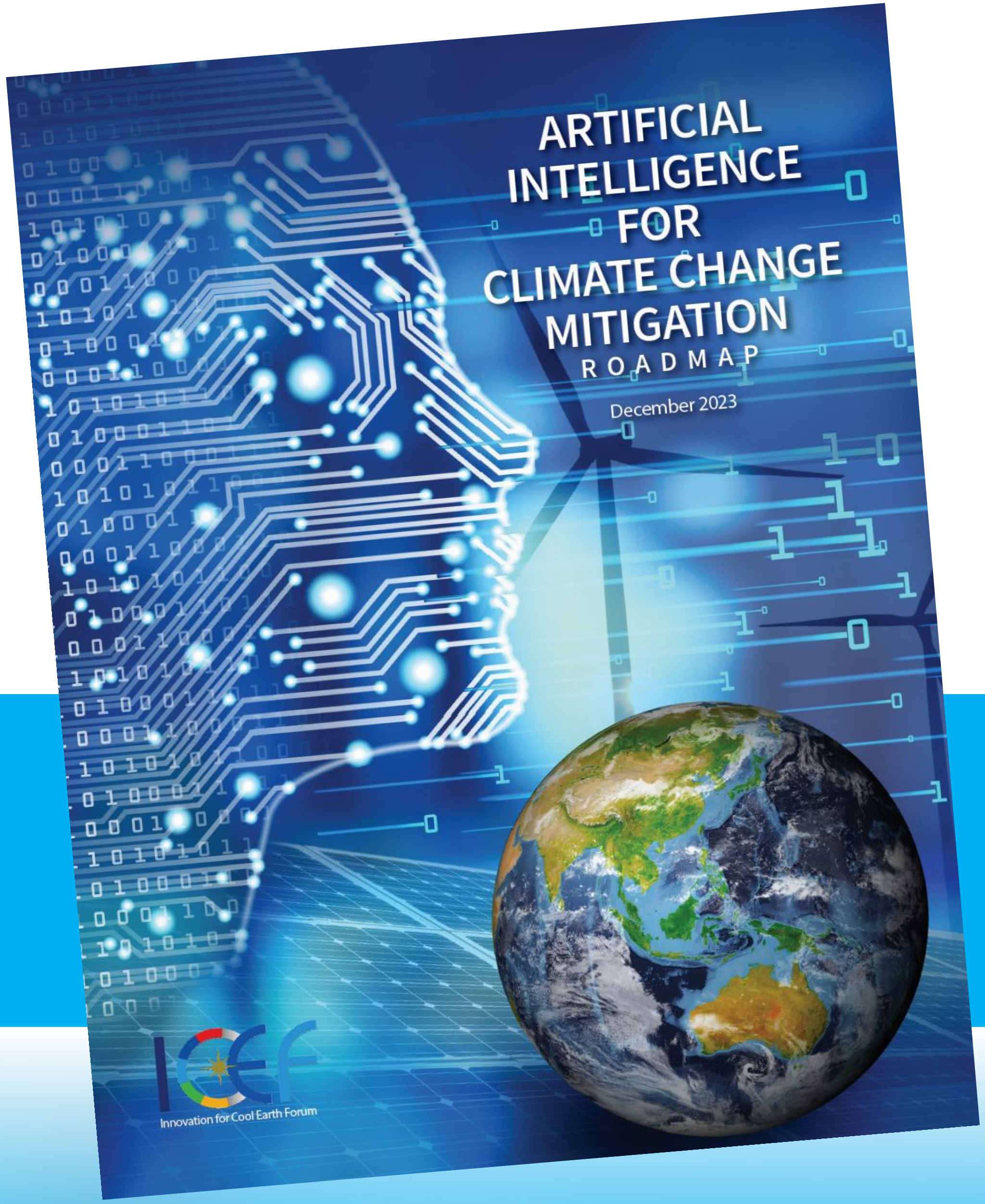


Innovation for Cool Earth Forum

David Sandalow, Colin McCormick, Alp Kucukelbir, Julio Friedmann, Trishna Nagrani, Michal Nachmany, Antoine Halff, Ruben Glatt, Kevin Karl, Matt Wald, Philippe Benoit, Alice Hill, Daniel Loehr, Fan Zhiyuan, Maria Frances Carter and others

Roadmap Special Session
ICEF Annual Meeting
October 10, 2024

AI FOR CLIMATE CHANGE MITIGATION ROADMAP (SECOND EDITION)

*First **AI for Climate Change Mitigation Roadmap** released December 2023.*

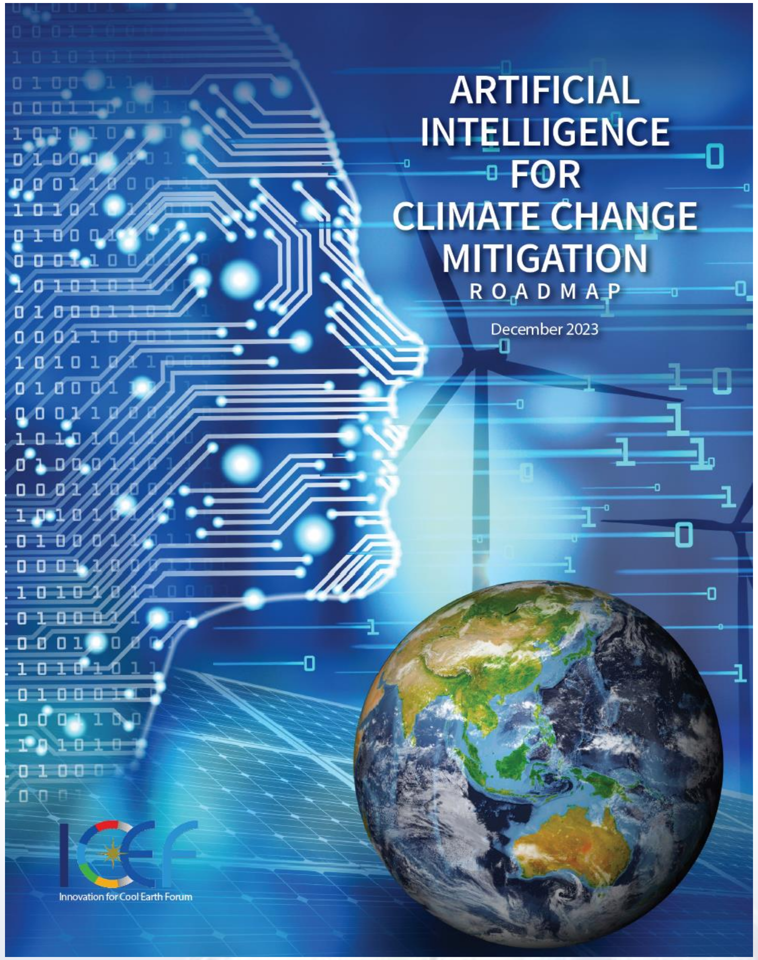
- *Available at academiccommons.columbia.edu and icef.go.jp/roadmap.*

TOPIC:

- ***HOW CAN AI HELP REDUCE EMISSIONS OF GREENHOUSE GASES?***

AI for Climate Change Mitigation Roadmap (Second Edition)

- *Draft for Comment released today*
- *Final to be released November 15 at COP29 in Baku*



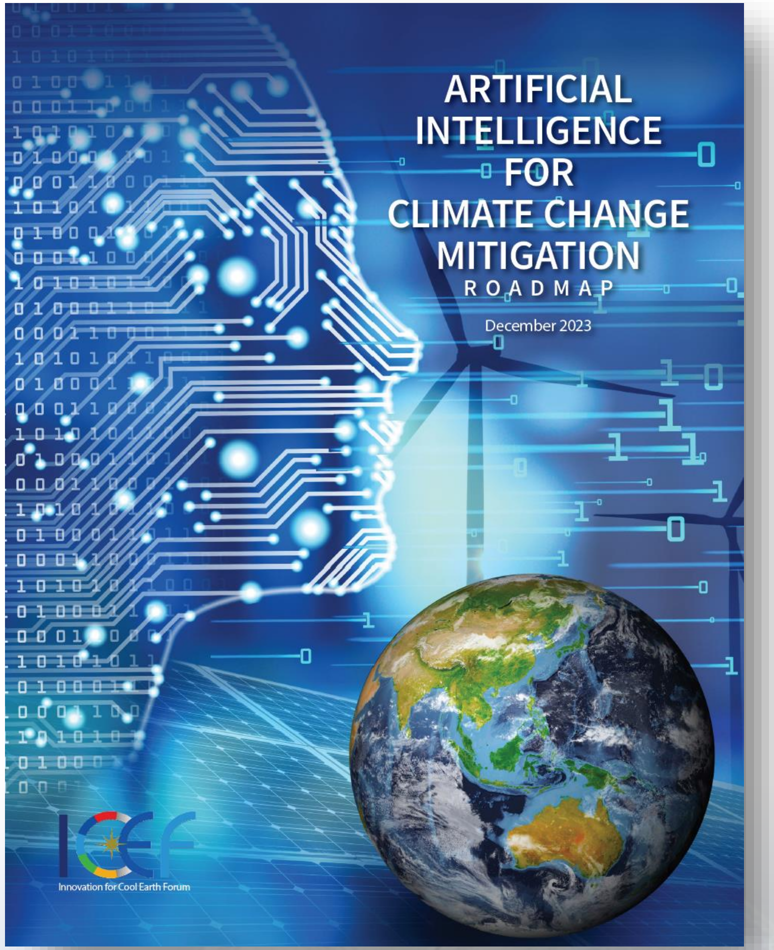
AI FOR CLIMATE CHANGE MITIGATION ROADMAP 2.0

PART I: **BACKGROUND**

- Chapter 1. INTRODUCTION TO ARTIFICIAL INTELLIGENCE
- Chapter 2. INTRODUCTION TO CLIMATE CHANGE

PART II: **SECTORS**

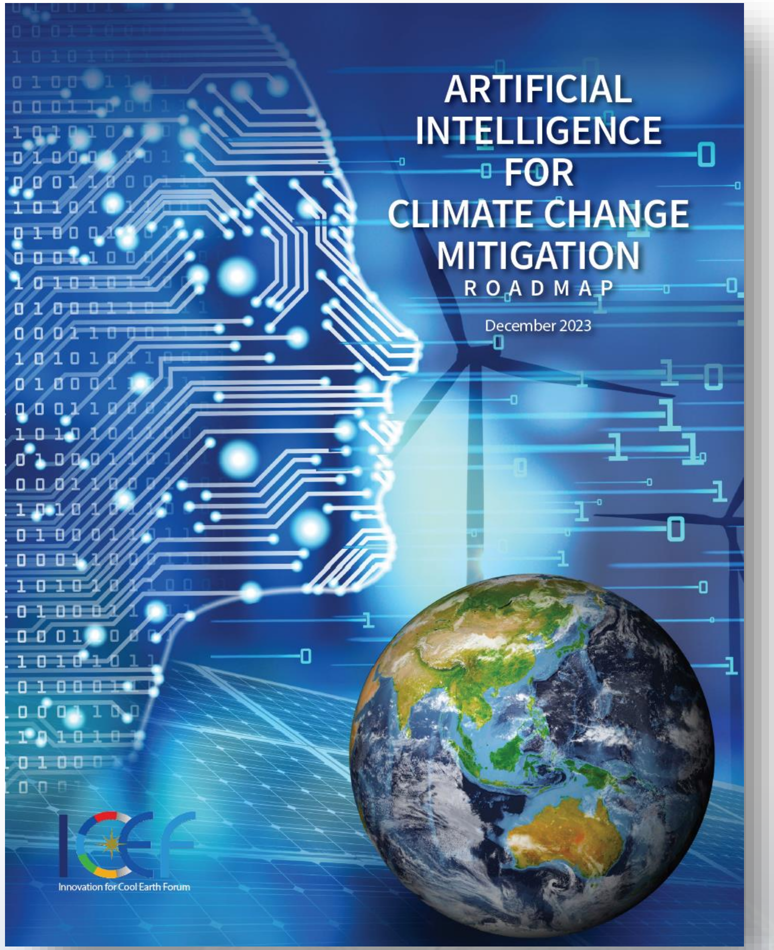
- Chapter 3. POWER GRID
- Chapter 4. FOOD SYSTEM
- Chapter 5. MANUFACTURING
- Chapter 6. ROAD TRANSPORT
- Chapter 7. AVIATION
- Chapter 8. BUILDINGS
- Chapter 9: CARBON CAPTURE
- Chapter 10: BUILDINGS



