax, pricing)	• Improve system integration and flexibility	

Renewables

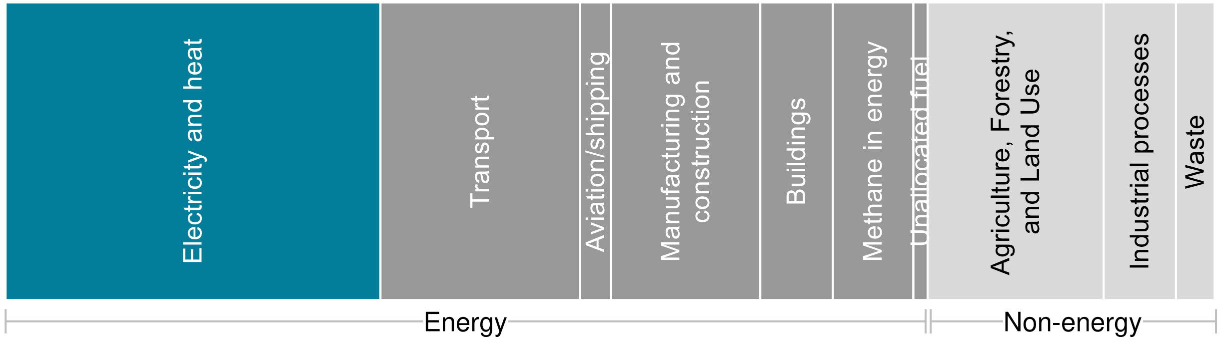
Note: (1) Data for 2019
Source: IEA; IRENA; OpenMinds research and lit. scan

3

Replacing fossil fuels with nuclear has high potential to decrease emissions, but requires public buy-in

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- Globally, nuclear supplies ~**10% of all electricity generation**
  - **In the U.S., nuclear provides** ~**18%** of utility-scale electricity generation
- To enable decarbonization in the power sector, the IEA's Announced Pledges Scenario **projects a ~50% (~200 GW) increase in nuclear capacity by 2040**
- **Nuclear is positively trending**, as 50+ countries (e.g., Finland and France) have plans to build new reactors

Background

- Global **fossil fuel electricity emissions account for** ~**30%** of anthropogenic GHG on a CO2-equivalent basis
- Nuclear is a particularly attractive alternative to fossil fuels in the power sector given **limited land use requirements, competitive marginal costs of electricity, and relative safety**
- However, nuclear has historically had **poor public perception** due to high-profile nuclear accidents (e.g., Fukushima)

Source: Climate Watch; Our Word in Data; IEA; Lit. scan

Solution details

- A large portion of the existing nuclear fleet is nearing the end of its originally planned operational life, but **regulatory approval for lifetime extensions** could allow these facilities to continue operation
- Economic case for nuclear would be greatly improved by **delivering new projects on-time and on-budget**
- **Disposal of radioactive waste** also poses a barrier to continued expansion of nuclear

Nuclear

OpenMinds

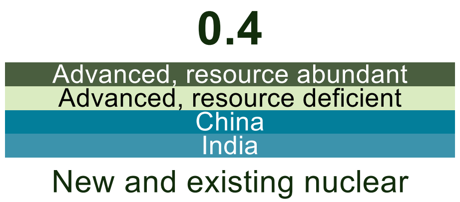
3

Nuclear energy could reduce emissions by ~0.4 Gt CO_2e in 2035 if construction accelerates in advanced economies

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	India
Markets	• Deliver projects on-time and on-budget • Address shortage of skilled labor • Increase capacity across supply chain	• Deliver projects on-time and on-budget • Improve land access for building of nuclear reactors	• Deliver projects on-time and on-budget • Secure contracts for stable import of uranium
Technology	• Develop small modular reactors (SMRs)	• Fully closed nuclear fuel cycle using recycled plutonium	• Development of fast reactors and thorium nuclear fuel cycle
Policy	• Reform of regulatory bodies and policies • Grant lifetime extensions to plants near end of license • Enhance incentives for nuclear development	• Continue commitment to air quality improvement and coal phase out • Align on agencies in charge of nuclear	• Meet coal phase out goals • Provide foreign aid for construction of nuclear plants

Nuclear

Note: (1) Data for 2019

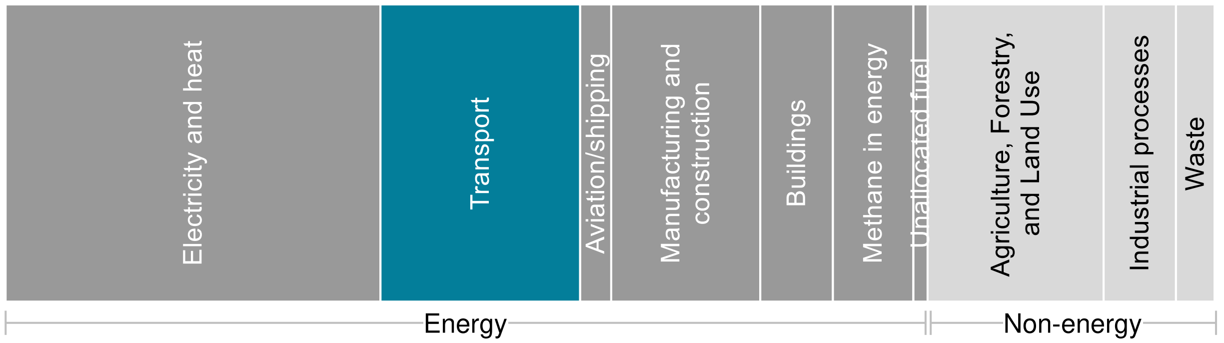
Source: Our World in Data; IEA; U.S. Department of Energy; World Nuclear Association; OpenMinds research and lit. scan

3

Improving fuel economy standards in LDVs would help reduce transport sector emissions

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- The majority of historical improvements in LDV fuel economy have been **driven by stricter government standards**
- Despite significant improvements in engine efficiency, fuel economy has **not improved at a similar rate due to increasing vehicle weight**
- The consumer **preference for SUV models has been a global trend**, particularly in the U.S. and China

Background

- **Road transportation represents ~12% of all anthropogenic GHG** on a CO2-equivalent basis
- By improving fuel economy, **vehicles can travel more miles per gallon of fuel consumed**, reducing the amount of carbon dioxide released into the atmosphere
- Improving LDV fuel economy is an **important complement to efforts to increase EV penetration**

Transportation efficiency

Source: Climate Watch; World Resources Institute; Our Word in Data; IEA

Solution details

- Fuel economy is **improved by maximizing the energy efficiency of the vehicle's engine and drivetrain**, reducing internal friction, optimizing aerodynamics, and minimizing weight
- **Government policy** will be a significant lever in improving LDV fuel economy, as will **advanced engine technologies and shifting consumer preferences** toward smaller, lighter vehicle models

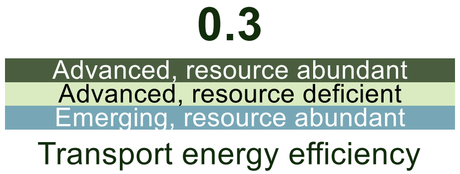
OpenMinds

Improving LDV fuel economy could reduce emissions by ~0.3 Gt CO_2e in 2035, driven mostly by regulation

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Note: (1) Data for 2019
Source: Our World in Data; IEA; OpenMinds research and lit. scan

Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	India	Other
Markets	• Increase number of hybrid vehicle models • Shift toward smaller, lighter models	• Shift toward smaller, lighter models	• Shift toward smaller, lighter models	• Decrease upfront purchase price
Technology	← • Improve fuel efficiency for ICE and hybrid LDVs →			
Policy	• Tighten fuel economy standards • Offer purchase incentives and subsidies • Adopt policies encouraging smaller, lighter models	• Tighten fuel economy standards • Adopt policies encouraging smaller, lighter models	• Tighten fuel economy standards	• Phase out fuel subsidies • Monitor vehicle trade flows

Transportation efficiency

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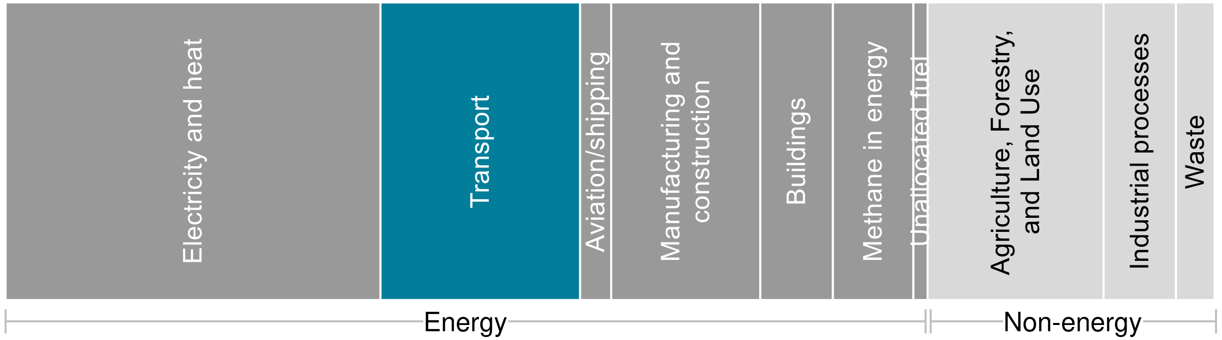
EV market has experienced rapid growth over the past several years, with continued momentum expected

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- In 2022, ~**14% of all cars sold globally were electric**, with continued momentum going into 2023
  - This penetration is **up from** ~**5% of new cars sold** in 2020
- **Government subsidies have supported sales** over the past several years
- Despite increasing penetration as a share of new vehicle sales, **EVs will take time to constitute a significant share of vehicles on the road** as the existing fleet turns over gradually

Background

- **Road transportation represents ~12% of all anthropogenic GHG** on a CO2-equivalent basis
- The global market for **electric vehicles has experienced significant growth** in recent years
- Increasing **awareness of climate change, advancements in battery technology,** government incentives, and falling costs have contributed to the rapid adoption of EVs

Solution details

- Continued EV adoption will be **driven by improved technology** (e.g., range, charging time, etc.) and **decreased upfront costs**
- Greater EV adoption will also **require expanding existing infrastructure**, including charging networks and power grids
- To maximize abatement potential, adoption of **EVs must be complemented with renewable energy integration**

Electric LDV

Source: Climate Watch; Our Word in Data; IEA

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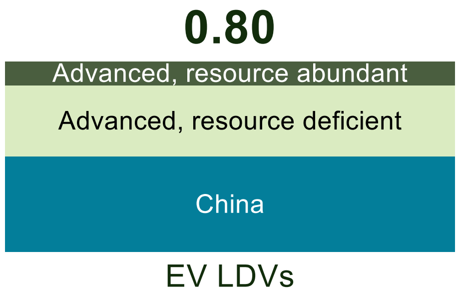
3

Increased EV penetration could reduce emissions by ~0.8 Gt CO_2e in 2035, through subsidies and technological innovation

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	Other
Markets	• Increase diversity of non-SUV EV vehicle models • Invest in vehicle charging infrastructure • Increase market competition to drive down upfront price	• Additional investment in vehicle charging infrastructure	• Decrease upfront purchase price • Improve access to low-cost charging infrastructure
Technology	• Improve vehicle range, charging time, and lower battery costs	• Improve vehicle range, charging time, and lower battery costs	• Improve vehicle range, charging time, and lower battery costs
Policy	• Achieve ICE phase-out targets • Improve supply chain resilience and diversification • Reform grid permitting	• Support purchase incentives and strict registration requirements	• Increase adoption of electrified 2- and 3-wheelers

Electric LDV

Note: (1) Includes plug-in hybrid electric vehicles
Source: Our World in Data; IEA; OpenMinds research and lit. scan

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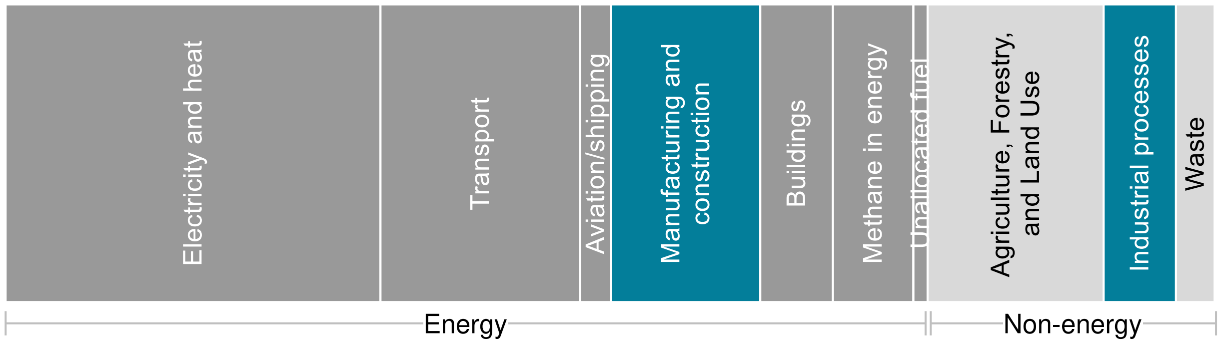
Heavy industry will require coordination to accelerate solutions

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- Industrial energy intensity has historically **improved at a rate of only ~1% p.a. since 2000**, lagging intensity improvements in transportation and buildings
- Adoption of new technology has been **gradual due to low production equipment turnover rates**
- However, some companies are starting to realize the **economic benefits of improved energy efficiency** in addition to improving their environmental footprint

Background

- In order to achieve reduced energy intensity, heavy industries (e.g., steel, cement, etc.) require **improved energy efficiency and electrification of processes**
- However, **many processes have high heat requirements** that render them difficult to abate
- Abatement will require company **coordination**, **government support, and technological development**

Solution details

- **Emerging economies present a growing opportunity** in the space because they can install lower carbon technology (e.g., monitoring, optimization software, etc.) during first construction of plants
- Opportunities for electrification such as electric arc furnaces, electric boilers, and induction heating are **greatest in low- and medium-heat processes**

Industrial Solutions

Source: Climate Watch; Our Word in Data; IEA

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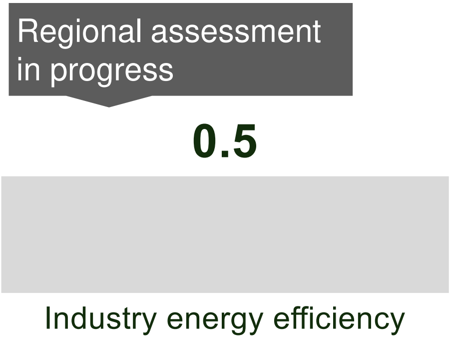
Industrial solutions could reduce emissions by ~0.5 Gt CO_2e by 2035, driven by less energy intensive processes

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	India	Other
Markets	• Invest in research and development • Electrify low- to medium-heat processes	• Establish carbon markets to financially incentivize growing companies to decarbonize	• Expand energy grid to support electrification of heavy industry	• Establish carbon markets to financially incentivize growing companies to decarbonize
Technology	• Enable use of electricity for high-heat processes	• Implement efficient technologies in new factories	• Improve monitoring and control technology	
Policy	• Provide incentives (i.e., green bonds) for energy efficient investments	• Subsidize research and development of efficient technologies	• Continue PAT[2] scheme in energy intensive industries • Expand minimum efficiency standards	

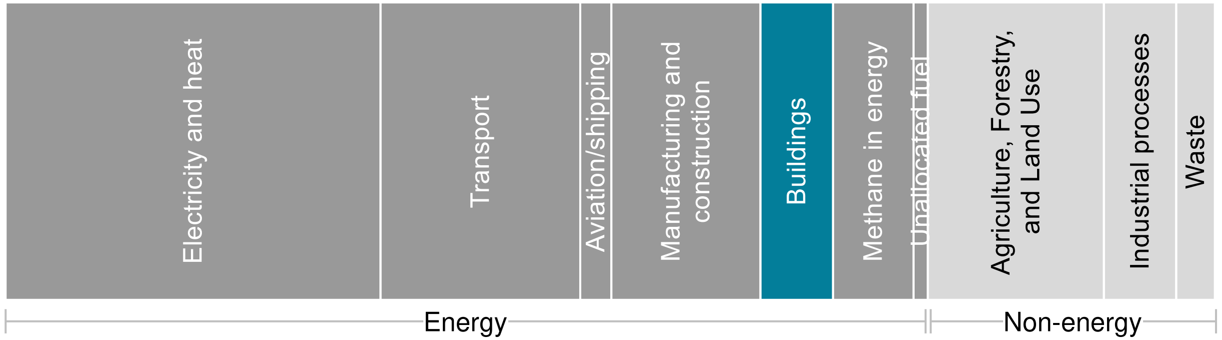
Note: (1) Data for 2019; (2) PAT = perform, achieve, and trade scheme, which is an energy efficiency trading scheme
Source: Our World in Data; IEA; OpenMinds research and lit. scan

3

Building emissions may be mitigated by transitioning to heat pumps, supported by public awareness

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- In 2021, heat pumps supplied only ~**10% of heating for all building types**
- Global **heat pump sales have grown at 11-13% p.a.** the past two years, with Europe in particular seeing significant growth as natural gas prices increased
- **Policy support has driven significant uptake** in countries such as Norway, Sweden, and Finland

Background

- **Almost half of building energy use** comes from space and water heating
- Heat pumps **function by extracting heat from a source** (usually air or ground) and then transferring that heat
- Heat pumps can lead to **50%+ in energy savings** compared to conventional heating systems (i.e., commercial electric)
- **Up to 3x energy is produced** compared to energy consumed by heat pumps

Source: Climate Watch; Our Word in Data; IEA; Lit. scan

Solution details

- Countries with high demand for heat pumps often face **supply chain issues**
- Expansion will require significant **growth in the number of contractors and the supply of heat pumps**
- High upfront costs of installation also deter consumers from purchasing heat pumps but can be addressed through **improved education about the lifetime cost competitiveness of heat pumps**

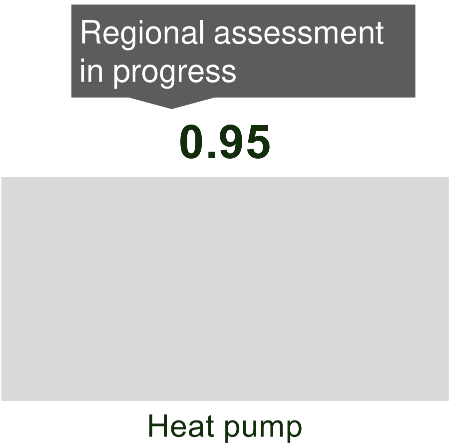
Heat Pumps

Heat pump development and deployment could play a critical role in lowering building emissions

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Actions across archetypes to achieve abatement potential

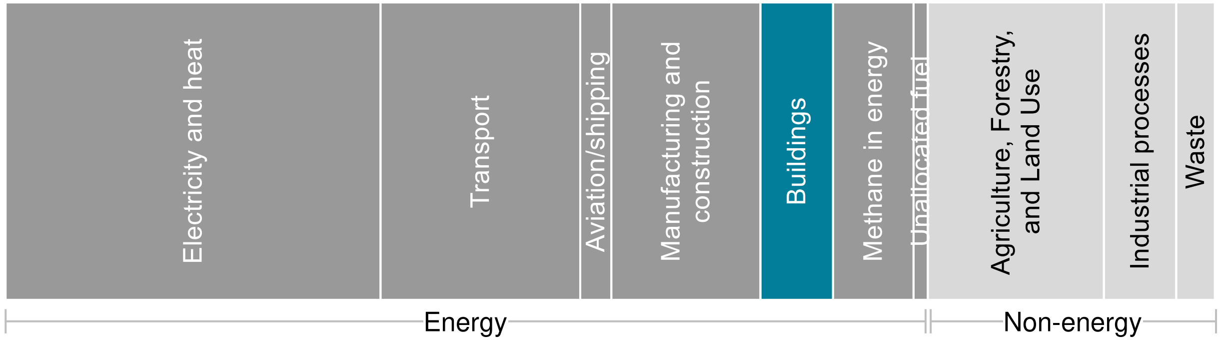
Enabler	Advanced	China
Markets	• Scale up heat pump manufacturing capacity • Promote heat pumps as economic option to consumers • Standardize qualifications and increase number of experts (e.g., plumbers, pipefitters, etc.) • Adopt alternative business models	• Increase number of heat pump installers, particularly in rural areas • Scale up heat pump manufacturing capacity
Technology	• Commercialize cold climate air-source heat pumps supported by gas furnaces • Develop and deploy electricity demand-side management technologies	• Develop and deploy electricity demand-side management technologies
Policy	• Provide subsidies to offset high initial installation costs of heat pumps	• Provide subsidies to offset high initial installation costs of heat pumps

Note: (1) Data for 2019
Source: Our World in Data; IEA; OpenMinds research and lit. scan

Technology to improve building efficiency is available, but requires support to achieve uptake

Emissions

Global greenhouse gas emissions – share of total (2019)



Current state

- **80+ countries have mandatory or voluntary building efficiency codes** in place (~30% increase since 2015)
- However, **building codes vary in coverage** (i.e., single family, multifamily, commercial, etc.), stringency, and level of enforcement
- **Broad uptake has been challenging** due to lack of incentives to adopt new technology and high upfront costs to consumers

Background

- To decrease emissions, **new and existing buildings will need to be more energy efficient** and have a higher share of their energy come from electricity
- **Space heating is the most energy intense** residential activity, followed by appliances and water heating
- Emissions can be reduced through **replacement with new technology and monitoring** to improve efficiency

Solution details

- Solutions **generally leverage existing technologies** (e.g., high R-value insulation, smart meters) but must be **adopted across new construction and existing buildings** through retrofits
- Regulations are an important driver of uptake, but they **require both adoption and enforcement**
- High upfront costs can be overcome by improved **education about cost savings** or increased cost competitiveness

Buildings efficiency

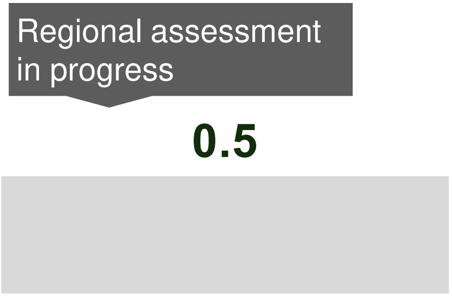
Source: Climate Watch; Our Word in Data; IEA; Lit. scan

Buildings energy efficiency could reduce emissions by ~0.5 Gt CO_2e by 2035, driven by retrofits and updated policies

Abatement potential

Projected greenhouse gas abatement by solution in 2035

Gigatons of CO_2-equivalent



Actions across archetypes to achieve abatement potential

Enabler	Advanced	China	India	Other
Markets	• Retrofit and replace existing units with low carbon appliances and materials	• Equip new buildings with low carbon appliances and materials	• Expand grid to enable electrification in buildings	• Improve cost competitiveness of energy efficient technologies
Technology	• Drive improvements in appliance efficiency and building materials (e.g., low carbon materials, cork insulation, etc.)			
Policy	• Subsidize efficiency improvements • Enforce minimum energy performance standards	• Develop disclosure requirements • Enforce and improve standards for near-zero energy buildings	• Enforce commercial efficiency standards • Subsidize LEED-certified buildings construction	• Establish new construction efficiency requirements • Update building codes for least efficient buildings

Note: (1) Data for 2019
Source: Our World in Data; IEA; OpenMinds research and lit. scan

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Agenda

01 Solutions approach

02 Solution assessment framework

03 Top 10 solutions overview

04 Country archetypes

05 Appendix A: Detail on Top 10 solutions

06 Appendix B: Background on methane

We identified metrics that characterize how countries make choices with respect to climate and energy

