Electric Energy Systems and Global Warming: Trends, Challenges and Opportunities

Texas Analog Center of Excellence Symposium
October 16, 2023
Univ of Texas at Dallas

Pramod P. Khargonekar
University of California, Irvine

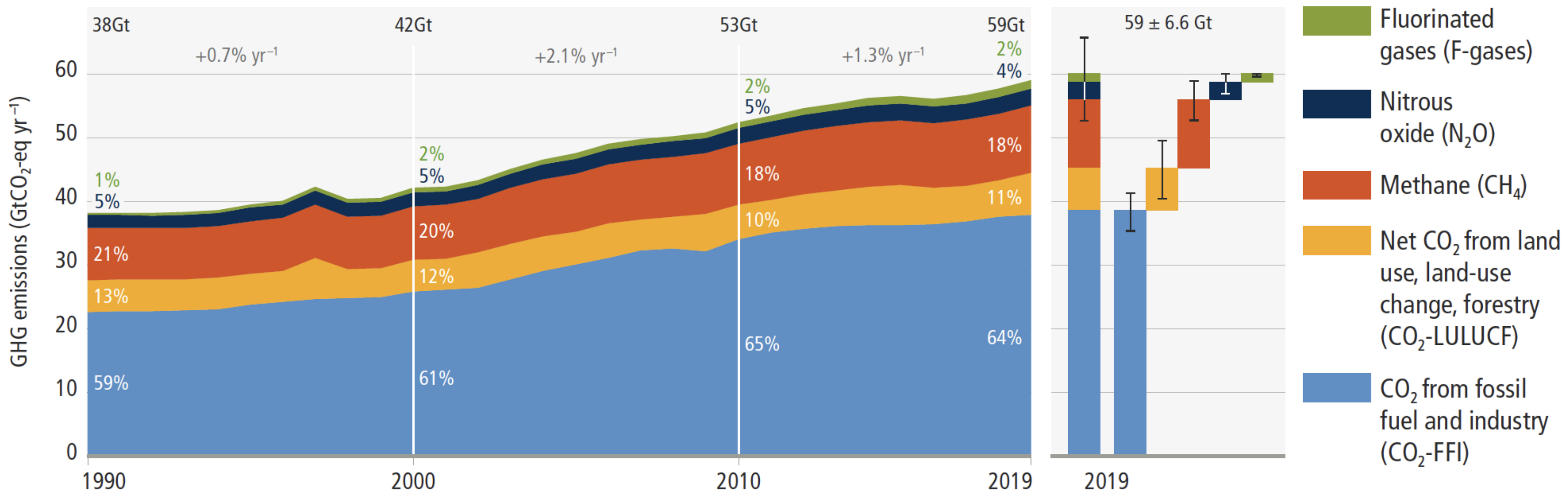
Outline

- Global warming and GHG emissions
- Energy system decarbonization
- Electric energy system
- ICT energy and carbon footprint
- Conclusions

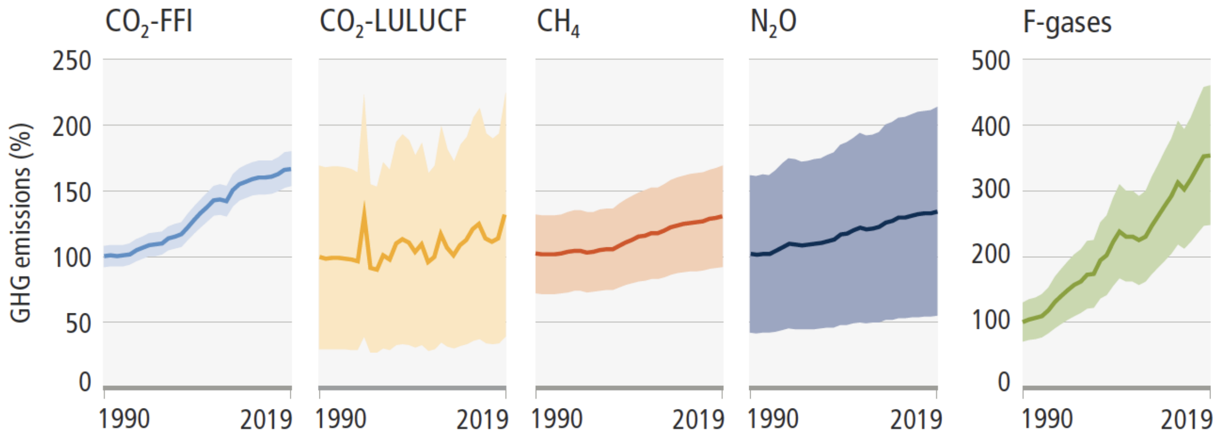
Global Warming and GHG Emissions

Global GHG Emissions

a. Global net anthropogenic GHG emissions 1990–2019 [5]



b. Global anthropogenic GHG emissions and uncertainties by gas – relative to 1990

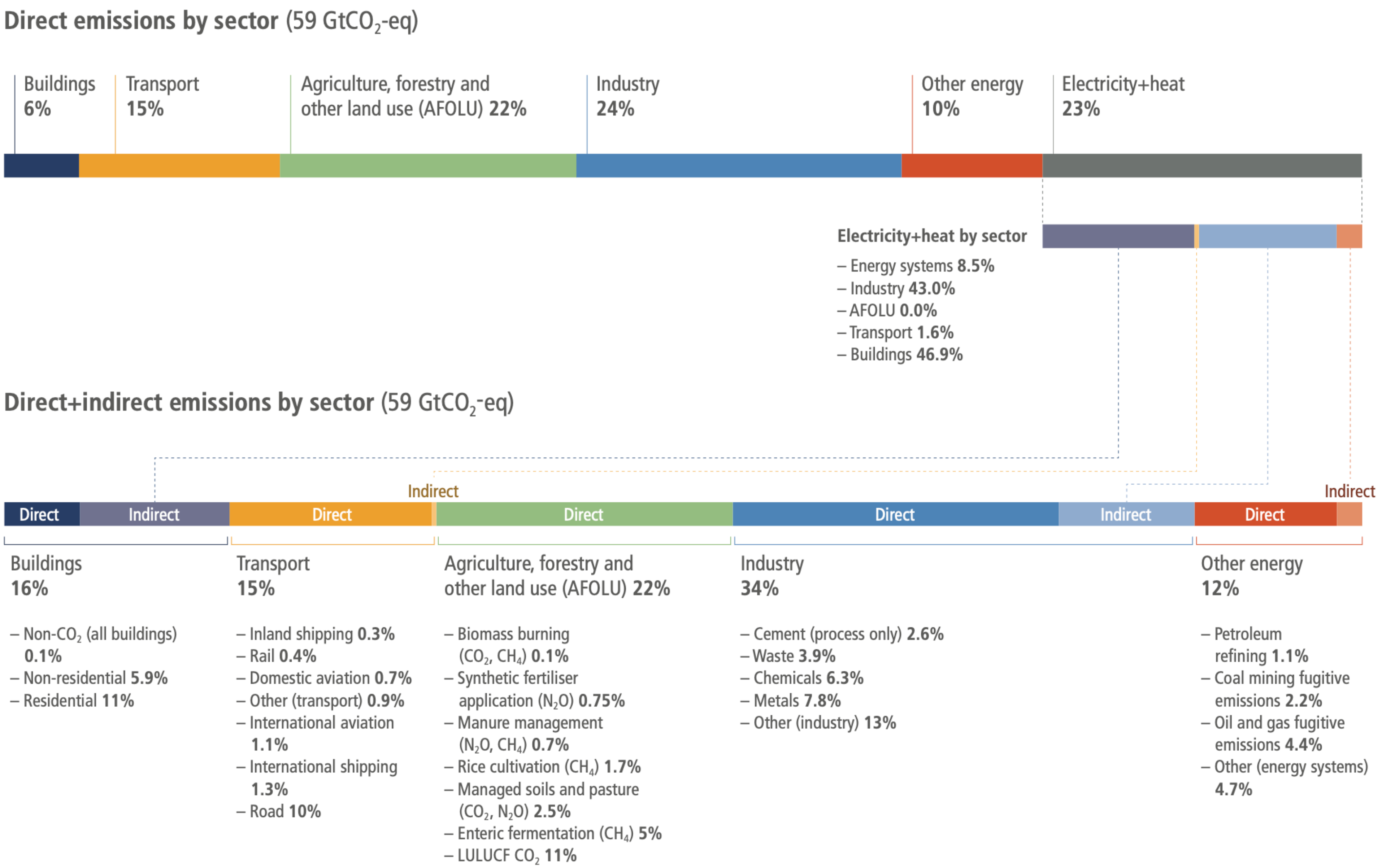


	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2-FFI	38 ± 3	15	167
CO_2-LULUCF	6.6 ± 4.6	1.6	133
CH_4	11 ± 3.2	2.4	129
N_2O	2.7 ± 1.6	0.65	133
F-gases	1.4 ± 0.41	0.97	354
Total	59 ± 6.6	21	154

The solid line indicates central estimate of emissions trends. The shaded area indicates the uncertainty range.

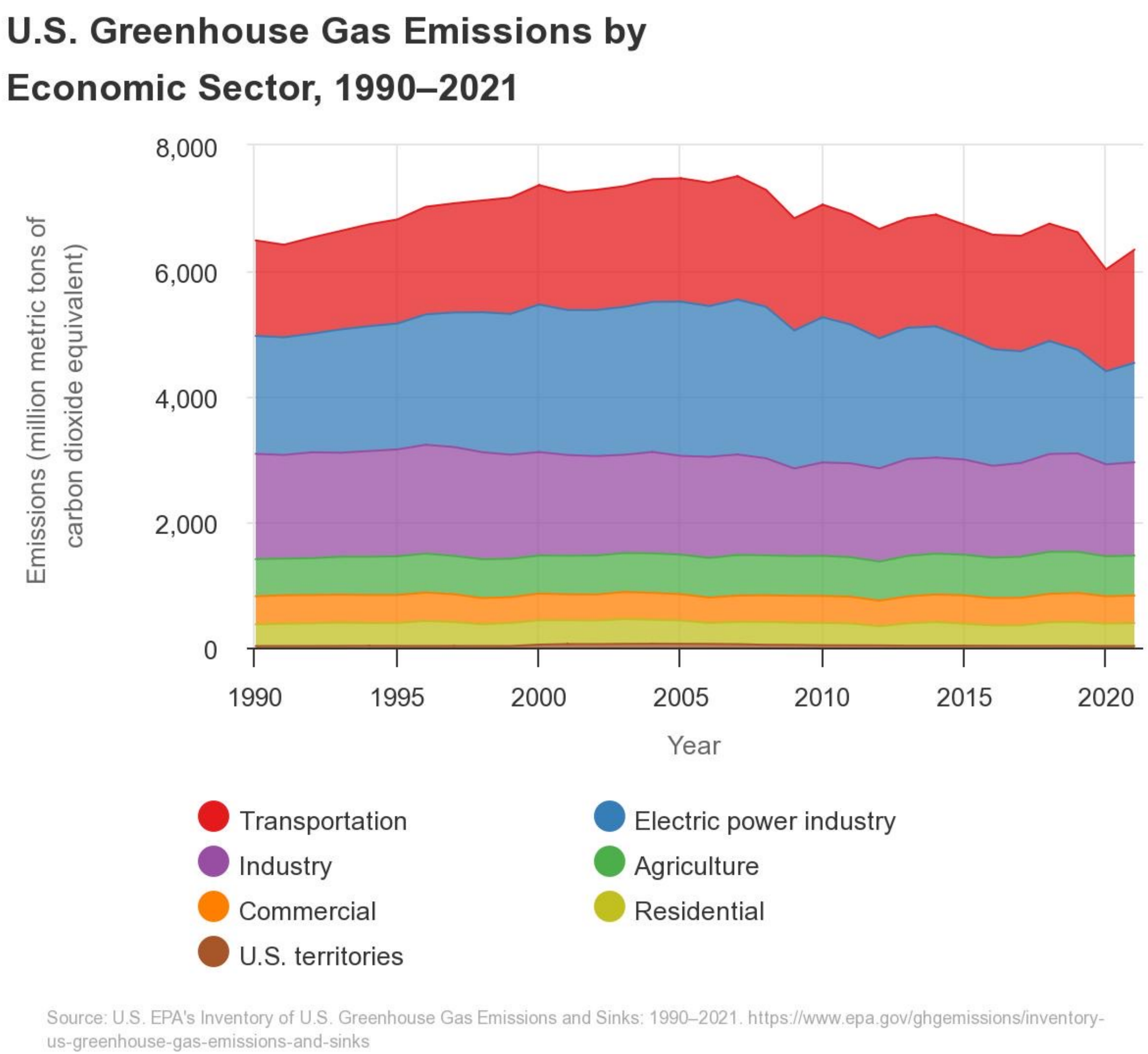
Source: IPCC AR6 WGIII SPM.1

Global GHG Emissions by Use

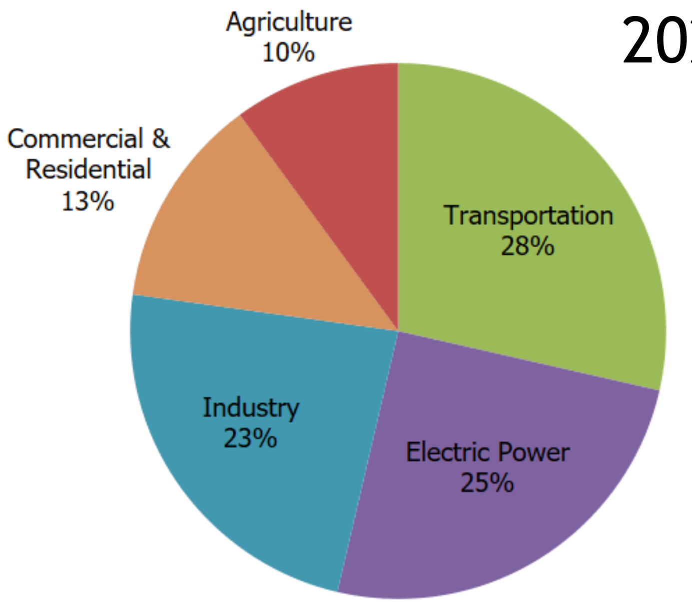


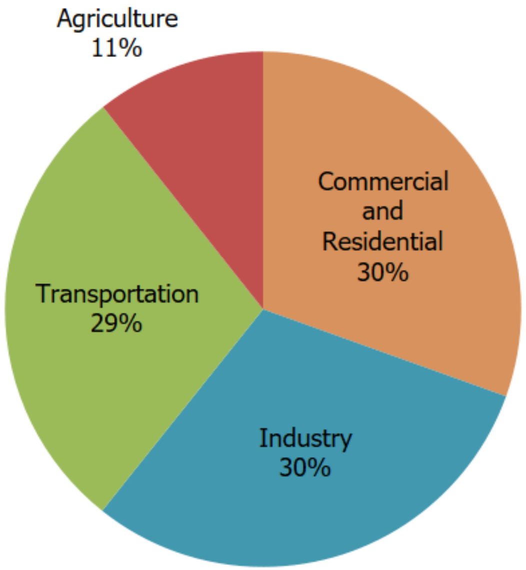
Sources: [IPCC AR6 WGIII]2.12, Lamb et al (2021), Minx et al (2021)

US GHG Emissions



2021

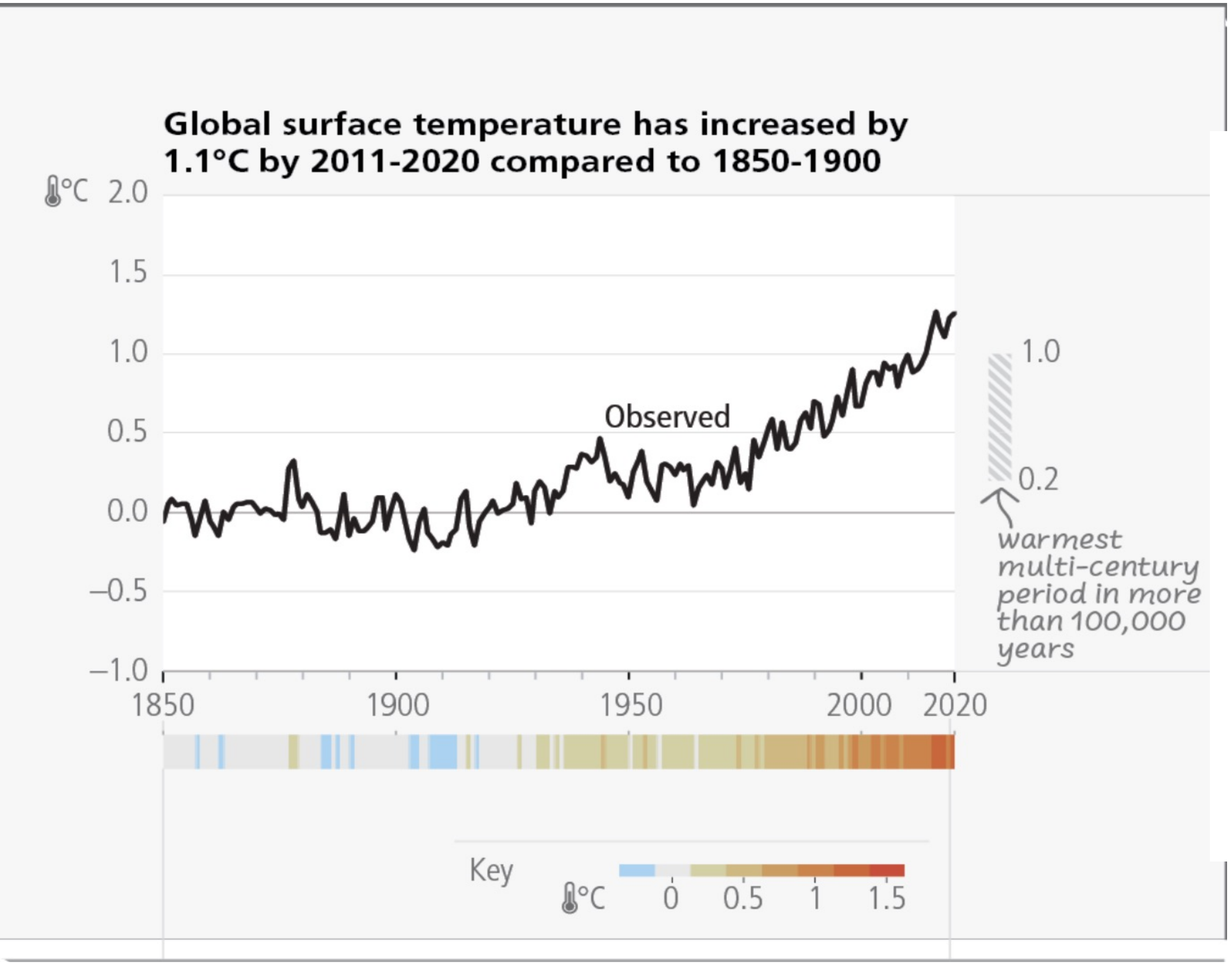


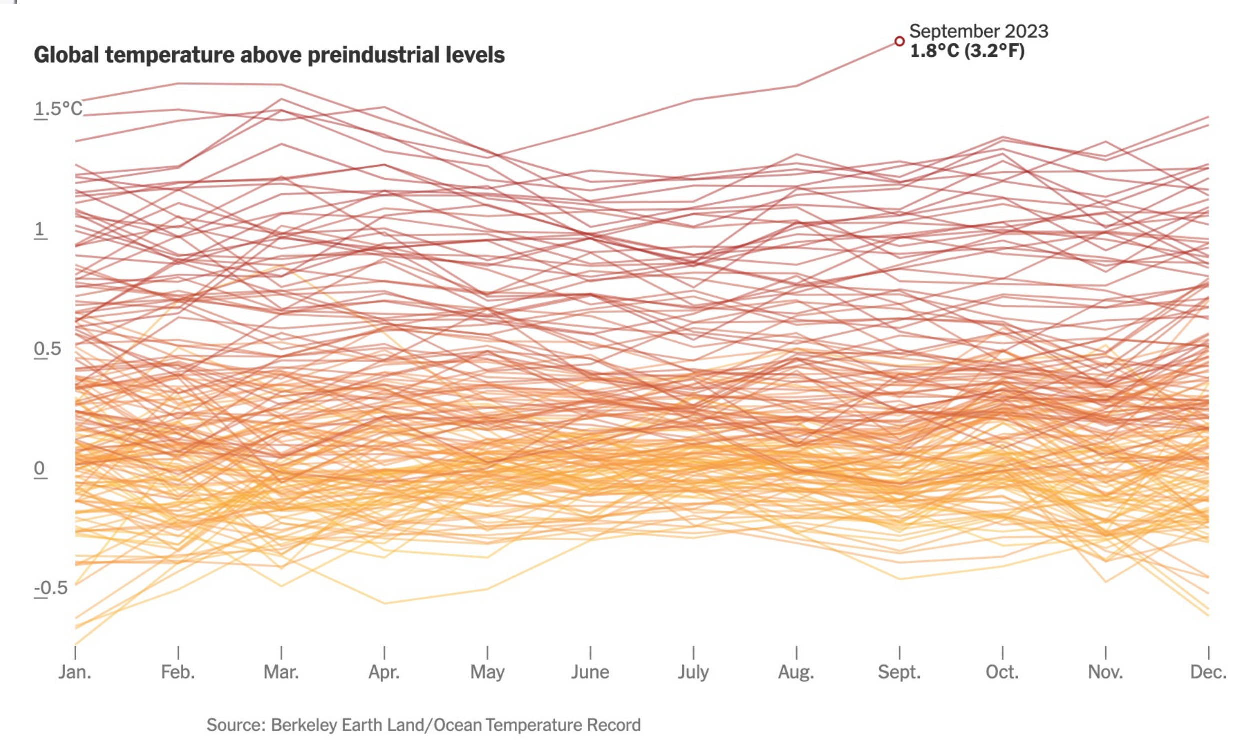


U.S. Environmental Protection Agency (2023). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2021

