Climate Change Mitigation and Adaptation: Role for Systems and Controls

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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.
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
Increases in Global Greenhouse Gas Emissions

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

2020 data only available for fossil and LULUCF CO$_2$
Temperature Increase Since the Start of Industrial Age: 1.1°C

Source: IPCC AR6 WG1 Report, 2021
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

Source: IPCC AR6 WG1 Report, 2021
Heavy Rainfalls and Flooding

Type of observed change in heavy precipitation
- Increase (19)
- Decrease (0)
- Low agreement in the type of change (8)
- Limited data and/or literature (18)

Confidence in human contribution to the observed change
- High
- Medium
  - Low due to limited agreement
  - Low due to limited evidence

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 since the 1950s

Source: IPCC AR6 WG1 Report, 2021
Agricultural and Ecological Droughts

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

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
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

2030 Emissions gap
CAT projections and resulting emissions gap in meeting the 1.5°C Paris Agreement goal

Historical
incl. LULUCF

1.5°C Paris Agreement compatible

Emissions gap in 2030 for 1.5°C
Changes from Sept 2020 to Nov 2021

Old

New

New NDCs to date narrow the gap in 2030 by around 3.3–4.7 GtCO₂e or 15–17%

Paris 1.5°C
23 – 27 GtCO₂e

Sept 2020 update

Paris 1.5°C
19 – 23 GtCO₂e

Nov 2021 update

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

Note: Totals may not add up due to rounding. This figure shows a comparison between two years across a 10-year span. The result of the economic recession in 2008 may have temporarily lowered the share of fossil fuels in total final energy consumption in 2009. The share in 2008 was 80.7%.

Source: Based on IEA data. See endnote 50 for this chapter.

Source: REN21, RENEWABLES 2021 GLOBAL STATUS REPORT
Estimated U.S. Energy Consumption in 2019: 100.2 Quads

Quad = 1.055 \times 10^{18} \text{ 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
Many analogous plans and scenarios from various organizations ...
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.

Technological innovation and “learning by doing”
Table A2. Regional variation in levelized cost of electricity (LCOE) for new generation resources entering service in 2022 (2019 dollars per megawatthour)

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Range for total system levelized costs</th>
<th>Range for total system levelized costs with tax credits¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Minimum</td>
<td>Simple average</td>
</tr>
<tr>
<td>Dispatchable technologies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Combined cycle</td>
<td>31.25</td>
<td>36.27</td>
</tr>
<tr>
<td>Combustion turbine</td>
<td>55.23</td>
<td>62.81</td>
</tr>
<tr>
<td>Non-dispatchable technologies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind, onshore</td>
<td>28.25</td>
<td>38.33</td>
</tr>
<tr>
<td>Solar photovoltaic (PV)³</td>
<td>32.13</td>
<td>38.57</td>
</tr>
</tbody>
</table>

Source: EIA, 2020
Battery Storage is Getting Cheaper

Lithium-ion battery price outlook

Source: BloombergNEF

Source: Bloomberg New Energy Finance
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

<table>
<thead>
<tr>
<th>Category</th>
<th>2020</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Read transport</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of PHEV, BEV and FCEV in sales: cars</td>
<td>5%</td>
<td>64%</td>
<td>100%</td>
</tr>
<tr>
<td>two/three-wheelers</td>
<td>40%</td>
<td>85%</td>
<td>100%</td>
</tr>
<tr>
<td>bus</td>
<td>3%</td>
<td>60%</td>
<td>100%</td>
</tr>
<tr>
<td>vans</td>
<td>0%</td>
<td>72%</td>
<td>100%</td>
</tr>
<tr>
<td>heavy trucks</td>
<td>0%</td>
<td>30%</td>
<td>95%</td>
</tr>
<tr>
<td>Biofuel blending in all products</td>
<td>5%</td>
<td>13%</td>
<td>41%</td>
</tr>
<tr>
<td>Rail</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of electricity and hydrogen in total energy consumption</td>
<td>43%</td>
<td>65%</td>
<td>96%</td>
</tr>
<tr>
<td>Activity increase due to modal shift (index 2020=100)</td>
<td>100</td>
<td>100</td>
<td>130</td>
</tr>
<tr>
<td>Aviation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic hydrogen-based fuels share in total aviation energy consumption</td>
<td>0%</td>
<td>2%</td>
<td>33%</td>
</tr>
<tr>
<td>Biofuels share in total aviation energy consumption</td>
<td>0%</td>
<td>36%</td>
<td>45%</td>
</tr>
<tr>
<td>Avoided demand from behaviour measures (index 2020=100)</td>
<td>0</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Shipping</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share in total shipping energy consumption: Ammonia</td>
<td>0%</td>
<td>8%</td>
<td>46%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioenergy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infrastructure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV public charging (million units)</td>
<td>1.3</td>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>Hydrogen refuelling units</td>
<td>540</td>
<td>16,000</td>
<td>90,000</td>
</tr>
<tr>
<td>Share of electrified rail lines</td>
<td>24%</td>
<td>47%</td>
<td>65%</td>
</tr>
</tbody>
</table>

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
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 CO₂ 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.
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
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
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/