Leveraging Control and Machine Learning to Accelerate Energy System Decarbonization

Workshop on Learning and Control for Decarbonized Energy and Transportation Systems

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Pramod P. Khargonekar
University of California, Irvine

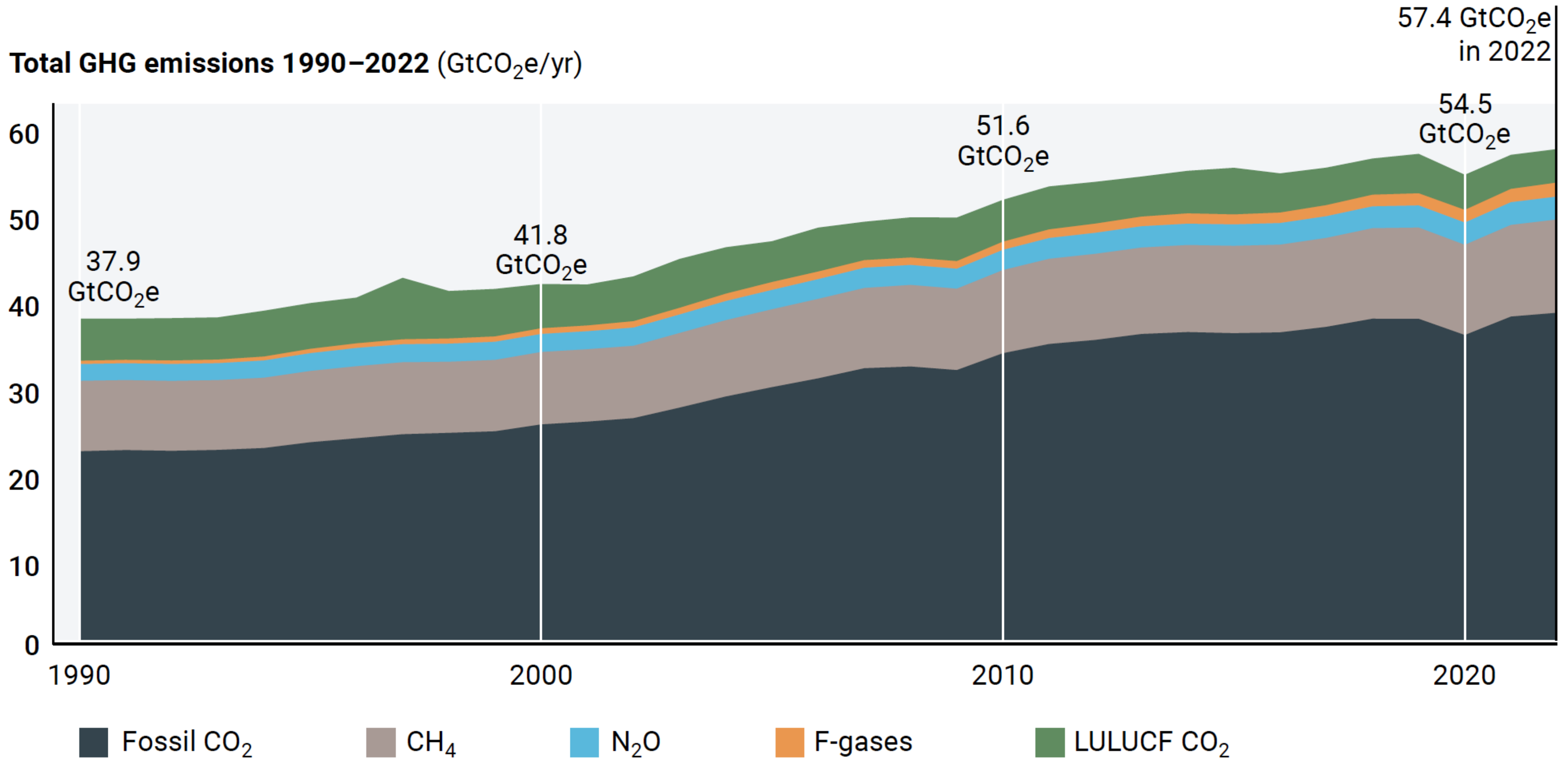
Outline

- Global warming and GHG emissions
- Energy system decarbonization
- Electric energy system
- Broader considerations

Global Warming and GHG Emissions

Global GHG Emissions

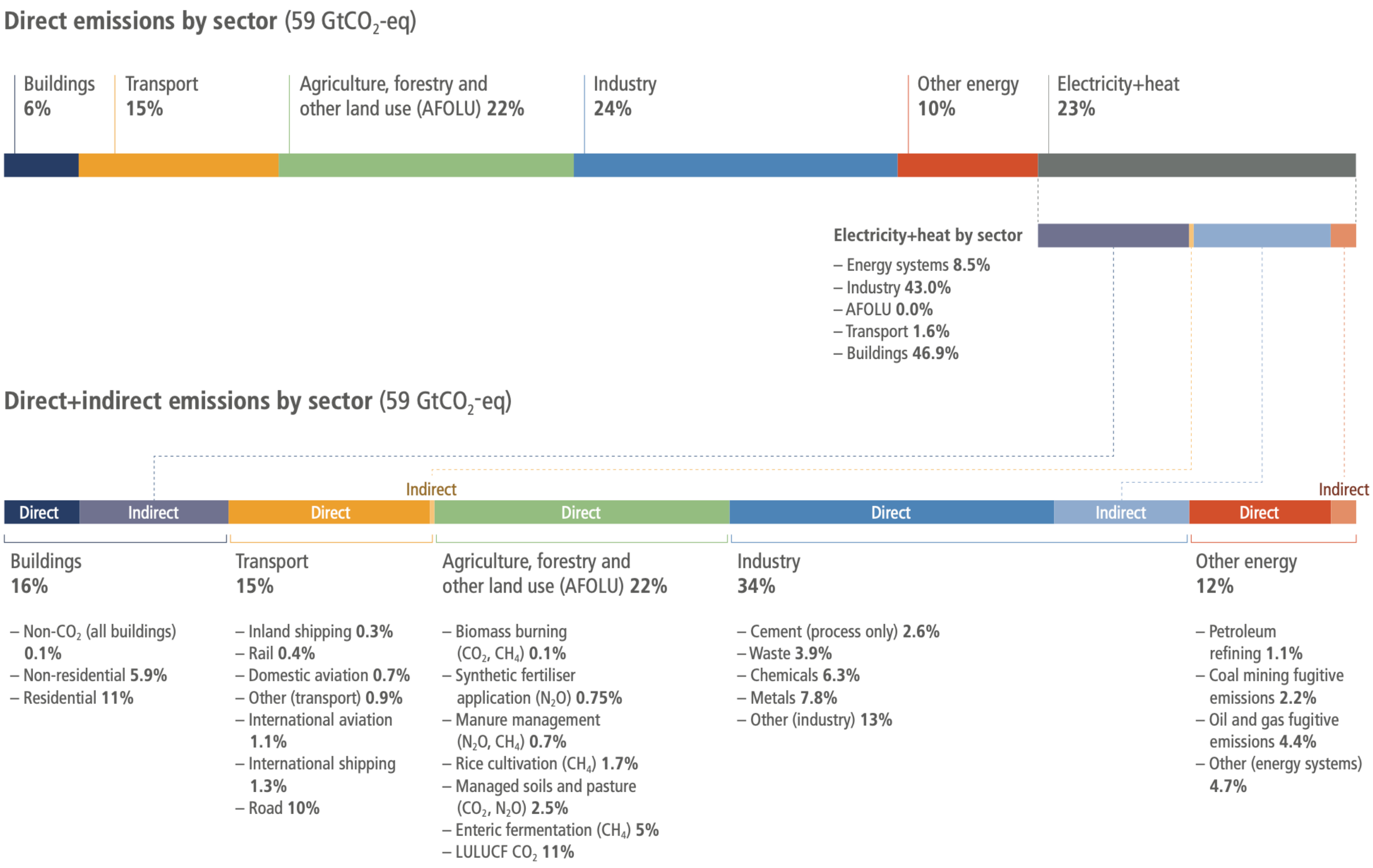
Figure ES.1 Total net anthropogenic GHG emissions, 1990–2022



