Climate Change Mitigation, Adaptation, and Resilience

CHALLENGES AND OPPORTUNITIES FOR THE CONTROL SYSTEMS COMMUNITY

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Summary

This paper is focused on the issues of climate change mitigation, adaptation, and resilience. A comprehensive and diverse collection of research opportunities for the control systems community is discussed along with considerations that provide a broader framework for this research.

Introduction

Climate change poses an existential threat to humanity. It is now indisputable that the primary cause of this threat is human activity resulting in high greenhouse gas emissions, which began during the Industrial Revolution and has continued to rapidly accelerate. The first warnings of impending and irreversible climate change were sounded decades ago, when governmental and intergovernmental policy makers had sufficient time to enact the changes needed to avoid the dire situation we find ourselves in today.

As asserted in the United Nations (UN) Intergovernmental Panel on Climate Change (IPCC) synthesis report [1], “All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%), involve rapid and deep and, in most cases, immediate greenhouse gas emissions reductions in all sectors this decade." Since greenhouse gas emissions are still on an increasing trajectory and with only six years left in this decade, it appears that very substantial global warming is all but inevitable – and its adverse impacts are already being felt around the world. Indeed, there are increasing risks of crossing major tipping points such as the Greenland ice sheet, Amazon rainforest, etc., which may unleash self-perpetuating and catastrophic positive feedback loops [2].

The global community must now focus on actions that will save the planetary ecosystem from the most dramatic potential consequences. Scientists, engineers, and policymakers are increasingly shifting away from the single-minded goal of avoiding climate change and toward the twin goals of (a) mitigating greenhouse gas emissions to minimize additional global warming beyond the 1.5°C threshold, and (b) adapting to the effects of climate change..

With the emergence and convergence of powerful new technologies in the last few decades, the control systems

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community is well-positioned to play a crucial role in this worldwide effort to tackle the challenges posed by anthropogenic climate change.

On the information and communication technologies (ICT) side, these promising developments include advanced communications, the industrial internet of things, machine learning, data analytics, and smart computing capabilities embedded in edge devices. In collaboration with experts in these and other fields, the control systems community can make vital contributions to climate resilience, including through the integration of key climate variables into the planning and operations of critical infrastructure systems; the leveraging of feedback to manage multiscale processes in resource-constrained settings; and the investigation of cross-sector interdependencies in societal systems.

Success will also depend on making major methodological changes–in particular moving beyond the traditional insularity of controls research. The control codesign approach represents one exciting opportunity in this context [3], [4]. Here, dynamic subsystem interactions are considered at the beginning of the design process and control concepts are applied to design the entire system—instead of relegating control development to the end of a traditional sequential design process. Control codesign can enhance the possibilities of finding optimal solutions, lowering system cost, and improving reliability and resilience—all of high importance for climate change mitigation and adaptation. Another opportunity relates to recognizing the importance of the human element in control systems. The recent interest in human-in-the-loop control and cyber-physical-human systems [5]–[7] is an encouraging development but the opportunity needs to be widely embraced and partnerships with other disciplines pursued. It is people's actions that will substantially influence the course and impacts of climate change—and it is people that are affected by them. Traditional strengths of control science and engineering, including modeling, identification, and optimization, will continue to be in demand, and tackling the climate crisis will require advances in dealing with large-scale uncertainty [8], heterogeneous systems, and multiple time scales.

In the rest of this article, we will first review current data and projections on climate change and its anthropogenic basis, noting in particular the recent assessment by the IPCC. Next, we will discuss several distinct targets for research and innovation for the controls community, including infrastructure systems, power generation and grids, industrial processes, transportation and logistics, and food and agriculture. The urgency of the climate crisis means that research-as-usual approaches must be eschewed. To that end, we discuss several important considerations related to sustainability, social justice, deployment-at-scale, education, and transdisciplinary collaborations. General sources we have relied on for this article include IPCC AR6 reports published in 2021-23 [9], [10], [11] and the IEA netzero roadmap published in 2021 [12]. We recommend these sources and [13], [14] for more detailed information and understandings. Greenhouse gas emissions statistics cited in this article are taken from the IPCC 2022 mitigation report [10] as shown in Figure 1 unless indicated otherwise. This article is an expanded version of our contribution (Chapter 2.1) in the Control Roadmap 2030 report published by the IEEE Control Systems Society [15].

Climate Change: the 2023 View

Earth's climate system is undergoing rapid changes not seen in at least the last 2,000 years. There is evidence that global average temperatures now are higher than the warmest period in the last 100,000 years, which was 6,500 years ago. The fundamental physical principles that govern the climate system are well established. It is important to note that the climate system is an increasingly coupled natural-human system. Human behavior now plays a large and essential role in the behavior of the overall climate system. Earth system models for climate are being improved and used to predict (along with uncertainty in the predictions) its future course.

The main causes of human activity-induced global warming include increases in emissions of CO_2, CH_4, N_2O, CO, volatile organic compounds, and black carbon. There is strong evidence that in 2019, atmospheric CO_2 concentrations were higher than at any time in at least 2 million years, and concentrations of CH_4 and N_2O were higher than at any time in at least 800,000 years. It is estimated that CO_2 concentration has increased from pre-industrial levels of 280 ppm to 412 ppm in 2020.

The concept of climate sensitivity is defined as the expected increase in global average temperature in response to the doubling of atmospheric CO_2 from pre-industrial levels. The recent Sixth Assessment report by IPCC [9] concludes that the (equilibrium) climate sensitivity is in the range of 2°C (high confidence) to 5°C (medium confidence). This provides a possible range of global warming as future greenhouse gas (GHG) concentrations increase.

The Sixth Assessment report provides very strong evidence that the global average surface temperature in the 2011-2020 decade was 1.09°C (confidence interval 0.95°C – 1.2°C) higher than the 1850-1900 baseline. In fact, each of the last four decades has been successively warmer than any decade that preceded it since 1850. The report leverages extensive research on natural drivers of climate change such as changes in incoming solar radiation, volcanic activity, and global biogeochemical cycles. It provides observational data on earth's climate system variables to find unequivocal evidence that the human activity-induced increases in greenhouse gases have "warmed the atmo-

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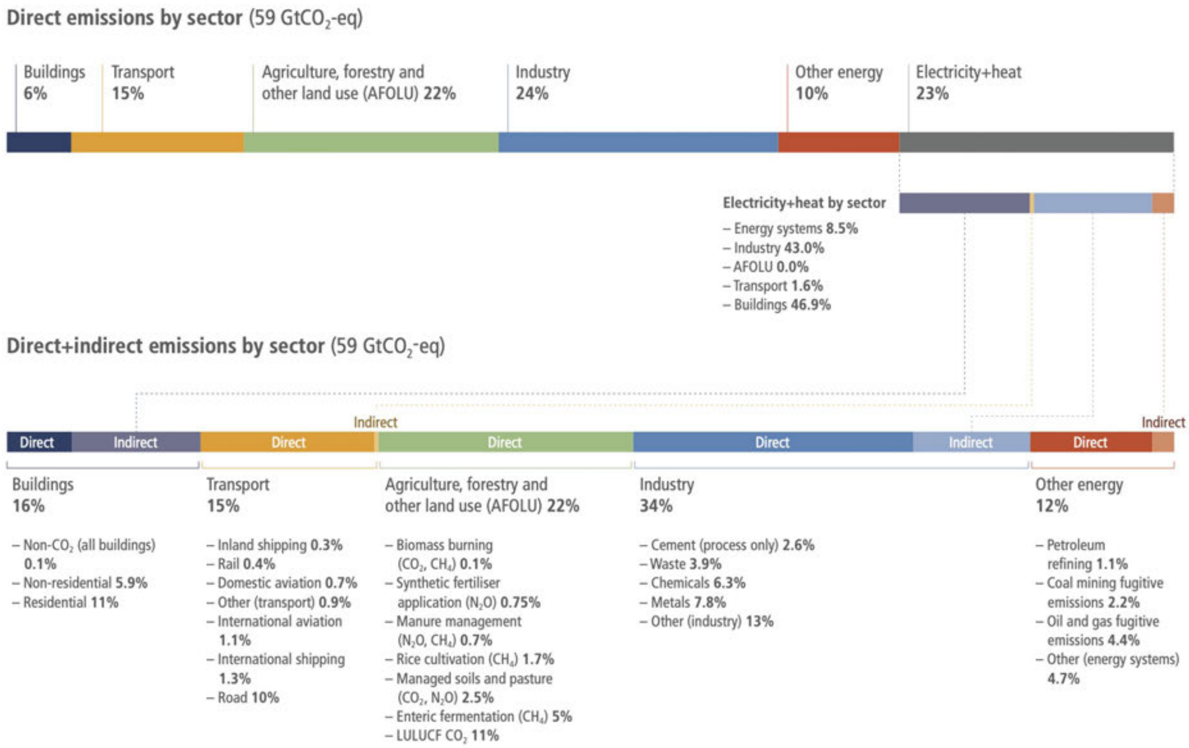