AI FOR CLIMATE CHANGE MITIGATION ROADMAP 2.0

PART III: **CROSS-CUTTING TOPICS**

- Chapter 11. LARGE LANGUAGE MODELS
- Chapter 12. GHG EMISSIONS MONITORING
- Chapter 13. MATERIALS INNOVATION
- Chapter 14. EXTREME WEATHER RESPONSE
- Chapter 15: GREENHOUSE GAS EMISSIONS FROM AI
- Chapter 16: GOVERNMENT POLICY
- Chapter 17: FINDINGS AND RECOMMENDATIONS



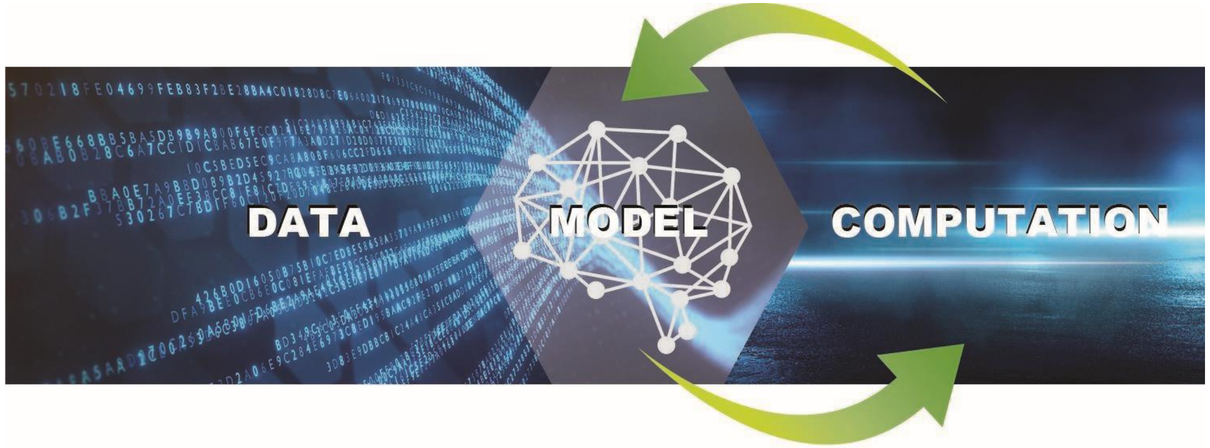
Part I: BACKGROUND

Chapter 1: INTRODUCTION TO AI

- Artificial intelligence (AI) is the science of making computers perform complex tasks

- AI differs from traditional software
  - Instead of relying on explicit programming, AI replies on historical data and simulation to “train” models and “learn” patterns

- Modern AI has far-reaching capabilities:
  - Detect
  - Predict
  - Optimize
  - Simulate



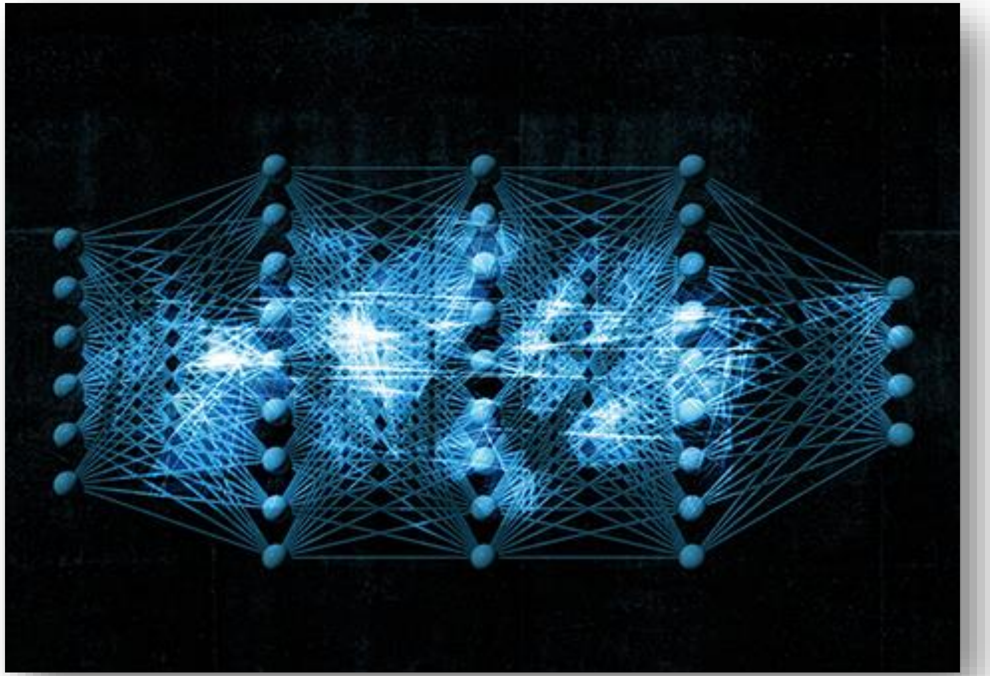
Chapter 1: INTRODUCTION TO AI

- AI requires data that is *available* and *accessible*:
  - available: digitized and well-measured
  - accessible: either open-source or for a cost

- AI has progressed rapidly because:
  - computing costs have declined dramatically
  - more data is readily available and accessible

- *Generative AI* is a type of AI that emerged in the past decade, enabling large language models such as ChatGPT

- Most AI systems require modest amounts of energy, but *generative AI* uses much more.
  - this is because *generative AI* uses significant energy both to train and to use



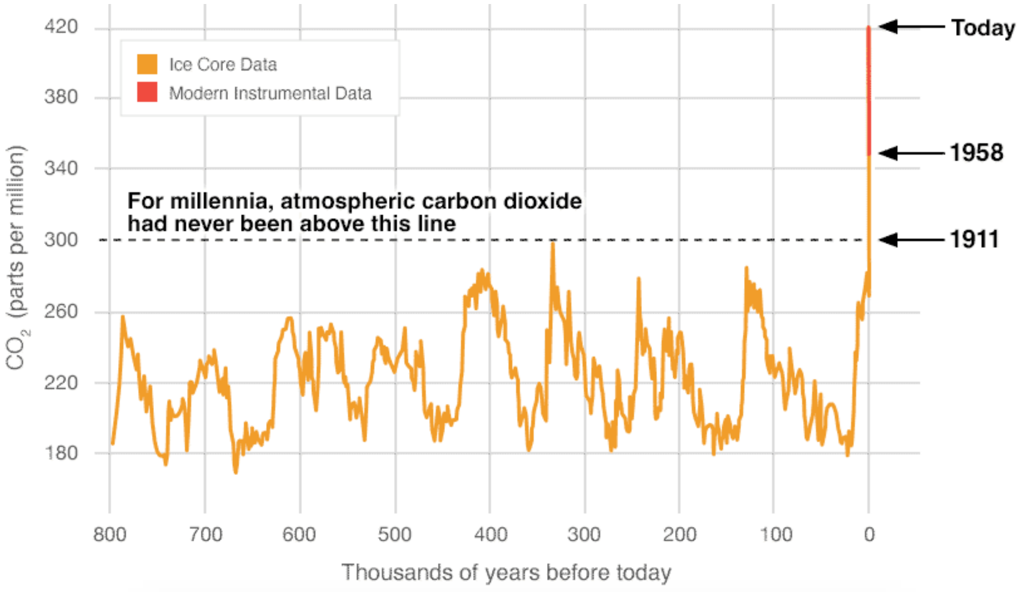
Chapter 2: INTRODUCTION TO CLIMATE CHANGE

- Atmospheric concentrations of heat-trapping gases are now higher than any time in human history.

- In terms of global average temperatures:
  - July 22, 2024 was the warmest day ever recorded.
  - 2023 was the warmest year ever recorded, by far.
  - The warmest 10 years ever recorded were the last 10 years.

- Recent heat waves, drought, fires and floods are all consistent with scientists' predictions of the impacts of climate change.

- Policies currently in place are not sufficient to reach the goals set in the Paris Agreement. The world is not on a path to meet its climate goals.



Chapter 2: AI CONTRIBUTIONS TO CLIMATE SCIENCE

AI is already making important contributions to understanding climate change:

- improving climate model performance
- identifying new climate processes and feedback
- attributing extreme events to human influence, and
- revealing additional climate drivers.