Source: [US EPA GHG Inventory]

Global Warming: What has already Happened





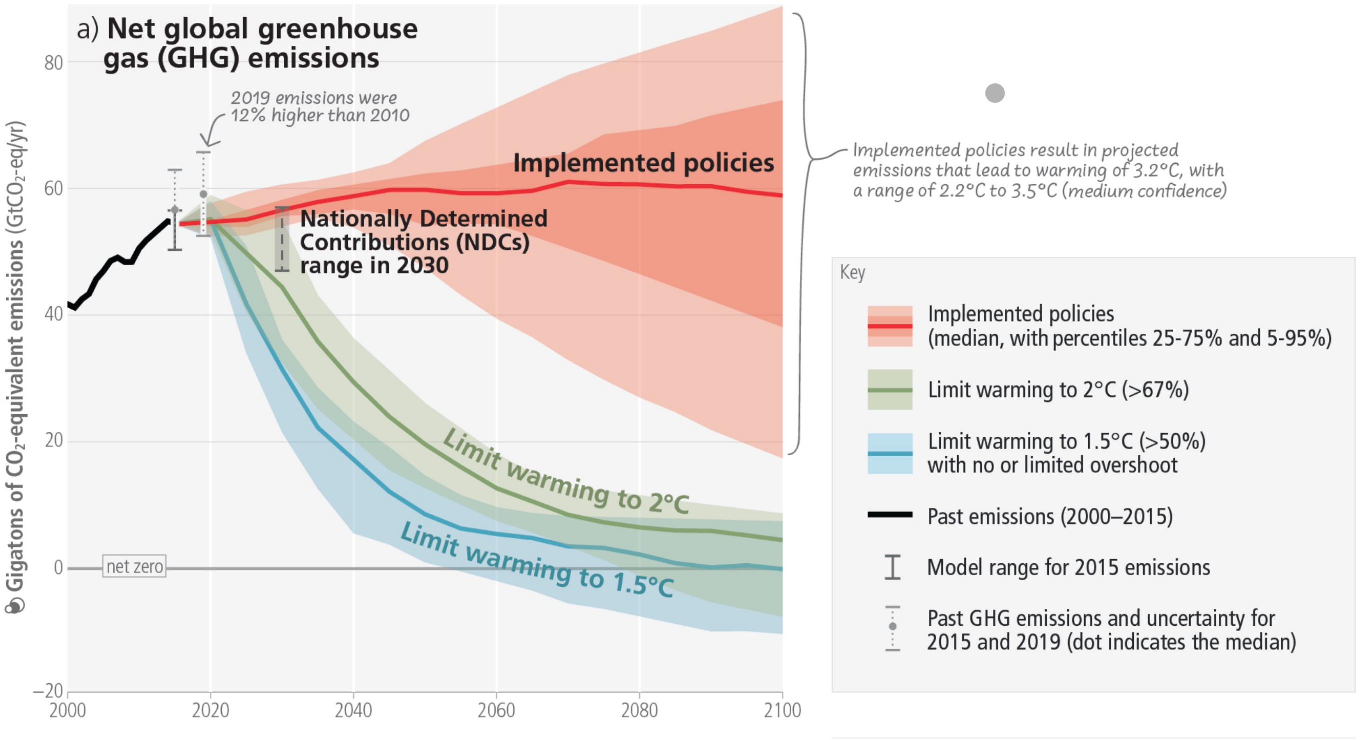
Source: Berkeley Lab

Source: IPCC AR6 WGII Report

GHG Reduction Imperative and Gap

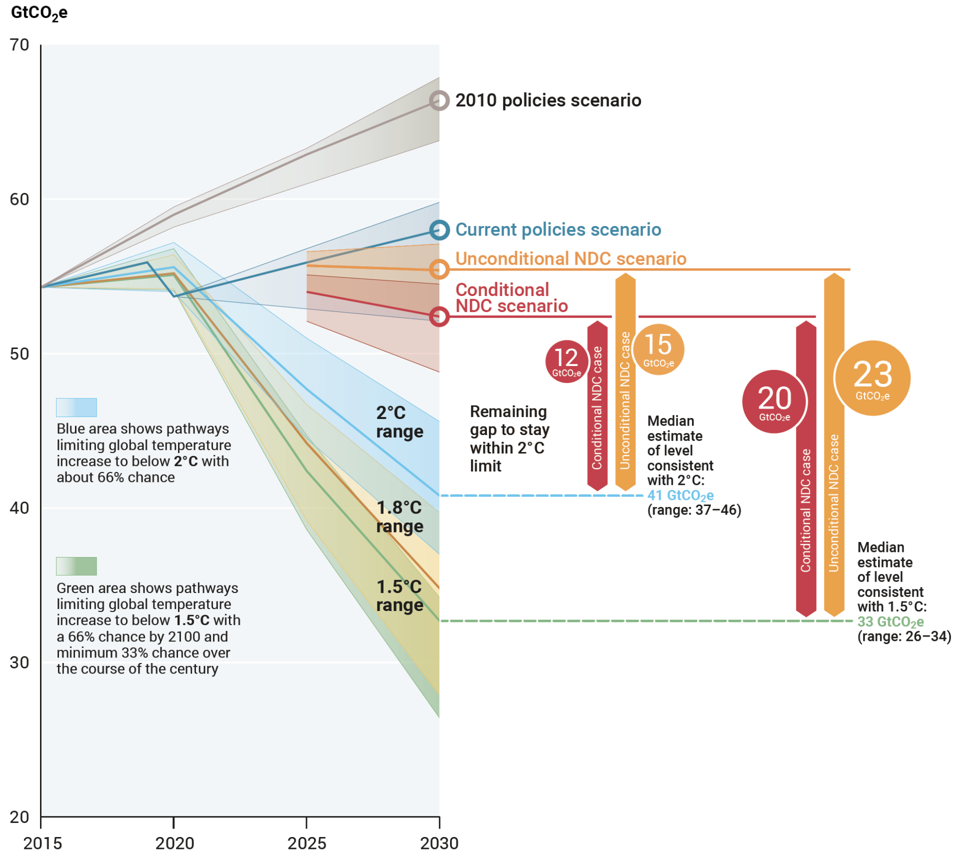
Limiting warming to 1.5°C and 2°C involves rapid, deep and in most cases immediate greenhouse gas emission reductions

Net zero CO_2 and net zero GHG emissions can be achieved through strong reductions across all sectors



Source: IPCC AR6 WGIII

Figure ES.3 Global GHG emissions under different scenarios and the emissions gap in 2030 (median estimate and tenth to ninetieth percentile range)



Source: UN Emissions Gap Report 2022

Energy System Decarbonization

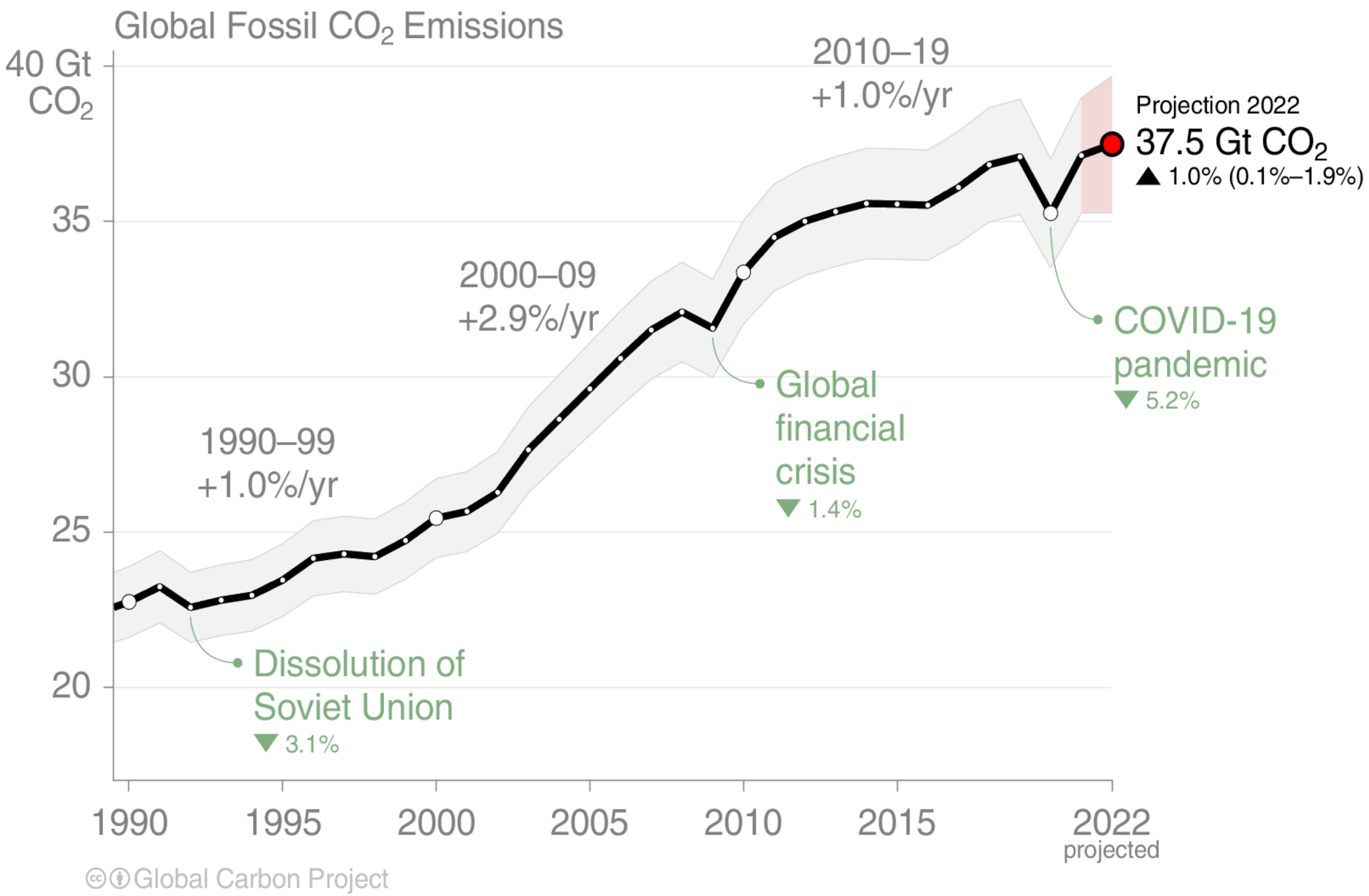
Big Picture: Climate Change and Energy System

Decarbonization of the energy system is essential to mitigate climate change

- Energy efficiency must be a big target
- Electric energy sector is likely to be the easiest to decarbonize due to falling wind and solar generation costs
- Transportation sector is much harder to decarbonize. Electrification of transportation currently offers the most viable path forward.
- Industrial and manufacturing emissions are much harder to reduce.
- Negative emissions solutions (carbon capture utilization and storage) will likely be necessary.
- Climate change impacts are already here. Therefore, adaptation and resilience are necessary.
- It is not an engineering or technology problem alone – public policy and human behavior will play very large roles.
- Younger generations see this as their big problem.

Energy system is immense, multiscale, distributed, interconnected and slow to change

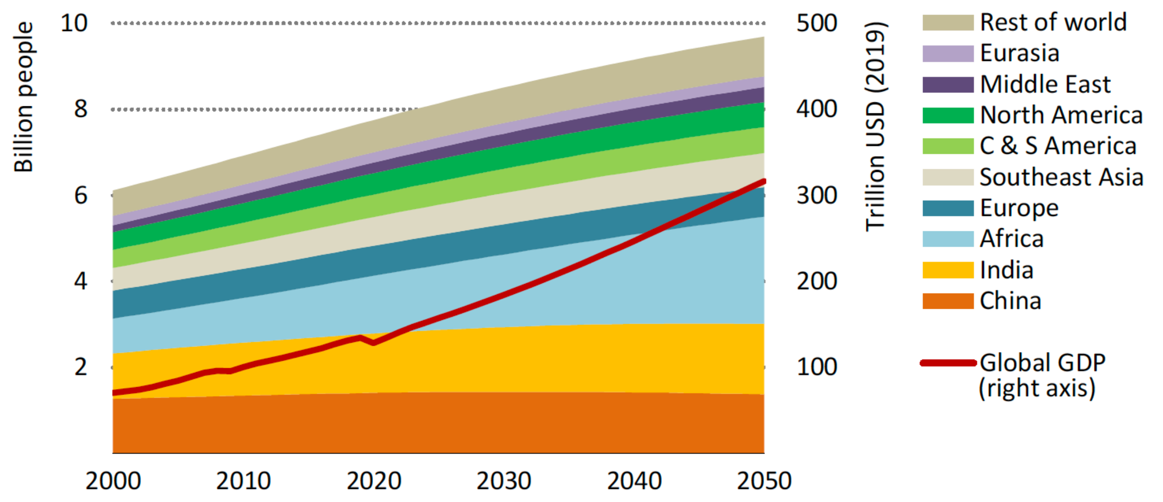
CO_2 Emissions from Fossil Fuels



Source: Global Carbon Project

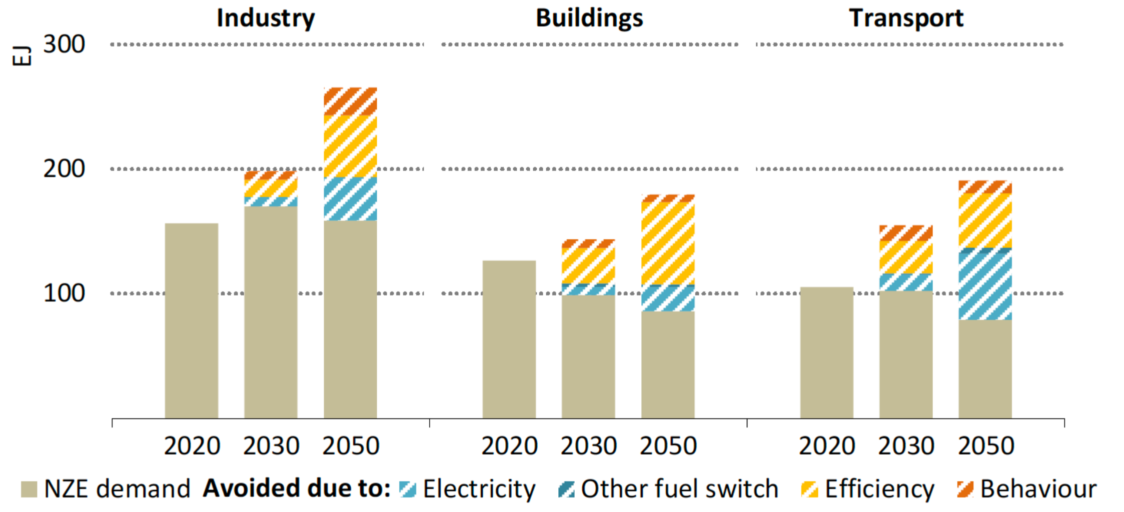
Projections of the Future

Figure 2.1 ▹ **World population by region and global GDP in the NZE**



By 2050, the world's population expands to 9.7 billion people and the global economy is more than twice as large as in 2020

Figure 2.13 ▹ **Total final consumption and demand avoided by mitigation measure in the NZE**



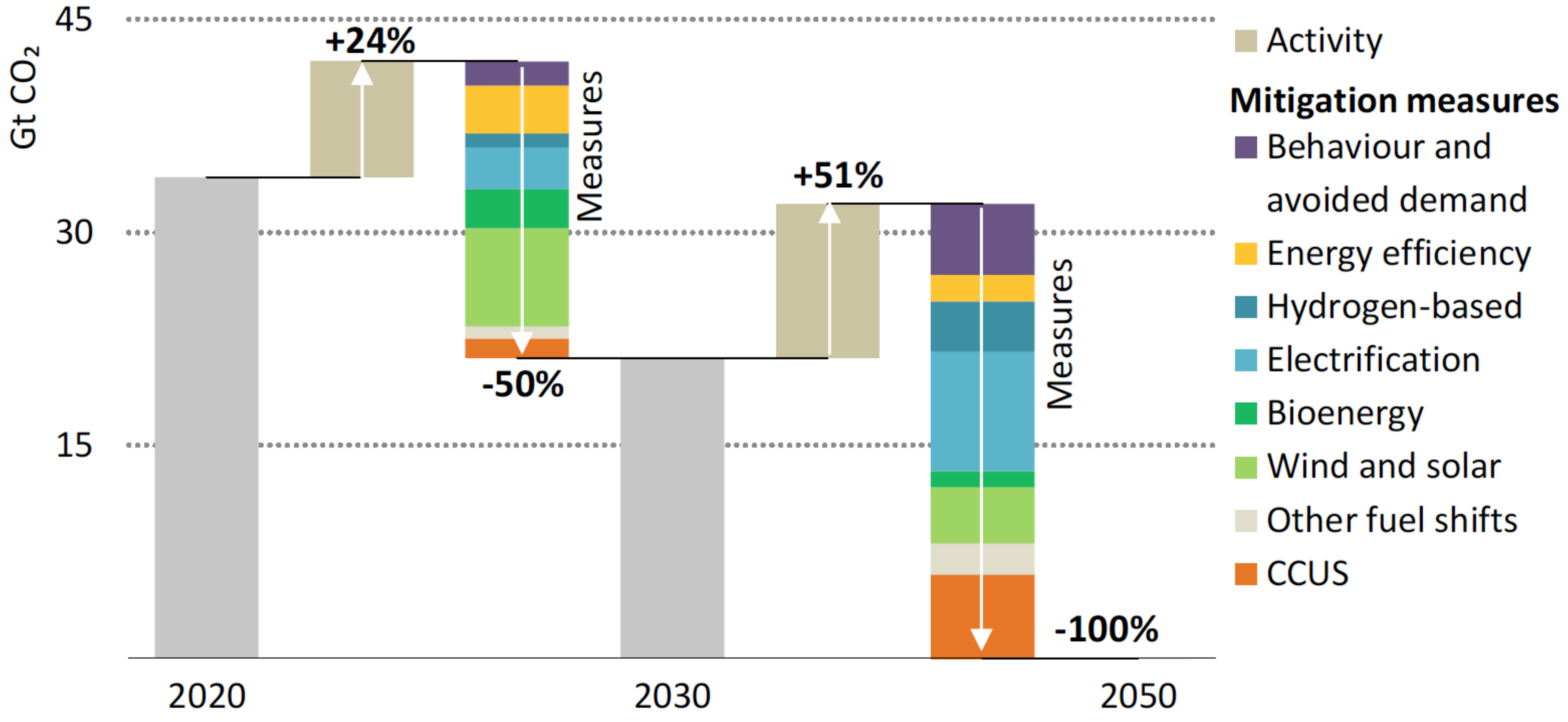
Energy efficiency plays a key role in reducing energy consumption across end-use sectors

