

Climate Change Mitigation and Adaptation: Role for Systems and Controls

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Outline

Climate Change

Energy System Perspective

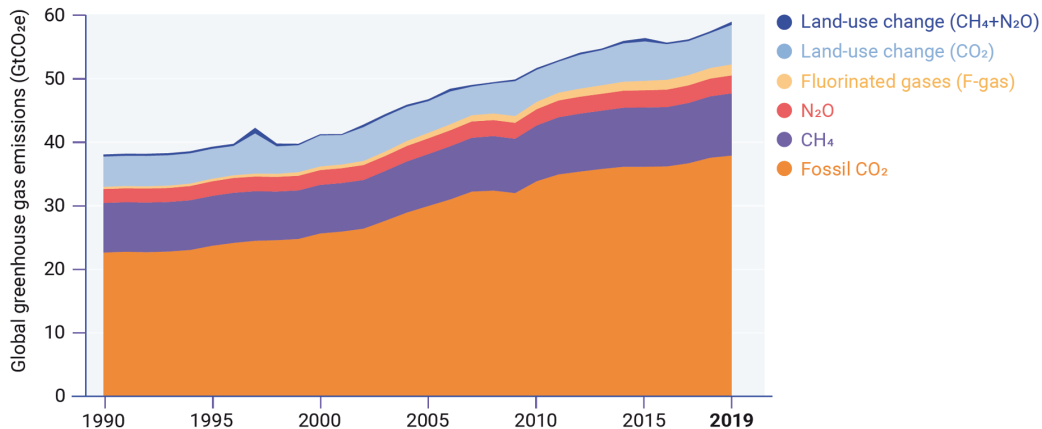
Strategic Directions in Decarbonization

Role for Systems and Control

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

Increases in Global Greenhouse Gas Emissions

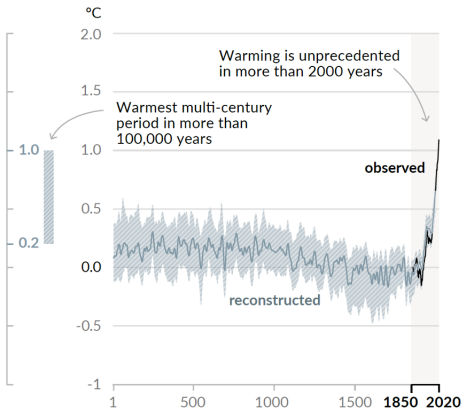
Figure ES.1. Global GHG emissions from all sources



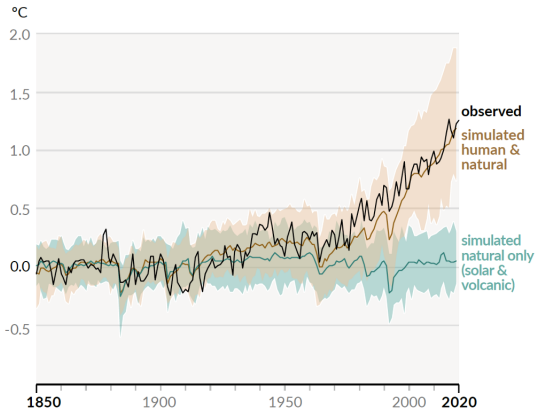
Temperature Increase Since the Start of Industrial Age: 1.1°C

Changes in global surface temperature relative to 1850-1900

a) Change in global surface temperature (decadal average) as **reconstructed** (1-2000) and **observed** (1850-2020)



b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850-2020)



Hot Extremes Increasing

Type of observed change
in hot extremes

● Increase (41)

● Decrease (0)

▨ Low agreement in the type of change (2)

■ Limited data and/or literature (2)

