Technology Governance
Policy Challenge

Green Technologies for Climate Mitigation, Adaptation and/or Intervention

An Anthology of Briefing Notes from the
2025 Technology Governance Policy Challenge

Green Technologies for Climate Mitigation, Adaptation and/or Intervention

An Anthology of Briefing Notes from the
2026 Technology Governance Policy Challenge

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Introduction

The planet is getting hotter. The leading models warn that global warming is on track to surpass 1.5°C in the 2020s and 2°C before 2050, reaching an estimated 2.7°C. This is far beyond The Paris Agreement goals to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

Research has shown that limiting global warming to 1.5°C will reduce the impact on human systems and ecosystems, but that any amount of warming will have negative economic, social and environmental impacts. Exceeding 2°C is the point where it is expected that the global climate system will reach negative critical thresholds that, when crossed, leads to large, accelerating and often irreversible changes in the climate system. These harmful tipping points in the natural world pose some of the gravest threats to humanity. The full damage caused by negative tipping points will be far greater than their initial impact.

Avoiding this fate will require technological innovation. New technologies fall generally into three buckets:

- Climate mitigation technologies designed to reduce future global emissions and thereby reduce the expected total level of warming.
- Climate adaptation technologies that make existing and future infrastructure and systems (including the global economy) less vulnerable to the impending and inevitable effects of climate change.
- Climate intervention including carbon dioxide (CO2) removal (CDR) or solar geoengineering to artificially modify global environmental conditions.

These technologies all present opportunities to address climate change, and create better long-term futures for humanity, as well as global ecosystems. However, they also have drawbacks. Many, such as CDR and direct air capture, while highly effective at removing CO2 from the atmosphere, are extremely expensive. Similarly, many alternative technologies used in climate mitigation and adaptation require critical minerals, which carry significant economic, social and environmental impacts of their own. Furthermore, the time and cost required for the research, development and deployment of these new technologies is at odds with the increasingly short time frame, not to mention challenges of political polarization, climate denialism, corporate lobbying and entrenched interests, and conflicting priorities for both the public and decision makers, such as ongoing geopolitical conflict.

In short, the world needs to govern climate technologies if they are to be leveraged to their full potential.

2026 Technology Governance Policy Challenge

In February 2026, the Balsillie School of International Affairs (BSIA) and the School of International Service (SIS) at American University co-hosted the Third Annual Technology Governance Policy Challenge on the theme of "Green Technologies for Climate Mitigation, Adaptation and/or Intervention." The event included teams from the IE University Madrid, Munk School of Global Affairs at the University of Toronto, Norman Patterson School of International Affairs at Carleton University, Sciences Po, Tecnológico de Monterrey, the University of Warwick, the University of Western Cape, as well as the BSIA and American University's SIS. For two days, graduate students from the nine schools met to present their ideas about how to leverage technology to combat climate change and advance the green energy transition.

This anthology is the product of their creativity. Students were given a real-world scenario in which the World Climate Research Programme (WCRP) and Intergovernmental Panel on Climate Change (IPCC) joined forces to convene a co-sponsored workshop on "High-impact events, tipping points and their consequences." Each team was asked to conduct analysis to identify the potential of emerging green technologies 1 to address climate mitigation, adaptation and/or intervention. This collection of policy briefs provides concrete guidance for state governments, the WCRP and the IPCC concerning the use of emerging technologies and identify any number of technologies that hold the most significant potential in any combination of climate mitigation, adaptation and/or intervention.

First and foremost, a huge congratulations to the students for your dedication to making the challenge such a tremendous success from the moment you signed up to participate in the fall of 2025 to the event itself. Many thanks to our colleagues at each of the participating schools for being such wonderful supporters of a nascent student competition that is just in its third year. To Interim Dean Rachel Sullivan Robinson, Simon Nicholson and Christine Gettings for their ongoing enthusiasm for not only the Technology Governance Challenge, but also the wider BSIA-SIS collaboration. To Joanne Weston and Emily Ferk at the BSIA who handled all of the logistics and to Sherwood Audio for working behind the scenes to make sure the technology ran smoothly. Thank you to our panel of judges — Beth Chalecki, Peter Massie and Ged McLean — for being so generous with their time. Thank you to our copy editor, Carol Bonnett, and graphic designer, Allie Visser, for their work in getting this anthology to press.