We considered many metrics…

Traditional energy reserves per capita	Energy consumption per capita	Emissions per capita	Access to electricity	Electricity prices	Percent electricity from renewables
Percent of average household income spent on electricity	Deaths from air pollution	GDP per capita	Access to technology	Access to clean water	Access to education
Access to clean cooking fuel	Wind potential	Solar potential	Other natural resource reserves (e.g., hydro)	Public transportation availability	

filtered based on several criteria…

The metric is measurable 〉 **Data for given metric is available for all or most countries** 〉 **Source for the data is reliable and recent** 〉 **Metric is meaningful for country-level decisions about energy and climate**

and two metrics emerged

- **Countries arrange themselves around two dimensions:** traditional energy reserves per capita & gross domestic product per capita
- These metrics will **inform how countries approach the energy transition**
- Additional considerations not included in current approach: current stated policy, public perception, geopolitical environment

Archetypes inform priorities and challenges for countries as they navigate the energy transition

Advanced economy

Resource abundant

A — Advanced economy with abundant traditional energy reserves

Challenge: Balance use of traditional energy with low carbon energy to maintain energy security & affordability, sustain economic growth, and achieve decarb goals

Resource deficient

B — Advanced economy with limited traditional energy reserves

Challenge: Invest in low carbon energy to enhance energy security, promote economic growth, and achieve decarb goals

Emerging economy

C — China

Challenge: Reduce reliance on traditional energy sources and emerge as a global leader in renewable technology innovation

D — India

Challenge: Balance decarb goals with growing energy demand in a manner that supports economic growth and strengthens energy sector

E — Emerging economy with abundant traditional energy reserves

Challenge: Balance meeting the needs of a growing economy via traditional energy production and use with investing in low carbon energy

F — Emerging economy with limited traditional energy reserves

Challenge: Expand access to affordable, reliable energy to drive economic growth and improve quality of life; build capital to fund transition to low carbon energy sources longer-term

Low-income economy

G — Low-income economy with untapped traditional energy reserves

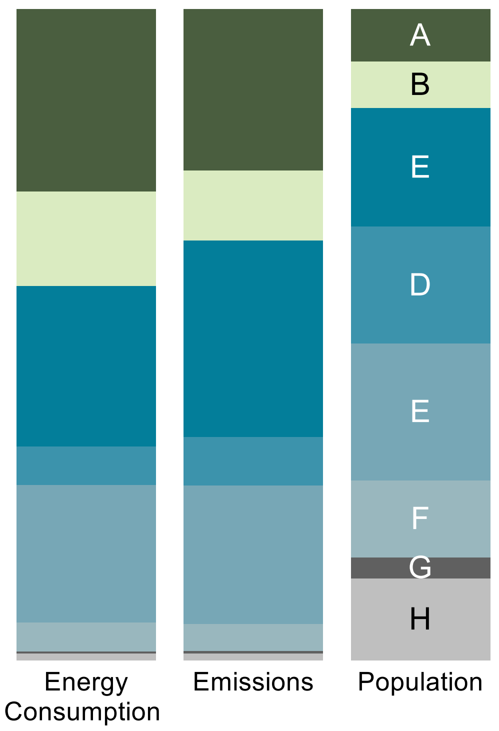
Challenge: Attract investment in traditional energy resources to improve energy access and spur economic growth

H — Low-income economy with limited traditional energy reserves

Challenge: Lift the country out of energy poverty with limited resources

← GDP per capita

Split by archetypes



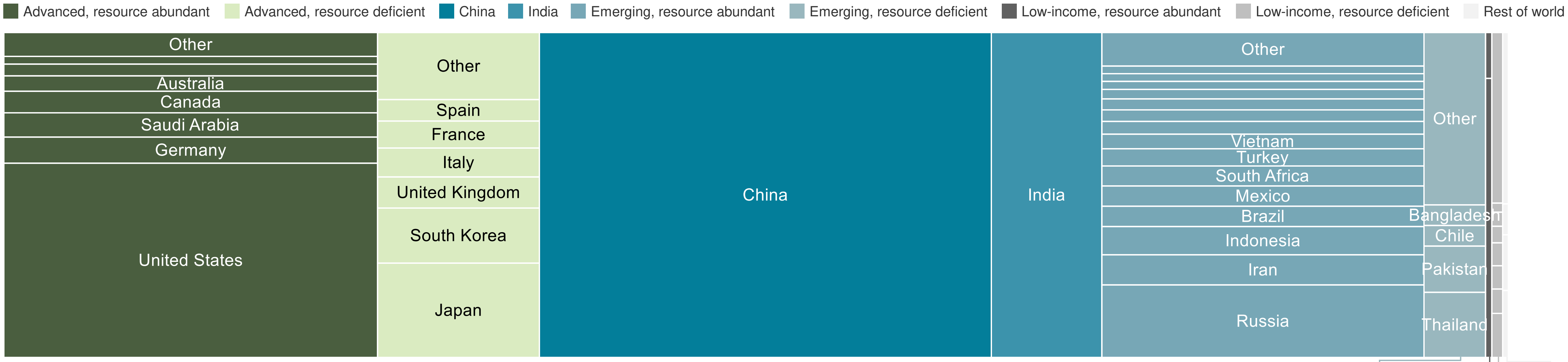
Note: GDP per capita <$5,100 – Low Income; $5,100 > & < $30,000 Emerging ; > $30,000 Advanced (2017 International $, PPP adjusted). Energy abundant countries fall into the 75th percentile of coal, oil and gas reserves per capita combined

Sources: Our World in Data, IEA, Global Carbon Atlas, EIA, EuroMonitor, World Bank

Crucially, economies not considered "advanced" account for the bulk of population, energy, and emissions

Total emissions by archetype

Percent of CO_2 emissions – 2019



	Advanced, resource abundant	Advanced, resource deficient	China	India	Emerging, resource abundant	Emerging, resource deficient	Low-income, resource abundant	Low-income, resource deficient	Rest of world
% of emissions	25%	11%	30%	7%	21%	4%	1%	0%	0%
% of final energy consumption	27%	13%	22%	7%	21%	5%	2%	2%	1%
% of population	8%	7%	18%	18%	21%	12%	11%	3%	1%

Globally, these countries account for **83% of the population**, **59% of primary energy consumption**, and **64% of anthropogenic CO_2 emissions**

Note: CO_2 emissions includes land use, land use change and forestry and excludes non-CO2 emissions like methane
Source: Flourish, Global Carbon Atlas, OWID, IEA, EuroMonitor, EIA, World Bank

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These archetypes provide important perspective on where solutions need to be deployed

	Characteristics		CO2 emissions by fuel (2019)[1]					Greenhouse gas emissions by sector (2019)[3]								
	GDP[5]	Pop.	Coal	Oil	Gas	Other[2]	Total	Electricity & heat	Transport	Mfr'ing. & Constr.	Other industry	Agri-culture	Buildings	Fugitive emissions	All other sources[4]	Total
A Advanced, resource abundant	27%	8%	5%	11%	8%	1%	**25%**	7%	5%	2%	1%	2%	2%	1%	1%	**21%**
B Advanced, resource deficient	19%	7%	3%	5%	3%	0%	**11%**	3%	2%	1%	1%	1%	1%	0%	1%	**10%**
C China	18%	19%	21%	4%	2%	3%	**30%**	11%	2%	6%	2%	1%	1%	1%	0%	**25%**
D India	7%	18%	5%	2%	0%	0%	**7%**	3%	1%	1%	0%	1%	0%	0%	0%	**7%**
E Emerging. resource abundant	20%	21%	6%	7%	7%	2%	**21%**	6%	3%	2%	1%	3%	2%	3%	4%	**25%**
F Emerging. resource deficient	6%	12%	1%	2%	1%	0%	**4%**	1%	1%	0%	0%	1%	0%	0%	1%	**6%**
G Low income, resource abundant	1%	3%	0%	0%	0%	0%	**<1%**	0%	0%	0%	0%	0%	0%	0%	0%	**<1%**
H Low income, resource deficient	2%	11%	0%	0%	0%	0%	**<1%**	0%	0%	0%	0%	2%	0%	0%	3%	**5%**
Total	**100%**	**100%**	**41%**	**31%**	**21%**	**7%**	**100%**	**32%**	**14%**	**13%**	**6%**	**12%**	**6%**	**7%**	**10%**	**100%**
Top 10 Solutions			Coal-to-gas switching, CCUS	Methane abatement	Methane abatement			Heat pumps, Building efficiency	Transportation efficiency and electrification	Industrial efficiency and electrification	Industrial efficiency and electrification		Building efficiency	Methane abatement		

Coal-to-gas switching · CCUS · Methane abatement · Heat pumps · Building efficiency · Transportation efficiency and electrification · Industrial efficiency and electrification · High impact areas

Note: (1) Share of global production-based CO2 emissions. Does not account for emissions embedded in traded goods. Excludes non-CO2 greenhouse gases like methane. Excludes land use change. (2) "Other" includes process emissions from cement manufacturing, flaring, and other industry process emissions. (3) Share of global greenhouse gas emissions, including non-CO2 GHG emissions like methane. Includes land use change. Does not include International Bunkers, which is 1,400 Mt of GHG (4) "All other sources" includes aviation/shipping, land use change and forestry, waste, and other fuel combustion. (5) % of global total
Source: Our World in Data; Climate Watch; Global Carbon Project; World Bank

Putting it all together, a picture emerges of where these solutions need to be deployed at the regional level…

Breakdown of projected emissions abatement potential by 2035 by solution by archetype – in CO_2e

Projected solution abatement potential by 2035 for relevant archetype/Total addressable archetype emissions from underlying source or end-use[3]

	Clean up traditional energy			Low-carbon electricity		Efficiency and electrification			
	Methane abatement for energy[1]	Coal-to-gas switching[2]	CCUS in electricity	Accelerate wind and solar	Promote nuclear	Transport energy efficiency	Accelerate EVs	Industry energy efficiency	Buildings energy efficiency
A Advanced, resource abundant	0.4 Gt/0.8 Gt	0.4 Gt/0.6 Gt	0.2 Gt/3.5 Gt	0.5 Gt/3.5 Gt	0.1 Gt/3.5 Gt	0.1 Gt/2.7 Gt	0.1 Gt/2.7 Gt	0.1 Gt/0.5 Gt	0.1 Gt/0.9 Gt
B Advanced, resource deficient	0.0 Gt/0.1 Gt	0.1 Gt/0.2 Gt	0.1 Gt/1.5 Gt	0.6 Gt/1.5 Gt	0.1 Gt/1.5 Gt	0.1 Gt/1.0 Gt	0.3 Gt/1.0 Gt	0.0 Gt/0.3 Gt	0.2 Gt/0.5 Gt
C China	0.3 Gt/0.6 Gt	0.2 Gt/2.0 Gt	0.0 Gt/5.6 Gt	0.6 Gt/5.6 Gt	0.1 Gt/5.6 Gt	0.0 Gt/0.9 Gt	0.4Gt/0.9 Gt	0.2 Gt/1.2 Gt	0.2 Gt/0.5 Gt
D India	0.0 Gt/0.1 Gt	0.1 Gt/0.5 Gt	0.0 Gt/1.2 Gt	0.1 Gt/1.2 Gt	0.1 Gt/1.2 Gt	0.0 Gt/0.3 Gt	0.0 Gt/0.3 Gt	0.0 Gt/0.2 Gt	0.0 Gt/0.2 Gt
E Emerging, resource abundant	0.6 Gt/1.5 Gt	0.2 Gt/0.5 Gt	0.0 Gt/3.2 Gt	0.4 Gt/3.2 Gt	0.0 Gt/3.2 Gt	0.1 Gt/1.6 Gt	0.0 Gt/1.6 Gt	0.2 Gt/0.5 Gt	0.0 Gt/0.8 Gt
F Emerging, resource deficient	0.0 Gt/0.1 Gt	0.0 Gt/0.1 Gt	0.0 Gt/0.5 Gt	0.1 Gt/0.5 Gt	0.0 Gt/0.5 Gt	0.0 Gt/0.4 Gt	0.0 Gt/0.4 Gt	0.0 Gt/0.2 Gt	0.0 Gt/0.1 Gt
G Low income, resource abundant	0.0 Gt/0.1 Gt	0.0 Gt /0.0 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.1 Gt	0.0 Gt/0.1 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.0 Gt
H Low income, resource deficient	0.0 Gt/0.0 Gt	0.0 Gt /0.0 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.0 Gt	0.0 Gt/0.1 Gt	0.0 Gt/0.1 Gt	0.0 Gt/0.1 Gt	0.0 Gt/0.1 Gt
Total	**1.3 Gt/3.3 Gt**	**1.0 Gt/3.9 Gt**	**0.3 Gt/15.6 Gt**	**2.3 Gt/15.6 Gt**	**0.4 Gt/15.6 Gt**	**0.3 Gt/7.1 Gt**	**0.8 Gt/7.1 Gt**	**0.5 Gt/3.0 Gt**	**0.5 Gt/3.0 Gt**

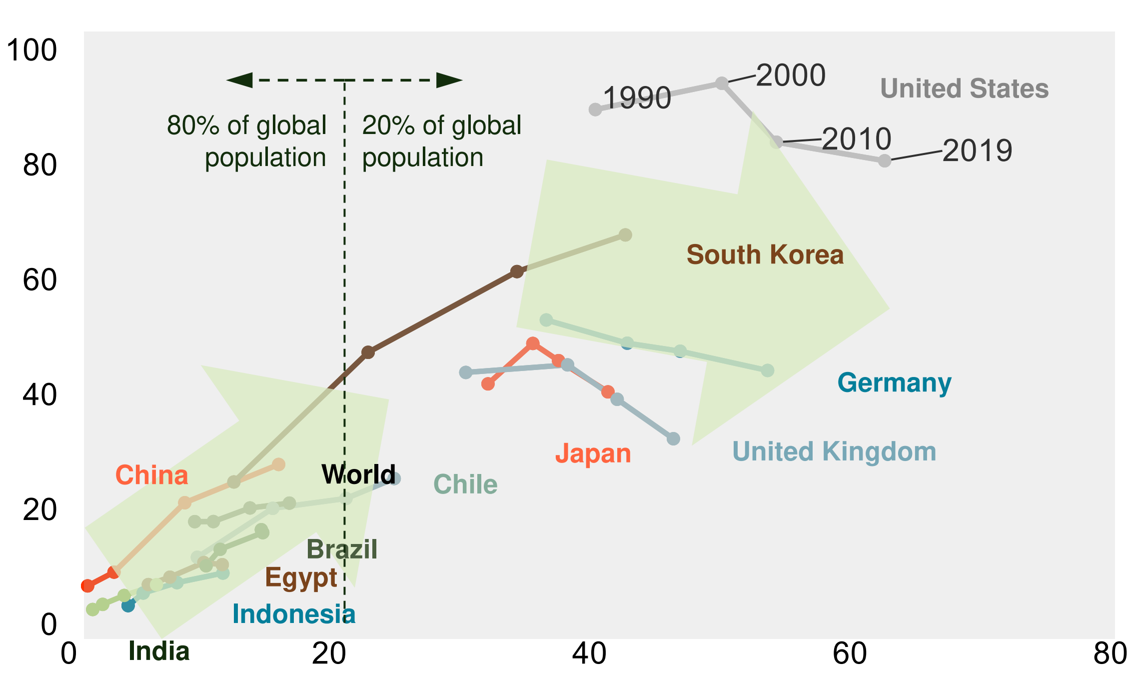
Work in progress

Note: (1) Considers all energy related methane emissions; tons of methane converted to CO2-equivalent using a GWP-100 factor of 30 (2) Projected solution abatement potential by 2035 reflects net emissions reduction on switching from coal to gas; total addressable archetype emissions reflect 50% of total emissions from coal power generation as gas power generation is ~50% less carbon intensive than coal power generation (3) Total addressable archetype emissions reflect 2019 emissions from relevant underlying source or end-use; these may overlap across solutions where multiple solutions target the same underlying emissions sources or end-uses (e.g., coal-to-gas switching and CCUS in electricity both target emissions from power generation)
Source: Our World in Data, IEA, Ember, Lit search; GEM

So far, only advanced economies have decoupled economic growth from energy consumption and emissions

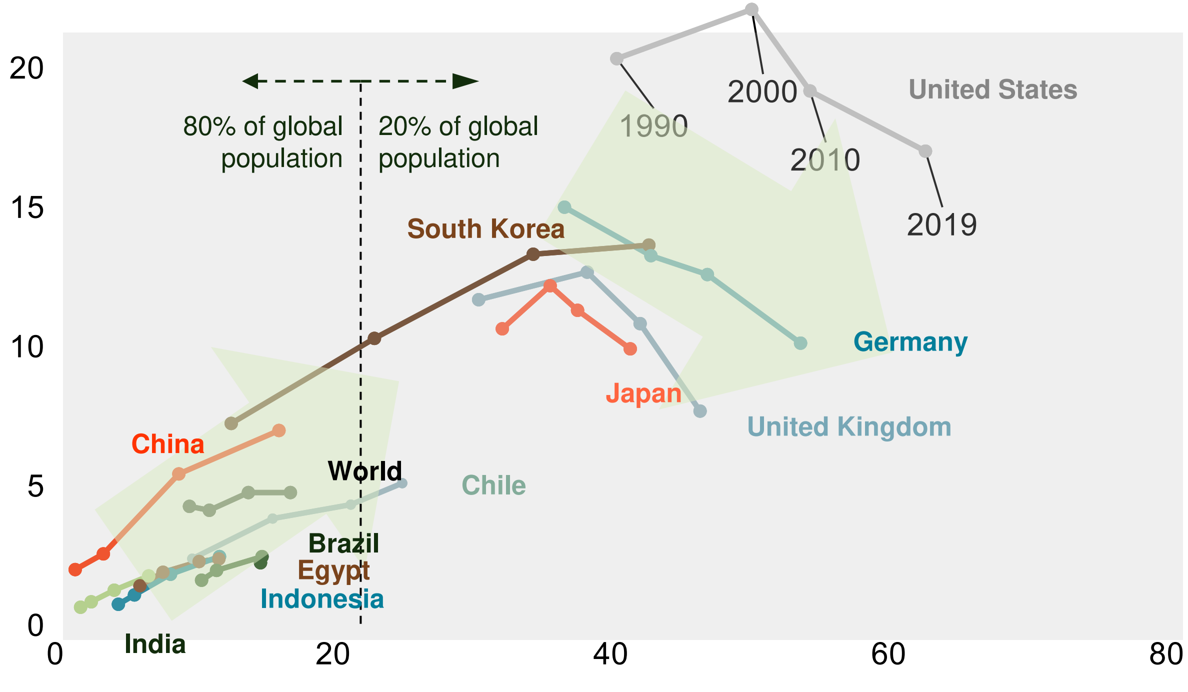
Primary energy consumption per capita

(MWh. Only 1990, 2000, 2010, and 2019 plotted for each country)



CO2 emissions per capita

(Tons of CO2*. Only 1990, 2000, 2010, and 2019 plotted for each country)



Note: * CO_2 emissions are consumption based (i.e., adjusted for trade) and do not include non-CO_2 emissions like methane
Source: Our World in Data; World Bank; Global Carbon Project; BP Statistical Review of World Energy, 2021

Detailed list of country archetypes (1/2)

Advanced, resource abundant	Advanced, resource deficient		China	India	Emerging, resource abundant	
Australia	Aruba	Panama	China	India	Algeria	Malaysia
Bahrain	Austria	Portugal			Angola	Mexico
Brunei Darussalam	Belgium	Puerto Rico			Argentina	Mongolia
Canada	Bermuda	Romania			Azerbaijan	Russia
Czechia	Cayman Islands	San Marino			Bolivia	Serbia
Denmark	Estonia	Singapore			Brazil	South Africa
Germany	Finland	Slovakia			Bulgaria	Trinidad & Tobago
Hungary	France	Slovenia			Colombia	Turkey
Israel	Hong Kong	South Korea			Egypt	Turkmenistan
Kuwait	Iceland	Spain			Equatorial Guinea	Ukraine
New Zealand	Ireland	St. Kitts and Nevis			Gabon	Uzbekistan
Norway	Italy	Sweden			Greece	Venezuela
Oman	Japan	Switzerland			Guyana	Vietnam
Poland	Latvia	United Kingdom			Indonesia	
Qatar	Lithuania				Iran	
Saudi Arabia	Luxembourg				Iraq	
United Arab Emirates	Malta				Kazakhstan	
United States	Netherlands				Libya	

Note: GDP per capita <$5,100 – Low Income; $5,100 > & < $30,000 Emerging ; > $30,000 Advanced (2017 International $, PPP adjusted). Energy abundant countries fall into the 75th percentile of coal, oil and gas reserves per capita combined. China and India fall within emerging abundant but are individual archetypes due to population size and unique characteristics
Source: Our World in Data

Detailed list of country archetypes (2/2)

Emerging, resource deficient			
Albania	Dominican Republic	Maldives	Seychelles
Antigua and Barbuda	Ecuador	Marshall Islands	Sri Lanka
Armenia	El Salvador	Mauritania	St. Lucia
Bangladesh	Eswatini	Mauritius	St. Vincent and the Grenadines
Barbados	Fiji	Moldova	Suriname
Belarus	Georgia	Montenegro	Thailand
Belize	Ghana	Morocco	Tonga
Bhutan	Grenada	Namibia	Tunisia
Bosnia and Herzegovina	Guatemala	Nauru	Turks and Caicos Islands
Botswana	Honduras	Nicaragua	Uruguay
Chile	Jamaica	North Macedonia	
Costa Rica	Jordan	Palau	
Cote d'Ivoire	Kosovo	Paraguay	
Croatia	Kyrgyzstan	Peru	
Curacao	Lao PDR	Philippines	
Cyprus	Lebanon	Samoa	

Low income, resource abundant
Chad
Nigeria
Papua New Guinea
Zimbabwe

Low income, resource deficient		
Afghanistan	Kiribati	Somalia
Benin	Lesotho	Sudan
Burkina Faso	Liberia	Tajikistan
Burundi	Madagascar	Tanzania
Cambodia	Malawi	Timor-Leste
Cameroon	Mali	Togo
Central African Republic	Micronesia	Tuvalu
Comoros	Mozambique	Uganda
DRC	Myanmar	Vanuatu
Djibouti	Nepal	Zambia
Ethiopia	Niger	
Gambia	Rwanda	
Guinea	Sao Tome and Principe	
Guinea-Bissau	Senegal	
Haiti	Sierra Leone	
Kenya	Solomon Islands	