Confidence in human contribution
to the observed change

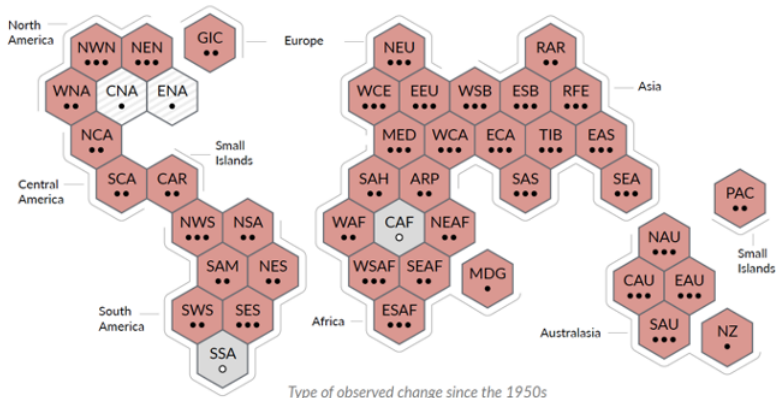
●●● High

●● Medium

● Low due to limited agreement

○ Low due to limited evidence

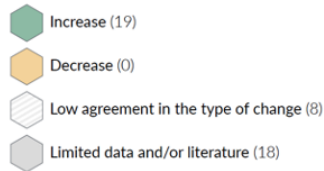
a) Synthesis of assessment of observed change in **hot extremes** and confidence in human contribution to the observed changes in the world's regions



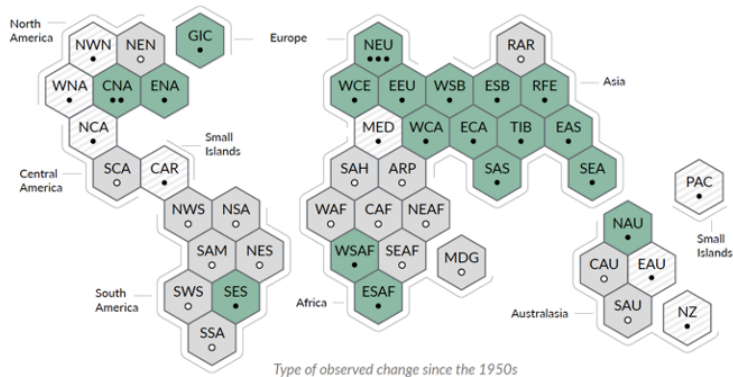
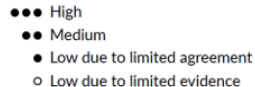
Heavy Rainfalls and Flooding

b) Synthesis of assessment of observed change in **heavy precipitation** and confidence in human contribution to the observed changes in the world's regions

Type of observed change
in heavy precipitation



Confidence in human contribution
to the observed change



Agricultural and Ecological Droughts

c) Synthesis of assessment of observed change in **agricultural and ecological drought** and confidence in human contribution to the observed changes in the world's regions

Type of observed change
in agricultural and ecological drought

● Increase (12)

● Decrease (1)

▨ Low agreement in the type of change (28)

○ Limited data and/or literature (4)

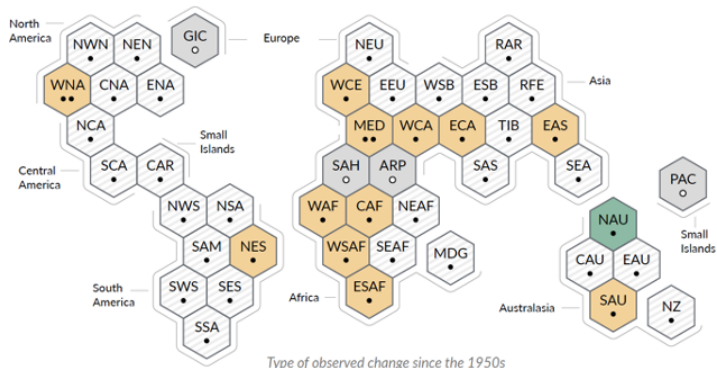
Confidence in human contribution
to the observed change

