EXECUTIVE SUMMARY

PART I – INTRODUCTION

Chapter 1 – INTRODUCTION TO ARTIFICIAL INTELLIGENCE (AI)

Artificial intelligence (AI) is the science of making computers perform complex tasks typically associated with human intelligence. Modern AI relies on machine learning (ML)—a type of software in which algorithms detect patterns from large data sets without being explicitly programmed. This differs from traditional software, which requires explicit programming of domain knowledge. AI instead relies on implicit programming by using historical data and simulations to train models to extract patterns.

AI has far-reaching capabilities. It can detect patterns, make forecasts, optimize systems and simulate what-if scenarios. Access to large, high-quality data sets is important for complex real-world applications of AI. These data can come from various public and private sector organizations. Tabular, time series, geospatial and text data are all commonly used in AI. Data must be properly measured, digitized and accessible to enable effective AI applications.

The release of ChatGPT in November 2022 generated extraordinary public attention to AI. ChatGPT quickly became the most rapidly adopted product in human history. Large language models (LLMs), like ChatGPT, demand significant amounts of energy to train and use. In contrast, not all AI systems are as resource-intensive, with many being efficient to deploy at scale.

Chapter 2 – INTRODUCTION TO CLIMATE CHANGE

Atmospheric concentrations of heat-trapping gases are now higher than at any time in human history. This is changing the Earth's climate. July 22, 2024 was the hottest day ever recorded; 2023 was the warmest year ever recorded; and the 10 warmest years on record are the last 10 years. Severe storms, droughts, floods and wildfires—all made more likely by global warming—have caused extraordinary damage in recent years. Sea-level rise threatens coastal cities around the world.

The Paris Agreement—adopted by over 190 nations in 2015—calls for holding the global average temperature increase to well below 2 °C (3.6 °F) above pre-industrial levels and pursuing efforts to limit the increase to 1.5 °C (2.7 °F). The world is not on a path to achieve these goals. Policies currently in place would result in a global average temperature increase of roughly 3 °C (5.4 °F) by 2100, and many of these policies are not being fully implemented.

AI is making important contributions to scientific understanding of climate change. AI is improving climate-model performance, providing more advanced warning of extreme weather events and helping attribute extreme weather events to the increase in heat-trapping gases in the atmosphere. AI's contributions to climate science will grow in the years ahead.

PART II – SECTORS

Chapter 3 – POWER SYSTEM

In 2023, carbon dioxide (CO_2) emissions from the power sector were roughly 28% of greenhouse gas (GHG) emissions globally. Most strategies for deep decarbonization foresee growing reliance on the power sector as vehicles, industry, space heating and other sectors shift from fossil fuels to electricity. To achieve global climate change goals, the power sector must grow and decarbonize at the same time.

AI is a key tool in addressing these challenges. At solar and wind power plants, for example, AI can help improve siting decisions, speed permitting and increase output with better weather forecasting. On long-distance transmission lines, AI can increase capacity with dynamic line rating. Virtual power plants and demand response programs are starting to rely heavily on AI tools. AI can accelerate innovations in battery chemistry, optimize battery usage and support vehicle-to-grid systems. In all these areas and more, AI's potential to help reduce greenhouse gas (GHG) emissions from the power sector is significant.

However, barriers including inaccessible data, lack of trained personnel and poor market design could hinder progress. Safety and security risks require priority attention. Data center power demand is growing faster than low-carbon power sources in some regions. Collaboration between governments, regulators and the private sector will be essential to realize AI's significant potential to contribute to power sector decarbonization.

Chapter 4 – FOOD SYSTEM

Food systems—including food production, processing, distribution, consumption and disposal—are critical to health and livelihood worldwide. Food systems are responsible for more than 30% of global GHG emissions. Climate change, in turn, poses substantial risks to food systems, threatening agricultural productivity, food security and supply chain stability.

