Climate Change Mitigation and Adaptation: Role for Systems and Controls

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Bode Prize Lecture
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Outline

Inaugural Bode Prize Lecture by Gunter Stein

Climate Change

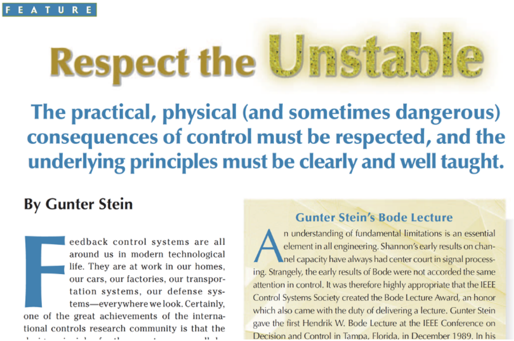
Energy System Perspective

Strategic Directions in Decarbonization

Role for Systems and Control

This document contains (blue) hyperlinks to papers and reports recommended for deeper study. Contact me for additional pointers to the literature.

Inaugural Bode Prize Lecture by Gunter Stein
IEEE Conference on Decision and Control, 1989



FEATURE

Respect the Unstable

The practical, physical (and sometimes dangerous) consequences of control must be respected, and the underlying principles must be clearly and well taught.

By Gunter Stein

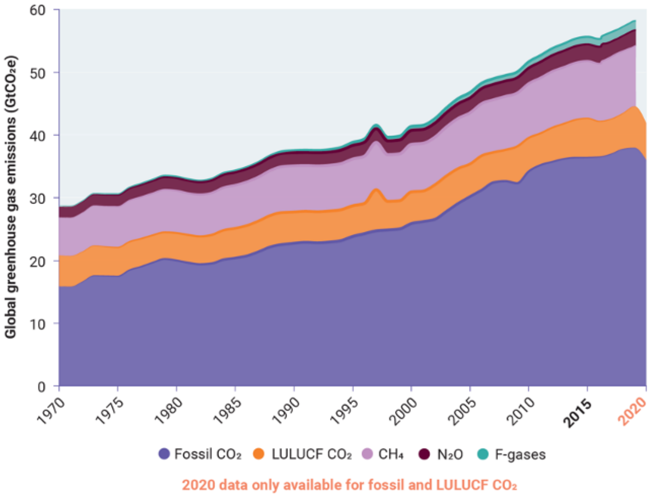
Feedback control systems are all around us in modern technological life. They are at work in our homes, our cars, our factories, our transportation systems, our defense systems—everywhere we look. Certainly, one of the great achievements of the international controls research community is that the

Gunter Stein's Bode Lecture

An understanding of fundamental limitations is an essential element in all engineering. Shannon's early results on channel capacity have always had center court in signal processing. Strangely, the early results of Bode were not accorded the same attention in control. It was therefore highly appropriate that the IEEE Control Systems Society created the Bode Lecture Award, an honor which also came with the duty of delivering a lecture. Gunter Stein gave the first Hendrik W. Bode Lecture at the IEEE Conference on Decision and Control in Tampa, Florida, in December 1989. In his

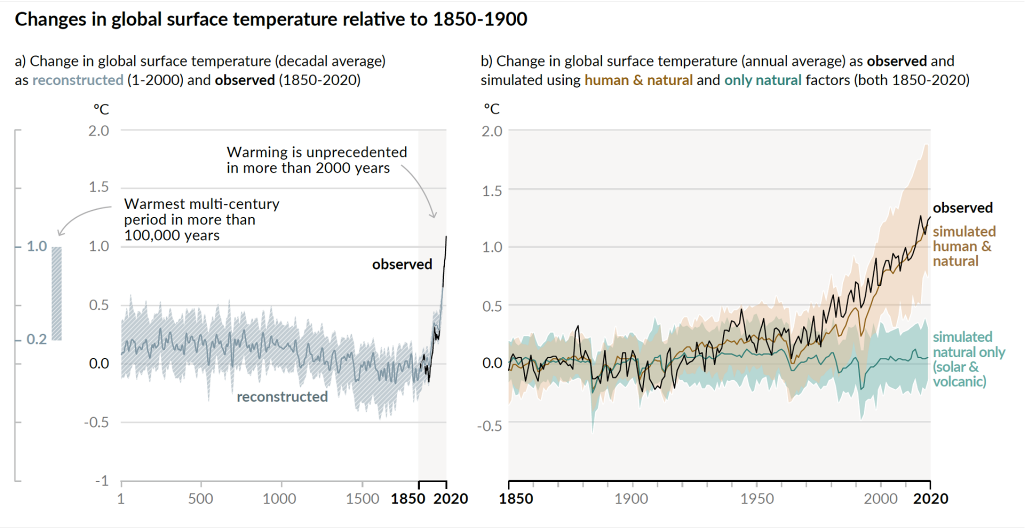
Increases in Global Greenhouse Gas Emissions

