Meeting the Energy-Climate Challenge:
Science, Technology, and Policy at a Crossroads

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Advances in technology are an important part of the solution to every energy-related challenge.

THE PRIMARILY DOMESTIC BENEFITS INCLUDE…

- Reducing dependence on imports of energy & energy-critical materials from unreliable suppliers
- Reducing the costs of energy & energy-intensive processes & services
- Enhancing US competiveness in global energy-technology markets
- Reducing health & safety risks from accidents in the energy system
- Reducing the emissions of conventional air pollutants and toxics
- Minimizing ecosystem/biodiversity impacts of energy supply
- Increasing the reliability & resilience of the energy system

THE PRIMARILY GLOBAL BENEFITS INCLUDE…

- Contributing to environmentally sustainable & politically stabilizing economic development abroad
- Reducing the contributions of energy supply & use to human disruption of global climate

The most challenging of these rationales in terms of how much they demand from energy-technology innovation is climate change. That's because of…

- the dominant role of energy-sector emissions in causing climate change;
- the high proportion of US & global energy supply that comes from the offending fuels/technologies;
- the barriers & long lead times slowing the penetration of new technologies in the massive US & global energy systems;
- the unmanageable consequences of failing to limit climate change adequately going forward;
- the mismatch between energy lead times and the pace of energy-system change that avoiding unmanageable climate-change demands.

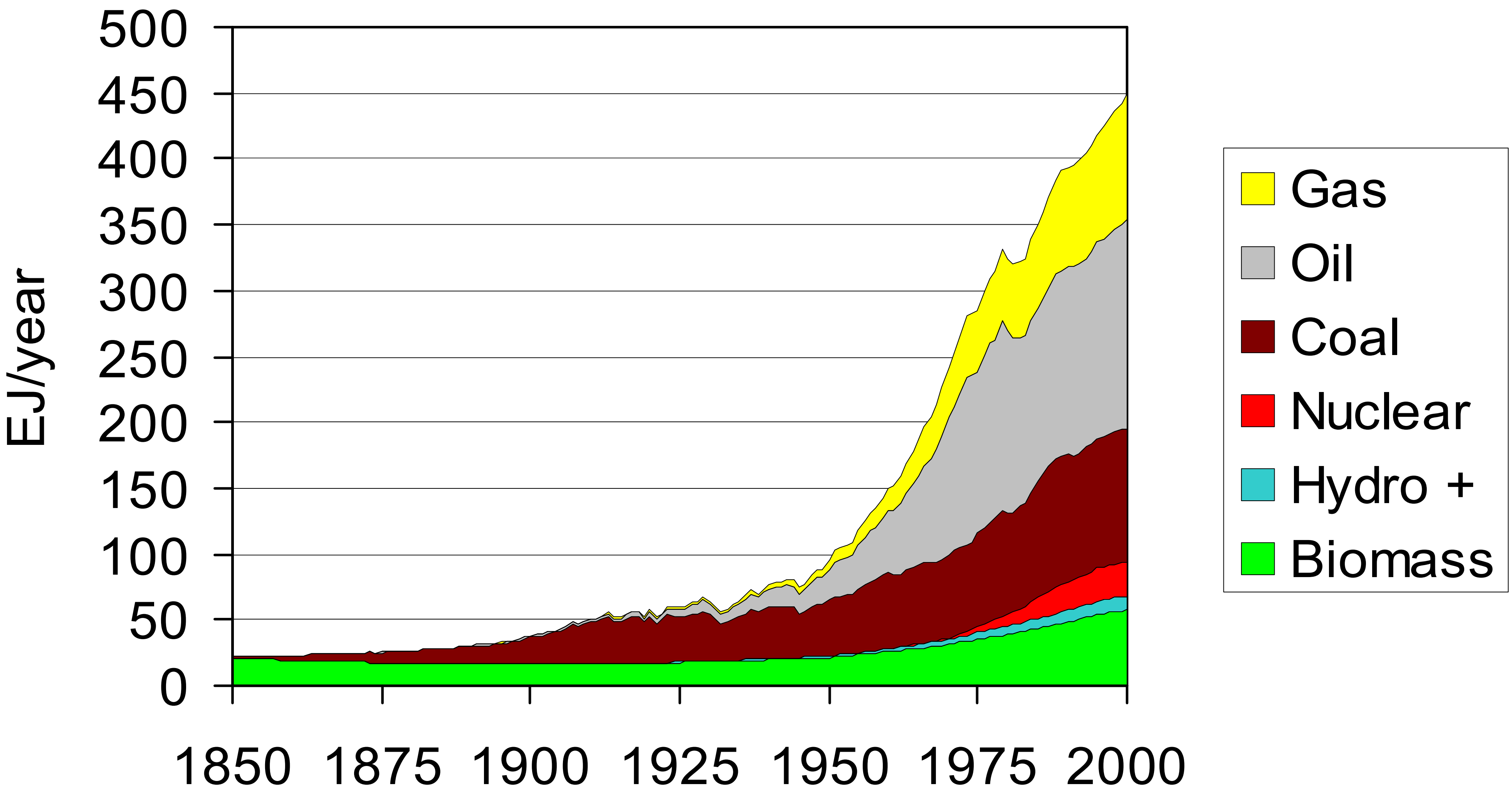
The combination poses great danger of climate catastrophe.

The rest of this talk elaborates on these propositions in terms of…

- world energy and climate change to date
- scenarios for energy and climate futures
- the option space for avoiding unmanageable climate harm
- policies and investments for lower emissions from the energy sector
- recent policy progress in the United States
- the path forward

World Energy and Climate Change to Date

Growth of world population & prosperity from 1850 to 2000 brought a 20-fold increase in energy use.



1.5%/yr growth 1850-1950 came mainly from coal; 3.1%/yr growth 1950-2000 came mostly from oil and natural gas. In 2000, fossil fuels were contributing 78% of global primary energy.

Economy, energy, & fossil CO_2 in 2021

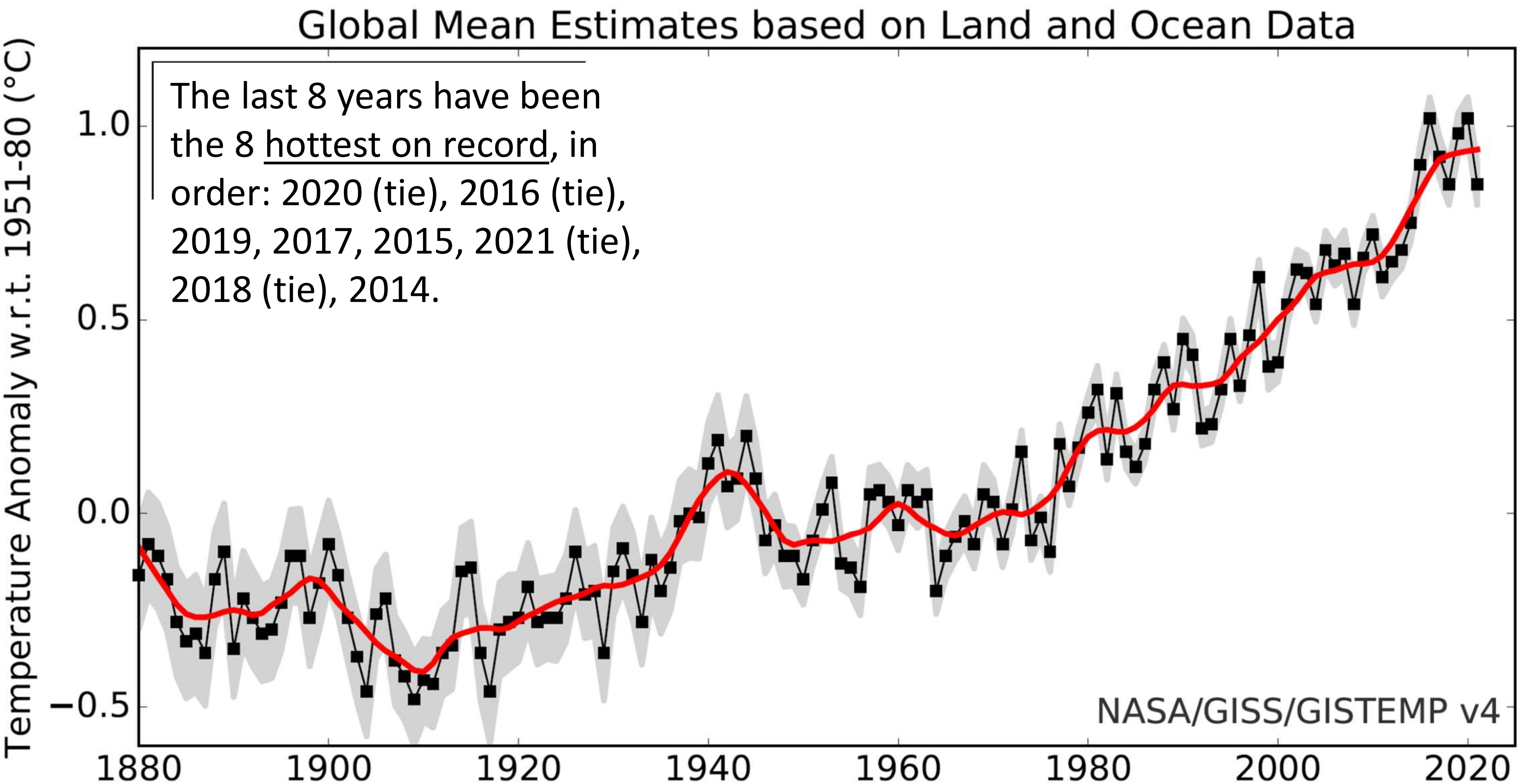
	population (millions)	ppp-GDP trillion US$)	energy (EJ)	fossil E (percent)	fossil CO_2 (MtC)
World	7840	146.7	645	76%	9308
China	1412	27.3	166	79%	2909
USA	331	23.0	96	79%	1291
India	1393	10.2	45	70%	701

Energy figures include estimates of traditional biofuel use.