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Alternative Energy Sources

From Liability to Asset: Enabling Synthetic Fuels from Carbon-intensive Industries through Carbon Capture, Utilization and Storage

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Issue

Industrial processes (cement, steel, chemicals and refining) account for roughly 20–25 percent of global carbon dioxide (CO_2) emissions, and the European Union should explore ambitious climate-conscious technologies such as carbon capture, utilization and storage (CCUS) as it is a key lever for near-term decarbonization.

Background

For this policy brief, the focus is on the European Union and its policy framework, The European Green Deal. The aim of this agreement is to achieve a climate-neutral, resource-efficient and globally competitive EU economy by 2050, while decoupling economic growth from resource use and ensuring a just transition for workers and regions (European Commission 2019). The European Commission's 2021 communication deems ongoing reliance on fossil carbon structurally unsustainable. It positions sustainable, climate-resilient carbon cycles as a core pillar of EU climate policy through reduced fossil carbon use, recycling from waste streams, biomass and ambient air, and the scaled deployment of carbon removal and utilization technologies such as carbon capture utilization and synthetic fuels (European Commission 2021).

The leader of this technology is currently the United States. They were able to scale up CCUS rapidly through enhanced financial incentives and funding options. They used tax credits and over US$12 billion in funding that was driving industrial and hub deployments despite political divides, even in states such as Texas (Park 2025). Another leading expert in this field is Canada, which just recently announced the Major Projects Office. This serves as a centralized mechanism to expedite planning for CCUS initiatives by coordinating federal and provincial reviews under a single streamlined process. It simplifies decision making through predefined timelines, risk-based assessments and early stakeholder engagement, reducing bureaucratic delays that have historically stalled large-scale energy projects.

In Europe, Denmark, the Netherlands and Norway have advanced CCUS deployment by leveraging EU-wide policies such as the Innovation Fund and the Connecting Europe Facility, alongside national incentives, such as the Carbon Contracts for Difference. These frameworks provide grants, subsidies and de-risking for capture, transport and storage infrastructure, enabling projects like Greensand/Bifrost (Denmark), Porthos (Netherlands) and Northern Lights (Norway) (Rose 2024).

Generally, the European Union provides policy support and funding for industrial CCUS-to-synthetic fuel hubs, including large investments for CO_2 transport and storage networks targeting 50 million tonnes annually by 2030 under the Net-Zero Industry Act (European Commission

2025a). The Emissions Trading System (ETS)-supported Innovation Fund covers up to 60 percent of CCUS projects, with over €12 billion originally allocated by 2024 (European Commission 2025b). Additional aid comes from the Recovery and Resilience Facility and Just Transition Fund for regions undergoing a just transition (European Commission 2025c). Market demand for ReFuelEU Aviation and FuelEU Maritime creates opportunities worth over €100 billion, supported by credit multipliers, exemplified by the eSAF Early Movers Coalition launched in December 2025 (European Commission 2025d; European Commission 2025e). InvestEU guarantees and Horizon Europe/LIFE R&D further support deployment (Fuels Europe n.d.). Establishing these as hubs helps turn industrial CO_2 liabilities into scalable e-fuel assets, in line with the Industrial Carbon Management Strategy.

The European Green Deal's CCUS ambitions face several critical hurdles. First, a projected €10 billion funding shortfall by 2030 threatens essential projects, as current Innovation Fund allocations fall short of deployment needs. Second, CO_2 transport infrastructure lags due to incomplete cross-border regulations and permitting bottlenecks that delay the development of hubs. Finally, capture costs routinely exceed EU ETS carbon prices, eroding project economics and deterring investor confidence (Rossi and Kupiec 2025).