●●● High

●● Medium

● Low due to limited agreement

○ Low due to limited evidence

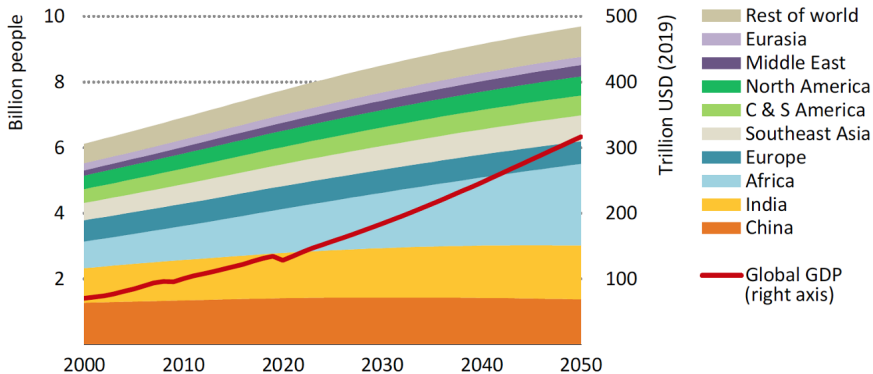


Climate Change — Impacts

- ▶ Sea level rise and impact on coastal populations
- ▶ Climate change driven migration
- ▶ Human and animal health impacts of hot extremes, wildfires, flooding, . . .
- ▶ Food-water-energy-agriculture
- ▶ Ocean acidification and impacts
- ▶ Jobs, work, economy

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

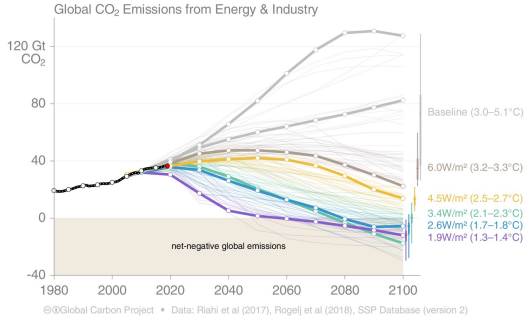
Figure 2.1 ▶ World population by region and global GDP in the NZE



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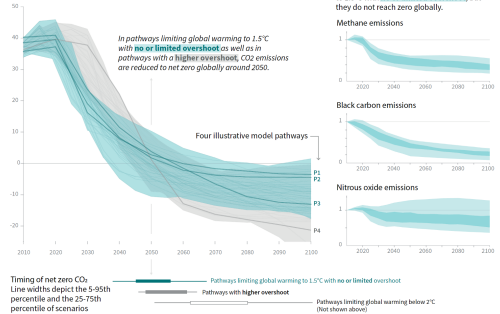
*By 2050, the world's population expands to 9.7 billion people
and the global economy is more than twice as large as in 2020*

Climate Change Mitigation — Pathways



Global total net CO₂ emissions

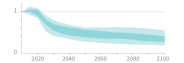
Billion tonnes of CO₂/yr



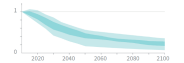
Non-CO₂ emissions relative to 2010

Emissions of non-CO₂ forcers are also reduced or limited in pathways limiting global warming to 1.5°C with **no or limited overshoot**, but they do not reach zero globally.