~2/3 of global GHG emissions are from fossil fuel, nearly all of it as CO_2

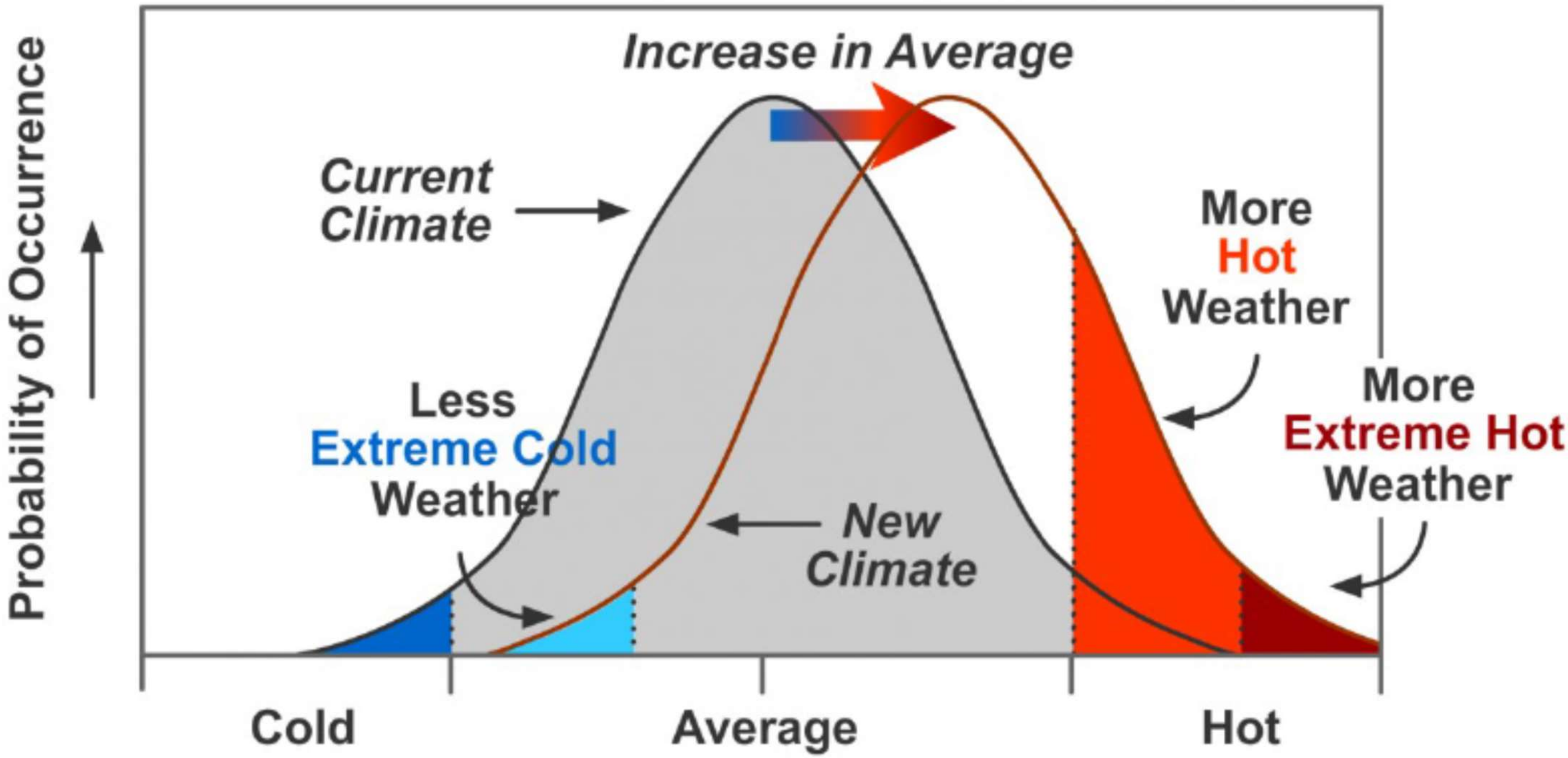
World Bank 2022, BP 2022, IEA 2022

Global warming driven mostly by anthropogenic CO_2 has been unequivocal for the past 50 years



Natural variability plus long-term natural cooling's offsetting GHG warming → roughly constant surface T until 1920. Cooling by human particulate emissions cancelled out GHG warming from WWII until 1970, after which the warming influence dominated.

In normal distributions, extremes change much faster than averages…as we're seeing.



In a warmer climate, temperature linked extremes that previously had probability of occurrence near zero occur with some regularity.

Observed impacts of global climate change to date

At just 1.1°C above 1900 global average T, we're already seeing, around the world, significant increases in…

- big wildfires
- long droughts
- powerful storms
- deadly heat waves
- torrential downpours & flooding
- permafrost thawing & subsidence
- pace of sea-level rise & coastal erosion
- range and virulence of pests & pathogens
- degradation of marine & terrestrial ecosystems
- impacts on distribution & abundance of valued species

All plausibly linked to climate change by theory, models,& "fingerprints".

On every one of these issues, all the new news from climate science has been bad news.

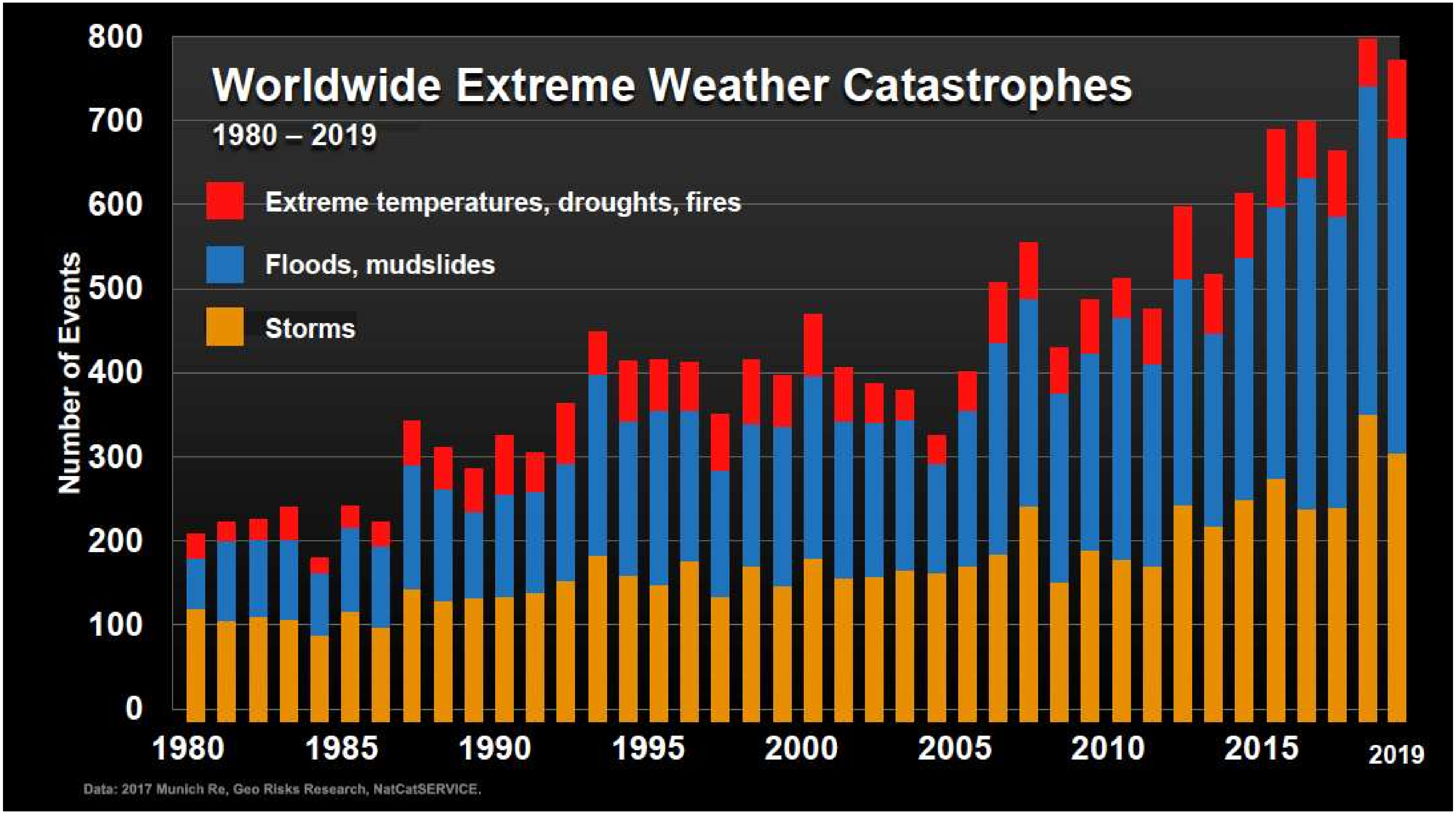
UNFCCC goal of avoiding "dangerous interference" is history.

Heat records being shattered everywhere

Among the all-time highs set in 2017-2022…

• Death Valley, CA	130°F	/ 54.4°C	Aug 2020
• Iran	129°F	/ 53.9°C	June 2017
• UAE	125°F	/ 51.8°C	Jun 2021
• Pakistan	124°F	/ 51.0°C	May 2022
• South Africa	122°F	/ 50.0°C	Nov 2018
• Canada	121°F	/ 49.6°C	Jun 2021
• Spain	117°F	/ 47.2°C	July 2017
• China	113°F	/ 45.0°C	Aug 2022
• Chile	113°F	/ 45.0°C	Jan 2017
• France	109°F	/ 42.8°C	July 2019
• England	104°F	/ 40.2°C	July 2022
• Siberia	100°F	/ 38.0°C	Jun 2020

