Energy System and Decarbonization Challenge

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Tutorial on Systems and Control Opportunities for Decarbonization of the Energy System

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Outline

Goal and Outline of the Tutorial Session

Why Decarbonize the Energy System?

Energy System Perspective

Key Directions

Major Challenges and Role for Systems and Control

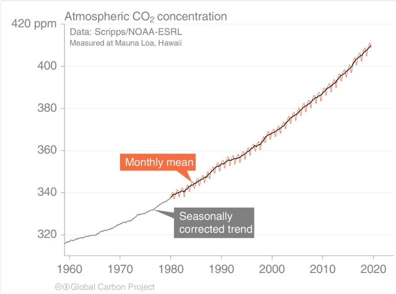
Throughout this document, there are embedded (blue) hyperlinks as pointers to papers and reports for further study.

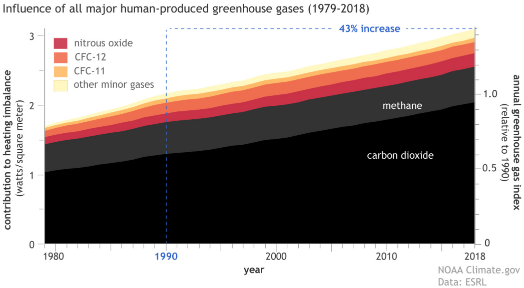
Goals and Outline of the Tutorial Session

- Goal: A primer for the systems and controls community on energy decarbonization challenges and opportunities
- Target audience: researchers who have not been previously exposed to energy systems
- Four parts:
  1. Pramod Khargonekar: Energy System and Decarbonization Challenge
  2. Anu Annaswamy: Deep Integration of Solar and Wind into the Electric Grid
  3. Mario Rotea: Systems and Control for Onshore and Offshore Wind Energy Production
  4. Jakob Stoustrup: Building Heating and Cooling Energy Consumption: A Systems and Control Perspective

Why Decarbonize?

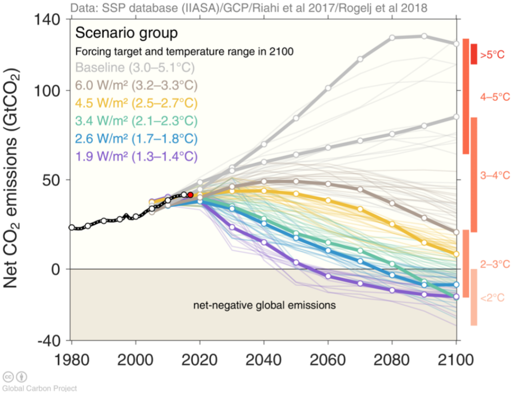
Atmospheric CO_2 Concentration and Other Greenhouse Gases