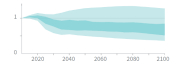
Methane emissions



Black carbon emissions



Nitrous oxide emissions

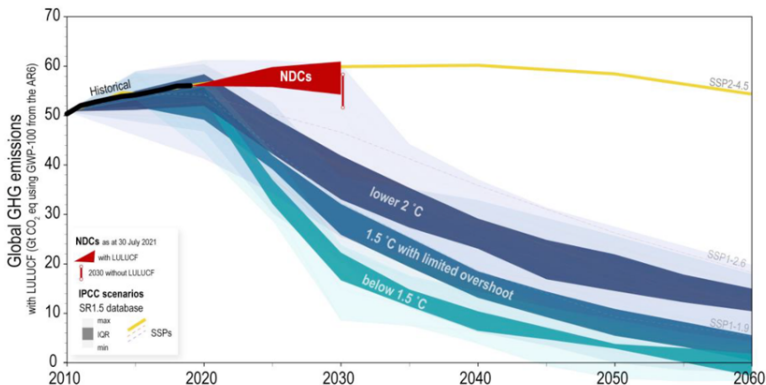


Sources: Global Carbon Project, IPCC Global Warming to 1.5°C, 2020

Climate Change Mitigation: Paris Agreement and COP26

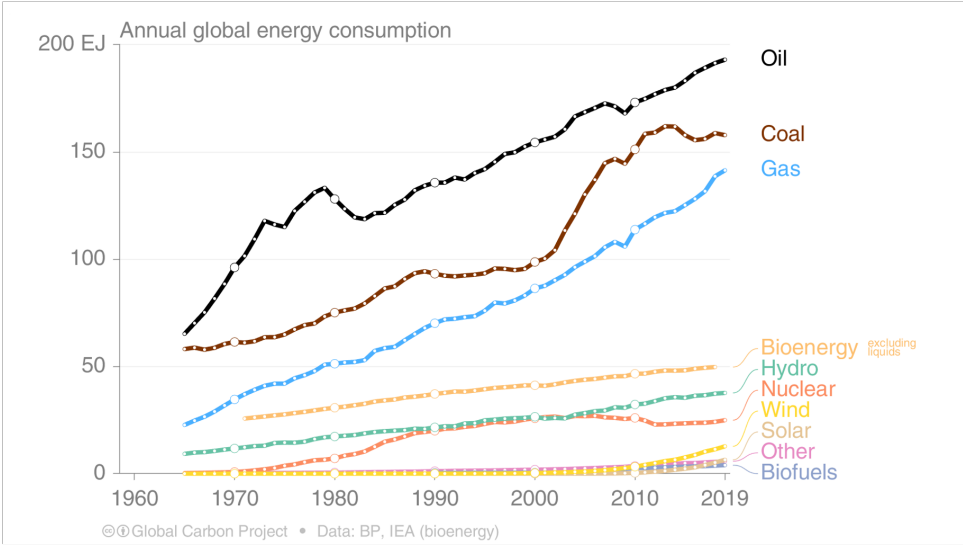
Figure 9

Comparison of global emissions under scenarios assessed in the Intergovernmental Panel on Climate Change Special Report on Global Warming of 1.5 °C with total global emissions according to nationally determined contributions



Energy System is Huge, Multi-Scale, Distributed, and
Interconnected

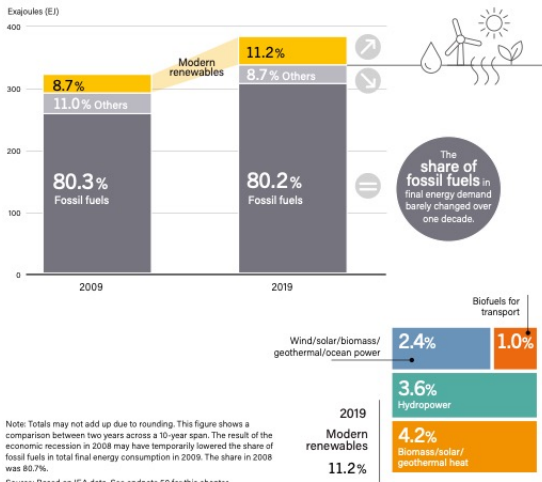
Global Energy Consumption by Primary Sources