Main types of weather disasters all increasing

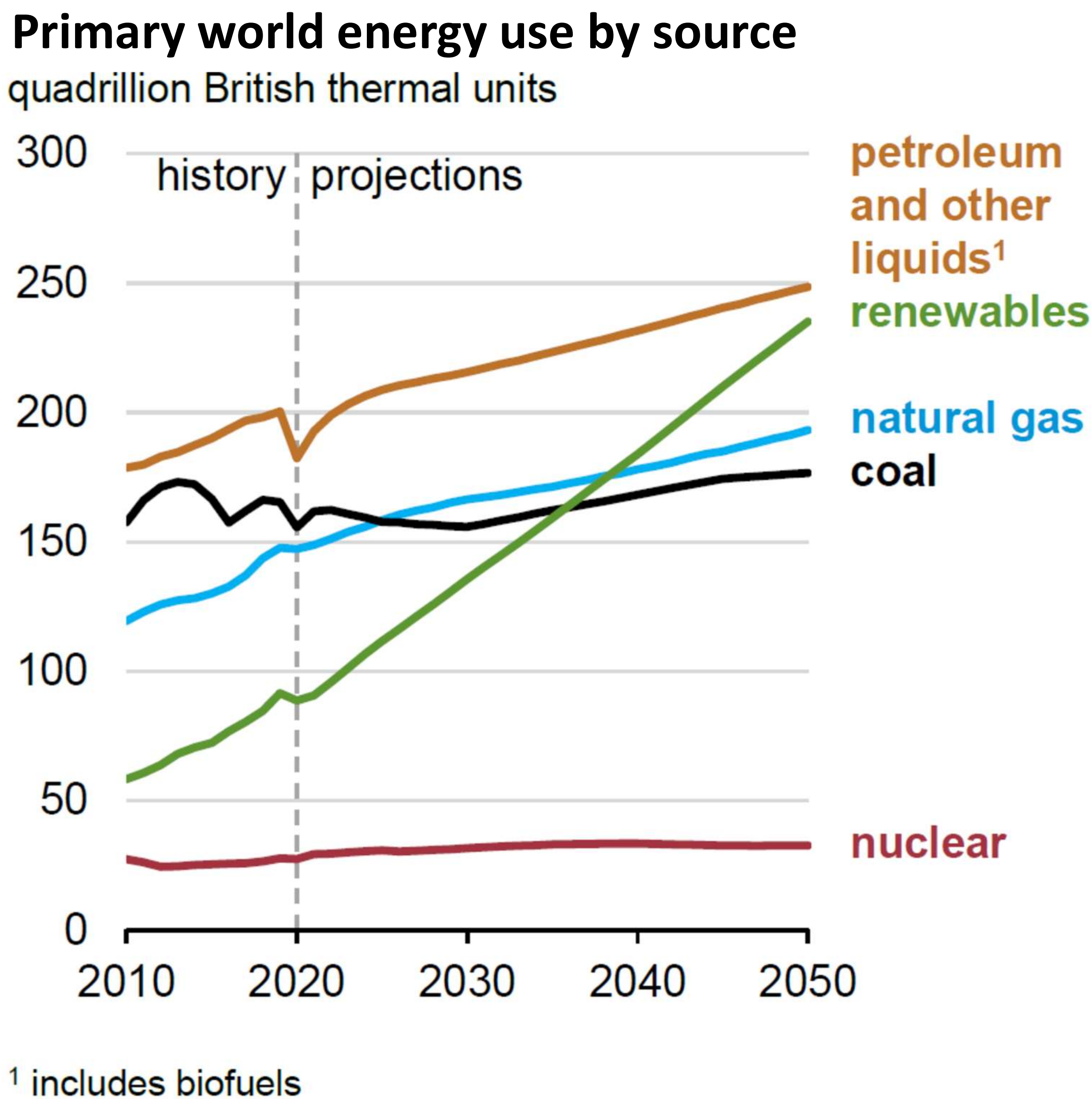


Year-to-year natural variability plays a role, but the trend is unmistakeable.

Munich Re

Scenarios for Energy & Climate Futures

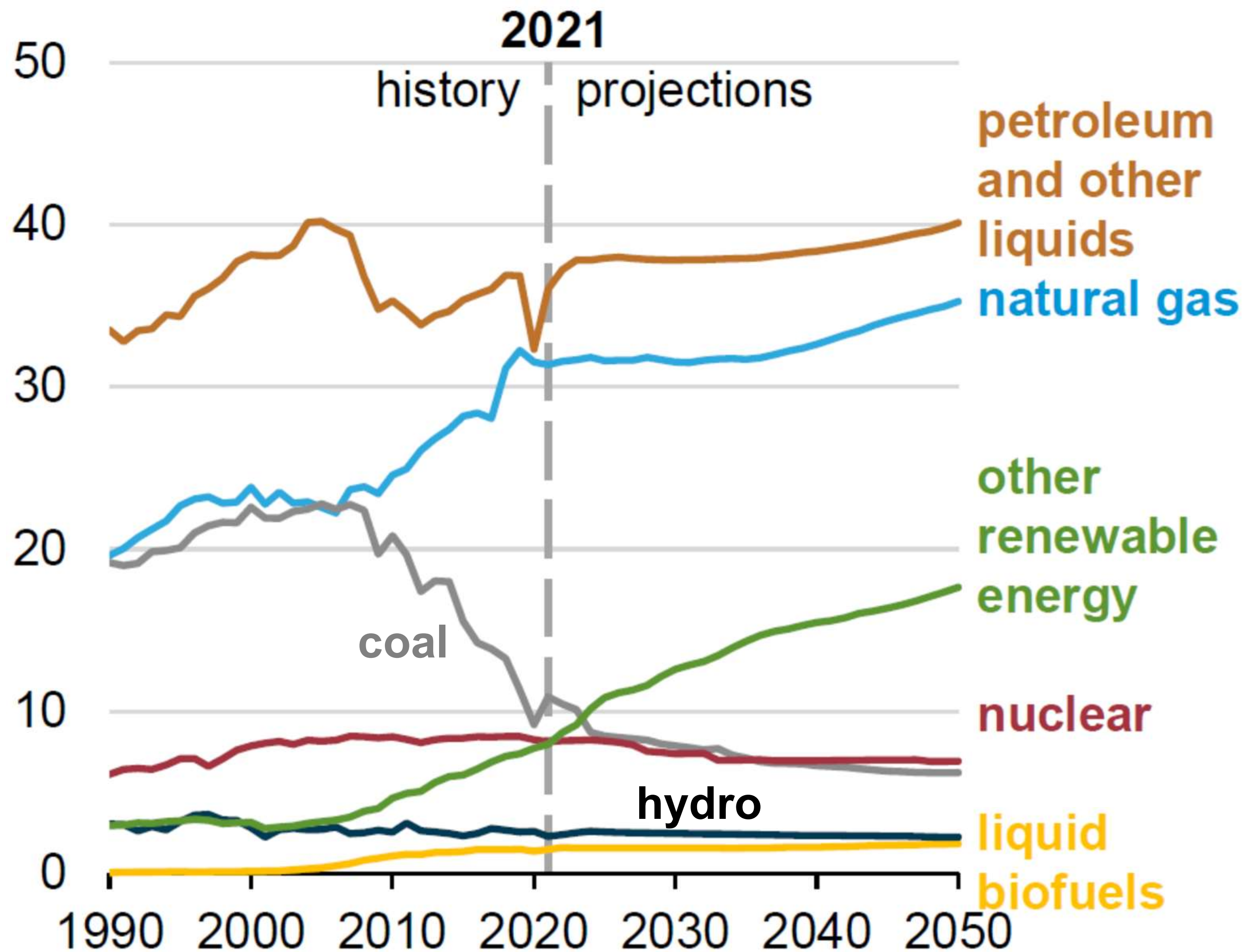
Sources of global energy use to 2050 in EIA's reference case



EIA, International Energy Outlook, 2021

Sources of US energy use to 2050 in EIA's reference case

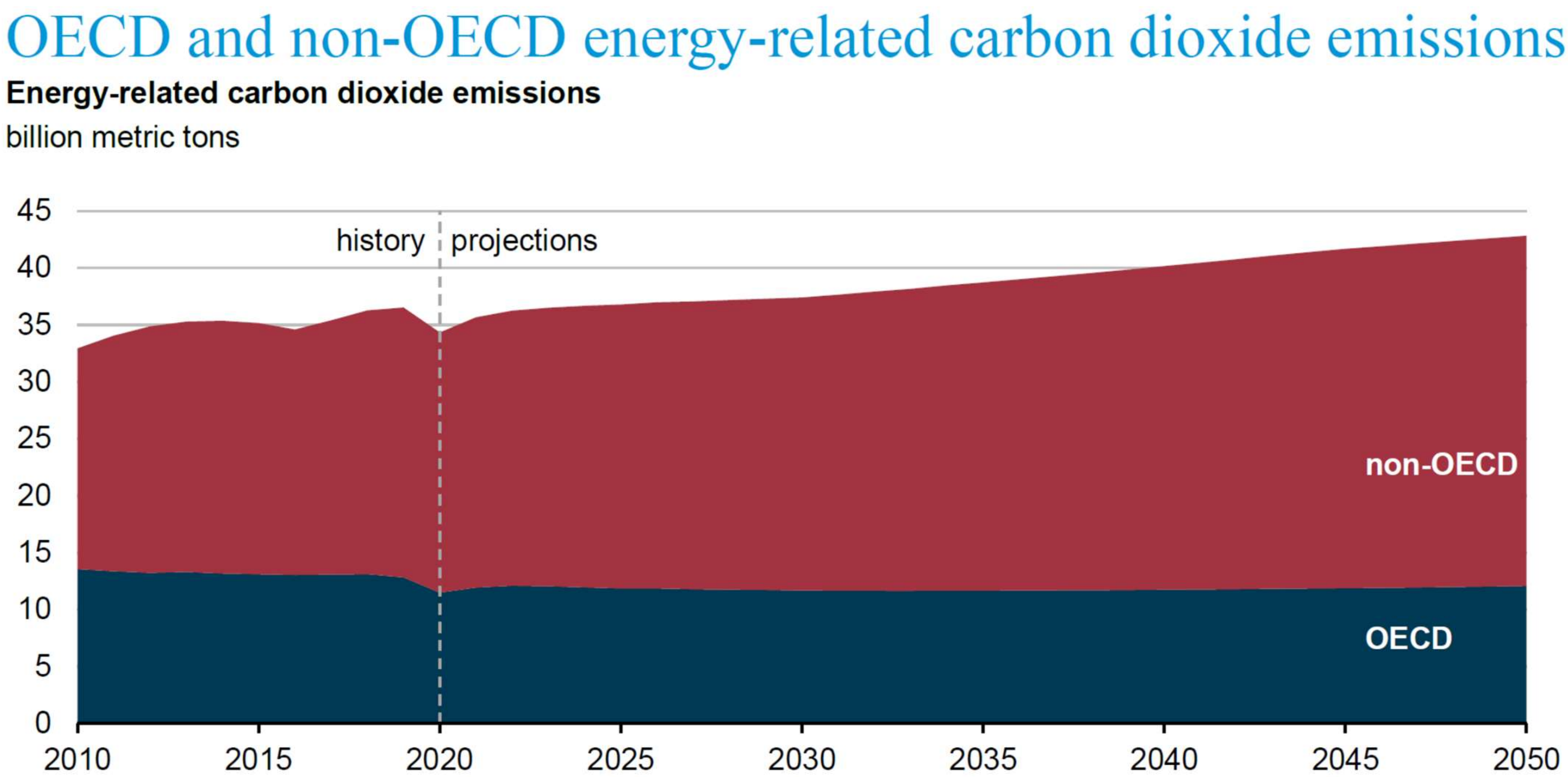
Primary US use by source
quadrillion British thermal units



EIA, Annual Energy Outlook, 2022

EIA "reference" projection of global fossil-CO_2 emissions

EIA "Reference Case" global fossil-CO_2 emissions projection from a base year of 2020



All of the projected growth is in developing countries.