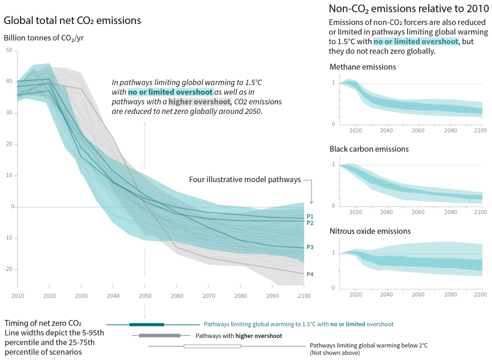




Sources: Global Carbon Project, Friedlingstein et al. (2019), Climate.gov

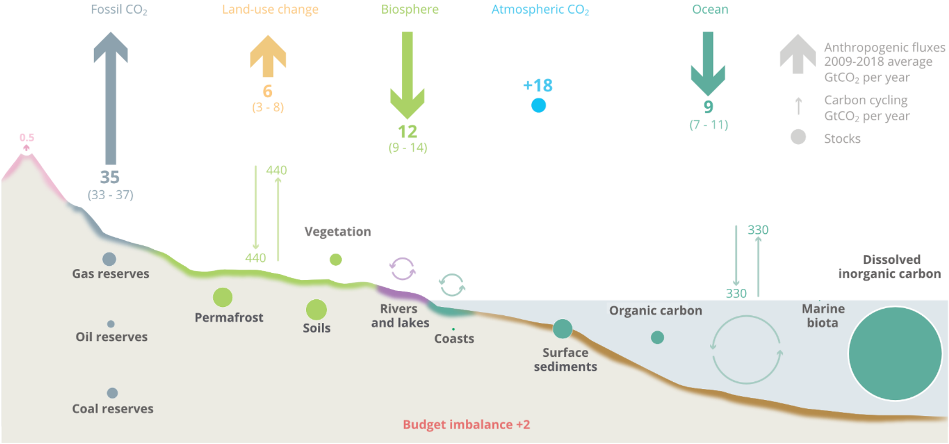
Global Warming and Emissions Scenarios





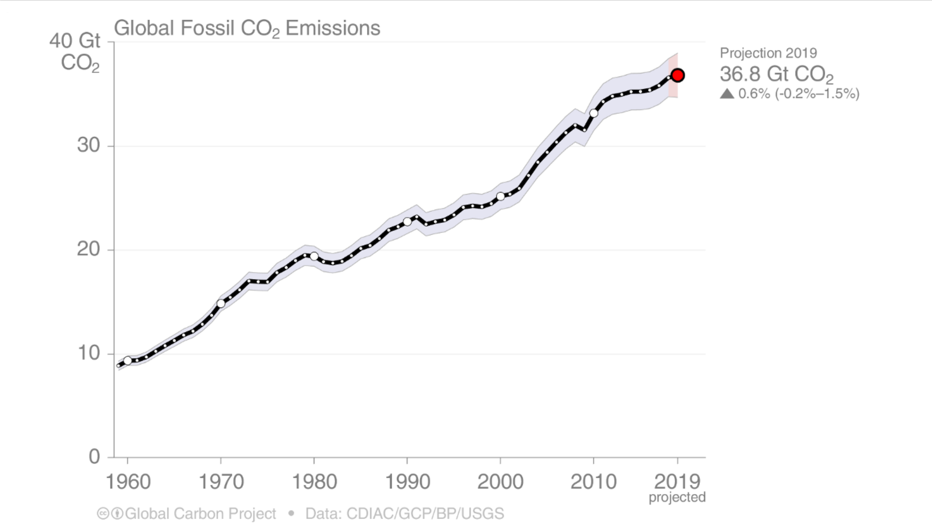
Source: Global Carbon Project, IPCC

Carbon Sources, Sinks, and Imbalance



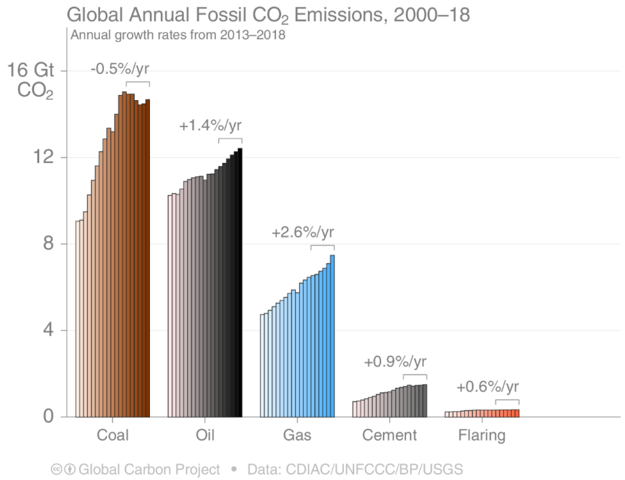
Source: Global Carbon Project, Friedlingstein et al. (2019)

Global Fossil CO_2 Emissions



Source: Global Carbon Project, Friedlingstein et al. (2019)