Global Energy Consumption: 2009-2019

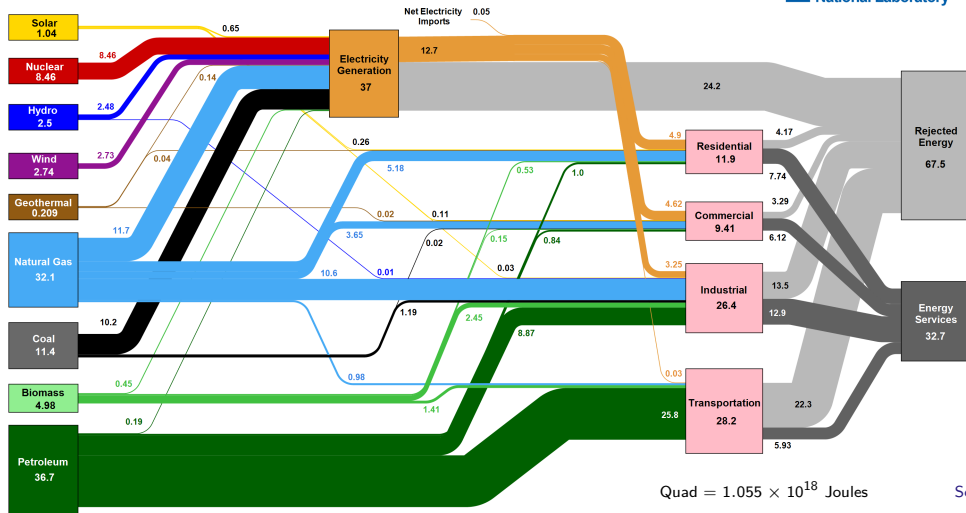


FIGURE 2.
Estimated Renewable Share of Total Final Energy Consumption, 2009 and 2019



US Energy Sankey Diagram

Estimated U.S. Energy Consumption in 2019: 100.2 Quads



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%

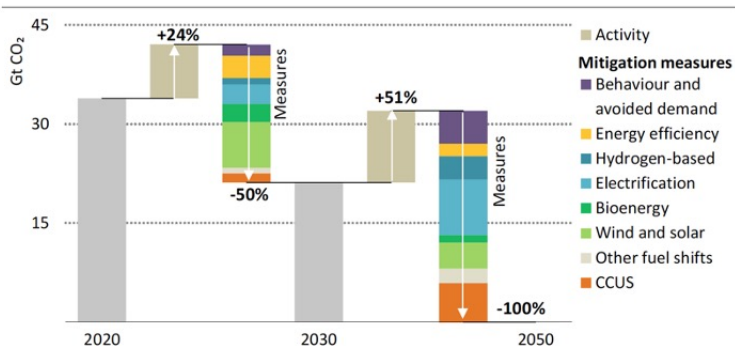
750M people lack access to electricity

2.6 Billion people rely on biomass/coal/kerosene for cooking

Economic growth and rising living standards will require more energy

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

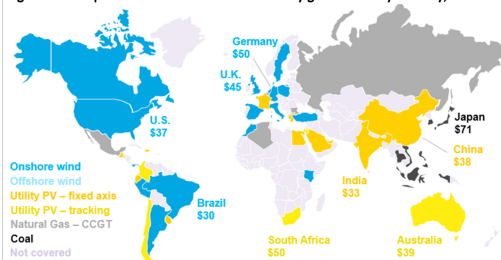
Major Strategies

- ▶ Replace fossil fuels in electricity generation: wind, solar, geothermal, nuclear, ...
- ▶ Energy efficiency, 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

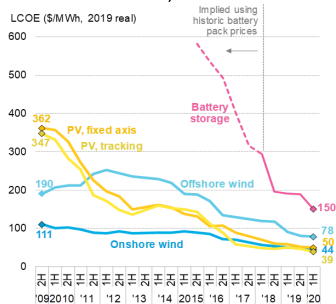
PV and Wind have been Getting Cheaper by the Year and are Now the Top Choice in Most of the World

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”

PV and Wind are Now Competitive with Natural Gas

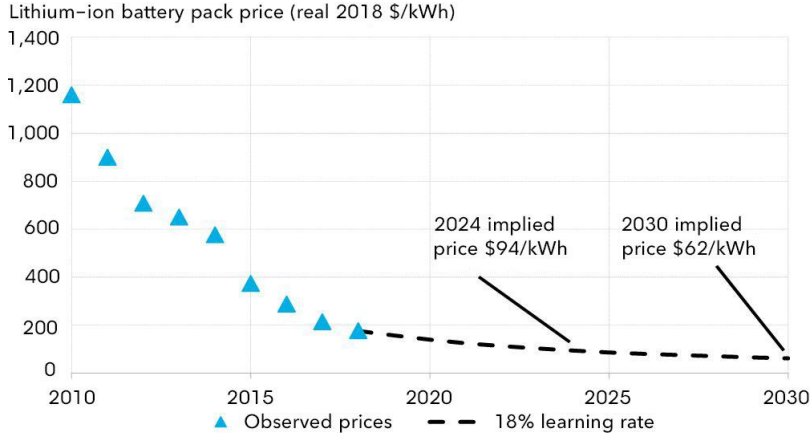
Table A2. Regional variation in levelized cost of electricity (LCOE) for new generation resources entering service in 2022 (2019 dollars per megawatthour)