EIA, International Energy Outlook, 2021

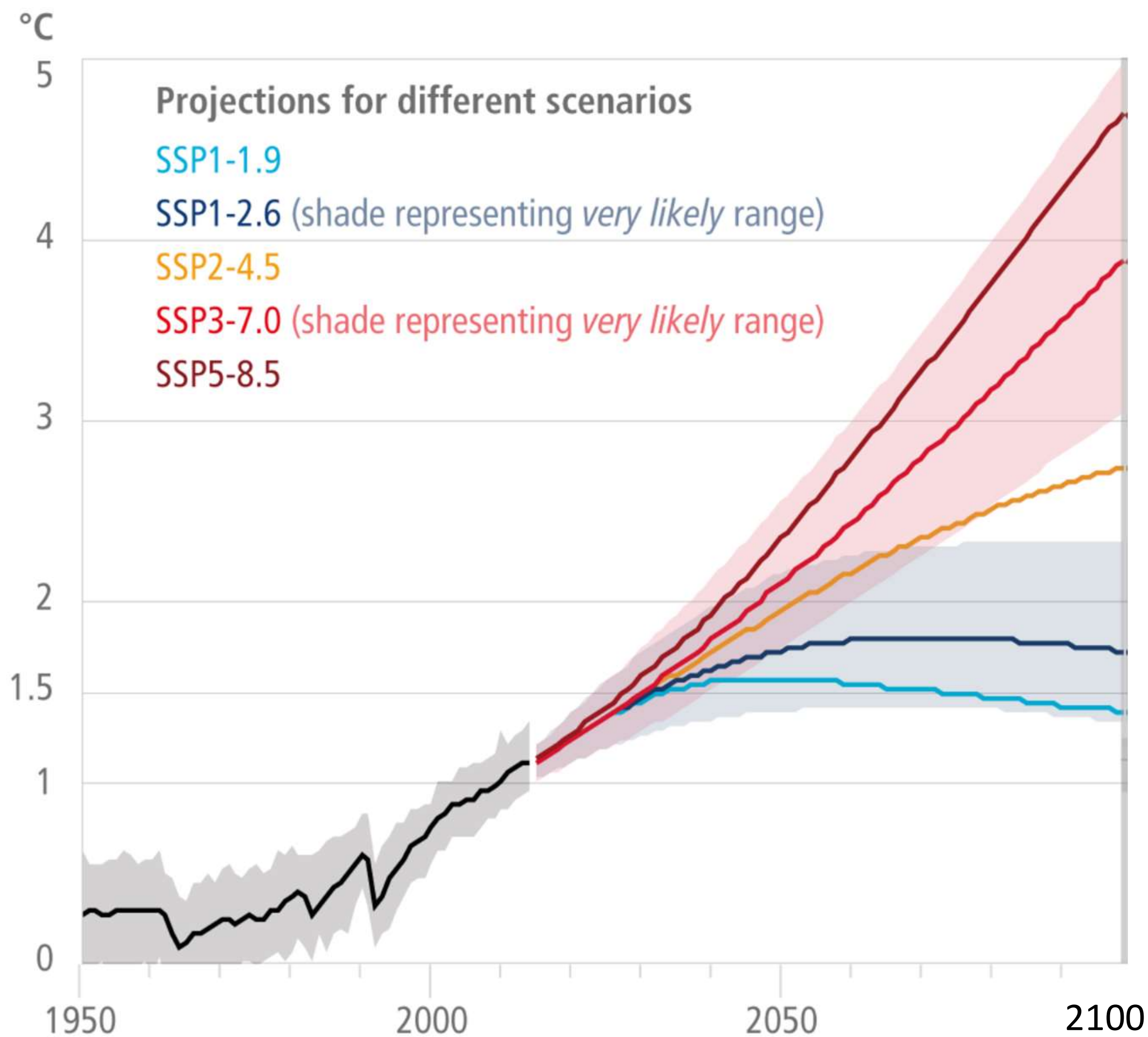
Global T continues to rise in all IPCC scenarios

Momentum in the climate system means T continues to go up even after atmospheric conditions stabilize.

And sea level continues to go up even after T stabilizes.

But there's an immense difference across scenarios.

T difference from 1850-1900 average



Last time T was 2ºC above 1900 level was 130,000 yr BP, with sea level 4-6 m higher than today.

Last time T was 3ºC above 1900 level was ~30 million yr BP, with sea level 20-30 m higher than today.

The EIA "Reference" emission forecast for the world would lead to ΔT in the range of 3-4ºC.

IPCC 2021

Expected further impacts under increasing T

- Human health: increasing heat stress & heat stroke; more smog & smoke deaths; spread & intensification of pathogens & vectors
- Extremes of wet and dry: longer droughts, bigger & hotter wildfires, more intense hailstorms/downpours/floods
- Agriculture: impacts of increasing extremes and invigorated pests & pathogens on crops and livestock
- Coastal zones: impacts of sea-level rise, stronger storms, and saltwater intrusion on cities & infrastructure
- Oceans: impacts of heating & acidification on marine food webs and fisheries; disappearance of most coral reefs
- National Security: vastly increased refugee flows

IPCC, WMO, AMS, US National Academies

Possibilities that become more likely as ΔT rises above 1.5-2°C

- Greatly accelerated sea-level rise from rapid disintegration of Greenland & Antarctic ice sheets submerges coasts
- Massive drying & fires in the (formerly) moist tropics impact health, economies, biodiversity, hemispheric weather patterns
- Most ocean fisheries crash due to warming, acidification, oxygen depletion, pollution…
- Collapse of the Atlantic Meridional Overturning Circulation shuts down the Gulf Stream, impacting U.S. & European weather
- Rapid CH_4 and CO_2 release from thawing permafrost & warming Arctic sediments & tropical wetlands accelerates all climate-related impacts

IPCC, WMO, AMS, US National Academies

The Option Space for Avoiding Unmanageable Climate Harm

There are only 3 options

1. Mitigation, meaning measures to reduce the pace & magnitude of the changes in global climate being caused by human activities.

2. Adaptation, meaning measures to reduce the adverse impacts on human well-being resulting from the changes in climate that do occur.

3. Suffering the adverse impacts and societal disruption that are not avoided by either mitigation or adaptation.

Note that:

- We're already doing some of each.
- What's at stake in society's choices is the future mix.
- Escaping immense suffering will require a lot of mitigation and a lot of adaptation—enough mitigation to avoid the unmanageable and enough adaptation to manage the unavoidable.

Mitigation options elaborated

REDUCING EMISSIONS

- Increased end-use efficiency in buildings, transport, industrial processes
- Equip old & new fossil- and biomass-fueled power plants with carbon capture, use, and sequestration (CCUS) technology
- Replace fossil- and biomass-fueled electric power plants with wind, solar, or nuclear plants
- Replace fossil-based transport fuels with cleanly produced electricity or hydrogen for light-duty vehicles and with sustainably grown biofuels or hydrogen for heavy-duty vehicles and aircraft
- Reduce deforestation & forest degradation with incentives plus stricter regulation & enforcement

Mitigation options elaborated (continued)

INCREASING SINKS

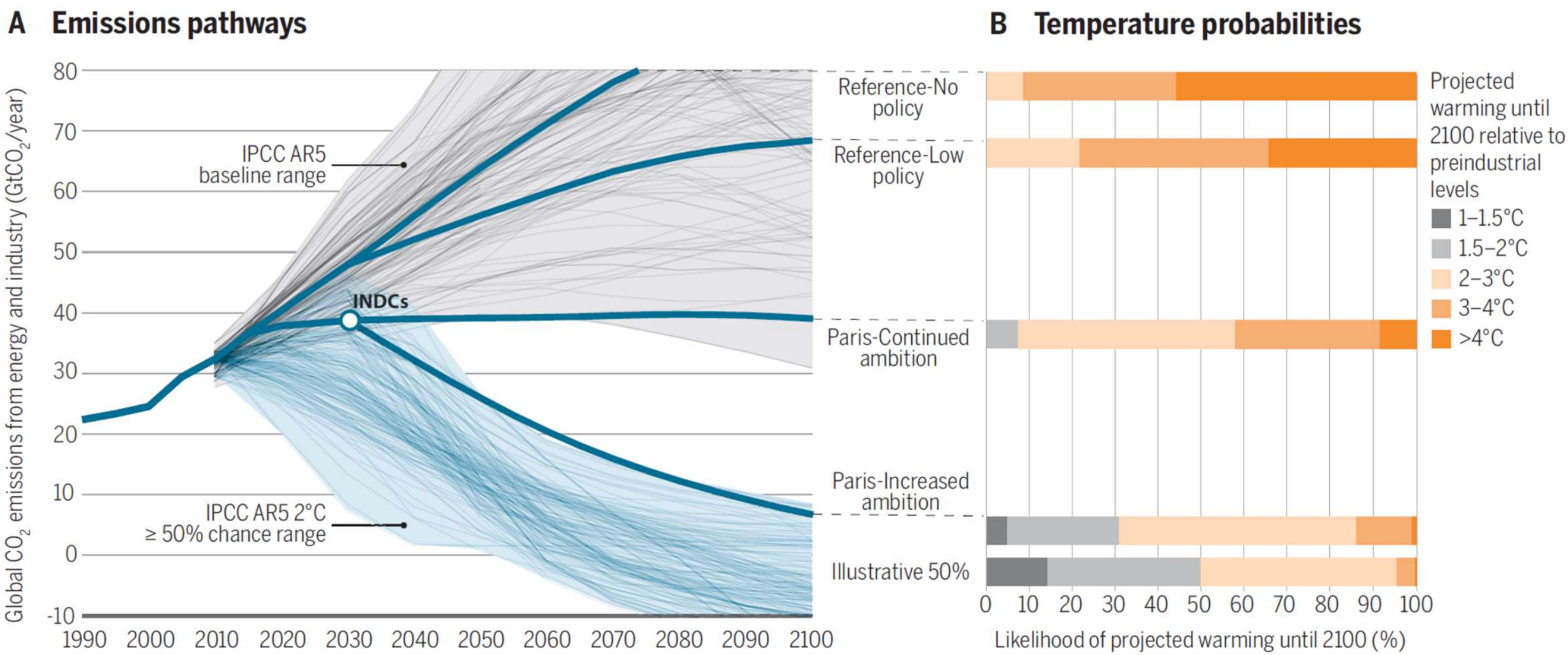
- Increase reforestation and afforestation
- Alter agricultural practices to store more soil carbon, release less CH_4 and N_2O.
- Burn sustainably grown biofuels in power plants with carbon capture & sequestration
- Develop affordable technological means to capture CO_2 from air for sequestration.