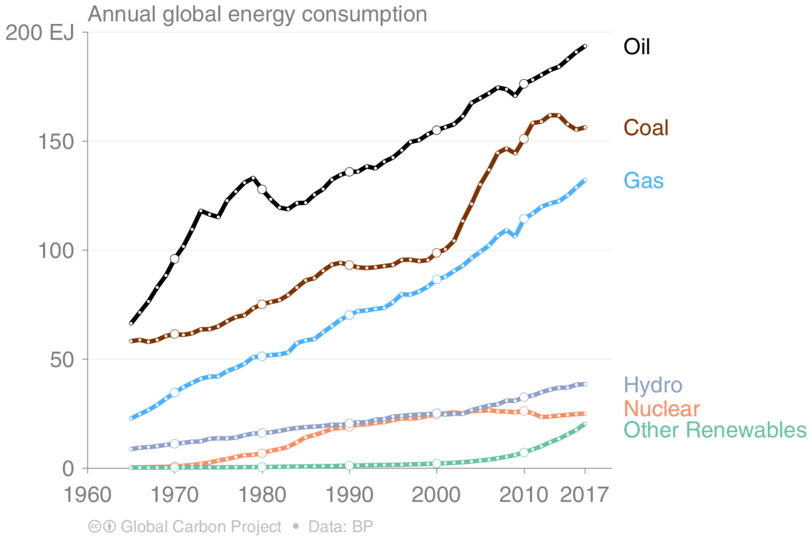
CO_2 Emissions by Sources



Source: Global Carbon Project, Friedlingstein et al. (2019)

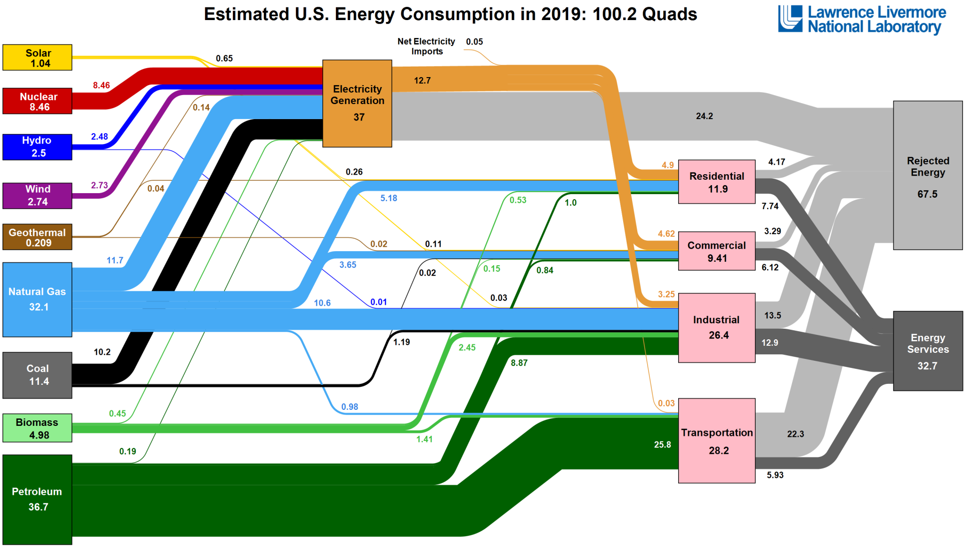
Energy System is Huge, Multi-Scale, Distributed, and Interconnected

Global Energy Consumption by Primary Sources



Source: Global Carbon Project, BP

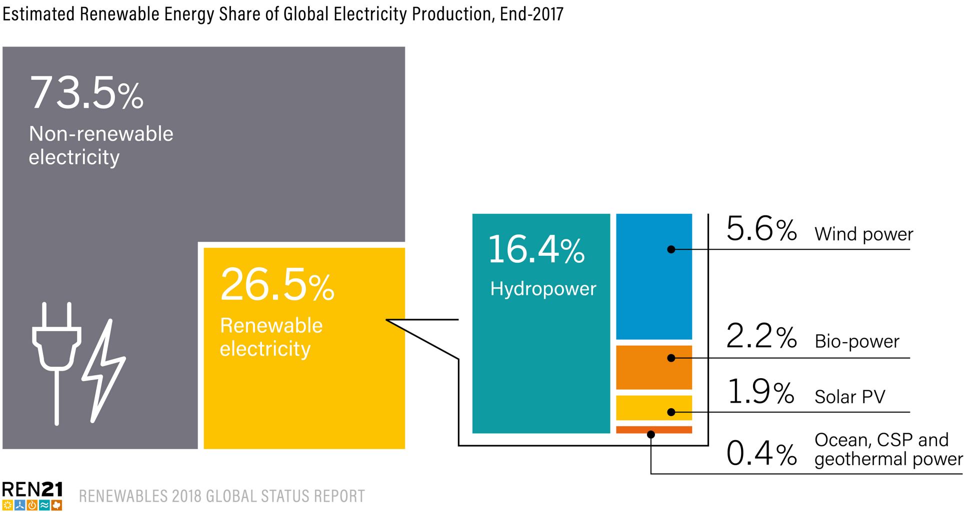
US Energy Sankey Diagram



Source: LLNL March, 2020. Data is based on DOE/EIA MER (2019). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant heat rate. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is