Plant type	Range for total system levelized costs				Range for total system levelized costs with tax credits ¹			
	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

Transport: Battery Storage is Getting Cheaper Leading to EV Acceleration

Lithium-ion battery price outlook



Source: BloombergNEF

Source: Bloomberg New Energy Finance

Power Generating Capacity Additions

FIGURE 7.
Annual Additions of Renewable Power Capacity, by Technology and Total, 2014-2020

Additions by technology (Gigawatts)

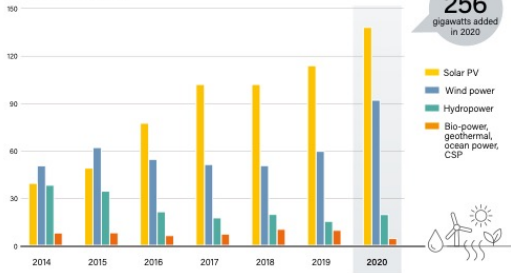
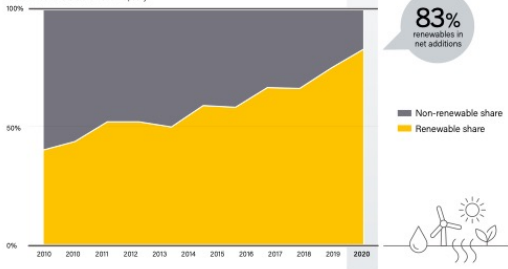


FIGURE 8.
Shares of Net Annual Additions in Power Generating Capacity, 2010-2020

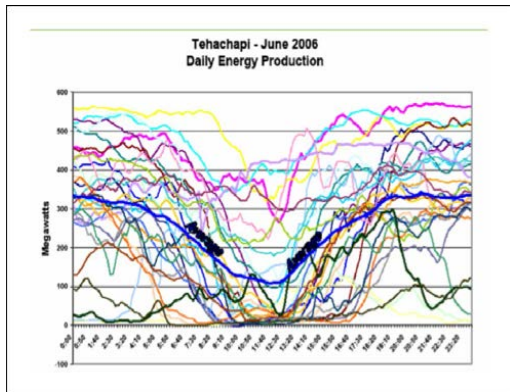
Share in Additions to Global Power Capacity



Key Challenge: Generation-Consumption balancing
Operation and control of the electric grid due to inherent variability and uncertainty of wind and solar generation

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

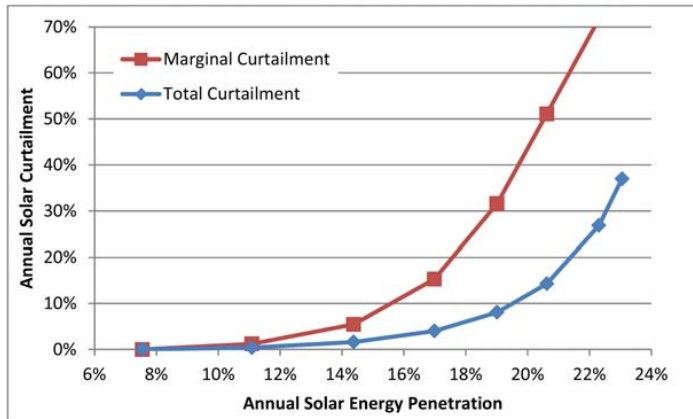


Figure 6. Annual marginal and total solar curtailment due to overgeneration under increasing penetration of PV in California in a system with limited grid flexibility

Enabling Deep Renewable Integration — Grid Modernization for Flexibility

- ▶ Storage: pumped hydro, battery, thermal, hydrogen, ...
- ▶ System operations: forecasting, sub-hourly dispatch, larger balancing areas
- ▶ Markets: market design, flexible ramp products
- ▶ Transmission: expansion, network management
- ▶ Load management: flexible loads, demand response, direct load control
- ▶ Flexible generation: CCGT, Hydro
- ▶ Distributed energy resources: roof-top solar, EVs, microgrids, ...

