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AI-Driven Sustainable Infrastructure Development

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ABSTRACT

The global imperative to build and maintain infrastructure that is simultaneously resilient, economically viable, and environmentally sustainable has intensified over recent decades. As urbanization accelerates, climate change introduces unprecedented stresses on physical systems, and resource constraints tighten, traditional approaches to infrastructure planning and management are proving inadequate. Artificial intelligence (AI) has emerged as a transformative force capable of fundamentally altering how infrastructure is conceived, constructed, operated, and maintained. This article examines the convergence of AI technologies and sustainable infrastructure development across multiple domains, including energy systems, transportation networks, water management, smart cities, and climate adaptation. It analyzes the mechanisms through which machine learning, deep learning, computer vision, natural language processing, and optimization algorithms are being deployed to improve efficiency, reduce emissions, minimize waste, and enhance the adaptive capacity of built environments. The article further explores the governance, ethical, and equity dimensions of AI-driven infrastructure, arguing that technological capability alone is insufficient without robust institutional frameworks and inclusive design principles. Drawing on emerging case studies and theoretical frameworks, the article concludes that the responsible integration of AI into sustainable infrastructure development represents one of the most consequential opportunities for addressing the interconnected crises of climate change, urban inequality, and resource depletion in the twenty-first century.

1. Introduction

Infrastructure forms the physical backbone of modern civilization. Roads, bridges, airports, power grids, water treatment facilities, telecommunications networks, and urban drainage systems collectively enable economic activity, social interaction, and the basic functions of daily life. Yet the infrastructure that sustains contemporary societies was largely designed and built under assumptions that no longer hold: stable climate conditions, predictable demand patterns, cheap fossil fuels, and relatively modest population concentrations. Today, each of these assumptions is under pressure.

The Intergovernmental Panel on Climate Change has repeatedly warned that unless greenhouse gas emissions are dramatically curtailed within the coming decades, average global temperatures will rise to levels that impose severe and potentially irreversible consequences on both natural and built environments. Flooding, extreme heat events, prolonged droughts, and intensified storm systems are already placing infrastructure systems under stresses they were not engineered to withstand. At the same time, rapid urbanization, particularly across the Global South, is creating enormous demand for new infrastructure, much of it in regions that lack the capital, institutional capacity, or technical expertise to deploy it effectively.

Into this context of converging pressures, artificial intelligence has arrived with remarkable speed and scope. Over the past decade, the dramatic expansion of computational power, the proliferation of sensor technologies and the Internet of Things, and the accumulation of vast digital datasets have combined to make AI tools not merely theoretically useful but practically deployable across a wide range of infrastructure applications. Predictive maintenance systems that detect the early signs of structural fatigue before catastrophic failure occurs, optimization algorithms that balance renewable energy supply with fluctuating demand in real time, and autonomous monitoring systems that can survey thousands of miles of pipeline with minimal human intervention are no longer speculative possibilities. They are operational realities in an increasing number of jurisdictions.

This article seeks to map the landscape of AI-driven sustainable infrastructure development in a comprehensive and critical manner. It begins by situating AI within the broader history of technological transformation in infrastructure planning and management. It then examines specific domains where AI applications are demonstrating measurable sustainability benefits, analyzes the challenges and risks that accompany the rapid deployment of these technologies, and concludes with reflections on the governance and equity dimensions that will determine whether AI serves as a genuinely democratizing force or merely deepens existing inequalities in infrastructure access and quality.

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2. The Historical Context of Technology and Infrastructure

To appreciate the significance of AI's role in sustainable infrastructure, it is useful to recall the long history of technological disruption in this domain. The industrial revolution fundamentally transformed infrastructure development through the application of steam power, iron and steel manufacturing, and advances in civil engineering. The construction of railways, canals, and the great urban sewage systems of the nineteenth century were feats of engineering that reshaped economies and societies. The twentieth century brought a second wave of transformation through electrification, the internal combustion engine, reinforced concrete, and digital computation. Each of these technological revolutions created new possibilities but also new dependencies, vulnerabilities, and environmental consequences.