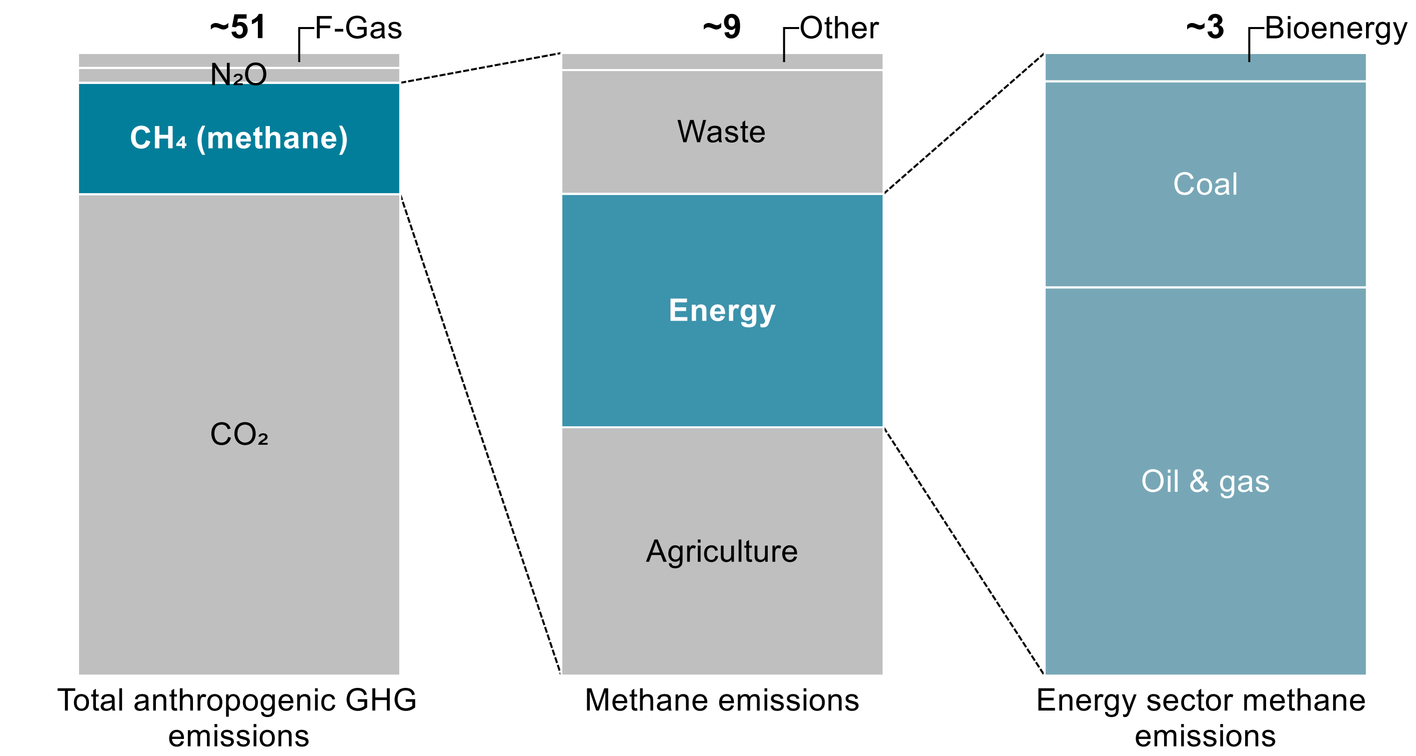
Note: GDP per capita <$5,100 – Low Income; $5,100 > & < $30,000 Emerging ; > $30,000 Advanced (2017 International $, PPP adjusted). Energy abundant countries fall into the 75th percentile of coal, oil and gas reserves per capita combined. China and India fall within emerging abundant but are individual archetypes due to population size and unique characteristics
Source: Our World in Data

Agenda

Global energy-related methane emissions account for ~7% of anthropogenic greenhouse gas emissions

Global anthropogenic greenhouse gas (GHG) emissions, 2019

BILLION TONS OF CO_2-EQUIVALENT



Methane is an extremely potent greenhouse gas: its **global warming potential is >80X** that of CO_2 over a 20-year period

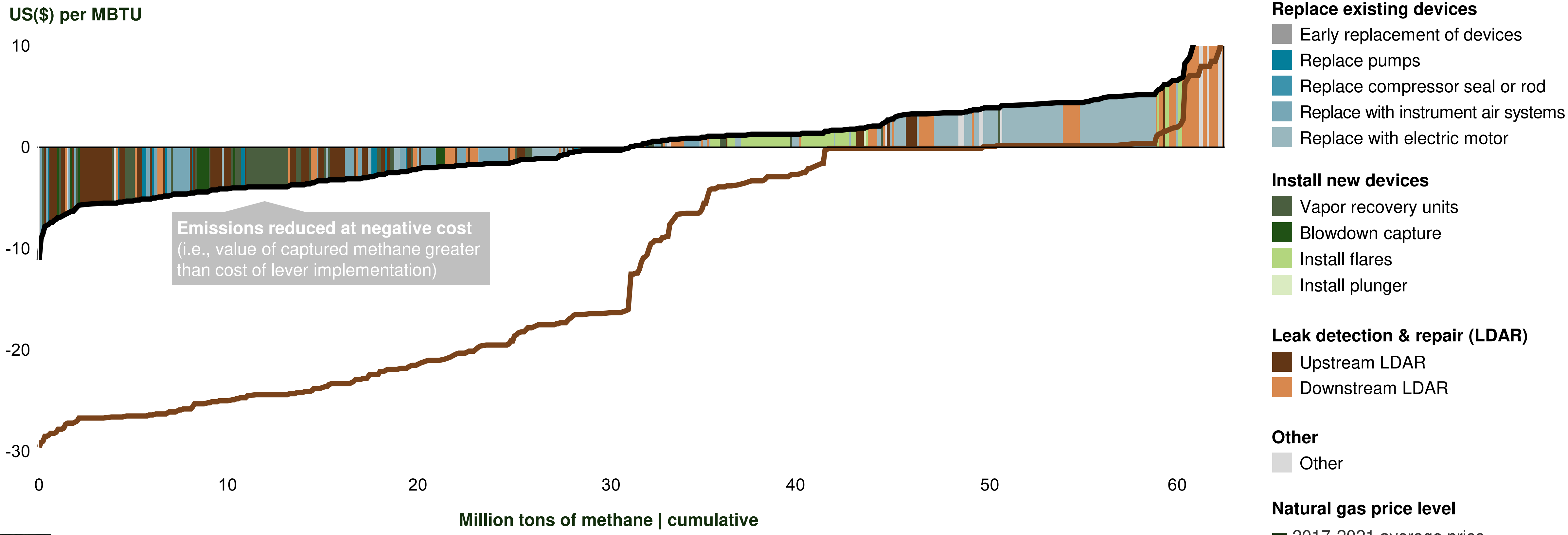
On a CO_2 equivalent basis, the **energy sector** (including coal) emitted **3-4 billion tons of methane in 2019**. This is approximately the equivalent of…

- **India's total GHG emissions** in 2019 (3.4 Gt CO_2-e)
- The annual emissions from **800 million passenger cars**

Note: GHG=greenhouse gas; passenger cars calculation assumes 4.6 metric tons of CO2 emitted per car (US average)
Source: Our World in Data; Climate Watch, Historical GHG Emissions; IEA, Methane Tracker

There is clear scope to reduce methane emissions in O&G, often cost effectively

Oil & gas methane abatement cost curve, 2017-2021 prices and 2022 prices (IEA analysis)



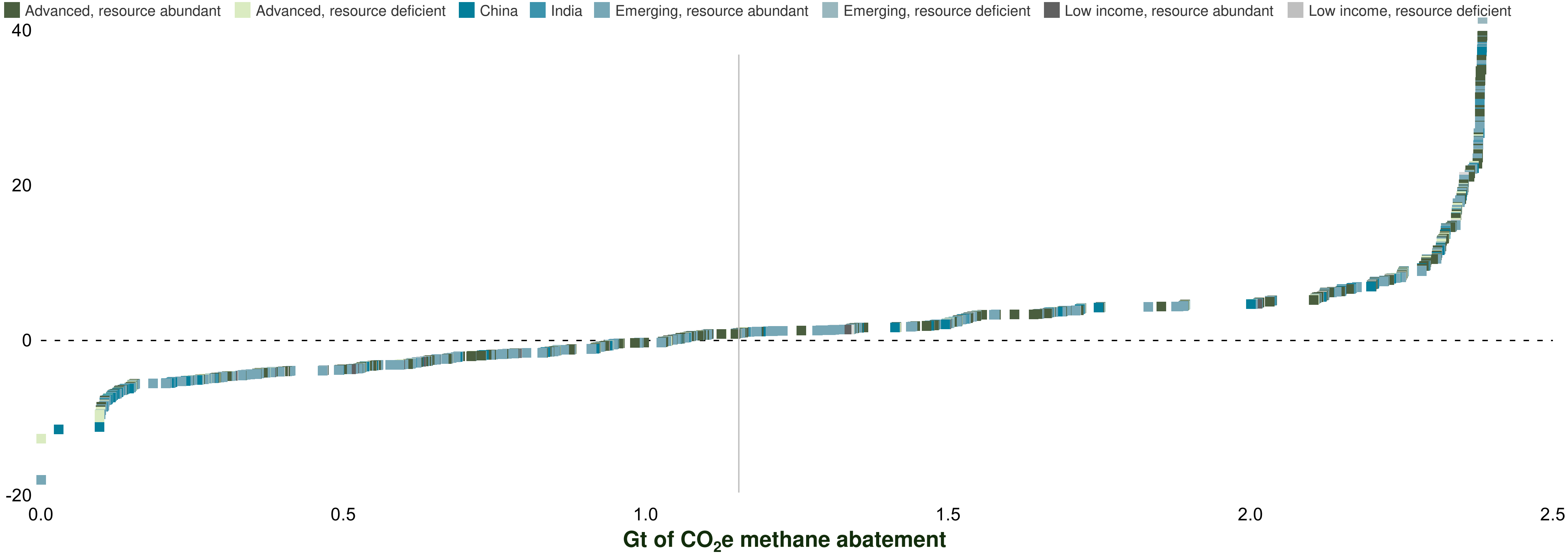
Note: Henry Hub average annual spot price: 2017-2021 = $2.92/Mbtu; 2022 = $6.45/Mbtu
Source: IEA

5

~1 Gt of CO2e of methane can be abated at net negative cost, with ~half coming from emerging resource abundant countries

Oil, gas, and coal methane abatement cost

$/MMBtu



Note: Methane cost assumptions based on average prices from 2017-21; methane to CO_2e conversion factor of 30; 1,000,000 Kt in 1 Gt
Source: IEA (2022), Global Methane Tracker 2022, IEA, Paris https://www.iea.org/reports/global-methane-tracker-2022, License: CC BY 4.0

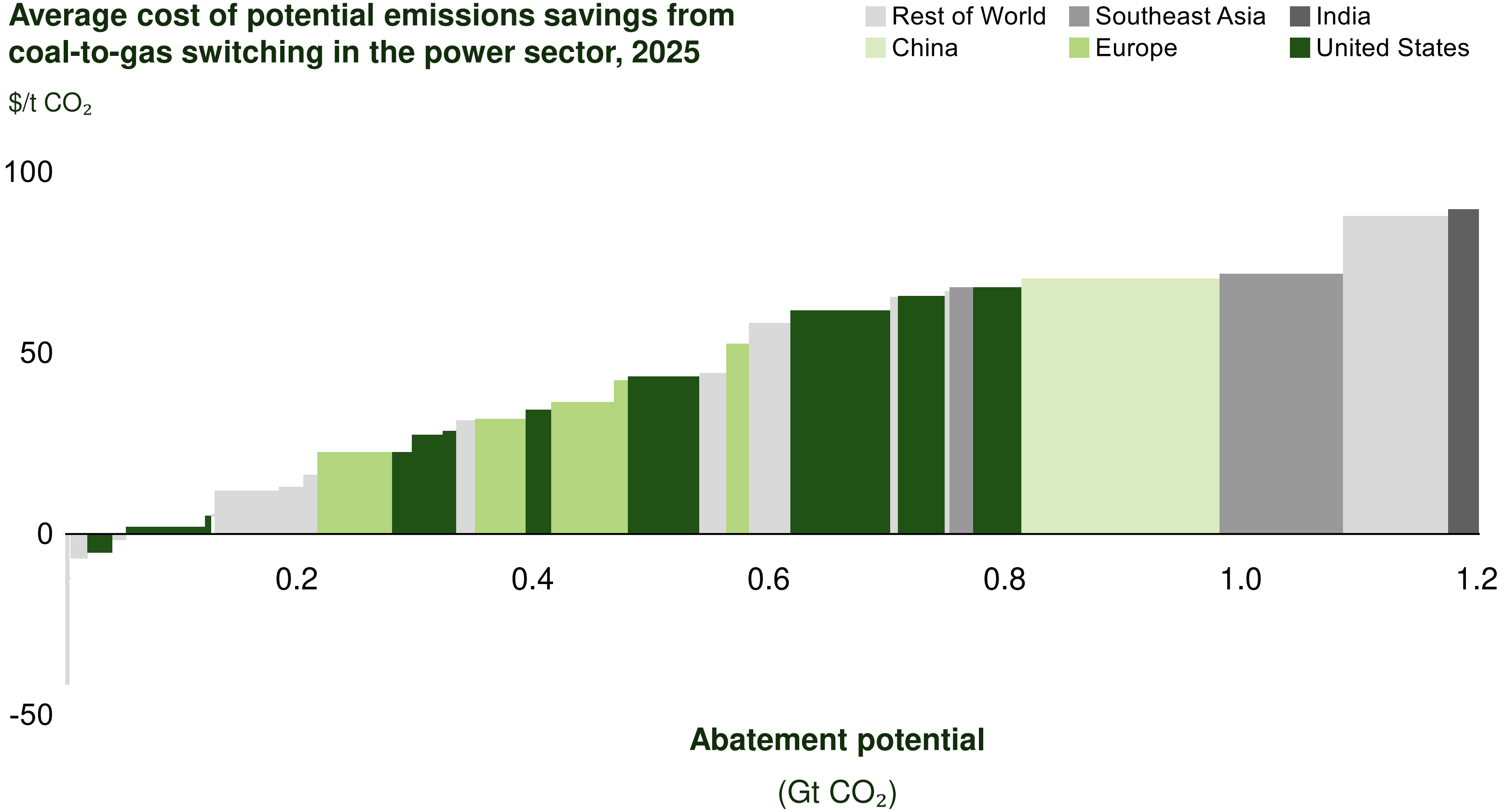
Methane Abatement

PRELIMINARY

Near-term abatement potential of ~1.2 Gt CO2, with nearly half concentrated in the U.S. and Europe

~1.2 Gt CO_2 can be abated globally by leveraging existing infrastructure

Average cost of potential emissions savings from coal-to-gas switching in the power sector, 2025



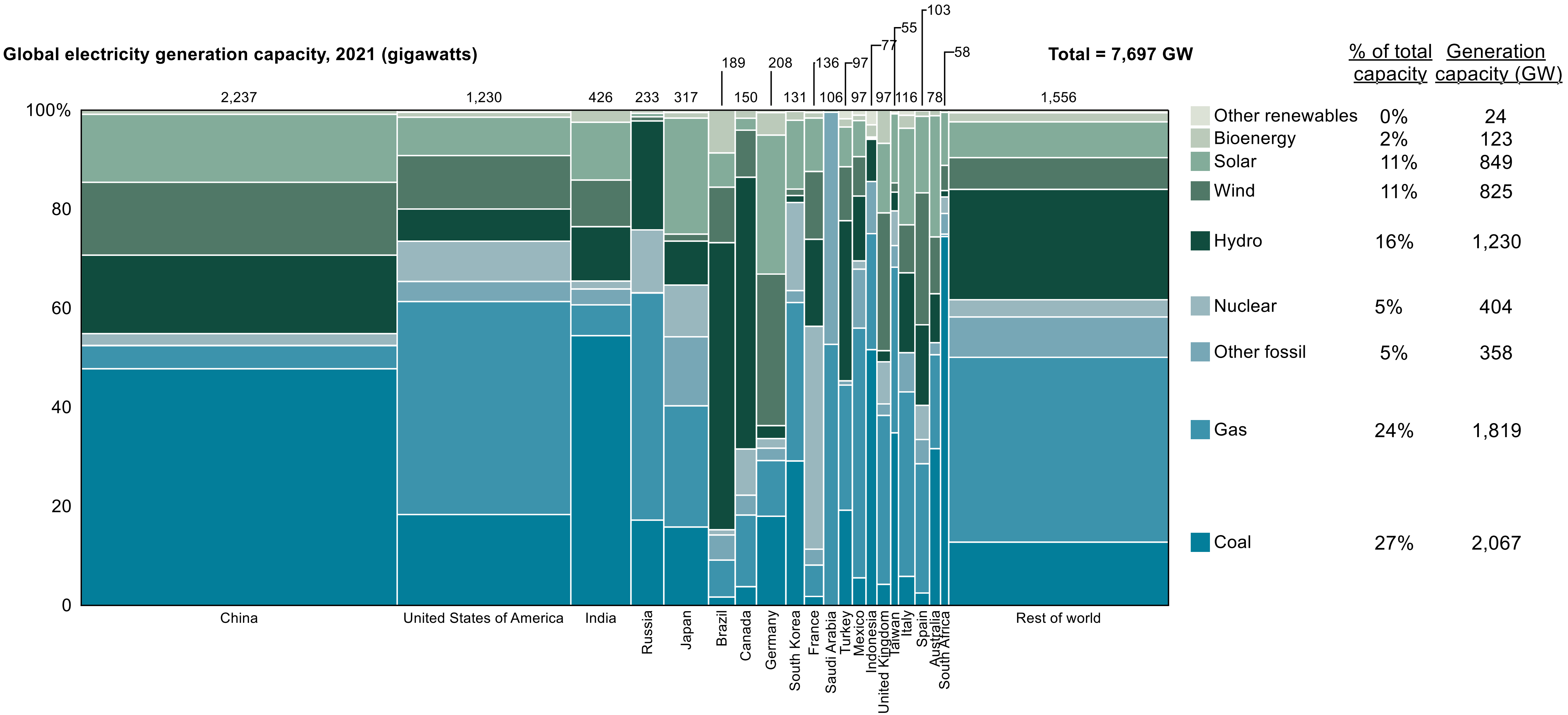
Source: IEA World Energy Outlook 2019

Commentary

- Globally, **~1.2 Gt CO_2 can be abated annually through coal-to-gas switching** in the near-term by leveraging existing infrastructure
  - Nearly half of near-term coal-to-gas switching **abatement potential concentrated in the U.S. and Europe**
- The marginal cost of this abatement ranges from -\$20/t to +\$90/t
  - **Marginal cost of abatement generally higher in China and India** given the high efficiency of the relatively young fleet of coal-fired power plants

OpenMinds

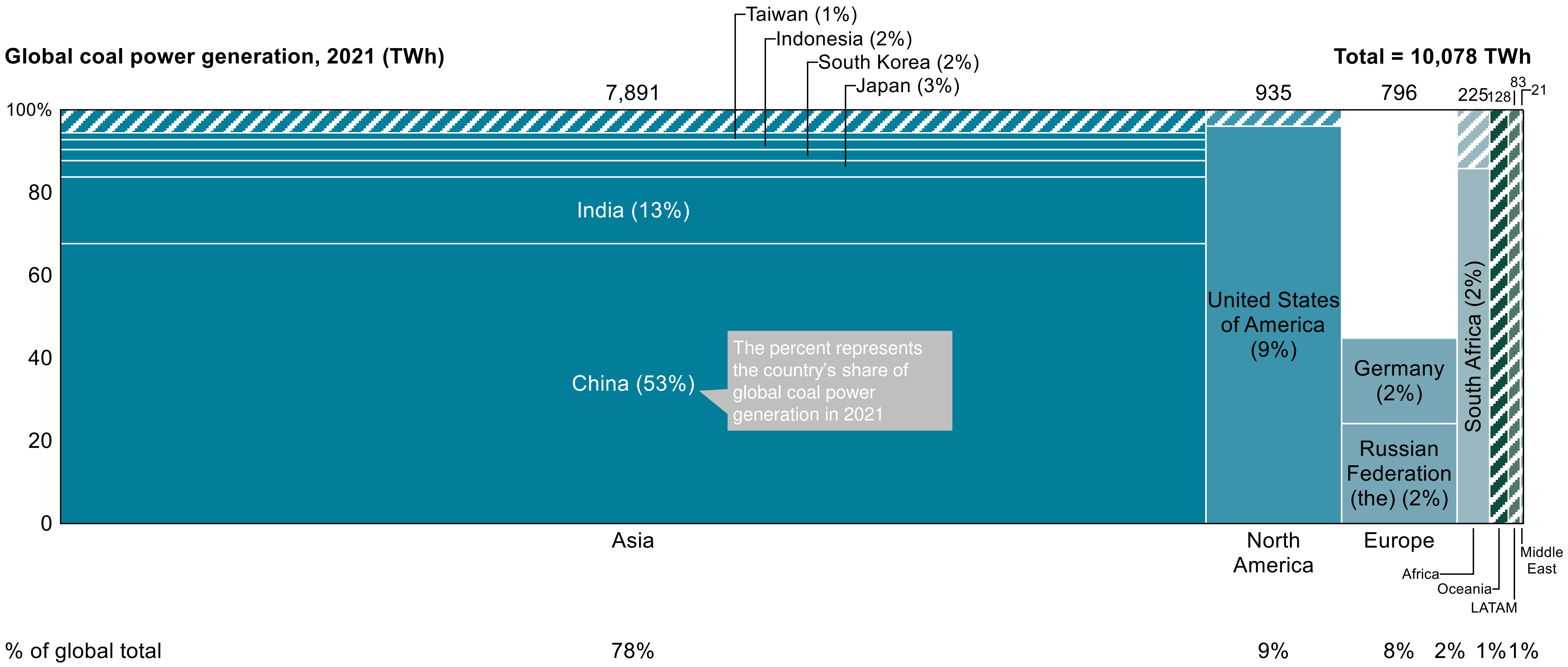
Global electricity generation capacity by country: Coal accounts for 27% of global total



Source: Ember

OpenMinds

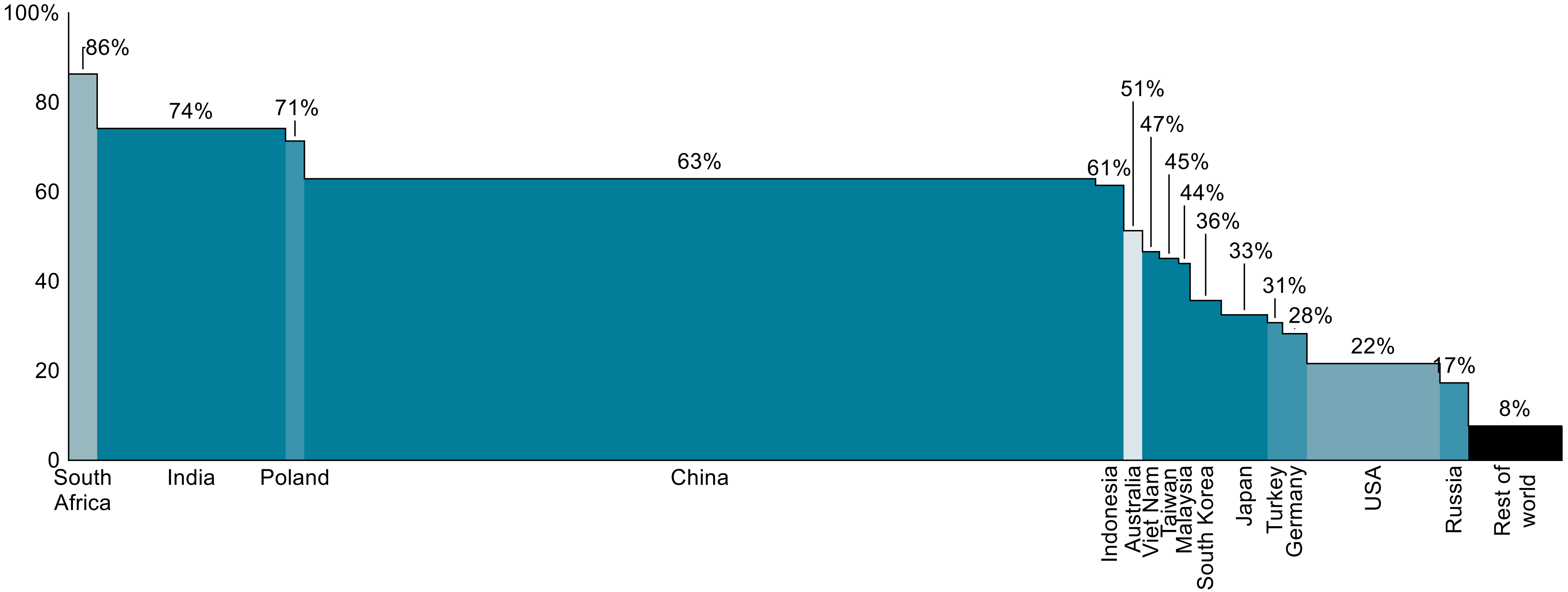
Coal in power generation: Ten countries account for 90% of global coal power production; China, India, and the US alone make up 75%