AI has significant potential to help reduce GHG emissions from food systems, while enhancing resilience. Key AI application areas include remote sensing for agricultural monitoring, modeling to optimize farm management decisions and accelerated breeding programs for climate-resilient crops. However, significant challenges persist, such as limitations in model interpretability and transferability, data biases and the risk of exacerbating existing inequalities in food systems.

To promote responsible AI deployment, AI guardrails (e.g., human-in-the-loop model improvement) and AI accelerators (e.g., collaborative data ecosystems) are both needed. Steps that would help AI reduce GHG emissions from the food system include increasing public research and development (R&D) funding, developing standardized benchmarks and data sets, investing in adaptive data collection systems and adopting participatory approaches for AI model development.

Chapter 5 – MANUFACTURING

The manufacturing sector accounts for roughly one-third of global GHG emissions. AI has significant potential to help decarbonize manufacturing by optimizing existing industrial processes and operations in cost-effective ways.

For example, AI can play an important role in steelmaking with electric arc furnaces—an important decarbonization technology in which steel is made with recycled scrap metal instead of coal. AI can help address the variability in each batch of scrap metal, recommending optimal production settings to adapt to the variability. Using AI tools, one Brazilian steel manufacturer achieved an 8% reduction in alloy additive consumption using AI, cutting both costs and emissions.

More broadly, AI can help decarbonize manufacturing by enabling manufacturers to adapt to production issues faster and better, avoid past mistakes by leveraging historical data, improve production yields, promote recycling and circularity by adapting to variable recycled feedstocks, minimize energy consumption, adopt alternative energy sources and optimize manufacturing schedules and supply chains to reduce logistical overhead.

Chapter 6 – ROAD TRANSPORT

Road transport is a critical part of the global economy. Current modes of road transport rely heavily on fossil fuels, producing roughly 12% of global GHG emissions.

AI has significant potential to help reduce GHG emissions from road transport. AI can speed deployment of electric vehicles (EVs) by improving siting of charging infrastructure, extending EV battery life and helping operate vehicle-to-grid networks. AI has significant potential to accelerate innovation in batteries, electric motors and alternative fuels. AI provides critical support for intelligent transportation systems, helps promote modal shifts and plays a central role in operating autonomous vehicles (which can reduce GHG emissions through platooning and other measures).

Several barriers could hinder progress. Lack of data, the absence of uniform data standards and a shortage of trained personnel are among the most significant. Using AI in road transport also creates risks, including bias, invasion of privacy and—in the case of autonomous vehicles—increasing GHG emissions as the use of individual vehicles becomes easier. To realize the full potential of AI to reduce emissions from road transport, governments should invest in smart transportation infrastructure; industry and standards organizations should work together on data standards for smart transportation technologies; and governments, industry and academia should work together on AI tools to accelerate innovation in batteries and other technologies that reduce GHG emissions from road transport.

Chapter 7 – AVIATION

Emissions from aviation are rapidly growing as both passenger and cargo demand continues to climb. AI has the potential to reduce aviation emissions and climate impacts in several ways. One especially promising approach is using AI to help predict when aircraft-induced condensation trails (contrails) will form and enable minor flight route changes to avoid them. (Emerging science has demonstrated that climate impacts from contrails are quite large—comparable to radiative forcing from direct CO_2

emissions from aviation.) AI can also predict key properties of novel formulations of sustainable aviation fuel (SAF), helping accelerate adoption of non-fossil-based fuels.

AI-based tools can improve engine and aircraft design to increase fuel efficiency. Using AI to simulate fuel combustion within aircraft engines can help optimize engine design and allow for testing of entirely novel design concepts. Similar approaches can improve engine cooling designs, increasing engine longevity. AI methods can also help design and test aircraft bodies, wings and nacelles to minimize aerodynamic drag and reduce weight, further boosting overall fuel efficiency. During aircraft operations, near-real-time decisions must be made about runway allocation, take-off/landing timing, and climb/descend trajectories. AI tools can help optimize all of these, boosting overall efficiency and reducing unnecessary fuel burn.