1 EJ = 277.778 TWH

Source: IEA

IEA Net Zero Emissions Measures

Figure 2.12 ⊳ Emissions reductions by mitigation measure in the NZE, 2020-2050

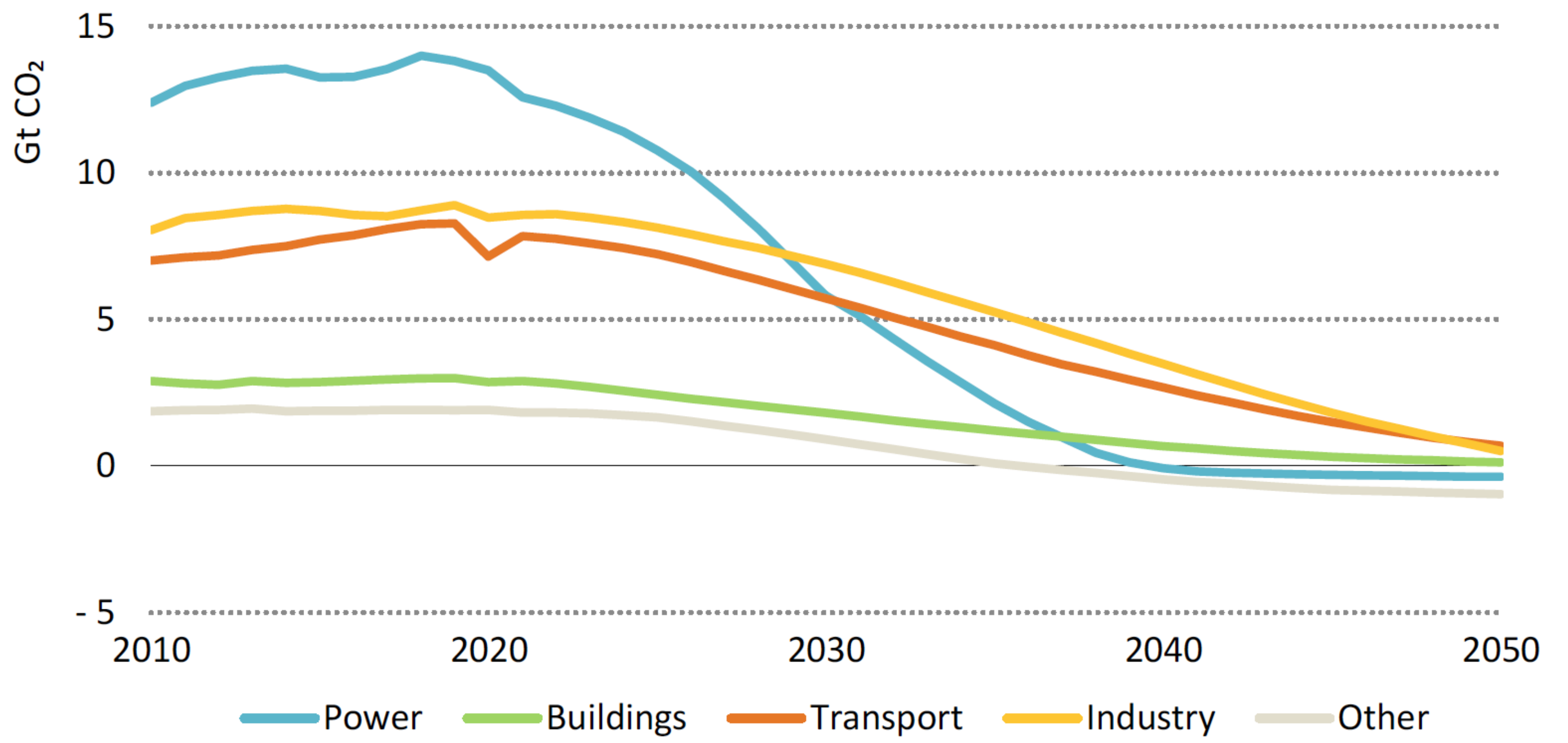


Solar, wind and energy efficiency deliver around half of emissions reductions to 2030 in the NZE, while electrification, CCUS and hydrogen ramp up thereafter

Source: IEA

CO2 Emissions by Sector in IEA Net Zero

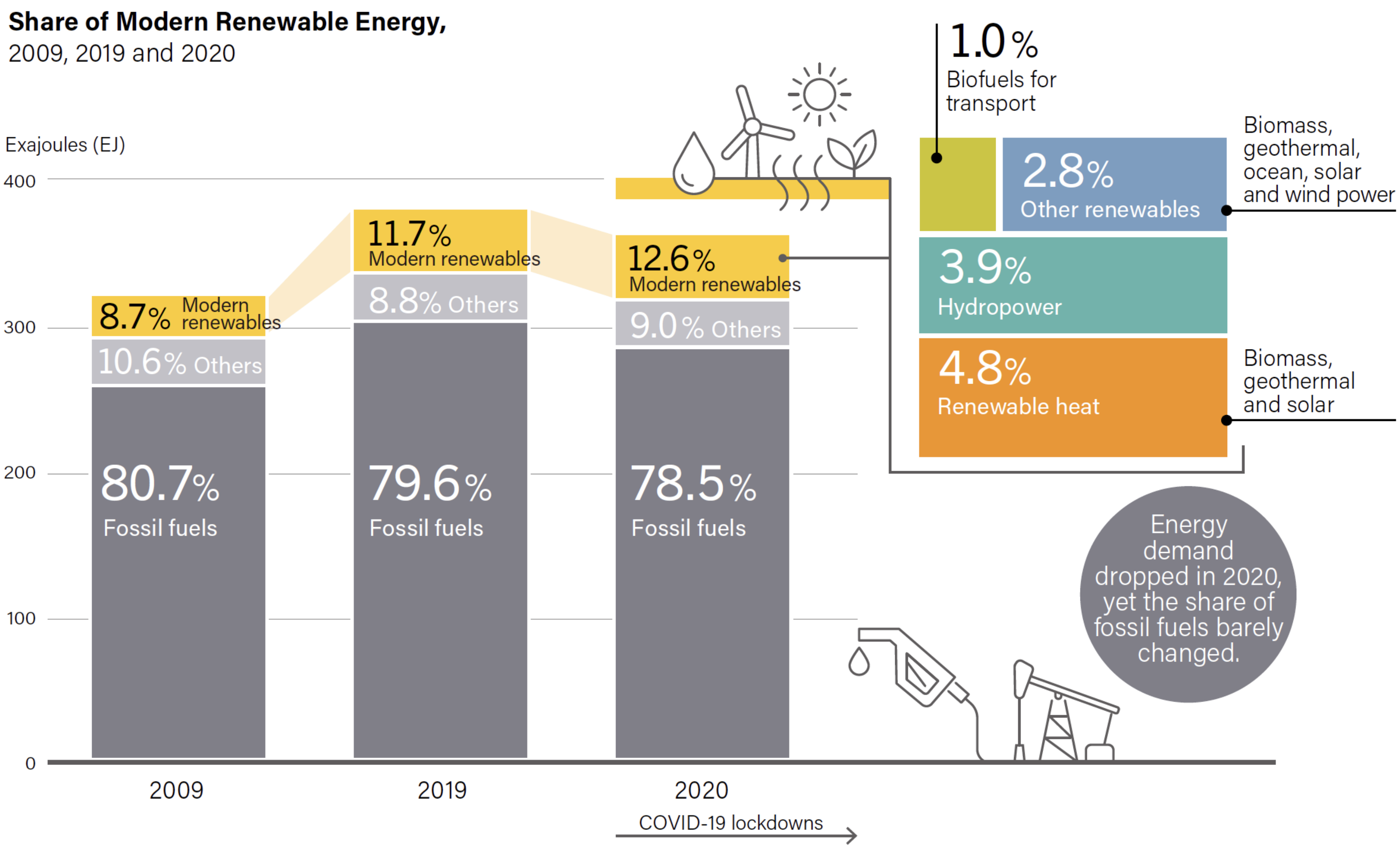
Figure 3.1 ▹ **CO_2 emissions by sector in the NZE**



Emissions fall fastest in the power sector, with transport, buildings and industry seeing steady declines to 2050. Reductions are aided by the increased availability of low-emissions fuels

Source: [IEA]

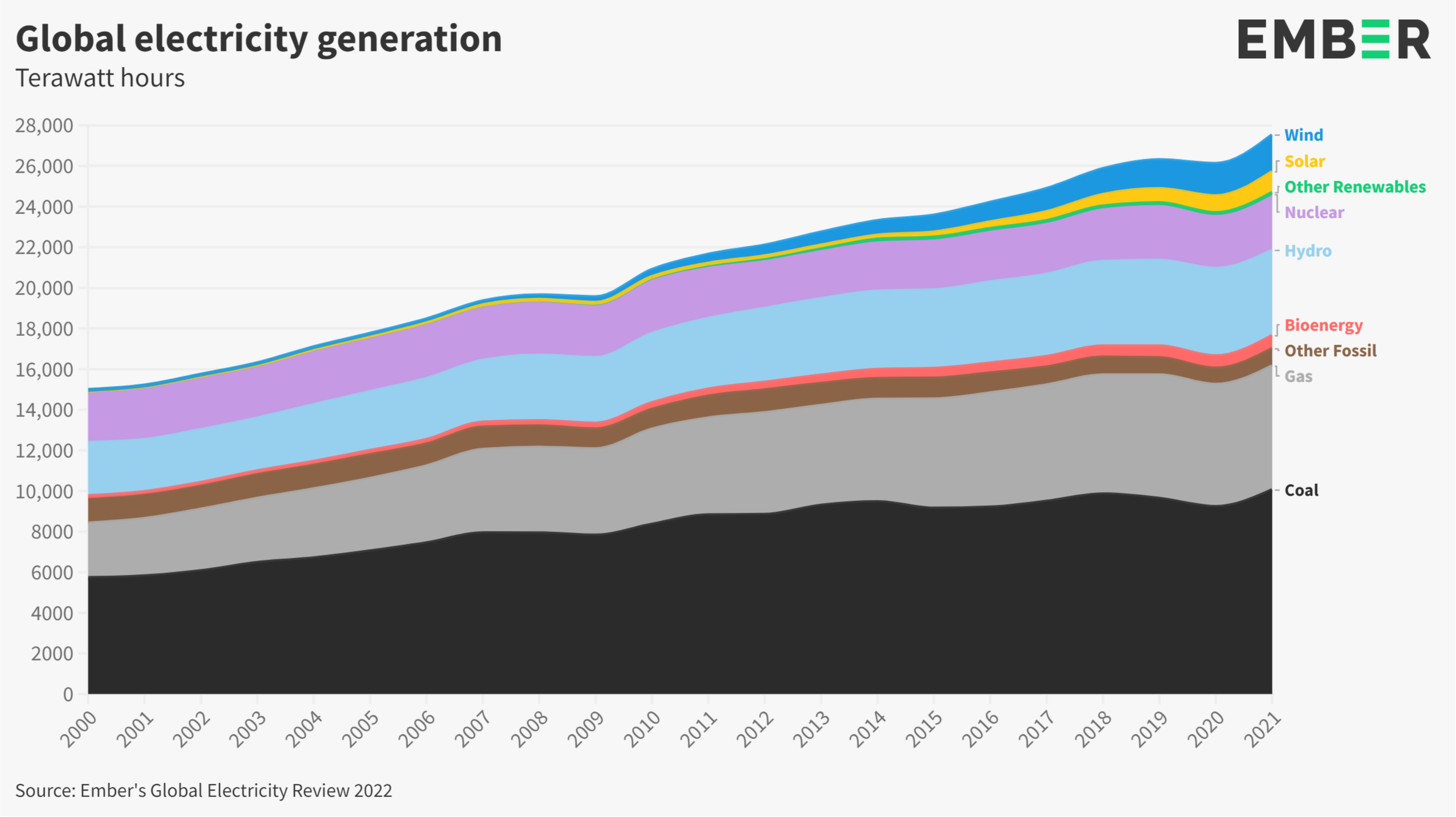
Growth of Renewable Energy in Context



Source: [REN21, 2022 Global Status Report]

Electric Energy System

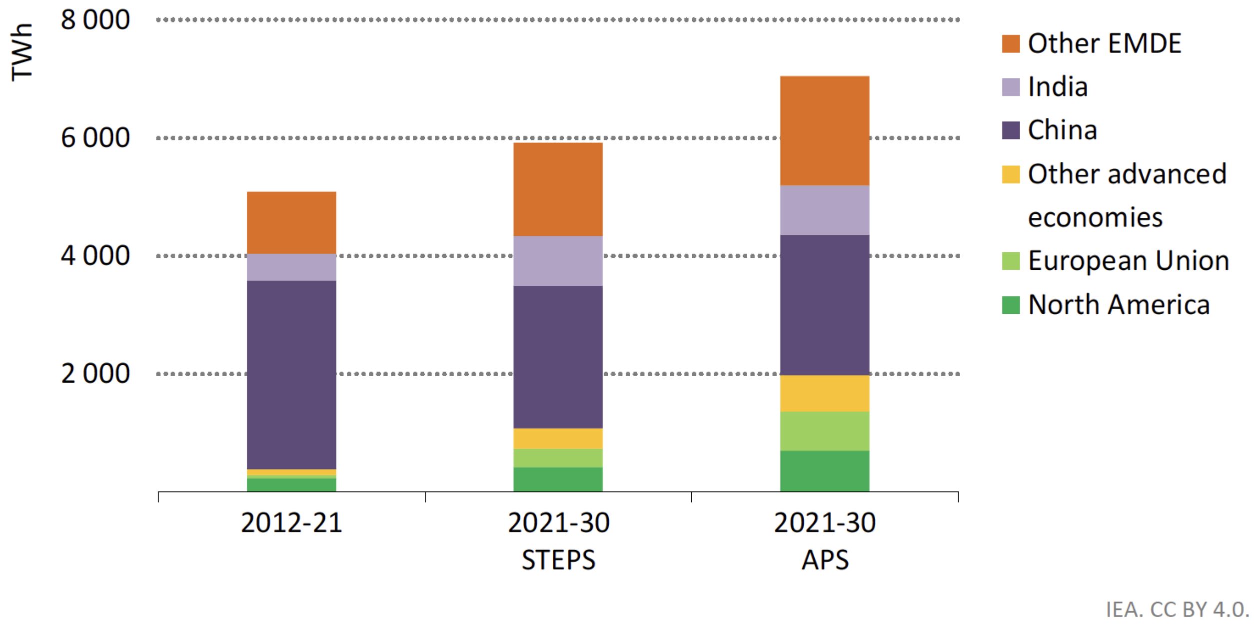
Global Electric Energy Generation



Source: [EMBER, Global Electricity Review, 2022]

Electricity Demand Growth

Figure 6.3 ▷ **Electricity demand growth by region and scenario, 2012-2030**

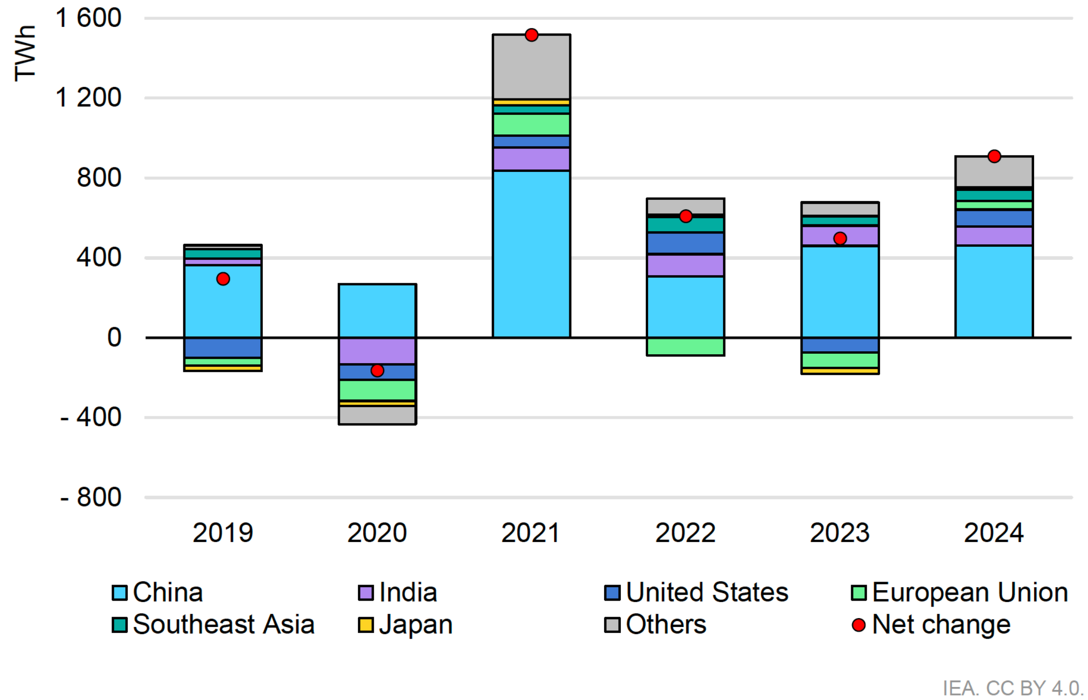


Global electricity demand growth picks up over the next decade, as a slowing in China is more than counterbalanced by strong increases in many other markets

Note: EMDE = emerging market and developing economies.