Major opportunity: forecasting, stochastic control, distributed control, and optimization to enable deep renewable electric energy integration

Transport Sector

- ▶ Energy efficiency in ground, air, and water transportation
- ▶ Electrification of cars, trucks, airplanes, ...
- ▶ Use of sustainable fuels, hydrogen, ...
- ▶ Necessary to account for the embodied energy, complete lifecycle and supply chains
- ▶ *Large existing fossil fuel transportation fleets*
- ▶ *EVs couple the electricity and transport systems*

Transport Sector Decarbonization

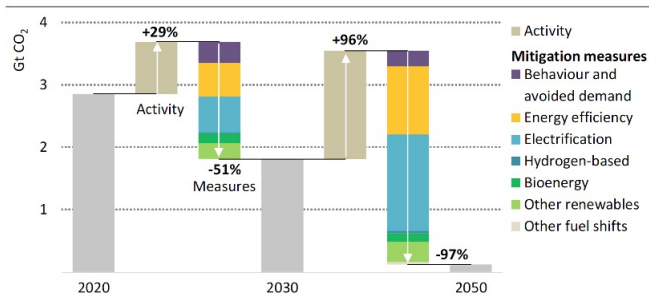
Table 3.4 ▶ Key milestones in transforming the global transport sector

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.

Buildings: Efficiency and/or Electrification

Figure 3.27 ▶ Global direct CO₂ emissions reductions by mitigation measure in buildings in the NZE



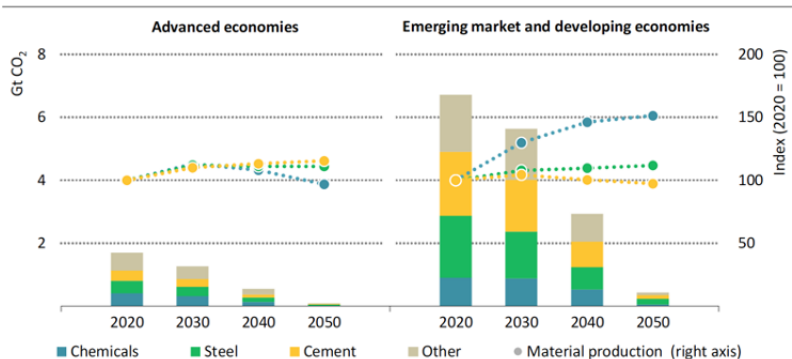
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Electrification and energy efficiency account for nearly 70% of buildings-related emissions reductions through to 2050, followed by solar thermal, bioenergy and behaviour

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

Industry Related Emissions

Figure 3.15 ▶ Global CO₂ emissions from industry by sub-sector in the NZE



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

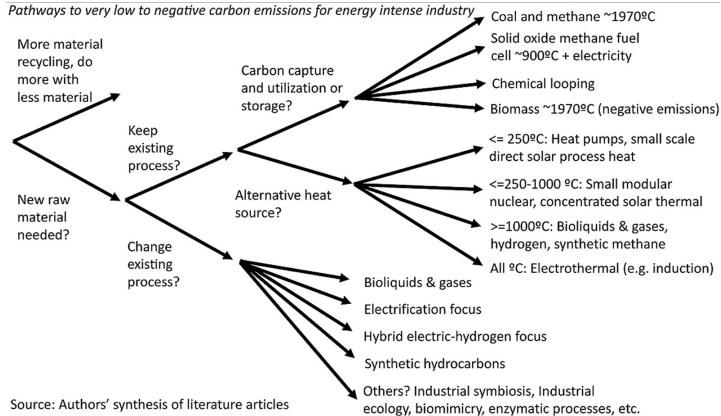
Note: Other includes the production of aluminium, paper, other non-metallic minerals and other non-ferrous metals, and a series of light industries.