MANAGING SOLAR RADIATION

- Increase reflectivity of Earth's surface
- Inject reflecting particles into the stratosphere

CO_2 mitigation needed for ΔT = 1.5-2°C (Paris goals)

Global CO_2 emissions & corresponding ΔT probabilities



INDCs = Intended National Determined Contributions

- "Reference – Low Policy" case: No chance of ΔT <2°C, 78% chance of ΔT ≥3°C
- "Paris – Continued Ambition" case: 8% chance of ΔT 1.5-2°C, 42% chance of ΔT ≥3°C
- "Paris – Increased Ambition" case: 30% chance of ΔT <2°C in 2100, 14% chance of ΔT ≥3°C
- Trajectories with ≥50% chance of ΔT <2°C in 2100 need negative emissions after 2075

Fawcett et al., SCIENCE, Dec 4, 2015

Some realities about mitigation options

- Global energy system can't be changed quickly: ~$30T is invested in it; normal turnover is ~40 yrs; stranded costs are an issue; and politics play a big role in energy choices everywhere.
- Notwithstanding the large role of CO_2 from fossil-fuel use, an adequate mitigation strategy must also address emissions of…
  - CO_2 from land-use change, gas flaring, and cement production
  - methane (CH_4), coming from oil & gas operations, coal mines, livestock, rice cultivation, biomass burning, garbage dumps
  - nitrous oxide (N_2O), coming from nitrogen fertilizers, feedlots, low-T combustion of N-containing fuels
  - hydrofluorocarbons (HFCs), coming from industry and consumer products
  - black carbon (soot), coming from diesel & 2-stroke motors, biomass burning
- Many developing countries will need financial assistance to make the needed mitigation investments (as they also will for needed adaptation investments.

Policies and Investments for Lower Emissions from the Energy Sector

Emission-reduction options & policy needs

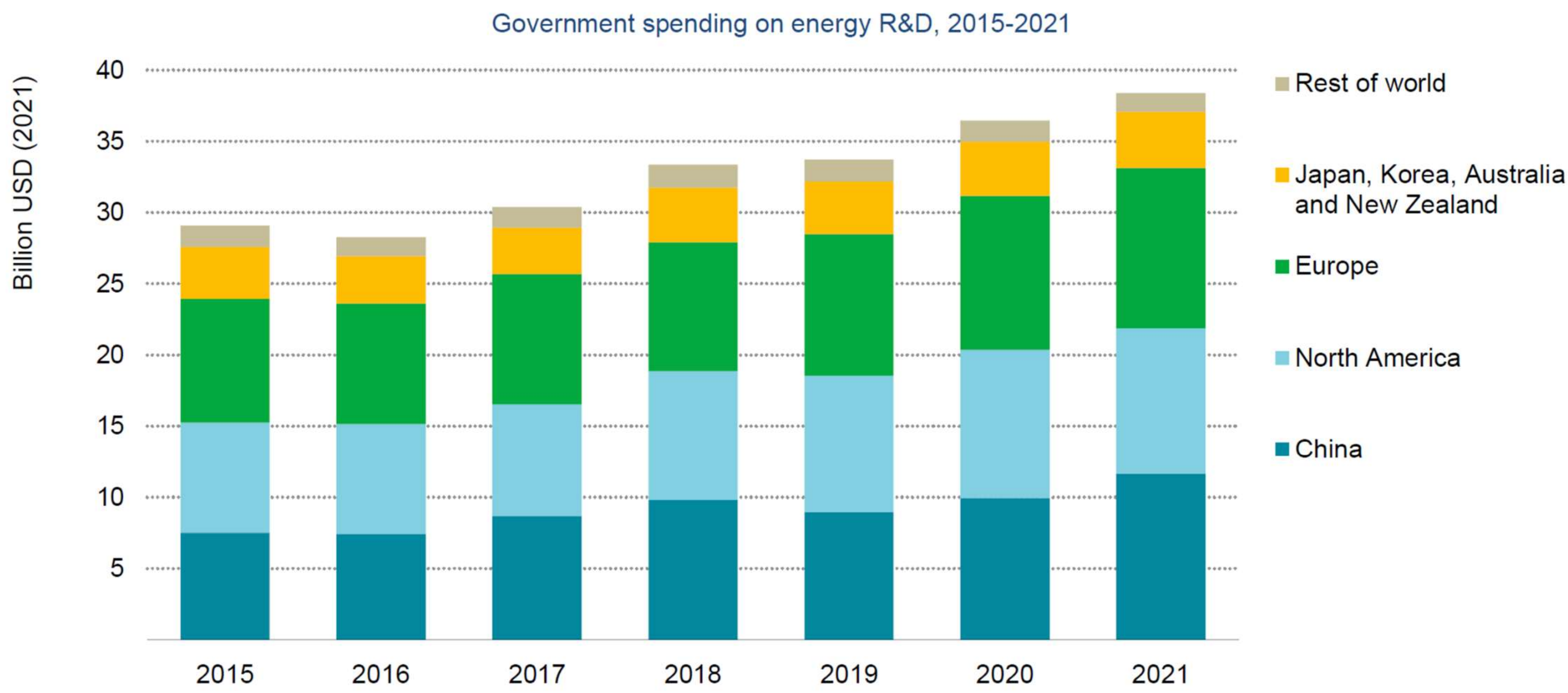
- Energy-efficiency & cleaner energy-supply technologies that are already economically competitive—and others that the private sector will bring to competitiveness in the next few years—could put the world on the path to deep emissions reductions between now and 2030, if they were very widely implemented.
  - Policies are needed to overcome barriers to deployment (information, financing, perverse incentive structure, supply-chain issues) for options economic now or soon.
- Somewhat costlier technologies could contribute sooner rather than later if the competitiveness gap were narrowed through direct subsidies, tax credits, regulation, and/or a carbon price, plus improvements achieved through RD&D and learning.
  - Of these policy options, most are being tried in some form in the USA, China, the EU, and India (the biggest emitters globally), but achieving carbon prices big enough to matter is the heaviest lift politically even though the most efficient economically.

Options & policy needs (continued)

- Successfully traversing the much deeper reduction trajectory needed between 2030 and 2050—and beyond—will require higher-performance technologies needing large investments in RD&D if they are to be available and affordable in time.
  - Because of long lead times, uncertainty of success, and the public-goods character of many of the benefits, governments will need to put up much of the money.
  - Virtually all respectable assessments conclude that government investments in energy RD&D need to increase at least 2-3 fold if the world is to meet even the 2°C Paris goal.
  - Government RD&D will not be enough, of course. Incentivizing increased private RD&D and forming public-private partnerships to facilitate the transition from lab to marketplace will also be essential.
- Beyond tech innovation, policy will need to support huge capital investments in deployment from now to 2050.

Global energy R&D increasing…but too slowly

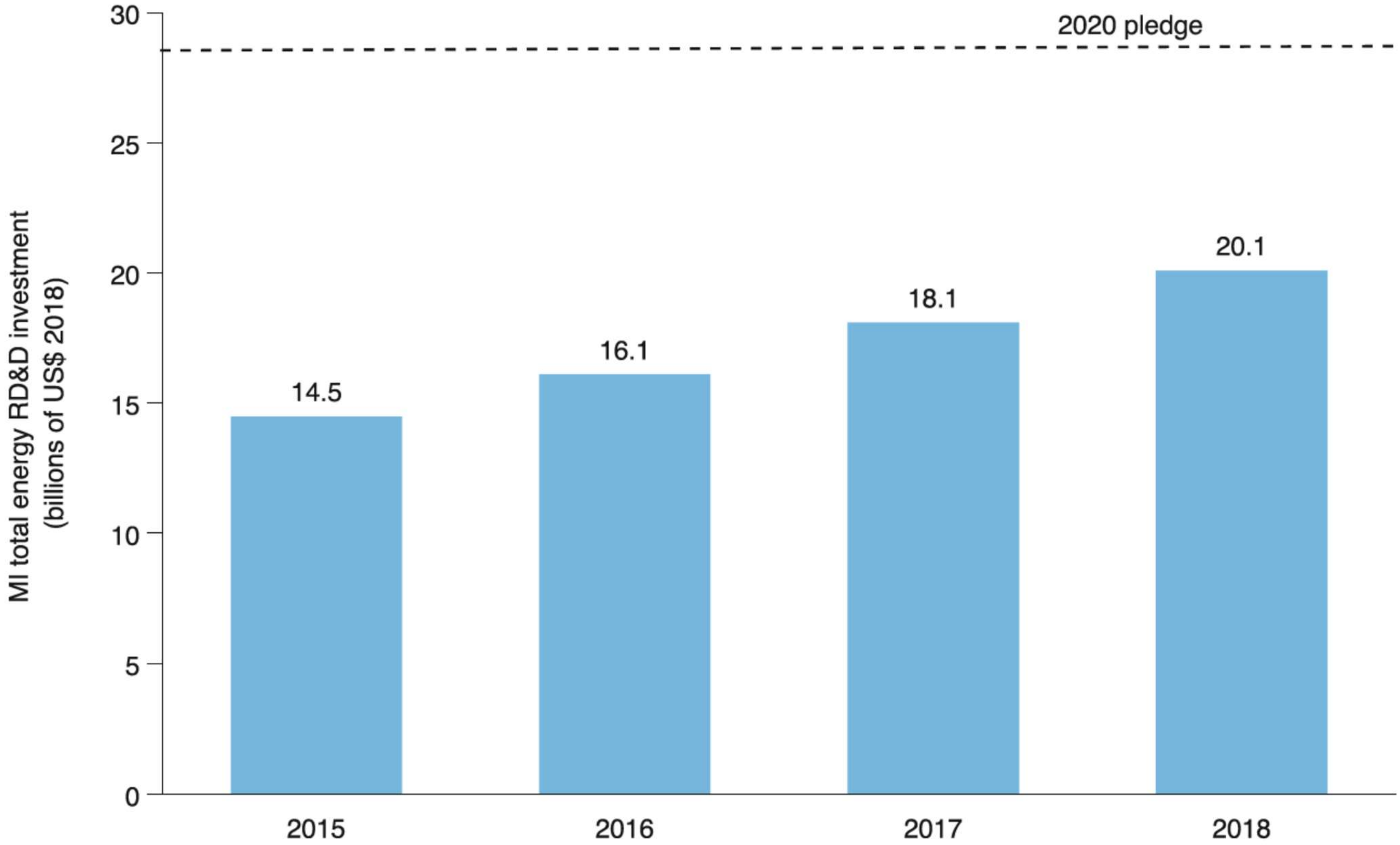
Government spending on energy R&D increased in 2021, but Covid-19 uncertainties slowed growth