The environmental costs of twentieth-century infrastructure development have been substantial. The carbon-intensive construction of highways, airports, and industrial facilities; the ecological disruption caused by large dams and flood control projects; the contamination of groundwater by poorly designed waste systems; and the urban heat island effects generated by vast expanses of impervious surfaces represent a legacy of damage that contemporary infrastructure policy must grapple with alongside the imperative to build new systems.

What distinguishes the present moment is not simply the introduction of a new technology but the convergence of a technological revolution with an urgent sustainability mandate. AI offers capabilities that are qualitatively different from earlier computational tools: the ability to learn from experience, to identify patterns in datasets of a scale and complexity that exceed human cognitive capacity, to adapt to changing conditions without explicit reprogramming, and to optimize across multiple competing objectives simultaneously. These capabilities are precisely what sustainable infrastructure development requires, because sustainability inherently involves navigating complex trade-offs across environmental, economic, and social dimensions that change over time and differ across spatial scales.

3. AI Applications in Energy Systems

The energy sector represents perhaps the most advanced frontier of AI-driven sustainable infrastructure development. The transition from fossil fuel-based power systems to those dominated by renewable energy sources introduces profound operational challenges. Solar and wind generation are inherently variable, producing electricity in patterns determined by weather and time of day rather than by demand. Managing power grids that incorporate large proportions of variable renewable energy requires real-time balancing of supply and demand at a level of precision and speed that exceeds traditional control systems.

Machine learning algorithms are being applied to forecast renewable energy generation with increasing accuracy, integrating data from satellite imagery, weather models, and historical performance records to predict solar irradiance and wind speed hours and days in advance. These forecasts enable grid operators to manage dispatch more effectively, reducing the need for expensive and polluting peaking power plants that are fired up only to cover short-term supply deficits. Reinforcement learning techniques are being deployed to optimize the operation of battery energy storage systems, determining when to charge and discharge storage assets to maximize their value in stabilizing grid frequency and voltage while minimizing battery degradation.

In building energy management, AI-powered systems are demonstrating significant efficiency gains by learning the thermal behavior of individual structures, occupancy patterns, and the relationship between indoor conditions and energy consumption. Systems that can predict how a building will respond to changes in HVAC settings, adjusting heating and cooling proactively rather than reactively, have been shown to reduce energy consumption by fifteen to thirty percent in commercial buildings without compromising occupant comfort. These gains, multiplied across the millions of commercial and residential buildings in major urban areas, represent a substantial contribution to emissions reduction.

The development of virtual power plants, in which AI platforms aggregate the distributed energy resources of thousands of individual solar installations, battery systems, and smart appliances into a coherent, dispatchable

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resource, is creating new possibilities for community-scale energy management. Algorithmic coordination allows these distributed assets to respond to grid signals collectively, providing services previously available only from large centralized generators while simultaneously enabling households and communities to participate actively in the energy transition and capture economic benefits from their investments in distributed generation.

4. Transforming Transportation Networks

Transportation infrastructure is both a major contributor to greenhouse gas emissions and a critical arena for AI-driven sustainability innovation. Surface transportation accounts for approximately twenty-three percent of global carbon dioxide emissions, and urban congestion imposes enormous economic costs while generating concentrated air pollution that disproportionately affects communities located near major roads and highways. AI is being deployed across the full lifecycle of transportation infrastructure, from design and construction through operations and maintenance.

In urban traffic management, machine learning systems that analyze real-time data from cameras, loop detectors, GPS traces, and mobile devices are enabling adaptive signal control that responds dynamically to actual traffic conditions rather than following fixed timing plans. Cities that have implemented AI-driven adaptive signal control have reported reductions in average travel time, fuel consumption, and vehicle emissions, with some systems demonstrating improvements of fifteen to twenty-five percent compared to conventional signal control. The aggregation of these improvements across dense urban street networks represents a meaningful contribution to reducing the environmental footprint of urban mobility.

The emergence of autonomous vehicles represents a more radical transformation, though its ultimate sustainability implications remain contested. Optimistically, autonomous vehicles could reduce energy consumption through smoother acceleration and deceleration profiles, enable denser vehicle platooning on highways, and facilitate the transition to shared mobility models that reduce the total number of vehicles on the road. More pessimistically, the energy demands of onboard AI computing systems, the potential for induced demand as autonomous vehicles make travel more convenient, and the risk that autonomous technology will primarily benefit wealthy individuals and accelerate suburban sprawl could outweigh these potential benefits. The sustainability outcomes of autonomous vehicle adoption will depend critically on policy decisions about how the technology is integrated into broader transportation and land use systems.