Source: UN Emissions Gap Report 2023

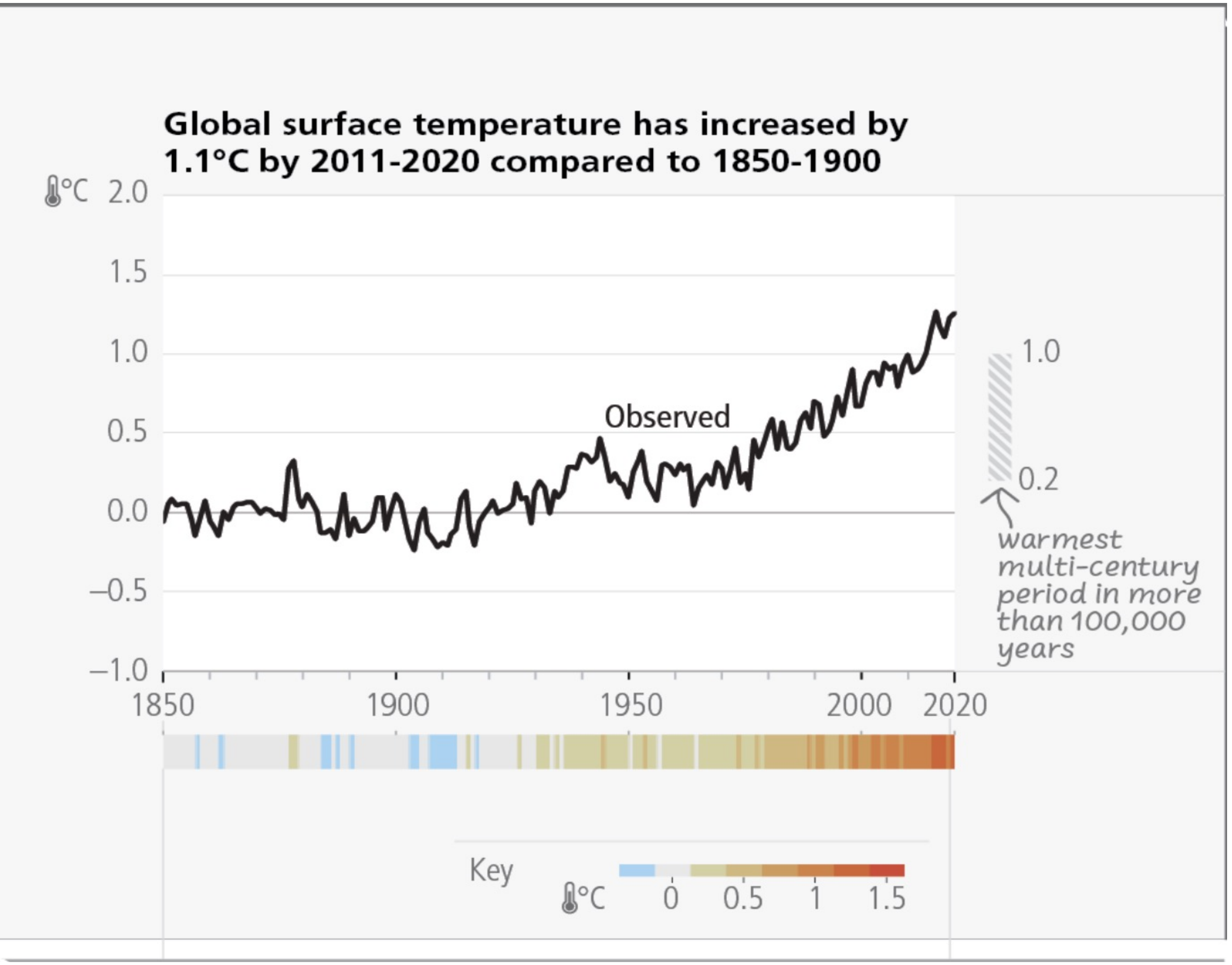
Global GHG Emissions by Use

Electricity + Transport ~ 38%

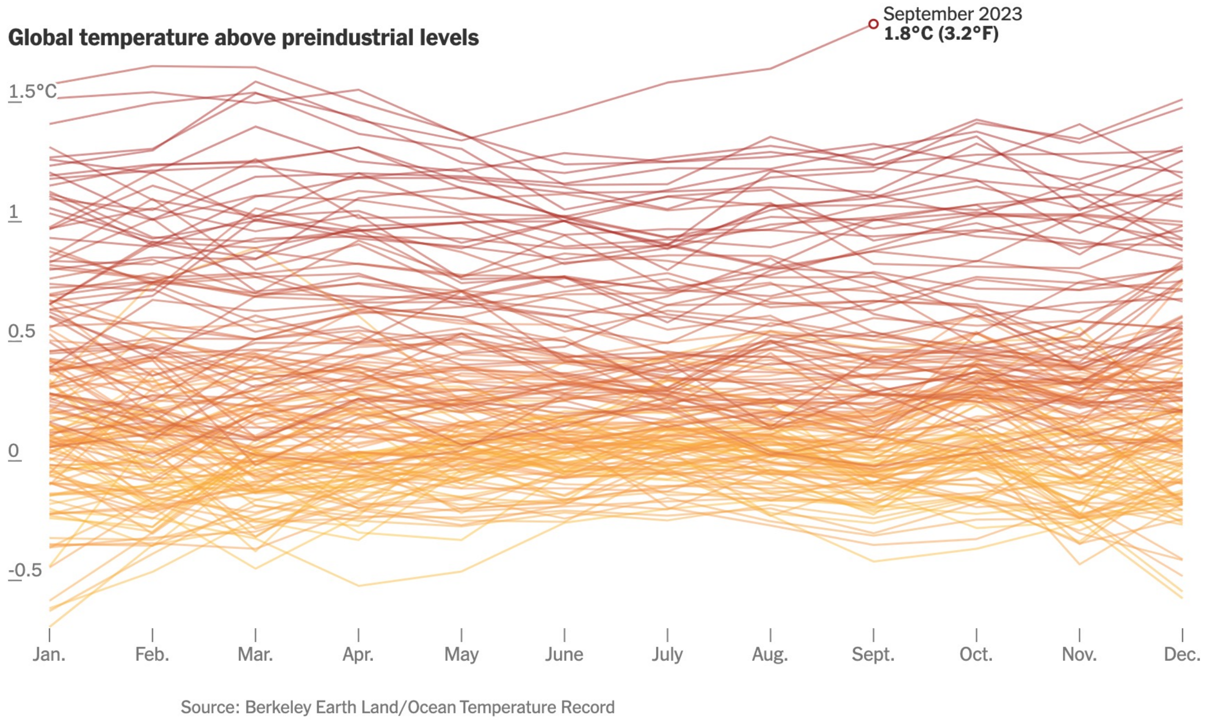


Sources: IPCC AR6 WGIII 2.12, Lamb et al (2021), Minx et al (2021)

Global Warming: What has already Happened



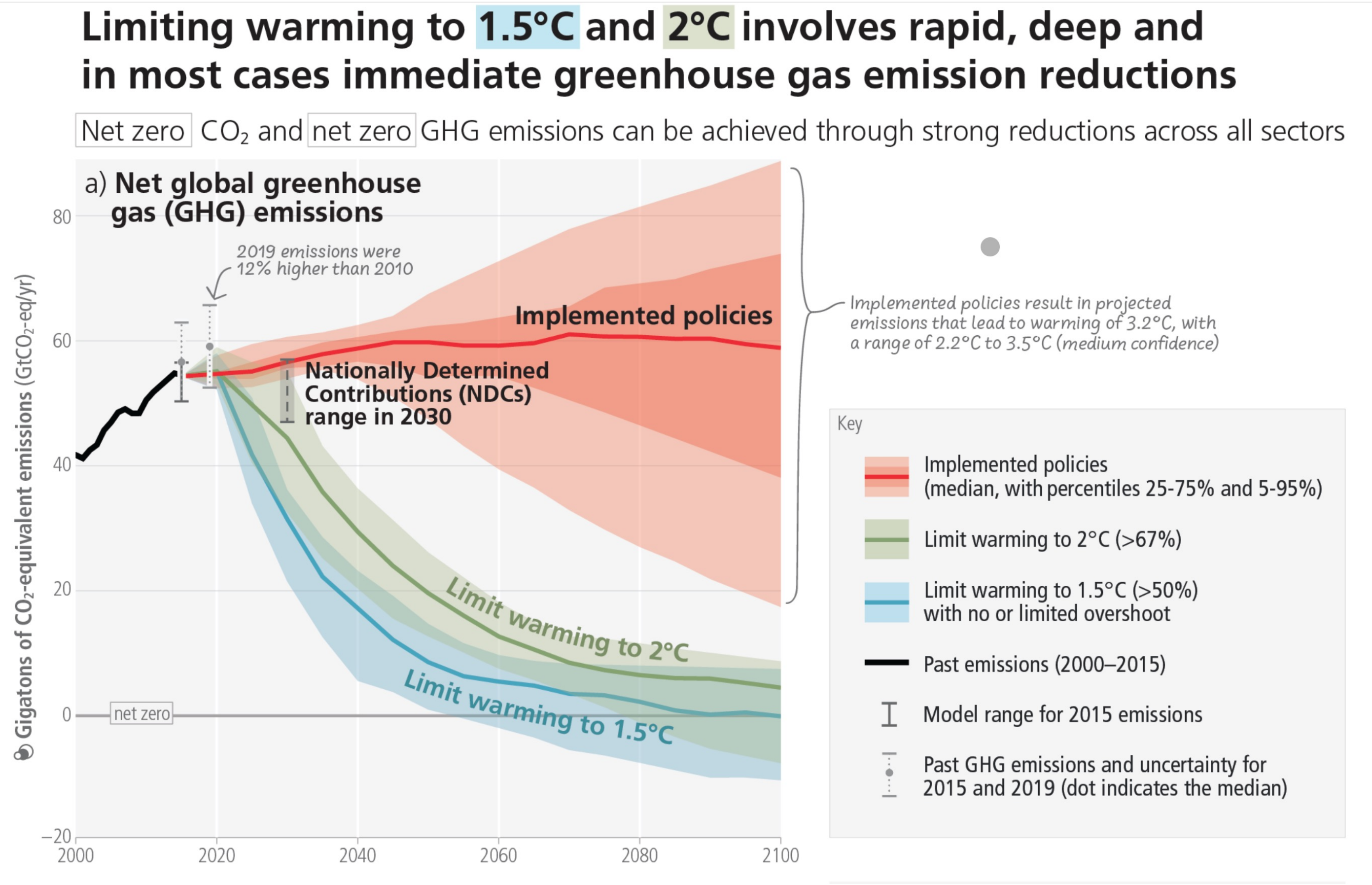
Source: IPCC AR6 WGII Report



Source: Berkeley Lab

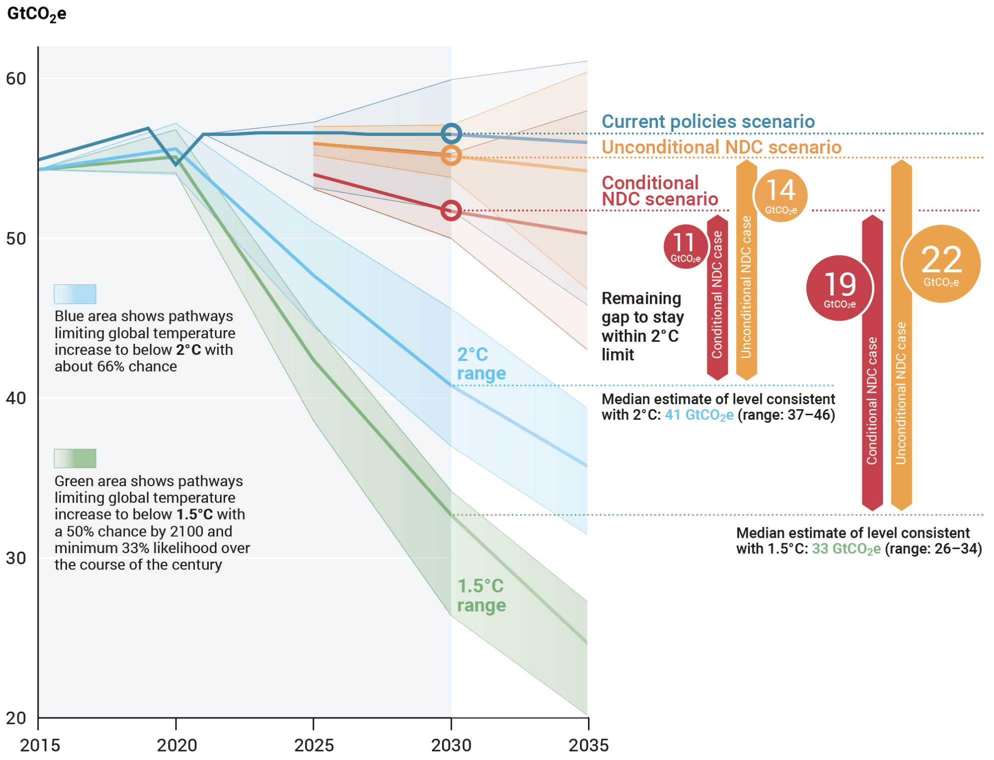
"The United Kingdom's Met office on Thursday warned that next year's average global temperature could breach a key planetary warming benchmark: 1.5 degrees Celsius (2.7 degrees Fahrenheit) above preindustrial levels." Washington Post, December 8, 2023.

GHG Reduction Imperative and Major Gaps



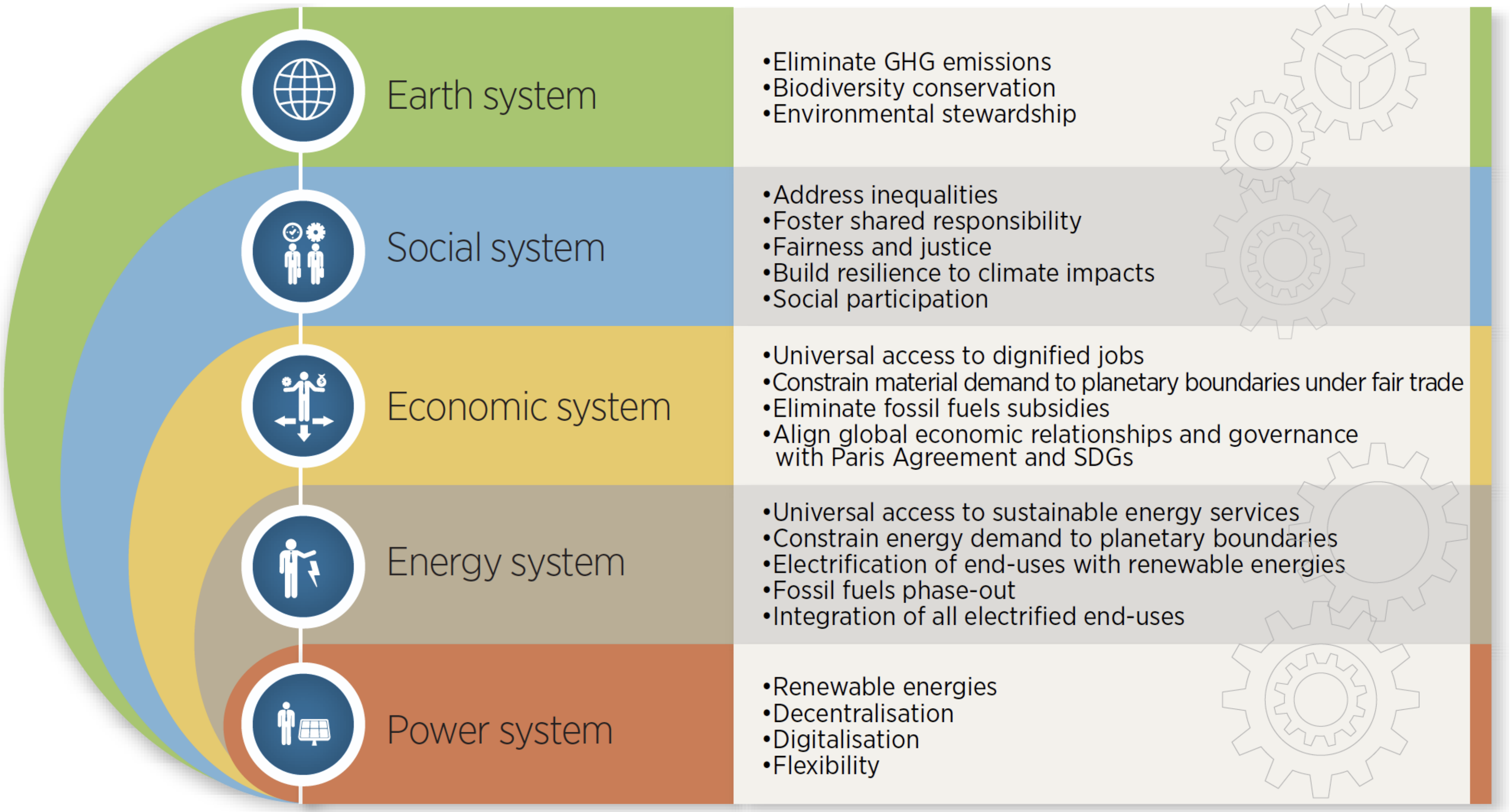
Source: [IPCC AR6 WGIII]

Figure ES.4 Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035 (median estimate and tenth to ninetieth percentile range)



Source: UN Emissions Gap Report 2023

Figure S-1. Cross-cutting transformations for a fair and just energy transition from the power, energy, social, economic and Earth systems



Note: GHG = greenhouse gas; SDGs = Sustainable Development Goals.