This brief advocates for expanding carbon capture systems at industrial sites in the European Union to convert captured CO_2 into synthetic fuels. By transforming unavoidable industrial emissions into valuable feedstocks, this approach directly operationalizes the Green Deal's second pillar, supports the creation of an integrated EU market for CO_2 capture, use and storage, and reinforces the European Union's leadership in low-carbon industrial innovation.

Scientific Background

Applications for CO_2 are endless and can be the answer for fuel alternatives and energy transformation in a climate that is increasingly at risk. Conventional carbon capture and storage (CCS) techniques involve capturing CO_2 from industrial byproducts, transporting it and injecting it into underground geological formations. Whereas shifting towards CCUS not only develops new fuel and energy sources but also alleviates growing concerns of traditional CCS relating to earthquakes, accidents or explosions (Fikru and Nguyen 2024). Limited by the high costs involved with the transportation and storage of CO_2, CCS applications require vast pipeline infrastructure and conducive offshore saline aquifers. Estimates currently have a high practical cost range of USD$4 to $45 per tonne of CO_2 transported by pipeline, contingent on geographic, geologic and institutional characteristics (Smith et al. 2021). CCUS systems solve issues relating to difficult emissions targets, the binding of economic activity and climate change, and the potential side effects and costs of long-term CCS techniques.

Historically, CO_2 has been captured from industrial process streams, although most of it is vented to the atmosphere, lacking any incentive or requirement to store it (Thambimuthu, Soltanieh and Abanades 2005). Natural gas purification, ammonia production and the cement and steel industries are high-value fields that could see large returns from reinterpreting their emissions. Instead of focusing on direct air capture, the most promising avenues for CO_2 capture stem from post-combustion, which is the most straightforward approach and forms the basis of the current infrastructure in CCS (Rajabloo et al. 2022). Furthermore, post-combustion can be retrofitted to existing technologies, making it the most mature and cost-efficient alternative.

Through novel methods of collection and processing, captured CO_2 can directly and indirectly produce valuable products. Through chemical synthesis (methanol, dimethyl ether and methane synthesis) or emerging technologies like electrochemical synthesis (fuel cell conversion), CCUS supports the conversion of CO_2 into synthetic fuels. Industrial plants are then able to generate power through synthetic fuels such as methanol, synthetic methane, synthetic crude or electrochemical conversion of CO_2 to electricity (Ishaq and Crawford 2023). Aside from acting as a raw material in the production of synthetic fuels, CCUS acts as a promising pathway to offset the costs of CO_2 capture and conversion.

Synthetic fuels from carbon capture result in liquids or gases through chemical synthesis using non-petroleum sources such as captured CO_2 and green hydrogen from renewable electricity-powered water electrolysis. Synthetic fuels like e-methanol and synthetic jet fuel create a closed carbon cycle — CO_2 released during use is offset by captured emissions — potentially reaching near-zero net emissions when powered by low-carbon electricity (Ruth and Stephanopoulos 2023). Life-cycle analyses show direct CO_2 hydrogenation can reduce greenhouse gas (GHG) emissions by up to 50 percent compared to petroleum jet fuels, depending on electricity's carbon intensity (Saad, Terlouw, Sacchi and Bauer 2024). Unlike biofuels, power-to-liquid with direct air capture needs 90 percent less land and avoids food crop competition, boosting sustainability (Ishaq and Crawford 2023). Multiple CO_2-derived fuels will likely coexist based on infrastructure compatibility across sectors (Ruth and Stephanopoulos 2023). These pathways also reduce reliance on fuel-exporting countries and are compatible with existing engines and infrastructure. Their high energy density benefits aviation and shipping, helping decarbonize hard-to-electrify sectors.