IEA World Energy Investment 2022

Mission Innovation clean-energy RD&D Funding

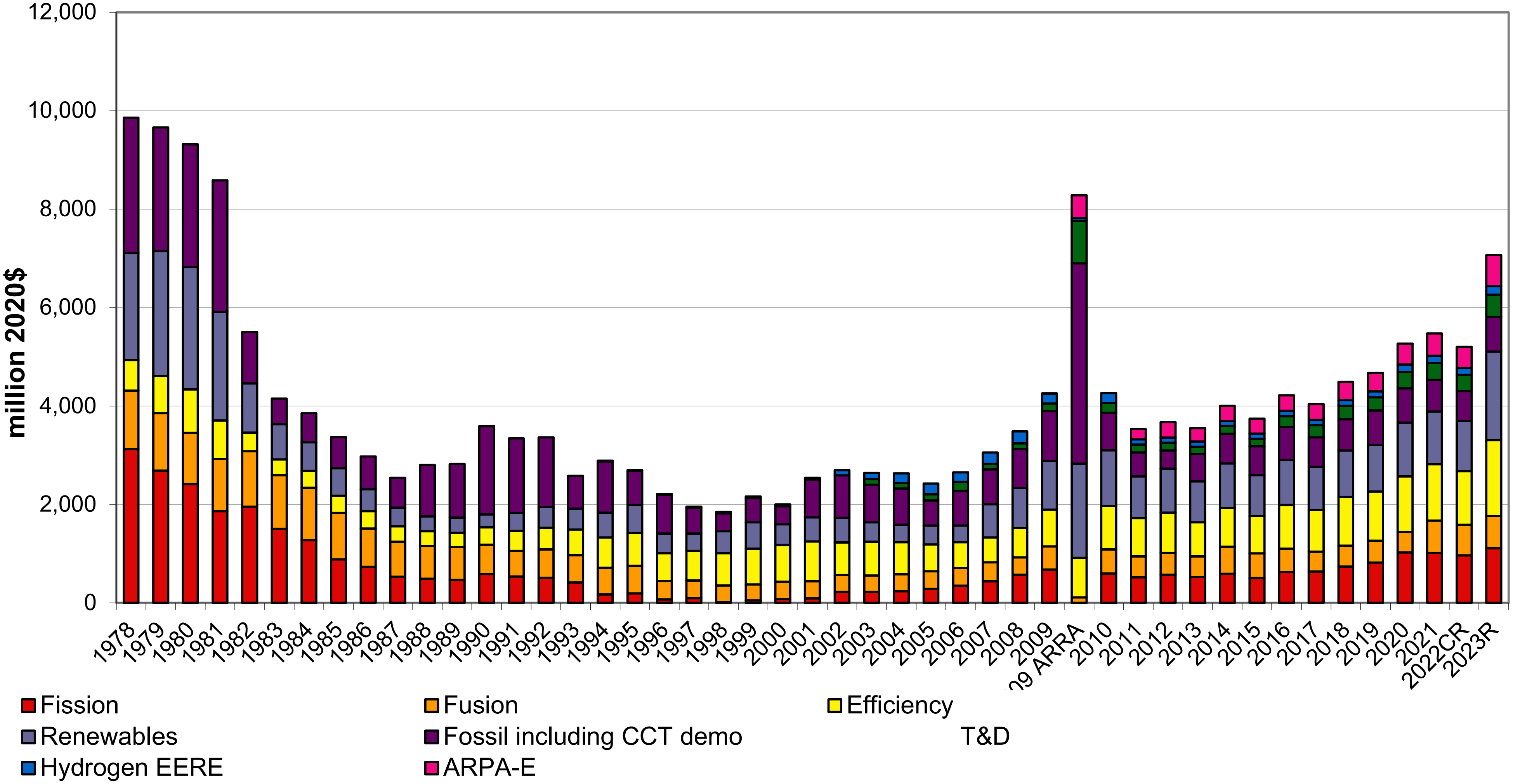
2X increase by 2020 pledged by 23 countries + EU in Dec 2015



Myslikova & Gallagher, NATURE ENERGY, Oct 2020

US gov't ERD&D still far short of late 70s levels

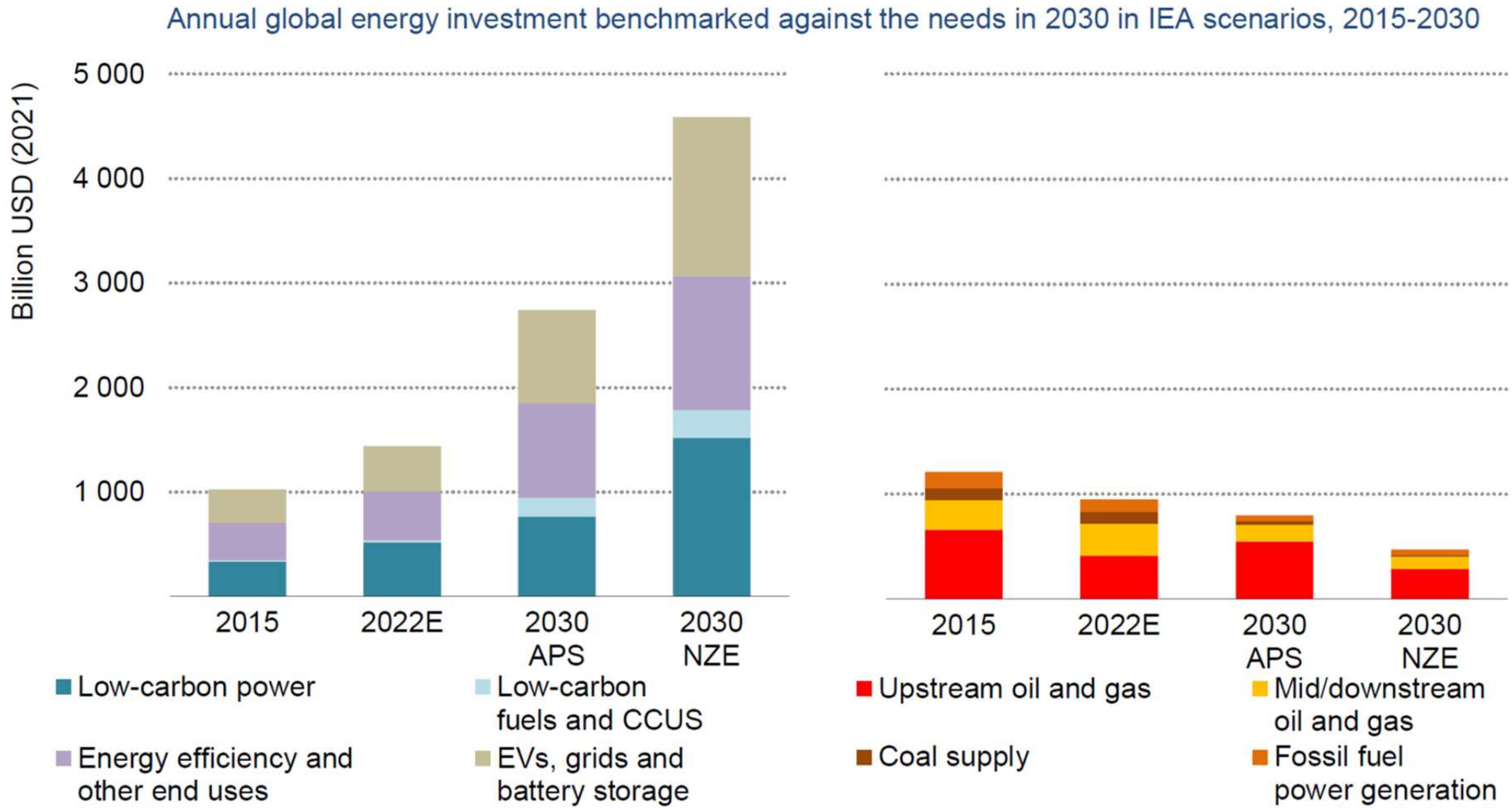
US DOE Energy RD&D Budget Authority from FY1978 to FY2023 request



Gallagher, K.S. and L.D. Anadon, "DOE Budget Authority for Energy Research, Development, and Demonstration Database," The Fletcher School, Tufts University; Department of Land Economy, University of Cambridge; and Belfer Center for Science and International Affairs, Harvard Kennedy School; April 8,

Estimated global capital investments in clean-energy infrastructure needed 2022-2030

A secure and affordable energy transition relies on a massive scale-up of investment in clean energy infrastructure



Notes: APS = Announced Pledges Scenario, the spending required to meet all country and regional climate pledges on time and in full. NZE = Net Zero Emissions by 2050 Scenario, the spending required to get the global energy sector to net zero by mid-century.

IEA World Energy Investment 2022

Recent Policy Progress in the United States

Energy-climate impact of Infrastructure Investment & American Jobs Act of 2021

ENERGY EFFICIENCY

- \$6.4 B for efficiency & weatheri-zation, to get by 2030…
- 5% of light-duty vehicles EVs
- 2% reduction in final energy demand

CLEAN ENERGY

- \$20B for clean-energy demos
- \$9.5B for clean-hydrogen R&D + 4 regional clean-fuel "hubs" (to get 6% increase in hydrogen supply in 2030)
- \$6B to prevent closure of existing nuclear plants

LAND SINKS

- \$5.4B for wildfire risk reduction & ecosystem restoration

CCUS

- \$4.6B for CO_2 transport & geo-logical storage
- \$3.5B to establish 4 regional direct air capture "hubs"