Figure ES.1. Global greenhouse gas emissions from all sources, 1970–2020



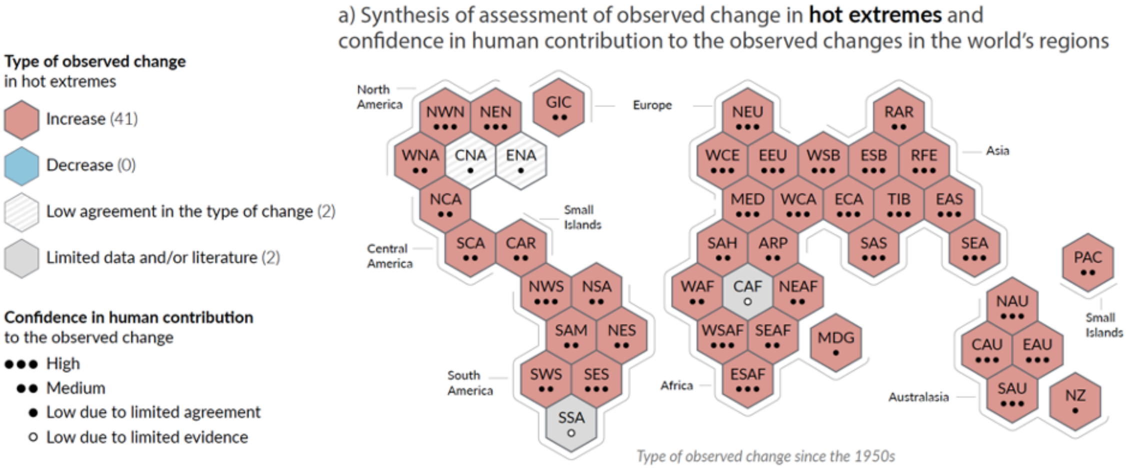
UNEP Emissions Gap Report 2021

Temperature Increase Since the Start of Industrial Age: 1.1°C



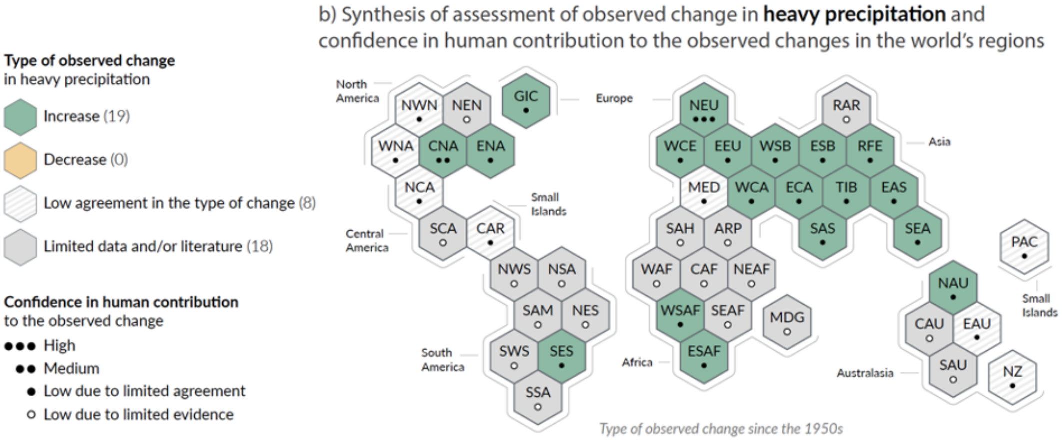
Source: IPCC AR6 WG1 Report, 2021

Hot Extremes Increasing



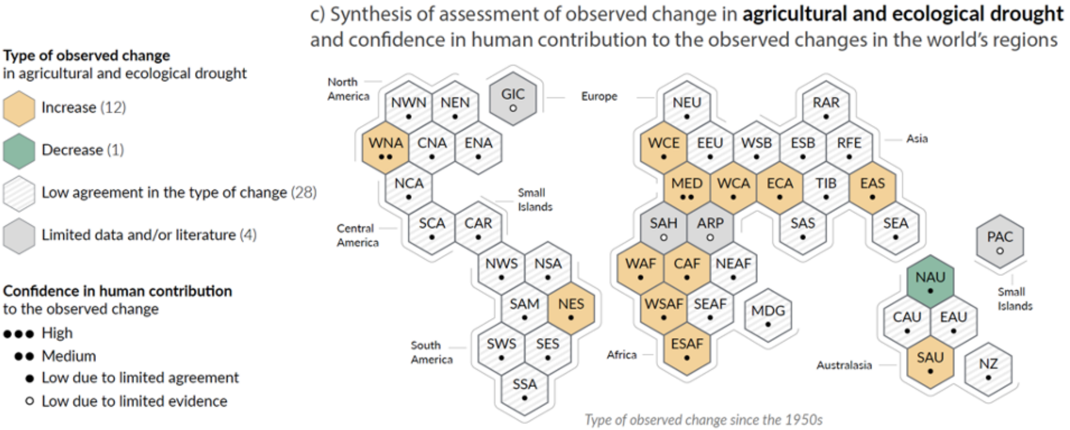
Source: IPCC AR6 WG1 Report, 2021

Heavy Rainfalls and Flooding



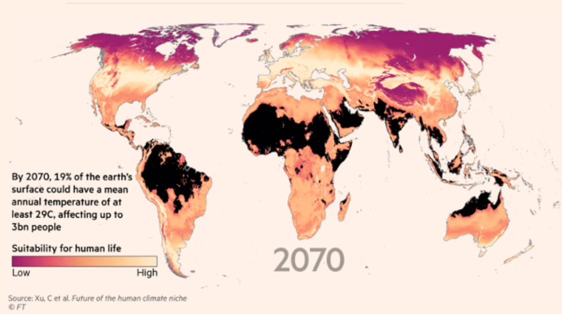
Source: IPCC AR6 WG1 Report, 2021

Agricultural and Ecological Droughts



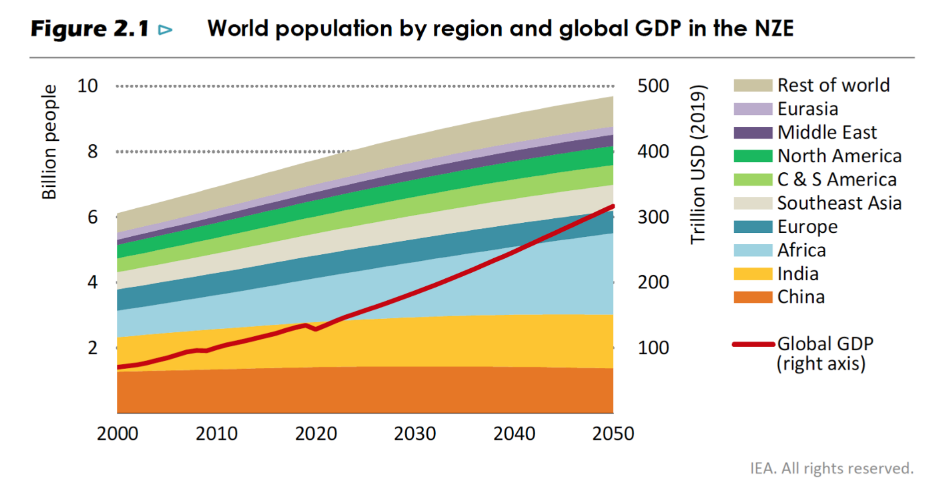