Source: Ember

Coal in power generation: Many of the top coal consuming countries are heavily dependent on it for power generation

Bar height: Coal power generation as a share of country electricity generation, 2021 (%)
Bar width: Country coal power generation as a share of global coal power generation, 2021



Source: Ember

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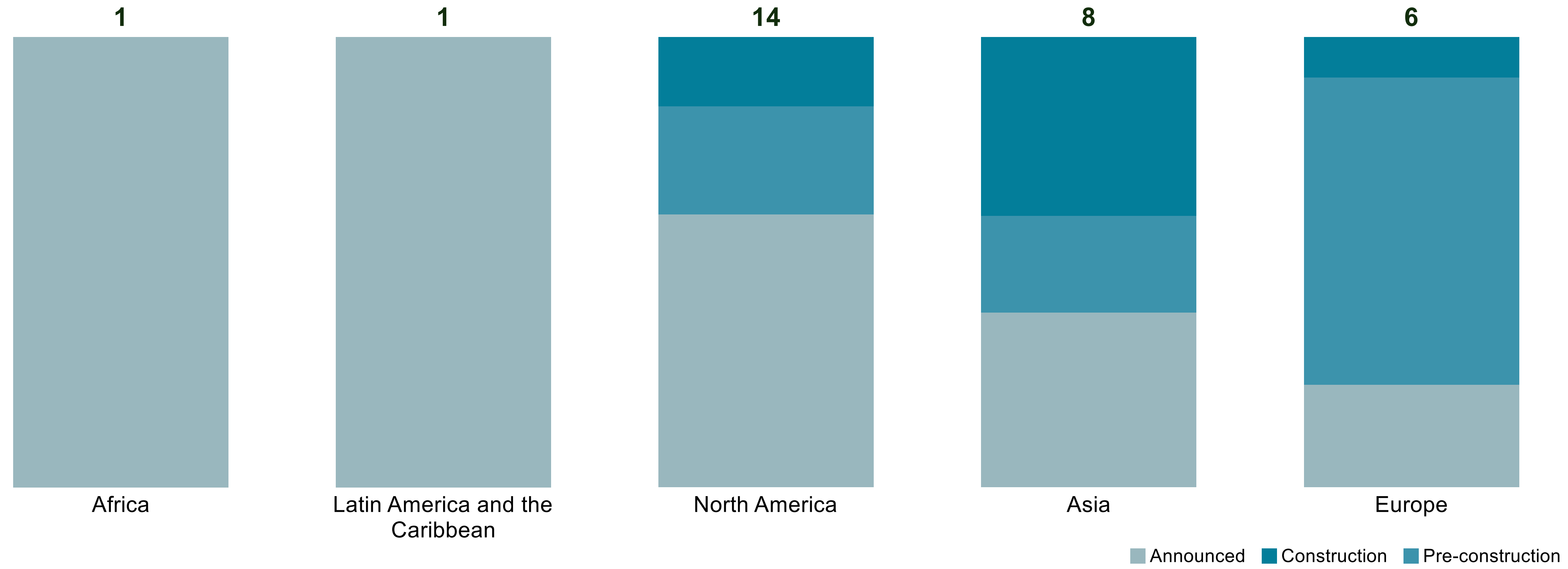
Coal-to-gas switching is under way in North America, Asia, and Europe…

Coal-to-gas conversions by region by development stage

As of February 2023 in GW



Source: Global Energy Monitor

Coal-to-gas switching

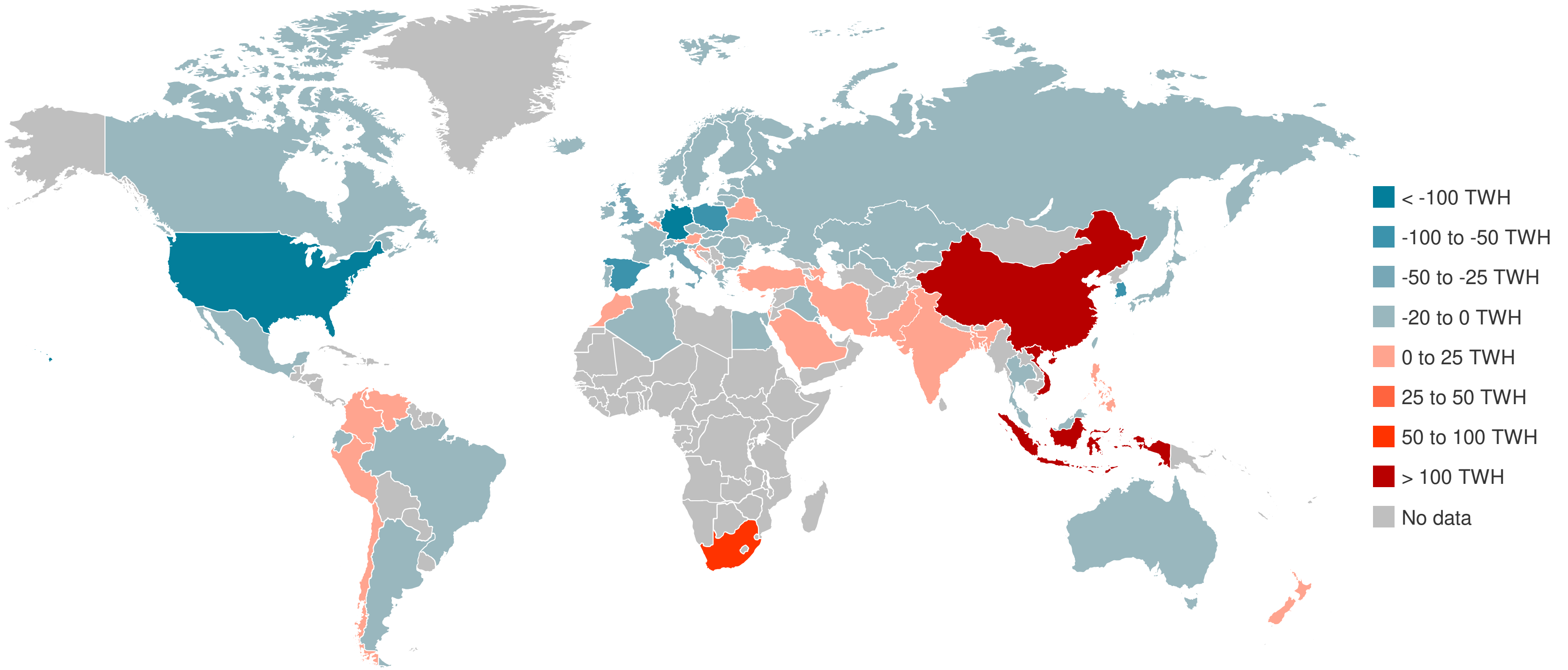
OpenMinds

…and coal energy consumption is trending down across many countries

Coal energy consumption decreased in most countries from 2018 to 2019

Annual change in coal energy consumption – 2019

Change in coal energy consumption relative to the previous year in terawatt-hours



Source: Our World in Data , NPR; Lit search

Commentary

- **Advanced economies**, both resource abundant and deficient, **were trending away from coal in 2019** compared to 2018
- **The Ukraine war resulted in a return to coal usage across the EU** as countries severed ties with Russian gas
  - EU has outlined a plan to **fully replace Russian gas by 2028**
  - EU reliance on coal likely to continue in near-term, plateau and again decrease ahead of 2035
- **India and China remain coal dependent** but have made verbal commitments to reduce coal usage by 2030s

Coal-to-gas switching

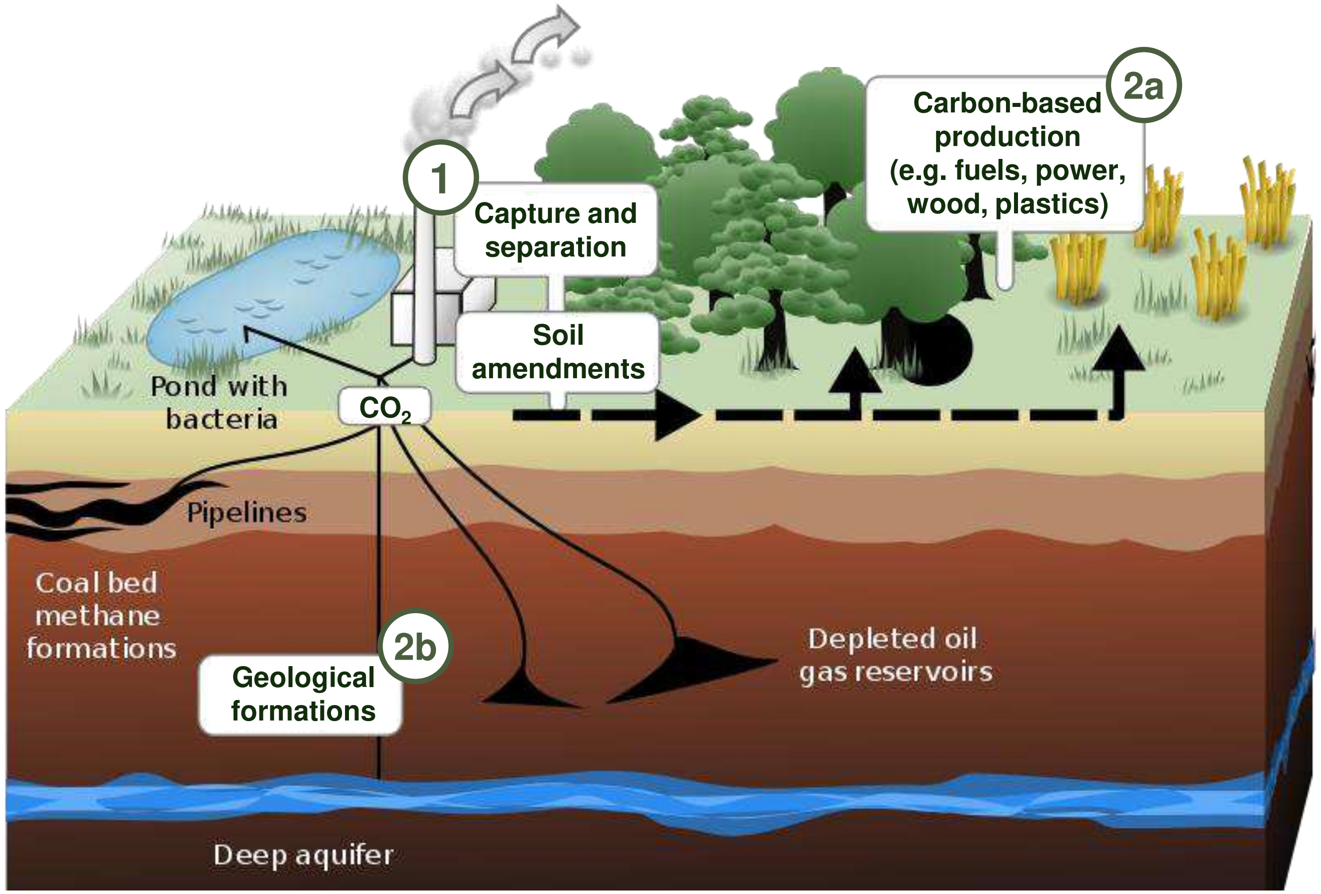
5

CCUS will be a necessary lever to achieve a low carbon economy

What is CCUS and how is it used?

- Carbon capture, utilization and storage (CCUS) is a term for **emissions reduction technologies that capture CO_2 and prevent its release into the atmosphere**
- CCUS technologies involve two broad stages:
  - (1) The **capture of CO_2** from **fuel combustion, industrial processes** or **directly from the air**, and either
  - (2a) **Re-usage** as a resource to create products or services, or
  - (2b) **Permanent storage** in geological formations
- CCUS will be key to companies **achieving ambitious energy transition targets**
- CCUS technologies are **particularly significant** for **hard-to-abate sectors** such as cement and steel
- **Regulatory support** will be crucial for CCUS technologies to **scale up** and **become economically viable**

Illustration of CCUS value chain

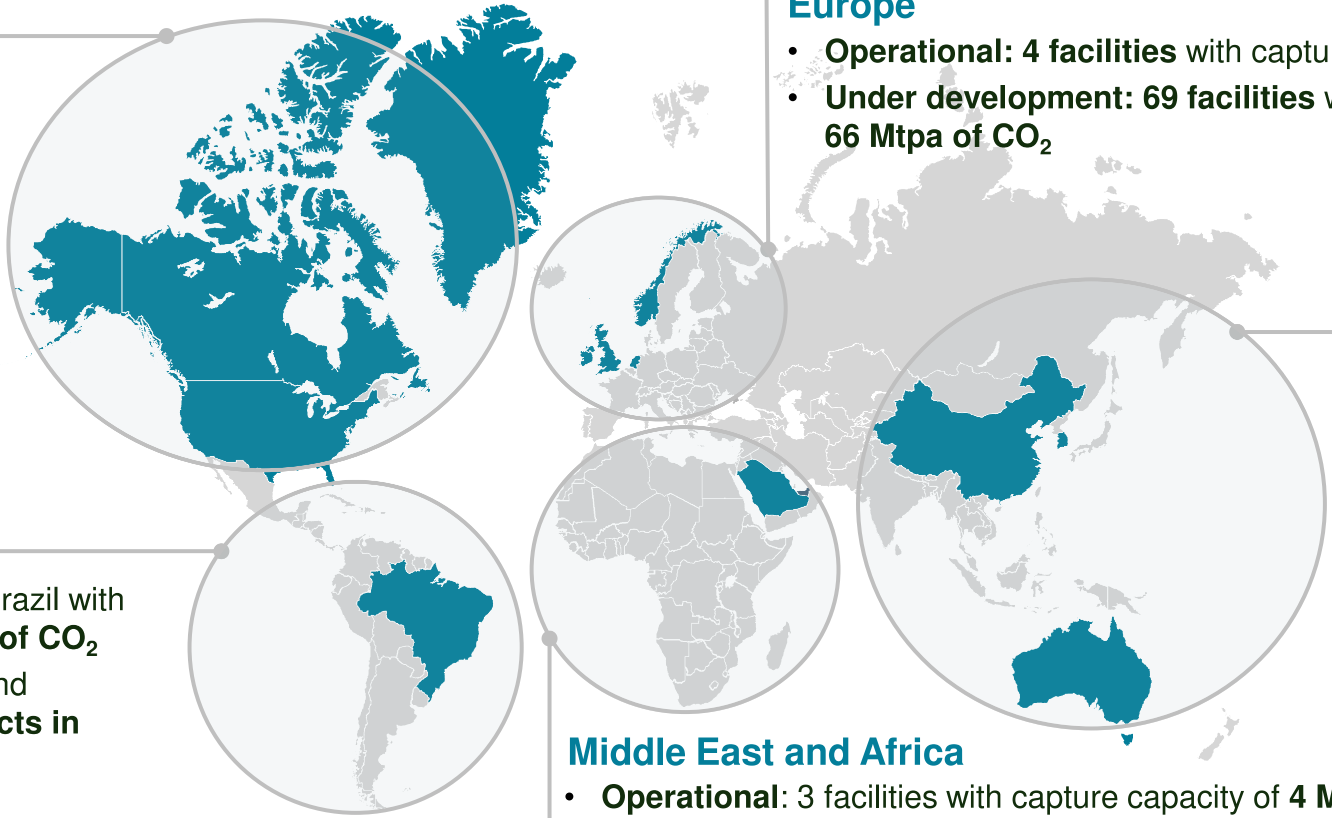


CCUS

OpenMinds

5

CCUS in electricity and industry: Currently 30 operational facilities with ~43Mtpa CO2 capacity; majority in N. America



North America

- **Operational: 18 facilities** with capture capacity of **24 Mtpa of CO_2** (13 facilities in the US, 5 in Canada)[1]
- **Under development:** 76 facilities with combined capture capacity of **94 Mtpa**

South America

- **Operational:** 1 **facility** in Brazil with capture capacity of **7 Mtpa of CO_2**
- **World Bank** CCS Trust Fund **funding 2 CCS pilot projects in Mexico**

Europe

- **Operational: 4 facilities** with capture capacity of **1.86 Mtpa of CO_2**
- **Under development: 69 facilities** with combined capture capacity of **66 Mtpa of CO_2**

Asia Pacific

- **Operational: 4 facilities** with capture capacity of **5.7 Mtpa of CO_2**
- **Under development: 17 facilities** with combined capture capacity of **37 Mtpa of CO_2**

Middle East and Africa

- **Operational**: 3 facilities with capture capacity of **4 Mtpa of CO_2**
- **Under development:** 3 facility with combined capture capacity of **3.3 Mtpa of CO_2**

CO_2

CCUS

Note: (1) Excluding two USA facilities currently suspended: Petra Nova coal station and Lost Cabin Gas Plant; Includes commercial facilities > 0.1MTPA and Orca DAC plant (Europe, 4ktpa); Large-scale defined as > 0.4Mtpa of CO_2 capacity
Source: Global CCS Institute Report, 2022; Lit search

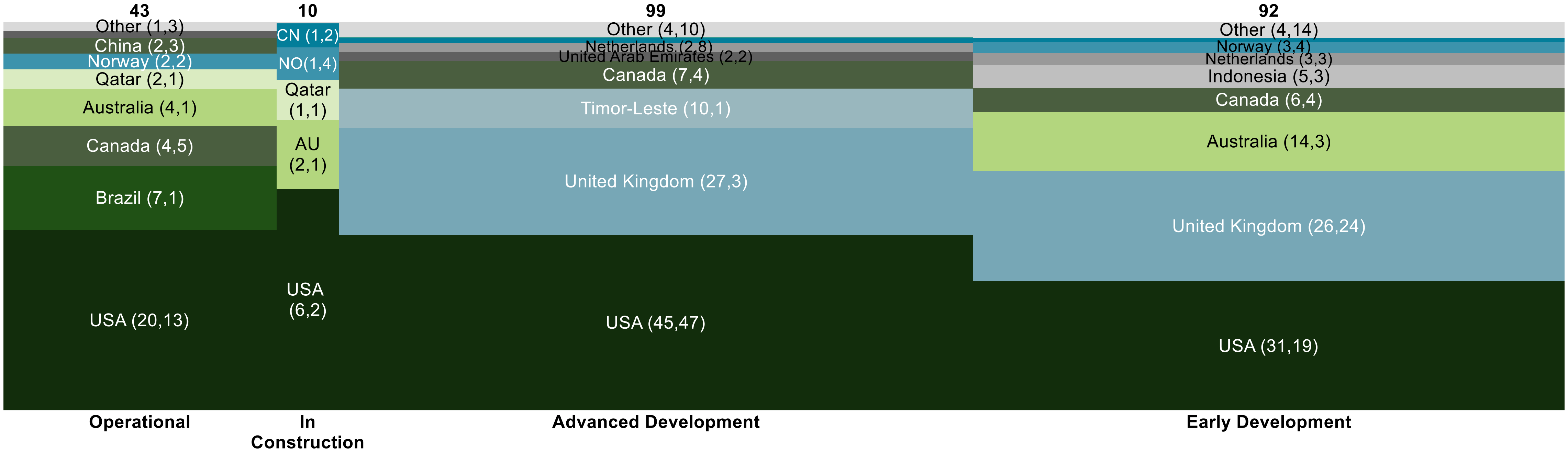
OpenMinds

5

Electricity and industry: Majority of capacity in the US, though Europe expected to see increasing share

More than ~75% of facilities are under early or advanced development

CCUS facilities by country and development stage
(volume Mtpa CO2, # facilities)



	Operational	In Construction	Advanced Development	Early Development
% of volume for perm. storage (not EOR)	29%	93%	93%	96%
# facilities	30	11	79	75

Note: "Other" includes Saudi Arabia, Hungary, Iceland, Norway, China, Belgium, Thailand, Sweden, Denmark, Australia, New Zealand, South Korea, France, Finland, Italy, Malaysia; Excluding 2 suspended operational facilities (2 Mtpa)
Source: Global CCS Institute Report, 2022, lit. search

OpenMinds

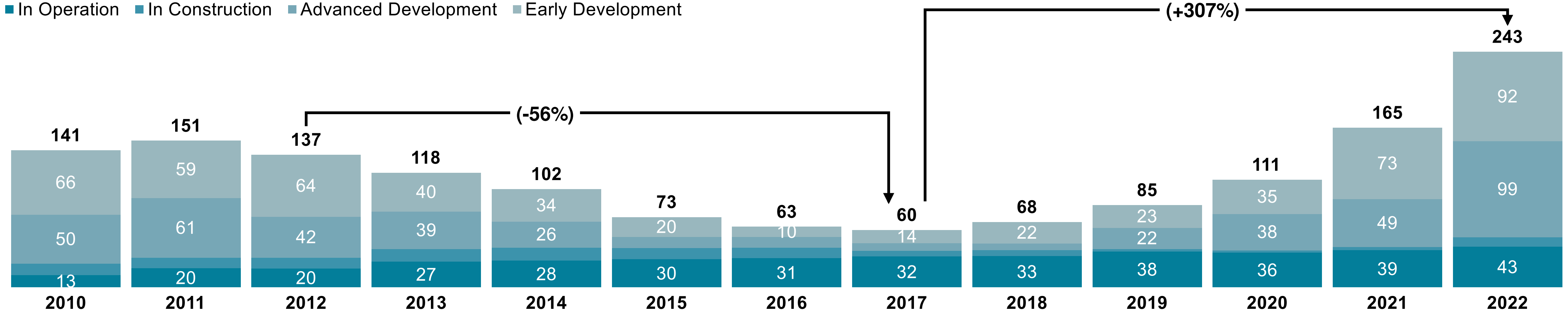
CCUS

5

Strong momentum in CCS capacity pipeline growth in past few years

Pipeline development of commercial CCS facilities by CO_2 capture capacity

2010-2022, MTCO$_2$ P.A.



Growth towards 2011 mainly driven by large **Natural Gas Processing projects**:

- Snøhvit CO_2 storage, NO (2008, 0.7 Mt/year)
- Century Plant, US (2010, 5 Mt/year)
- Petrobras Santos Basin, BR (2011, 4.6 Mt/year)

Continuous decrease in both early and advanced development phase projects from 2011-2017 driven by

- Need for recovery after financial crisis of '08-09 in private and public sector
- Low/stagnating carbon emission costs in Europe (EUA) and the US (LCFS) until 2017

Operational capacity saw a slow and steady growth during the same period from 20 to 32 Mt/Year (2012 to 2017)

Strong growth in dev. pipeline driven globally by **growing interest in CCUS** to reach net zero emission targets

- 83% of countries now with CCS in national long-term strategy
- Recognized as a decarbonisation lever at COP26
- Strong policy makers and investors appetite for committing to new projects (e.g. IRA's 45Q boost in the USA, Fit for 55 in Europe, dedicated CCUS funds in UK, NL, USA, etc.)