Source: IRENA, Innovation Landscape for Renewable Powered Future, 2019.

Energy System Decarbonization

Big Picture: Climate Change and Energy System

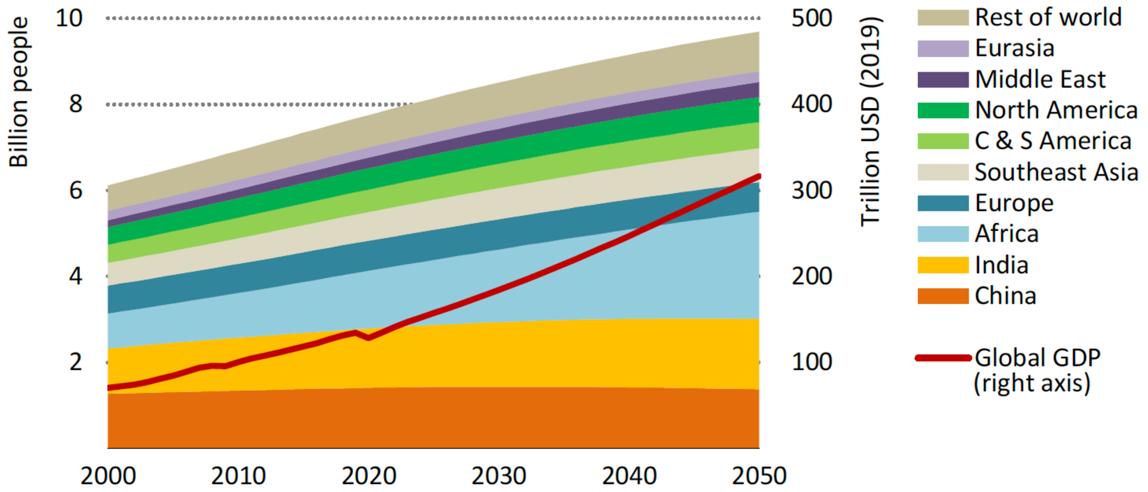
Decarbonization of the energy system is essential to mitigate climate change

- 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

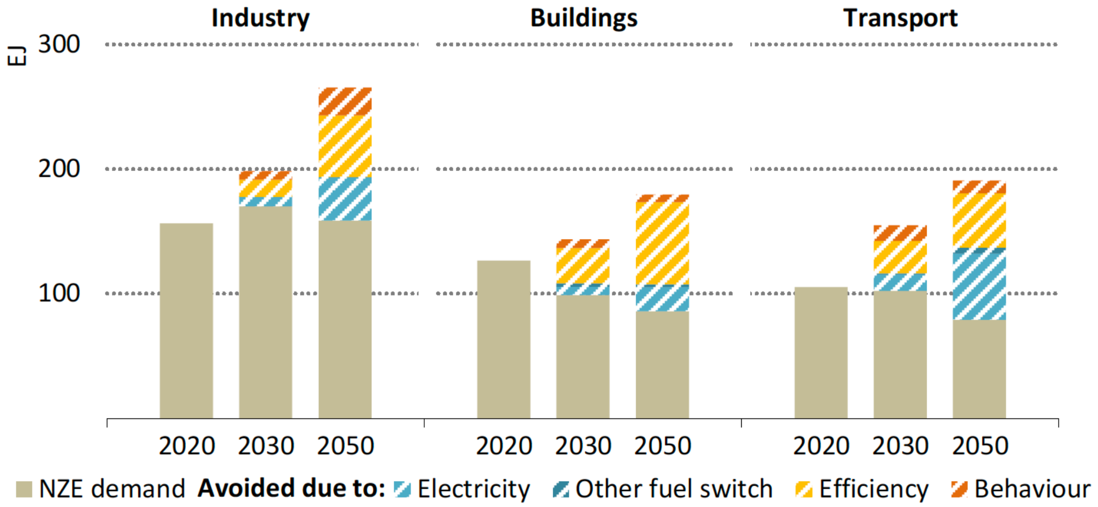
Projections of the Future

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



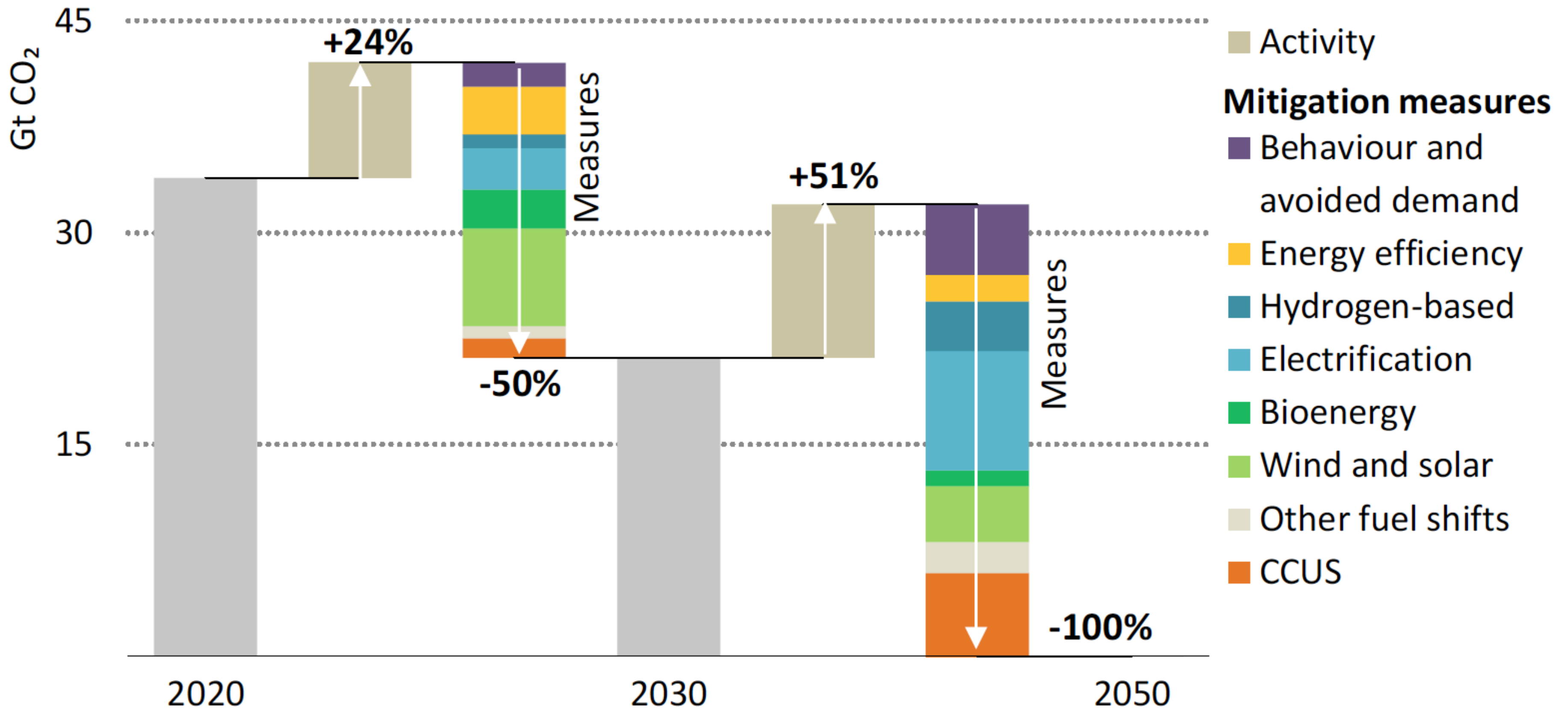
Energy efficiency plays a key role in reducing energy consumption across end-use sectors

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

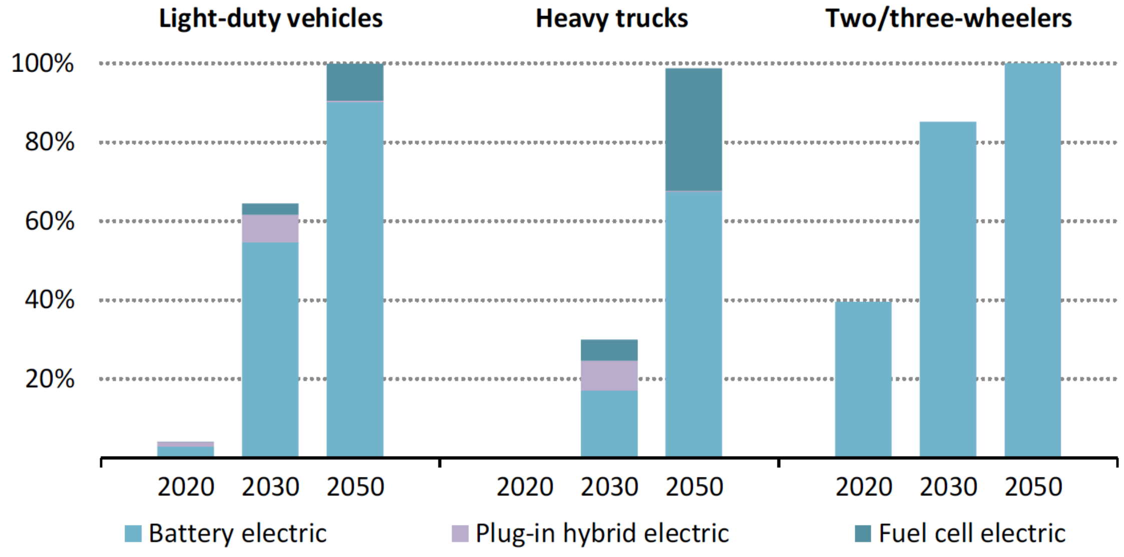


Solar, wind and energy efficiency deliver around half of emissions reductions to 2030 in the NZE, while electrification, CCUS and hydrogen ramp up thereafter

Source: [IEA]

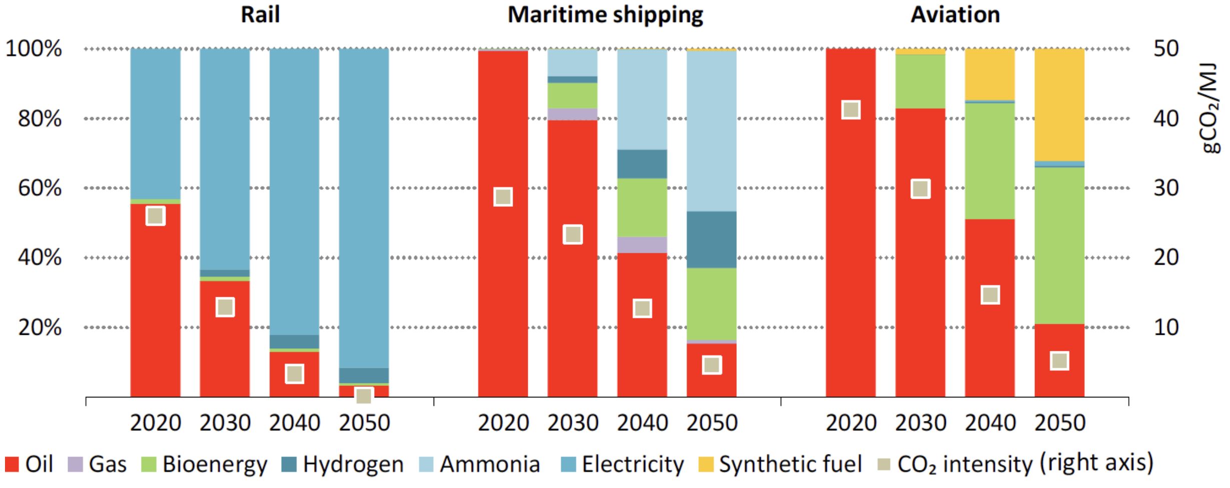
Transportation Decarbonization

Figure 3.23 ▷ **Global share of battery electric, plug-in hybrid and fuel cell electric vehicles in total sales by vehicle type in the NZE**