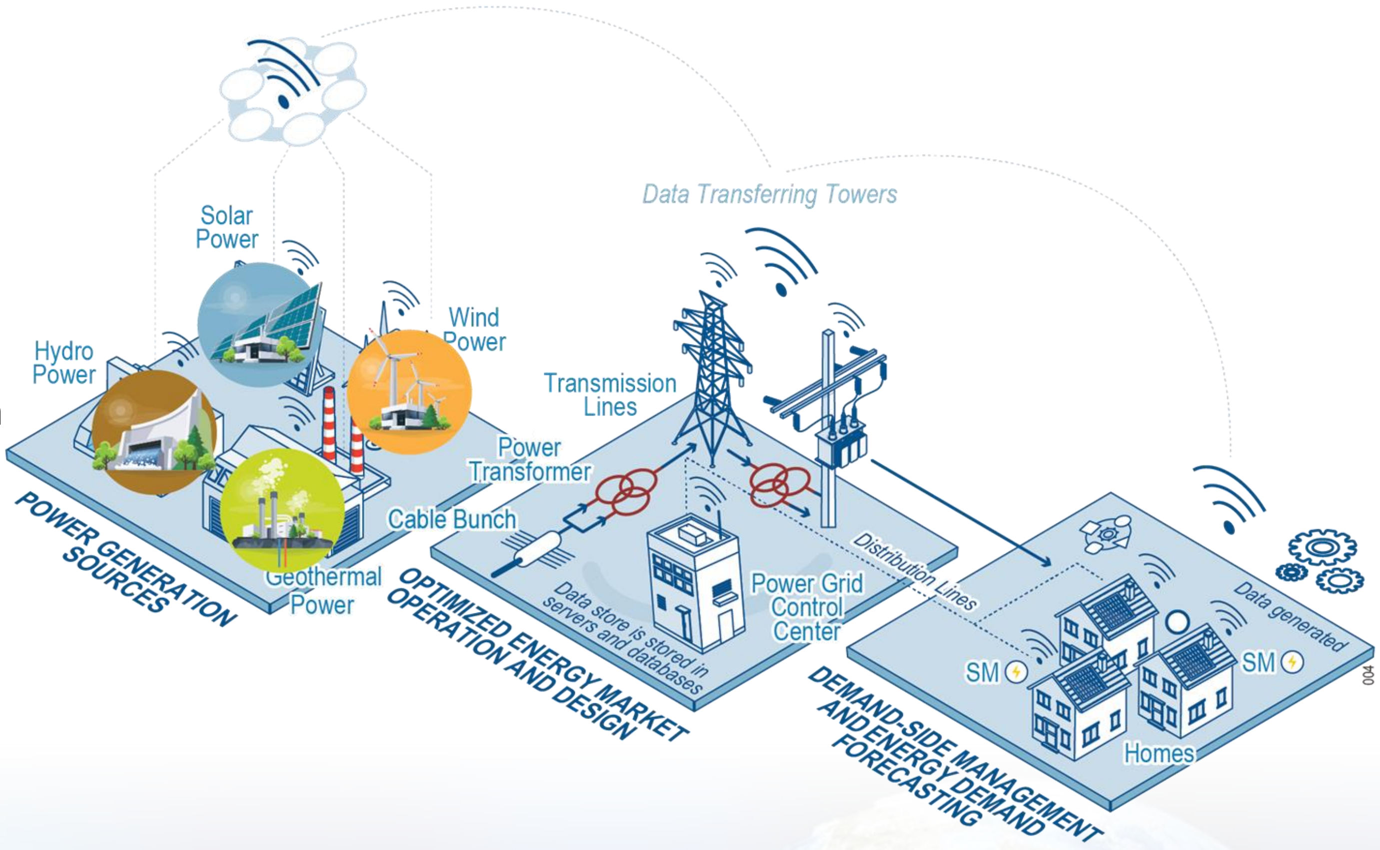
Part II:
SECTORS

Chapter 3: POWER SECTOR

- Roughly 25% of global greenhouse gas emissions today.
- Power sector is central to deep decarbonization. For the world to achieve net-zero emissions, the power sector must grow and decarbonize in the years ahead.

- AI is already helping decarbonize the power sector, including by:
  - optimizing location of generation and transmission assets
  - increasing output at solar and wind farms

- AI can do much more
  - dynamic line rating
  - optimal power flow analysis
  - virtual power plants
  - innovative battery chemistries

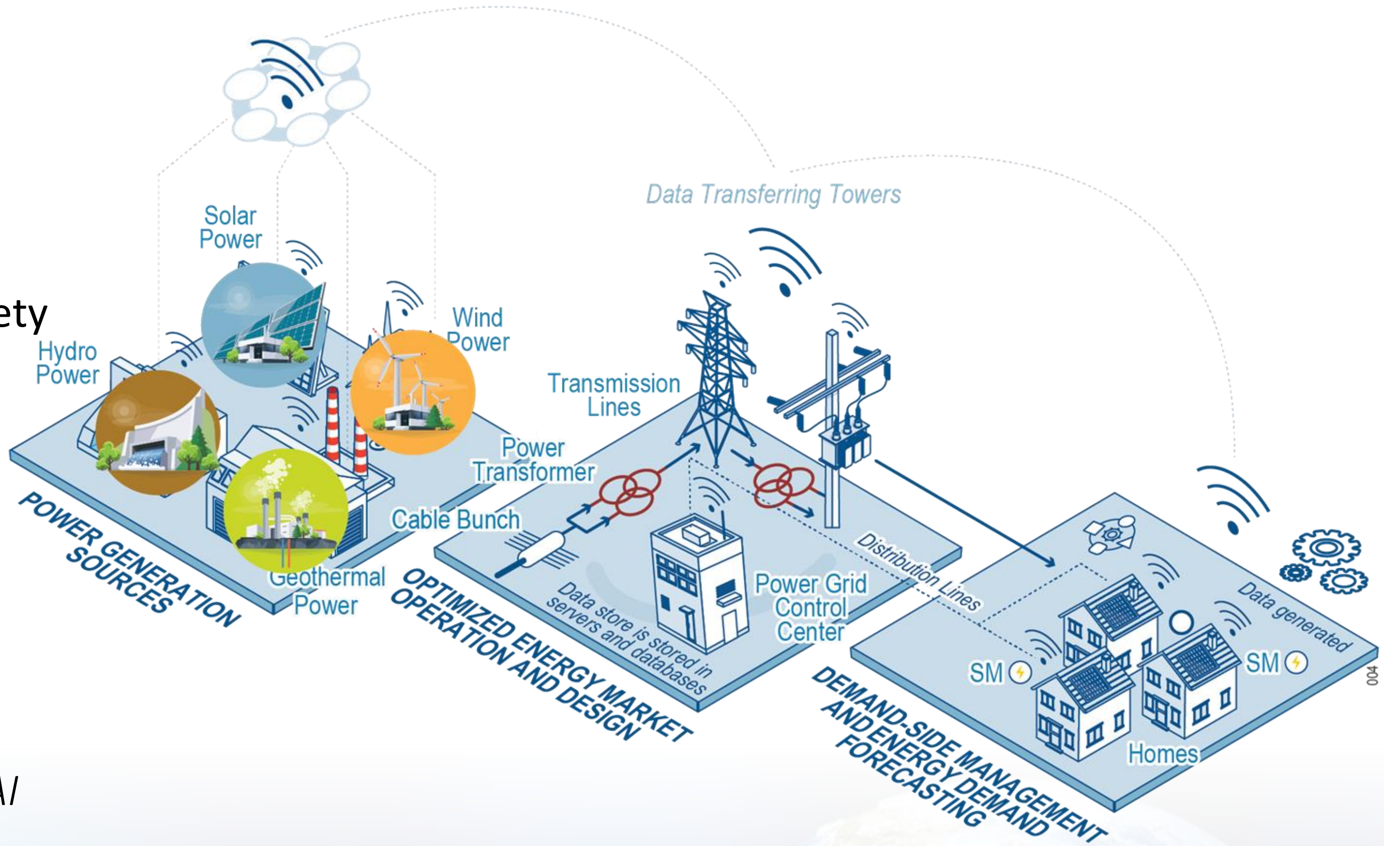


Chapter 3: POWER SECTOR

- Barriers include:
  - lack of well-developed models
  - lack of trained personnel
  - utility business models and culture

- Using AI in real-time operations creates security and safety risks.

- Recommendations include:
  - *National governments, electricity regulators and utilities should work together to develop data standards for all aspects of grid operations.*
  - *Utilities and electricity regulators should launch programs for training power sector workers to use AI technologies.*
  - *Electricity regulators should create clear regulatory frameworks to support using AI in energy management.*



Chapter 4: FOOD SYSTEMS

- Over 30% of global greenhouse gas emissions.
- Climate change impacts including droughts, floods, heat waves and the spread of pests threaten food systems.
- AI can contribute to more sustainable food systems in many ways, including:
  - integrating data from soil sensors and satellites to create fertilizer management plans that minimize NOx emissions while maximizing crop yields, and
  - creating virtual farms that simulate different crops, weather conditions and soil properties to help optimize agriculture practices.

Chapter 4: FOOD SYSTEMS

Recommendations include:

- *National governments should expand public R&D funding for applying AI methods in remote sensing, agricultural systems modeling and other food system applications.*
- *National governments, private companies and civil society organizations should establish collaborative data ecosystems for food systems.*
- *Professional societies, academic institutions and international organizations should develop and promote guidelines on the appropriate use of AI in food systems, covering issues such as data privacy, model transparency and potential biases.*
- *Academic institutions and research organizations should engage farmers, extension agents and community organizations to ensure that AI solutions are aligned with local needs and priorities.*

Chapter 5: MANUFACTURING

Roughly 1/3 of global greenhouse gas emissions, including "hard to abate" industries like steel, cement, chemicals.

AI can help in many ways:

- Decarbonizing the process of making things
  - — Enabling recycling/circular feedstock
- Decarbonizing supply chains
  - — Optimizing manufacturing schedules
- Implementing dematerialization strategies
  - — Designing stronger/lighter materials
- Decarbonizing maintenance of equipment
  - — Forecasting process conditions

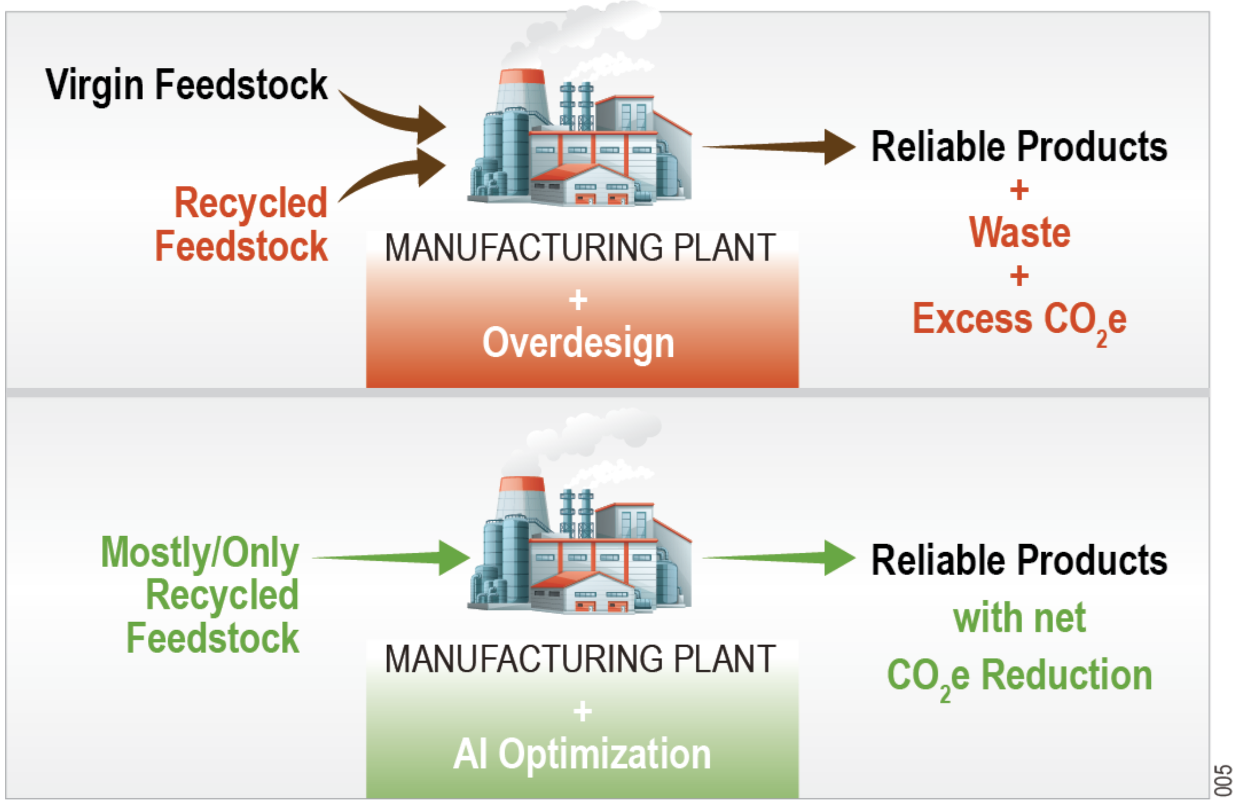
Chapter 5: MANUFACTURING

Important barriers and risks include:

- Lack of manufacturer incentive to decarbonize
- Additional safety risk of adopting AI-based workflows

Recommendations include:

- *Private companies should develop, maintain, and release AI-ready datasets.*
- *Private companies should develop clear processes to accelerate adoption of AI within their organizations.*
- *Governments and academia should develop educational opportunities at the intersection of AI and manufacturing.*



Chapter 6: ROAD TRANSPORT

- Roughly 12% of global greenhouse gas emissions.