Source: LLNL

Electric Energy Sector



Source: Ren21

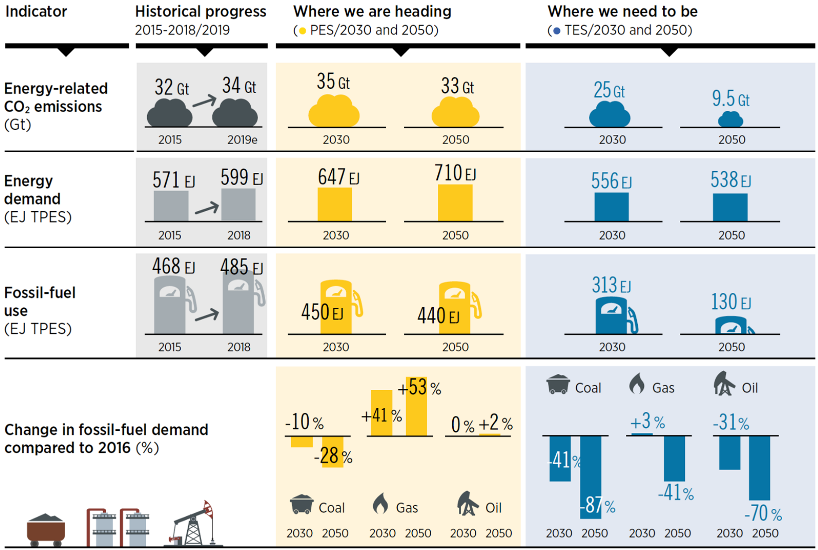
Major Energy Transitions are Slow

- 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%

1 Billion people lack access to electricity
2.8 Billion people rely on biomass for cooking and heating
Economic growth and rising living standards will require increasing amounts of energy

Source: V. Smil

Where do We Need to Go?



Source: IRENA, Global Energy Renewables Outlook 2050

Major Strategies

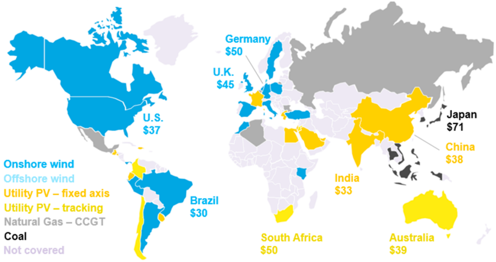
- Replace fossil fuels in generation of electricity: wind and solar power
- Increase energy efficiency
    1. Building heating and cooling
    2. Combined heat and power
    3. Industry (manufacturing) energy efficiency
    4. Automotive efficiency
- Transportation: Electric cars and trucks

Key Trends: Signs of Hope and Big Challenges

Toward a 100% Renewable Future

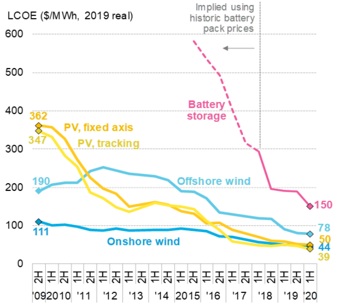
PV and Wind have been Getting Cheaper by the Year and are Now the Top Choice in Most of the World

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.

Major Opportunity: Systems and control for wind and solar electricity optimization

Mario Rotea talk on wind generation

Source: Bloomberg

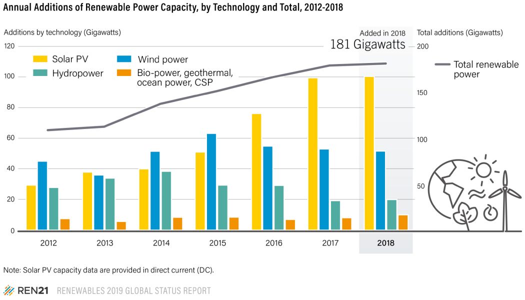
PV and Wind are Now Competitive with Natural Gas