Sales of battery electric, plug-in hybrid and fuel cell electric vehicles soar globally

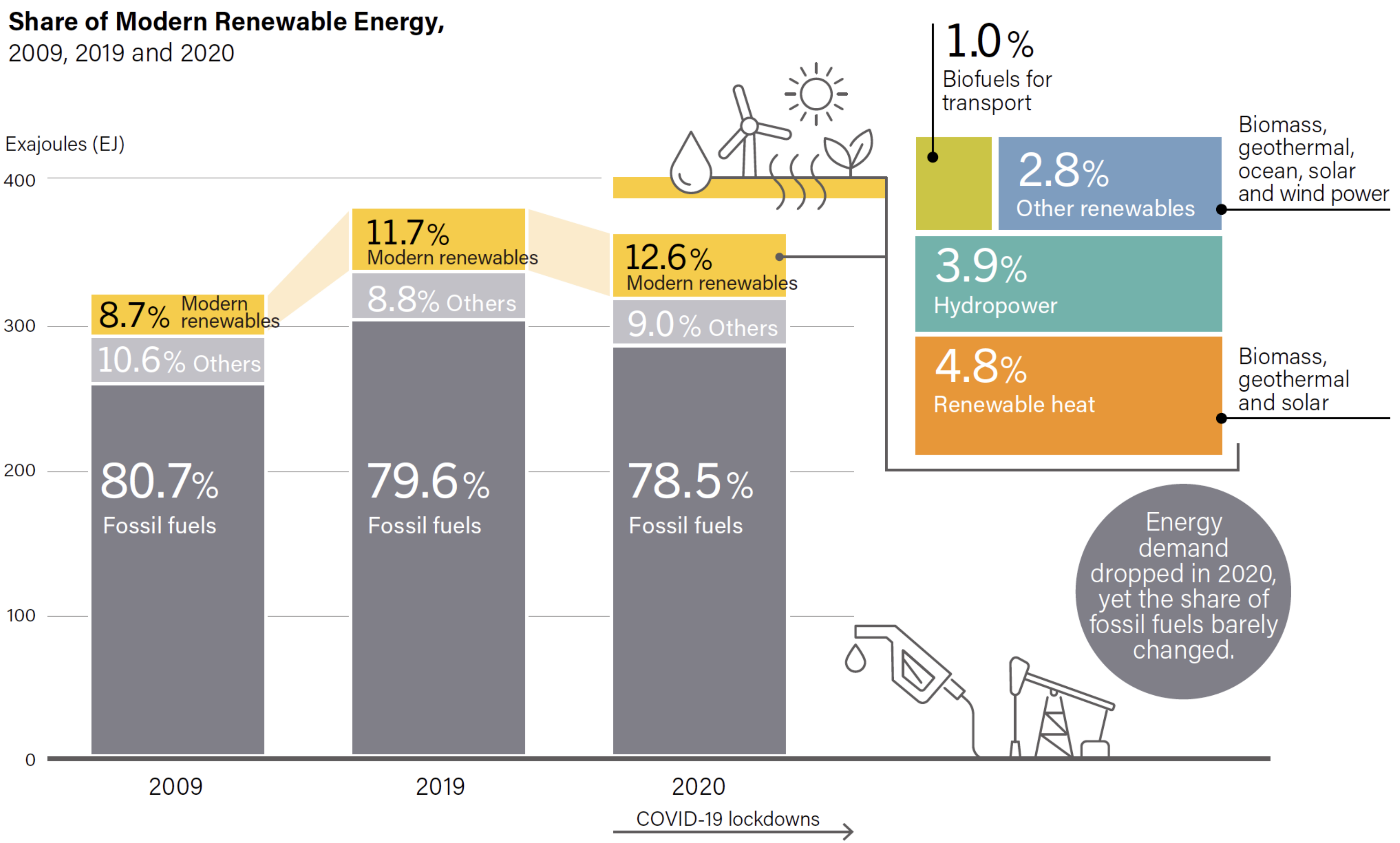
igure 3.25 ▷ **Global energy consumption by fuel and CO_2 intensity in non-road sectors in the NZE**



Railways rely heavily on electricity to decarbonise, while shipping and aviation curb emissions mainly by switching to low-emissions fuels

Source: IEA

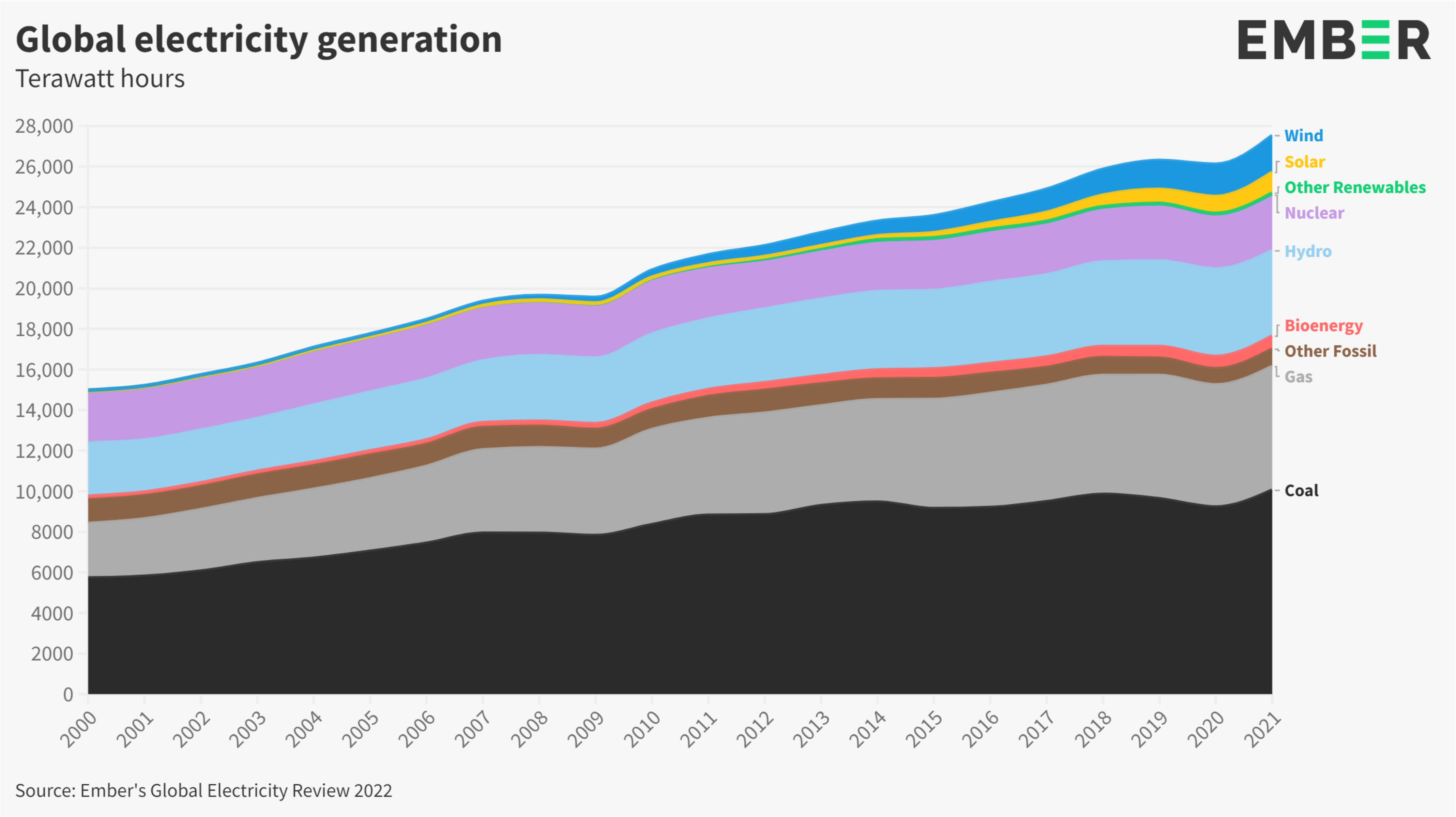
Growth of Renewable Energy in Context



Source: [REN21, 2022 Global Status Report]

Electric Energy System

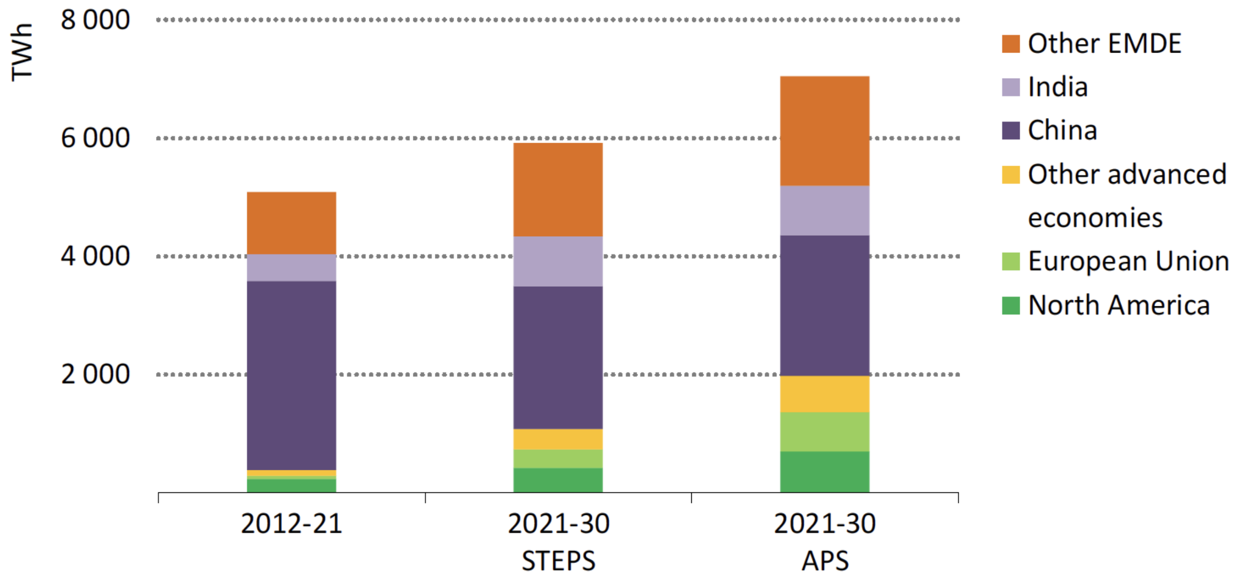
Global Electric Energy Generation



Source: EMBER, Global Electricity Review, 2022

Electricity Demand Growth

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

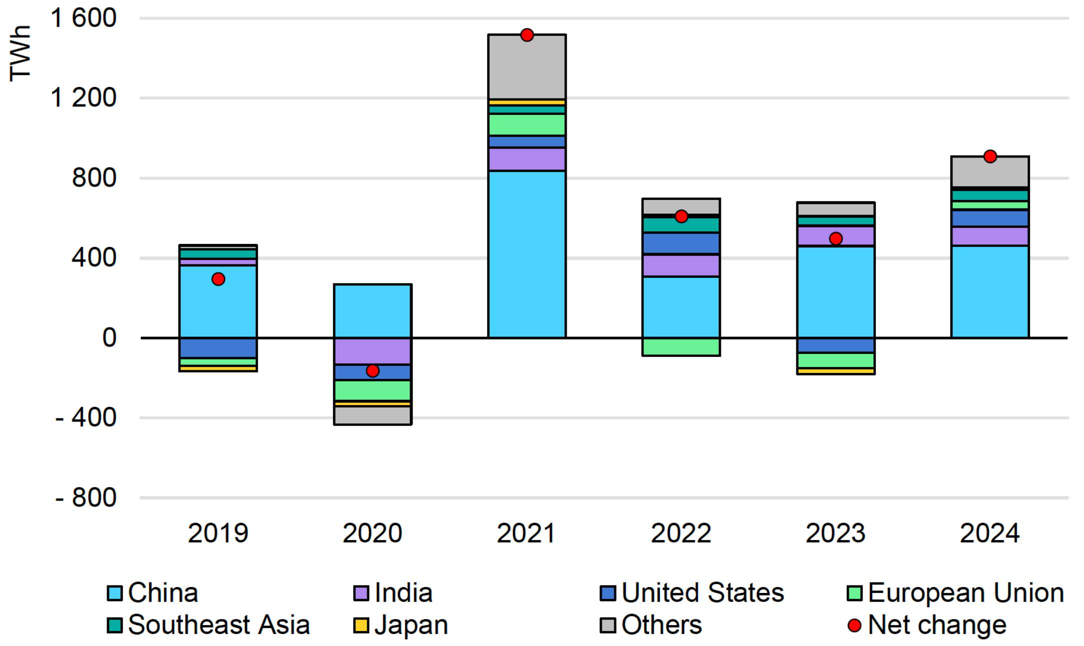


Global electricity demand growth picks up over the next decade, as a slowing in China is more than counterbalanced by strong increases in many other markets

Note: EMDE = emerging market and developing economies.