to get 16 million metric tons of CO_2 per year captured by 2030

NON-CO_2 EMISSIONS

\$11.3B to reclaim abandoned coal mines

\$3.7B to plug abandoned oil & gas wells

Princeton University ZERO Lab, https://repeatproject.org/policies

Energy-climate provisions in the Inflation Reduction Act of 2022

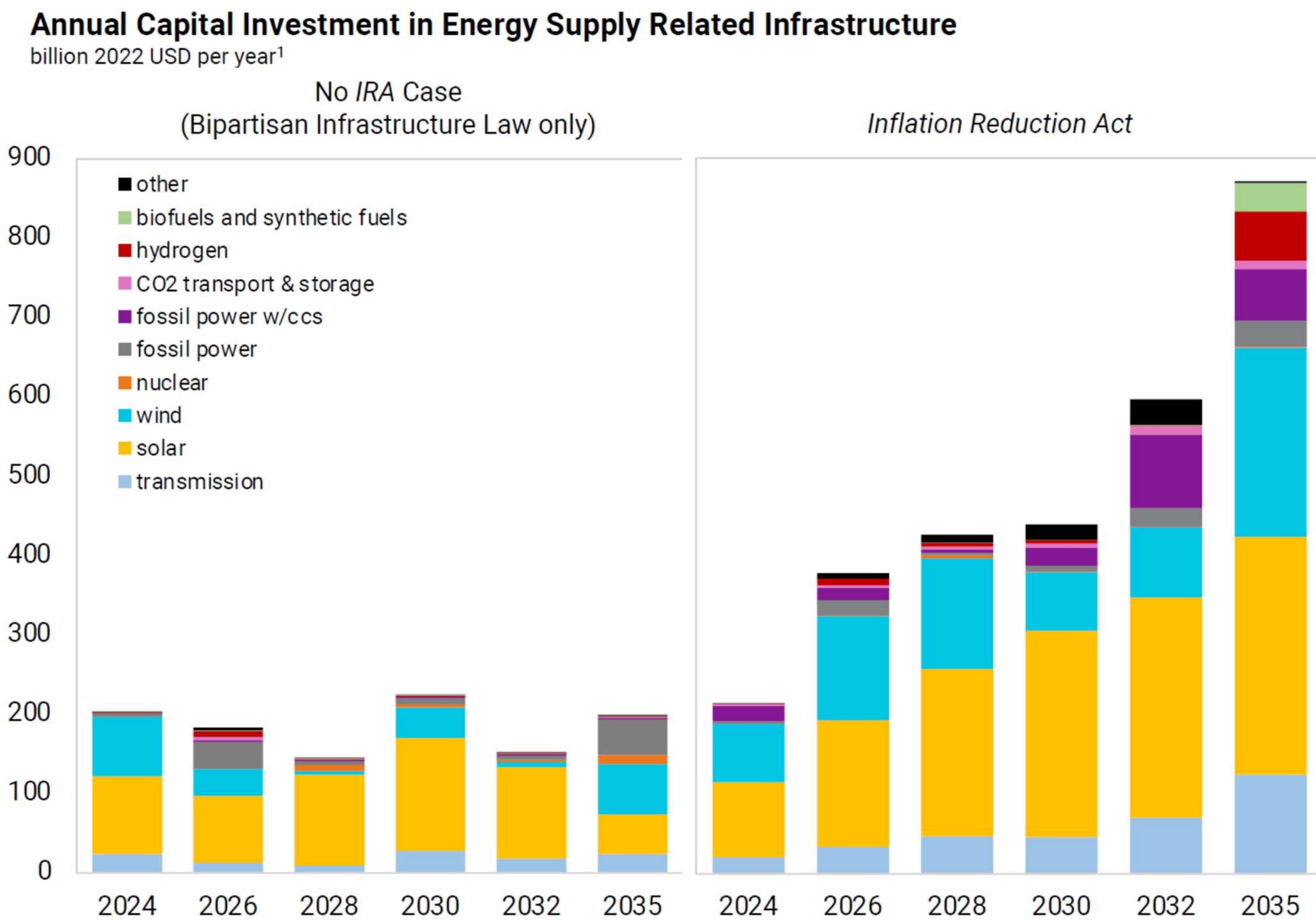
Main categories with estimated costs over the period 2022-2032

• Clean electricity tax credits	$161B
• Air pollution, hazardous materials, infrastructure	$ 40B
• Individual clean-energy incentives	$ 37B
• Clean manufacturing tax credits	$ 37B
• Clean fuel and vehicle tax credits	$ 36B
• Conservation, rural development, forestry	$ 35B
• Building efficiency, electrification, industrial, DOE grants and loans	$ 27 B

Princeton U's Zero-carbon Energy Systems Research & Optimization Lab estimates that the IRA will result in…

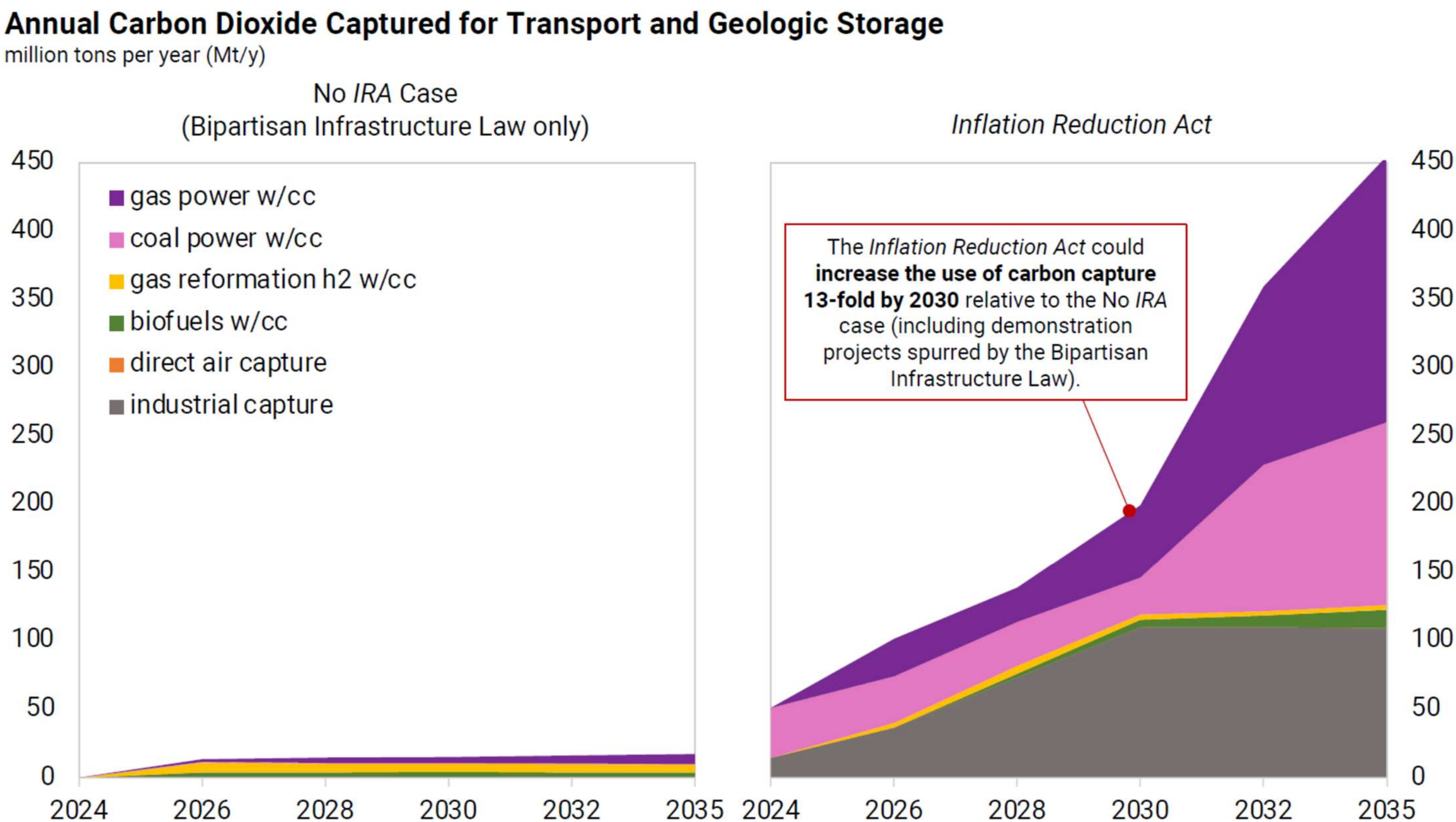
- >$4.1T add'l cap investment in new energy-supply infrastructure to 2032
- $334B annual investment in wind & solar PV by 2030
- $28B annual investment in CCS by 2030
- $4B annual investment in hydrogen production by 2030
- cumulative GHG reductions totaling ~6.3 billion tons by 2032