AI is also proving valuable in infrastructure condition monitoring and maintenance planning for transportation assets. Computer vision systems that analyze imagery from drones, satellites, and inspection vehicles can detect pavement cracking, bridge deck deterioration, and rail track defects at scales and with a consistency that human inspectors cannot match. Predictive maintenance models that integrate sensor data from structural health monitoring systems with historical maintenance records and environmental data can identify assets most likely to require intervention in the near term, enabling transportation agencies to allocate scarce maintenance budgets more effectively and extend infrastructure service life.

5. AI in Water Management and Resilience

Water infrastructure represents one of the most complex and consequential domains for AI application. Water systems must simultaneously satisfy demands for drinking water, agricultural irrigation, industrial uses, and ecological flow requirements while managing the risks of flooding, drought, and contamination. These demands are being intensified by climate change, which is altering precipitation patterns, accelerating glacier melt, raising sea levels, and increasing the frequency and intensity of extreme weather events.

In water distribution networks, AI-powered leak detection systems are demonstrating the ability to identify and localize pipe leaks with far greater precision and speed than traditional acoustic inspection methods. By analyzing pressure signals, flow measurements, and acoustic data from networks of sensors, machine learning models can pinpoint the location of leaks within small segments of pipe, enabling maintenance crews to excavate only where necessary and reducing the time during which water is lost to leakage. In many municipal water systems, leakage

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accounts for fifteen to forty percent of treated water production, representing not only a significant financial loss but a substantial waste of the energy and chemicals consumed in water treatment.

Flood forecasting and management represents another domain of active AI application. Hydrological models that integrate data from rain gauges, stream gauges, soil moisture sensors, and radar precipitation estimates have long been the foundation of flood warning systems. AI techniques, particularly deep learning models applied to time series data, are enabling more accurate short-term flood forecasts that can provide communities with additional hours of warning time, enough to evacuate vulnerable populations, close flood barriers, and position emergency resources. Google's Flood Forecasting Initiative has demonstrated the ability to generate flood predictions for rivers lacking conventional monitoring infrastructure by training models on satellite-derived data, extending the reach of early warning systems to populations in the developing world who are often the most exposed to flood risk.

Stormwater management is being transformed through AI-enabled real-time control of drainage infrastructure. Traditional stormwater systems are designed to passively convey runoff from storms of a specified return period, providing little operational flexibility. By installing sensors and actuators in detention ponds, weirs, and gates, and coupling them with AI control algorithms that forecast rainfall and optimize storage utilization in real time, cities are achieving substantial improvements in flood control performance and water quality without the capital cost of expanding physical infrastructure. These smart stormwater systems are also being used to capture additional runoff for groundwater recharge or non-potable uses, contributing to the resilience of water supplies under drought conditions.

6. Smart Cities and Integrated Urban Infrastructure Management

The concept of the smart city, in which digital technologies are deployed pervasively to improve the efficiency and quality of urban services, has evolved considerably since it first gained currency in the early years of the twenty-first century. Early smart city initiatives were often criticized for prioritizing technological novelty over genuine public benefit, concentrating resources in wealthy neighborhoods, and creating new risks of surveillance and data misuse. More recent approaches have sought to address these concerns by grounding smart city investment in clearly defined sustainability and equity objectives, engaging communities in the design and governance of data systems, and developing open standards that prevent vendor lock-in.

At its best, AI-driven smart city infrastructure creates the possibility of unprecedented coordination across systems that have historically been managed in isolation. Traffic management systems that communicate with transit operations centers, energy management platforms, and emergency services dispatch can optimize the performance of the urban transportation system as a whole rather than maximizing the performance of individual subsystems. Building energy management systems that respond to signals from the grid operator, adjusting demand to align with periods of high renewable generation, can simultaneously reduce building operating costs and grid emissions intensity. Waste collection systems that use sensor data from smart bins to optimize collection routes can reduce fuel consumption and vehicle emissions while improving service levels.