Regulatory frameworks for aviation are appropriately focused on safety and may inadvertently present a barrier to adopting some AI-based methods. Industry, innovators and governments must work together closely to realize the benefits of AI for climate mitigation in aviation. Work on contrails should be a top priority. Towards that end, national governments should increase the coverage and quality of publicly available meteorological data, require all commercial and private aircraft to report non-CO_2 climate impacts (including contrail formation) and release these data publicly.

Chapter 8 – BUILDINGS

Buildings are responsible for roughly 18% of global GHG emissions. This includes emissions throughout the building life-cycle—from design to steel and cement manufacturing to construction to operation to demolition.

AI can play an important role in reducing CO_2 emissions from buildings. In the design stage, AI can help improve energy efficiency, site placement and material choices. During construction, AI can assist in waste management, facilitate prefabrication and help identify emission-reduction opportunities on site. When a building is operational, AI can optimize HVAC (heating, ventilation and air conditioning) and other mechanical systems, reducing energy consumption based on real-time data on building occupancy and usage patterns. AI has the potential to help buildings generate clean energy on-site, optimizing solar panel placement and integrating building-generated energy with broader grid demands. AI can enable efficient categorization of construction waste, facilitating reuse of materials.

Approaches must be adapted to diverse local contexts, especially to conditions in developing economies, where the vast majority of building construction will take place in the decades ahead. Key stakeholders' lack of familiarity with AI technologies is a significant barrier. Governments, the private sector and professional associations should develop a platform to disseminate best practices regarding implementing AI in reducing building energy use and emissions. Multilateral development banks, national/bilateral organizations and other donor agencies should develop a program of technical assistance and funding to increase stakeholders' capacity to develop AI innovation programs for the buildings sector.

Chapter 9 – CARBON CAPTURE

Ambitious climate goals require widespread deployment and safe operation of carbon management, including carbon capture, use and storage (CCUS). Today, CCUS faces challenges in deployment, including project economics, permitting and public acceptance. AI has the potential to significantly reduce costs and accelerate deployment of CCUS, including radical improvements in performance and dramatically faster project implementation.

AI could improve every aspect of CCUS research, development and deployment. From an early innovation perspective, AI can help identify new materials for carbon capture and use, including sorbents, catalysts and membranes. AI applications, such as digital twinning, could dramatically improve efficiency and costs of facility design and operations. Pipeline routing and subsurface characterization could benefit from AI tools reducing risks, costs and local impacts. Non-technical concerns could also benefit from AI applications. For example, AI could speed drafting and review of air permits and approval of injection wells and could facilitate environmental monitoring or maintain environmental justice standards.

To manifest these benefits, decision-makers must ensure adequate access to key data volumes to train these advanced tools and applications. Similarly, a workforce—from researcher to regulator—must be trained in AI to ensure good outcomes and avoid challenges of AI bias or hallucination.

Chapter 10 – NUCLEAR POWER

Nuclear reactors could make a larger contribution to reducing carbon emissions if the costs could be lowered. AI is already being used to optimize fueling and maintenance of current-generation reactors, and shows promise in aiding in the design of the advanced reactors that are moving toward commercialization. AI may also improve efficiency of nuclear safety regulation.

Boiling water reactors (BWRs) are already using AI in core design and monitoring, reducing enrichment requirements and cutting the volume of spent fuel, as well as avoiding unnecessary shutdowns. AI shows promise in helping plants move away from maintenance based on operating hours or calendar days and towards intervals based on interpretation of plant data to pinpoint the likelihood of future equipment failure. AI can also interpret scans of irradiated concrete to reduce uncertainty about its condition, and it can be helpful in equipment design for advanced fission reactors and even for fusion reactors.

But the application of AI to nuclear power faces challenges. The industry does not have large volumes of readily accessible data about operations and component performance, for example. Further, bringing AI into a complex, tightly linked safety-critical system will require careful planning and vetting of software tools.

PART III – CROSS-CUTTING TOPICS

Chapter 11 – LARGE LANGUAGE MODELS (LLMs)

Large language models (LLMs) have captured the public's imagination through the human-like output of popular products like ChatGPT. These LLMs are already helping mitigate climate change. LLMs are helping make sense of vast repositories of climate change information from many sources in multiple languages, identifying sentiment and argument structure in climate change discussions, and summarizing climate change risks and impacts described in the growing body of climate research.