Source: IEA Net Zero Report

Year-on-year change in electricity demand in selected regions, 2019-2024



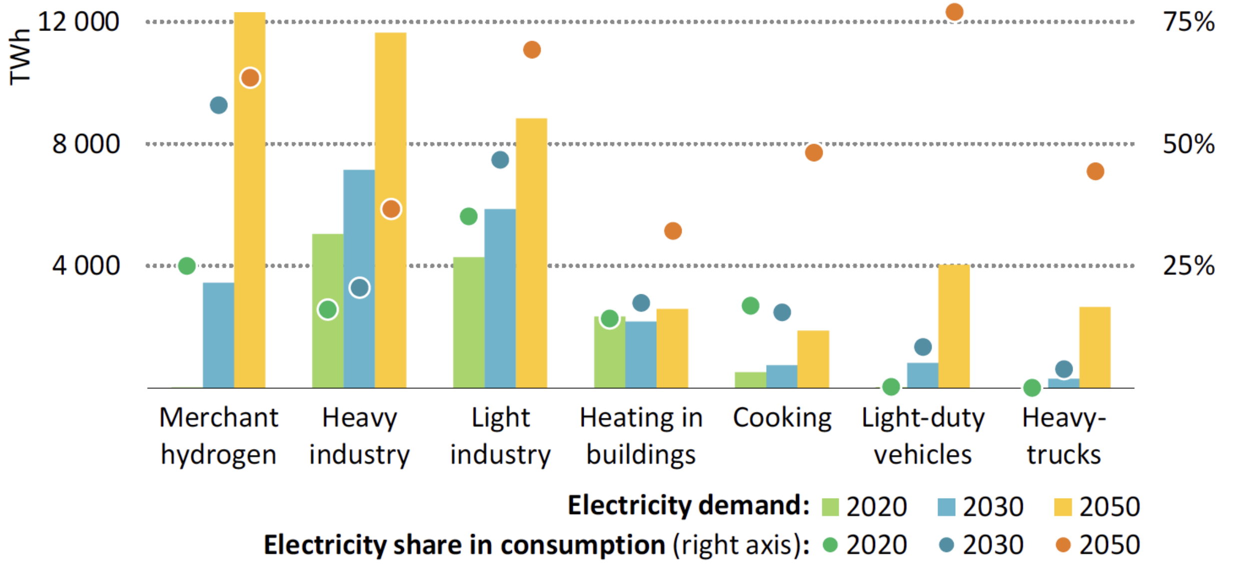
Source: IEA Electricity Market Report, 2023

Electricity Demand by Sector

Table 2.5 ▹ Key global milestones for electrification in the NZE

Sector	2020	2030	2050
Share of electricity in total final consumption	20%	26%	49%
Industry			
Share of steel production using electric arc furnace	24%	37%	53%
Electricity share of light industry	43%	53%	76%
Transport			
Share of electric vehicles in stock: cars	1%	20%	86%
two/three-wheelers	26%	54%	100%
bus	2%	23%	79%
vans	0%	22%	84%
heavy trucks	0%	8%	59%
Annual battery demand for electric vehicles (TWh)	0.16	6.6	14
Buildings			
Heat pumps installed (millions)	180	600	1 800
Share of heat pumps in energy demand for heating	7%	20%	55%
Million people without access to electricity	786	0	0

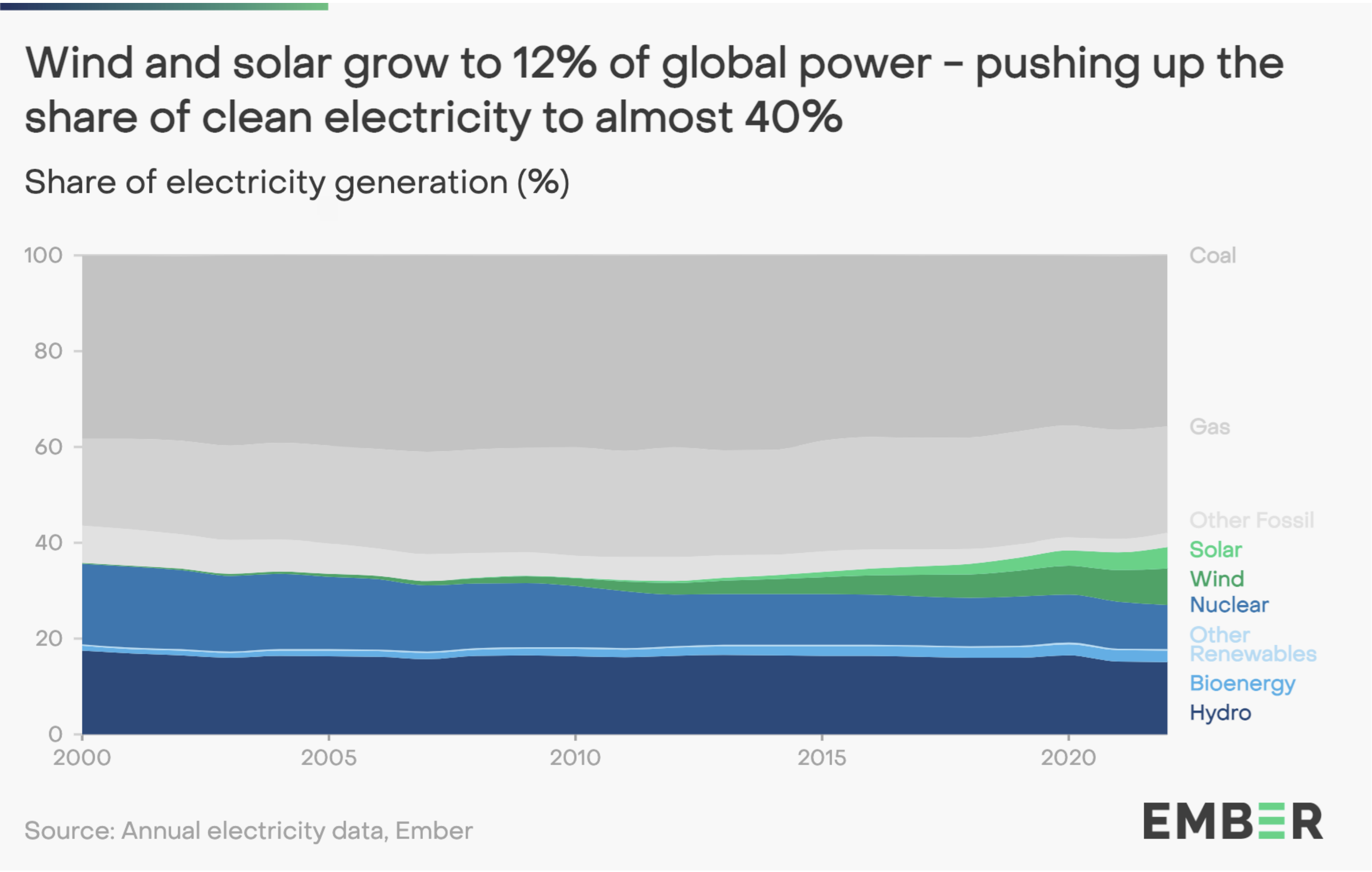
Figure 2.16 ▹ Global electricity demand and share of electricity in energy consumption in selected applications in the NZE

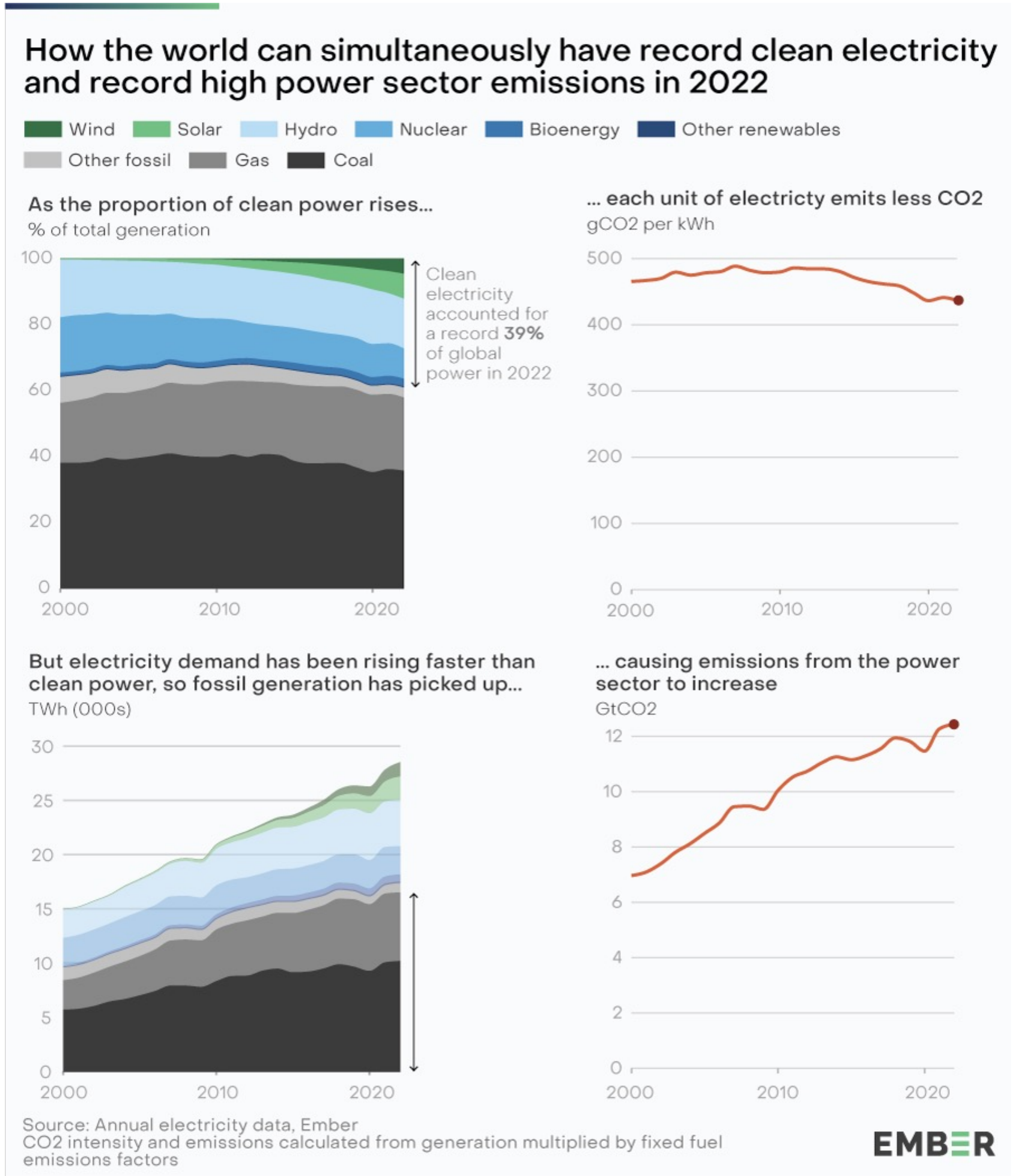


Global electricity demand more than doubles in the period to 2050, with the largest rises to produce hydrogen and in industry

Source: IEA Net Zero Report

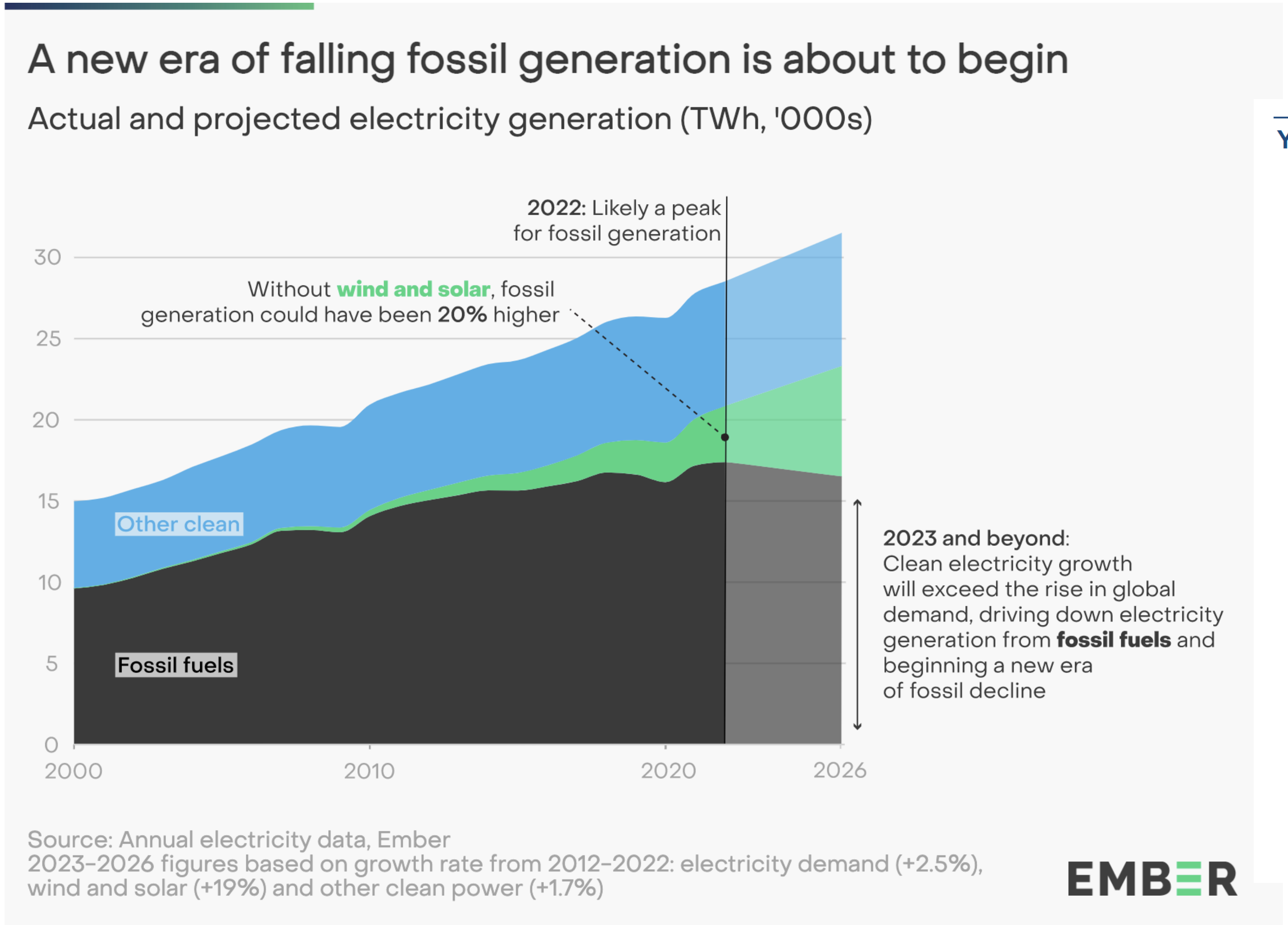
Electric Energy Production by Sources

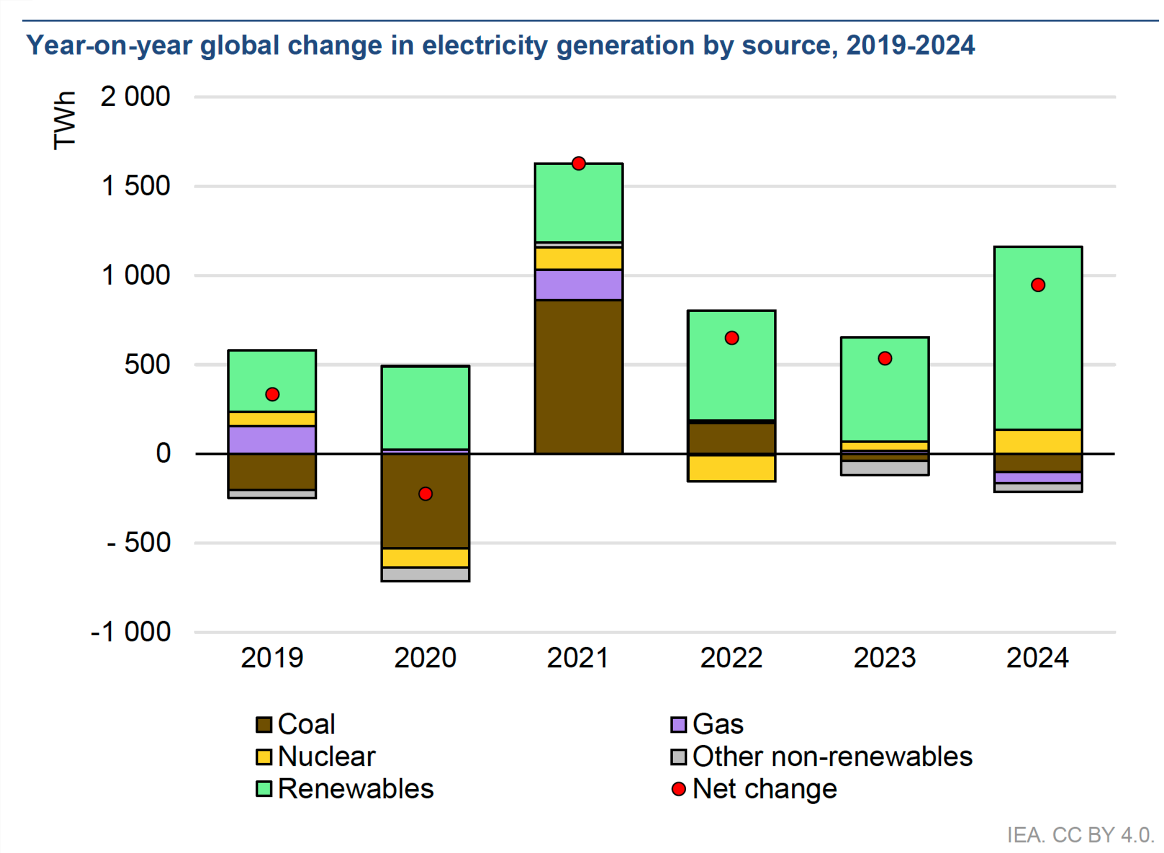




Source: [EMBER, Global Electricity Review, 2022]

We May be at an Inflection Point

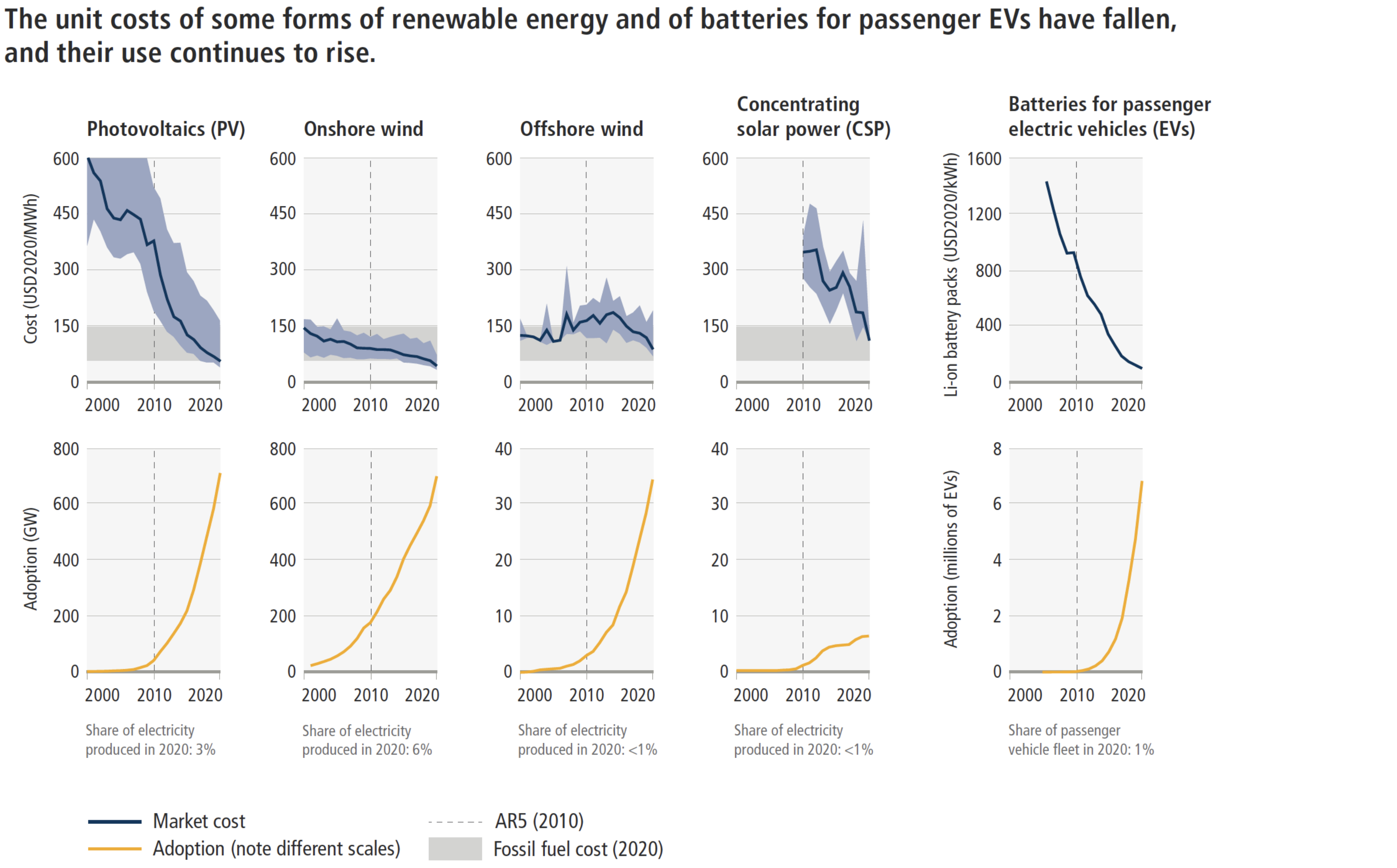




Source: IEA Electricity Market Report, 2023

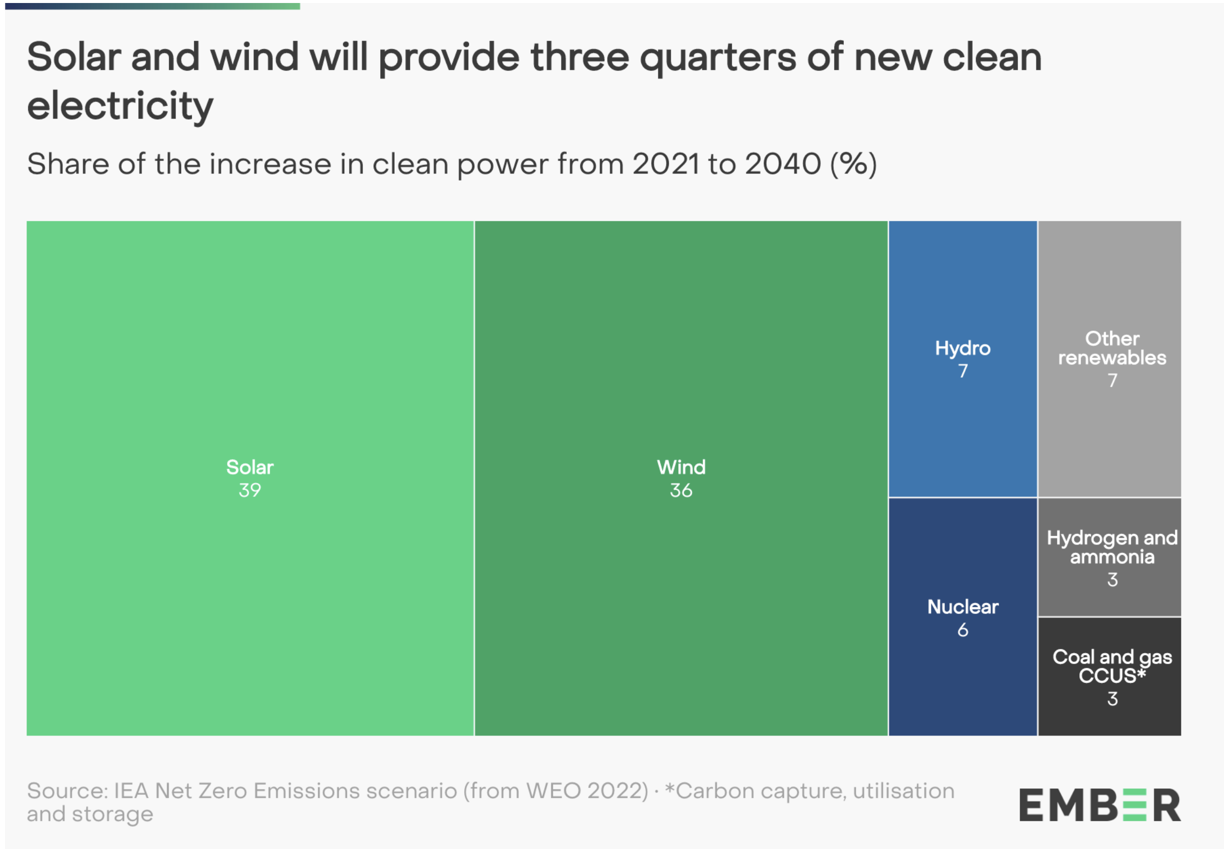
Source: EMBER, Global Electricity Review, 2022