Majority of projects expected to materialize by 2030

CCUS

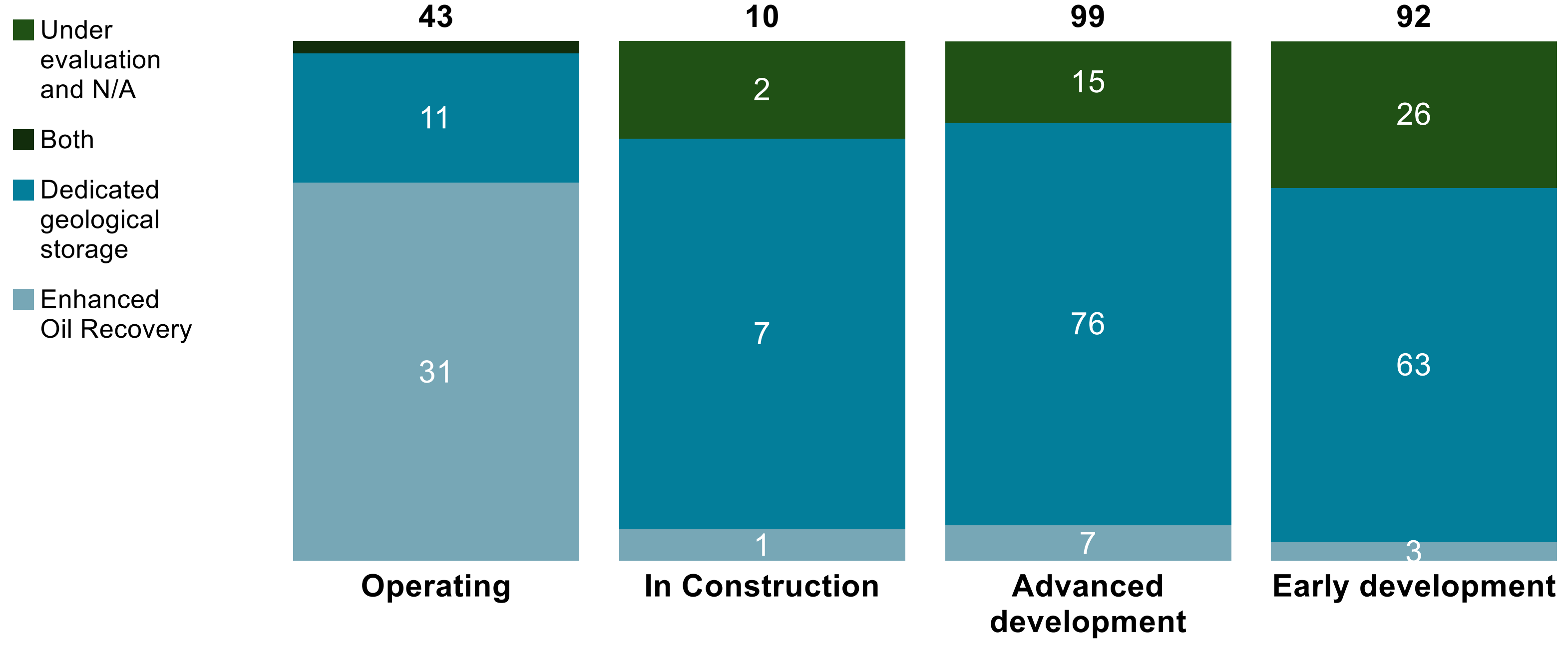
Note: Large-scale defined as > 0.4Mtpa of CO_2 capacity; 2021 and 2022 figures retreated with a new methodology, 2 suspended operational facilities excluded in 2021 and 2022 (2 Mtpa, Petra Nova and Lost Cabin Gas plant)
Source: Global CCS Institute Report, 2019, 2020, 2021 and 2022

OpenMinds

5

Electricity and industry: Majority of CCS facilities use Enhanced Oil Recovery, but geological storage growing

Global CCS facility capacity by storage type (2022, Mtpa)



	Operating	In Construction	Advanced development	Early development
# In evaluation & NA	1	4	16	29
# EOR plants	20	2	4	4
# Geological torage plants	9	5	59	42

Note: Excluding 2 suspended operational facilities (2 Mtpa)
Source: Global CCS Institute Report, 2022

Key considerations

- **Enhanced Oil Recovery** helps permanently store the **CO_2 that would have otherwise been emitted** to the atmosphere
- **31 Mtpa of CO_2 are currently stored** each year by **20 CO_2—EOR facilities in operation; additional 11 Mtpa will be stored by 10 plants in pipeline**
- **CO_2—EOR is not suitable for every oil field** and dependent on the capture cost of CO_2 which is the most expensive operational cost element of CO_2—EOR facility

CCUS

OpenMinds

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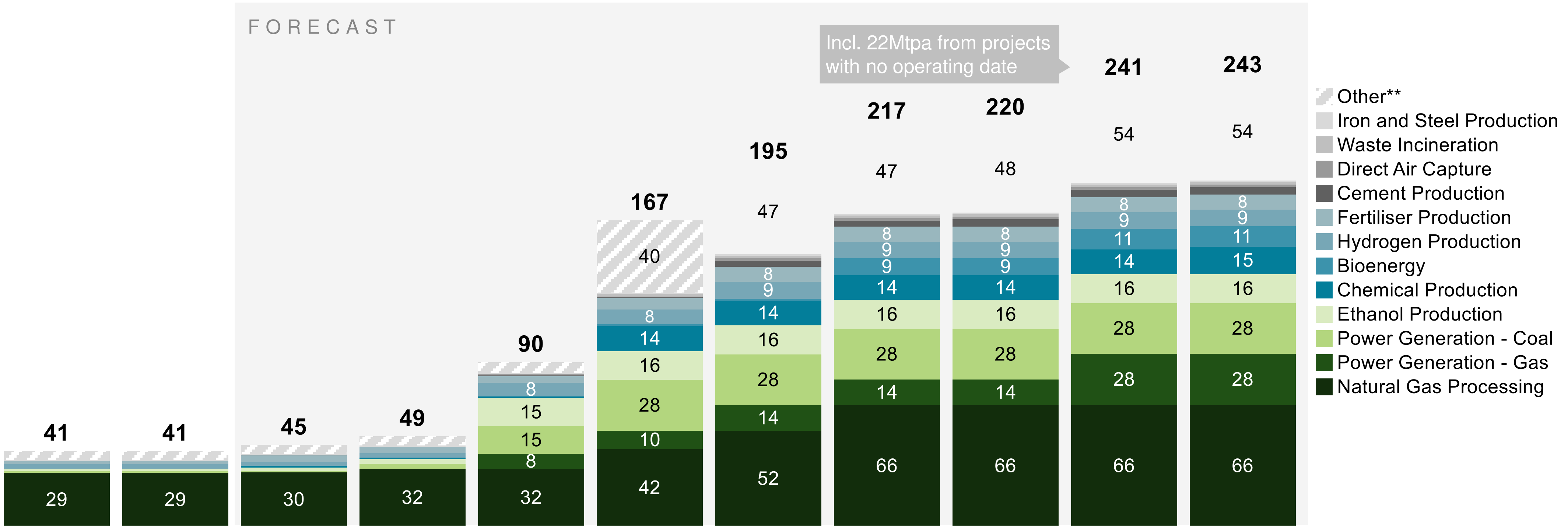
Electricity and industry: CCUS projects are emerging in a number of different applications

CCS cumulative capture capacity development by application and region, 2020-30

(Mt/year)



	2020	2021	2022	2023	2024	2025	2026	2027	2028*	2029*	2030
Americas	31	31	33	34	64	99	112	116	116	125	125
EMEA	6	6	6	6	13	54	56	64	65	73	75
APAC	5	5	6	10	13	15	27	37	38	43	43

Note: Projects with due dates in "mid 20s" were allocated in years 2024-26 (10Mt in 2024, 13 in 2025, 10 in 2026); projects with no due date were allocated to 2029 *) Capacity not yet announced for majority of 2028-2030 projects, being in the early development phase; **) Other applications include methanol production (2 projects), oil refining (4 projects), synthetic gas (1 project) and various fuel projects (24 projects)
Source: GCCSI, Global status of CCS 2021; IEA

CCUS

OpenMinds

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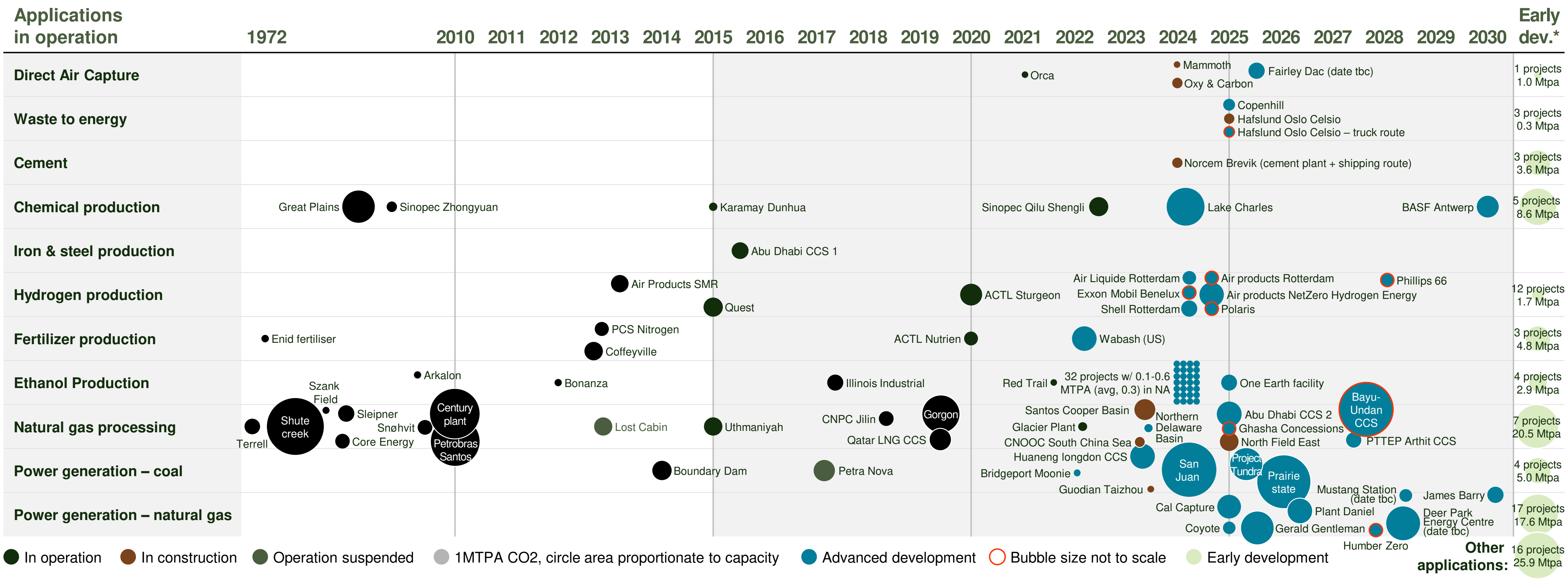
Electricity and industry: Projects coming online through 2030 bring total CO2 capture capacity to ~245Mtpa

Commercial CCS facilities by industry, commencement of operation, and CO_2 storage option



Note: Petra Nova paused operations in May 2020, due to low oil prices (E&E News, accessed 2020, November 11); (*) Capture capacity currently evaluated (not always estimated for each project)
Source: Global CCS Institute Report, 2022

CCUS

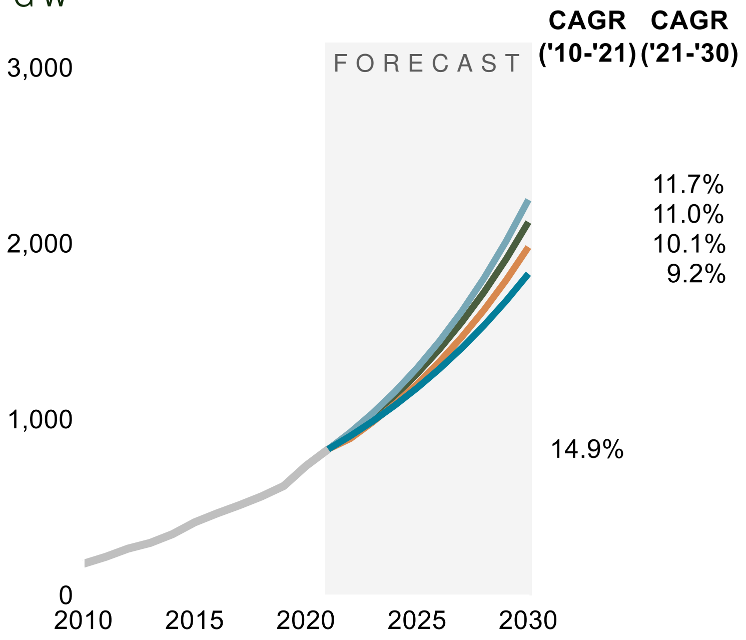
OpenMinds

5

Renewables: Realistic "today-forward" scenarios project continued growth in wind and solar capacity

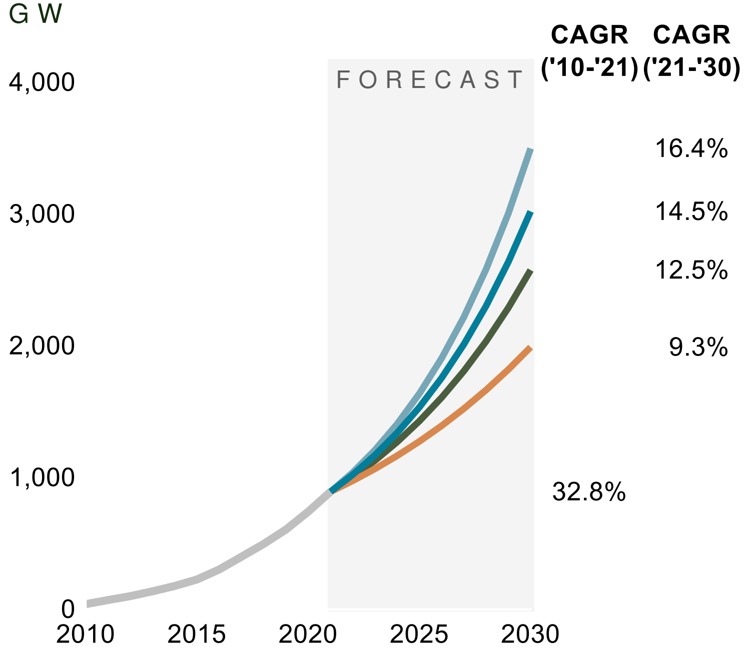
Wind capacity grows ~9-12% p.a.

Global installed wind capacity



Solar capacity grows ~9-16% p.a.

Global installed solar capacity



Historical | IEA Stated Policies | IEEJ Advanced Technologies

Commentary

- In these "today-forward" scenarios, **wind and solar continue to add capacity rapidly** through 2030, though at slightly reduced growth rates compared to historical trends from low bases
- All scenarios envision **faster growth in solar than wind** through 2030
  - IEEJ Advanced Technologies scenario projects large **majority of the world's wind and solar capacity located in Asia** by 2030
- OpenMinds projections represent **potential levels of capacity from implementation of the 'Top 10 Solutions' only** and do not consider the impact of additional policies, regulations, or solutions

Renewables

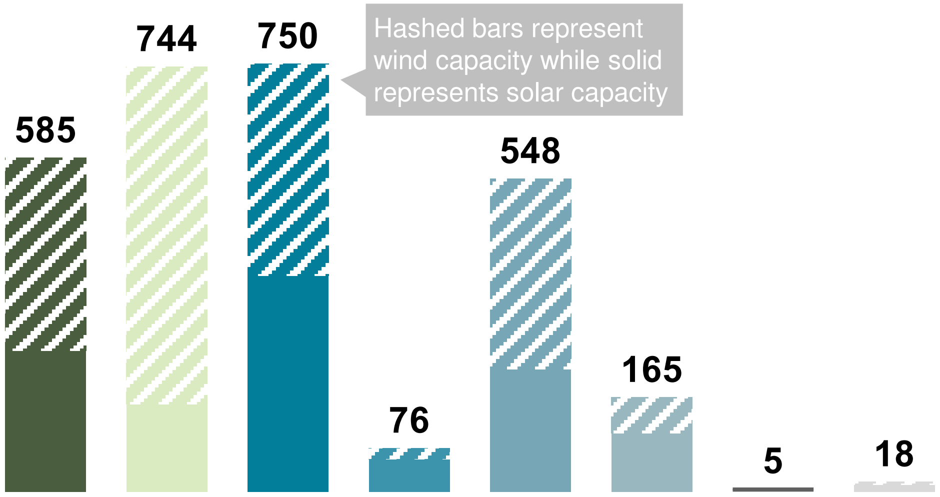
Note: (1) OpenMinds capacity projections are illustrative and do not represent a future scenario but rather the cumulative impact of the implementation of the OpenMinds 'Top 10 Solutions' only
Source: IEA, IEEJ; Climate Interactive

Advanced and emerging archetypes are adding both solar and wind energy but are bearish on nuclear (excl. China and India)

China leads solar and wind installations

Solar and Wind capacity in development[1]

G W

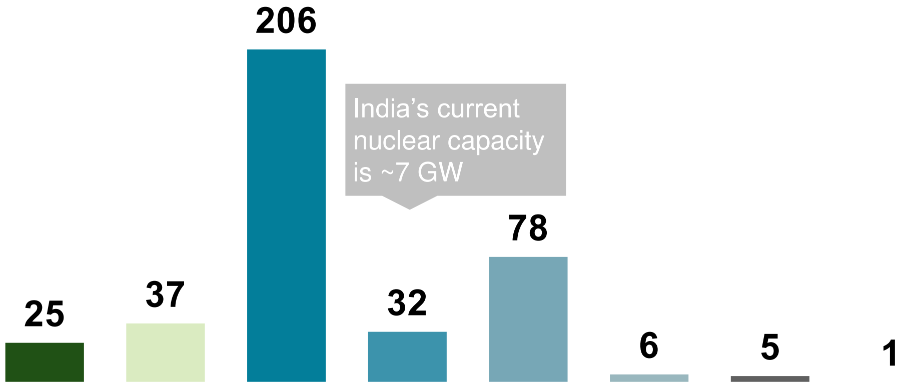


In-progress	59%	67%	78%	68%	62%	68%	55%	33%
Announced	41%	33%	22%	32%	38%	32%	45%	67%

China and India are aggressively expanding nuclear

Nuclear capacity in development[1]

G W



In-progress	51%	81%	58%	42%	48%	76%	100%	0%
Announced	49%	19%	42%	58%	52%	24%	0%	100%

Legend:
- Advanced, resource abundant
- Advanced, resource deficient
- China
- India
- Emerging, resource abundant
- Emerging, resource deficient
- Low income, resource abundant
- Low income, resource deficient

Note: (1) In development capacity includes announced, pre-construction, and under construction capacity
Source: Global Energy Monitor Solar, Wind, and Nuclear

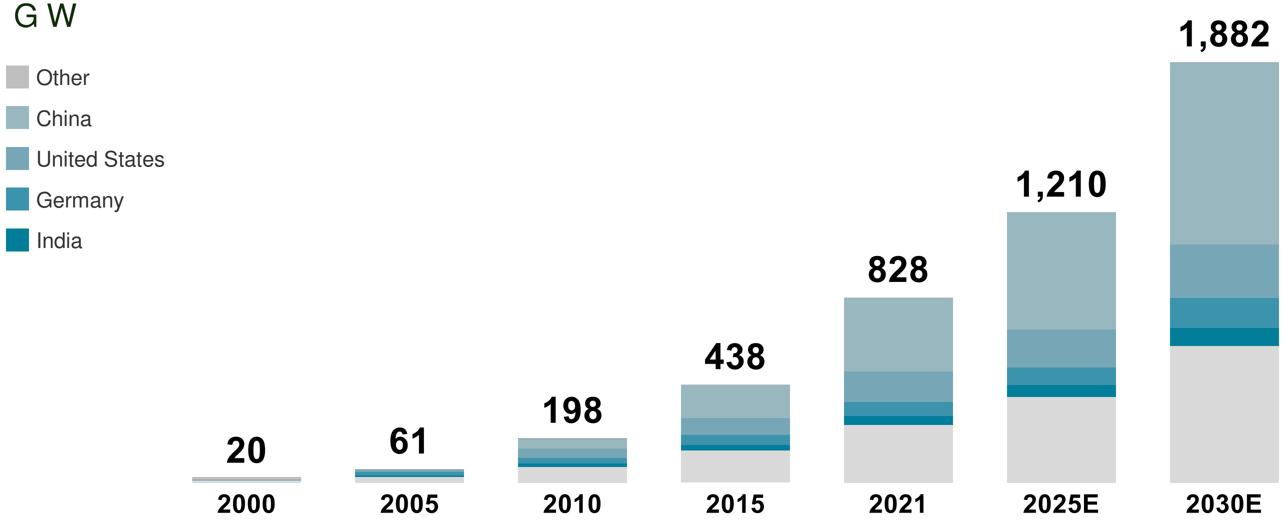
5

Wind energy penetration to grow globally, driven by government support and technological advancements

Energy generation through wind has seen a CAGR of ~20% historically but is expected to grow at a slower rate; China to lead the growth

Installed wind capacity

G W



CAGR '00-'21	CAGR '21-'30E
15%	9%
41%	11%
22%	6%
13%	9%
19%	8%
20%	10%

	2000	2005	2010	2015	2021	2025E	2030E
On-shore	99.5%	98.8%	98.5%	97.2%	93.5%	91.4%	85.9%
Off-shore	0.5%	1.2%	1.5%	2.8%	6.5%	8.6%	14.1%

On-shore growth is expected to slow down with **off-shore gaining >10% share** at **~19% CAGR** during **2020-35**

Source: Global data, Global Wind Energy Council Report

Key factors driving wind energy growth globally

- **Regulatory support** is a key driver with policies for **tax credits** (US), **target installations** and **better tariffs** (China), and development of overall renewable ecosystem
- **Tech advancements** for **efficient turbines** (higher towers & bigger blades) have led to reduction of LCOE by ~7% p.a. in the past 10 years

Wind energy's growth is moderated at 8-10% CAGR

- **Challenges with approvals for setting-up wind farm and land allocation in emerging countries** due to complex processes and permit requirements

Renewables

OpenMinds

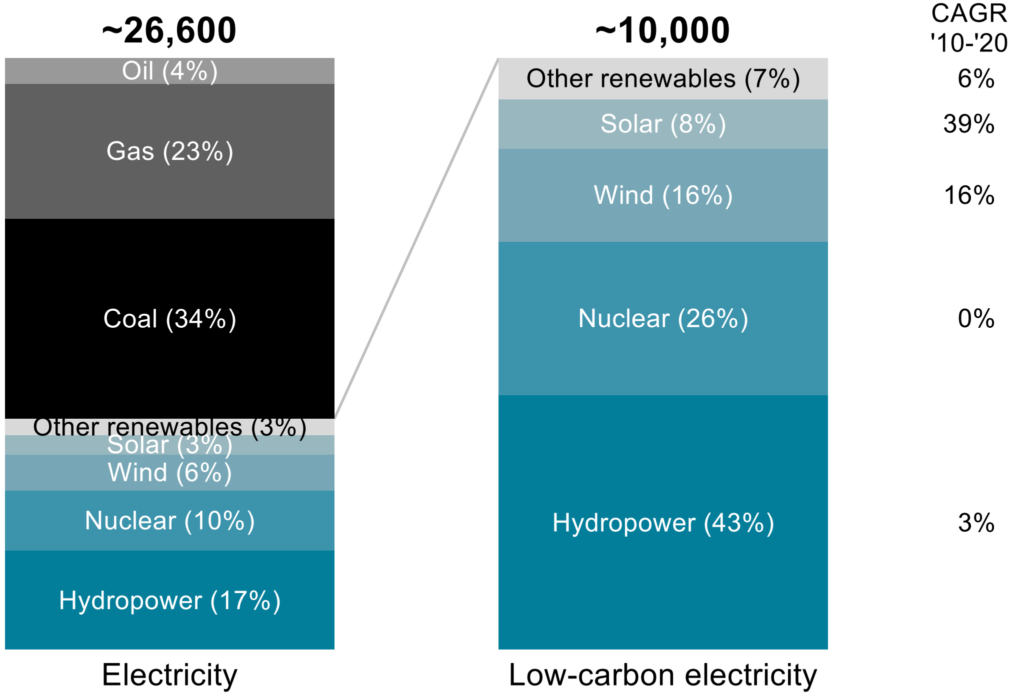
5

New and existing nuclear: Today's GW-scale nuclear market is large, supplying ~10% of electricity worldwide