FIGURE 1 Direct versus direct and indirect emissions of greenhouse gases, expressed as precent of total 59 gigatons of CO2-equivalent (CO2eq) emissions in 2019 by sector. Source: Figure 2.12 in [10], copyright IPCC, used with permission.

sphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred."

Global warming has already had significant consequences. The emerging techniques from climate change attribution science allow us to causally connect global warming to specific observed events. For example, the report concludes that globally averaged precipitation over land has increased since 1950 and that human influence contributed to this phenomenon. The frequency and intensity of flooding events have increased. There are increases in agricultural and ecological droughts in many parts of the world, including west, central, and south Africa; west and central Europe; the Mediterranean; and western North America. Human activity is implicated in all these cases.

It is virtually certain that human-induced climate change is the main driver of hot extremes (including heat waves) that have become more frequent and more intense since the 1950s. It is very likely that human activity is causing ocean warming, the observed retreat of glaciers, and the decrease in Arctic ice. This, in turn, has increased global mean sea levels by 0.2m between 1901 and 2018. Moreover, increased levels of greenhouse gasses caused by human activities have resulted in ocean acidification and reduction in ocean oxygen levels, changing the migration patterns of large fish and sea mammals.

Climate change is happening around the world with increased frequency and magnitude of extreme weather events. (Cold extremes, including cold waves, have become less frequent and less severe.) The future evolution of the climate system will depend on how human behavior and policies will affect natural systems. The current human population stands at 8.1 billion and is expected to increase to 9.5 billion by 2050. Much of this increase will occur in Asia and Africa, with modest increases in the Americas. Underdeveloped economies and societies in Asia, Africa, and other parts of the world naturally and justifiably aspire to higher standards of living and food-energy-water security. Thus, demand for energy, water, food, cement, metals, and other resources is expected to increase. Thus, there is a strong imperative to meet these demands while avoiding further climate change damage.

Mitigation, Adaptation, and Resilience

There are numerous scenarios for how socio-economic-technological systems should and will evolve and intertwine with climate change. The Paris climate agreement, which was formally adopted in 2016, commits the world "to limit global warming to well below 2°C, preferably to 1.5°C, compared to pre-industrial levels." Nevertheless, as mentioned earlier, the 1.5°C target appears almost surely to be exceeded, hence the need to focus on adaptation and

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resilience in response to climate change, even as global coordination is harnessed to limit further greenhouse gas emissions and global warming. Both strategies will be required to ensure a livable, sustainable planet.

Numerous global, national, regional and local organizations are developing mitigation, adaptation, and resilience strategies to deal with climate change processes and impacts. These roadmaps vary significantly across nations and regions. These variations reflect social, economic, political, and technological realities of various nations. Some of the most important differences arise from the level of economic and technological development. Developing nations have a much greater need for energy and natural resources for improving the standard of living for their citizens. Accordingly, the United Nations has taken the "nationally determined contributions" approach to global coordination and cooperation. We quote from the UN: "Nationally determined contributions (NDCs) are at the heart of the Paris Agreement and the achievement of its long-term goals. NDCs embody efforts by each country to reduce national emissions and adapt to the impacts of climate change." The interested reader is referred to [16] for the 2022 synthesis report on the NDCs across the world.

To understand the challenges and opportunities in climate change mitigation, let us consider Figure 1 taken from the latest IPCC climate change mitigation report [10]. This figure depicts greenhouse gas emissions in two related but different ways: direct which do not account for end use and combined direct and indirect emissions where emissions from electricity and heat production are further attributed to its end use sectors. Thus, the challenge is to reduce and eliminate the greenhouse gas emissions from all these sectors. For a very recent perspective on greenhouse gas emissions information and data, see [17].

Renewable energy production using solar photovoltaics and wind and its integration into the electric energy grids comprise the most promising direction at this time. This is driven by very impressive reductions in the costs of these generation technologies. Renewable electricity can reduce the use of coal, oil, and natural gas in electricity production. In addition, if we can replace fossil fuels with clean electric energy in transportation, industry, and manufacturing, resulting greenhouse gas emissions in these sectors can be reduced. However, for certain processes and use cases, electric energy is not yet viable. In such cases, renewable electricity can be converted into the so-called green hydrogen (or other fuels or chemicals). Besides energy system decarbonization, agriculture, land-use, and forestry are other domains for mitigation strategies [18], [19].

While climate change mitigation is fundamentally a global problem requiring coordinated actions across a multitude of organizations and nations, adaptation and resilience to climate change are more local and regional in nature. It is now quite clear that we need to simultaneously work on mitigation as well as adaptation and resilience [20]. Major risks from climate change are:

» Increase in hot extremes
» Increase in heavy precipitation
» Increase in wildfires
» Increase in droughts
» Increased scarcity of food and water
» Ocean acidification
» Sea level rise

Adaptation refers to the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate change and its effects. Resilience refers to the capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure. Resilience is a positive attribute when it maintains capacity for adaptation, learning and/or transformation. Certain mitigation strategies are synergistic with adaptation and resilience while others result in major trade-offs. For example, reforestation for carbon sequestration can also lead to reduction in landslide hazards. For further reading on synergies and trade-offs between mitigation and adaptation, please see [21]. The UN Sustainable Development Goal 13 is closely related to these issues.

Targets of Opportunity for Control Systems Scientists and Engineers

The urgency and scale of the climate-change problem should be an immediate call to arms for collaboration among scientists, engineers, social scientists, humanists, policymakers, and communities. Control scientists and engineers have a crucial role to play.

In this section, we address a number of socio-economic-technological sectors or domains in which research and innovation are required and where the controls community can play a leadership role. Figure 2 provides an overall schematic illustrating the interconnections between these sectors and some of the associated technology enablers and applicable control methods and tools. It should be kept in mind that new cross-sector connections are arising as climate mitigation solutions are incentivized and implemented. For example, electrification of transportation via electric vehicles is creating the potential for strong coupling between electric energy and transportation sectors. This coupling poses challenges for grid management as well as opportunities for increased resilience by leveraging stored energy in batteries. Increasing use of heat pumps for building heating and cooling furthers the coupling between buildings and electric energy systems. Hydrogen

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as an energy carrier can help couple electric energy, transportation, fertilizers, and chemicals.