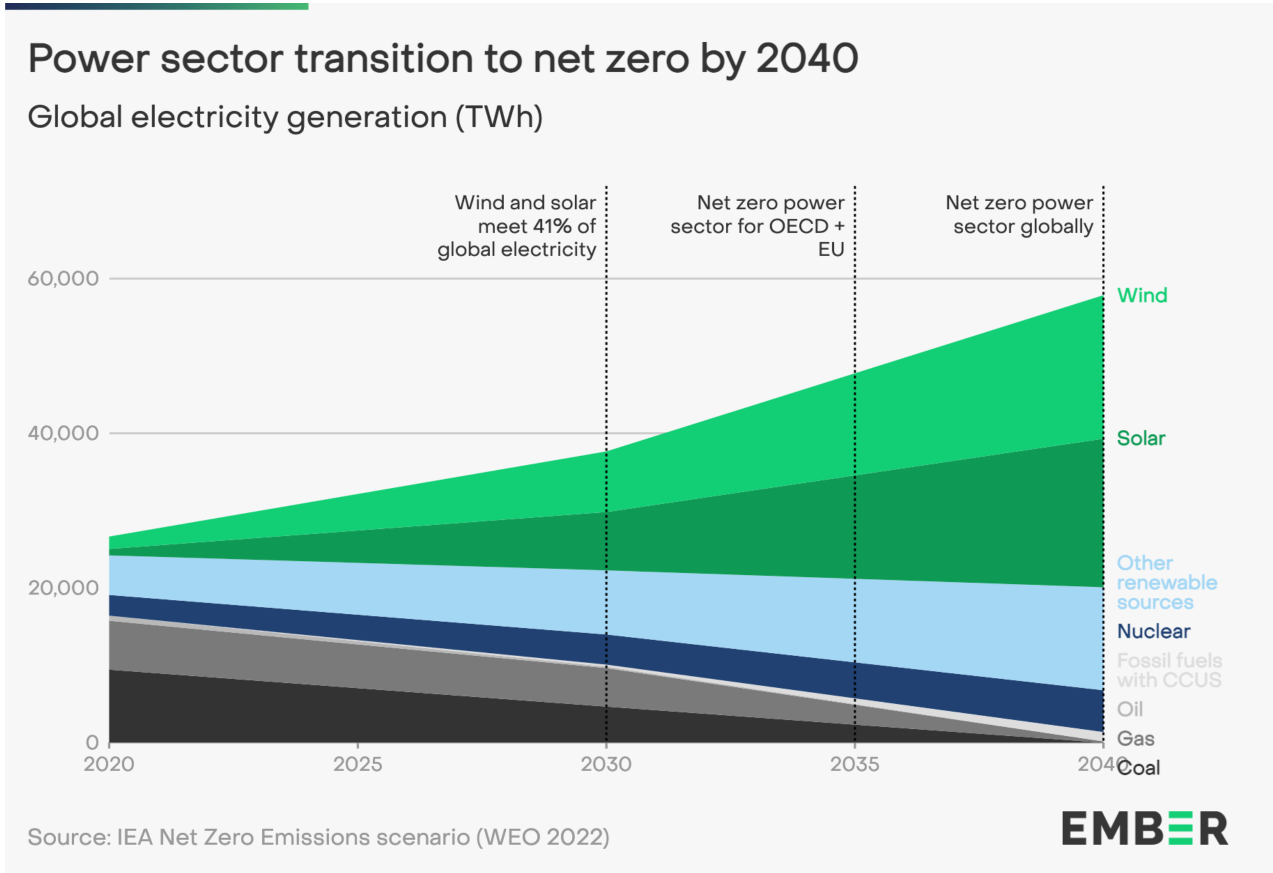
Sources of Hope: Solar, Wind, Storage Costs Decline



Source: IPCC AR6 WGIII

Electricity Generation and IEA Net Zero

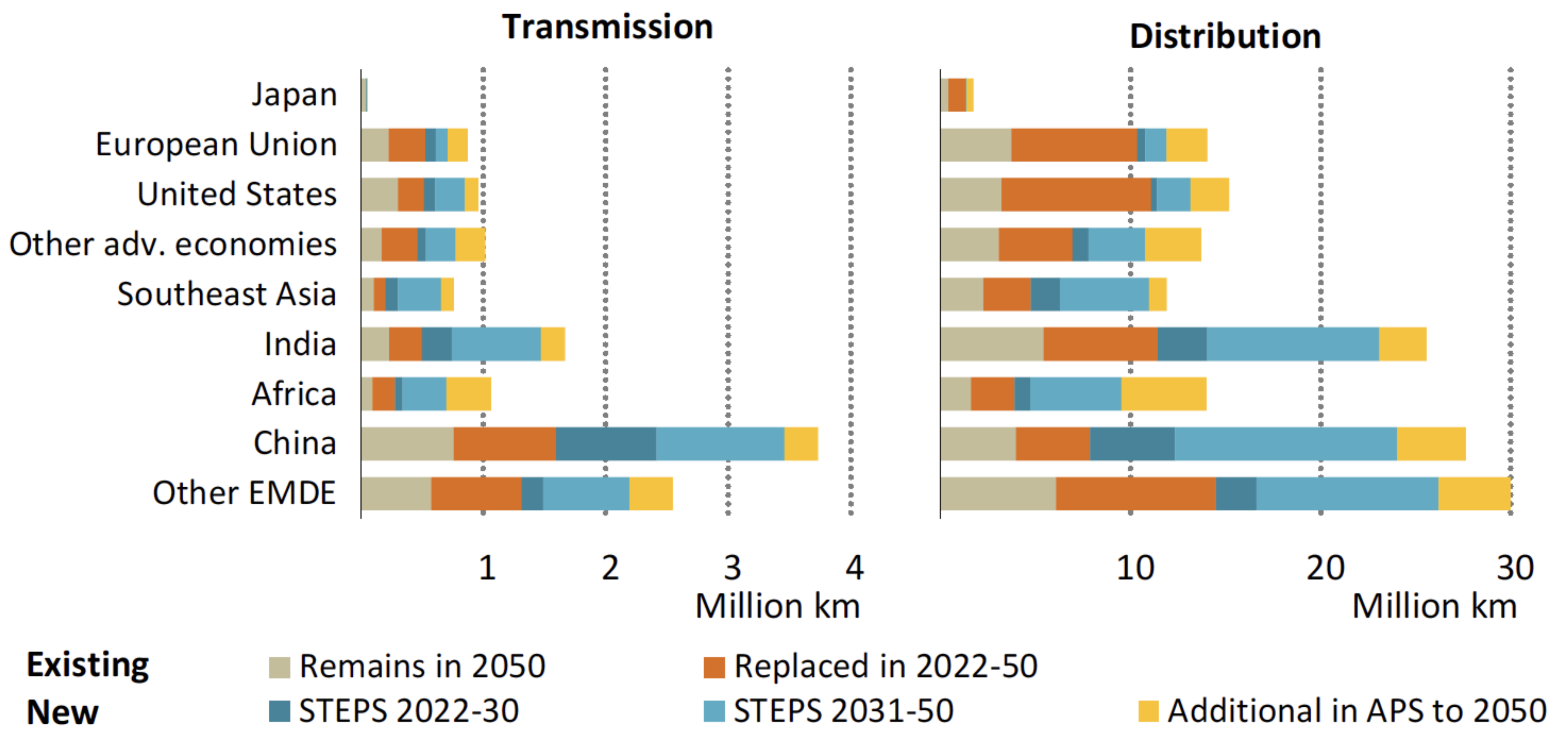




Source: [EMBER, Global Electricity Review, 2022]

Transmission and Distribution Grid Buildout

Figure 6.19 ▷ Grid development by type, region and scenario, 2022-2050



Source: [IEA Net Zero Report]

Wind and Solar in the US

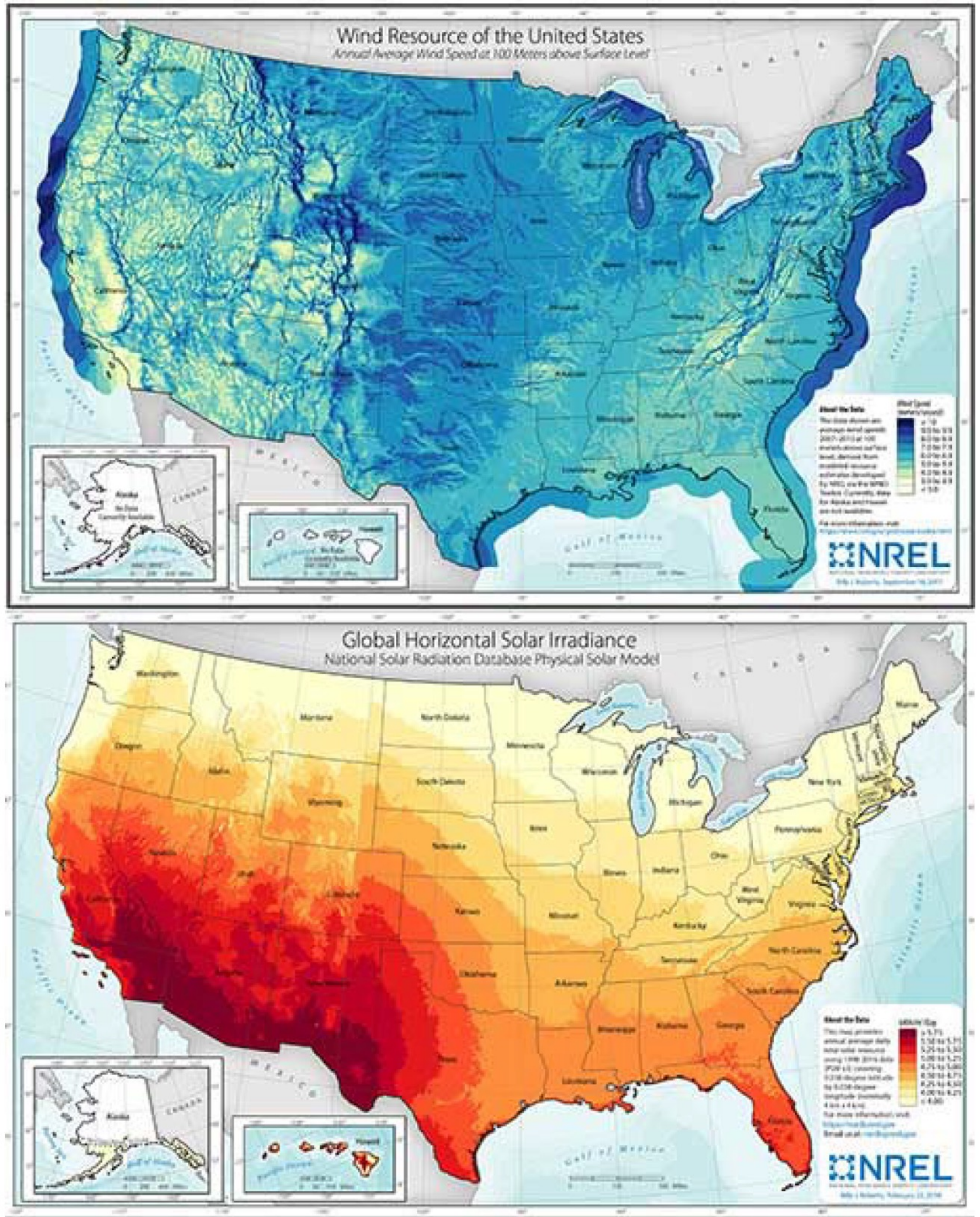


Figure 25. Wind and solar resource maps of the United States show that many of the best resources are in locations remote from demand centers in the eastern part of the country, which require new transmission.

Source: [Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035](), NREL/TP-6A40-81644

Transmission Buildout Scenarios

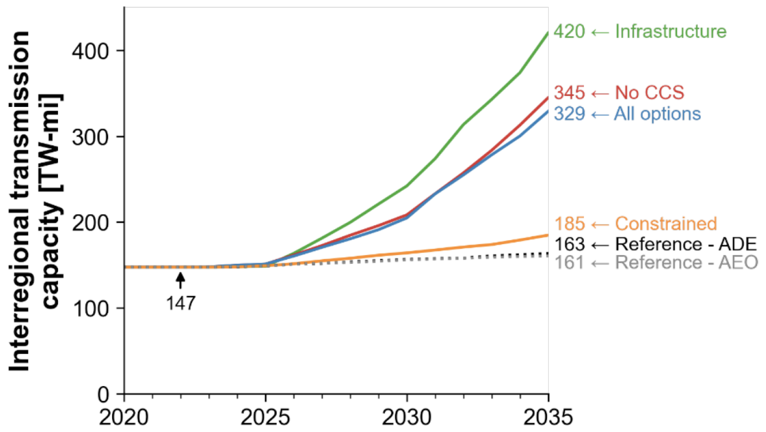


Figure 26. Interregional transmission capacity grows substantially in three of the four scenarios (ADE demand case).

This result allows greater access to high-quality (low-cost) wind resources and provides the benefits of spatial diversity.

ADE: accelerated demand electrification

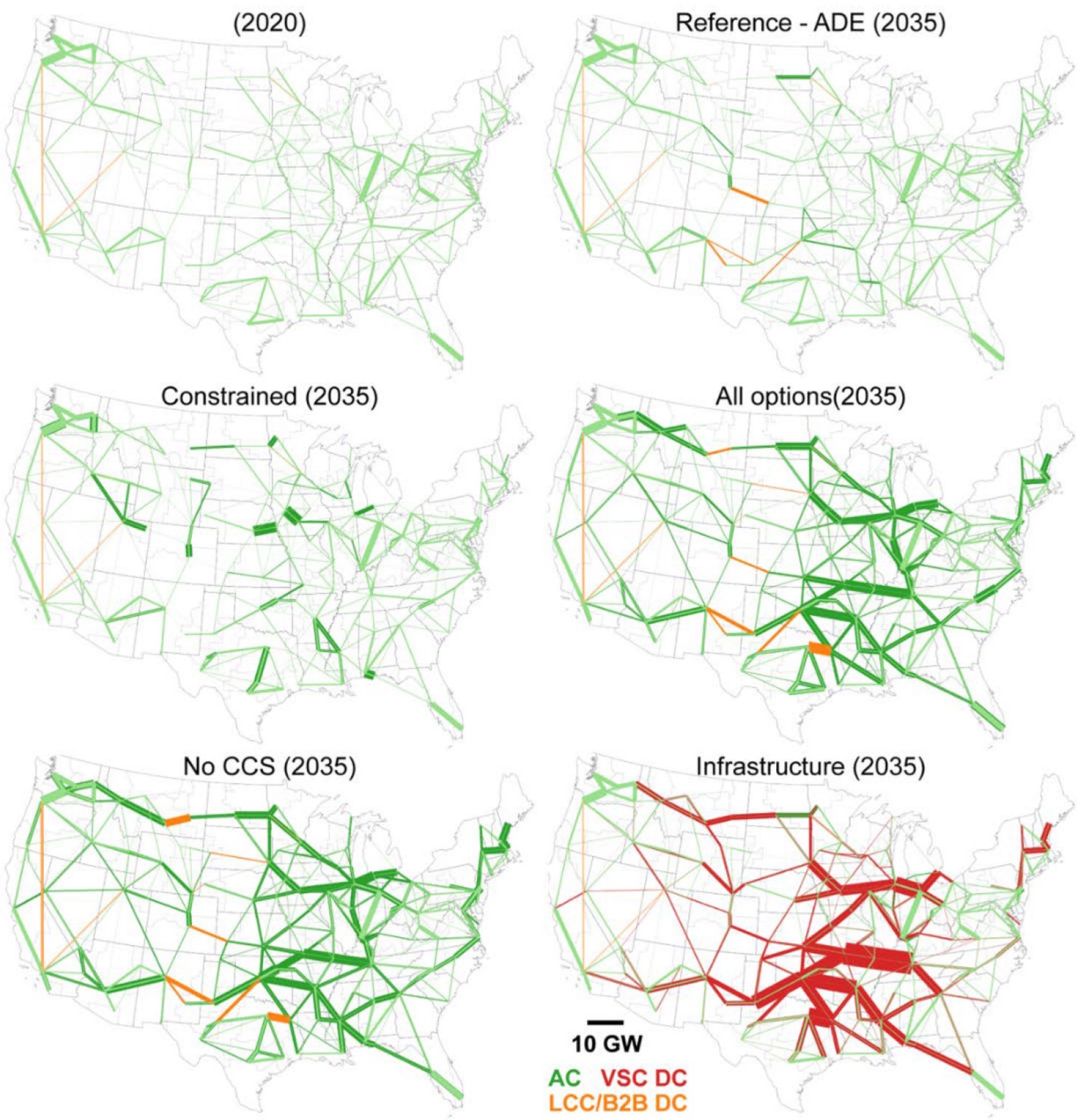
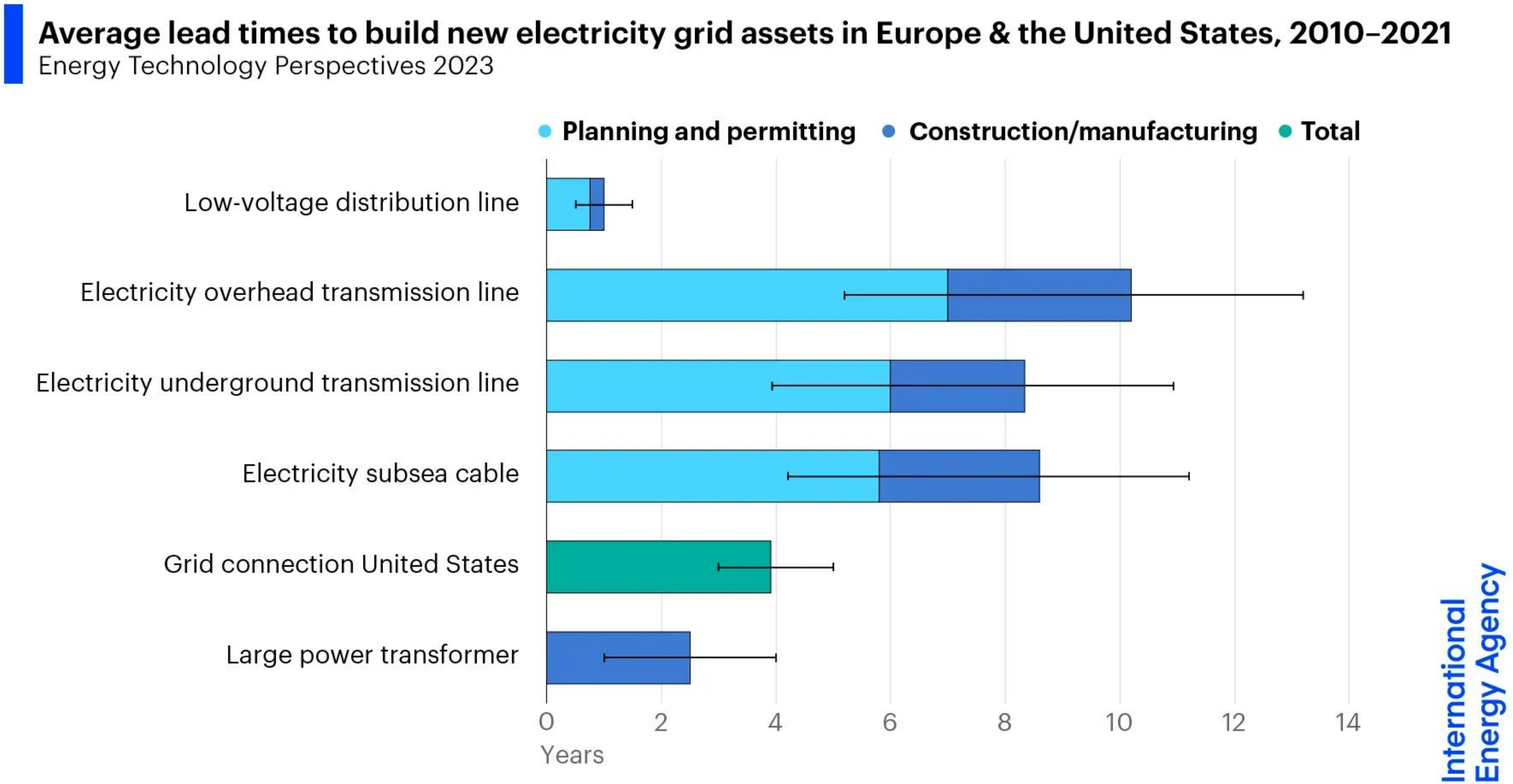