The deployment of AI in urban infrastructure management generates vast streams of data about the behavior and activities of city residents, raising fundamental questions about privacy, consent, and the appropriate boundaries of public surveillance. The case of Sidewalk Toronto, the high-profile smart city development proposal advanced by Alphabet's Sidewalk Labs and ultimately cancelled in 2020, illustrated the degree to which public trust in data governance frameworks can determine the political viability of even technically sophisticated infrastructure projects. Building the institutional and legal infrastructure necessary to govern urban data systems in ways that protect individual rights while enabling collective benefits remains one of the central challenges of smart city development.

7. AI for Climate Adaptation and Resilience Planning

Beyond the mitigation of greenhouse gas emissions, AI is playing an increasingly important role in helping infrastructure systems adapt to the climate change that is already occurring and will continue for decades regardless of how rapidly emissions are reduced. Adaptation planning requires understanding how climate risks will evolve

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across space and time, how physical infrastructure systems will respond to those risks, and how to allocate scarce adaptation resources most effectively. Each of these challenges benefits from AI's capacity to process large, multi-dimensional datasets and to identify patterns and relationships that would be invisible to conventional analytical approaches.

Climate risk assessment for infrastructure assets has historically relied on relatively coarse regional climate models and simplified vulnerability assessments. AI is enabling more granular and dynamic risk assessment by integrating high-resolution climate projections with detailed asset inventory data, geospatial analysis, and machine learning models trained on historical records of infrastructure failure. Utilities, transportation agencies, and municipalities are beginning to use these capabilities to develop climate risk registers that identify which assets face elevated risk over different time horizons and under different emissions scenarios, providing a foundation for prioritizing adaptation investment.

Nature-based solutions, which use or mimic natural processes to provide infrastructure services such as flood control, water purification, coastal protection, and urban cooling, are receiving growing attention as cost-effective and ecologically beneficial complements to engineered infrastructure. AI is being applied to optimize the design and placement of nature-based solutions by modeling the performance of different configurations of wetlands, green roofs, urban forests, and coastal vegetation under various climate scenarios. These models can also quantify the co-benefits of nature-based solutions in terms of biodiversity, air quality, and community wellbeing, providing a more complete basis for comparing them with conventional infrastructure options.

8. Sustainable Construction Through AI-Enabled Design and Materials Innovation

The construction phase of infrastructure development is responsible for a substantial share of its total lifecycle environmental impact. Concrete production alone accounts for approximately eight percent of global carbon dioxide emissions, and the extraction of construction materials, transportation of heavy goods, and energy consumption of construction equipment add considerably to this total. AI is being applied across the construction sector to reduce material use, improve construction process efficiency, and accelerate the development of lower-carbon materials and construction methods.

Generative design tools that use AI algorithms to explore vast spaces of possible structural configurations are enabling engineers to discover designs that use significantly less material than those produced by conventional methods while meeting or exceeding structural performance requirements. By formulating structural optimization problems mathematically and applying algorithms borrowed from evolutionary biology or machine learning, these tools can identify solutions that would not be intuitively obvious to human designers, exploiting the full potential of modern materials and fabrication techniques. The application of these tools to bridge design, building structures, and civil infrastructure is yielding documented reductions in material use of ten to thirty percent.

In construction project management, machine learning systems that integrate data from project schedules, material deliveries, equipment utilization, weather forecasts, and labor productivity records are enabling more accurate prediction of construction delays and cost overruns. By identifying patterns in historical project data that are associated with poor outcomes, these systems can alert project managers to early warning signs and recommend preventive actions. The reduction of construction delays and rework not only improves project economics but also reduces the carbon footprint of construction by minimizing the equipment operating hours and material waste associated with inefficient construction processes.

Materials science is another domain where AI is accelerating progress toward sustainability. The development of novel low-carbon cement formulations, high-performance concrete mixes that use industrial by-products such as fly ash and slag, and bio-based construction materials has historically been slow because the experimental characterization of material properties is time-consuming and expensive. Machine learning models trained on existing materials databases can predict the properties of novel material formulations from their composition and processing parameters, enabling researchers to identify promising candidates for experimental validation much more efficiently. This acceleration of the materials discovery process has the potential to dramatically expand the toolkit of low-carbon construction materials available to practitioners within the coming decade.