- AI has significant potential to help reduce CO_2 emissions from road transport by accelerating innovation in:
  - electric vehicles
  - alternative fuels
  - intelligent transportation systems, and
  - shifts towards modes of transportation that emit less carbon.

- Barriers include a lack of data, the lack of uniform standards for data and a shortage of personnel with AI training.

- Risks include bias, invasions of privacy and increases in greenhouse gas emissions caused by the deployment of autonomous vehicles.

Chapter 6: ROAD TRANSPORT

Recommendations include:

- *Local governments should invest in sensors and smart infrastructure for intelligent transportation systems.*

- *National governments should establish comprehensive regulations for AI applications in EV technology on topics including data privacy, usage and storage.*

- *National governments, industry and academia should invest in AI research for battery and electric motor innovations.*

- *Governments, academia and industry should develop centralized data-sharing platforms where researchers can access and share datasets related to alternative fuels.*

- *Governments, industry, and academia should form consortia to develop AI-driven mobility platforms in major cities.*

Chapter 7: **AVIATION**

AI can help in many ways:

- Avoid climate-warming contrails
  - Predict where and when they will form
  - Recommend small altitude changes to prevent them
- Accelerate sustainable aviation fuel (SAF)
  - Predict key properties of new SAF formulations
- Enable efficient aircraft design
  - New wing, body, engine designs
  - Speed up virtual wind tunnel testing
- Improve airport operations
  - Optimize runway use
  - Minimize unnecessary fuel burn

Important barriers and risks include:

- Regulations focus on safety
- Must adapt to accommodate appropriate use of AI

Chapter 7: AVIATION

Recommendations:

- *<u>National governments</u> should increase R&D funding for applying AI/ML methods to aircraft and engine design, fuel efficiency, enabling the use of SAF, and contrail avoidance.*
- *<u>National governments</u> should increase the coverage and quality of meteorological data.*
- *<u>National governments, philanthropy and private companies</u> should collaborate on modeling of aircraft contrail formation and avoidance.*
- *<u>National governments</u> should require reporting on contrail formation by airlines.*
- *<u>Carbon accounting bodies</u> should update accounting rules to include non-CO2 impacts of aviation.*
- *<u>National governments</u> should ensure aviation regulatory frameworks are compatible with AI/ML innovation.*

Chapter 8: BUILDINGS

Roughly 1/4 of greenhouse gas emissions, throughout the building lifecycle — from design to steel and cement manufacture to construction to operation to demolition.

AI can help in many ways:

- Improve building design
  — Optimize site placement and material choices
- Reduce emissions during construction
  — Improve waste management and facilitate prefabrication methods
- Optimize building operations
  — Operate HVAC based on real-time building occupancy data
- Enable buildings to generate clean energy
  — Optimize solar panel placement

Chapter 8: **BUILDINGS**

Important barriers and risks include:

- Lack of data from diverse local contexts and geographies
- Safety risk of adopting AI workflows in HVAC/power generation

Recommendations include:

- *Governments and the private sector should pilot AI-supported technological improvements in design, materials, construction and demolition.*
- *Governments should develop R&D programs for AI improvements in emissions efficiency of building operations (including HVAC system, lighting, heating, elevators and other mechanical systems).*
- *Municipalities should explore more restrictive commercial-building energy use and emissions standards that leverage AI-based solutions.*

Chapter 9: CARBON CAPTURE

AI can help in many ways:

- Discover new carbon capture materials
- Help design new capture reactors
- Help integrate into more industrial facilities
  - Reduces cost, risk
  - improves performance
- Optimize CO2 transportation and storage
  - Improve siting, monitoring of pipelines and dedicated CO2 storage sites
  - Reduce costs and risk, including community and EJ
- Accelerate permitting and community acceptance
  - Reduce permit submission and review time

Chapter 9: **CARBON CAPTURE**

Important barriers and risks include:

- Access to data, including local facility and geologic data
- Geographic bias, especially for geological data sets.

Recommendations include:

- *National governments and private companies should expand current RD&D programs in carbon capture to include AI methodologies*
- *National governments and private companies should use AI to improve resource characterization for carbon capture, with emphasis on characterization of geological storage resources.*
- *National governments should use AI, including large language models and other generative AI platforms, to streamline the permitting processes for carbon capture.*

Chapter 10: NUCLEAR ENERGY

Nuclear power provides low-carbon, dispatchable power in large quantities.

AI can help in many ways:

- Improve existing site operation
  - Increase power yields
  - Extend life for aging reactors
  - Reduce waste
- Discover new materials
  - Reduce corrosion
  - Improve waste storage
- Help design new reactors, uses and fuel cycles
  - Dramatically reduce cost, waste volumes
  - Improve safety, public acceptance
  - Expand application base beyond electricity generation

Nuclear reactor core, Muehleberg, Switzerland-- https://cen.acs.org/energy/nuclear-power/Combating-corrosion-worlds-aging-nuclear/98/i36

Chapter 10: NUCLEAR ENERGY

Important barriers and risks include:

- Access to utility and operator data (in part, based on security)
- Hallucinations could have outsized impacts

Recommendations include

- *Nuclear regulators should expect AI to play a role in reactor design, safety analyses and recommendations for operating procedures.*
- *Nuclear plant owners should engage with the scientific community to provide access to high-quality data that can drive AI development and deployment.*
- *The civilian nuclear industry should scrutinize AI technologies funded by government dollars through science R&D agencies for applicability to their operations.*

Nuclear reactor core, Muehleberg, Switzerland

https://www.shutterstock.com/image-photo/blue-glow-water-nuclear-reactor-core-1873697335

Part III: CROSS-CUTTING ISSUES

Chapter 11: LARGE LANGUAGE MODELS

- Natural language processing is more than 70 years old. Large language models (LLMs) are the latest development.

- LLMs are already being used to assist with climate change mitigation, including by improving search and translation of climate information, summarizing scientific literature and monitoring public sentiment around climate issues.

- In the future, LLMs could speed renewable energy permitting, advance climate change education, generate real-time insights from environmental data and support personal climate actions.

- Challenges include limited interpretability of LLMs, risks of incorrect information or bias, and significant computational resource requirements of LLM’s.

Chapter 11: LARGE LANGUAGE MODELS

Recommendations include:

- *Private companies and academic researchers should continue to develop LLMs specifically trained on climate data and ensure they are openly available so the public can both improve them and benefit from them.*
- *National governments, private companies and academic researchers should cooperate on developing public challenge competitions on proposed climate mitigation use cases of LLMs to advance their development.*
- *National governments and private companies should expand current research and development (R&D) programs in addressing known issues with LLMs, so the public can place greater trust in LLMs, especially when applied to climate change.*
- *LLM developers and users should publish fine-grained measurements of LLMs' carbon footprint by adopting tools to track and report the GHGs emitted by their compute time.*

Chapter 12: GHG EMISSIONS MONITORING

AI is helping to significantly improve information on *sources of greenhouse gas (GHG) emissions*.

- Analyzing vast amounts of data from earth-observation satellites, airplanes, drones, land-based monitors, the Internet of things, social media and other technologies

AI has been particularly important in improving *methane emissions* monitoring.

- Processing data from methane sensors at scale
- Combining input from multiple satellites
- Integrating satellite information with data generated by other types of sensors

AI is also being used to better understand sources of *CO_2 emissions*.

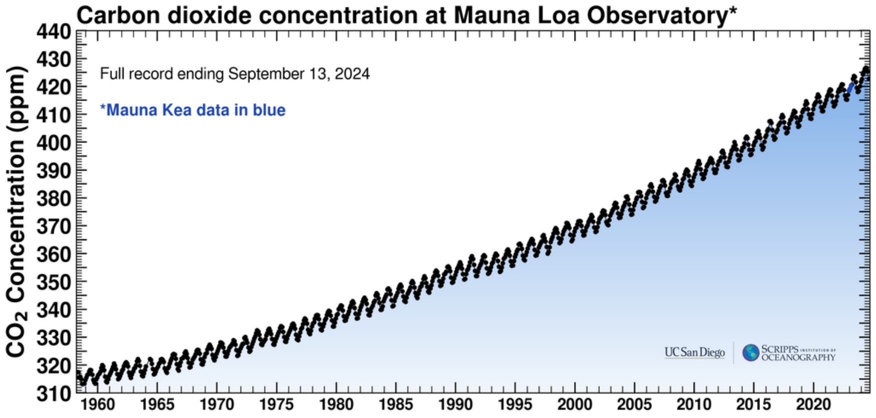
- AI algorithms can be trained to survey the world's vegetation at high spatial resolution.

Japanese IBUKI-2 GHG monitoring satellite

Chapter 12: GHG EMISSIONS MONITORING

Barriers to using AI for emissions monitoring include

- lack of AI literacy and experience with AI,
- conflicting data,
- sovereignty concerns, and
- uncertain financial models.