In the future, LLMs can do even more to fight climate change. They can serve as tutors in climate education, depict personalized climate consequences and suggest individualized climate actions. They can advance basic science in climate change mitigation, from materials discovery for better batteries and carbon capture to sophisticated management of the power grid. They can help shortcut the current maze of permitting requirements that are slowing deployment of carbon-free power.

Barriers to using LLMs to mitigate climate change include issues with trusting "black boxes," which can "hallucinate" incorrect information. Risks include bias, security threats, harmful use and LLMs' own emissions of GHGs. National governments, LLM developers and other stakeholders should create and share LLMs trained on climate data while establishing benchmarks and training programs to ensure their effective use in addressing climate change. They should increase R&D efforts, promote transparency in tracking LLMs' carbon footprint and work to advance LLM applications in fighting climate change.

Chapter 12 – GREENHOUSE GAS (GHG) EMISSIONS MONITORING

Accurate information about GHG emissions is vital for addressing climate change. Historically, GHG data have been fragmented and sometimes incomplete, with significant time lags, limiting the ability to design effective mitigation strategies. AI is now playing a critical role in overcoming this limitation by analyzing vast amounts of data from satellites and other technologies to provide more complete, near-real-time emissions monitoring.

AI's contributions are particularly notable in monitoring methane emissions. Methane is increasingly monitored by AI-driven tools that use satellite imagery to detect, quantify and attribute emission events. This approach has allowed policymakers and companies to identify "super-emitters" and pinpoint chronic methane leaks from industries like fossil fuel extraction and waste management, which were previously mostly unreported. AI is also revolutionizing CO_2 emissions tracking by integrating large data sets from different sectors, such as transportation and industry, to provide real-time data. AI is also facilitating transparency in carbon-offset markets by enabling detailed monitoring of natural carbon sinks, such as forests, through satellite imagery.

To help realize AI's potential to revolutionize emissions monitoring, national governments should encourage the United Nations Framework Convention on Climate Change (UNFCCC) to update guidance on preparing national emissions inventories so that it explicitly allows the use of AI-enabled data rather than just emissions factor–based assessments. National governments and appropriate international bodies should continue ongoing efforts toward standardizing AI-enabled emissions data and should consider setting up formal processes to certify AI-assisted emissions data and data providers.

Chapter 13 – MATERIALS INNOVATION

Advanced materials with special properties are vital for decarbonization because they underpin many low-emitting technologies. Examples include catalysts, battery anodes, solar photovoltaics, wind turbine blades, HVAC refrigerants, superconductors, carbon-capture sorbents and high-strength magnets.

Historically, advanced materials were discovered through accident or tedious, expensive trial and error. Several decades ago, advances in materials science theory and computing power enabled a transition to a more computational basis for materials discovery. However, the standard methods for identifying new advanced materials through computation require large computing resources and are still too slow to fully meet the needs of materials innovation for decarbonization.

Recently, computational materials science has begun using AI methods. These methods are already having an important impact. In some cases, AI models can fully replace conventional science-based approaches, greatly speeding up processing times. In other cases, AI can help quickly interpret results of materials-characterization experiments, enabling rapid, high-throughput testing of advanced materials candidates. One especially promising development is using natural-language AI to synthesize the vast materials-science technical literature and to quickly produce accurate literature reviews and precise processing steps for materials production. Most recently, generative AI methods have been able to propose entirely new classes of advanced materials that had not previously been envisioned as relevant to decarbonization. While these advances are highly promising, much better integration between materials science and AI research is needed to fully realize the potential of this technology for climate mitigation.

Chapter 14 – EXTREME WEATHER PREDICTION

AI can help build resilience to extreme weather events fueled by climate change, such as severe droughts, intense storms and powerful wildfires. It can also strengthen resilience to flooding caused by accelerating sea-level rise. These events have caused thousands of deaths and major economic damage, with global losses estimated at $2.86 trillion from 2000 to 2019.