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9. Equity, Ethics, and the Governance of AI in Infrastructure

The transformative potential of AI in sustainable infrastructure development is real, but so are the risks that its benefits will be distributed unequally and that its deployment will create new forms of harm and injustice. Infrastructure inequality is already one of the most persistent and consequential dimensions of social inequality worldwide. In wealthy countries, infrastructure gaps between affluent suburbs and economically distressed urban neighborhoods or rural communities have accumulated over decades of disinvestment. In low- and middle-income countries, hundreds of millions of people lack access to reliable electricity, clean water, adequate sanitation, and paved roads. If AI-driven infrastructure innovation is accessible only to well-resourced jurisdictions, it could widen rather than narrow these gaps.

The risk of algorithmic bias in AI infrastructure systems is not merely theoretical. Predictive maintenance models trained on historical inspection records may reflect past patterns of unequal maintenance investment, directing future resources toward already well-maintained assets while neglecting those in disadvantaged communities. Traffic optimization systems trained on data from smartphone users may optimize for the mobility of wealthier, more digitally connected populations while disregarding the needs of those who rely on walking, cycling, or public transit. Water system optimization algorithms may prioritize large commercial customers over residential users in ways that reflect existing power imbalances rather than equity objectives.

Addressing these risks requires deliberate attention to equity in the design, training, and evaluation of AI infrastructure systems. This includes collecting more representative data, establishing equity metrics as explicit optimization objectives alongside efficiency and cost objectives, auditing AI systems for disparate impacts, and creating mechanisms for community participation in the governance of AI infrastructure platforms. It also requires ensuring that the institutions that manage infrastructure, including utilities, transportation agencies, and municipal governments, have the capacity and the mandate to use AI responsibly, which in many cases will require significant investment in workforce development and organizational capability building.

The international dimensions of AI infrastructure governance are also significant. Many of the AI platforms and data systems that are being deployed in infrastructure management are developed and controlled by a small number of large technology companies, most of them headquartered in the United States or China. This concentration of capability creates dependencies that may compromise the sovereignty of national infrastructure systems and raises questions about how data generated by public infrastructure is controlled and used. International frameworks for data governance, technology transfer, and AI safety standards in infrastructure applications are still in their infancy and will require sustained diplomatic and institutional effort to develop.

10. Emerging Case Studies and Lessons from Implementation

A growing body of real-world implementation experience is beginning to yield insights into the conditions under which AI-driven sustainable infrastructure development succeeds or struggles. The city of Singapore, which has invested heavily in building a comprehensive digital twin of its urban infrastructure, offers one of the most advanced examples of integrated AI-enabled infrastructure management. By creating detailed three-dimensional virtual representations of the built environment, coupled with real-time sensor data from across the city's infrastructure systems, Singapore's Urban Redevelopment Authority and other agencies can simulate the impact of proposed infrastructure changes, test operational scenarios, and optimize system performance before implementing changes in the physical world.

In the domain of water management, the city of Amsterdam has pioneered the use of AI to optimize the operation of its complex network of canals, pumping stations, and storm drainage infrastructure, which must manage water levels across a low-lying urban area that is highly vulnerable to flooding. By integrating weather forecasts, tidal data, and real-time monitoring of canal levels into a machine learning-based control system, Amsterdam's water authority has been able to improve flood management performance while reducing pumping energy consumption. The project has also generated methodological insights into the challenges of deploying AI in safety-critical infrastructure systems, including the importance of maintaining human oversight and the need to design AI systems that fail gracefully when

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operating conditions fall outside the range of the training data.

Kenya's experience with off-grid solar energy systems offers a contrasting lesson from the context of developing country infrastructure. The rapid expansion of pay-as-you-go solar home systems across East Africa, enabled in part by AI-powered credit scoring algorithms that assess the creditworthiness of rural households without formal credit histories, has brought electricity access to millions of people who would otherwise face years of waiting for grid extension. These systems demonstrate the potential of AI to enable leapfrogging of traditional infrastructure development pathways in contexts where conventional approaches are prohibitively slow or expensive. They also illustrate the importance of data privacy governance, as the financial and behavioral data collected by solar companies represents a sensitive asset that requires careful stewardship.