Nuclear accounts for ~10% of global electricity supply

Global power production

2020, TWH

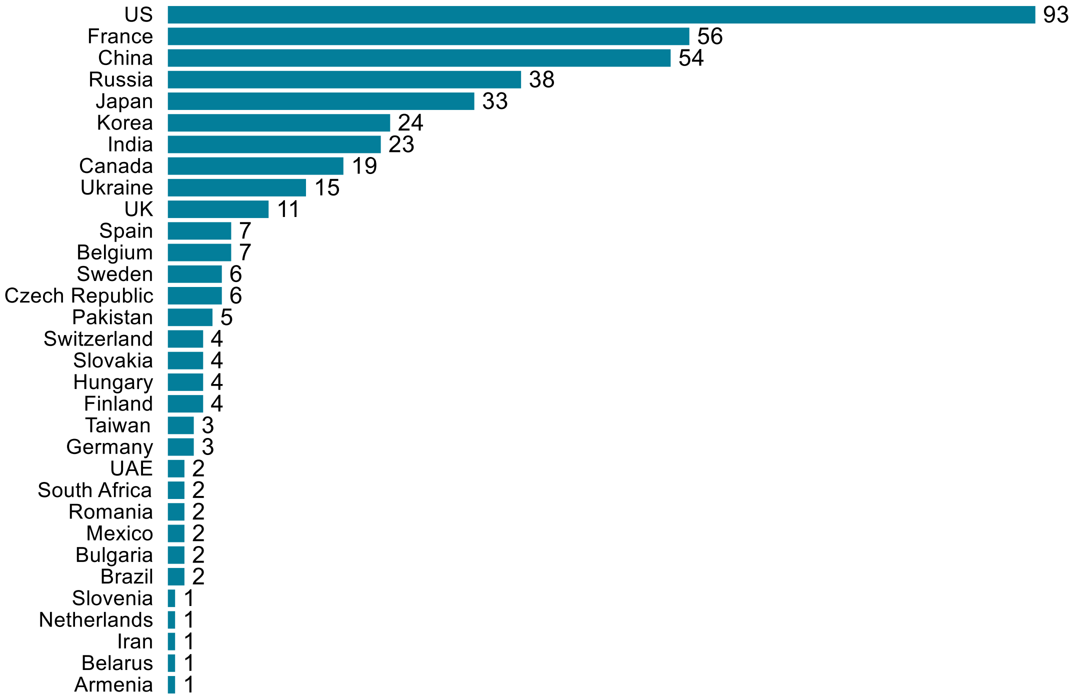


Source: Our World in Data, IAEA

Nuclear power plants operate in 32 countries

Number of operational reactors

AS OF DEC 2021



Nuclear

OpenMinds

5 Nuclear

New and existing nuclear: Nuclear is attractive but lags in public acceptance compared to other energy sources

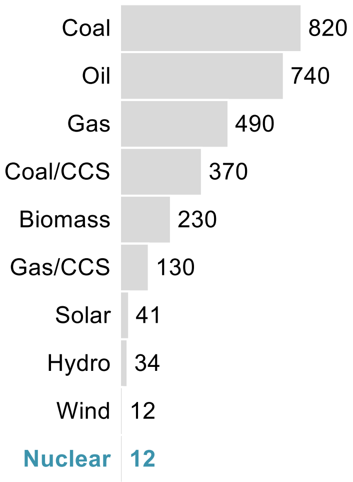
Sustainability

CO_2 EMISSIONS

⊕ Nuclear fission does **not emit CO_2**

GHG emissions

gCO2-eq/kWh



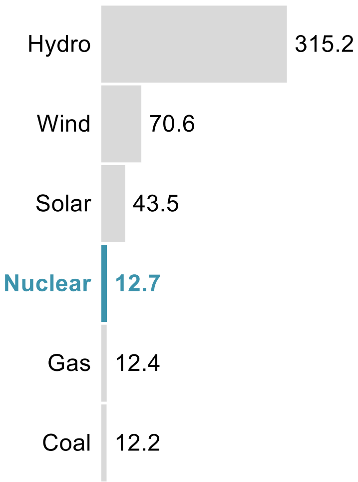
Include life cycle CO2 emissions, e.g., concrete

LAND USE

⊕ Dense energy **limiting land use**

Land requirement per energy sources

Acres/MWh

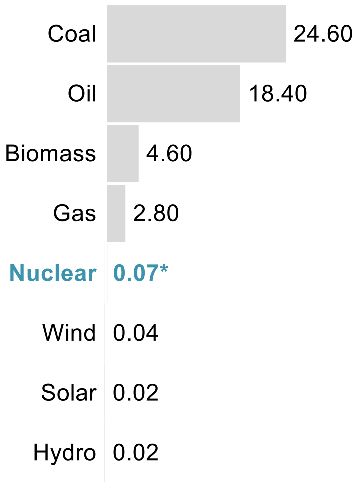


Safety

⊕ Among the **safest** energy sources looking at facts

Death rate from accidents and air pollution

Death/TWh



Competitiveness

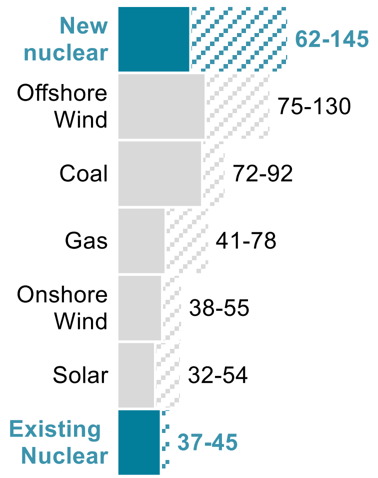
LCOE

⊕ **Competitive** when system costs are considered

Levelized Cost of Electricity (LCOE)

USD/MWh

does NOT include system costs



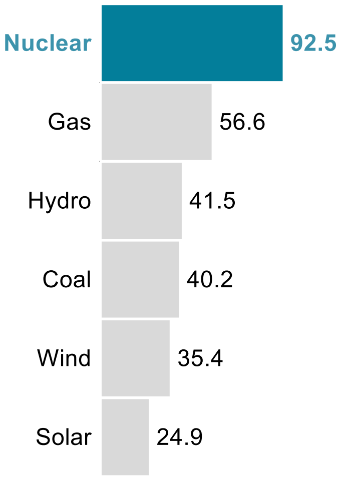
LCOE differs between sources, discount rates & geographies

CAPACITY FACTOR

⊕ **Dispatchable/firm power** with high-capacity factor

Capacity factor

US, 2020 - %



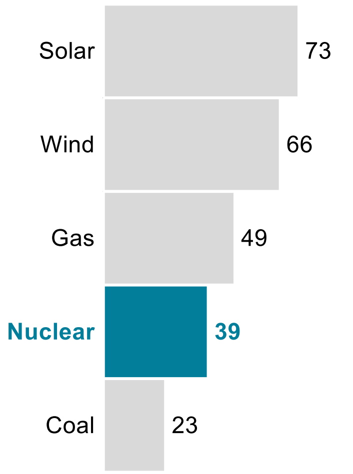
Differences largely driven by dispatchable vs. intermittent behavior

Perception

⊖ Negative **public perception**

Share of respondents willing to "see more emphasis" by energy source

Gallup Survey, US, %, March 2021



Highly dependent on geography; Positive trend on nuclear support in some regions

Note: * Includes deaths from Chernobyl and Fukushima accidents as well as deaths from occupational accidents (largely mining and milling)
Source: OWID, Bill Gates "How to avoid a climate disaster", US EIA, Morgan Stanley, IPCC; NIAUK; Bain analysis

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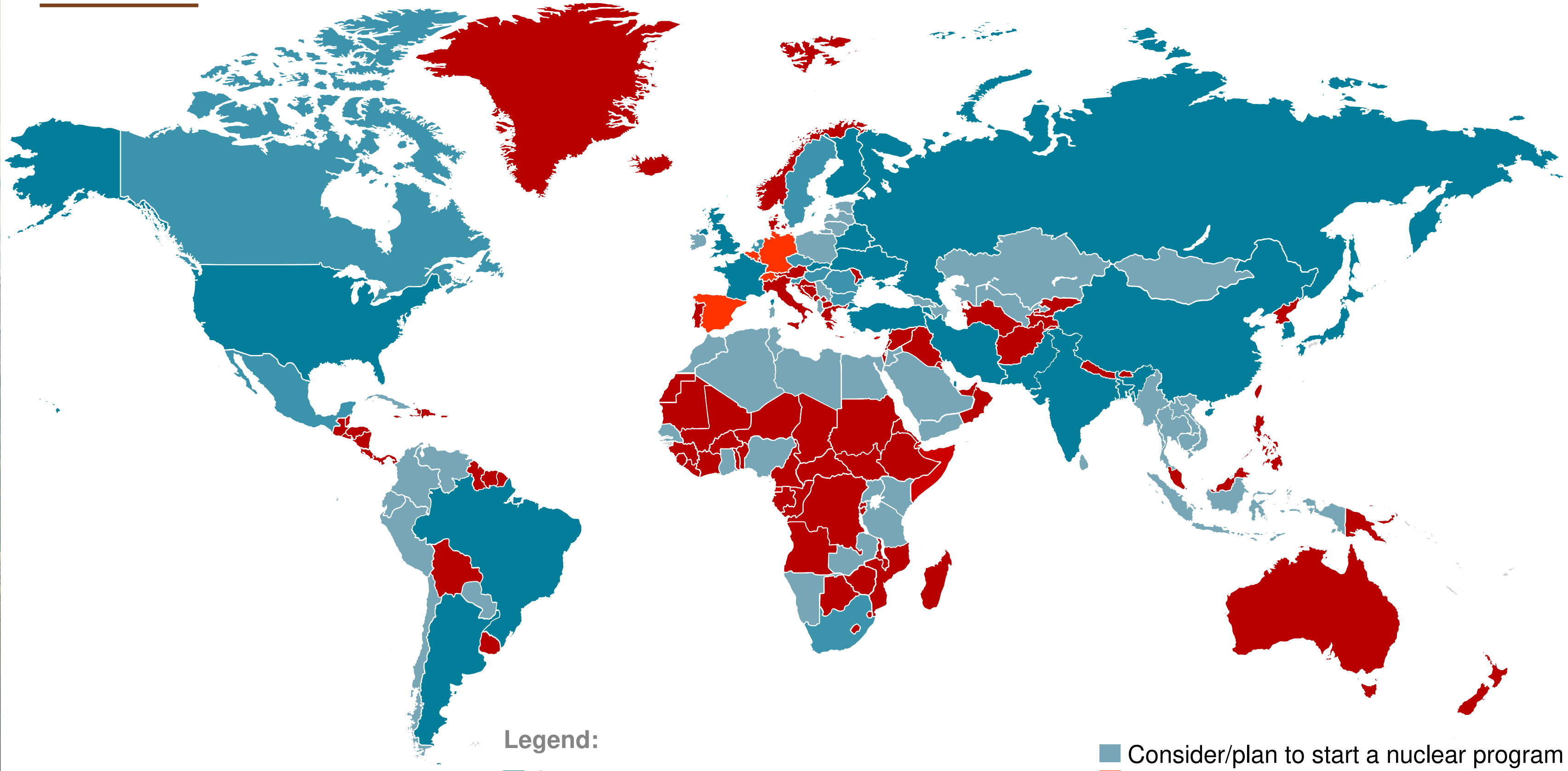
While every energy technology has benefits and limitations, nuclear is crucially both low carbon and firm as an electricity source

Desired characteristics	Clean energy: GW-scale nuclear fission	Clean energy: Small & advanced nuclear fission	Clean energy: Renewables	Fossil based energy: Natural Gas	Fossil based energy: Oil	Fossil based energy: Coal
Summary perspective	Operated in 30+ countries but debated option	Improve some aspects of existing nuclear technologies	Strong growth market, but practical limits to scale over time	Transition fuel depending on local supply conditions	EVs approaching viability which will put long-term oil at risk	Pledge to phase-out coal in many countries
Carbon Low/no carbon fuel consistent with Net Zero	🟢	🟢	🟢	⚪	🔴	🔴
Economics Low Levelized cost of Electricity (LCOE)	⚪	?	🟢	🟢	🟢	🟢
Safety performance Factual view on deaths per energy output	🟢	🟢	🟢	⚪	🔴	🔴
Safety perception Perceived risks	⚪	⚪	🟢	🟢	🟢	🟢
Resource availability Fuel is easily extractable, limited/no imports	🟢	🟢	🟢	⚪	⚪	⚪
Dispatchable energy source Available "on demand"	🟢	🟢	🔴	🟢	🟢	🟢
Resource density High energy density, reduces space required	🟢	🟢	🔴	🟢	🟢	🟢
Waste Limited waste byproducts	🔴	🔴	🟢	🟢	🟢	🔴
Critical raw material Limited use of critical raw materials, rare earth	🟢	🟢	⚪	🟢	🟢	🟢

Source: Market participants interviews

New and existing nuclear: Adoption of nuclear is starting to change, with 50+ countries considering new programs

Sentiment toward nuclear power largely differs by region



Legend:
- Operating NPPs and new NPPs under construction
- Operating NPPs, no new NPP under construction
- Consider/plan to start a nuclear program
- Phasing out nuclear power
- No NPPs in operations or planned

Note: As of January 2022
Source: PRIS, World Nuclear Association, lit. search

Commentary

- The potential of nuclear energy as a part of a broad, low carbon portfolio is becoming **attractive to governments that want to take action on climate change**
  – Nuclear energy innovation part of Biden's campaign pledge to address climate change
- **Mixed sentiment** in Europe
  – **Wave of anti-nuclear movements in Europe** (e.g. Germany) driven by fear created by high-profile disasters such as Chernobyl and Fukushima
  – **Nuclear new build plans** to reach Net Zero (e.g. Finland, France, Netherlands, Czech Republic, Poland, Estonia)

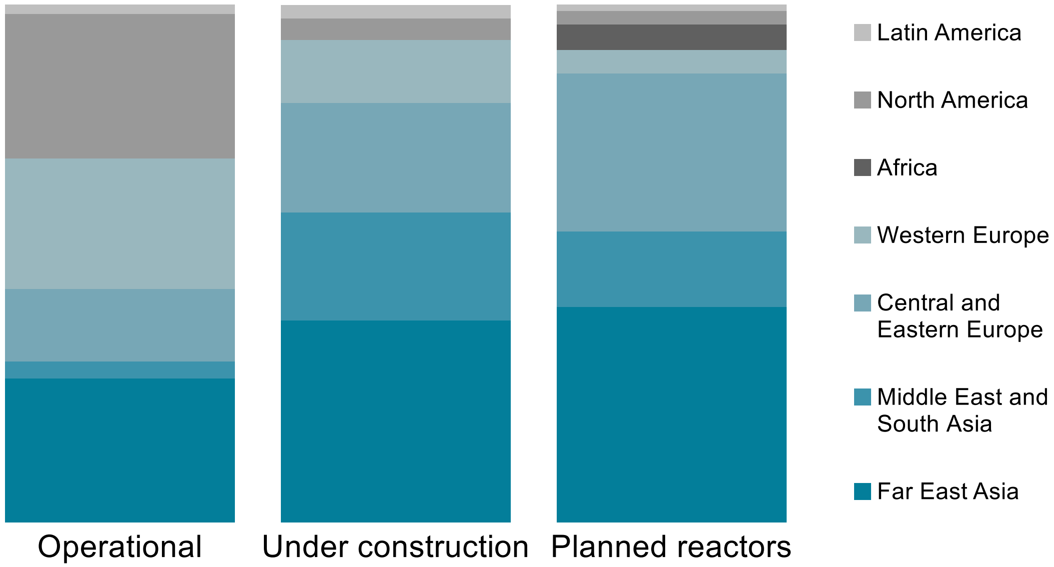
Nuclear

Nuclear new build growth is expected to come primarily from countries in Asia

Asia accounts for >50% of NPPs under construction and planned NPPs

Current NPP capacity by region

DEC. 2021, NET MW



Note: Gross MW shown for planned reactors bar. (1) As of January 2022
Source: IAEA, World Nuclear Power Reactors & Uranium Requirements, lit. search

India and China are leading the push for more nuclear energy

China: Goal of becoming global leader in nuclear energy space

- 54 nuclear reactors in operation with 14+ under construction and +35 reactors planned[1]
- Air pollution concerns have created opportunities for nuclear

India: Nuclear is part of push to provide access to electricity for growing population

- 23 nuclear reactors in operation with 6+ under construction and 14+ reactors planned[1)]
- Government expects to have 10% of its energy generated by nuclear power in 10 years (currently only ~3% of total energy)

Western Europe: Public sentiment towards nuclear has declined post-Fukushima and remain mixed

- Some countries (e.g., Germany) are phasing out nuclear
- Eastern European countries, France, Finland, the Netherlands (and UK) support the development of new nuclear projects
- Disposal and storage of radioactive waste are key concerns among population

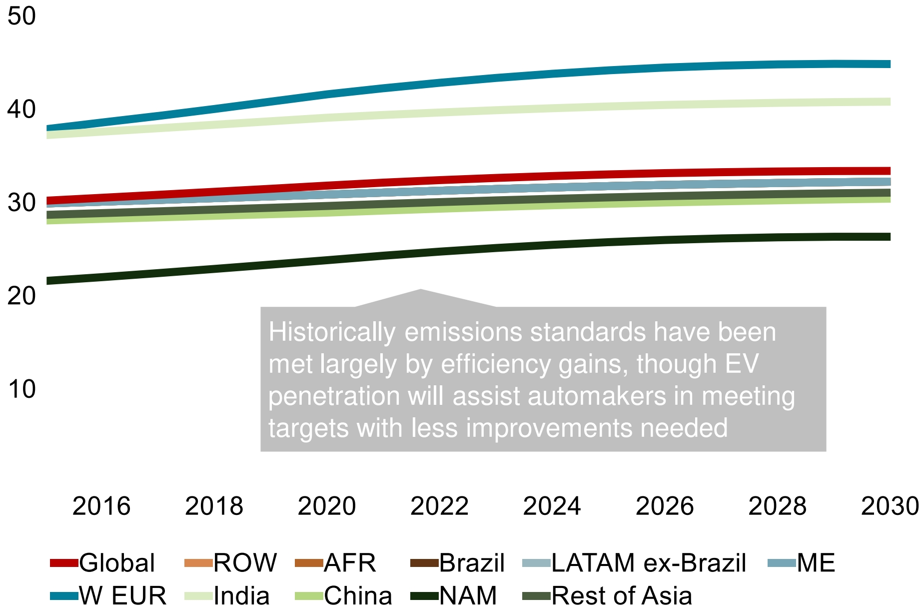
5

Improvements expected to continue near historical rates driven by global standards

LDV fuel efficiency has improved at ~1% each year, driven by gains in NAM and Western Europe

LDV Car Parc fuel efficiency

Weighted miles per gallon of gasoline/diesel



CAGR '15-'20	CAGR '20-'30
1%	0%
1%	0%
1%	0%
2%	1%
1%	0%
1%	1%
1%	0%
2%	1%
1%	0%
1%	0%
1%	0%

Emission standards significantly impact LDV fuel economy

	Past targets for new vehicles	Future targets for new vehicles
NAM	• US policy under Obama required 5% improvement in emissions; Trump reduced to 1.5% through 2026 (potentially superseded by Biden's new executive order)	• Biden's plan would require ~10% emissions reductions in 2023 and ~5% every year after through 2026
EU	• Beginning in 2009, EU set emissions standards that required new vehicles to reach 95g/km in 2021 • Ambitious targets set for 2015 were already achieved by 2013	• In 2020, EU set new targets for 2025 of 15% annual reduction in average emissions • EU has put in place legislation to reduce total emissions by at least 40% by 2030
China	• China phase IV passenger vehicle consumption required an annual drop of emissions from 2012 to 2020 by ~4% annually	• China phase V passenger vehicle consumption standards published end of 2019 continues same requirements of ~4% annual improvements
India	• Annual emissions reductions of ~2% required from 2006 to 2017 • In 2015, India adopted fuel consumption regulations with targets phasing in starting 2017, and stepping up in 2022	• India's target set for 2023 requires a 1.5% annual improvement in emissions

Transportation efficiency

Note: Emissions are directly tied to fuel efficiency

Source: GFEI Global Status Report, IEA Oil Market Report 2021, https://ec.europa.eu/clima/policies/transport/vehicles_en, https://www.usnews.com/news/business/articles/2021-08-06/explainer-the-impact-of-joe-bidens-new-fuel-economy-rules

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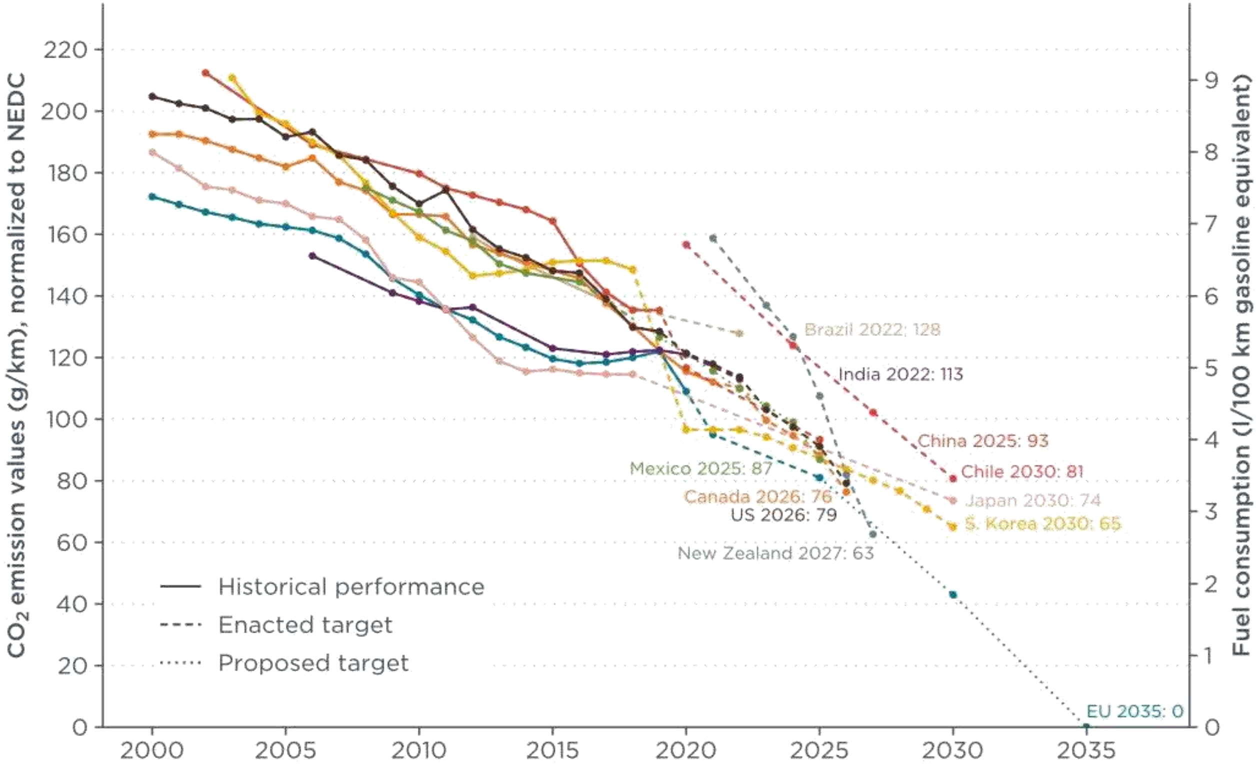
Transportation energy efficiency: Fuel efficiency standards are a key tool in mitigating CO2 emissions