Source: IPCC AR6 WG1 Report, 2021

Climate Change — Additional Impacts



- Sea level rise and impact on coastal populations
- Human and animal health impacts of hot extremes, wildfires, flooding, ...
- Ocean acidification and impacts
- Climate change driven migration
- Jobs, work, economic, and societal disruptions

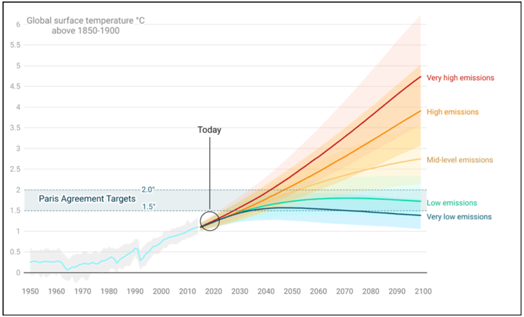
What Lies Ahead? World Population and Economies will Continue to Grow

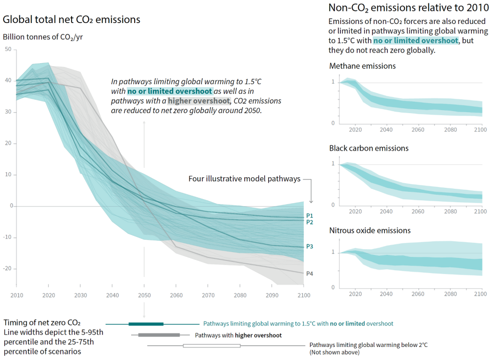


By 2050, the world's population expands to 9.7 billion people and the global economy is more than twice as large as in 2020