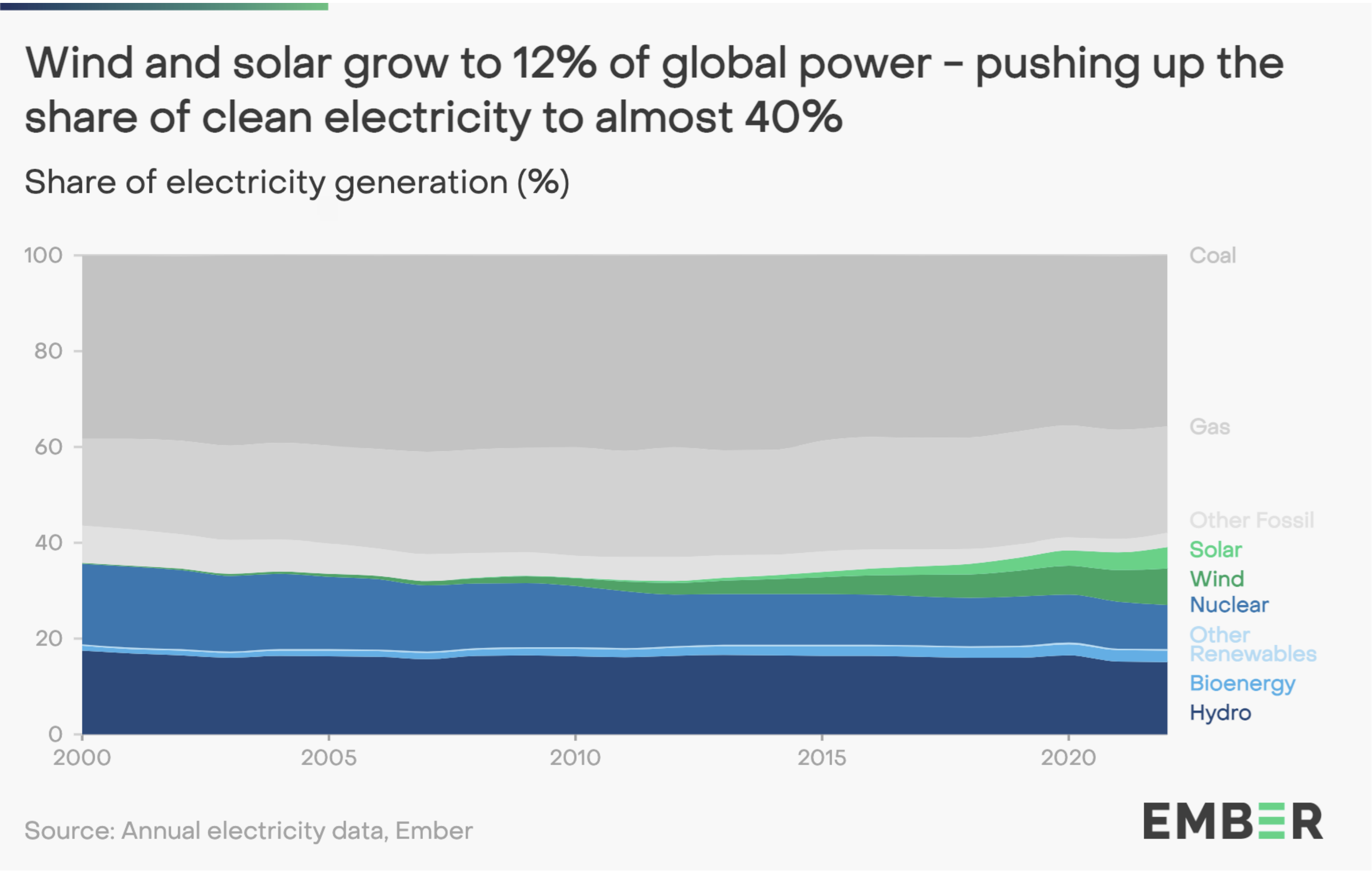
Source: IEA Net Zero Report

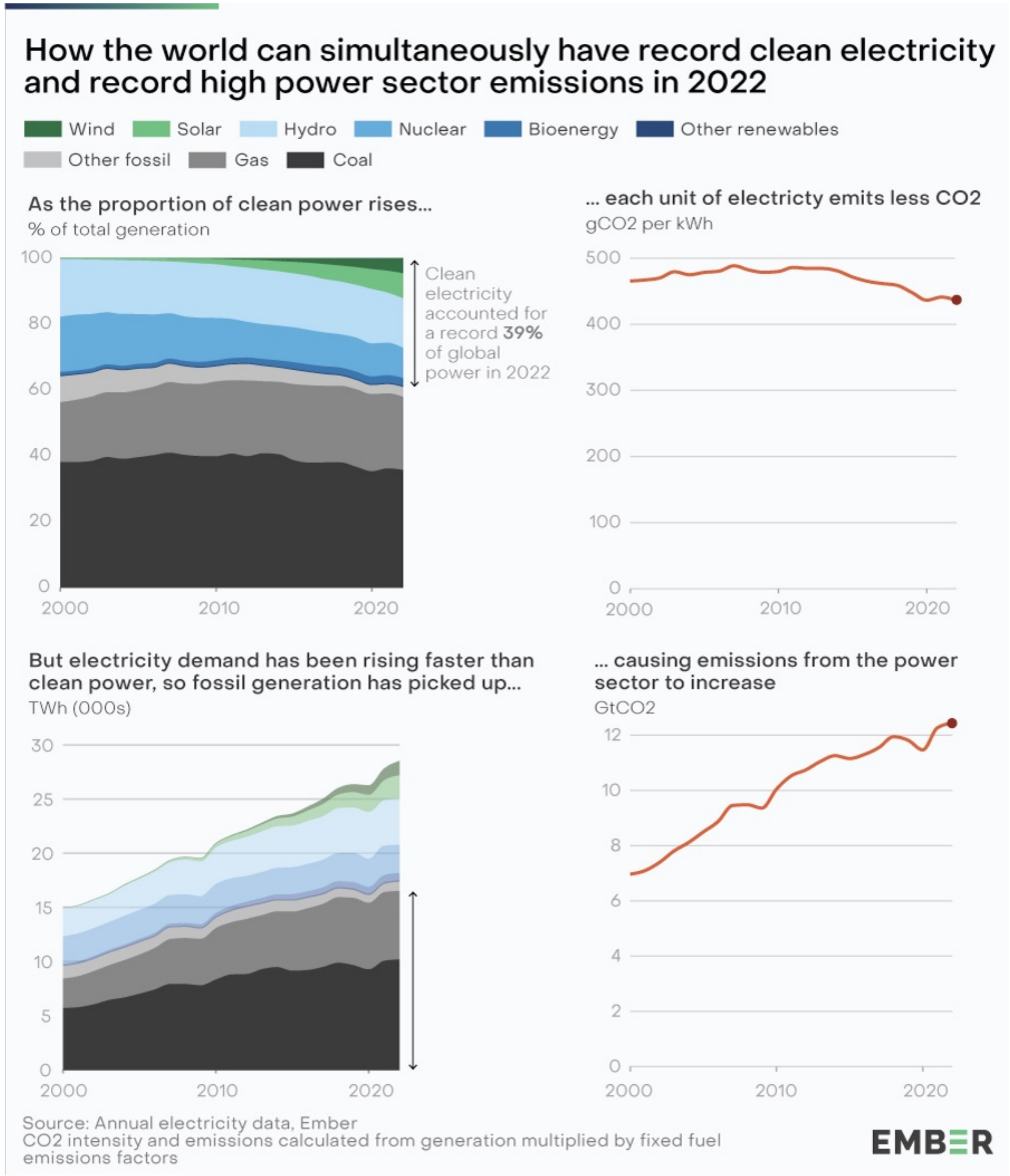
Year-on-year change in electricity demand in selected regions, 2019-2024