Adaptation strategies range from long-term infrastructure improvements to short-term emergency response. AI-based forecasting models are becoming increasingly accurate, using far less time and energy and costing less than conventional forecast models. Thanks to these emerging capabilities, the role of AI in enhancing forecasting and enabling better early warning systems for extreme weather events is becoming increasingly important. AI is providing vital tools for disaster preparedness and response, especially in regions with limited forecasting capabilities today.

Despite these advances, significant barriers to the widespread adoption of AI-enhanced forecasting remain. Insufficient data, technical expertise and financial resources limit progress. Transparent and interpretable AI models are critical to building trust and confidence among meteorologists and emergency responders. Governments and international organizations must invest in AI-driven weather models, support infrastructure development and ensure equitable access to early warning systems globally. Collaboration between the public and private sectors is essential to harness the full potential of AI in mitigating the growing risks of climate change and safeguarding vulnerable populations.

Chapter 15 – GREENHOUSE GAS (GHG) EMISSIONS FROM AI

AI systems need energy for manufacturing silicon chips, training and running AI models, and more. This energy use does not necessarily result in significant GHG emissions. When the electricity at a data center comes from new solar, wind or nuclear power, for example, the GHG emissions from data-center operations are modest. GHG emissions from AI computation are currently less than 1%—and perhaps much less than 1%—of the global total. Better data collection and assessment methodologies are needed to provide a more precise estimate with high confidence.

Data center power demand is growing steeply in many places around the world, due in part to demand for AI. Estimates of near-term growth vary widely. Sharply growing demand for AI computation will very likely lead to increased GHG emissions in the near-term. Efficiency improvements in AI hardware and software, as well as the use of low-carbon energy in the AI supply chain, will constrain but not prevent this emissions growth.

In the medium- to long-term, AI could result in either net increases or net decreases in GHG emissions. In part because AI is a transformational technology in the early stages of deployment, the range of uncertainty is enormous. Future GHG emissions from AI depend on a number of factors, including (1) growth in demand for AI, (2) improvements in the energy efficiency of AI hardware, (3) improvements in the energy efficiency of AI software, (4) use of low-carbon electricity in computation for AI, (5) use of AI to reduce production costs in the fossil fuel sector and (6) use of AI to reduce GHG emissions throughout the economy—such as the many AI applications discussed in this Roadmap. Each of these factors is highly uncertain, and they interact in complex ways.

Chapter 16 – GOVERNMENT POLICY

Governments play an important role in using AI for climate change mitigation—collecting data used in AI models, funding clean energy research programs that use AI tools, establishing policies that shape the use of AI in the power and transport sectors, and more. Governments also play an increasing role in managing risks from AI, which is essential in promoting trust in well-functioning AI systems.

Government AI policies vary widely. Europe's approach has been called "rights-driven," the US approach "market-driven" and China's approach "state-driven." Government attention to AI has grown rapidly in the past several years, with discussions on topics including liability rules, labeling requirements, data privacy protections, workforce training programs and safety standards. Although government policies with respect to AI are evolving rapidly, these policies tend to change much more slowly than AI technologies themselves.

Governments can help realize AI's potential to contribute to climate change mitigation with policies and programs in a range of areas. Governments should invest in data collection, curation and standardization; fund development of large-scale open-source foundational models tailored to address climate challenges; incentivize AI applications that contribute to climate mitigation with regulatory frameworks, financial incentives and public recognition programs; invest in education and training programs to develop a skilled AI workforce; facilitate knowledge sharing and collaboration between experts in climate mitigation and experts in AI; and establish ethical guidelines for developing and deploying AI applications to help foster trust in well-functioning AI applications for climate change mitigation.