Source: IEA Netzero by 2050

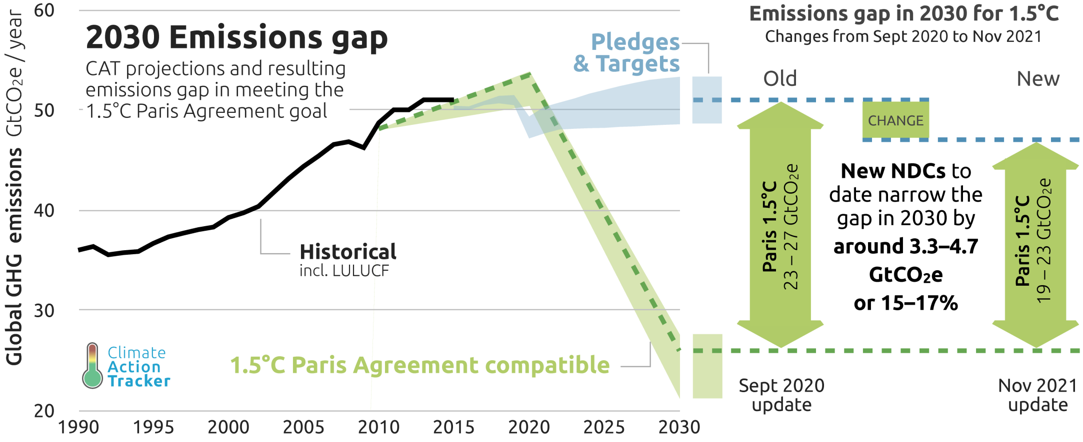
Climate Change Mitigation — Pathways





Sources: IPCC AR6 WG1 Report, 2021, IPCC Global Warming to 1.5°C, 2020

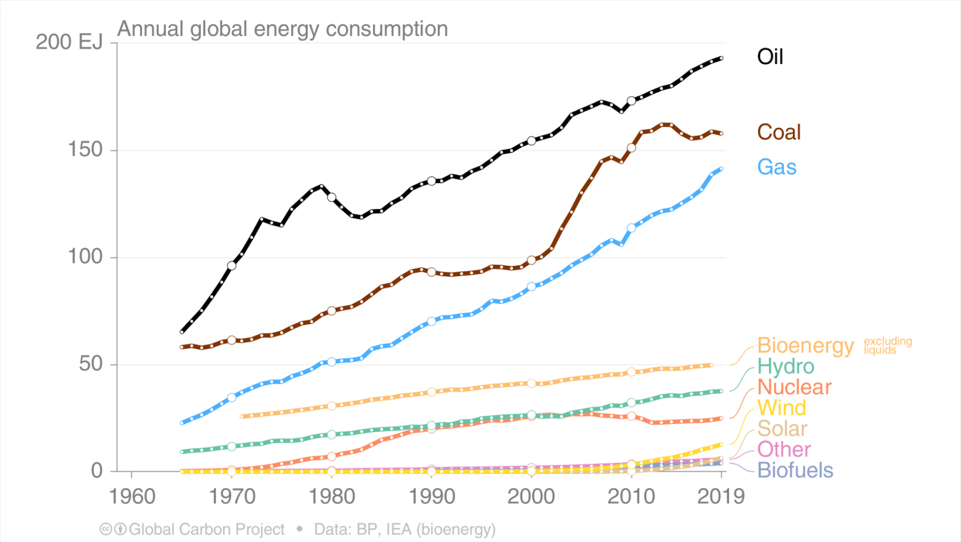
COP: Paris Agreement, Glasgow, and Beyond



Source: Carbon Action Tracker

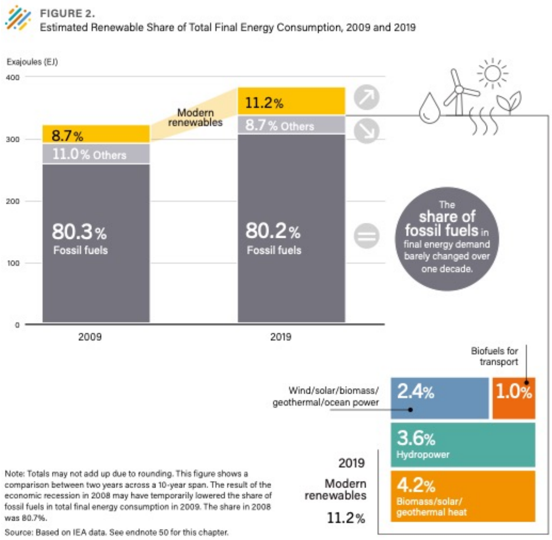
Energy System is Gigantic, Multi-Scale, Distributed, Dynamic, and Interconnected