Continued improvement in fuel efficiency reflects enacted policy targets and demonstrated historical improvement (policy schedules as of Dec 2022)



Note: NEDC = New European Drive Cycle, a test designed to assess emission levels of car engines
Source: GFEI Global Status Report; ICCT International Council on Clean Transportation

Commentary

- **Fuel efficiency standards are an important tool in lowering total emissions** and are among the most effective climate-change mitigation measures to have been implemented in the past decade
- In observed countries, **fuel efficiency has improved ~1-2% p.a.** over the last two decades
- Enacted policy targets (as of December 2022) suggest this **trend will continue**

Transportation efficiency

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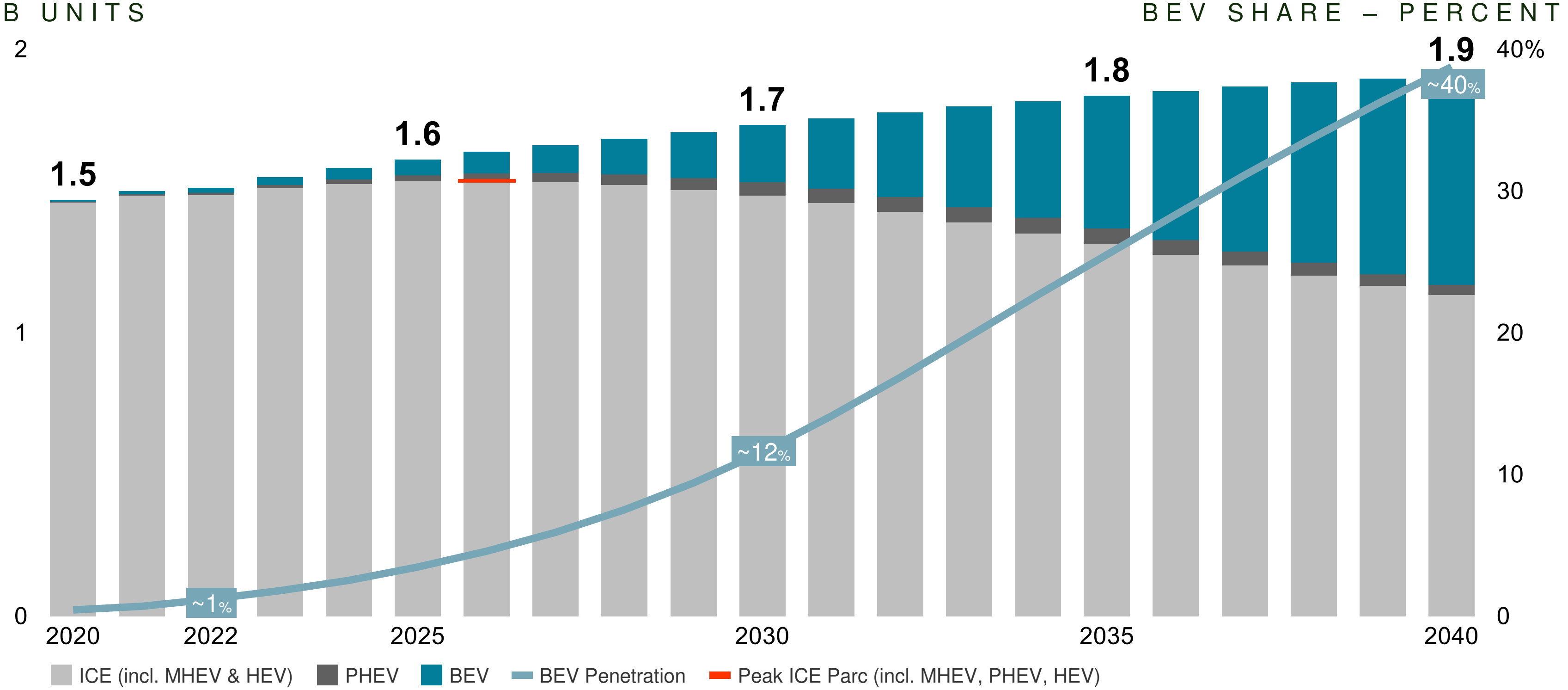
Global car parc expected to reach ~12% BEV penetration by 2030 and ~40% by 2040

Global LV car parc

Global LV car parc by engine type



Note: Scrapping rate forecast from 2028 based on rolling 5-year average
Source: IHS Markit/ S&P Mobility (January 2023); Bain EV Market Model

Commentary

- **ICE (incl. PHEV) vehicles in the car parc expected to peak in 2027**, with ~1.6B ICEs on the road
- **Global car parc expected to grow** to ~1.9B vehicles in 2040
- **ICE vehicles continue to dominate**, but share of car parc expected to decline at an increasing rate
- **BEV penetration increasing rapidly** after 2030 as penetration of new car sales grows

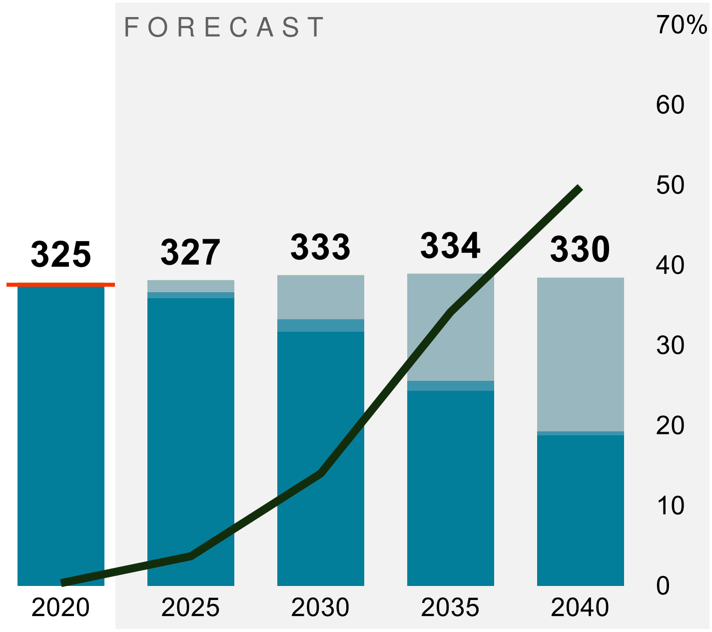
Electric LDV

China leads EV adoption, 45% of car parc projected to be electric by ~2035

Europe

LV car parc by engine type

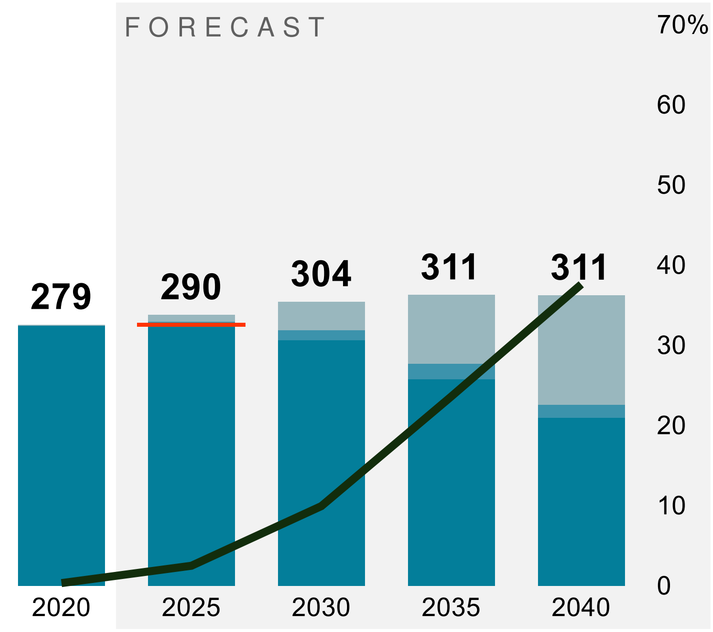
M UNITS



USA

LV car parc by engine type

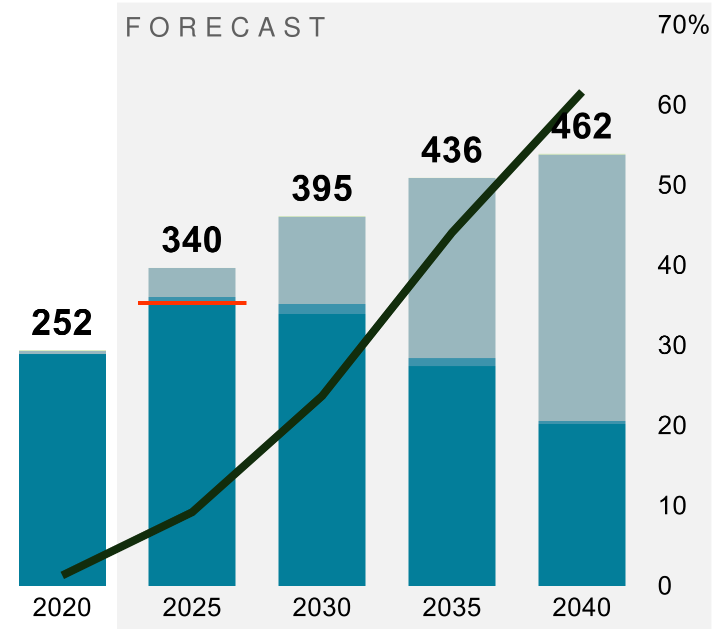
M UNITS



China

LV car parc by engine type

M UNITS



ICE (incl. MHEV & HEV) | PHEV | BEV | BEV Penetration | Peak ICE Car Park (incl. MHEV, PHEV, HEV)

Source: IHS Markit/ S&P Mobility (January 2023); Bain EV Market Model

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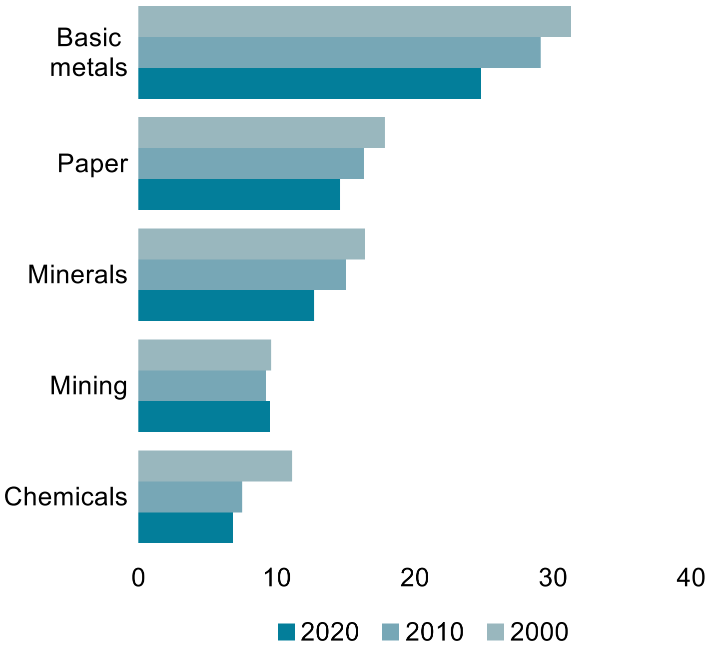
Industrial Efficiency

Opportunity in industrial efficiency likely to grow but coordination needed in low-margin industries

Gains in industrial energy intensity have been steady over past decade

MJ per dollar value added



Source: IEA Energy Efficiency Indicators Data Explorer; IEA Energy Efficiency 2022 report

Heat needs are most important determinant of efficiency priorities

- Solutions include both **electrification of industrial processes and application of other technologies** that improve overall energy efficiency in industrial processes
  - Key industries for consideration include **steel**, **cement**, petrochemicals, and raw materials mining and processing
- Electrification opportunities are greatest in **low-medium heat processes**; technologies include:
  - Electric arc furnaces and electric boilers
  - Industrial-scale induction heating
- Other technologies promoting industrial efficiency include:
  - Converting **high heat processes** to more efficient or **cleaner fuels** (e.g., coal to gas)
  - Adopting **next-generation processes** that require less heat or are otherwise more efficient (e.g., low clinker concrete)

Long equipment lifetimes and high upfront costs are main uptake drivers

- Widespread **adoption in industry is likely to be gradual** as production equipment often has a long lifespan
  - Some equipment can be retrofitted, but **replacement at end of life is often more feasible** due to cost and down time
- Relevant industries often characterized by low margins where **high upfront investments are challenging in a competitive landscape**
  - **International standards**, **coordination** among industry leaders, or **subsidies** could help speed adoption
- **Opportunity likely to grow** as demand for concrete, steel, and other basic materials increases in emerging economies

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Multiple drivers will influence the rate of heat pump adoption

Climate/number of heating degree days (HDDs)

Heat pump technology is **best suited for ambient climates** where heating degree days (i.e., the number of days per year with temperatures below 65ºF) **are lower;** heat pump tech uses electricity to extract heat from the outside air or ground in order to heat.

While heat pumps can be used in colder climates (e.g., the Midwest, Northeast)**, they are less effective in heating the whole home** with the same efficacy as furnaces (the predominant heating tech in the US).

Total cost of ownership (TCO)

Upfront cost

Upfront cost is determined by the **tradeoff between heat pumps vs. the alternative** (either standalone HVAC or furnace, or the combination) and **influenced by government incentives**

Electricity and natural gas price differentials

Relative spread between electricity and gas prices **varies greatly by region** given established infrastructure; **potential gas bans** may also influence HP adoption

Contractor recommendations & consumer preferences

Customers typically defer to **contractor recommendations** when replacing their existing HVAC and/or furnace, thus broader **HP adoption will be heavily influenced by contractors.**

Contractors **often avoid recommending drastic changes** in technology for consumers if there haven't been issues previously; while heat pumps can work well, **they do not deliver the same effect (i.e., instant blast of hot air)** that furnaces do, which customers in colder climates often prefer.

PRELIMINARY

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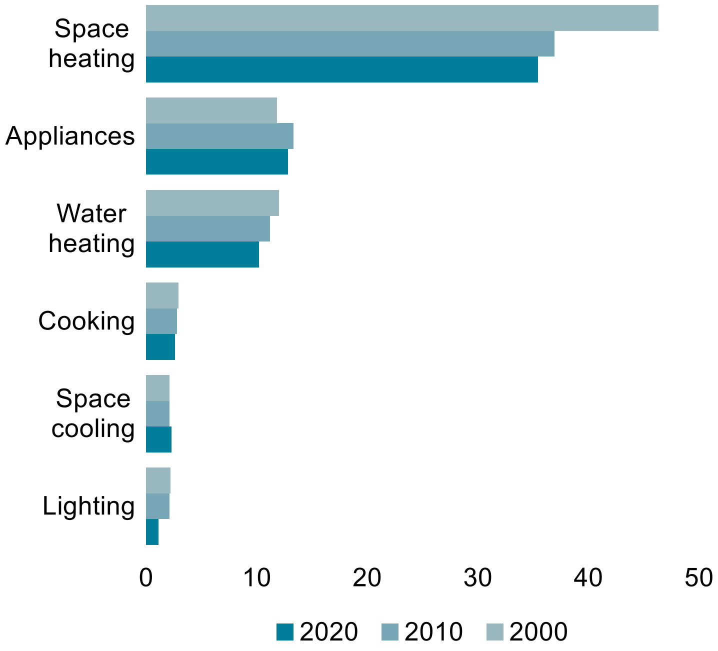
Buildings efficiency: Several proven technologies are available, but achieving broad uptake is challenging

Gains in buildings energy intensity have been modest over past decade

GJ per dwelling



Source: IEA Energy Efficiency Indicators Data Explorer; IEA Energy Efficiency 2022 report

Efficiency priorities differ between advanced and emerging economies

- Buildings efficiency includes **applications of technologies in residential and commercial settings** that can be incorporated in **new construction or through retrofitting** existing structures
- In advanced economies, prioritized technologies include:
  - High R-value insulation
  - High efficiency HVAC systems
  - Smart meters
  - High efficiency appliances
  - High efficiency windows
- In emerging economies, **switching from traditional biomass to cleaner fuels** is imperative

Regulation and upfront cost are the main purchase drivers

- **Regulations can be an important driver of uptake** in buildings energy efficiency technologies
  - Global residential appliance energy use governed by regulations is ~70-80%, but is often **much lower in emerging economies**
- Solutions generally have **higher upfront costs relative to less-efficient technologies**, but usually result in **lower energy bills** that pay off the investment over several years
  - **Subsidies in advanced economies** are a common tool to help reduce upfront investment

Buildings efficiency

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Notes and key sources for 'Top Ten Solutions'

Solution	Marginal cost of abatement	End-user cost perspective
Abating methane emissions from energy	Source: IEA methane abatement cost curve Note: weighted average price; range represents max and min	Many positive ROI opportunities (e.g., upstream leak repair); ROI sensitive to gas prices (e.g., see MACC for '17-'21 average vs. '22 on slide 64)
Coal-to-gas switching	Source: IEA WEO 2019 (p. 213) Note: weighted average price	Involves upfront investment in new or retrofitted equipment; ROI varies with commodity price environment for coal and natural gas
CCUS in electricity and industry	Source: G.S. Carbonomics 2021 Note: weighted average price of CCUS in coal and NG applications; range represents max and min	Higher cost vs. operating without CCUS absent subsidy or tax, trending down according to cost curve analysis
Renewables (i.e., solar and wind)	Source: G.S. Carbonomics 2021 Note: weighted average price of utility-scale solar PV, onshore wind, and offshore wind; range represents max and min	Somewhat lower cost for utility-scale solar and wind vs. fossil fuels (LCOE), trending down as technology and manufacturing processes continue to improve
New and existing nuclear	Source: Bain Intersect model	Higher cost vs. other fuels due to high capex requirements and regulatory burden, trending unclear
Transportation energy efficiency	Source: IEA Abatement costs for road vehicles Notes: average of hybrid car in $60/bbl scenario; range represents max and min	Higher upfront cost, but long-term benefits to the consumer from lower fuel costs; other key drivers include weight and engine efficiency
Electric LDVs	Source: G.S. Carbonomics 2021 Note: weighted average price of switching to EVs from ICE vehicles in urban and rural gasoline and diesel vehicles	Somewhat higher upfront cost vs. ICEs today, trending down; major investment in charging networks required to achieve high penetration rates
Industrial efficiency and electrification	Source: G.S. Carbonomics 2021 Note: weighted average price of four industrial efficiency and electrification interventions	Varies by application and end use sector; often involves high upfront costs with extended payback periods that can be challenging in low-margin industries
Heat pumps	Source: G.S. Carbonomics 2021 Note: weighted average of heat pumps, excluding applications with hydrogen	Near parity vs. existing technology, trending down; often involves higher upfront costs with extended payback periods
Buildings efficiency	Source: G.S. Carbonomics 2021 Note: weighted average of appliance efficiency standards	Often involves higher upfront cost with a payback period; subsidies can be effective in boosting penetration; solutions differ in advanced vs. emerging economies

Agenda

01 Solutions approach

02 Solution assessment framework

03 Top 10 solutions overview

04 Country archetypes

05 Appendix A: Detail on Top 10 solutions

06 Appendix B: Background on methane

Methane abatement: Executive summary

Overview of methane emissions in oil & gas

- Methane (CH_4) is an **extremely potent greenhouse gas**. While it remains in the atmosphere for only about 12 years (versus decades to thousands of years for CO_2), its **global warming potential is >80X that of CO_2** over a 20-year period, and it is responsible for at least **one-quarter of global warming in the industrial area**
- Methane emissions from the **oil & gas sector account for 4-5% of global anthropogenic greenhouse gas emissions** on a CO_2-equivalent basis, or roughly **2.5 billion metric tons of CO_2-e** annually, the equivalent of the annual emissions from **500 million passenger cars**
  - **Venting** in upstream O&G is the source of two-thirds of O&G-related methane emissions globally
  - Nearly half of **fugitive** (unintended) emissions occurs in **gas pipelines and LNG facilities**

The outlook for methane abatement in oil & gas

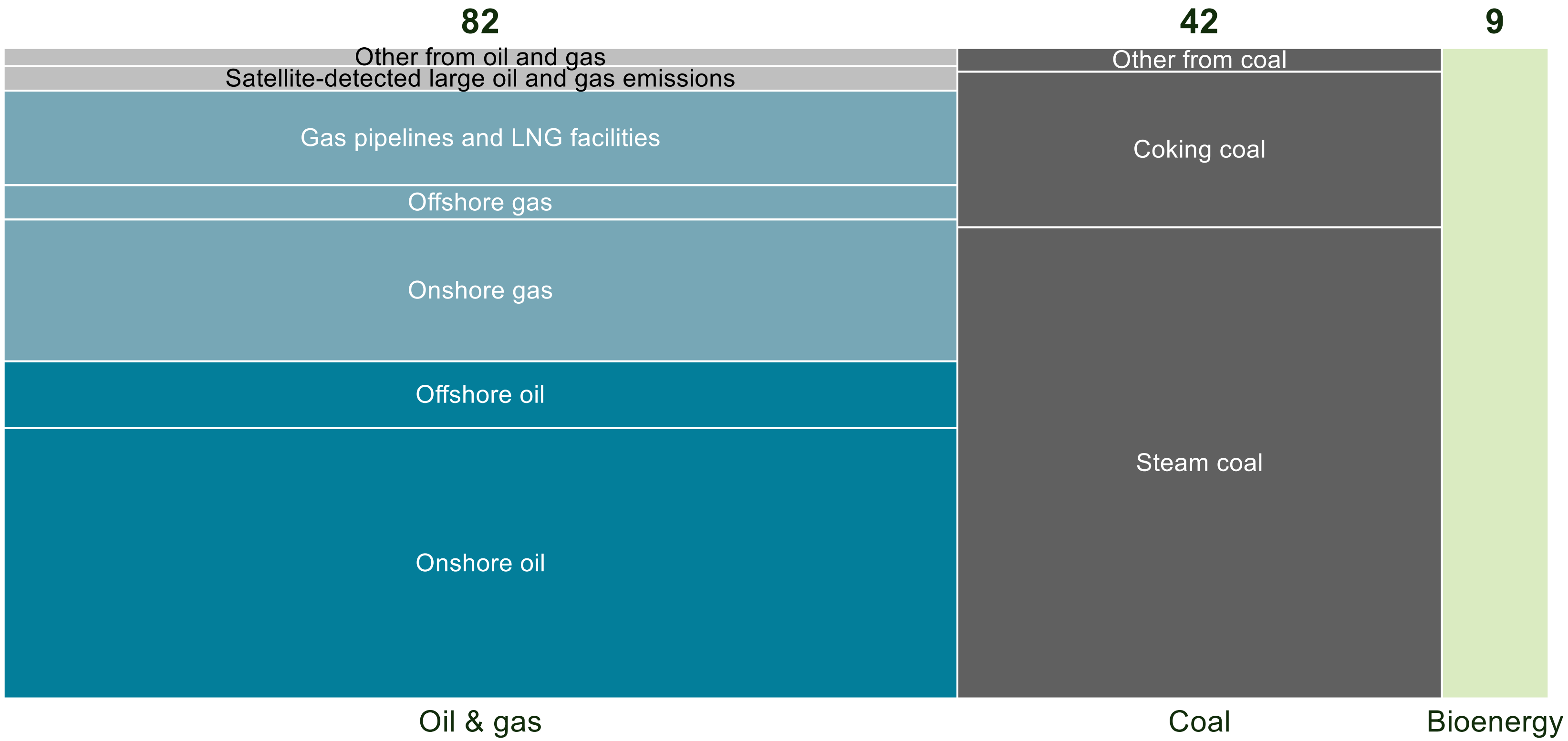
- Because of its potency and lifespan, reducing methane emissions quickly is **one of the best ways to slow global warming**, and there is **clear scope to reduce emissions cost effectively**, in part because methane has commercial value
- Moreover, it is imperative O&G operators address these emissions to **maintain their social license to operate**. For example, at leakage rates of ~3-4% per unit of natural gas produced, natural gas in electricity generation is on par with coal in terms of overall climate impact
- There is significant policy and corporate momentum behind methane abatement. 150 countries have signed the **Global Methane Pledge**, and **recently enacted and proposed regulations in the US, EU, and UK would strengthen existing regulatory regimes**
- There are a **wide range of abatement products and services** to address methane emissions in O&G, from leak detection and repair (LDAR) to replacing existing equipment (e.g., compressors) to designing fossil fuel infrastructure differently
- In the US, achieving a 30% reduction **could require annual abatement spending of ~$2-2.5B through 2030** (preliminary figure) inclusive of LDAR, installing new controls, and replacing existing devices