Keeling Curve - https://keelingcurve.ucsd.edu/

Recommendations:

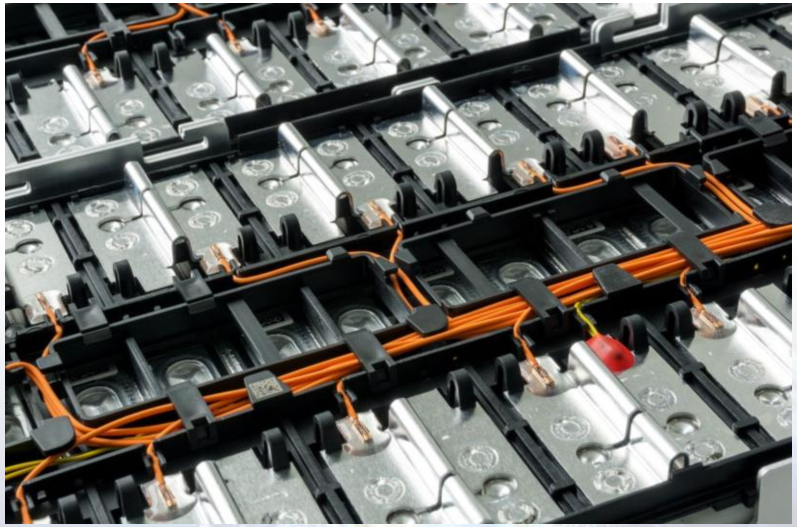
- *<u>National governments</u> should encourage UNFCCC to update guidance on preparing national emissions inventories to explicitly allow the use of AI-enabled data.*
- *<u>Carbon accounting bodies</u> should develop rules for the inclusion of AI-enabled emissions data as part of corporate carbon footprints, supply chain emissions tracking, and other uses.*
- *<u>National governments</u> and <u>international bodies</u> should consider how best to set up the housing and governance regime of AI-enabled emissions data and continue efforts toward standardization and ground-truthing.*

GOSAT-2 (JAXA) - https://global.jaxa.jp/projects/sat/gosat2/

Chapter 13: **MATERIALS INNOVATION**

- New materials are vital for low-carbon technologies
  - Batteries, PV, membranes, catalysts, refrigerants, superconductors, sorbents, magnets, etc.
- Computational design speeds up discovery
  - Much better than trial-and-error search (Edison)
  - Requires lots of computing power

- AI vastly reduces computing time
  - Summarize and integrate thousands of research articles
  - Search millions of possible materials
  - Identify tiny fraction worth physically testing
  - Pinpoint exact formula for production



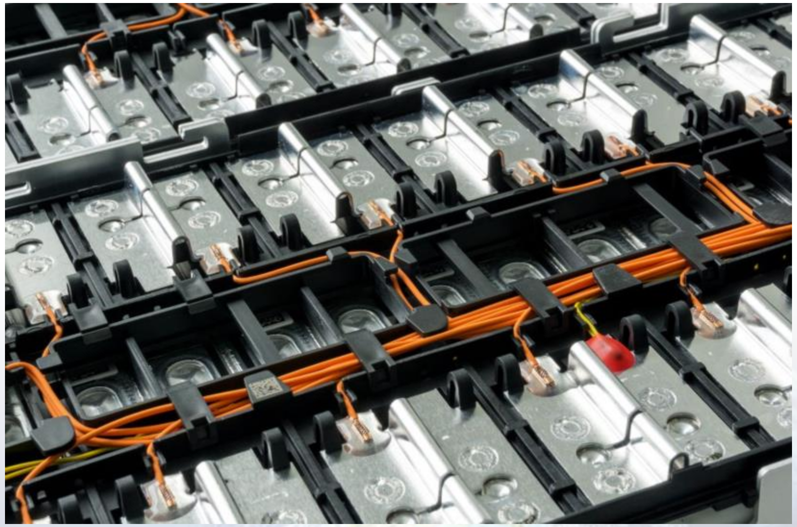
Important barriers and risks include:

- Limited AI training of many materials scientists
- Too few large datasets of key material properties

Chapter 13: **MATERIALS INNOVATION**

Recommendations:

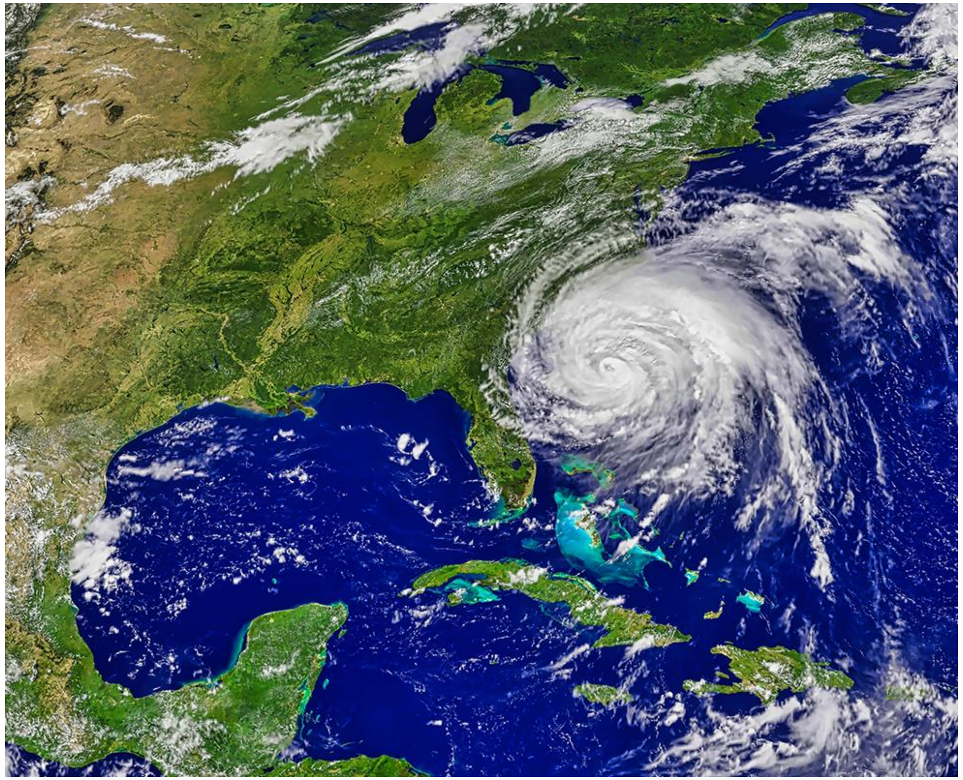
- *National governments should increase R&D funding for AI-enabled materials discovery, including funding for automated materials testing labs.*
- *Private companies should specify materials classes of interest, including benchmarks and manufacturing constraints*
- *National governments, academia and private companies should collaborate to release AI-ready datasets of materials properties.*
- *National governments and academia should support AI and ML education as part of materials science curricula.*
- *Scientific publishers should ensure publications are compatible with AI-enabled research synthesis tools.*



Chapter 13: **EXTREME WEATHER RESPONSE**

AI can help in many ways:

- AI/ML-enabled forecasting is now as accurate as conventional weather models in many circumstances.
- Much faster processing time and much lower power consumption (1000x or more).
- Can expand access to state-of-the-art weather forecasting.
- AI is making rapid improvements in forecasting river flooding and wildfire events.
- Similar progress in longer-term forecasting for drought, crop failure.



Hurricane Irene (2011)

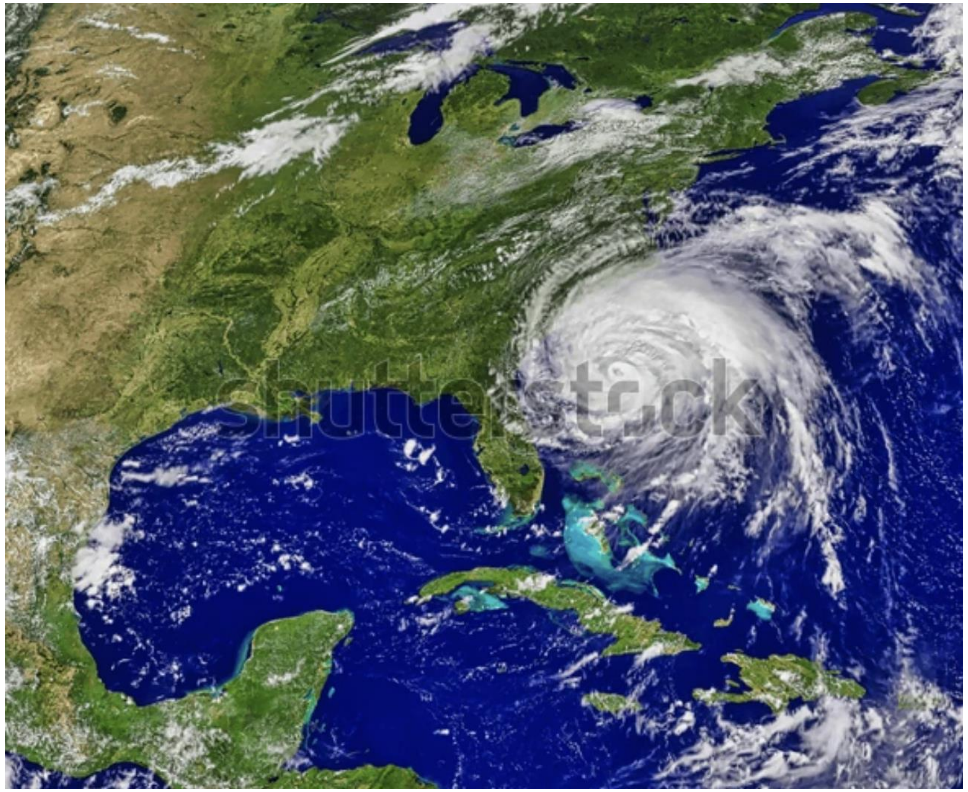
Important barriers and risks include:

- Limited data, especially in Global South.
- Insufficient technical expertise and capacity; lack of confidence.
- Lack of supporting infrastructure.
- Financial constraints.

Chapter 13: **EXTREME WEATHER RESPONSE**

Recommendations include:

- *<u>National governments, international organizations, and private companies</u> should invest in AI forecasting models and collaborate on evaluating their accuracy and reliability.*
- *<u>National governments</u> should integrate AI/ML training into professional development for weather and related agencies.*
- *<u>National governments and international organizations</u> should support the development of the necessary infrastructure for disseminating forecasts and warnings effectively.*
- *<u>Emergency management and humanitarian aid agencies</u> should implement AI-enabled decision-support systems to optimize response strategies during extreme weather events.*



Hurricane Irene (2011)

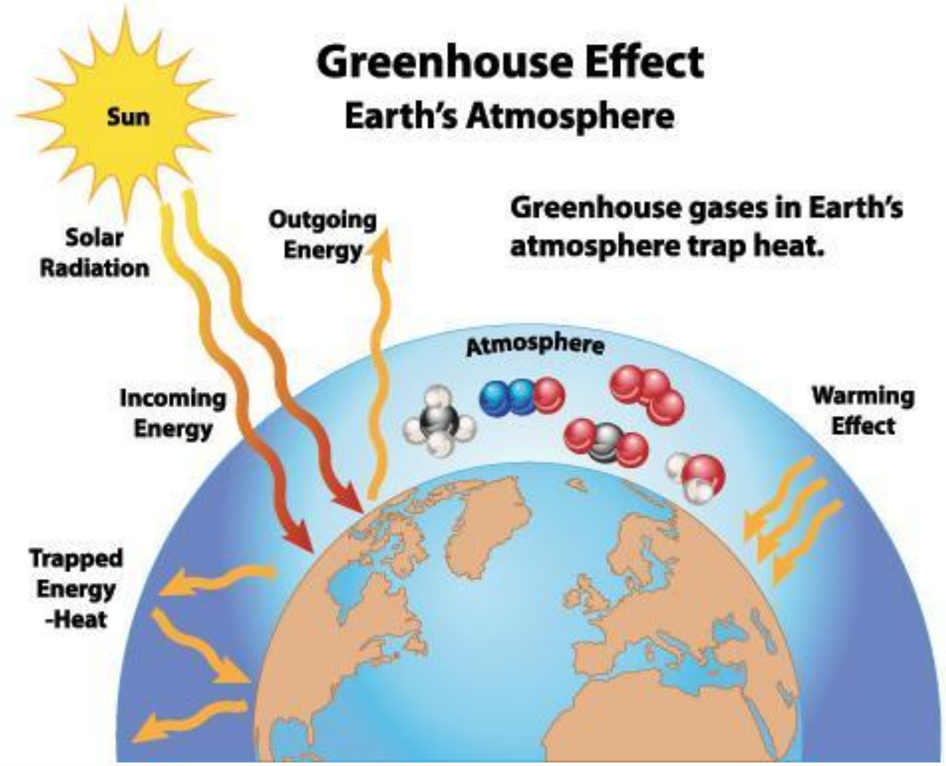
Chapter 15: GREENHOUSE GAS EMISSIONS FROM AI

1. GHG emissions from AI computation are currently less than 1%—and perhaps much less than 1%—of the global total.

2. GHG emissions from AI computation will very likely rise in the near-term.

3. In the medium- to long-term, AI could result in net increases or net decreases in GHG emissions. The range of uncertainty is enormous.