For mitigation, energy system decarbonization is a major objective [12], [22], [23]. The International Energy Agency (IEA) has developed a roadmap for attaining net-zero GHG emissions in the energy sector by 2050 [12]. In 2022, in the aftermath of the energy crisis, IEA released a revised roadmap in its World Energy Outlook report [24]. FIgure 3 reproduces a graphic visualization of the key milestones in this roadmap and the trajectory to net zero emissions. Specific milestones are indicated for each quinquennium through 2050. For example, by 2025, nearly half of global electricity should be from low-emissions sources; by 2030, 60% of cars sold globally should be electric vehicles; by 2035, CO_2 capture and sequestration should have accounted for 3 gigatons of the gas; and by 2050, the installed capacity of electrolyzers for clean hydrogen production should reach 3,650 gigawatts.

We note that improving energy efficiency is the "lowest hanging fruit" and a first-order priority in the progress towards reduction and elimination of greenhouse gas emissions [25]. Energy efficiency cuts across most of the sectors/domains discussed below, although the approaches to improving efficiency vary. Suffice it to say, automation and control will be crucial to achieving these improvements.

In each sector or domain, we provide a capsule summary of the opportunity target, followed by three illustrative research priorities for control scientists and engineers. (The limitation to three opportunities is solely because of space restrictions, not a lack of additional research areas with high-impact potential.) We have also indicated the timeline in which each opportunity could be expected to have broad societal impact–by which we mean that the technology would be fully matured and deployment at scale underway–as follows:

» Short term: Societal impact by 2030
» Medium term: Societal impact during 2030 – 2040
» Long term: Societal impact post-2040

Electric Energy Systems

A dramatic transformation of power grids is underway. The world is moving from the historical model of centralized, dispatchable power generation based on fossil fuels to a distributed system in which most power generation is from renewable sources. The vision is to create an autonomous, continuous, secure, and decarbonized power grid that is both efficient and affordable. Today's grid technologies and operations are poorly suited for massive-scale penetration of renewable generation. New advances in control technologies and architectures, transitioning from conventional centralized controls to more distributed and hierarchical controls, will be essential to ensure that tomorrow's grids are stable, reliable, scalable, and cost-effective.

There is a large body of literature at the intersection of climate change and electric energy systems. The concept of smart grid was introduced more than 20 years ago. Its major goals included integration of renewable generation and demand side management. The control systems community recognized this opportunity and released a 2030 vision report [26] in 2013. As such, this is a sector where the control and systems community has already made strong contributions, which appear regularly in major journals such as the *IEEE Transactions on Power Systems* and the *IEEE Transactions on Smart Grid*. We refer the interested reader to [27]–[33]. The future challenges and opportunities cover all aspects of deep penetration, greater than 60% wind and solar globally by 2050, of variable renewable generation across transmission and distribution networks, and that division itself may need to be revisited. Given the very wide spatial and temporal scales of the power grids, inherent variability of wind and solar generation, and the complex techno-economic nature of the electric energy system, there are ample opportunities for the control systems community to contribute to this challenge.

Example opportunities include:

» Control design using new power electronics technologies for enabling renewable integration (short-term)
» New economic models for dynamic electricity pricing across different timescales (medium-term)
» Distributed optimization and control for deep integration of renewable generation, storage, and demand management (medium-term)

Electric Power Generation

A major priority is to replace fossil fuel-based electricity production with renewable energy such as wind, solar, and geothermal. Wind and solar energy costs have decreased dramatically in many regions and nations, with the levelized cost of energy at parity with or better than fossil fuel generation [34]. Wind energy is beginning to expand to deep water locations, where the wind is generally stronger and steadier, but where the still-developing floating wind turbine technology is required for economic feasibility [35]. Additional renewable sources, such as marine and riverine hydropower [36]–[38], are also promising avenues for enhancing carbon-free generation. While marine energy conversion technologies are still relatively nascent, marine energy can be more reliably predicted and is steadier over time compared to wind and solar energy. All of these renewable energy technologies will be important in achieving net-zero emissions economies around the world. Opportunities for the controls community exist at multiple levels, from turbines to generator assemblies to grid interfaces.

Nuclear energy is another option for carbon-free electricity, with a large installed base. Significant nuclear

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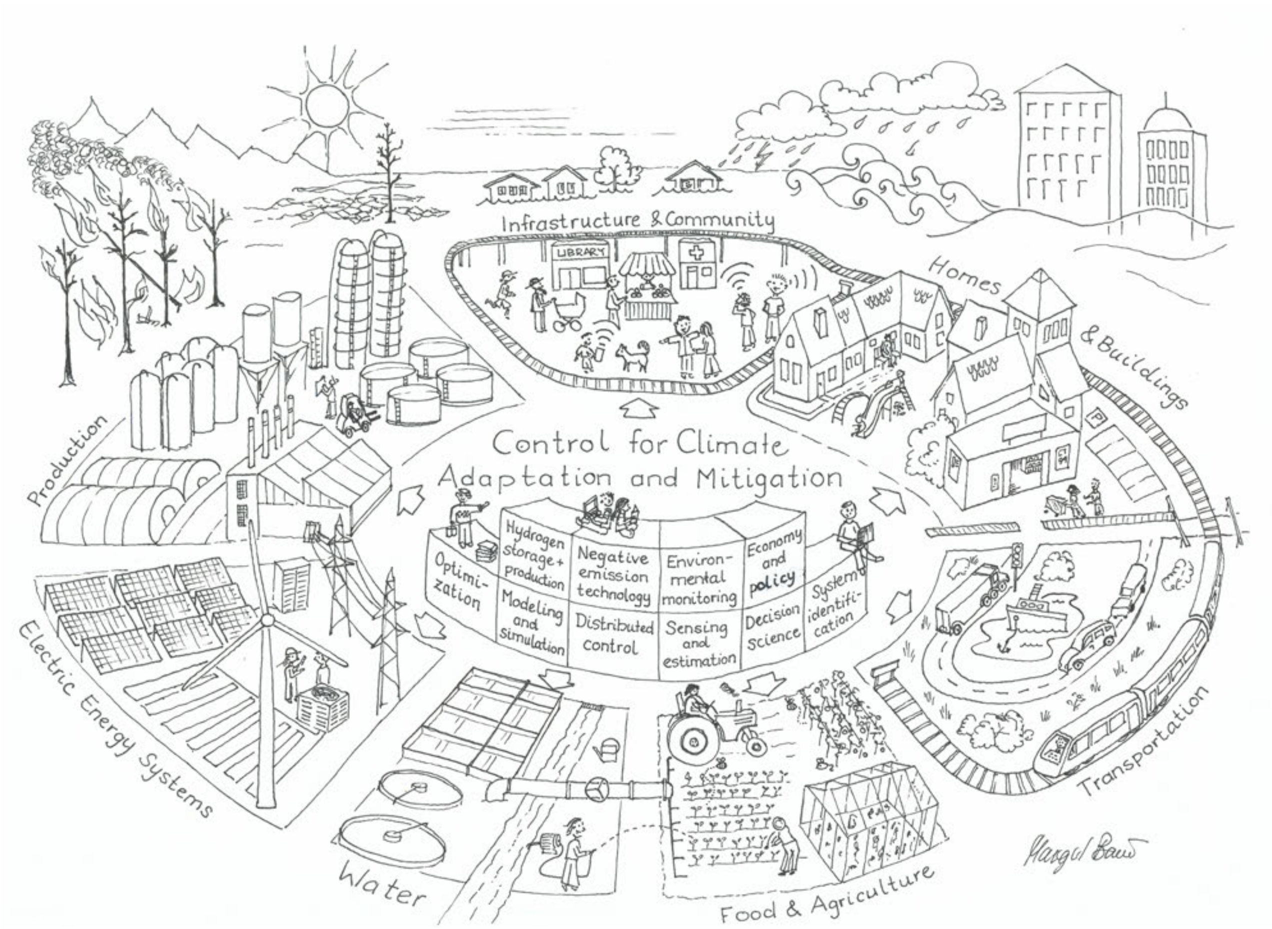