Source: IEA; IPCC; EPA; Ocko et al., “Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming” (2021); S&P Global Market Intelligence, “Natural gas use may affect climate as much as coal does if methane leaks persist” (2021)

Within energy-related methane emissions, the oil and gas sector accounts for almost two-thirds of the global total

Global energy-related methane emissions by segment – 2022

MILLION METRIC TONS OF METHANE



Sector	Methane, MT	% of total
Oil	46	34%
Gas	37	27%
Coal	42	31%
Bioenergy	9	7%
Total	**133**	**100%**

Note: Tons of methane converted to CO2-equivalent using a GWP-100 factor of 30
Source: IEA, Methane Tracker

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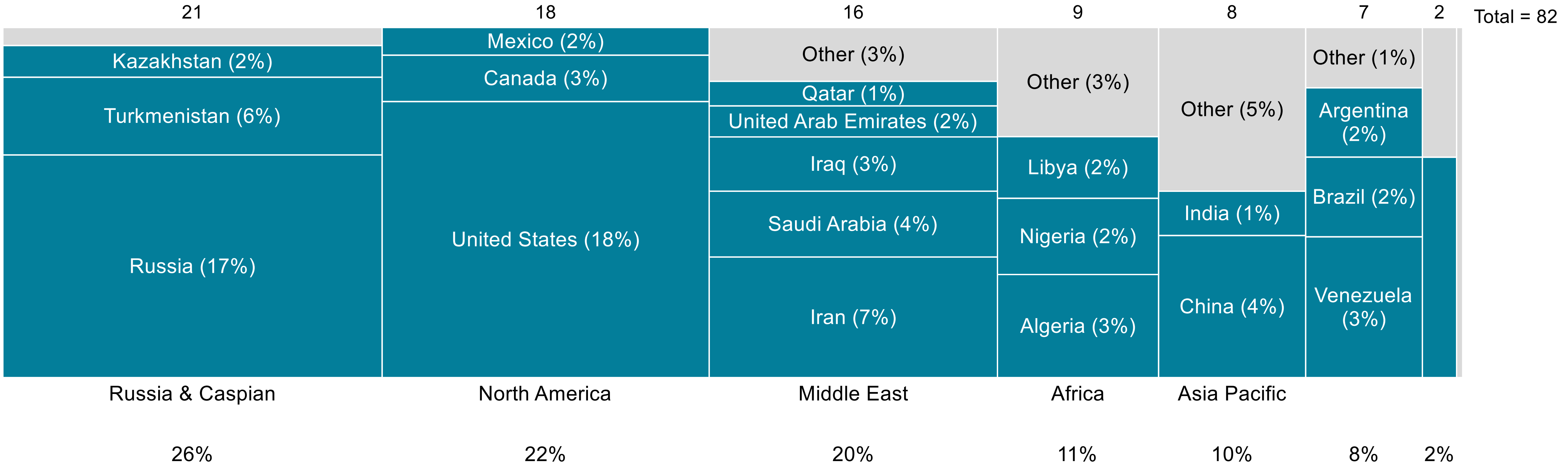
And within the oil & gas sector, the top 20 methane emitting countries (including the EU) account for more than 80% of the global total

Global energy-related methane emissions by segment – 2022

Million metric tons of methane



Note: Europe includes European Union countries, plus UK, Ukraine, Israel, Norway, and other countries in Europe
Source: IEA, Methane Tracker

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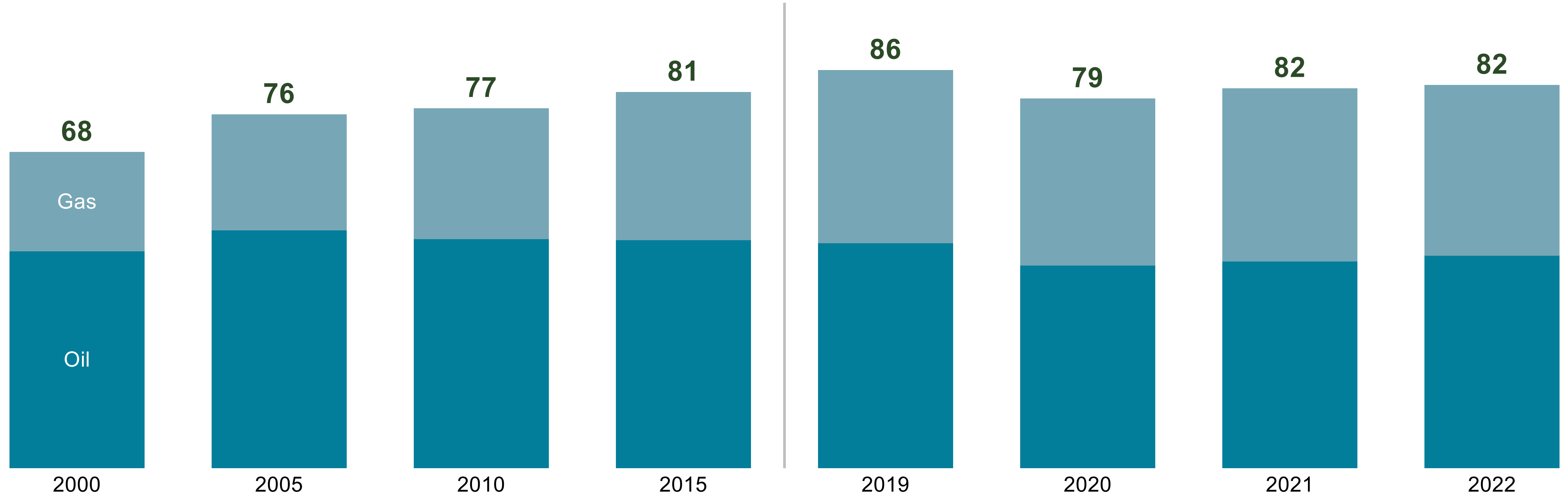
Oil & gas sector methane emissions have plateaued in recent years

Global energy-related methane emissions by segment – 2022

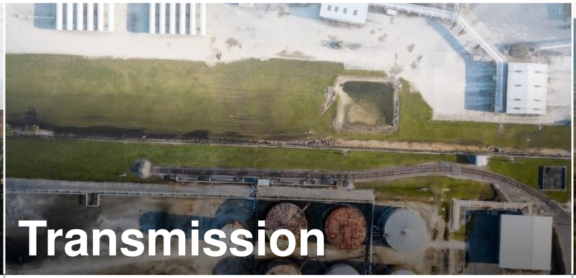
MILLION METRIC TONS OF METHANE



Source: IEA

Emissions occur across the gas value chain, but in oil, the vast majority of emissions are in upstream production

O&G VALUE CHAIN



SOURCES OF EMISSIONS

Production

Natural gas and oil wells

- Used to increase pressure of gas in the gathering pipelines
- **Emission sources:** Leaks, gas driven pneumatic devices, compressors

Gathering compressor

- **Emission sources:** Leaks, unloading liquids from wells, gas driven pneumatic devices, compressors, storage tanks, dehydrators, flaring

Processing

Gas processing plant

- Cleans raw natural gas (removing impurities and non-methane hydrocarbons), producing pipeline quality natural gas
- **Emission sources:** Compressor venting, leaks, blowdowns during routine maintenance

Transmission

Transmission compressor

- Compressor stations which maintain gas pressure along pipeline
- **Emission sources:** Venting of gas for maintenance and repair, leaks, pneumatic devices, compressor seal oil de-gassing

Storage

- Stockpiled in underground storage facilities
- **Emission sources:** Compressor venting and leaks

Distribution

Gas Gates

- Measures and decompresses gas before being placed into final sales lines
- **Emission sources:** Leaks from unprotected steel mains, service lines and metering/ regulating stations

Source: EPA; IEA

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Oil & gas methane emissions fall broadly into three categories: venting, fugitive and incomplete flaring

Venting

DESCRIPTION

US emissions 64%

Europe emissions 43%

- **Intentional release of methane** used to power the operation of equipment (e.g., pneumatic devices) or as part of maintenance requirements

EXAMPLE MITIGATION MEASURES

- **Retrofitting or replacing components** which are operationally driven by natural gas, with lower emitting devices which emit less or run on electricity
- **Installing new equipment:** Vapour Recovery Units (VRUs), installing flares, etc.

Fugitive

US emissions 27%

Europe emissions 41%

- **Unintentional emissions resulting from leaks** out of valves, faulty seals, pipe flanges, etc.

- **Leak Detection and Repair (LDAR) programs** which **survey sites with a variety of technologies** (infrared cameras, acoustic leak detectors, laser spectroscopy on drones, satellites data)
- Increasing survey frequency and new technology used to reduce emissions

Incomplete flare

US emissions 3%

Europe emissions 1%

- Flaring is used to **dispose of unwanted NG as a by-product of oil extraction**
- Methane is released into the atmosphere as a **result of incomplete combustion**

- **Operational mgmt. of flare maintenance** to prevent malfunction
- **Process changes** which allow operators to use the gas onsite
- **Installing portable CNG or mini-LNG facilities** to treat gas onsite

Source: EPA; IEA

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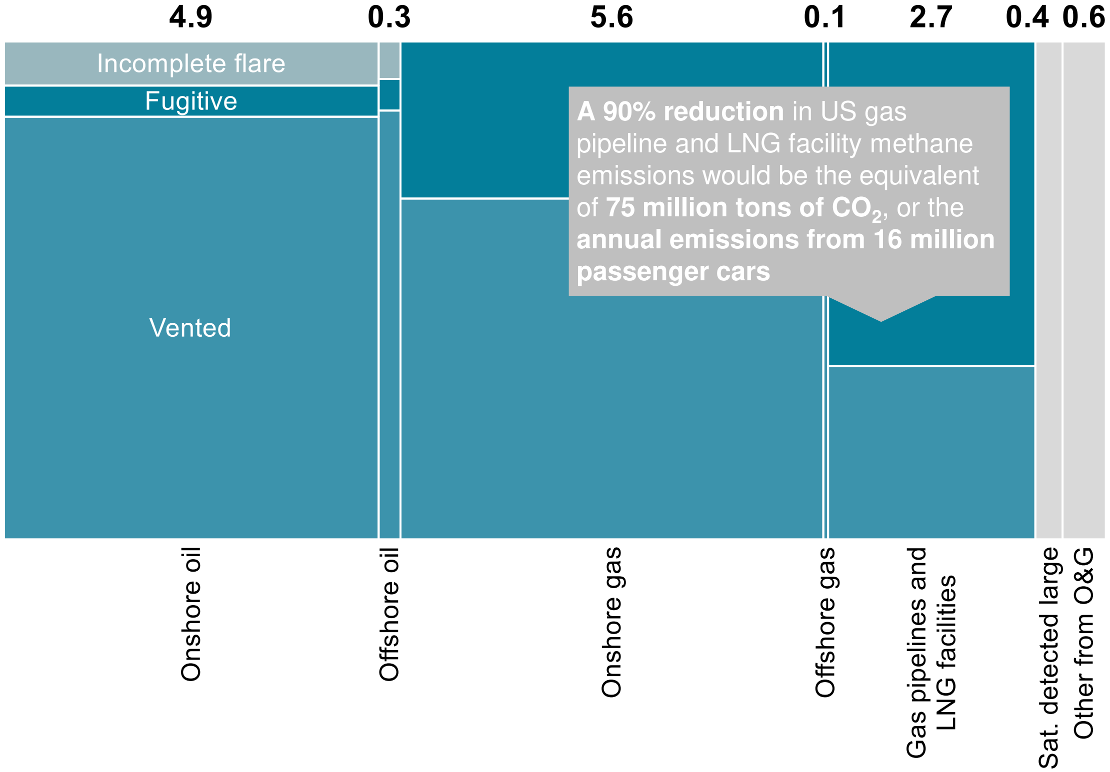
In the US and Europe, the sources of O&G methane emissions differ somewhat, but in both cases, fugitive emissions are problematic in the gas value chain

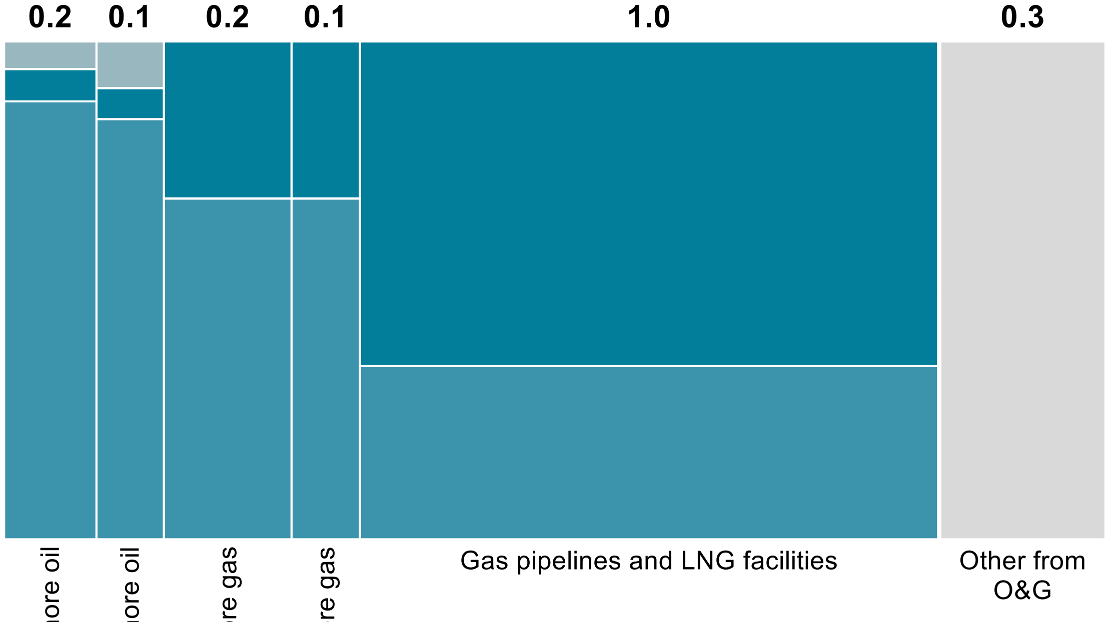
US oil & gas methane emissions

2022, MT TOTAL = 14.5



UK/Europe oil & gas methane emissions

2022, MT TOTAL = 1.9



Note: Calculation assumes GWP-100 factor of 30 and 4.6 metric tons of CO2 emitted per passenger car in the US per year. Europe includes European Union countries, plus UK, Ukraine, Israel, Norway, and other countries in Europe
Source: IEA, Methane Tracker

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Policy: Since COP26 in 2021, 150 countries have signed onto the Global Methane Pledge, committing to reduce methane emissions by 30% by 2030

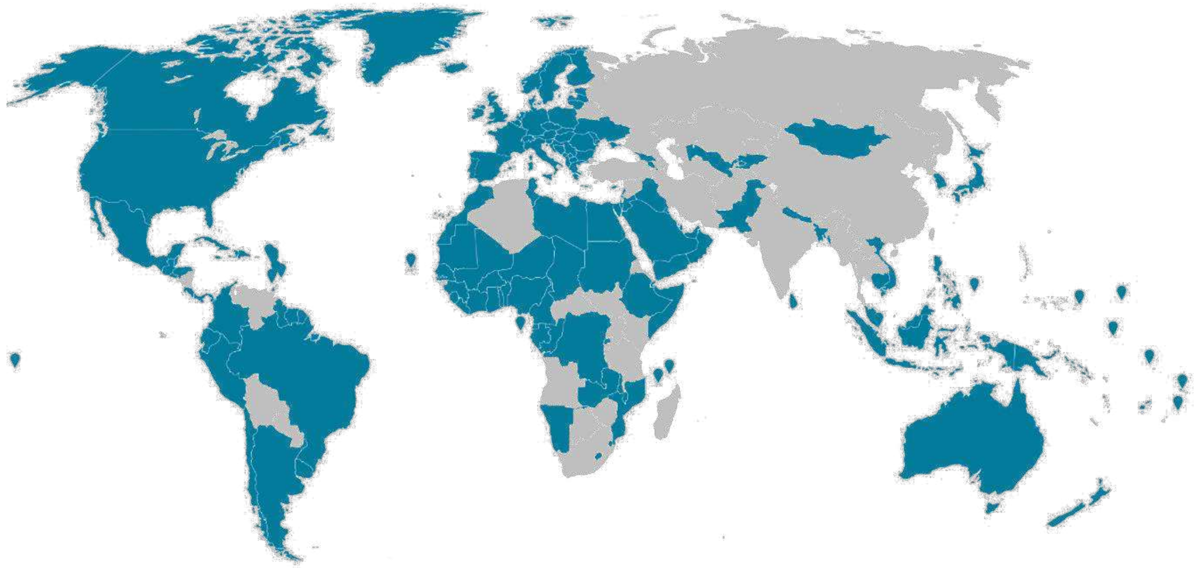
The Global Methane Pledge

The Global Methane Pledge was launched at COP26 in Nov 2021. Since then, **more than 150 countries have signed on**

By joining the pledge, **countries commit to reduce methane emissions** (from all sources) **by at least 30%** below 2020 levels by 2030

In June 2022, the US, EU, and 11 countries launched the **Global Methane Pledge Energy Pathway** to catalyze methane emissions reductions in O&G

Meeting the Global Methane Pledge target has the **potential to reduce end-of-century warming by 0.2°C**, the equivalent of the entire global transport sector adopting net zero emission technologies



Global Methane Pledge

Source: IEA; Global Methane Pledge; US Department of State

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Policy: Many countries already have at least some oil & gas methane emissions regulations in place

Category	Regulation	US	Norway	Saudi Arabia	Brazil
Prescriptive methane	Permitting requirements	Regional	National	National	National
	Leak detection and repair	National			
	Restrictions to flaring or venting	Regional	National		National
	Technology standard	National			National
	Enforcement and related provisions	National	National	National	National
Performance based	National or sectoral reduction targets and plans	Regional			
	Facility or company emissions standards	Regional			
	Process or equipment emissions standards	National			
	Flaring or venting standards	Regional			National
Economic	Taxes, fees and charges	Regional	National		National
	Emissions trading schemes and certified reduction credits				National
	Loans, grants and other financial incentives	National			
Information based	Emissions estimates and quantification	National	National		National
	Measurement requirements	Under consideration	National		
	Reporting requirements	National	National		National

Regional policies · National Policies

Note: Polices as of January 2021
Source: IEA, Driving Down Methane Leaks from the Oil & Gas Industry, Table 2

Policy: Momentum is growing—recently enacted and proposed US and EU rules could meaningfully strengthen existing regulatory regimes

US: IRA-imposed fees and proposed EPA regulations will tighten emissions requirements

- **The IRA includes a fee on methane emissions** from O&G operations (“waste emissions charge”)
  - 2025: $900/ton (for emissions reported in 2024)
  - 2026: $1,200/ton
  - 2027 and thereafter: $1,500/ton
- A November 2022 EPA proposal under consideration would, among other things, **require routine monitoring** at **all well sites** for fugitive emissions, regardless of production size, and would **oblige operators to repair leaks**

EU and UK: Stringent LDAR requirements were recently enacted

- The EU Parliament voted on May 9 for stricter measures to reduce methane emissions, including **stringent leak detection and repair (LDAR) requirements** for fossil fuel infrastructure
  - Companies operating fossil fuel infrastructure would be required to check for leaks as often as every 2 months
- The Parliament also asked the European Commission to develop a framework to **ensure exporting countries abide by similar rules**
- The UK, through its Net Zero Strategy (NZS), has **committed to reducing routine flaring and venting to zero by 2030 or sooner**

Source: Center for Strategic & International Studies, “What’s Next for Oil and Gas Methane Regulations”; Politico, “EU lawmakers back tougher rules on methane emissions”; United Kingdom methane memorandum (November 2022)

6

Abatement levers: Across both LDAR and equipment modifications, there is a range of potential products & services to address O&G methane emissions

	Leak Detection & Repair	New Equipment & Replacements
New Equipment & Replacements	Assessment of **baseline on leakage quantity & source**	**Assessment of process effectiveness & equipment standards, to create baseline.**
	Co-creating **desired end** state with customer, incl. **sustainability potential & pay-back**	
Implementation of monitoring software	**Placement of smart components** on desired equipment and **installation of monitoring software**	
Diagnostic and benchmarking	**Interpretation of aggregated data**, including benchmarking against other facilities, identification and diagnostic of **largest leakages in the infrastructure**	
Engineering Solutions Design	Design of **EPC + O&M work required**	Design of **EPC + O&M work required**
Hardware modifications & upgrades		**Installation of third party equipment** which reduces venting, flaring or increases energy efficiency where diagnostic has shown need for improvements
Equipment maintenance & leak repair	**Maintenance work to repair leak sources**	
Data interpretation & savings verification	Interpretation of data to **assess whether modifications have delivered the desired savings**, and verification of savings as needed to apply for savings incentives/rebates	
Continuous monitoring	**Real-time monitoring** of infrastructure methane emissions performance, **identifying faults and areas for improvement continuously**	

Summary

- Methane is among the most potent greenhouse gases and is responsible for at least one-quarter of global warming
- Methane emissions from the oil & gas sector alone account for 4-5% of all anthropogenic greenhouse gas emissions
- Reducing these emissions could have a major impact on the world's warming trajectory through the end of century…
- …And doing so is necessary for natural gas to play a beneficial supporting role through the energy transition
- Among the broader set of climate change solutions, methane abatement is among the most cost effective and appealing
- Consequently, there is considerable regulatory and corporate momentum to tackle O&G sector methane emissions
- There are a wide range of abatement products and services to address methane emissions in the oil & gas value chains
- In the US alone, achieving a 30% reduction could require annual abatement spending of more than $2 billion