Source: IEA Electricity Market Report, 2023

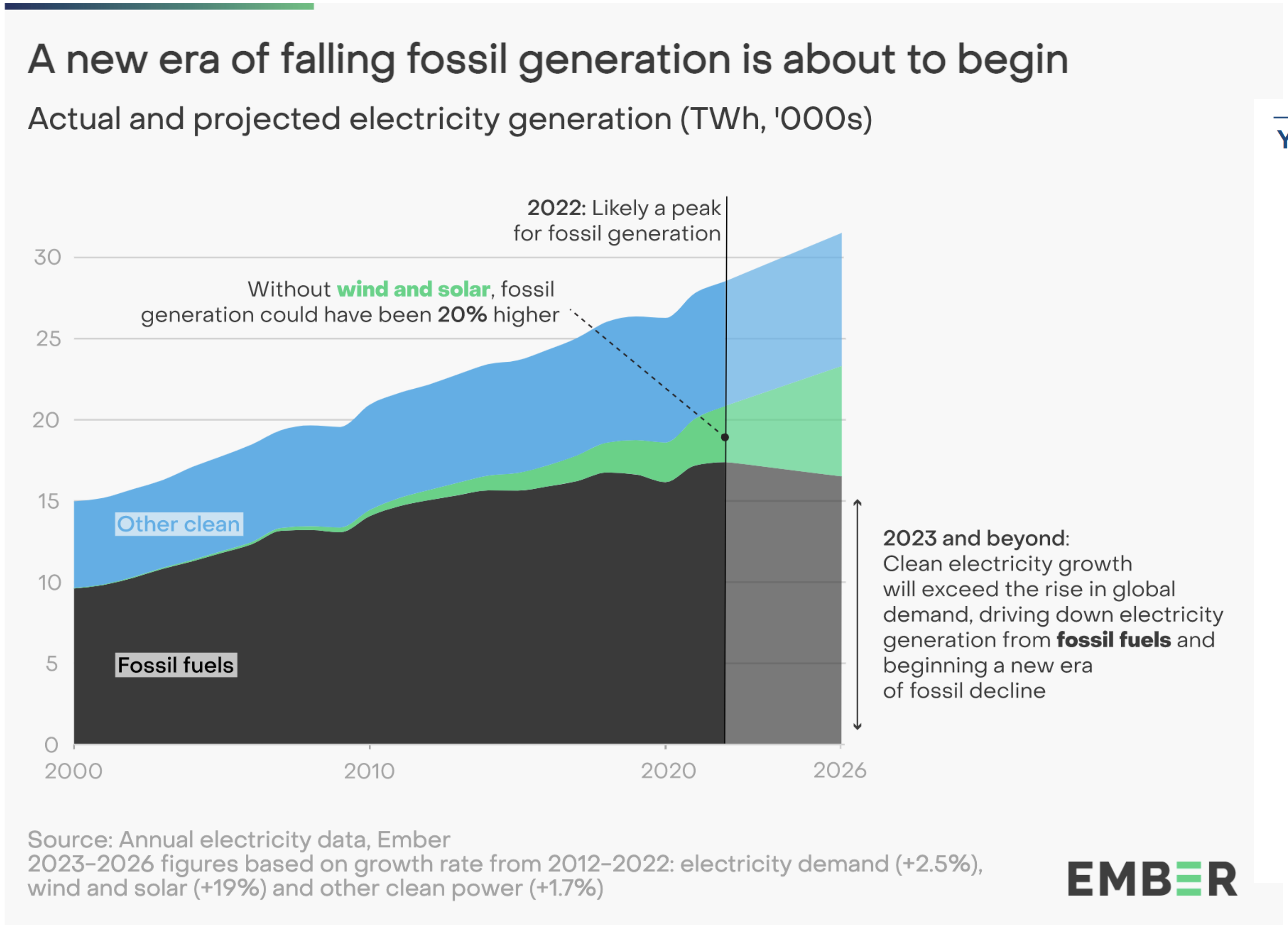
Electric Energy Production by Sources

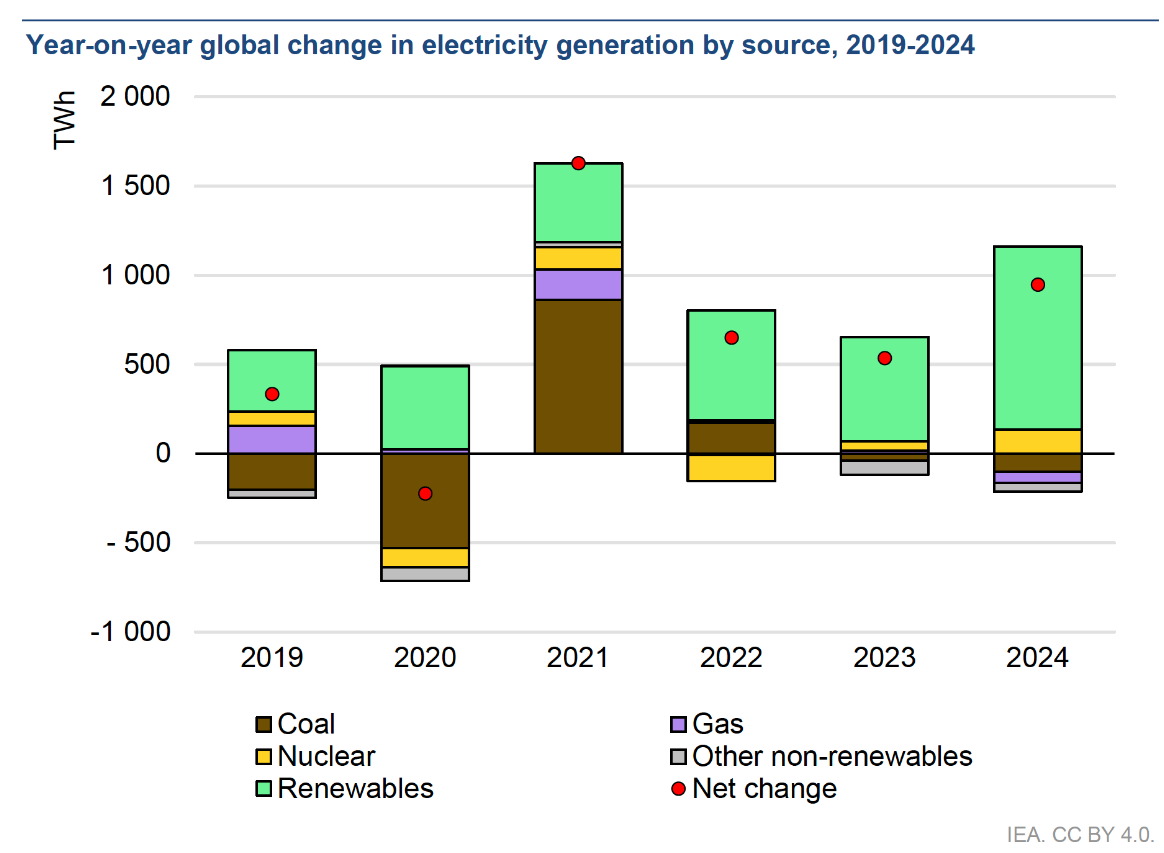




Source: [EMBER, Global Electricity Review, 2022]

We May be at an Inflection Point

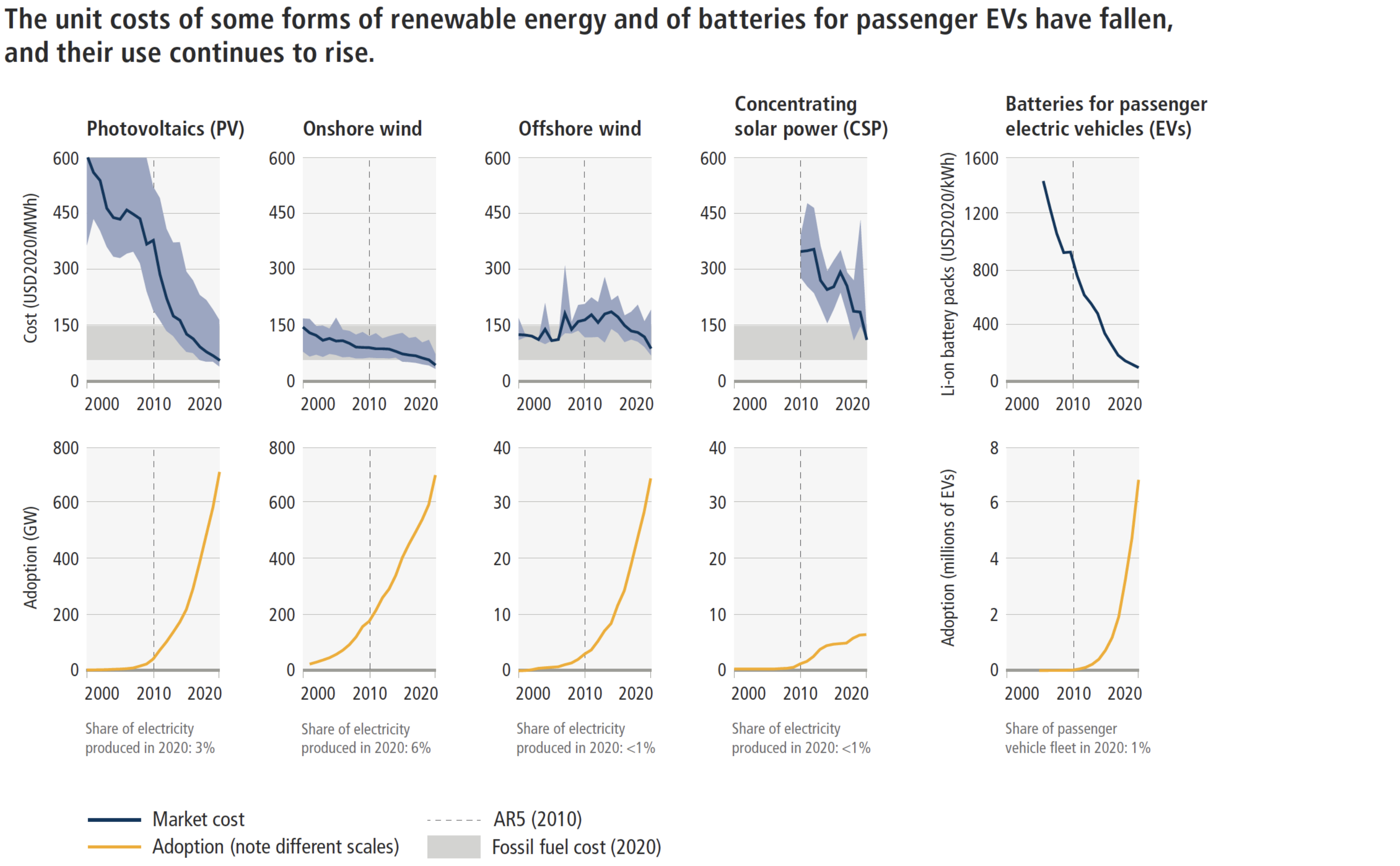




Source: IEA Electricity Market Report, 2023

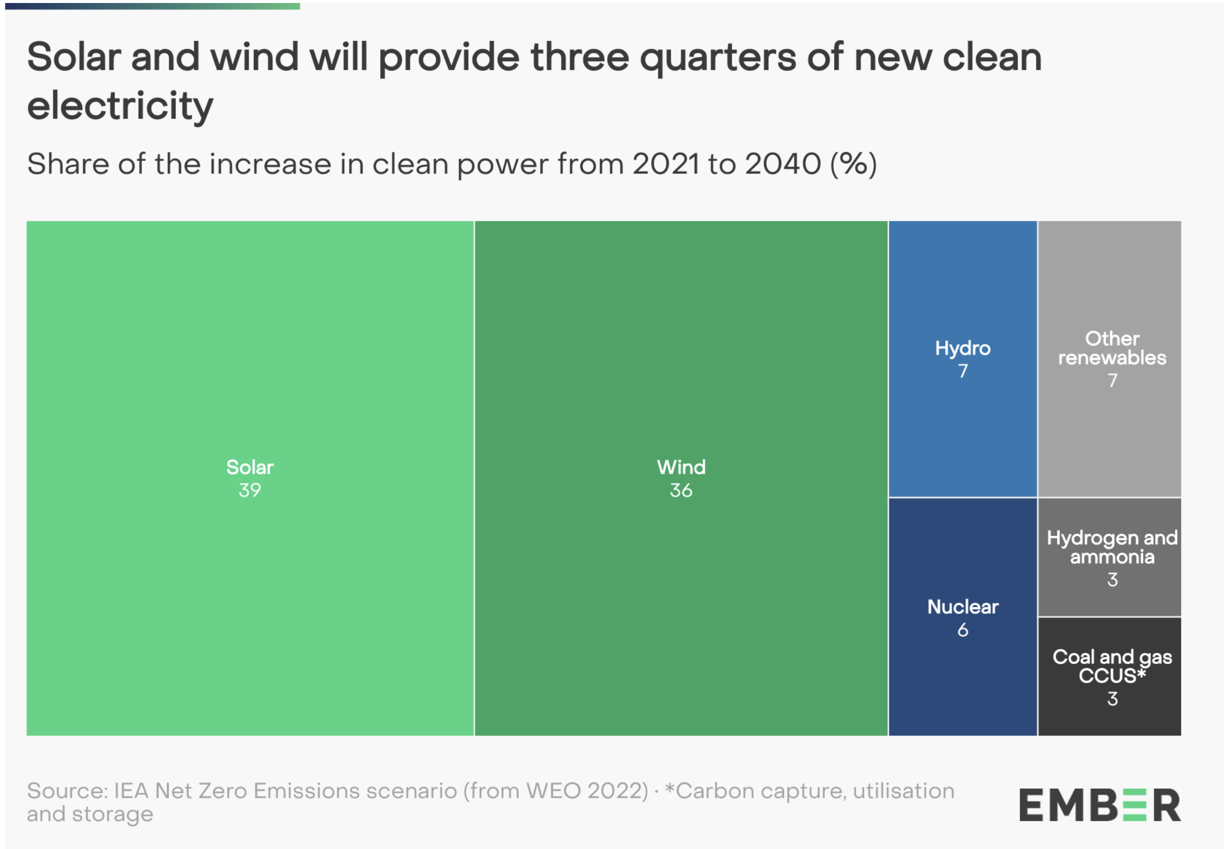
Source: EMBER, Global Electricity Review, 2022

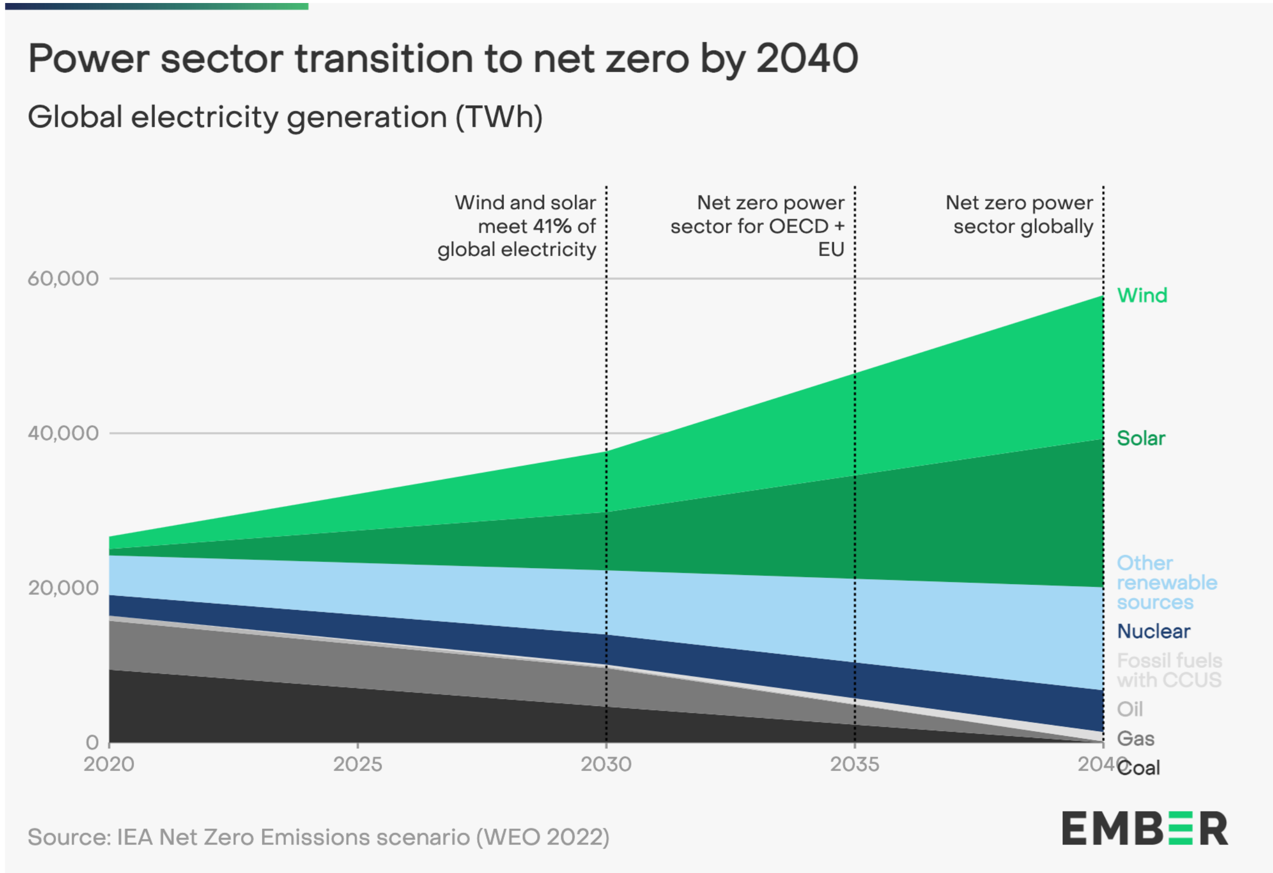
Sources of Hope: Solar, Wind, Storage Costs Decline