FIGURE 2 Control technology and tools can play a central role in addressing a wide range of challenges associated with climate change adaptation and mitigation. These challenges involve infrastructure and communities, food and agriculture, water, transportation, energy systems, production, homes and buildings, and other domains that directly impact humans and their interactions with the natural environment.

capacity is being added in emerging and developing economies, especially China, but in advanced economies retirements have outpaced capacity additions over the last decade [39]. New developments in the field are generating interest, however, along with opportunities for control research. Notable here are small modular reactors, several designs for which have been proposed or are under construction. At an earlier technology readiness level, nuclear fusion [40] has become a technology of great interest from governments and the private sector. See [41] for the importance of control engineering in this area.

Example opportunities include:

» Dynamic management and optimization of large-scale renewable energy generators (short-term)
» Control co-design for floating offshore wind, tidal, and wave power generators (medium-term)
» Optimization of coupled cross-sector electricity generation, including hydrogen and biofuels (long-term)

Transportation

Decarbonizing road, rail, air, and marine transportation, which accounts for about 15% of global greenhouse gas emissions, is another high priority for climate change mitigation and adaptation. For road vehicles, electric vehicles (EVs), in concert with increasing renewable generation, represent a game-changing solution. EVs have made dramatic progress over the last few years, in technology as well as deployment, and penetration rates are continuing to increase. But deep EV penetration is required—the IEA projects that oil share will need to drop to slightly over 10% in the transport sector worldwide if net-zero emissions are to be achieved by 2050 [12] — and this poses substantial technical challenges, which are opportunities for control research. Large-scale EV charging (an example of sector coupling between transportation and electricity), will place stresses on the distribution grid, requiring distributed, optimal charging algorithms [42]. Consumers, both individuals and businesses, will need to

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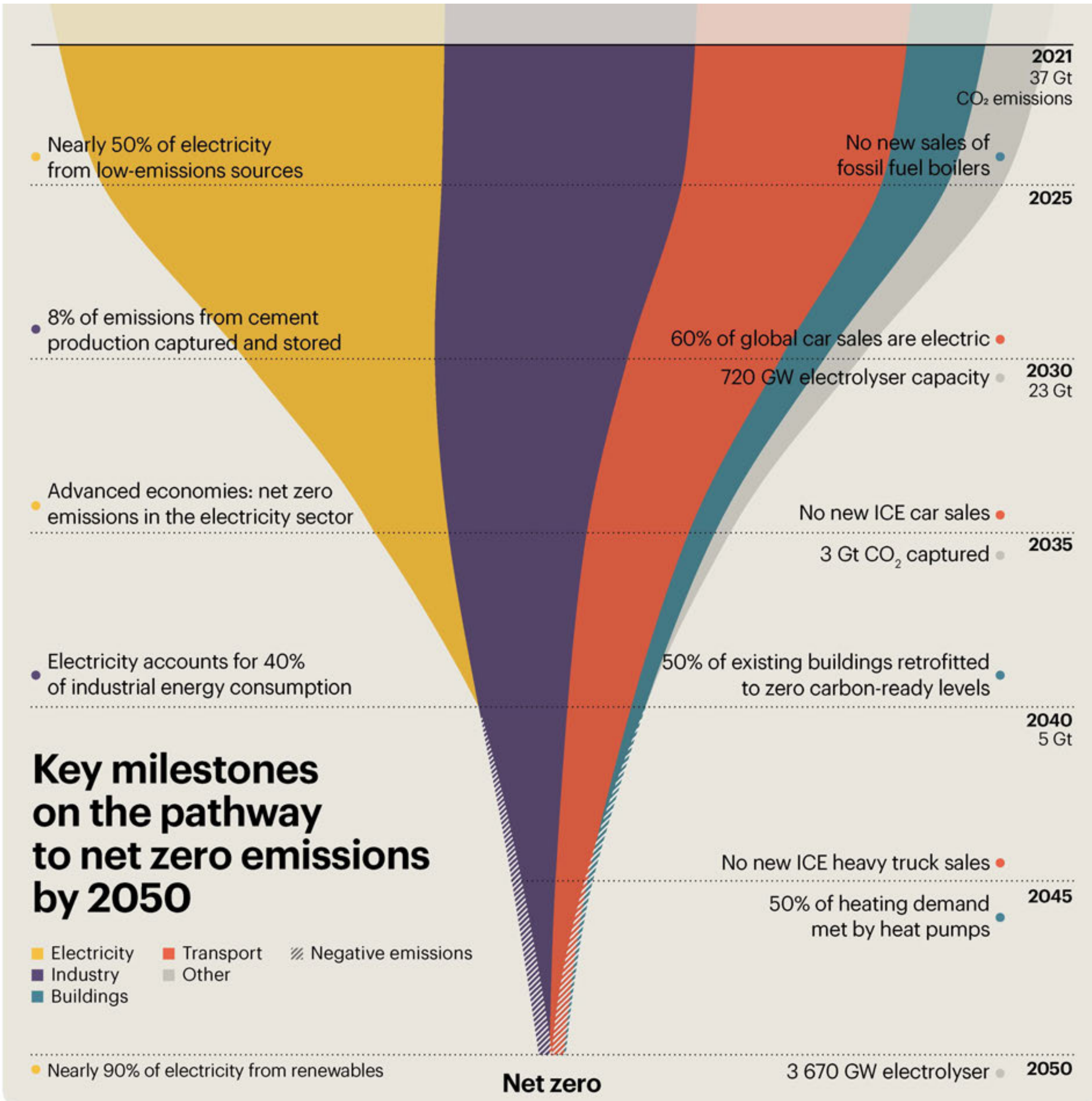

FIGURE 3 Key Milestones on the Roadmap to net-zero greenhouse gas emissions from the energy sector by 2050. Source: [24]; license: CC BY 4.0.

be incentivized, with psychological factors such as range anxiety and loss avoidance being considered. Advances in the design, modeling, and control of batteries are also a priority item.

Electric vehicles are mobile energy storage systems, the benefits of which can extend beyond the movement of people and goods. Vehicle-to-grid and vehicle-to-facility (V2X) discharging holds considerable promise, including for climate change adaptation—e.g., grid management and disaster relief. Control and optimization in this context will need to integrate geospatial, map, and weather information.

We note that the IEEE has very recently started a new journal, the *IEEE Transactions on Transportation Electrification,* for research in this topic.

The decarbonization of air and marine transport is in the exploratory stage. In addition to electrification, other energy strategies, such as hydrogen and ammonia, also need to be developed [43]. There are opportunities to use wind energy in shipping. This opens up a gamut of research opportunities for the controls community, not only at the level of individual vehicles but also for logistics

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and freight networks.

Example opportunities include:

» Sensing and control for batteries, fuel cells, and emerging powertrains such as hydrogen and ammonia (short-term)

» Novel cyber-physical-human system designs for energy-efficient smart mobility, including V2X power flows (medium-term)

» Control for decarbonization of multiscale transportation networks (long-term)

Homes, Buildings, and Facilities

Homes and buildings account for about 16-17% of global greenhouse gas emissions. Some level of decarbonization will automatically occur as renewable generation is expanded, but other opportunities in the built environment also exist. The focus should not be limited to individual buildings, whether residential or commercial; larger scales of habitation are also promising targets. We need to remember that these are places where people live and work, and thus human behavior must be considered.