- On the one hand, demand for AI is growing fast.
- On the other hand, significant improvements are likely in:
  - energy efficiency of AI equipment
  - optimization techniques in AI models
- World's largest data center operators are also world's largest purchasers of zero-carbon electricity.



Chapter 15B: DATA CENTER POWER DEMAND

In 2023, roughly 1.5% of global electricity demand came from data centers.

- US-3%; China-3.5%; EU-3.5%; Japan-1-2%.

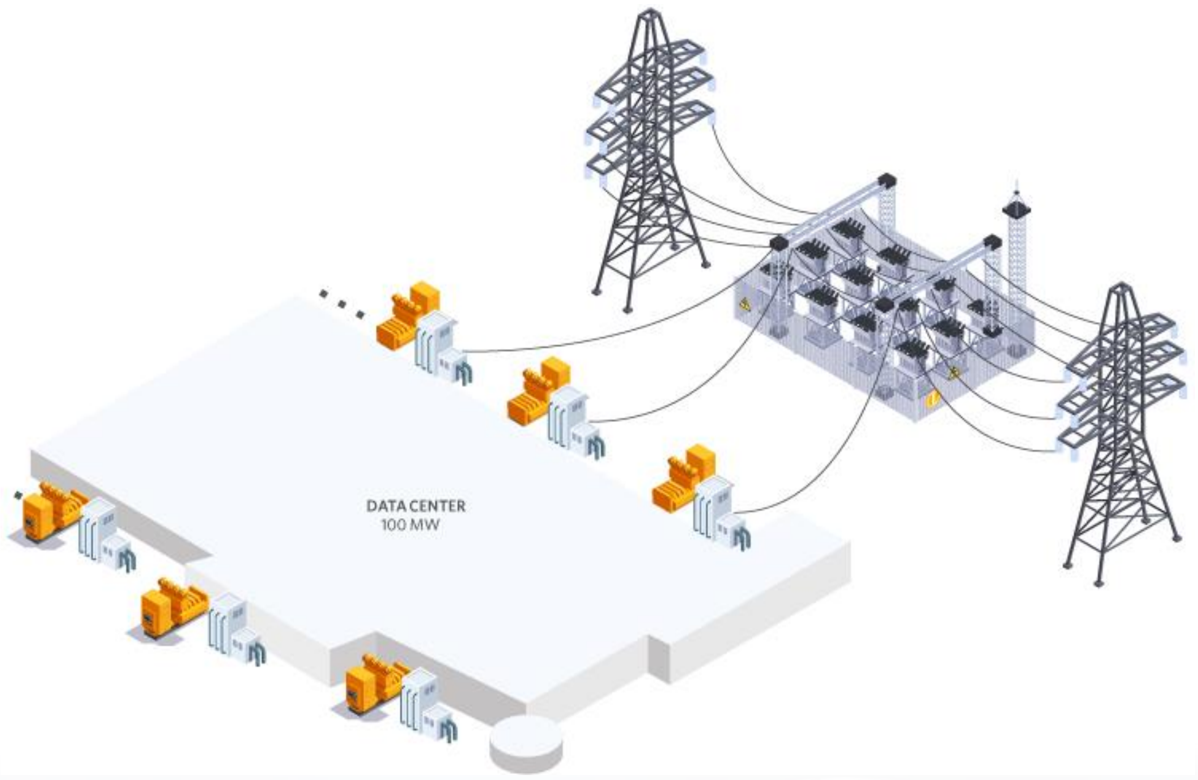
A comparison: 4% of global electricity demand came from aluminum smelters.

Data center power demand is growing fast

- Goldman Sachs Research projects 160% growth globally by 2030; many similar estimates

Data center demand growth is coming from many sources, not just AI.

- 5G networks, streaming services, social media and online gaming
- Yet AI is perhaps the most important factor.



Chapter 16: GOVERNMENT POLICY

Government policies with respect to AI are evolving rapidly, addressing topics including liability, labeling, safety and data privacy.

Few governments have policies that specifically address the use of AI for climate.

We explore:

- policies that promote the use of AI for climate change mitigation, and
- policies that manage risks related to AI

Trust in well-functioning AI is essential for AI to help address climate change. Governments can play a pivotal role.

Chapter 16: **GOVERNMENT POLICY**

Recommendations include:

1. *<u>Governments</u> should prioritize development of a climate-relevant data ecosystem, including investing in data collection and promoting data interoperability standards.*
2. *<u>Governments</u> should help fund development of large-scale open-source foundational models tailored to addressing climate challenges.*
3. *<u>Governments</u> should use their convening power to facilitate knowledge-sharing and collaboration between experts in climate mitigation and experts in AI.*
4. *<u>Governments</u> should establish ethical guidelines for developing and deploying AI applications to help foster the trust and confidence in AI*

Chapter 17: FINDINGS AND RECOMMENDATIONS

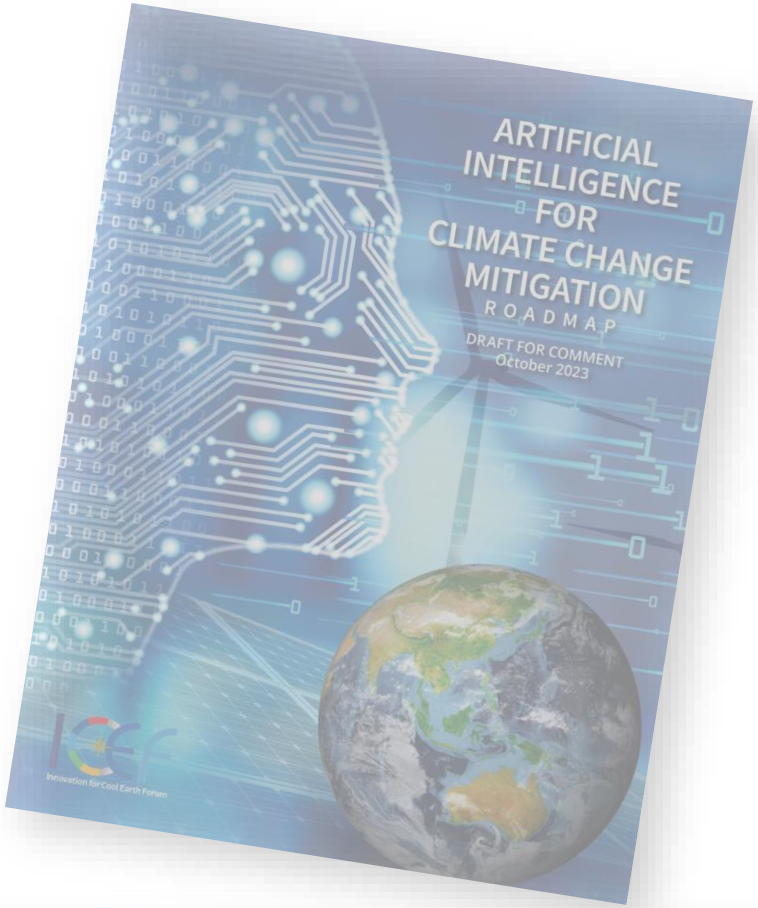
FINDINGS

1. AI is currently 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.

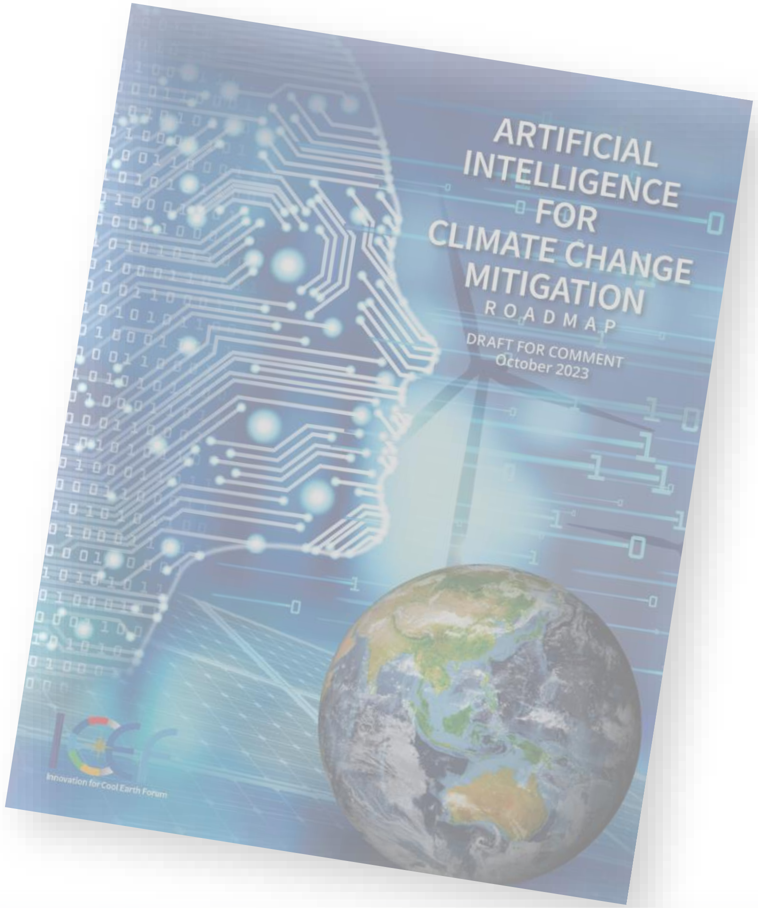
3. The principal barriers to using AI for climate change mitigation are (i) the lack of available, accessible and standardized data and (ii) the lack of trained personnel.

4. Other barriers to the use of AI for climate mitigation include cost, lack of available computing power and institutional issues.



Chapter 17: **FINDINGS AND RECOMMENDATIONS**

FINDINGS



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. Only a tiny fraction of greenhouse gas emissions associated with AI operations are related to AI applications for climate change mitigation.

8. 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.