Global Energy Consumption by Primary Sources



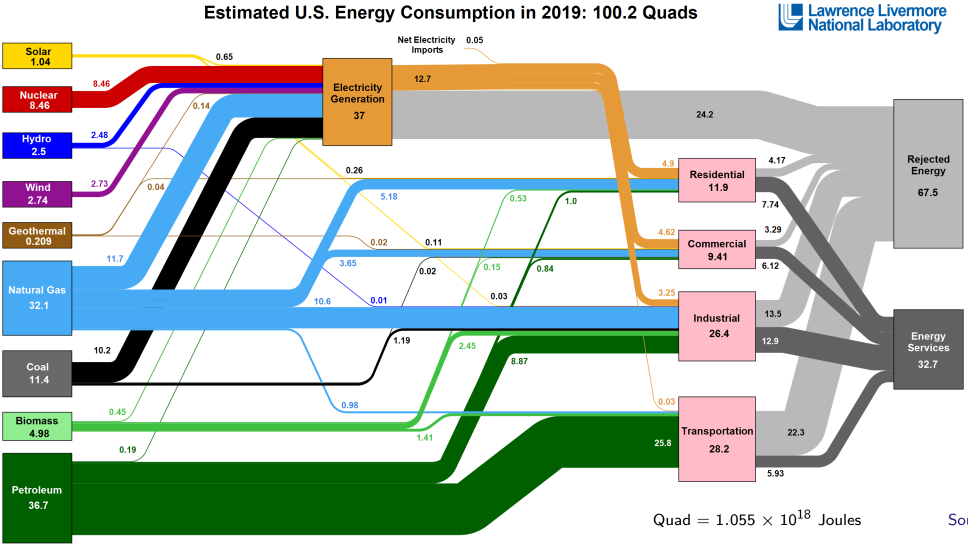
Source: Global Carbon Project

Global Energy Consumption: 2009-2019



Source: REN21, RENEWABLES 2021 GLOBAL STATUS REPORT

US Energy Sankey Diagram



Quad $= 1.055 \times 10^{18}$ Joules

Source: LLNL

Major Energy Transitions are Slow

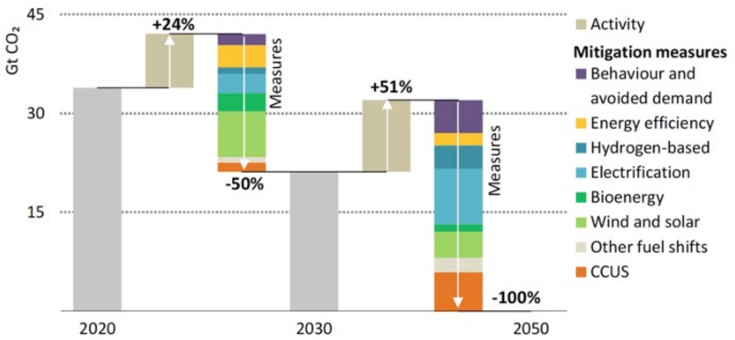
- Coal: 5% to 50% in 60 years starting in 1840
- Oil: 5% to 40% in 60 years starting in 1915
- Natural gas: 5% to 25% in 60 years starting in 1930
- Modern renewables $\approx$ 5%

750M people lack access to electricity
2.6 Billion people rely on biomass/coal/kerosene for cooking
Economic growth and rising living standards will require more energy
Energy is a major factor in achieving UN SDGs

Source: V. Smil

IEA Net Zero Scenario

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

Many analogous plans and scenarios from various organizations . . .

Source: IEA Net Zero by 2050

Major Strategies

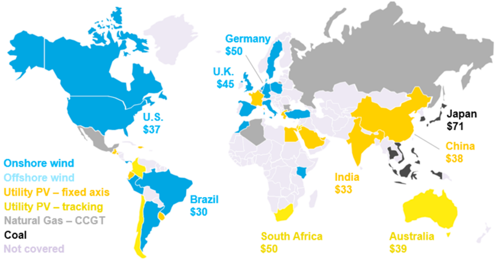
- Ubiquitous energy and material efficiency
- Decarbonize electricity generation: wind, solar, geothermal, nuclear, ...
- Electrification, sustainable fuels, hydrogen, ... in:
  1. Transportation
  2. Building heating and cooling
  3. Industry and manufacturing
- Negative emissions technologies: carbon capture, utilization, and storage; nature based solutions

Key Trends: Signs of Hope and Big Challenges

Toward a Net Zero Carbon Future

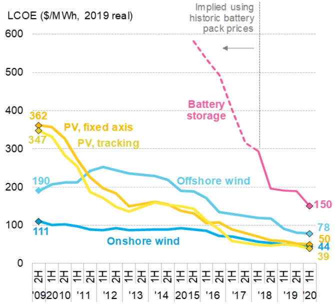
PV and Wind have been Getting Cheaper by the Year and are Now the Top Choice in Most of the World

Figure 1: Cheapest source of new bulk electricity generation by country, 1H 2020



Source: BloombergNEF. Note: LCOE calculations exclude subsidies or tax-credits. Graph shows benchmark LCOE for each country in $ per megawatt-hour. CCGT: Combined-cycle gas turbine.

Figure 2: Global LCOE benchmarks – PV, wind and batteries



Source: BloombergNEF. Note: The global benchmark is a country weighted-average using the latest annual capacity additions. The storage LCOE is reflective of utility-scale projects with four-hour duration, it includes charging costs.

Technological innovation and "learning by doing"

Source: Bloomberg

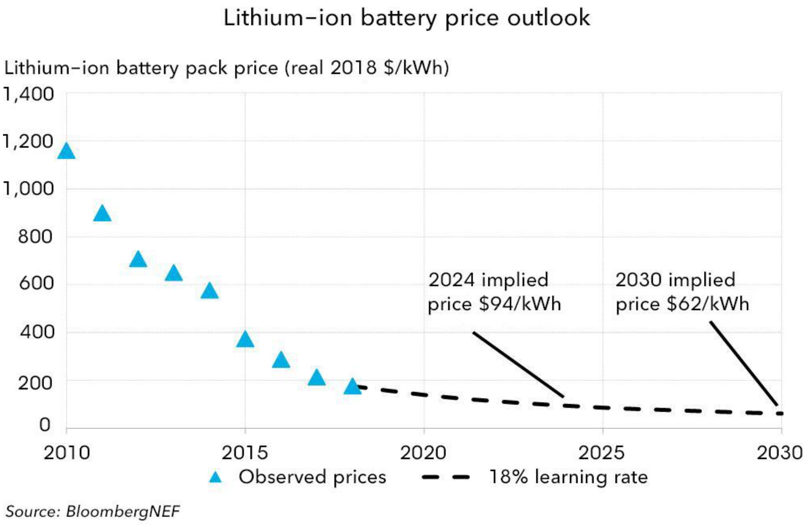
PV and Wind are Now Competitive with Natural Gas in the US

Table A2. Regional variation in levelized cost of electricity (LCOE) for new generation resources entering service in 2022 (2019 dollars per megawatthour)

	Range for total system levelized costs				Range for total system levelized costs with tax credits[1]			
Plant type	**Minimum**	**Simple average**	**Capacity-weighted average[2]**	**Maximum**	**Minimum**	**Simple average**	**Capacity-weighted average[2]**	**Maximum**
Dispatchable technologies								
Combined cycle	31.25	36.27	33.53	45.06	31.25	36.27	33.53	45.06
Combustion turbine	55.23	62.81	64.19	73.61	55.23	62.81	64.19	73.61
Non-dispatchable technologies								
Wind, onshore	28.25	38.33	36.65	64.03	19.31	29.40	27.71	55.09
Solar photovoltaic (PV)[3]	32.13	38.57	37.44	51.97	24.84	29.82	28.88	39.95