A major opportunity is to match energy needs with renewables in a flexible manner, i.e., using demand management and automated demand response. Specific growth sectors such as data centers need dedicated focus. For larger facilities, microgrids are an option that can integrate onsite renewable generation, combined heat and power, electrical and thermal storage, demand response, and grid power. Islanding capabilities allow microgrids to serve climate-change adaptation and resilience purposes as well. The decision making required for coordination of assets and reliable facility operation is a complex dynamic optimization problem [44].

Alternatives to fossil fuels for heating homes and buildings are an urgent need—one of the first milestones in the IEA net zero roadmap, ambitiously targeted for 2025, is “no new sales of fossil-fuel boilers” [12]. Heat pump technology has made considerable progress but widespread penetration in all climates requires more research and development.

Example opportunities include:

» Greenhouse gas emissions-aware energy management for data centers (short-term)

» Automation and control for intelligent microgrids and demand response (short-term)

» Control codesign and operation of energy-efficient geothermal heat pumps for heating and cooling (medium-term)

Industry and Manufacturing

Approximately, 34% of global greenhouse gas emissions arise from the extensive use of power and heating in industry, and both must be addressed. In addition, the diversity of facilities implies that opportunities are sector-specific and require detailed process knowledge. Electrification of industry and manufacturing is one pathway to greener industry, but important sectors with large GHG footprints are difficult to electrify. One example is cement, which represents a vast amount of embodied carbon in construction material [45]. In some sectors, new industrial processes, with new modeling, optimization, and control needs, may need to be developed as alternatives to energy-intensive and hard-to-decarbonize processes.

A very useful and detailed review of technology options for deep decarbonization of energy intensive manufacturing can be found in [46]. This paper offers a decision-tree framework for decarbonizaton of the manufacturing sector: “1) dematerialize or recycle/reuse, 2) keep the core existing process or make fundamental changes, and 3) if the existing process is kept does one go to carbon capture and storage or to GHG free process heating?” Moves toward circular economies, which emphasize resource efficiency, reduced waste, and reuse, can also help the sustainability of manufacturing; the inherent feedback loops involved imply strong control connections. It is quite evident that there are numerous opportunities for manufacturing process modeling, sensing, control, and optimization in this area.

The tools unleashed by Industry 4.0, or “Smart Manufacturing” technologies, offer transformative potential for enabling a steady transition towards net zero greenhouse gas emissions. Notable among these are digital twins, artificial intelligence and machine learning, industrial internet of things (IIoT), intelligent sensors, and 5G/6G networks [47]. Control engineers can (and should) take the initiative in exploiting the numerous synergies with their areas of expertise.

Example opportunities include:

» Advanced process control, optimization, and data analytics over the manufacturing value chain, for increased energy and operational efficiency, utilization of waste heat, and equipment transitions towards greener fuels (short-term)

» Control co-design for greenfield net-zero projects leveraging Industry 4.0 enablers (medium-term)

» Process design, control, and optimization for monitoring, capturing, and storage of greenhouse gases (methane, CO_2) and for utilization of captured gases (long-term)

Data, Computing, and Communications

The estimated amount of computation used to train deep learning neural network models increased 300,000 times between 2012 and 2017 [48]. Computational workloads for AI and digital transformation are expected to grow up to 100-fold, outstripping GPU scaling and Moore’s law [49]. Since 2010, global internet traffic has expanded 20-fold [50]. Crypto mining energy use has expanded about

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3,000% from 2015 to 2022. The climatic repercussions of large-scale information and computing technologies (ICT) can no longer be ignored.

These growth rates for data services would portend catastrophe if not for favorable developments related to energy efficiency and renewable energy usage [50]. Energy use in large data centers has grown 20-40% annually over the past several years, but estimated electricity consumption in data centers globally is limited to 1 – 1.3% of global final electricity demand. This statistic, however, excludes energy used for cryptocurrency mining, which is estimated to have accounted for another 0.4% of global electricity demand in 2022. The efficiency gains extend to data transmission networks as well, which are also responsible for 1 – 1.5% of global electricity use. Mobile-access network energy efficiency has improved by 10 – 30% annually recently. Major European telecom network operators reported tripling of data traffic but only 1% electricity consumption growth.

Emissions have also grown modestly. Data centers and data transmission networks accounted for about 0.9% of energy-related GHG emissions, or 0.6% of total GHG emissions) in 2020. The trends are favorable in the context of the dramatic growth in data services, but they are still in the wrong direction. The current explosion of interest we are witnessing in generative AI is another cause for concern on GHG emissions. IEA's Net Zero by 2050 Scenario suggests that emissions related to data services will need to drop by half by 2030. For an example of the use of stochastic control formulations for the use of renewable energy in data centers, see [51].

Example opportunities include: :

» Energy optimization of algorithms, on both software (e.g. model architectures in machine learning, performance optimization in blockchain networks) and hardware (e.g. hardware-aware execution control) levels (short-term)

» Optimization of computing infrastructure and hardware, encompassing data storage, parallelization, and repurposing (medium-term)

» Development of distributed or decentralized algorithms, leveraging large-scale edge and cloud computing and optimizing resource allocation based on greenhouse gas considerations (medium-term)

Hydrogen Ecosystem and Renewable Fuels

The developing hydrogen ecosystem, spurred by substantial financial investments globally, is offering significant opportunities for engineers and scientists working in process measurements and control systems research and development as well as in project lifecycle implementation. Major hydrogen strategies have been announced in the EU, Japan, China, US, India, Australia, and other nations. For example, a current focus in the U. S. is on regional clean hydrogen hubs [52] with plans for concentrated clusters at one site integrating hydrogen production, storage, transportation, and utilization; new ideas for control systems integration and network planning will be needed.

In addition to its demand as a replacement for fossil fuels, hydrogen is an important commodity used in large quantities in many industrial processes such as petroleum refining, fertilizer and other chemical production, treatment of metals, and food processing. Hydrogen and its derivatives are expected to contribute 10% of the total emissions reductions towards the net-zero path by 2050 at the lowest cost [53], equivalent to 80 GT of CO_2. Clean hydrogen and synthetic hydrogen-based fuels such as ammonia, methanol, and e-methane are thus growth areas of opportunity.

Green hydrogen, where the power required for electrolysis and other processes comes from renewable sources, (or pink/red hydrogen from nuclear power), is the ideal solution for producing hydrogen. At least in the near term, blue hydrogen, with natural gas and carbon capture, utilization, and storage (CCUS) is also a promising growth area [54], and a potential application for control co-design concepts [3] as well.

Example opportunities include:

» Design and implementation of control systems for production of green hydrogen, including electrolyzers and repurposing of existing carbon-intensive industrial equipment to clean-burning hydrogen or other low-carbon fuel options (short-term)

» Control systems design, development and engineering in the expanding infrastructure around carbon capture, transportation and sequestration technologies, where hydrocarbons such as natural gas are used for production of hydrogen, or for other chemical processes (medium-term)

» Integrated, networked planning and control for hydrogen hubs and clusters (long-term)

Food and Agriculture

Agriculture, forestry, and land use activities account for 22% of global greenhouse gas emissions. In addition, the impact of climate change on crop cultivation is expected to be drastic. This sector will need to rapidly evolve in order to gain flexibility and adaptability to environmental changes and to optimize production. Opportunities exist in land-use management, farming processes, and food distribution, among others.