Figure 27. Maps of transmission capacity in 2020 and 2035 (ADE demand case) show substantial additions into wind-rich regions of the United States.

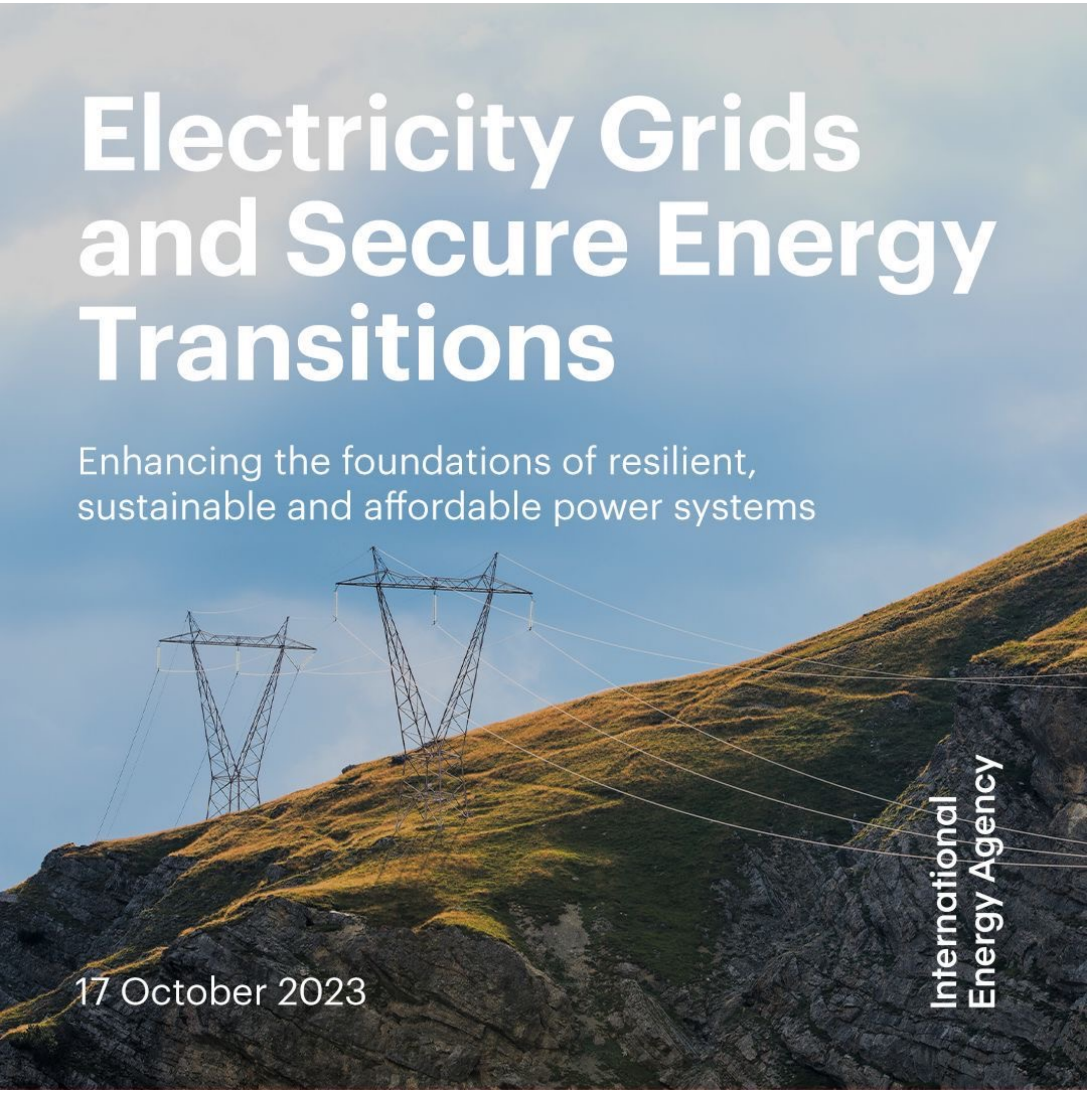
Transmission capacity is differentiated into alternating-current (AC) and two direct-current (DC) technologies: lines using voltage source converters (VSC) and lines using line-commutated converters (LCC) or back-to-back interties (B2B).[52]

Source: [Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035](), NREL/TP-6A40-81644

Constructing Electric Grids Takes Years



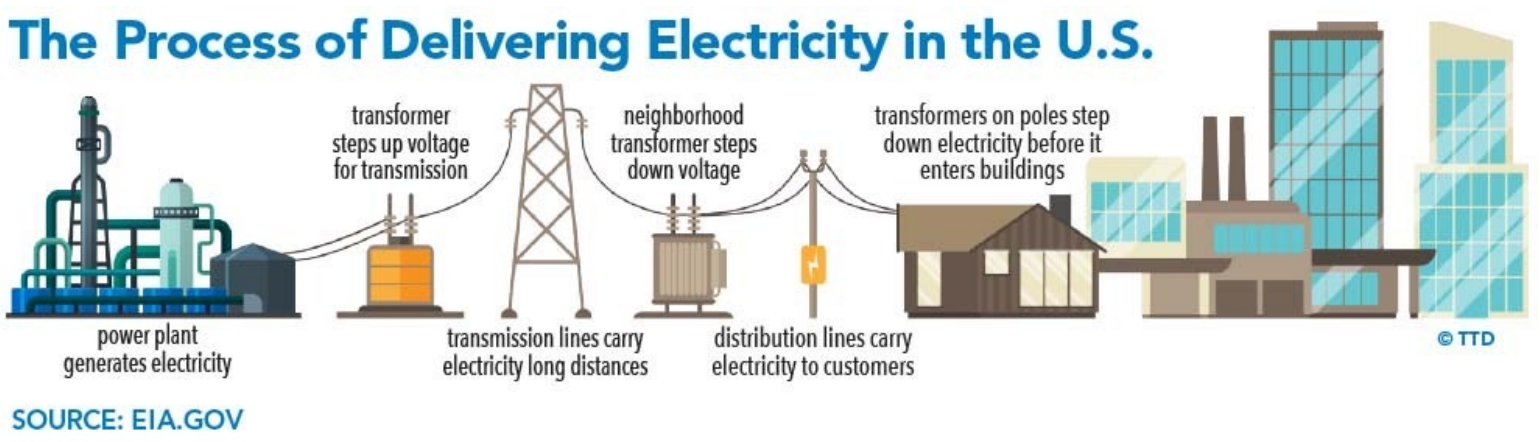
Sources: IEA, Energy Technology Perspectives 2023

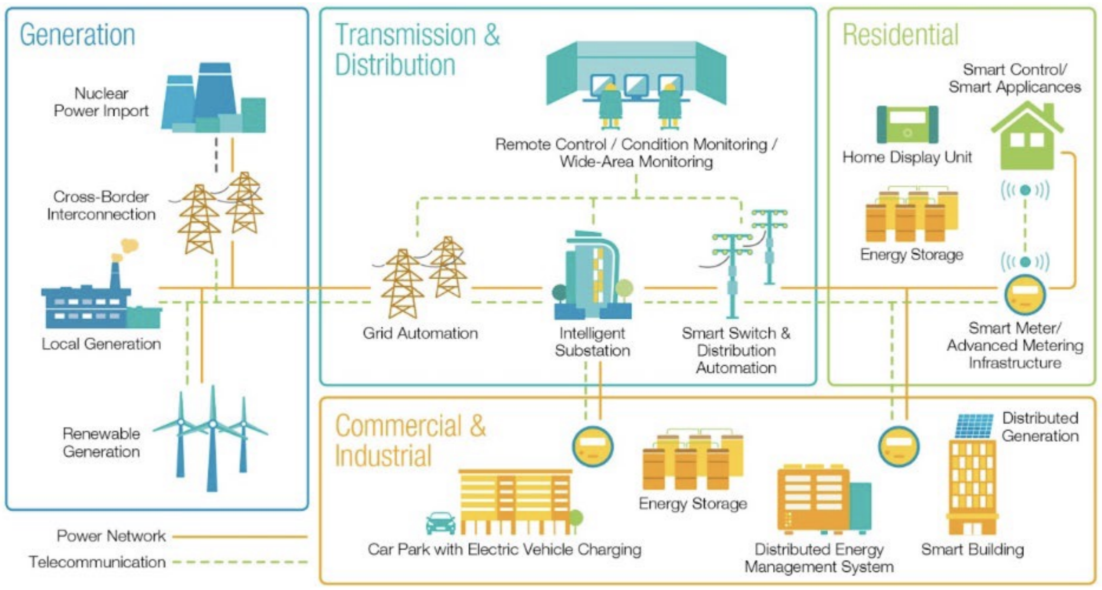


"At least 3 000 gigawatts (GW) of renewable power projects, of which 1 500 GW are in advanced stages, are waiting in grid connection queues – equivalent to five times the amount of solar PV and wind capacity added in 2022."

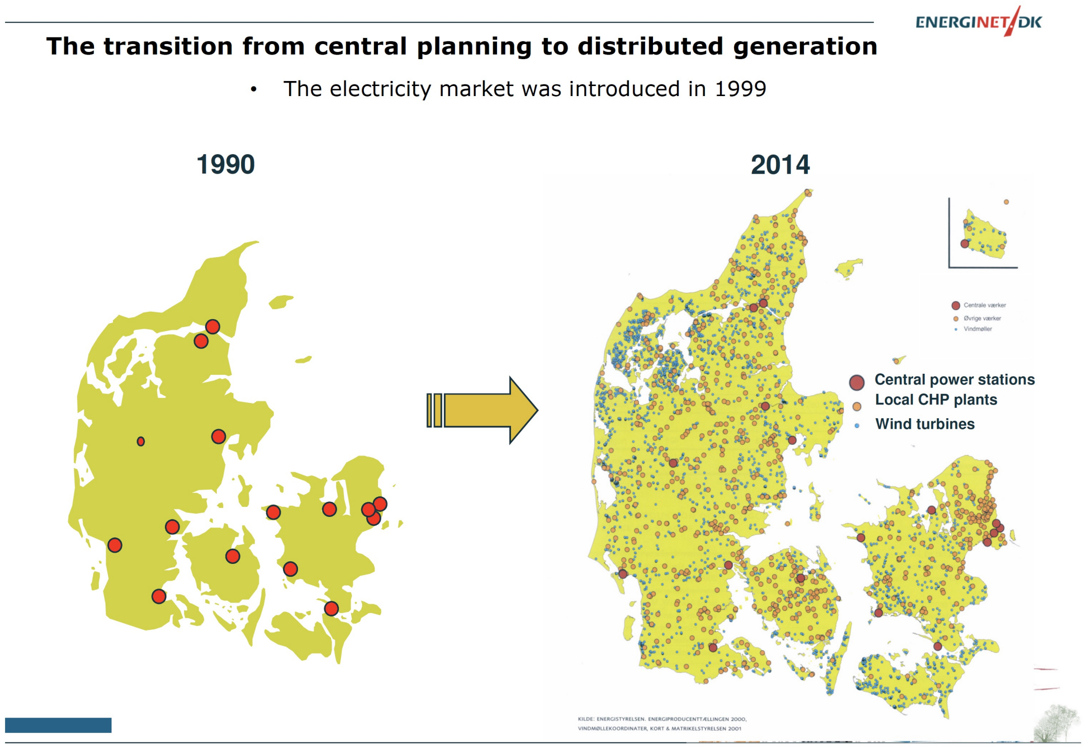
Source: [IEA Electricity Grids and Secure Energy Transitions, 2023]

Electric Energy System is Transforming



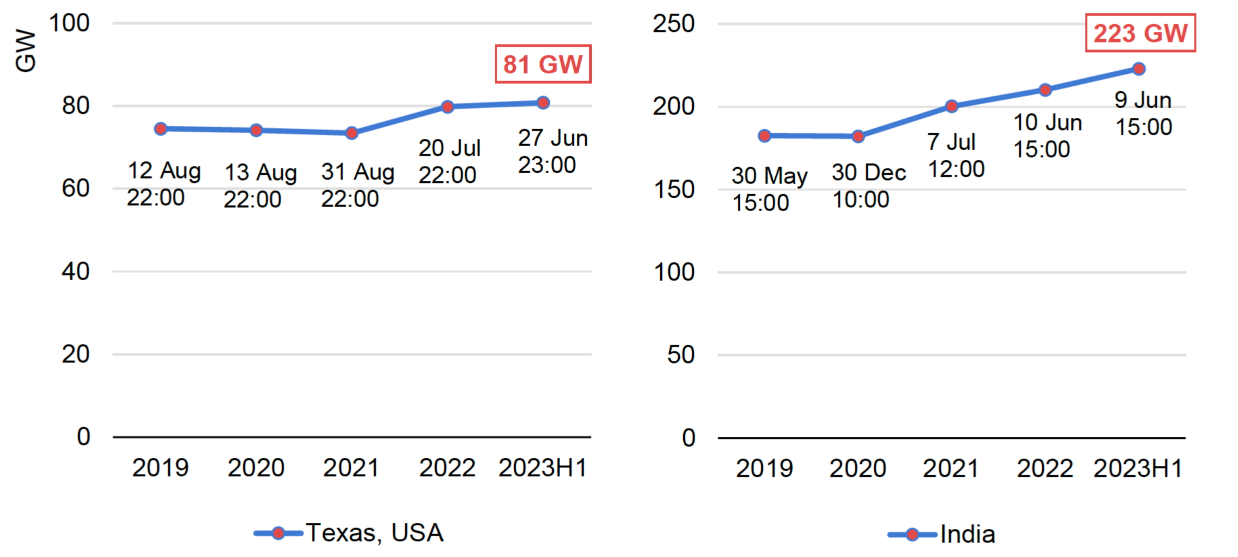


Source: CLP, Power Transmission and Distribution in the Smart Grid



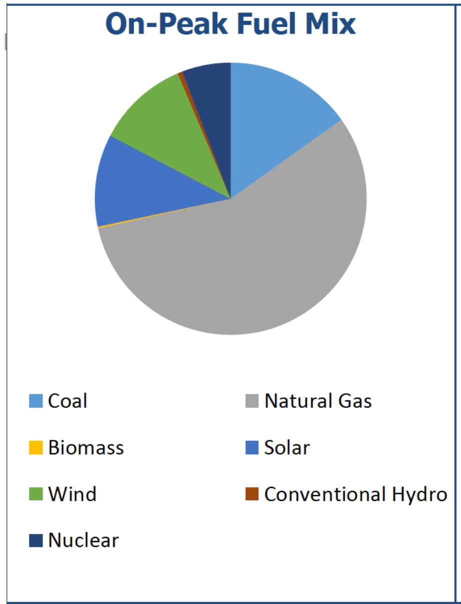
Peak Demand

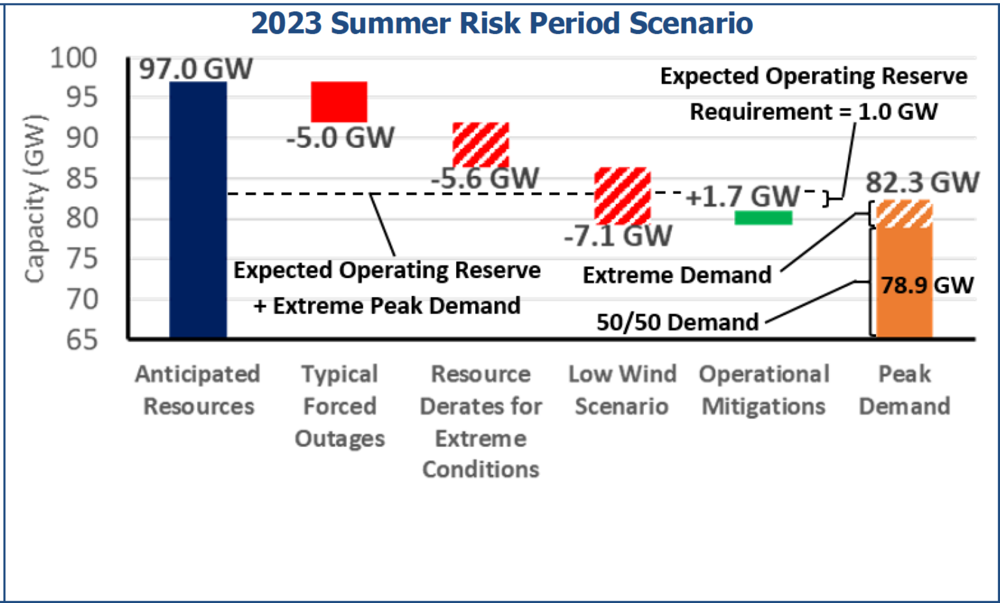
Evolution of the annual grid peak load in Texas (left) and in India (right), 2019-2023H1



Source: IEA Electricity Market Report, 2023

Texas Grid Reliability Analysis





Source: NERC, 2023

Management and Control of Electric Grids

- Modern electric power systems are large scale, spatially distributed, dynamic, interconnected systems
- Highly reliable, economic, and (aspire to be) carbon-free
- Electric energy is difficult to store in large quantities
- Major engineering constraint: generation = consumption
- Traditional paradigm: adjust supply to match stochastic time-varying demand
- A complex techno-economic management and control system operating at multiple time-scales to achieve the above goal
- Wind and solar generation cannot be controlled as easily
- New control paradigm: match stochastic generation with stochastic demand