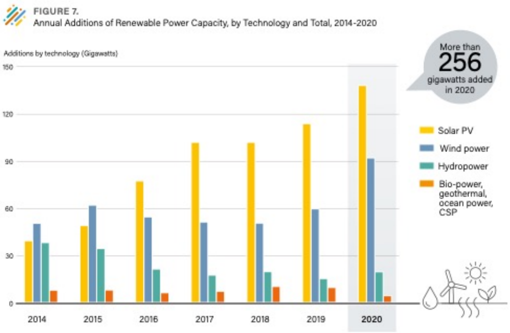
Source: EIA, 2020

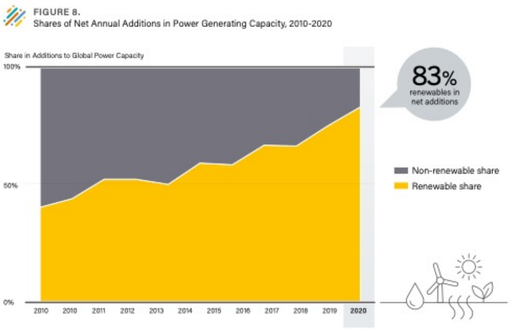
Battery Storage is Getting Cheaper



Source: Bloomberg New Energy Finance

Power Generating Capacity Additions



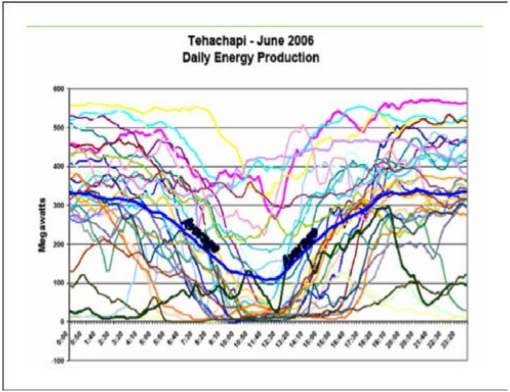


Key Engineering Challenge: Ensure Demand(t) = Supply(t)
Design, operation and control of the electric grid in the face of inherent variability and uncertainty of wind and solar generation

Source: Global Status Report 2021, REN21

PV and Wind Are Random and Variable in All Time Scales

- Wind and PV power output depend on wind speed and solar irradiance
- Power output varies at all time scales: annual, seasonal, monthly, daily, hourly, sub-hourly
- Accurate forecasts can help but inherent variability is still a challenge
- These variations pose the biggest challenge to deep integration of renewable electricity



Projected Solar Curtailment

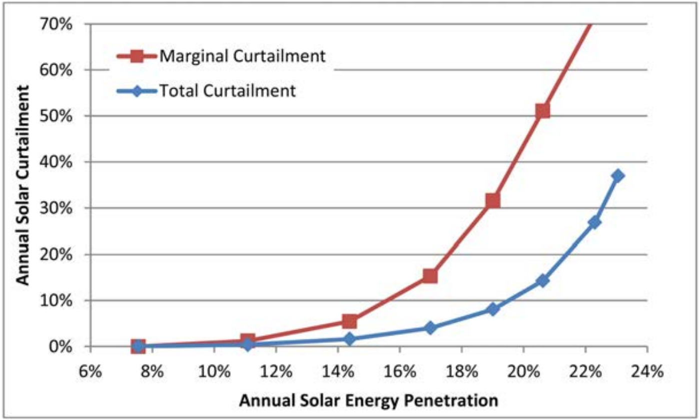


Figure 6. Annual marginal and total solar curtailment due to overgeneration under increasing penetration of PV in California in a system with limited grid flexibility

Source: Denholm et al, NREL, 2016

Enabling Deep Renewable Integration — Grid Flexibility

- Storage: pumped hydro, compressed air, battery, thermal, hydrogen, ...
- System operations: forecasting, scheduling and dispatching algorithms
- Markets: market design for renewable integration and storage
- Transmission: expansion, network management
- Load management: flexible loads, demand response, direct load control
- Flexible generation: CCGT, Hydro
- Distributed energy resources: roof-top solar, storage, EVs, microgrids, ...

Transport Sector Decarbonization

Table 3.4 ▷ Key milestones in transforming the global transport sector

Category	
Road transport	• 2035: no new passenger internal combustion engine car sales globally
Aviation and shipping	• Implementation of strict carbon emissions intensity reduction targets as soon as possible.