Chapter 17 – FINDINGS AND RECOMMENDATIONS

A. Findings

1. AI is contributing to climate change mitigation in important ways.
2. AI has the potential to make very significant contributions to climate change mitigation in the years ahead.
3. The principal barriers to using AI for climate change mitigation are (i) the lack of available, accessible and standardized data and (ii) the lack of trained personnel.
4. Other barriers to using AI for climate mitigation include cost, lack of available computing power and institutional issues.
5. GHG emissions from AI computation are currently less than 1%—and perhaps much less than 1%—of the global total.
6. GHG emissions from AI computation will very likely rise in the near-term.
7. In the medium- to long-term, AI could result in either net increases or net decreases in GHG emissions. In part because AI is a transformational technology in the early stages of deployment, the range of uncertainty is enormous.
8. Only a tiny fraction of GHG emissions associated with AI operations are related to AI applications for climate change mitigation.
9. Trust in AI is essential for AI to deliver substantial benefits in mitigating climate change. To earn this trust, AI applications must undergo risk assessments that address a range of concerns. Risks related to safety, security, model accuracy, misinformation and disinformation require the closest attention.
10. Open-source foundation models have the potential to contribute to climate change mitigation by providing more organizations opportunities to access AI tools.
11. Significant resources and sustained focus—by governments, corporations, philanthropies and other stakeholders—will be required for AI to reach its potential in helping mitigate climate change.

12. Several recommendations in last year's ICEF *Artificial Intelligence for Climate Change Mitigation Roadmap* have been adopted by key stakeholders.

B. Recommendations

1. *Every organization working on climate change mitigation should consider opportunities for AI to contribute to its work.*
2. *Governments, businesses and philanthropies should fund fora in which AI experts and climate change experts jointly explore ways AI could contribute to climate change mitigation.*
3. *Governments should assist in developing and sharing data for AI applications that mitigate climate change.*
    a. *Governments should systematically consider opportunities to generate and share data that may be useful for climate mitigation.*
    b. *Governments should establish policies to promote standardization and harmonization of climate and energy-transition data.*
    c. *Governments should establish climate data task forces composed of key stakeholders and experts.*
4. *Companies with datasets relevant to climate change mitigation should consider sharing portions of these datasets publicly.*
5. *Every organization working on climate mitigation should prioritize AI skills-development and capacity-building.*
    a. *Governments and foundations should launch AI-climate fellowship programs.*
    b. *Government agencies with responsibility for climate issues should regularly review the capabilities of their staff with respect to AI.*
    c. *Every organization working on climate change mitigation should require minimum AI literacy from a broad cross-section of employees.*
6. *Educational institutions should offer courses that provide familiarity with AI and its uses in climate mitigation.*
7. *Governments should adopt policies to minimize GHG emissions from AI's computing infrastructure, including requiring AI developers and data center operators to disclose GHG emissions associated with their operations on a full life-cycle basis.*
8. *Organizations that use AI for climate change mitigation should assess and address potential risks of AI tools.*

9. *All government agencies with responsibility for climate change, including environment and energy ministries, should create an Artificial Intelligence Office, responsible for assessing opportunities, barriers and risks with respect to AI in all aspects of the agency's mission.*

10. *Governments should provide substantial funding for developing and applying AI applications for climate mitigation.*

    a. *Governments should fund AI for climate change mitigation programs with a focus on emissions reduction potential, not just new AI methods*

    b. *Governments should help increase the availability of computing power for AI projects related to climate change mitigation.*

11. *Governments, philanthropies and information technology companies should play a pivotal role in funding development of large-scale open-source foundation models tailored to address climate challenges.*

12. *Governments should launch international platforms to support cooperative work on AI for climate change mitigation.*

    a. *Member countries in the Clean Energy Ministerial (CEM) and Mission Innovation (MI), as well as other stakeholders, should participate actively in the CEM/MI AI initiative.*

    b. *The United Nations Framework Convention on Climate Change (UNFCCC), International Energy Agency (IEA) and Food and Agriculture Organization of the United Nations (FAO), among other organizations, should build AI-for-climate issues centrally into their work programs.*

    c. *One or more global organizations should be tasked with helping reconcile any conflicting AI-enabled data on GHG emissions.*