Source: IPCC AR6 WGIII

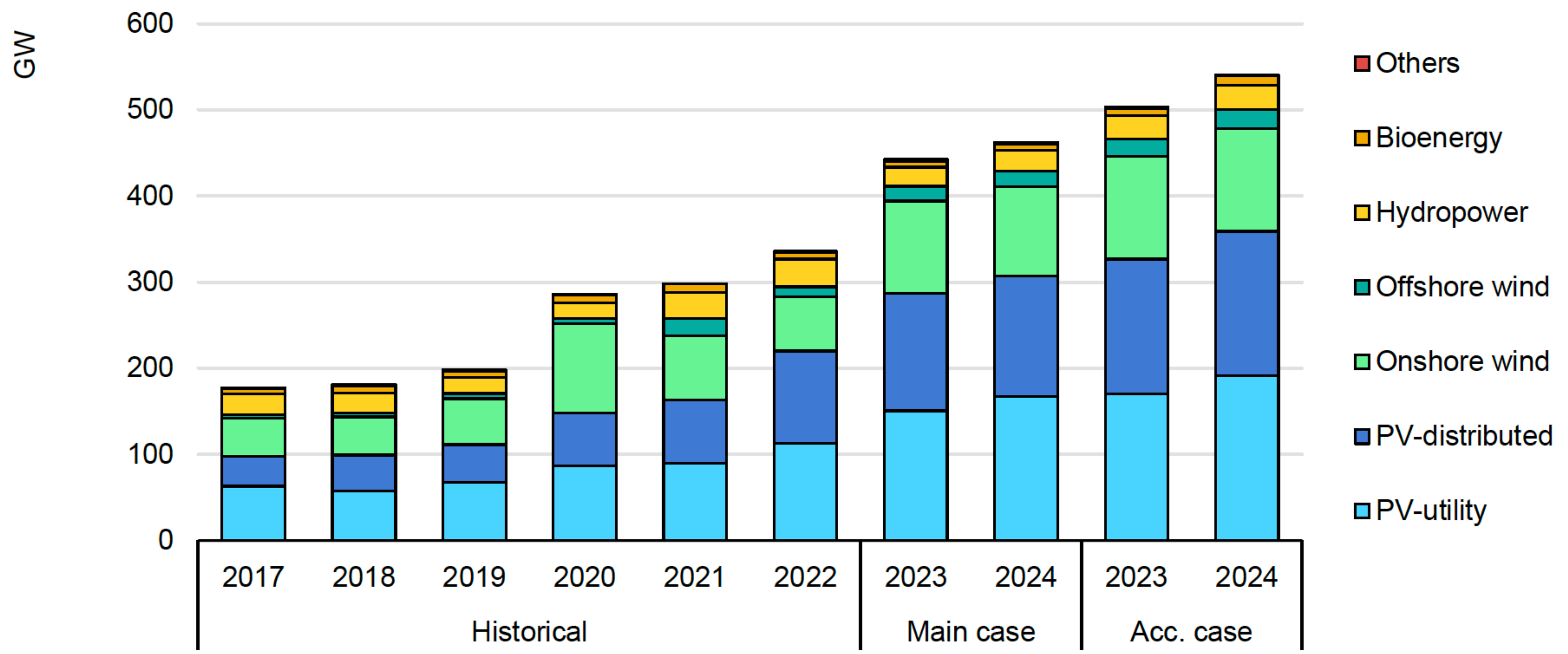
Electricity Generation and IEA Net Zero





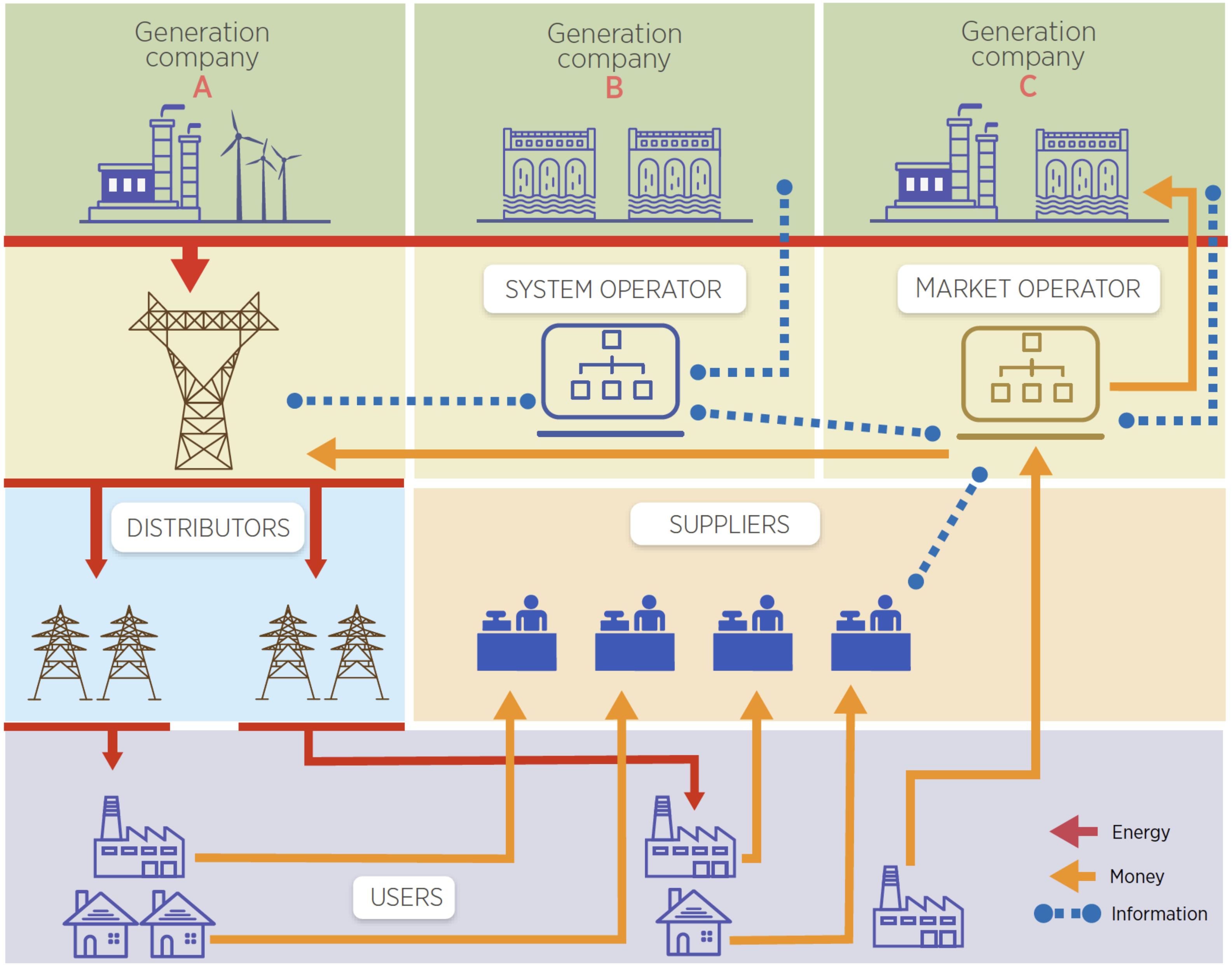
Source: [EMBER, Global Electricity Review, 2022]

Net renewable electricity capacity additions by technology, historical, main and accelerated cases



Source: IEA, Renewable Energy Market Update, Outlook for 2023 and 2024, June 2023

FIGURE 12. Liberalised power system structures – illustrative



Source: IRENA, [RE-organizing power systems for the transition, 2022]

Renewable Curtailment due to Supply-Demand Imblance

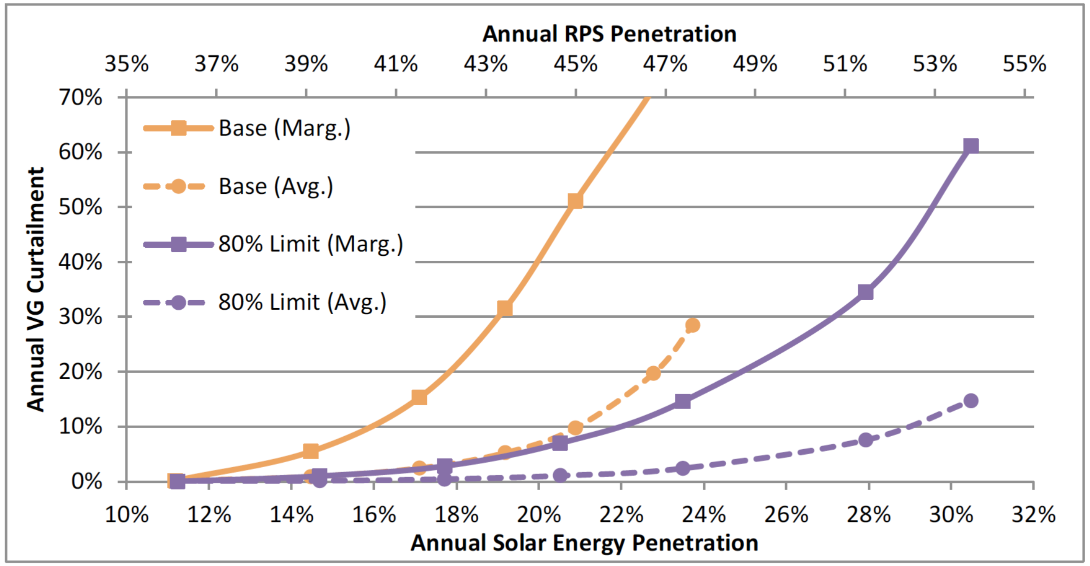
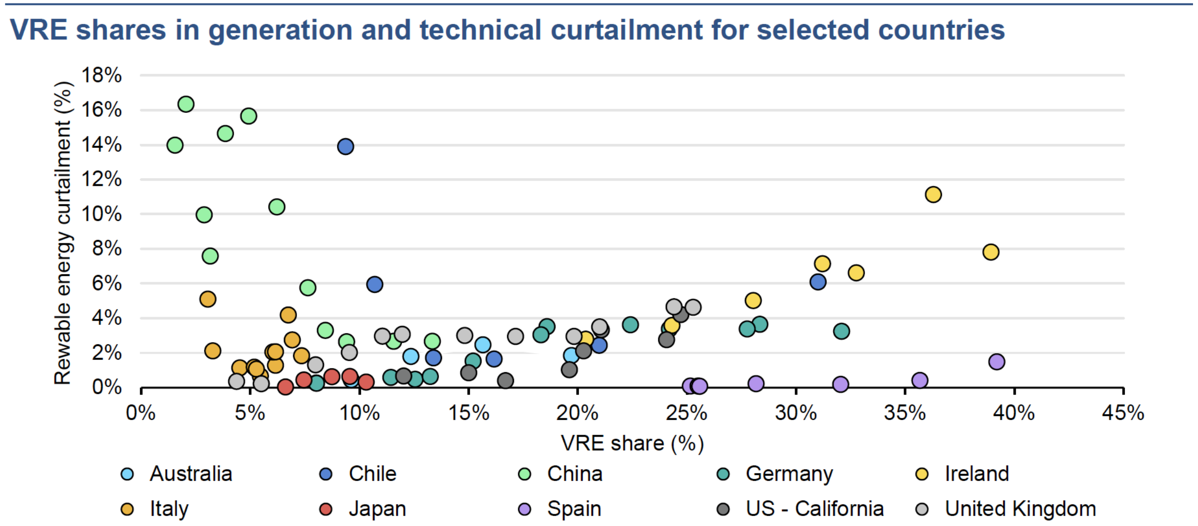
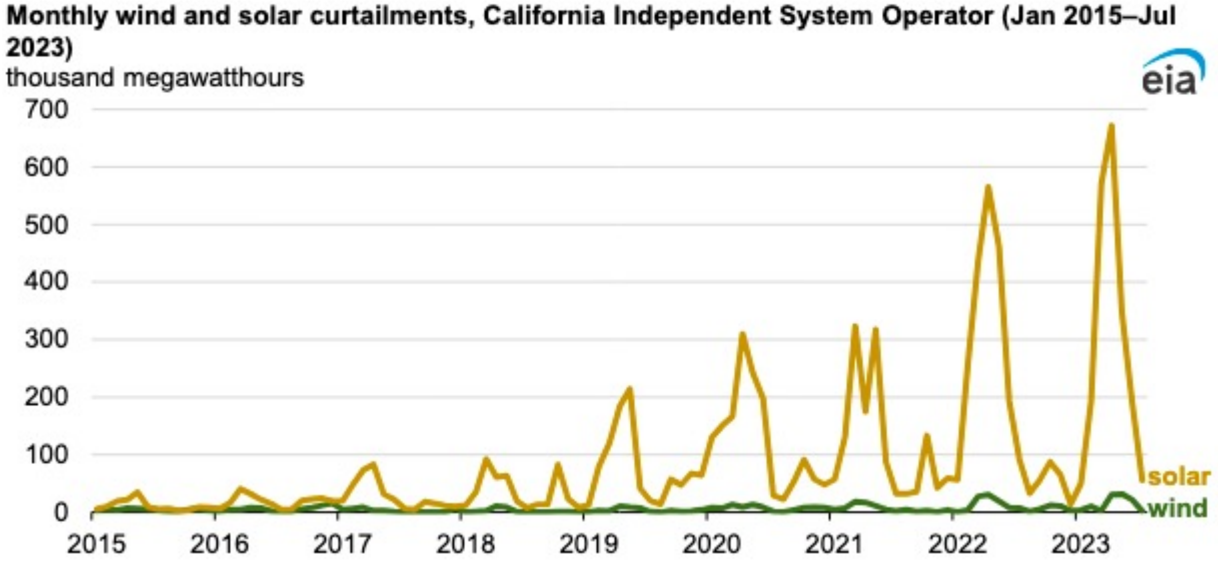