Category		2020	2030	2050
Road transport				
Share of PHEV, BEV and FCEV in sales:	cars	5%	64%	100%
	two/three-wheelers	40%	85%	100%
	bus	3%	60%	100%
	vans	0%	72%	100%
	heavy trucks	0%	30%	99%
Biofuel blending in oil products		5%	13%	41%
Rail				
Share of electricity and hydrogen in total energy consumption		43%	65%	96%
Activity increase due to modal shift (index 2020=100)		100	100	130
Aviation				
Synthetic hydrogen-based fuels share in total aviation energy consumption		0%	2%	33%
Biofuels share in total aviation energy consumption		0%	16%	45%
Avoided demand from behaviour measures (index 2020=100)		0	20	38
Shipping				
Share in total shipping energy consumption:	Ammonia	0%	8%	46%
	Hydrogen	0%	2%	17%
	Bioenergy	0%	7%	21%
Infrastructure				
EV public charging (million units)		1.3	40	200
Hydrogen refuelling units		540	18 000	90 000
Share of electrified rail lines		34%	47%	65%

Note: PHEV = plug-in hybrid electric vehicles; BEV = battery electric vehicles; FCEV = fuel cell electric vehicles.

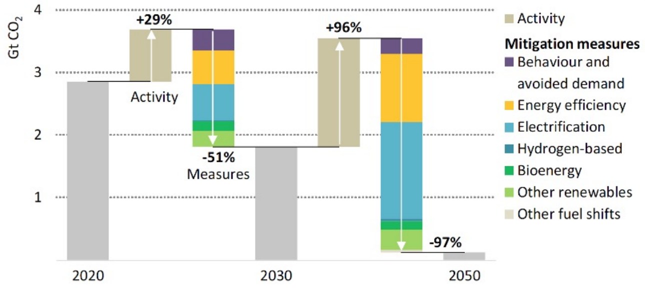
Source: IEA Net Zero by 2050

Key Challenges: Transport Sector

- Energy efficiency in ground, air, and water transportation
- Electrification of transportation couples these two big systems
- Sustainable fuels:
  - Synthetic hydrogen based fuels
  - Biofuels
- Necessary to account for the embodied energy, complete lifecycle and supply chains

Buildings: Efficiency and/or Electrification

Figure 3.27 ▷ **Global direct CO_2 emissions reductions by mitigation measure in buildings in the NZE**



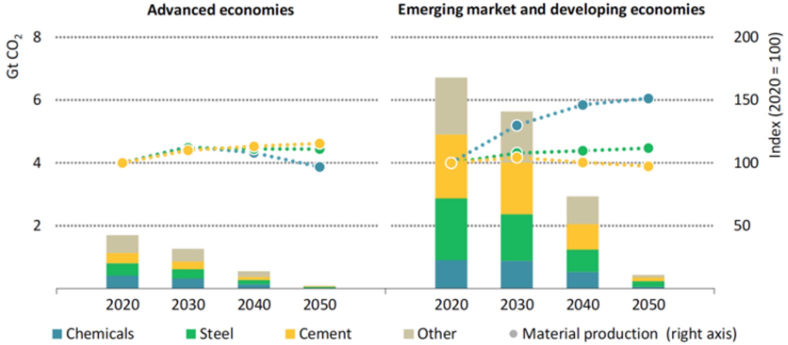
Electrification and energy efficiency account for nearly 70% of buildings-related emissions reductions through to 2050, followed by solar thermal, bioenergy and behaviour

- Major opportunity: Building energy efficiency through modeling, sensing and controls.
- Building Electrification: Heat pumps

Source: IEA Net Zero by 2050

Industry Related Emissions

Figure 3.15 ▷ Global CO_2 emissions from industry by sub-sector in the NZE



The majority of residual emissions in industry in 2050 come from heavy industries in emerging market and developing economies

Note: Other includes the production of aluminium, paper, other non-metallic minerals and other non-ferrous metals, and a series of light industries.

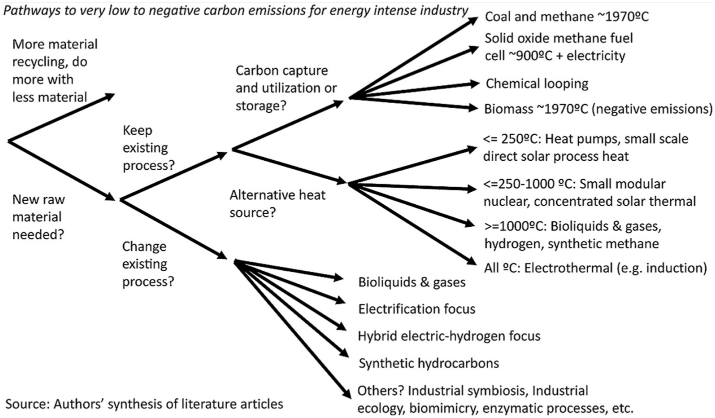
Source: IEA Net Zero by 2050

Approaches to Decarbonization in the Industry Sector

- Energy efficiency
- Material efficiency in production and recycling
- Material efficiency in products
- Fuel switching: use of renewables
- Process improvements and innovation
- Carbon capture and sequestration

It is a very hard problem.

Conceptual View for Decarbonization in Industry



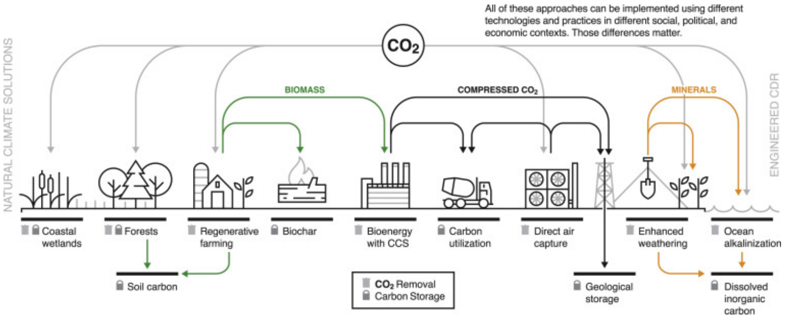
Source: Battaille et al. (2018)

Example: Hydrogen for low carbon steel manufacturing.