Effect of IRA on energy capital investment



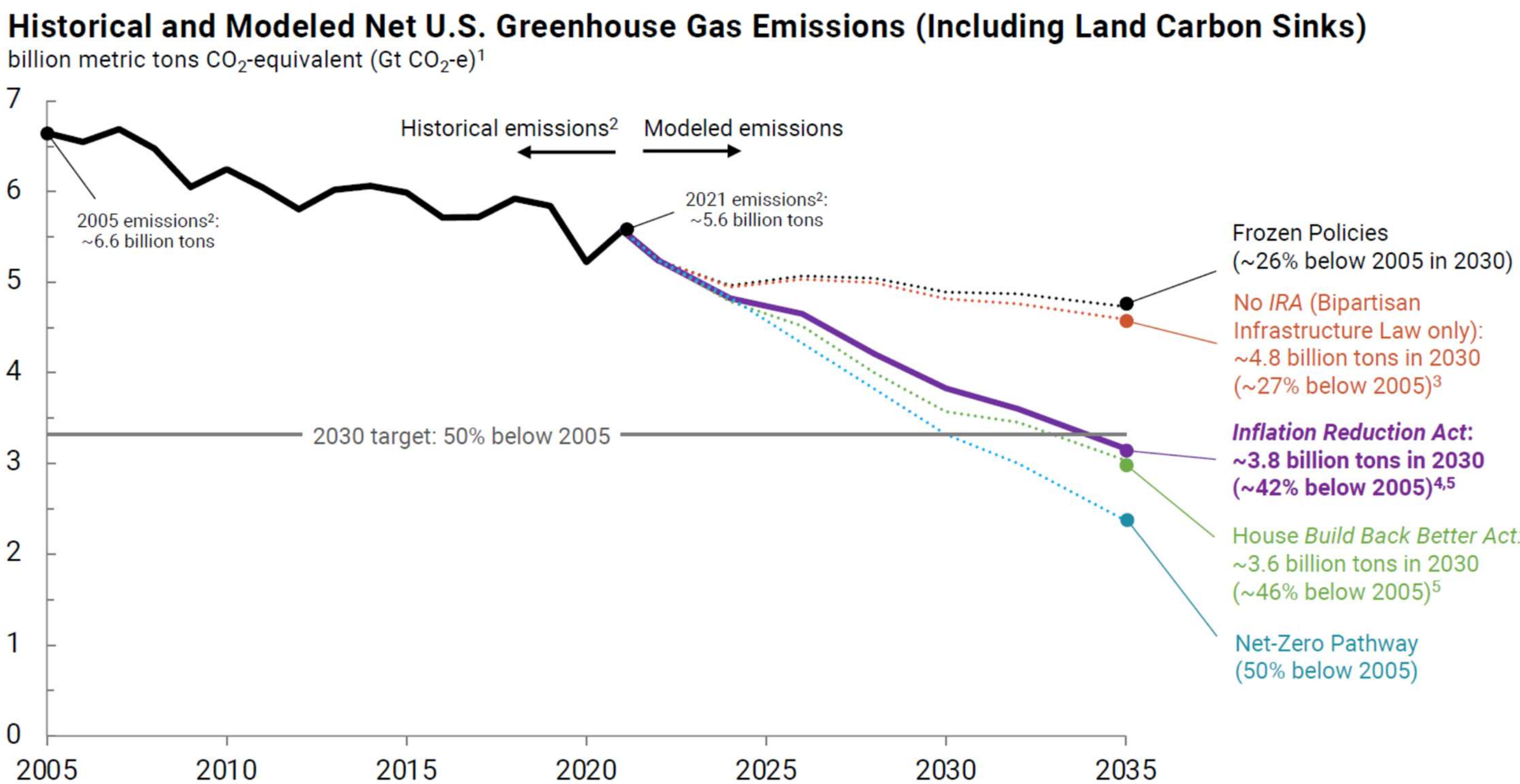
Princeton University ZERO Lab, Aug 2022

Effect of IRA on Carbon Capture & Storage



Princeton University ZERO Lab, Aug 2022

Projected emissions after recent US legislation

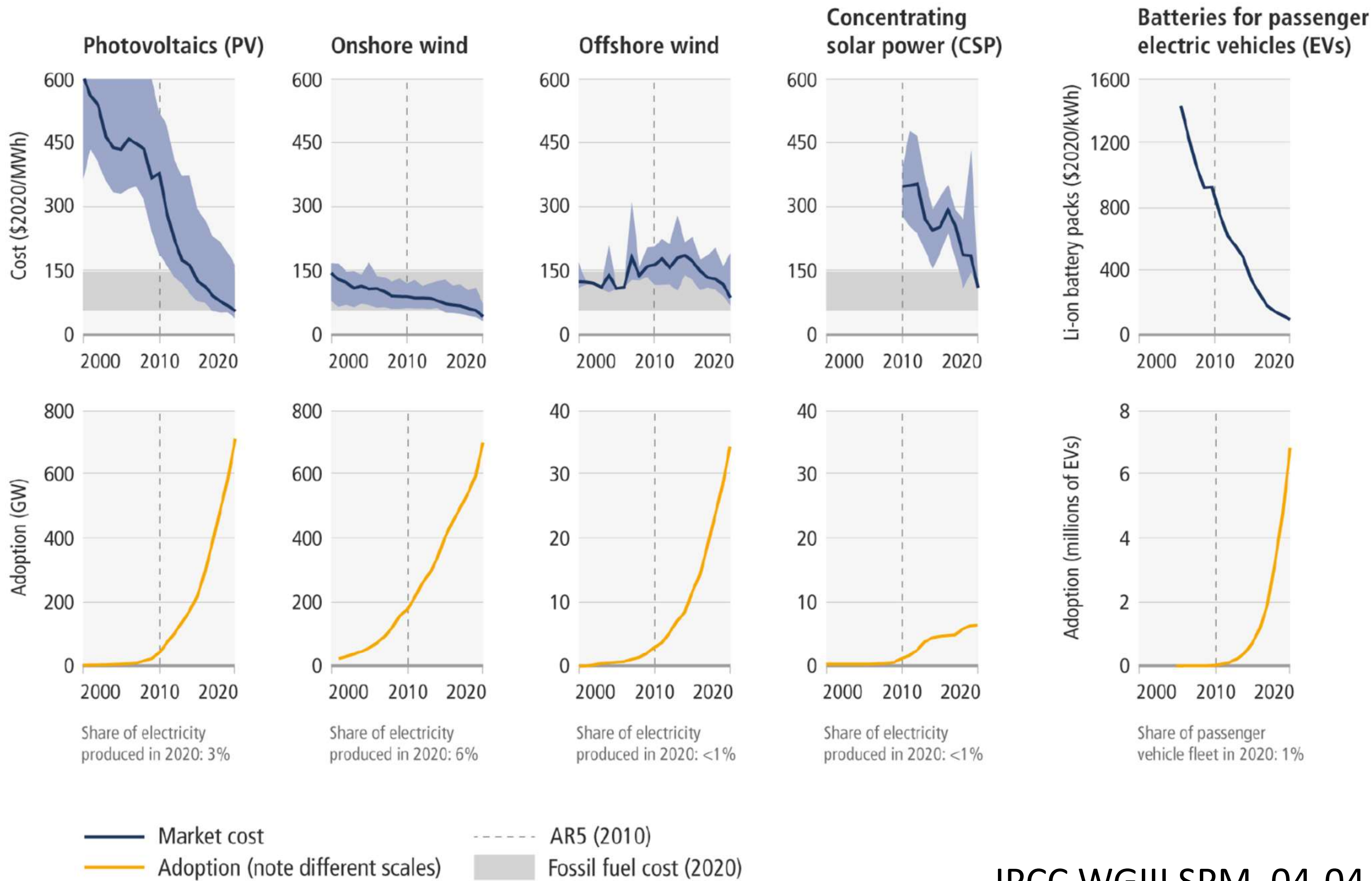


Princeton University ZERO Lab, Aug 2022

The path forward

Global trends worth continuing

The unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen, and their use continues to rise.



IPCC WGIII SPM, 04-04-22

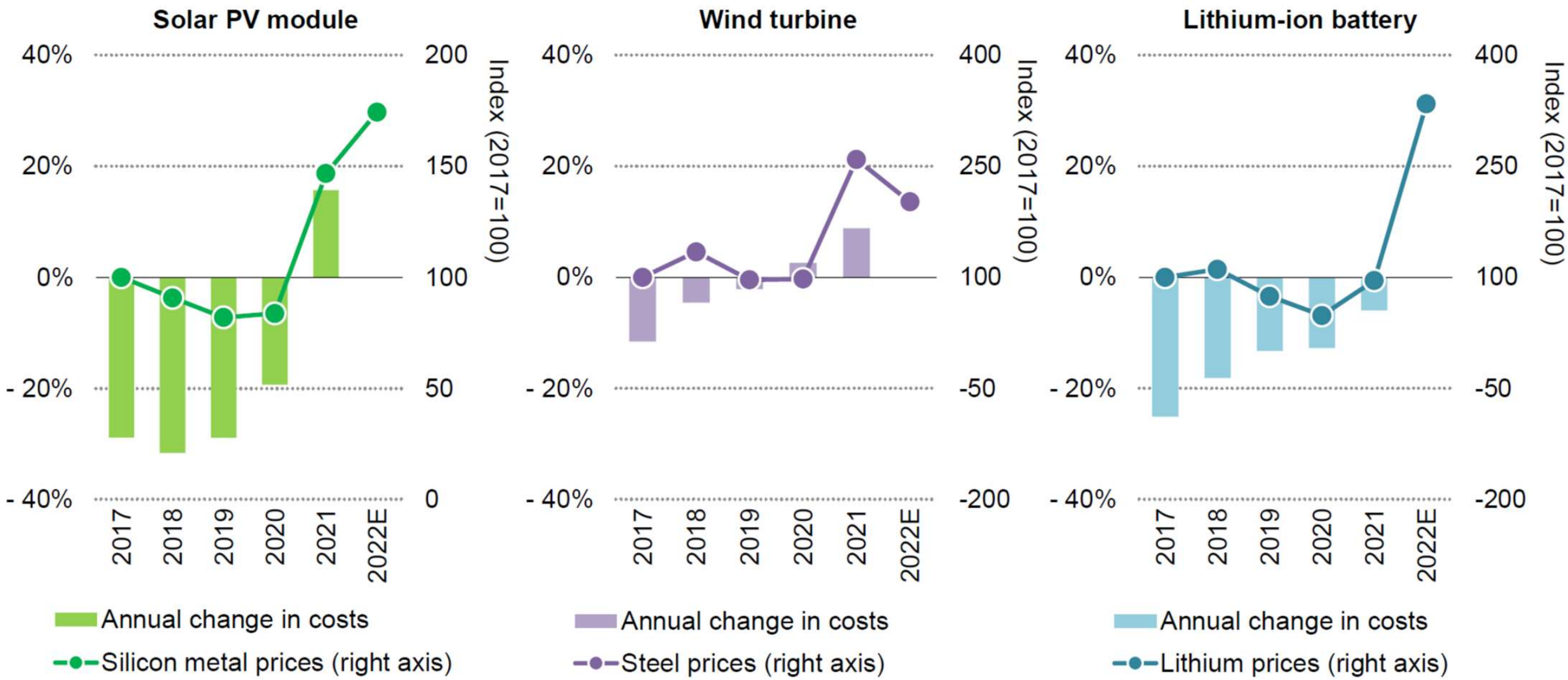
A clean-energy-technology wish list

- More efficient buildings & industrial processes
- A smarter, more efficient electricity grid
- Improved batteries, longer-term storage technology
- More efficient photovoltaic cells
- Improved hydrogen production, transport, storage
- More durable & affordable fuel cells
- Drop-in fluid biofuels from sustainably grown feedstocks that don't compete with food & forests
- CO_2 capture & storage/re-use for fossil & biofuel electricity generation and industry
- Advanced nuclear reactors with lower costs, high safety, & proliferation-resistant fuel cycles
- Practical fusion

An important technical/economic challenge

Critical minerals threaten to reverse the trend of declining costs for clean energy technologies

Technology cost trends and key material prices for a solar PV module, wind turbine and lithium-ion battery, 2017-2022



For many of the clean-energy technologies we seek to expand, innovations that reduce dependence on limited or vulnerable materials will be important.

IEA World Energy Investment 2022

Political obstacles needing increased attention

- Elected officials' grasp of the realities about climate-change stakes, scale of needed remedies, time scale of energy transitions compared to time scale of worsening climate-change impacts

  → Lack of political will to support action at the needed scale

- Public grasp of the same

  → Lack of priority on climate action, pressure on elected officials

- NIMBY (Not in My Back Yard) trending toward BANANA (Build Absolutely Nothing Anywhere Near Anybody)

  → Imperiling electric-grid expansion and siting of even the cleanest energy-supply installations, as well as sequestration of CO2 and nuclear waste

- Environmentalist antipathy to "fossil bridge" with CCUS

  → Risk of missing ambitious emission targets no matter what else is done

- Rejection of public-private-academic & internat'l collaborations

  → Lost opportunities to accelerate progress & universalize it

What scientists & engineers should do

- Get getter at explaining realities, especially that…
  - excessive climate change threatens every aspect of physical well-being—life, health, food, water, infrastructure, ecosystem services, economies, peace…
  - while more climate change is inevitable, there will be far less change and far less suffering if society invests heavily and early in mitigation and adaptation
  - if we as a society focus only on the costs of mitigation and adaptation and not on the economic and wider benefits of avoiding the worst impacts of climate change, we will invest far too little
  - when some cleaner energy options seem at first to be too expensive, it's worth remembering that they often can be made more competitive by research, learning, and policies that credit them with their climate benefits
  - international energy-technology cooperation can accelerate progress here; and, when it advances emission reductions in other countries, this benefits us all.

What scientists & engineers should do (continued)

- Tithe a fraction of your time to communicating these insights to legislators, other government officials, and whomever else you can get to listen.
- Join and take active part in NAE and other professional-society working groups addressing energy strategy & climate change.
- Build and take part in clean-energy & energy-efficiency collaborations across disciplinary and project stovepipes (include social scientists!), across public/private/academic/civil-society sectors, and across nations.

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