The development of the Agriculture 4.0 paradigm–the integration of sensors, actuators, algorithms, and digitalization–is especially notable for control researchers. Agriculture 4.0 comprises a set of technologies that combine sensors, enhanced machines and equipment, information systems, and intelligent decision and management with the objective of optimizing production by accounting for

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variabilities and uncertainties within agricultural systems. The concept of Agriculture 4.0 consists in the harmonious and interconnected use in agriculture of two different digital technologies: (i) precision agriculture for carrying out targeted agronomic interventions, which take into account both farming requirements and the physical and biochemical features of the land; and (ii) smart farming, i.e., the digital connection between field activities and all other related processes. Autonomous multimodal and multivehicle systems are among the visions being explored [55].

The entire food supply chain also presents opportunities for control. The perishable nature of food products, which is not a factor in many other supply chain applications, is an important dynamical aspect that must be considered. On the land-use side, agrivoltaics represent an opportunity to integrate farming with power generation [56].

Example opportunities include:

» Coordination of uninhabited aerial and ground vehicles for agriculture and other land use (short-term)
» Management and optimization of food supply chain for sustainable product distribution integrating greenhouse gas footprints (medium-term)
» Control of agrivoltaics for integrated agriculture and power generation (medium-term)

Water

The deleterious impacts of climate change on water are numerous and evident. Most fundamentally, climate change is leading to more extreme and frequent droughts, flooding, storms, etc. [11], [57], [58]. Because of excessive extraction to support human activities, water levels are already being depleted in rivers, streams, aquifers, and freshwater lakes. On the other hand, sea level rise will increasingly impact water systems in coastal regions. Water scarcity is affecting agriculture worldwide. If left unaddressed, the adequacy of food supplies for a growing global population will be in question.

Hydropower causes sector coupling between energy system decarbonization and adaptation to water related issues. Increased frequencies of floods and storm surges raise a different kind of critical concern, one that relates to climate change adaptation as well as mitigation. As a result, water system management, control, and optimization is a major opportunity [59], [60]. One of the most important contributions we can make is to leverage and substantiate "measure-model-manage" as a paradigm.

Example opportunities include:

» Management and optimization of agricultural irrigation and its associated infrastructure (short-term)
» Development of dynamic models and control strategies for water conservation in communities, including behavioral change (medium-term)
» Control and optimization of water treatment, including resilient and autonomous mobile facilities (medium-term)

Infrastructures and Communities

An outcome of climate change is that extreme weather is becoming an increasingly serious threat to critical infrastructures such as electric power grids, transportation (road, rail, and air) systems, water treatment and distribution, communication networks, and public safety. Some of these infrastructures are critical targets of opportunity on their own and are discussed in other sections. However, many infrastructures have dynamic interdependencies: power and gas, power and transportation, transportation and communications. Currently, models, tools, and methods for spatiotemporal allocation of resiliency-improving resources for safe operations, distributed energy supply, and demand management are limited in their ability to account for impacts of extreme weather, stakeholder preferences about infrastructure deployment, and prevailing social and political economy constraints [61]. To address these limitations, we need to advance the state-of-the-art on three fronts: predictive modeling and uncertainty characterization about extreme-weather and correlated failure events; risk-aware and equitable allocation of distributed resources to hedge against the impacts under a range of contingency scenarios; and network control under disruption modes that integrate both automatic and human-mediated response actions.

Current technology and policy trends for achieving net-zero (or net positive) targets suggest that such design decisions for critical interdependent infrastructures must account for cross-sectoral coupling to support a range of functionalities in a cost-effective and reliable manner. For example, increasing electrification in building and transportation sectors, integration of variable renewable energy generation sources, and cross-sectoral emissions trading essentially make the design of future electricity and natural gas infrastructure a joint planning problem [62]. Here, we must also consider demand and supply shifts under climate-induced interannual weather variations and tight operational constraints of the systems, which typically operate under different timescales. We believe that advances in data-driven stochastic and robust optimization (and control) can play a significant role in systematic modeling of such design problems and their algorithmic implementations.

Traditionally, coastal cities are protected with hard structures that reflect a storm's energy; but these solutions are not effective in dissipating energy and often become ineffective due to erosion and flooding of unprotected neighboring regions. Recently there has been a significant interest in nature-based solutions or coastal green infrastructure such as mangroves, marshes, and coastal

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forests. While researchers from the environmental and coastal hydrodynamics community and urban planners have already embarked on the agenda of modeling and planning of green infrastructure, the control systems community can play a significant role by providing solutions to monitor coastal infrastructure, evaluating damage by utilizing predictive information on storm surges and flooding, and designing adaptive (i.e., control-based) solutions to limit disruptions of critical infrastructure in coastal zones. A related avenue of research is to advance autonomous systems for monitoring human health and dispatching humanitarian assistance and disaster response in the wake of events such as hurricanes, extreme floods, and wildfires.

Example opportunities thus include:

» Strategic allocation of distributed resources in infrastructure and infrastructure networks in extreme weather and climate events for adaptation and repair (medium-term)
» Design of net-zero (or net-positive) smart cities with holistic models encompassing multiple vertical functions (medium-term)
» Design of resilient coastal structures and management systems capable of withstanding expected sea-level rise (long-term)

Negative Emissions Technologies

Completely eliminating the use of fossil fuels is thought to be close to impossible even by 2050 or beyond. Their use in buildings, transport, industry, agriculture, and even electricity production will continue in many parts of the world for decades to come. While certain greenhouse gases have relatively short lifetimes (making them particularly important targets for more immediate focus for reduction), CO_2 lifetime is in thousands of years [63]. As a result, most global warming roadmaps include the need for developing technologies that can remove CO_2 from the atmosphere or the oceans. Since they are likely to be needed in the future, it is important to focus research efforts on such technologies [64].

The captured CO_2 can then be stored in geological or biological sinks or in valuable products. There are two principal approaches to removal of CO_2: natural climate solutions (forests, coastal wetlands, regenerative farming) and engineered systems for carbon capture, utilization and storage (CCUS). (There are some approaches that combine these two, for example, bioenergy with CCUS.) Engineered technologies for CCUS is an active area of research and innovation. Recently, the U. S. Department of Energy has announced a "carbon shot" with the goal of developing technologies that can capture CO_2 from the atmosphere and store it at gigaton scales for less than $100/net metric ton. In addition to technological research, setting a market context that can incentivize the development of negative emissions technologies will be important.

Example opportunities:

» Design and control of direct-from-air CO_2 capture systems (medium-term)
» Measurement, tracking, and optimization of emerging carbon markets (medium-term)
» Design and operation of artificial photosynthesis systems (long-term)

Geoengineering

Geoengineering refers to deliberate, large-scale interventions in the earth's climate system. (Some of the negative emissions technologies discussed above are sometimes included in geoengineering.) Solar radiation management is the idea of cooling the planet by reflecting a fraction of incoming solar radiation back before it reaches the earth. It is a controversial idea but one that is being investigated and is a potential research topic. In 2021, the U. S. National Academies of Science, Engineering and Medicine released its report on solar radiation management [65]. Proposed approaches to solar radiation management include stratospheric aerosol injection (SAI), thinning high clouds so that more heat can escape, increased scattering by brightened clouds, and space reflectors. Ocean fertilization, another geoegineering approach, refers to the idea of adding nutrients to the upper layers of the ocean to stimulate phytoplankton activity and reduce atmospheric CO_2.