Chapter 17: FINDINGS AND RECOMMENDATIONS

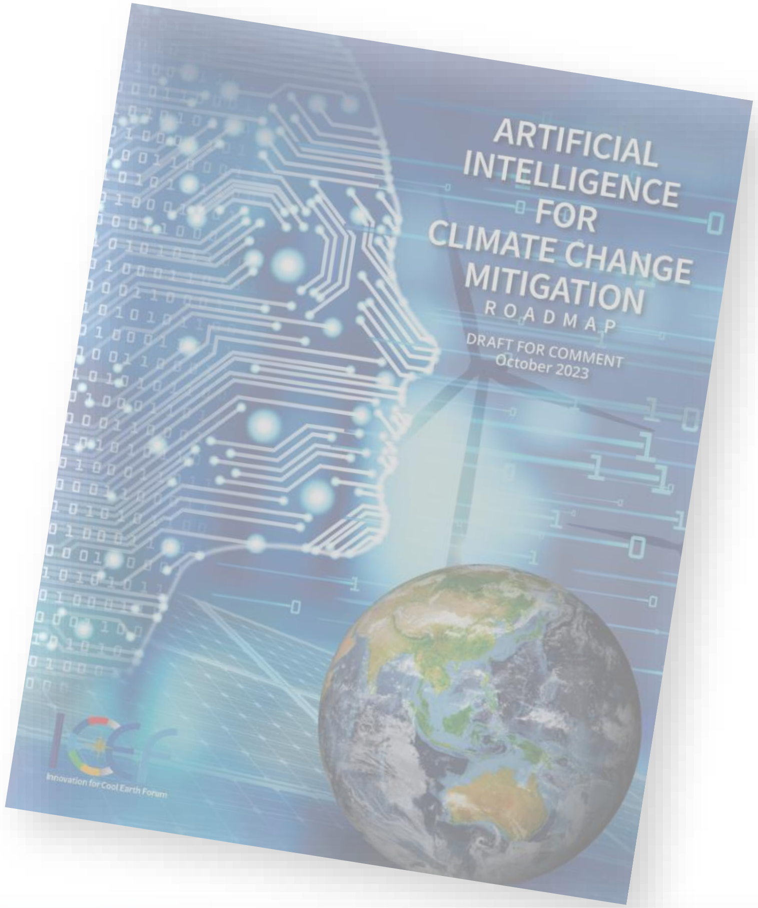
FINDINGS

9. Trust in AI is essential for AI to deliver substantial benefits in mitigating climate change.

10. Significant resources—by governments, corporations, philanthropies and other stakeholders—will be required for AI to reach its potential in helping mitigate climate change.

11. Open-source foundation models have the potential to contribute to climate change mitigation by providing more organizations opportunities to access AI tools.

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



Chapter 17: FINDINGS AND RECOMMENDATIONS

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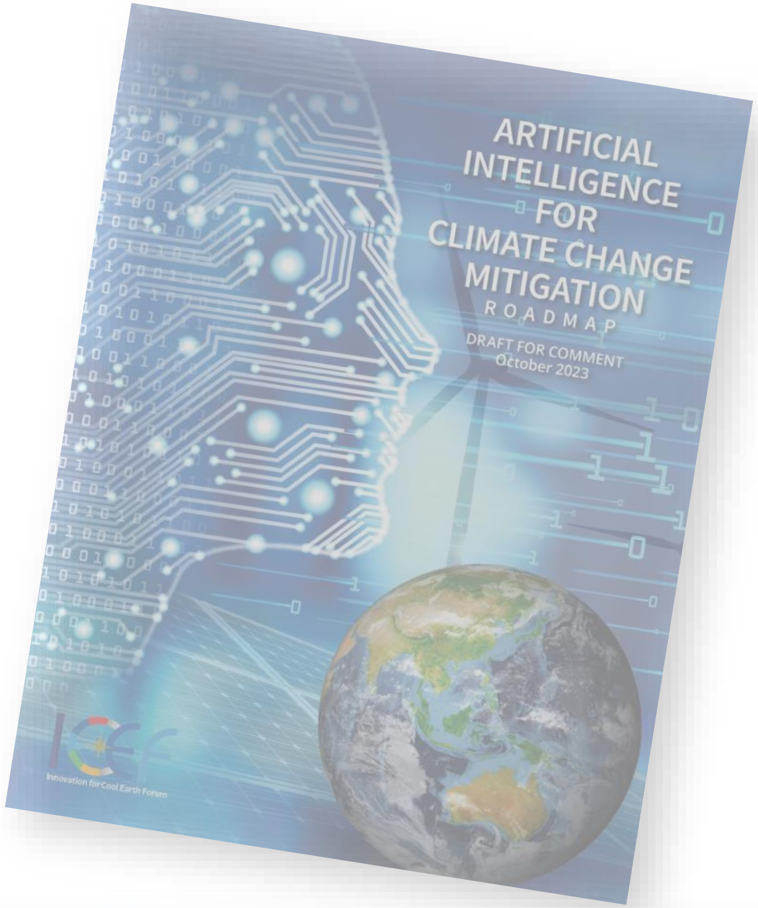
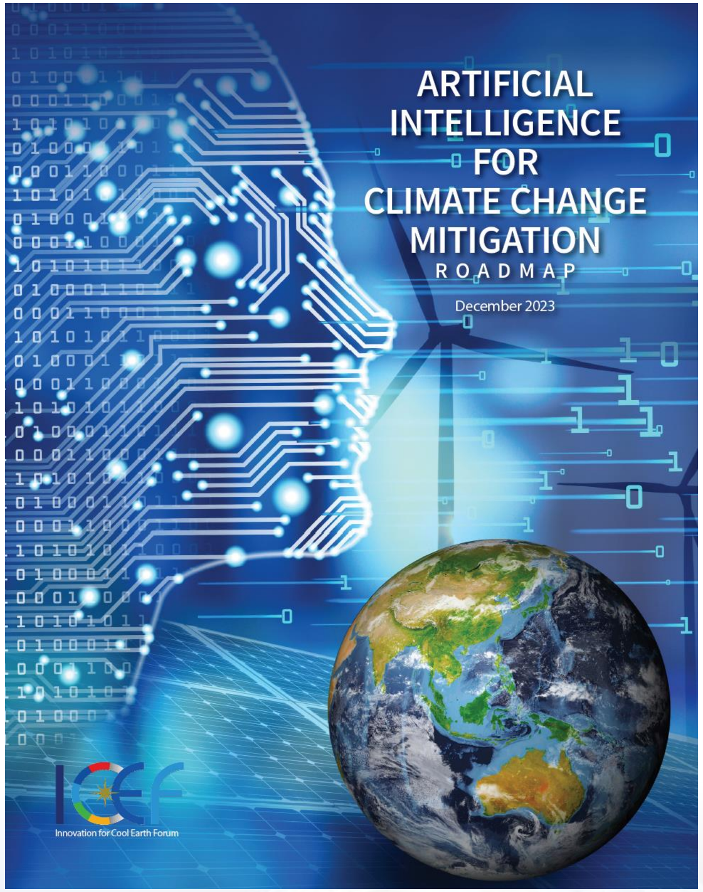


Chapter 17: FINDINGS AND RECOMMENDATIONS

RECOMMENDATIONS

1. *Every organization working on climate change mitigation should consider opportunities for artificial intelligence to contribute to its work.*
2. *Every organization working on climate change mitigation should prioritize AI skills-development and capacity-building.*
3. *Governments, businesses and philanthropies should fund fora in which AI experts and climate change experts interact with each other to explore ways AI could contribute to climate change mitigation.*



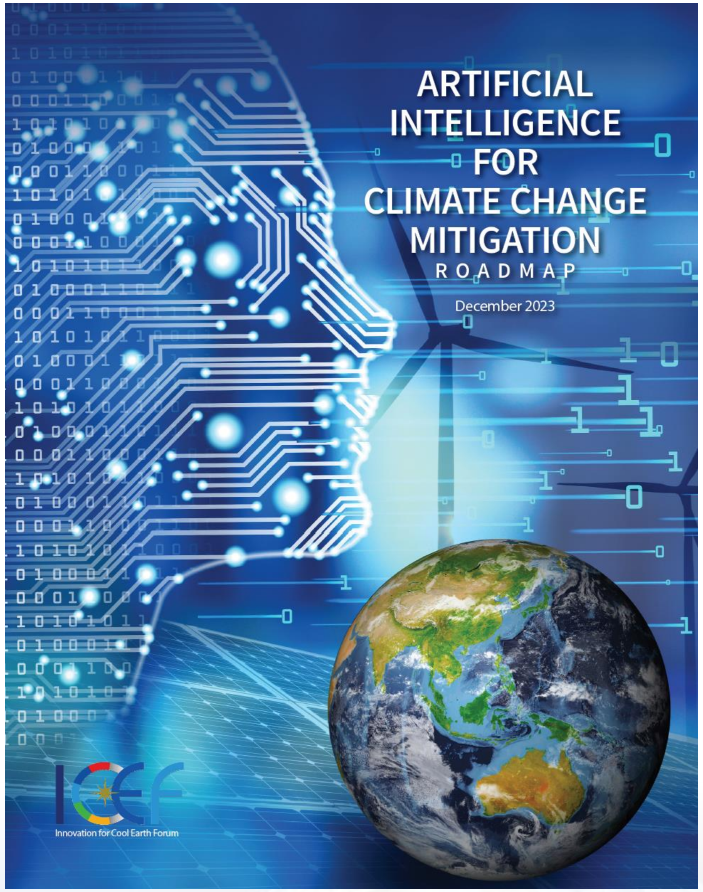
Chapter 17: FINDINGS AND RECOMMENDATIONS

RECOMMENDATIONS

4. <u>Governments</u> should assist in the development and sharing of data for AI applications that mitigate climate change.

5. <u>Governments</u> should provide substantial funding for the development and application of AI applications for climate mitigation.

6. <u>Governments, philanthropies and information technology companies</u> should play a pivotal role in funding the development of large-scale open-source foundation models tailored to address climate challenges.

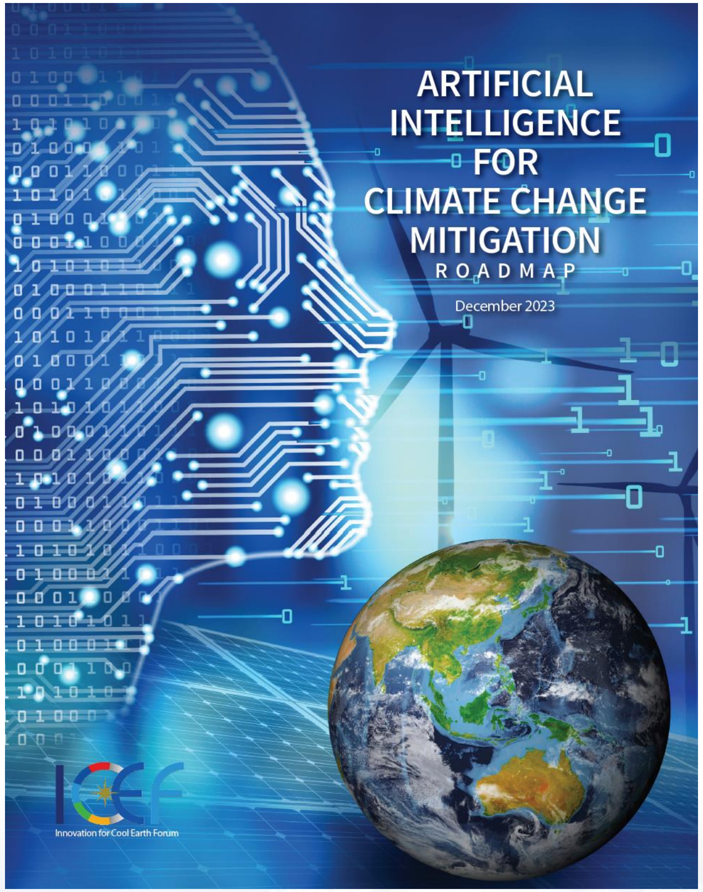


Chapter 17: FINDINGS AND RECOMMENDATIONS

RECOMMENDATIONS

7. Companies with datasets relevant to climate change mitigation should consider sharing portions of those datasets publicly.