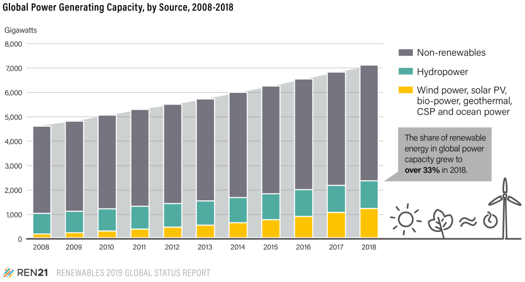
Table A2. Regional variation in levelized cost of electricity (LCOE) for new generation resources entering service in 2022 (2019 dollars per megawatthour)

	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

Power Generating Capacity Additions



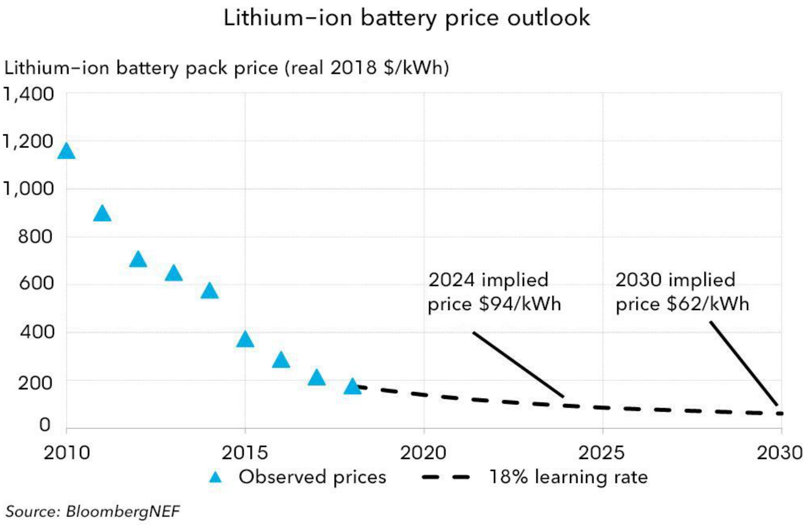


Major Challenge: Operation and control of the electric grid due to inherent variability and uncertainty of wind and solar generation