As processes and impacts of solar geoengineering interventions are not well understood and have numerous, potentially serious, negative consequences [66], considerable caution needs to be exercised in even contemplating such geoengineering projects–and control scientists can help sound alarm bells where needed. We have included this topic here because of the crucial role that controls can play, especially regarding the understanding and analysis of long-term dynamics under uncertainty. Example opportunities include:

» Modeling and estimation of solar radiation management interventions using ground-based, airborne, and spaceborne instruments (medium term)
» Modeling of ultrascale spatiotemporal ecosystems, taking into account the interconnections among terrestrial, oceanic, and atmospheric dynamics (long-term)
» Risk-sensitive optimization and control under high long-term uncertainty, with awareness of the potential for catastrophic unmodeled effects (long-term) (long-term)

Environmental Monitoring

The truism that we cannot control what we cannot measure is relevant for climate change mitigation and adaptation. Sensing, estimation, and monitoring will be necessary to assess continuing greenhouse gas emissions and the effectiveness of control strategies for reducing them. Instrumen-

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tation on the ground, on and underwater, in the sky, and in space will be required, along with integrated analytics incorporating spatiotemporal dynamic models. For example, internet-of-things technologies, which are being deployed for such monitoring [67], provide a foundation upon which more sophisticated estimation and control techniques can be developed.

Environmental monitoring is needed across the planet. The management and conservation of forests, which are effective carbon sinks that can absorb and lock-up greenhouse gases for extended time durations, is one priority topic. To be effective, environmental monitoring must be undertaken as an international collaboration. In this regard, collaborative efforts with UN World Meteorological Organization (WMO), NASA, NOAA, ESA, and other similar national and international organizations should be explored.

Example opportunities include:

» Fault detection and alarm management for large-scale instrumentation networks (short-term)
» Regional and planetary-scale spatiotemporal estimation and filtering (medium-term)
» Cooperative monitoring of the environment with fixed and mobile sensors (medium-term)

Socio-Technical Systems

It is now well-understood that advances in solving the complex problems facing the world today will not be made only by engineers and scientists. Nor will they be solved alone by social scientists and policy makers. Instead, the problems are inherently socio-technical in nature and must be solved through transdisciplinary collaborations among specialists from many fields. These may not be control problems, but they are fundamentally system-theoretic problems and abound with multiscale dynamics, distributed interconnected agents, extensive uncertainty, and feedback. A broader systems thinking perspective is required [68], [69]. The control systems community has tools to help address these problems, but more work is needed to render these tools useful and usable beyond the siloed technical applications in which they are employed today.

As we dramatically broaden, or attempt to broaden, the span of systems and control in as human- and planet-centered a context as climate change, we need to be cognizant not only of application domains but also of societal, economic, and environmental underpinnings and overlays. Decisions concerning energy and infrastructure systems have time horizons that last decades. They must be made in the face of very large uncertainties. The emerging field of decision making under deep uncertainty [8] offers potential for new directions by leveraging knowledge from control and decision theory. The interconnections among different critical infrastructure sectors have been noted above, but interplays with societal imperatives, such as resilience, equity, and social justice must also be brought within our methodological frameworks, and will be especially crucial for climate-change adaptation strategies.

Example opportunities include:

» Explicit design for energy justice incorporating the social impact of grid generation and distribution (medium-term)
» Modeling and control of distributed, socio-technical systems under large-scale uncertainty (medium-term)
» Integrated policy and infrastructure design for climate-change adaptation in affected communities (long-term)

Broader Perspectives

Climate change mitigation and adaptation is complex and not just an engineering or technology problem. It requires a collaborative effort among engineers, technologists, economists, and those developing social, regulatory, and public policies. We need to be aware of this broader context as we develop frameworks for impactful research, education, and real-world translations. The social licence for technological innovation and transformation is hard to obtain, easy to lose, and requires constant communication and demonstration of the benefits.

Sustainable Economic Growth

Sustainability requires a balanced interplay between society, the economy, and the environment. The key question to address is how we can create and maintain a prosperous society with high quality of life for all, without the negative impacts that have historically harmed our environment and communities in the name of development. Economic growth is part of the solution, particularly for developing nations that need to raise standards of living and improve health, nutrition, and education for billions of people. Economic growth must be accomplished while effectively managing natural resources and preserving them for current and future generations. Our vision needs to shift from consumption and waste to regeneration and recirculation–a shift that will enable future generations to thrive.

From a climate change mitigation perspective, we must minimize the need for fossil fuel energy sources while meeting economic growth targets. This is a major challenge and requires efforts in a range of directions. Rapid reduction in the costs of mitigation technologies will surely help. However, given that such cost-competitive technologies do not either currently exist in several areas or cannot be deployed fast enough, we can expect that fossil fuel-based energy sources will be used for a few decades to come as can be seen in the IEA Net Zero roadmap [12].

It is also important to steer economic growth toward a sustainable future, i.e., green growth. Investments in sus-

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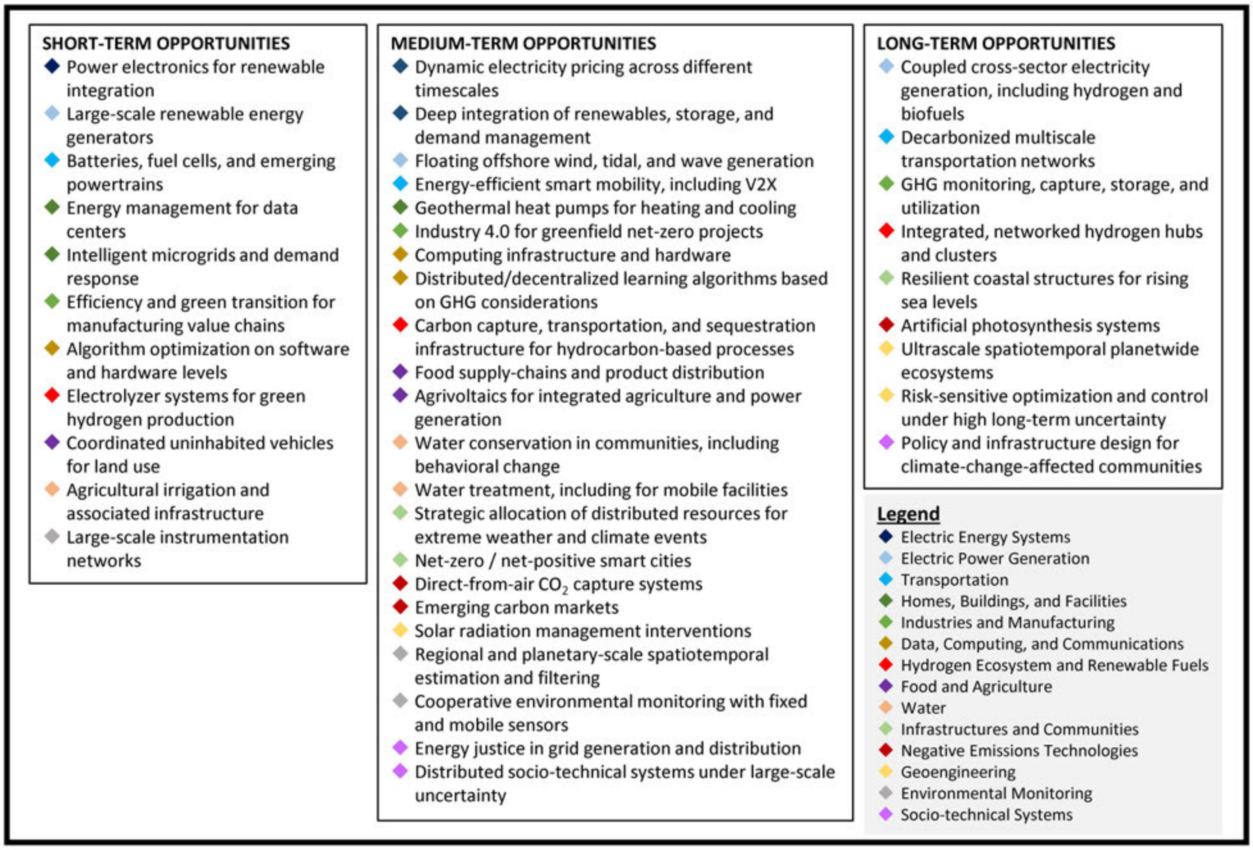

FIGURE 4 Selected opportunities for control scientists and engineers to address climate change and mitigation. The color coding indicates the subsection in this article where the topic is further elaborated.

tainable development, elimination of fossil fuel in various sectors, creation of circular economies, and climate change adaptation and resilience can enable economic growth and long-term sustainability.

