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

- Land-use change (CH₄+N₂O)
- Land-use change (CO₂)
- Fluorinated gases (F-gas)
- N₂O
- CH₄
- Fossil CO₂

UNEP 2020 Emissions Gap Report
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

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 — 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

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

Global CO₂ Emissions from Energy & Industry

Baseline (3.0–5.1°C)
6.0 W/m² (3.2–3.3°C)
4.5 W/m² (2.5–2.7°C)
3.4 W/m² (2.1–2.3°C)
2.6 W/m² (1.7–1.8°C)
1.9 W/m² (1.3–1.4°C)

net-negative global emissions

Global total CO₂ emissions
Billions of tonnes of CO₂/yr

Four illustrative model pathways

Timing of net zero CO₂
Line widths depict the 5-95th percentile and the 25-75th percentile of scenarios

Non-CO₂ emissions relative to 2010
Emissions of non-CO₂ forces 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
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

Source: UN FCCC/PA/CMA/2021/8, 2021
Energy System is Huge, Multi-Scale, Distributed, and Interconnected
Global Energy Consumption by Primary Sources

© Global Carbon Project • Data: BP, IEA (bioenergy)

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
US Energy Sankey Diagram

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

Quad = 1.055 × 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 ≈ 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

Source: V. Smil
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

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)

<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
Transport: Battery Storage is Getting Cheaper Leading to EV Acceleration

Lithium-ion battery price outlook

Source: BloombergNEF

Source: Bloomberg New Energy Finance
Key Challenge: Generation-Consumption balancing
Operation and control of the electric grid due to 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
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 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*
## 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><strong>Road transport</strong></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><strong>Rail</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Share of electricity and hydrognes 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><strong>Aviation</strong></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>6%</td>
<td>45%</td>
</tr>
<tr>
<td>Avoided demand from behaviour measures (index 2020=100)</td>
<td>0</td>
<td>20</td>
<td>38</td>
</tr>
<tr>
<td><strong>Shipping</strong></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>0%</td>
<td>2%</td>
<td>17%</td>
</tr>
<tr>
<td>Bioenergy</td>
<td>0%</td>
<td>7%</td>
<td>21%</td>
</tr>
<tr>
<td><strong>Infrastructure</strong></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>18,000</td>
<td>90,000</td>
</tr>
<tr>
<td>Share of electrified rail lines</td>
<td>34%</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
Buildings: Efficiency and/or Electrification

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.
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.

Source: Morrow et al, 2020
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

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