ICT Energy and Carbon Footprint

Information and Communications Technology Sector

- ICT Sector consumes about 3-4% of global electricity production
- ICT Sector contributes about 1.3% of total GHG emissions
- Data centers consume about 1% of global electricity production
- Data centers contribute 0.2% of total GHG emissions
- Machine learning computations are energy intensive. Therefore, we need to keep an eye on the growth rates of this sector.
- Energy efficiency is an unalloyed good thing!
- More details in the panel session

ICT Sector Electricity Consumption and GHG Footprint

Table 7 ICT sector use stage electricity consumption and GHG emissions in 2020

ICT sector part	Use stage electricity (TWh)	Embodied GHG emissions (Mtonne CO_2e)	Use stage GHG emissions (Mtonne CO_2e)	Total GHG emissions (Mtonne CO_2e)
User devices [A]	421	208	228	436
Networks [B]	247	31	155	186
Data centers	223	30	95	126
Enterprise networks	25	3	13	16
Total [C]	916	272	492	764

[A] Including IoT and surveillance cameras, [B] Including telecommunication satellites, [C] Rounded values

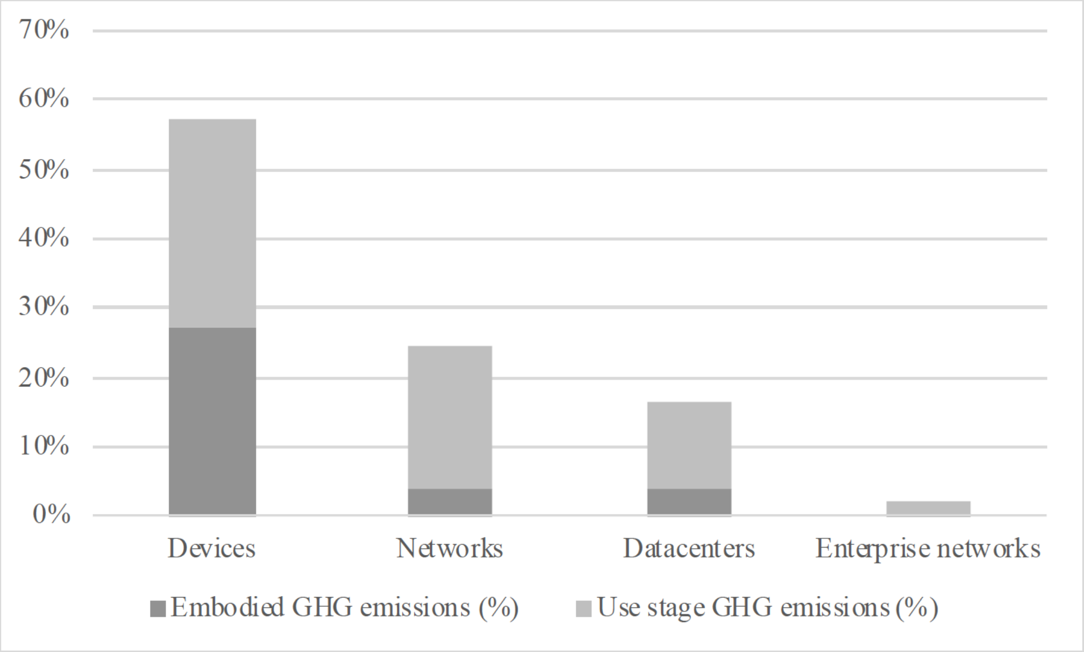


Figure 3 Total ICT sector carbon footprint 2020

- ICT electricity use: ~3-4% of total
- ICT GHG footprint: ~1.3% of total
- Data centers electricity use: ~1%
- Data centers GHG footprint: ~.2% of total

Source: Malmodin et al (2023)

ICT GHG Trend

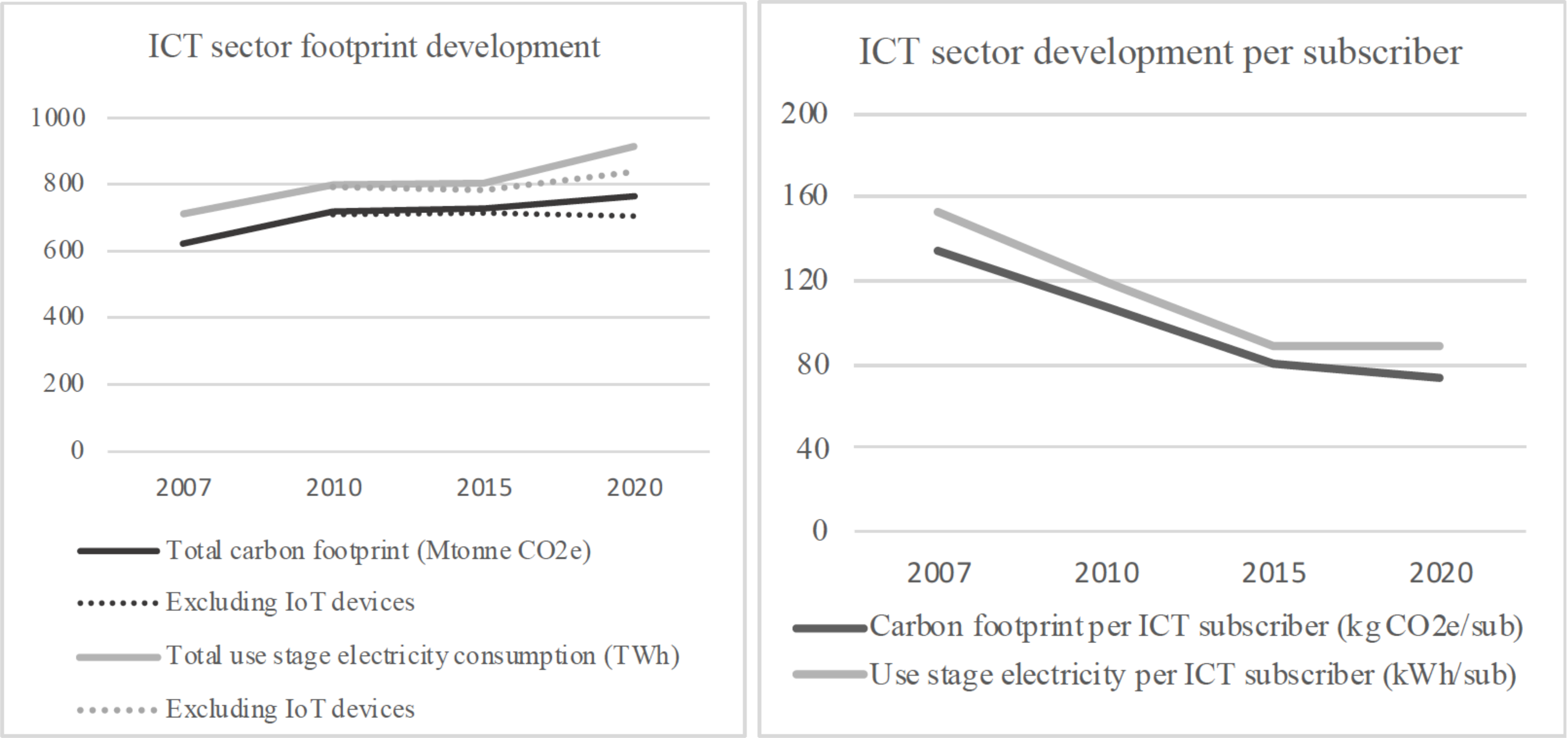


Figure 5 Development of ICT sector's carbon footprint (left), where the dotted lines show the development without impact from IoT devices in Table 6 and the total ICT sector footprint per subscriber (right)

Source: Malmodin et al (2023)

ICT GHG Breakdown by Sector

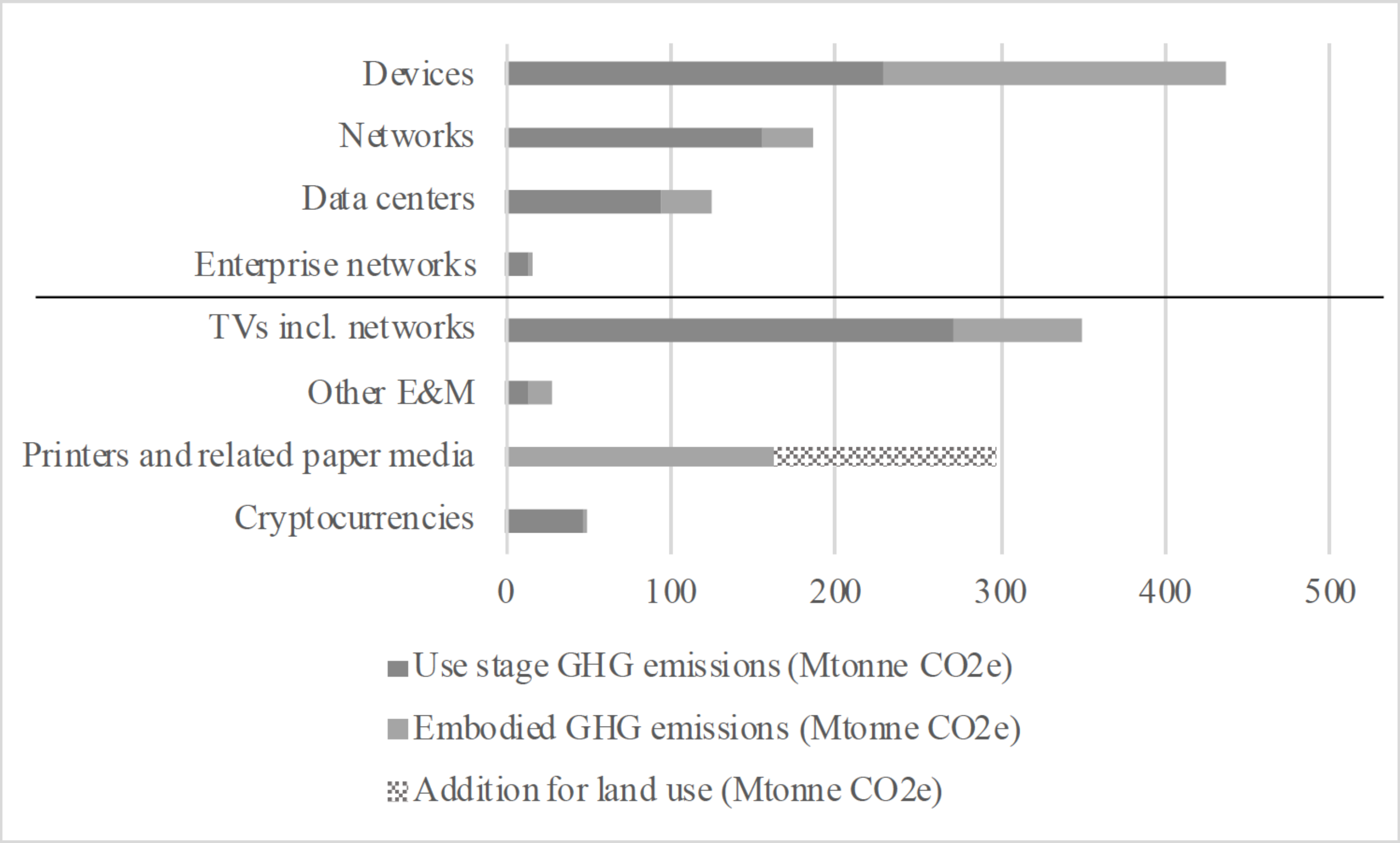
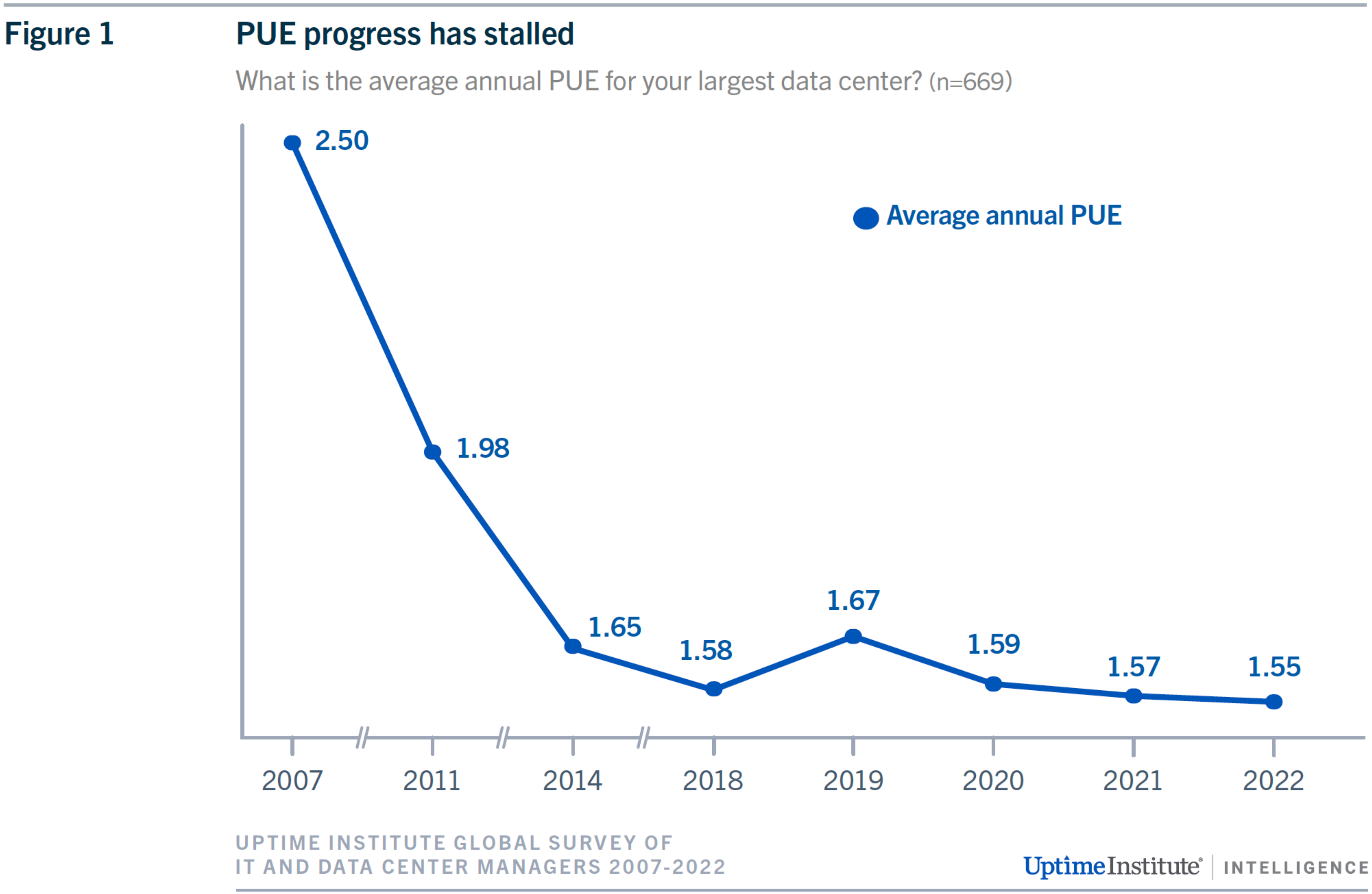


Figure 6 Carbon footprint of ICT sector (above the horizontal line) and relating sector/activities

Source: [Malmodin et al (2023)]

Data Centers

Data Center Energy Utilization Efficiency

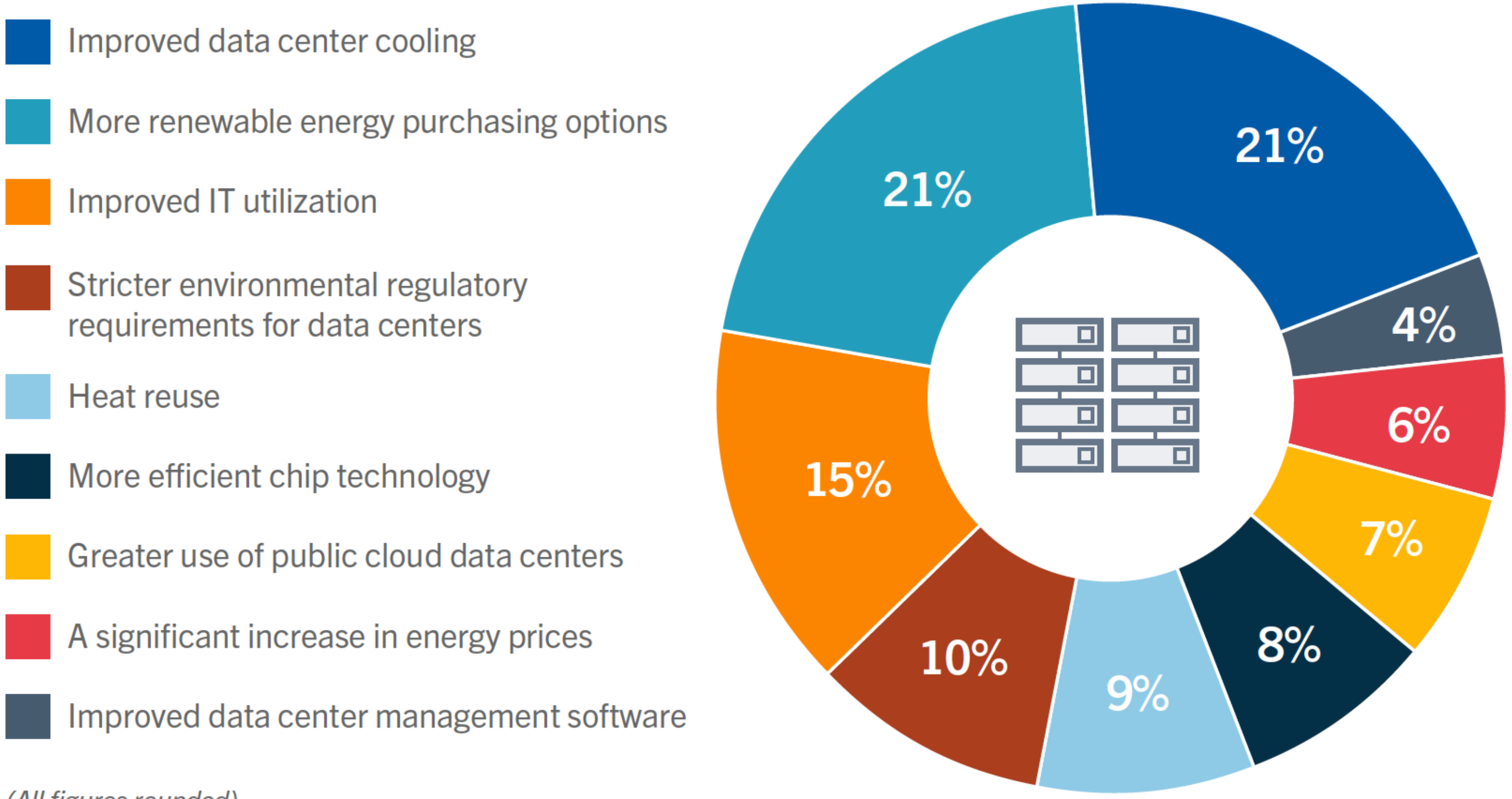


Source: [Uptime Institute, 2022]

Data Center Energy Sustainability

Figure 8 **Renewables, cooling are biggest drivers for sustainability gains**

In your opinion, which of the following will have the biggest impact in making the data center industry more environmentally sustainable in the next three to five years? Choose one. (n=667)



(All figures rounded)