Opportunity: process design, modeling, sensing and controls to enable new industrial processes.

Negative Emissions Technologies

- All climate change mitigation scenarios depend on carbon capture, utilization and storage technologies.
- Opportunity: Process modeling, optimization and control for CCUS.



Source: Morrow et al, 2020

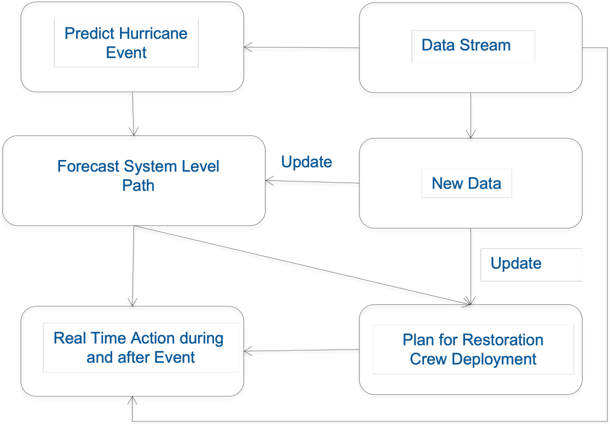
Climate Change Adaptation

- Adaptation and resilience are increasingly necessary.
- They can potentially be synergistic with mitigation, e.g., microgrids.
- Infrastructure resilience against large extreme events, e. g., storms, hurricanes, wildfires, . . .
  - Electric power grids
  - Transportation networks
  - Communication networks

Resilient Interdependent Infrastructures

- Resilience goal: Minimize loss of infrastructure services during the event and time to recovery after the event
- Key infrastructures have interdependencies: electric, transport, water, communications, ...
- Electric grids:
  - Preemptive de-energization
  - Deployment of distributed energy resources, e. g., rooftop solar, batteries, ...
  - Microgrids
  - Resilience through data integration, forecasting, feedforward decision-making, ...

Example: Data and Decisions for Resilience in Electric Grids



Khargonekar, Real-Time Decisions and Control For Power Grid Resilience: Leveraging Data and Analytics, Portland, 2018

Climate Change Mitigation and Adaptation:

Pervasive Opportunities for Systems and Controls

Our Research Directions

- Renewable producers and storage in electricity markets and operations
- Strip packing for peak load minimization
- Causation based cost allocation principles and algorithms
- Distributed control for integration of renewable sources
- Matching markets for distributed energy resources
- Stochastic optimization for residential energy management
- Cybersecurity and smart grid

Papers and presentations here.

It's Systems Everywhere!

- Systems are ubiquitous in climate change mitigation and adaptation technologies and challenges
- Multi-scale and mixed hierarchies: spatial, temporal, organizational, regulatory, ...
- Ubiquitous needs for
    1. Systems oriented problem conceptualization and formulation
    2. Information, physical, and organizational architectures
    3. Modeling and simulation
    4. Sensing, monitoring, estimation, prediction, ...
    5. Control (co-)design
    6. Decision and control algorithms: distributed, stochastic, nonlinear, robust, game-theoretic, learning, ...
- Emerging field: Decision making under deep uncertainty

Systems and Control in a Transdisciplinary Context

- Transdisciplinary collaboration absolutely essential for energy and climate problems.
- Domain experts from engineering, physical sciences, computing, social and behavioral sciences, humanities need to come together with end-users and communities to conceptualize, formulate and solve these problems.
- Systems and control experts could/should become members of such interdisciplinary teams.
- Emerging convergence research paradigm

Engineering Research to Technological Transitions

- Energy system solutions must scale in the real-world, else they won't make a difference.
- It is possible: PV Solar, wind, storage are inspirational success stories!
- Research needs be connected to real-world innovation at a relatively rapid time-scale.
- Technological innovations have a combinatorial character.
- Evolutionary reconfiguration in systems change and technological transitions.
- Deepening understanding of research and technological innovation systems.

Beyond Science and Engineering Research

- It is not an engineering and science problem alone — it is about the humans, communities, and societies.
- Be mindful of social justice, generational equity, and global nature of the problems.
- Students are very interested in addressing these problems.
- Critical role for educators.
- New narratives for the future of human civilization.

IEEE CSS Control for Societal Challenges Roadmap 2030

- Visioning activity co-led by A. Annaswamy, G. Pappas, and K. Johansson
- Theme 5: Control for Climate Change Mitigation and Adaptation
- Co-leaders: P. P. Khargonekar and T. Samad
- Group Members:
  - A. Chakrabortty
  - F. Dabbene
  - M. Fujita
  - M. Garcia-Sanz
  - D. Gayme
  - G. Hug
  - M. Ilic
  - I. Mareels
  - K. Moore
  - L. Pao
  - A. Rajhans
  - J. Stoustrup
- You are invited to join us.

Thank you!

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https://faculty.sites.uci.edu/khargonekar/