Anu Annaswamy talk on electric grid and renewables

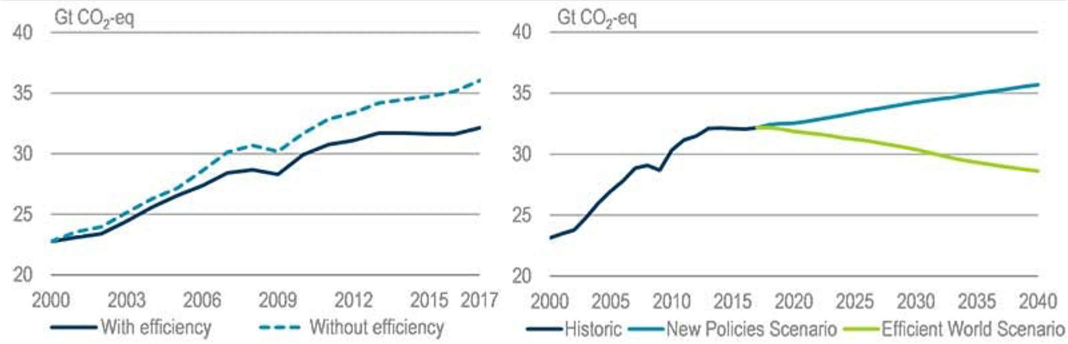
Source: REN21

Battery Storage is Getting Cheaper Leading to EV Acceleration



Source: Bloomberg New Energy Finance

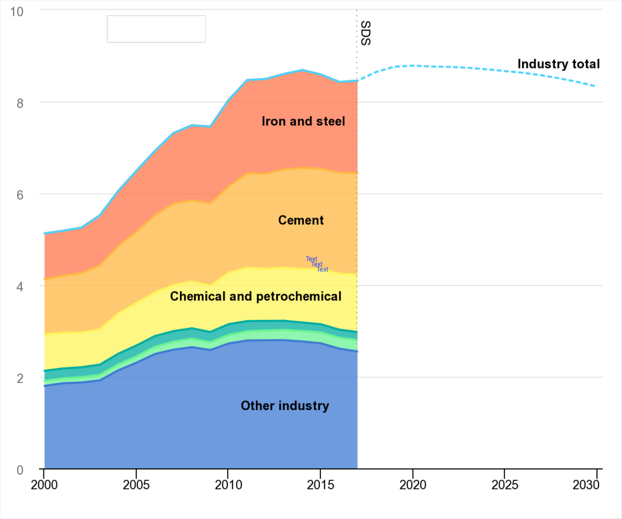
Efficiency Gains need to Accelerate

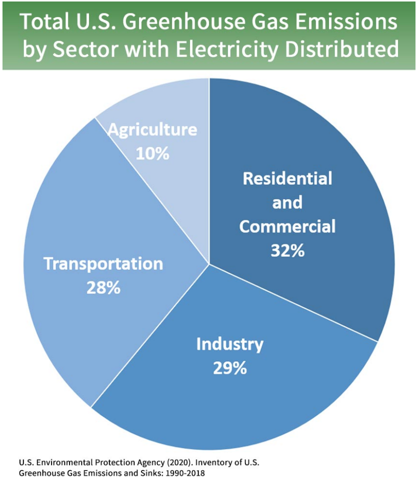


Major Challenge: Building energy efficiency improvements
Jakob Stoustrup talk on building heating and cooling

Source: IEA

Industry Related Emissions





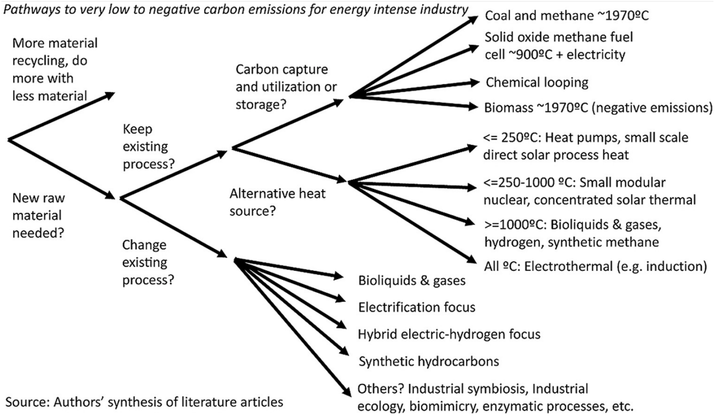
Sources: IEA, EPA

Approaches to Decarbonization of Energy 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)

Systems and Control have a Major Role

Perspective for How We Might Think

- Energy system solutions must scale, else they don't make a difference
- Costs play a huge role
- Energy problems require multidisciplinary collaboration
- Domain experts from engineering, physical sciences, computing, and behavioral sciences need to come together to formulate and solve these problems
- Connecting research to innovation and deployment
- Pervasive opportunities for systems and control experts to contribute to advancing progress toward a decarbonized energy system

Systems and Control Opportunities for Industry Energy Decarbonization

- Information, control and decision architectures
- CPS: sensors, networks, computing, IoT
- Control oriented modeling for energy efficiency at various levels:
  1. Process
  2. System
  3. Systems of systems
- Control: Feedforward, feedback, robust, nonlinear, model predictive, stochastic.
- Optimization: Discrete and continuous
- IFAC is ideally positioned to make an impact in this area

Post COVID-19 Outlook

- Estimated 17% drop in CO_2 emissions by April 2020.
- Very large financial recovery packages in many countries to maintain and create jobs
- Their design could accelerate energy system decarbonization or lock us into fossil fuel based energy infrastructures — need to embed vision of low carbon future
- Key policies that lead to economic recovery and also climate change mitigation.
  1. Renewable energy, storage, grid modernization, CCS
  2. Building energy efficiency
  3. Education and training for unemployed workers
  4. Climate friendly agriculture
  5. Clean energy R&D

Le Quéré et al. (2020), Hepburn et al. (2020)

What is Next

- Anu Annaswamy: Deep Integration of Solar and Wind into the Electric Grid
- Mario Rotea: Systems and Control for Onshore and Offshore Wind Energy Production
- Jakob Stoustrup: Building Heating and Cooling Energy Consumption: A Systems and Control Perspective

Thank you!

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