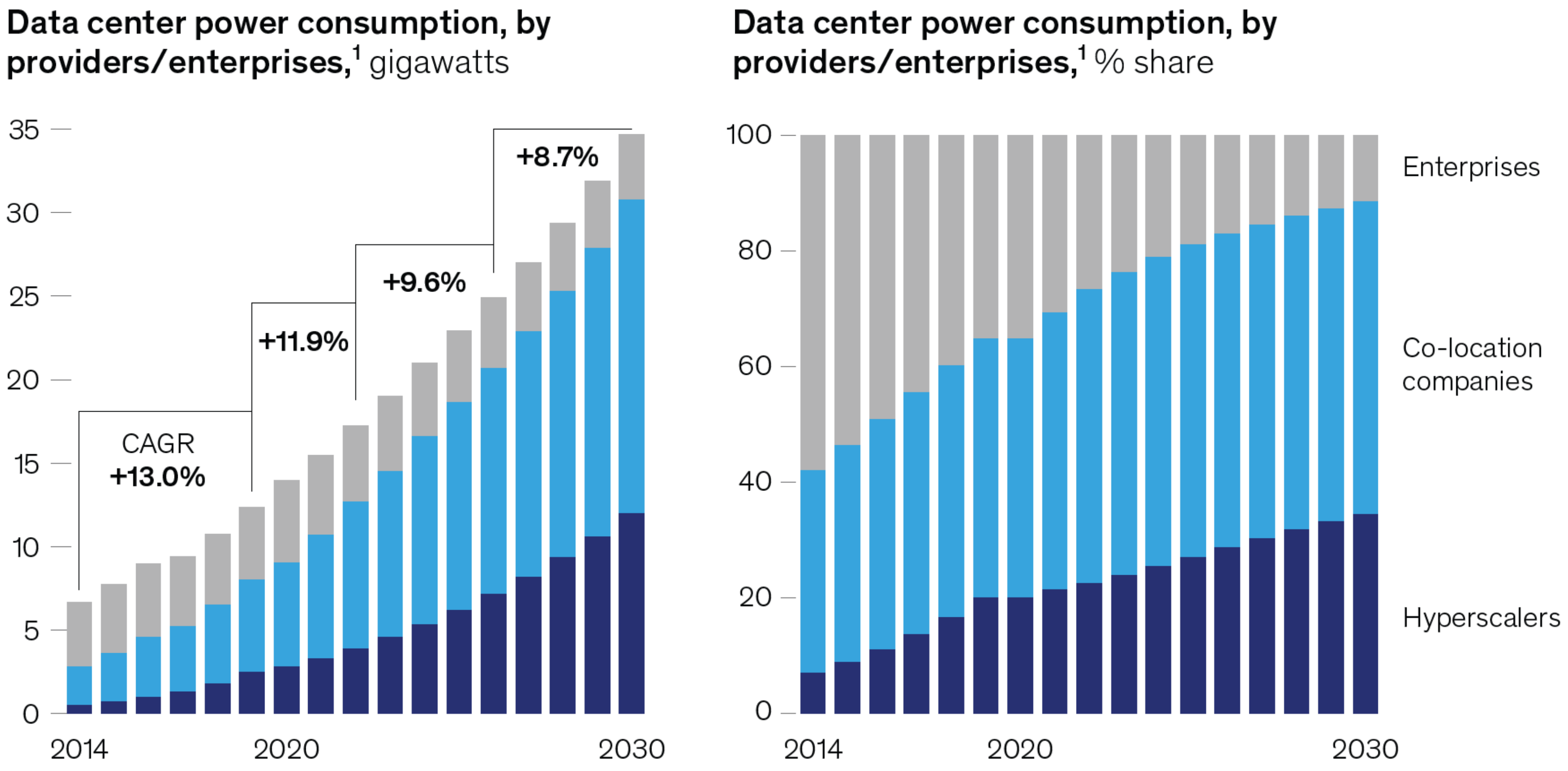
UPTIME INSTITUTE GLOBAL SURVEY OF IT AND DATA CENTER MANAGERS 2022

UptimeInstitute® | INTELLIGENCE

Source: Uptime Institute, 2022

US Data Center Growth

US data center demand is forecast to grow by some 10 percent a year until 2030.



[1]Demand is measured by power consumption to reflect the number of servers a data center can house. Demand includes megawatts for storage, servers, and networks.

Source: [McKinsey, 2023]

Ireland Data Center Electricity Growth

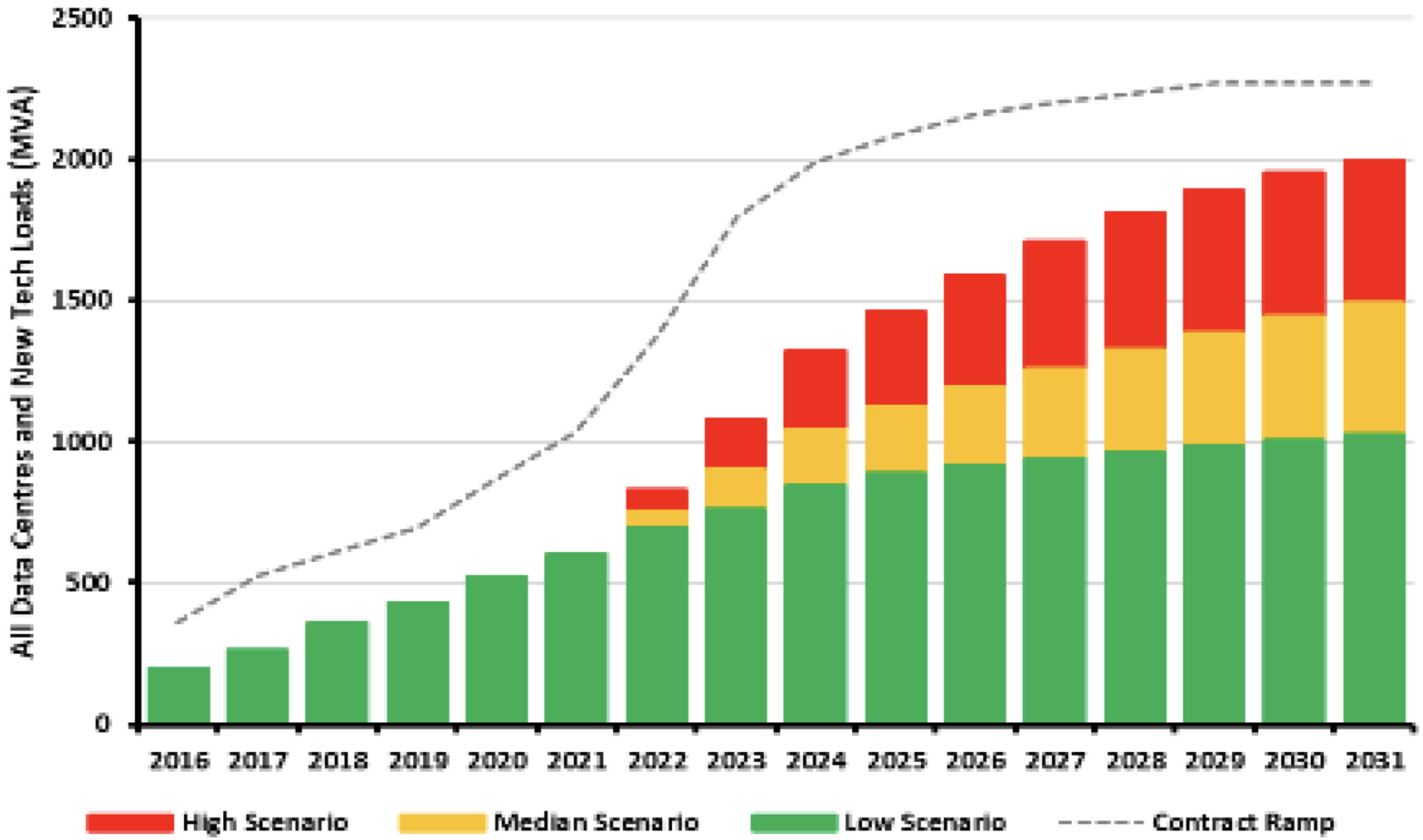


Figure 2.1 - Ireland demand expected from assumed build-out of data centres and new tech loads. EirGrid incorporate this demand into the low, median and high demand forecast scenarios for 2031

Source: [EIRGRID and SONI, All-Island Generation Capacity Statement 2022-2031]

Ireland Data Center and New Technology Loads

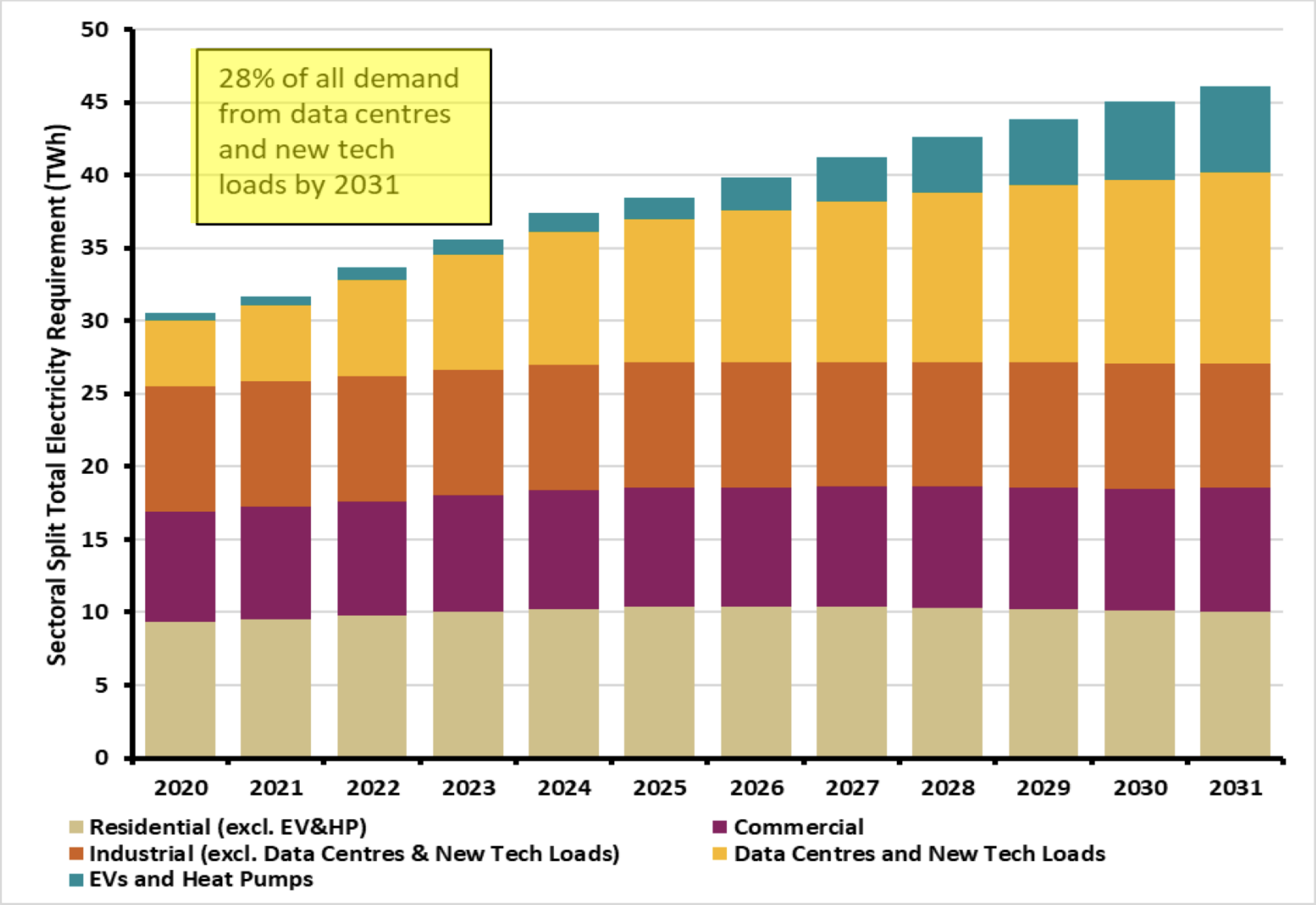


Figure 2.5 - For the Ireland median demand scenario, this illustrates the approximate split into different sectors. EirGrid estimate that 28% of total demand will come from data centres and new tech loads by 2031

Source: [EIRGRID and SONI, All-Island Generation Capacity Statement 2022-2031]

Ireland Data Centers


HOME > NEWS > GRID LEVEL

Ireland isn't going to limit data centers despite high energy use

Announcement comes as government issues an amber warning for the grid

June 13, 2023 By: Georgia Butler Have your say

Enterprise Minister Simon Coveney added that there is "no technology-based economic growth without data centers."

"The challenge for us isn't to reduce the number of data centers in Ireland. The challenge is to find a way of powering them with sustainable abundant power by capturing the potential of, in particular, offshore wind, which I think you'll see a significant change in investment in the next few years."

However, Social Democrat TD Jennifer Whitmore expressed concern and argued that the new statistics show that the previously dismissed warnings of data center consumption reaching 30 percent by 2030, are now looking like a reality.

"The CSO statistics released today indicate we are on course to meet or even exceed that figure," said Whitemore.
"Responsibility for meeting our climate action targets should not fall on individual customers while the Government conveniently ignores runaway energy consumption by data centers."

Machine Learning

Energy Impacts of AI Industry

BBC | Sign in | Home | News | Sport | Reel | Worklife

NEWS

Home | War in Ukraine | Climate | Video | World | US & Canada | UK | Business | Tech | Science

Tech

Warning AI industry could use as much energy as the Netherlands

Joule

Commentary

The growing energy footprint of artificial intelligence

Alex de Vries[1,2,3,*]

“While the exact future of AI-related electricity consumption remains difficult to predict, the scenarios discussed in this commentary underscore the importance of tempering both overly optimistic and overly pessimistic expectations.”

Source: A de Vries, Joule, 2023

Machine Learning Carbon Footprint

The Carbon Footprint of Machine Learning Training Will Plateau, Then Shrink

David Patterson[1,2], Joseph Gonzalez[2], Urs Hölzle[1], Quoc Le[1], Chen Liang[1], Lluis-Miquel Munguia[1], Daniel Rothchild[2], David So[1], Maud Texier[1], and Jeff Dean[1]

1. *Model.* Selecting efficient ML model architectures while advancing ML quality, such as sparse models versus dense modes, can reduce computation by factors of ~5–10.
2. *Machine.* Using processors optimized for ML training such as TPUs or recent GPUs (e.g., V100 or A100), versus general-purpose processors, can improve performance/Watt by factors of 2–5.
3. *Mechanization.* Computing in the Cloud rather than on premise improves datacenter energy efficiency[3], reducing energy costs by a factor of 1.4–2.
4. *Map.* Moreover, Cloud computing lets ML practitioners pick the location with the cleanest energy[4], further reducing the gross carbon footprint by factors of 5–10[5].

“Four best practices can reduce ML training energy by up to 100x and CO2 emissions up to 1000x.”

Source: Google, 2022, 2204.05149

ARPA-e COOLERCHIPS

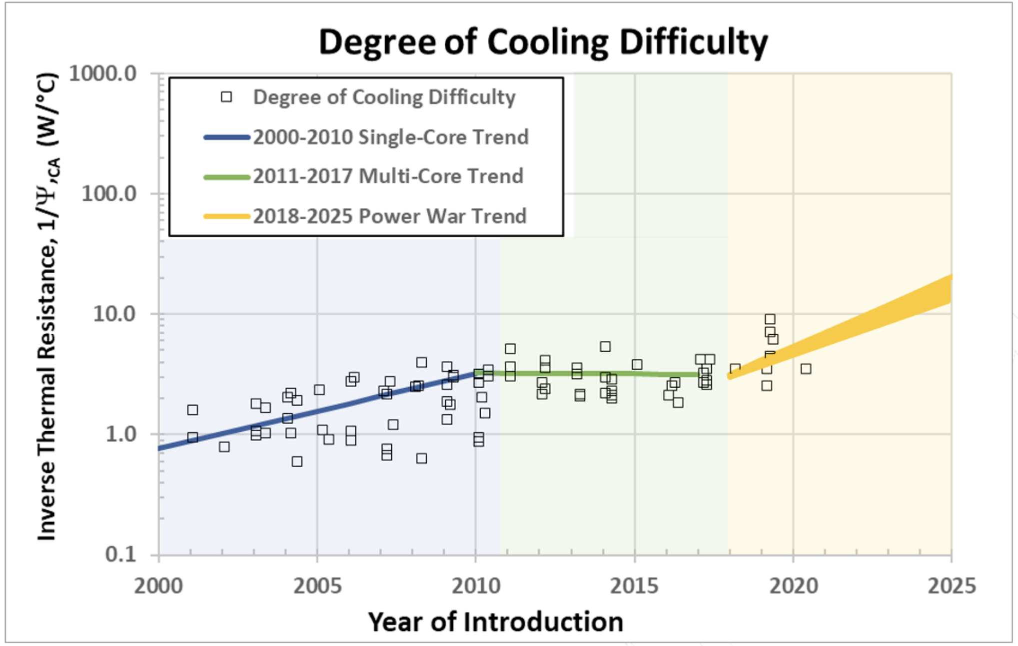
COOLERCHIPS

Home / Technologies / Search Our Programs

Cooling Operations Optimized for Leaps in Energy, Reliability, and Carbon Hyperefficiency for Information Processing Systems

• Efficiency • Electrical Efficiency

PRINT



Source: ASHRAE, 2021

- Flexnode - Prefab Modular Liquid-cooled Micro Data Center
- HP - Embedded Microfluidic Cooling for Nextgen High Power Server Architectures
- HRL Laboratories - Aligned Graphite Microchannel Cooling (AGMC) System with Additively Manufactured Manifolds
- Intel Federal - Enabling Two-Phase Immersion Cooling to Support High TDP
- JetCool Technologies - Sub-One PUE through Silicon Cooling Efficiency
- National Renewable Energy Laboratory (NREL) - COOLERCHIPS Technical Evaluation Team
- Nvidia - Green Refrigerant Compact Hybrid System for Ultra-Efficient and Sustainable HPC Cooling
- Purdue University - Confined Direct Two-phase Jet Impingement Cooling with Topology Optimized Surface Engineering and Phase Separation Using Additive Manufacturing
- Raytheon Technologies Research Center - EXTRACT: Extra Efficient Data Centers Using Avionics Cooling Technology
- University of California, Davis (UC Davis) - Holistic Modular Energy-efficient Directed Cooling Solutions (HoMEDUCS) for Edge Computing
- University of Florida - Hyperefficient Data Centers for Deep Decarbonization of Large-scale Computing
- University of Illinois - Holistic Rack-to-Processor Power and Thermal Co-Design for Future Servers
- University of Maryland (UMD) - Multi-Objective Optimization Software for COOLERCHIPS
- University of Missouri - Dual-mode Hybrid Two-phase Loop for Data Center Cooling
- University of Texas at Arlington (UT Arlington) - Holistic Co-Design of Novel Hybrid Cooling Technology for the Data Center of the Future

Source: arpa-e

Energy and Network Aware Workload Management for Sustainable Data Centers with Thermal Storage

Yuanxiong Guo, *Student Member, IEEE*, Yanmin Gong, *Student Member, IEEE*, Yuguang Fang, *Fellow, IEEE*, Pramod P. Khargonekar, *Fellow, IEEE*, and Xiaojun Geng, *Member, IEEE*

Abstract—Reducing the carbon footprint of data centers is becoming a primary goal of large IT companies. Unlike traditional energy sources, renewable energy sources are usually intermittent and unpredictable. How to better utilize the green energy from these renewable sources in data centers is a challenging problem. In this paper, we exploit the opportunities offered by geographical load balancing, opportunistic scheduling of delay-tolerant workloads, and thermal storage management in data centers to facilitate green energy integration and reduce the cost of brown energy usage. Moreover, bandwidth cost variations between users and data centers are considered. Specifically, this problem is first formulated as a stochastic program, and then, an online control algorithm based on the Lyapunov optimization technique, called Stochastic Cost Minimization Algorithm (SCMA), is proposed to solve it. The algorithm can enable an explicit trade-off between cost saving and workload delay. Numerical results based on real-world traces illustrate the effectiveness of SCMA in practice.

Index Terms—Data center, energy management, thermal storage, load scheduling, Lyapunov optimization

Conclusions

- Climate change is one of the central challenges of our time.
- Energy system decarbonization is a fiendishly difficult imperative.
- Electric energy system sustainability is a viable path forward.
- ICT electric energy and carbon footprints are notable.
- Data center and machine learning energy minimization are worthy goals.

Comments

Ideas

Questions?

pramod.Khargonekar@uci.edu
http://faculty.sites.uci.edu/khargonekar/