From Research to Large-Scale Deployment

Climate change mitigation and adaptation require solutions that can be implemented at scale. Typically, energy-generating and energy-consuming systems are large-scale systems, e.g., electric grids, transportation, buildings and cities, and manufacturing. Because we are in a race to decarbonize the energy system before global warming exceeds 2°C or even goes well beyond, the transition from research to large-scale deployment is a major challenge. Dramatic reductions in the costs of wind and solar electricity are, therefore, inspiring developments.

Fortunately, there is an increasing understanding of research-based innovations. National-scale testing and experimental infrastructures will be needed. Government funding agencies are increasingly focusing on the need for high-impact innovations. While approaches to scaling of solutions to climate mitigation are becoming increasingly clearer, analogous approaches to scaling of climate change adaptation and resilience solutions are in their infancy. The controls research community should systematically, creatively, and aggressively think about the research-to-real-world transition.

Tight coordination and collaboration between academic researchers and industrial communities can be especially helpful. Developing collaborative networks with shared goals, datasets, and mutually reinforcing activities can be a powerful approach to ensure research results have real-world impacts. Closer ties with policymakers and regulatory bodies will be needed to expedite the adoption and scale-up of solutions.

Education and Awareness

Today's students are deeply interested in and motivated by climate change mitigation and adaptation. Many of them see these as "their problems" that their generation

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will have to deal with. There is little doubt that many students interested in control systems are also interested in the challenges posed by climate change. As such, there are opportunities to include topics related to climate change in undergraduate and graduate-level controls education. These can range from using examples and projections of climate change impacts in undergraduate courses to multi-disciplinary advanced courses at the M.S. and Ph.D. levels. A specific opportunity is a course on control methods for sustainability.

Data assimilation techniques, which are based on foundational techniques of Kalman filtering and other estimation techniques, have become mainstream in numerical weather prediction [70], [71] and are now being explored in climate modeling [72], [73]. These are examples of the relevance of systems and control fields to climate as a dynamical system. Awareness of the relevance of control science and engineering to climate, energy, and sustainability needs to be instilled in the broader public –an audience that educators within our discipline rarely reach out to.

Equity and Social Justice

Historically, the effects of climate change and environmental degradation have dramatically impacted the disadvantaged and poorer sections of society worldwide. For example, the impact of fossil fuel plants on air quality has been disproportionately borne by poor and minority communities. Similarly, climate change impacts such as flooding, droughts, and wildfires disproportionately impact these same communities. Heat waves affect poor households without adequate air-conditioning, leading to loss of life. Sea level rise is expected to affect poorer nations, leading to large migrations. Developing nations have borne the brunt of climate change yet have made a relatively small contribution to global warming. These are the nations that need better energy infrastructures in order to develop their economies.

The relationship between economic, social, and global inequality and environmental degradation is complex [74]. Ironically, unless implemented with appropriate considerations, commercialization of new climate-related technologies can further exacerbate issues of economic and social inequality. For example, cheap solar PV and electric vehicles might not be affordable to poorer segments of the population, putting them at a further disadvantage in benefitting from subsidized energy technologies. Perversely, the increased costs of climate change mitigation and adaptation might worsen the burdens on disadvantaged communities.

The controls community must be fully cognizant of these energy justice, inter-generation equity, and global economic development issues as it engages in work related to climate change mitigation and adaptation.

Transdisciplinary Collaborations

It is important to note that climate change mitigation and adaptation problems are beyond the remit of any single discipline. Progress on climate change problems will require collaboration among engineering, business, social-economic-behavioral sciences, and humanities. The controls community does not necessarily have the right models to deal with these broader perspectives, particularly where socio-economic-technical intersections occur.

Thus, it is not helpful to think of these problems as control problems per se. Rather, the controls community should partner with experts from other domains and fields to form collaborative teams to address the large-scale, urgent, and daunting challenges. Forming such teams is a challenge considering the additional time and resources needed to develop effective and functional teams. Fortunately, there is a large body of literature, tools, and techniques for convergent transdisciplinary research and innovation [75], [76]. The controls community should also be proactive in rewarding and recognizing its members working on such collaborations, as their work does not easily fit into the traditional framework for publications, presentations, and professional advancement.

Concluding Comments

The enormous challenges posed by climate change mitigation and humanity's sustainable adaptation to its effects offer signature opportunities for systems and control scientists and engineers. As is evident from this article, the scope and scale of opportunity for the controls community are broad and deep, spanning numerous technology and industry sectors. Multiple, specific challenges in these sectors offer opportunities for examination by experts in systems, design, modeling, controls, decision-making, optimization, and related topics. A summary of the opportunities examined in this chapter–recognizing that these are but a subset of the vast array of opportunities open to the controls community to showcase its capabilities to help address climate change and mitigation–is shown in Figure 4.

The climate change challenge is of urgent and existential importance. It renders historical paradigms of control-centric research, translation, and development inadequate. Transdisciplinary collaborative partnerships are necessary, and these must extend beyond science and engineering disciplines to also embrace the humanities and social sciences. Early engagement with industry and government will also be crucial so that deployments can take place at scale and as rapidly as possible. We have humanity's future to gain but little time to lose.

Call to Action: SIDEBAR?

For young researchers

Climate change is among humanity's most important challenges, if not the single most important. It will affect our lives and our communities for decades to come. It encompasses a very large and diverse set of technical topics. Because of its inherently transdisciplinary nature, it will catalyze continued intellectual growth and ever-expanding perspectives. You will have opportunities to work with colleagues from other fields of knowledge on collective goals. You will also have opportunities to work in a variety of organizations, including academic, private industry, non-profit, policy, and government.

For systems and control professional organizations

Professional societies such as the International Federation of Automatic Control, the European Control Association, the Asian Control Association, the IEEE Control Systems Society, the American Society of Mechanical Engineers, the American Institute of Chemical Engineers, the Society for Automotive Engineering, and other national and international organizations should provide appropriate organizational leadership so that control systems researchers and practitioners have ample opportunities to exchange ideas, undertake impactful projects, and receive suitable encouragement and recognition from engaging in climate and energy related research. Special sessions, conferences, journal issues, and new publications should be considered. It is important for the leaders of professional societies to recognize that engaging in research related to climate change topics may be outside the comfort zone of many researchers due to the fundamentally interdisciplinary nature of climate change research.

For funding agencies

The importance of climate change cannot be emphasized enough. To address this challenge and develop urgent and effective solutions, robust financial and programmatic support from government, private, and philanthropic organizations is essential. There is a great variety of research topics within this overall theme. Thus, one or more of these topics is likely to align with any given funding agency's goals. It is very important to keep in mind that climate change research is inherently transdisciplinary. Control systems experts can make important and essential contributions. But to realize this potential, research funding programs should be designed with care, encourage transdisciplinary collaborations, and include systems and control in such program designs.

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