11. Future Directions and Research Priorities

The rapid pace of AI development ensures that the landscape of application in sustainable infrastructure will continue to evolve in ways that are difficult to predict with precision. Several emerging directions appear particularly significant for shaping the medium-term trajectory of the field. The continued development of foundation models, large-scale AI systems trained on diverse data that can be adapted to specific infrastructure management tasks with relatively modest additional training, has the potential to dramatically lower the technical and economic barriers to AI adoption in infrastructure contexts that lack large domain-specific datasets.

The integration of AI with physical infrastructure through embedded sensing and actuation, often described as cyber-physical systems, will create new possibilities for real-time adaptive management of infrastructure assets. Bridges, pipelines, and buildings instrumented with networks of sensors that continuously report on structural conditions, coupled with AI systems that can interpret this data and trigger maintenance interventions or operational adjustments automatically, represent a fundamentally different approach to infrastructure management that could extend asset service lives, reduce failure risks, and improve performance.

Research on the explainability and interpretability of AI infrastructure systems is essential for building the trust of operators, regulators, and the public. Infrastructure management decisions often have significant safety and equity implications, and decision-makers need to understand the reasoning behind AI recommendations well enough to evaluate their appropriateness and to take responsibility for the outcomes. Developing AI systems that can provide meaningful explanations of their recommendations in terms that infrastructure professionals can evaluate and act on is a significant research challenge that has received insufficient attention relative to the effort devoted to improving raw predictive performance.

Finally, the development of methodologies for evaluating the sustainability impact of AI infrastructure applications is urgently needed. While individual case studies have documented significant efficiency and emissions benefits, the field lacks robust frameworks for assessing the full lifecycle environmental impact of AI infrastructure systems, including the energy and material costs of computing infrastructure, the impacts of hardware manufacturing and disposal, and the indirect effects of AI-enabled changes in infrastructure behavior on land use, travel demand, and resource consumption. Without such frameworks, it is difficult to ensure that AI applications are genuinely contributing to sustainability objectives rather than generating efficiency gains in some dimensions while creating new forms of environmental burden in others.

12. Conclusion

The integration of artificial intelligence into sustainable infrastructure development represents both an extraordinary opportunity and a profound responsibility. The technical capabilities that AI brings to infrastructure planning, construction, operation, and maintenance are genuinely transformative, offering the prospect of infrastructure systems that are more efficient, more resilient, more responsive to changing conditions, and less environmentally damaging than those produced by conventional approaches. In a world facing the intertwined challenges of climate change, rapid urbanization, resource depletion, and persistent infrastructure inequality, these capabilities are urgently needed.

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However, technological capability is never sufficient by itself. The history of infrastructure development is replete with examples of technologies that promised transformative benefits but whose ultimate impacts were shaped more by the social, political, and institutional contexts in which they were deployed than by their intrinsic technical characteristics. AI in infrastructure will be no different. Whether it serves as a force for sustainability and equity or amplifies existing inequalities and creates new forms of environmental harm will depend on decisions about governance, data rights, investment priorities, and institutional capacity that are fundamentally political rather than technical in nature.

Building the institutional infrastructure to govern AI-driven physical infrastructure wisely, transparently, and equitably is therefore as important as developing the technical capabilities themselves. This requires investment in regulatory capacity, international cooperation on standards and data governance, community engagement in infrastructure planning and oversight, and deliberate attention to the equity implications of AI deployment from the earliest stages of system design. It also requires a research agenda that is willing to ask hard questions about the conditions under which AI applications truly deliver sustainability benefits and to develop the methodological tools necessary to answer them rigorously.

The stakes of getting these decisions right are high. Infrastructure shapes the material conditions of human life in the most fundamental ways, determining access to energy, water, mobility, and economic opportunity. AI-driven sustainable infrastructure development, pursued thoughtfully and governed wisely, has the potential to contribute significantly to a more equitable and environmentally sustainable future. Realizing that potential will require not only technical ingenuity but also institutional creativity, political courage, and an unwavering commitment to the proposition that the benefits of technological progress should be shared broadly across society and across generations.

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