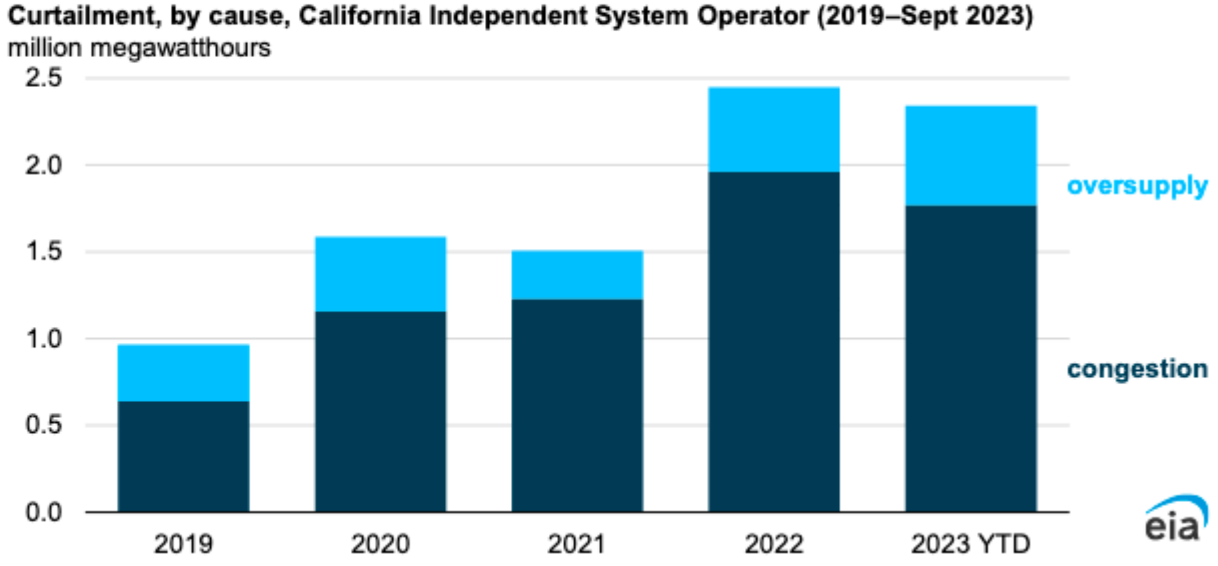
Figure 24. Marginal and average annual curtailment due to overgeneration under increasing penetration of PV in California after adding mandated storage, removing local generation constraint, and increasing maximum instantaneous VG penetration to 80%



Source: Denholm et al, Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart, November 2015

Source: IEA, Renewable Energy Market Update, Outlook for 2023 and 2024, June 2023

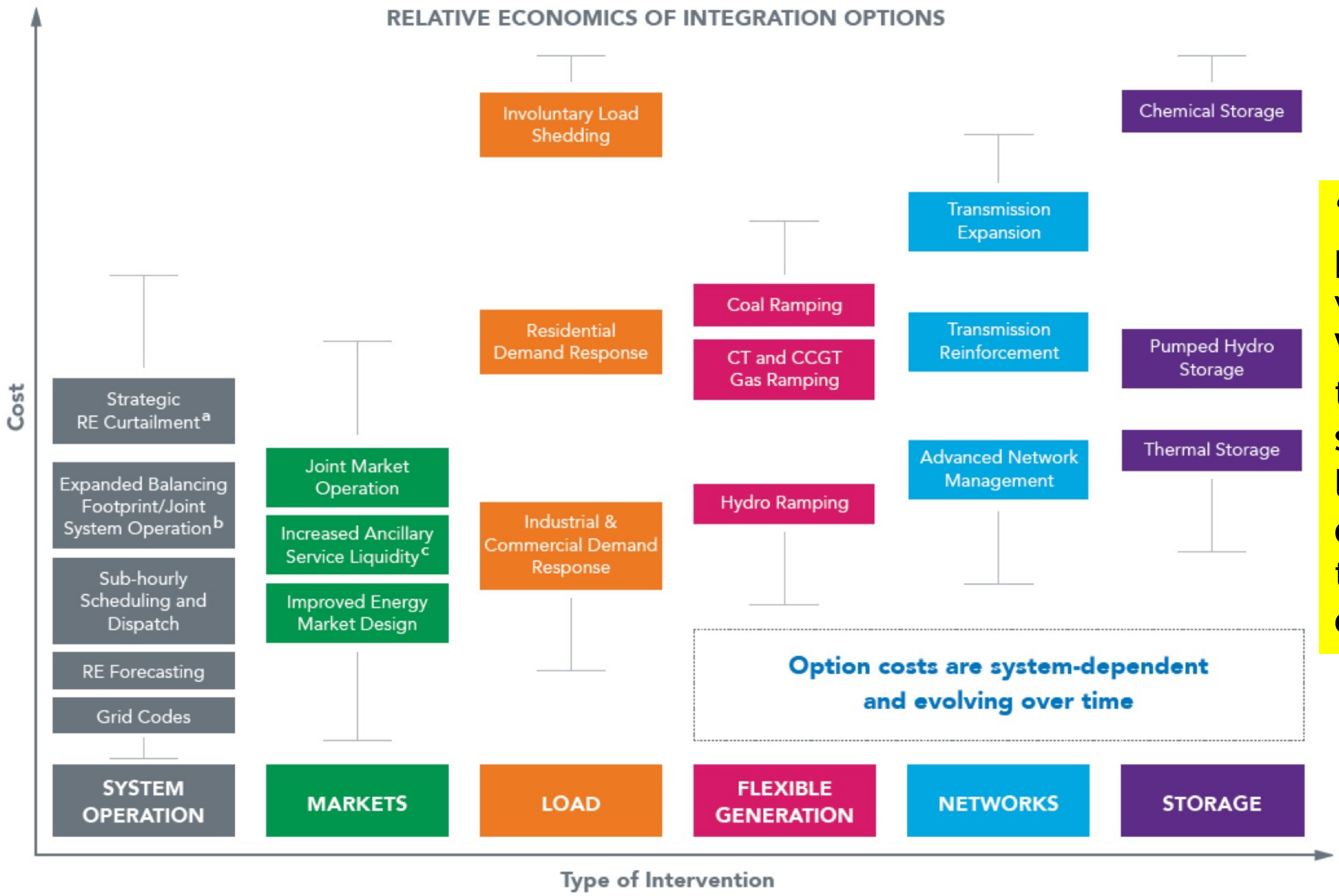




In 2022, California produced 52,927 gigawatt-hours of wind and utility-scale solar power. Curtailment ~5%

Source: [EIA](), 2023

Grid Flexibility is the Key to Renewable Integration



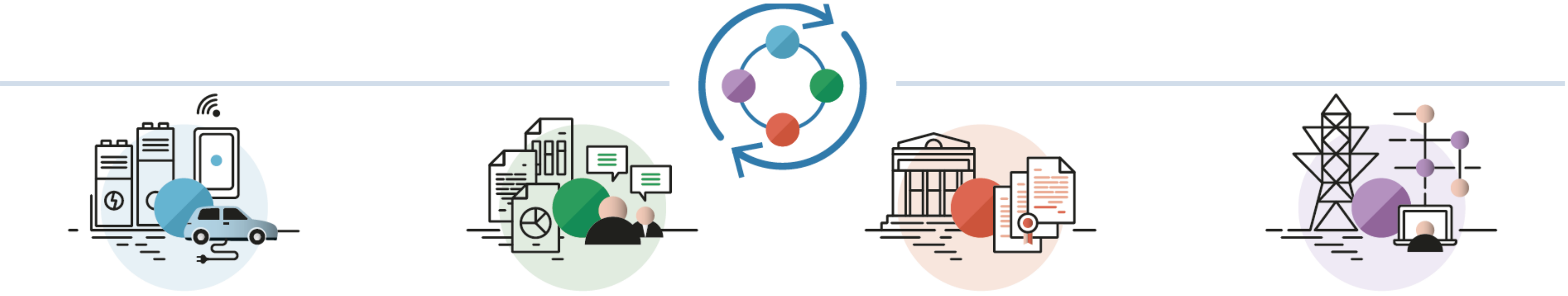
"Flexibility is the capability of a power system to cope with the variability and uncertainty that VRE generation introduces into the system in different time scales, from the very short to the long term, avoiding curtailment of VRE and reliably supplying all the demanded energy to customers".

Source: IRENA, Power System Flexibility for the Energy Transition, 2018

Source: Cochran et al, Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy, NREL, 2015

Research and Innovation for Deep Renewable Integration

Figure 8 The landscape of innovations



ENABLING TECHNOLOGIES

1 Utility-scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

Research opportunities behind each area of innovation

Source: IRENA, Innovation Landscape for Renewable Powered Future, 2019.

Research Opportunities: Enabling Deep Renewable Integration

Learning and control for management of distributed power systems with high penetration of wind and solar

- System operations and control: forecasting, sub-hourly dispatch, larger balancing areas, transmission, distribution, …
- Markets: market designs, flexible ramp products
- Dynamic control and optimization of energy storage for short, medium, and long-term system needs
- Demand side management: demand response, direct load control, harnessing load flexibility
- Distributed energy resources: roof top solar, EVs, microgrids

Our Research Directions

Architecture: Grid with Intelligent Periphery	Renewable Producers and Storage in Electricity Markets	Cost Causation-based Cost Allocation for Renewable Integration
Distributed Control Algorithms Grid Management and Control	Stochastic Optimization for Residential Energy Management and Data Centers	Matching Markets for Distributed Energy Resources
EV Charging Optimization	Deep Reinforcement Learning for Dynamic Matching	Demand Response and Incentives

Broader Considerations

- Multidisciplinary collaborations are essential for success
- Solutions must be cost effective and scalable
- Infrastructures last for decades requiring decision making under deep uncertainty
- Research must connect with innovation and deployment
- It is necessary to go beyond engineering and technology
- Social and economic justice should be central in our thinking
- Students are very interested in working on these issues

Comments

Ideas

Questions?

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