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

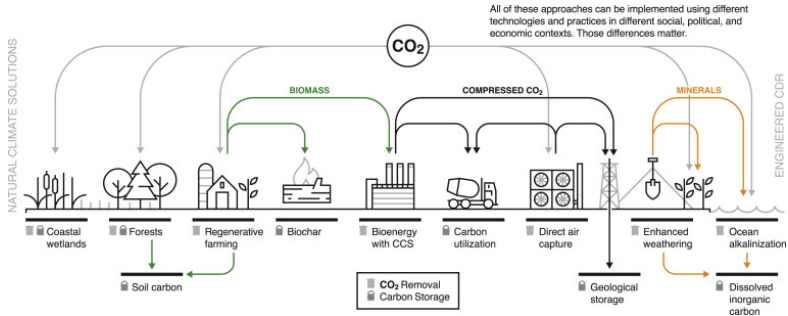


Source: Battaille et al. (2018)

Potential 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.



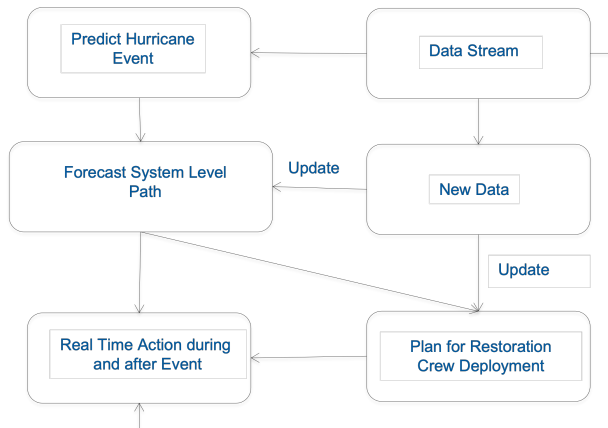
Climate Change Adaptation

- ▶ Adaptation is necessary and can potentially be synergistic with mitigation
- ▶ Key adaptation strategies:
 - ▶ Resilient infrastructures
 - ▶ Food: agriculture, livestock, fisheries in the face of heat, droughts, land degradation, ...
 - ▶ Climate resilience of public health systems
 - ▶ Coastal flooding, sea level rise, ocean ecosystems, ...
 - ▶ Responding to mass migrations
 - ▶ ...

Resilient Interdependent Infrastructures

- ▶ Threats: storms, hurricanes, flooding, wildfires, . . .
- ▶ Key infrastructures and their interdependencies: electric, transport, water, communications, . . .
- ▶ Resilience goals: Minimize loss of infrastructure services during the event and time to recovery after the event
- ▶ Electric grids:
 - ▶ Pre-emptive de-energization
 - ▶ Deployment of distributed energy resources, e. g., rooftop solar, batteries, . . .
 - ▶ Microgrids
 - ▶ Resilience through data integration, forecasting, decision making, control, . . .

Data and Decisions for Resilience in Electric Grids



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

How We Might Think — Systems and Control in an Interdisciplinary Context

- ▶ Energy system solutions must scale, else they won't make a difference.
- ▶ Infrastructures last for decades or centuries requiring decision making under deep uncertainty.
- ▶ Energy and climate problems require interdisciplinary collaboration.
- ▶ Domain experts from engineering, physical sciences, computing, social and behavioral sciences, humanities need to come together to conceptualize, formulate and solve these problems.
- ▶ Systems and control experts could become members of such interdisciplinary teams.

How We Might Think: Beyond Science and Engineering Research

- ▶ Connecting research to innovation and deployment.
- ▶ It is not an engineering and science problem alone — it is about the human condition.
- ▶ Be mindful of social justice, generational equity, and global nature of the problems.
- ▶ Students are very interested in addressing these problems. They are acutely aware that this is about their future.
- ▶ Time is of the essence.

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. Chakraborty
 - ▶ F. Dabbene
 - ▶ M. Fujita
 - ▶ M. Garcia-Sanz
 - ▶ D. Gayme
 - ▶ G. Hug
 - ▶ M. Ilic
 - ▶ I. Mareels
 - ▶ K. Moore
 - ▶ L. Pao
 - ▶ A. Rajhans
 - ▶ J. Stoustrup

Thank you!

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