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



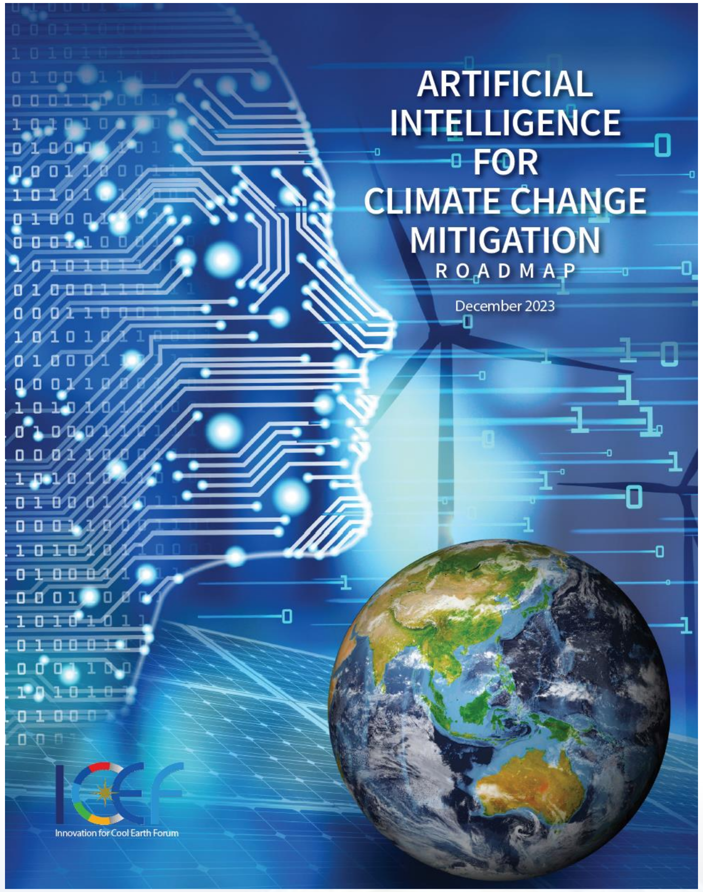
Chapter 17: FINDINGS AND RECOMMENDATIONS

RECOMMENDATIONS

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

10. Governments should work to accurately characterize and minimize greenhouse gas emissions from AI's computing infrastructure.

11. Organizations that use AI for climate change mitigation should assess and address potential risks from AI tools.



INNOVATION ROADMAP PROJECT

Innovation for Cool Earth Forum

- 12 clean energy roadmaps since 2015
  - *Artificial Intelligence for Climate Change Mitigation (Dec. 2023)*
  - Others include *Low-Carbon Ammonia (2022), Carbon Mineralization (2021), Biomass Carbon Removal & Storage (BiCRS) (2020), Industrial Heat Decarbonization (2019), Direct Air Capture (2018)*
- Sponsored by Japan's Ministry of Economy, Trade and Industry (METI) and New Energy and Industrial Technology Development Organization (NEDO)

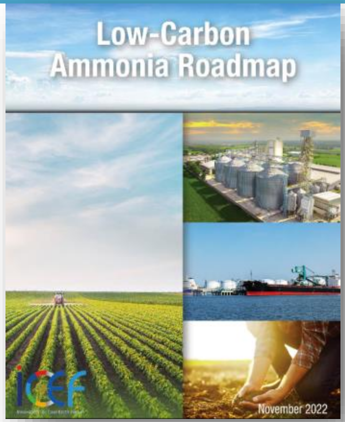
INNOVATION ROADMAP PROJECT

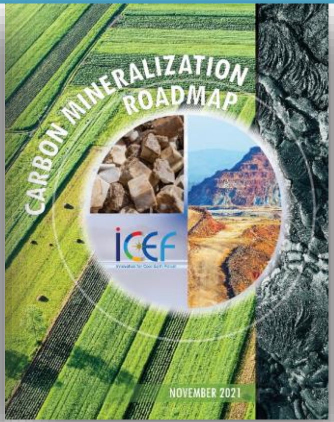
HOESUNG LEE—former Chair, IPCC: “The ICEF roadmaps provide important research on a wide range of technologies for helping achieve net zero emissions. They are an important resource for anyone working on these issues.”

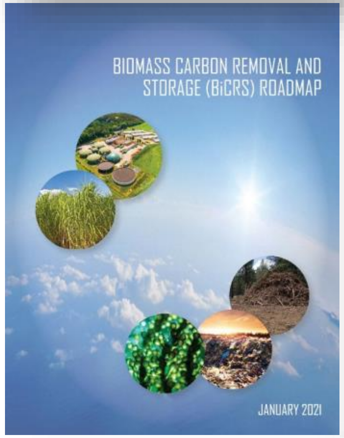
VACLAV SMIL—energy historian: The ICEF roadmaps "provide essential information on different aspects of our energy systems and how they might change over time. I recommend them for anyone interested in this challenging topic.”

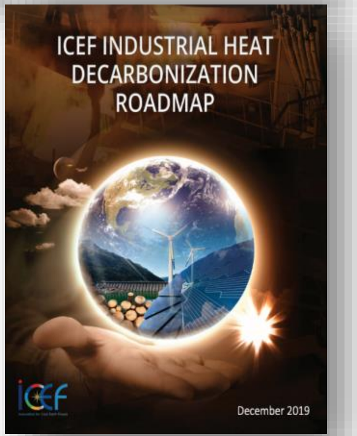
ALISSA PARK—Dean, UCLA School of Engineering: "The ICEF roadmaps...are an excellent resource for researchers and practitioners who cross disciplinary boundaries to develop transformative solutions for climate change.”

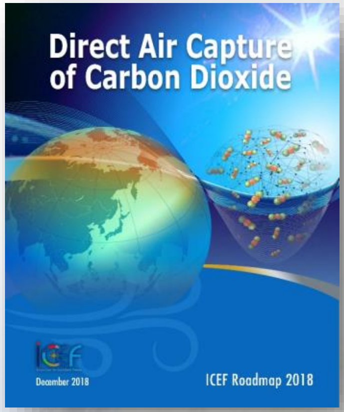
icef.go.jp/roadmap

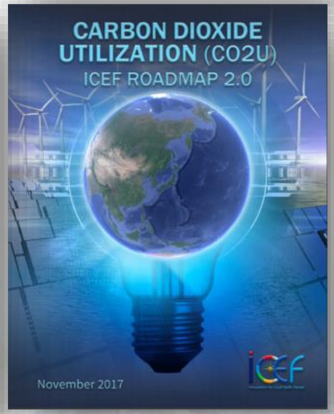


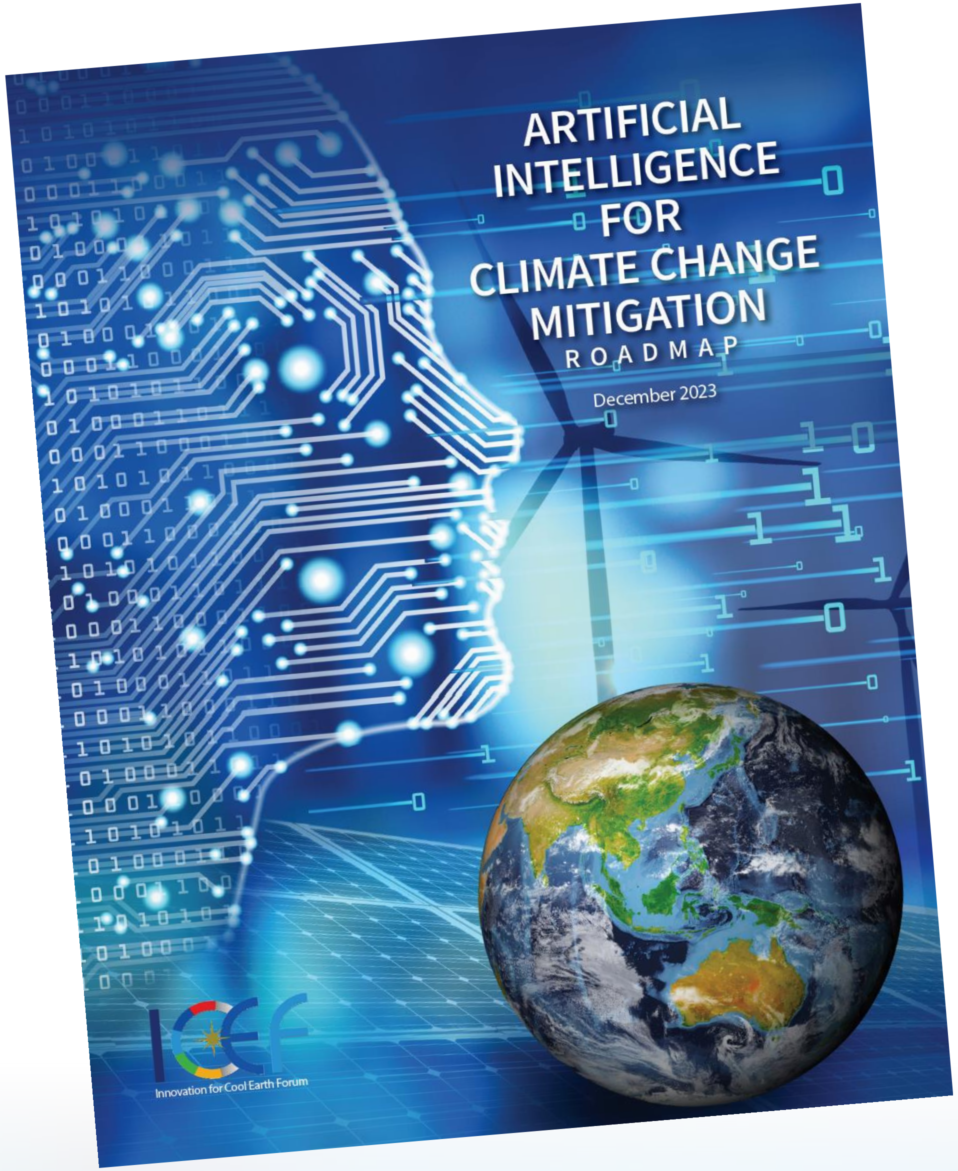












Innovation for Cool Earth Forum

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