Short-term Adoption

As the greatest CO_2 polluters, this brief identifies aviation and commercial freight as critical sectors for near-term adoption of synthetic fuels. Including passenger transport, the aviation industry accounts for approximately 2.5–3.5 percent of global GHG effects, with an expectation of 4.7 percent of global emissions by 2050. Together, land, air and sea transport, the three primary forms of commercial freight, generate over 10 percent of global GHG emissions annually (Al-Mohannadi, Ertogral and Erkoc 2024). The logistics and transport ecosystem represents an opportunity to collaborate, standardizing synthetic fuel blends for aviation, trucking and shipping as well as establishing partnerships with synthetic fuel manufacturers.

These sectors possess robust organizational capacity for coordinating a transition to synthetic fuels. The American Society for Testing and Materials (ASTM), an international organization responsible for the standardization of jet fuels, provides specifications for sustainable alternative fuel (SAF) blends. As of 2022, the ASTM has identified seven different SAF production pathways, including green hydrogen, ethanol and methanol, that are certified to be blended with conventional kerosene at up to a 50 percent blending ratio (Teoh et al. 2022). Likewise, the International Maritime Organization (IMO), a specialized agency of the United Nations engaged in safety rulemaking in the maritime sector, implemented the Annex VI of The International Convention for the Prevention of Pollution from Ships to limit air pollution from ships. In 2023, the IMO strengthened its own goals to achieve net-zero GHG emissions by 2050 using synthetic fuel internal combustion engines, such as methanol, ammonia, hydrogen and fuel cell technologies (Aui et al. 2025). Although international coordination for land freight, including trucking and other long-distance transportation, is limited, cooperation between the private sector and government could produce similar results.

Current projections for SAF integration into commercial fuel markets significantly reduce GHG emissions when compared to fossil fuels. An increase in synthetic fuel supply could reduce aviation CO_2 emissions by 15 percent in 2050 relative to the baseline scenario with conventional fuels. Without supply bottlenecks, aviation CO_2 emissions could continue reductions by 5.5–9.5 percent over 15 years if the adoption rate of SAF increases by one to two percent annually (Teoh et al. 2022). Similarly, broader techno-economic projections that accommodate recent innovations in synthesis chemistry and process intensification, which improve energy efficiencies by up to 20 percent and reduce production costs by 30–40 percent, demonstrate that e-fuels can achieve carbon reductions of 70–90 percent compared to conventional fossil fuels. However, commercial viability hinges on further cost reductions to below US$3/kg alongside robust policy support (Awais Ali et al. 2025).

Although electric batteries provide alternatives to synthetic fuels, they are a less reliable or efficient option for commercial freight, where infrastructure and energy capacity are underdeveloped for long-distance travel. In the short-term, the high investment required to purchase electricity-powered transport trucks and to scale up charging infrastructure remains a barrier to implementation (Frenzel et al. 2021). However, electric vehicles remain the salient option for consumer-based transportation, where the carbon footprint for individuals is negligible in comparison.

Recommendations

Given these considerations and the identified gaps in current CCUS and synthetic fuel policies, the following recommendations aim to enable industrial CO_2 and by-products to be systematically redirected into low-carbon synthetic fuel production in the European Union. As identified by the International Energy Agency (IEA), current concerns regarding CCUS adoption pertain to the high costs of infrastructure and project development timelines (IEA 2024). Considering the agency's recommendations and the necessity for immediate action against climate change, the advised policy package titled *Carbon Reimagined* enumerated below is strongly recommended.

The creation of a "Carbon Refurbishment Office" to oversee inter-organizational relationships and align governmental objectives with creator and user industry actors. This office would serve as the public-sector connection for industry hubs of creators and users within the circular carbon economy of synthetic fuels generated from CCUS infrastructure. It would also act as the channel to organize funding through expedited loan and permit approval processes, as well as provide guidance on creating industry hubs to navigate the planning and approval processes for CCUS projects.

The creation, support and backing of industrial hubs with identified creator and user sectors. Dispersing the initial cost of CCUS infrastructure is the primary goal of early adoption processes, allowing for both large- and small-creator industries to pool resources for costly CCUS additions to their existing infrastructure. Furthermore, incentivizing cooperation between identified creator and user industry actors coupled with the *Carbon Reimagined* policy package creates an internal circular carbon economy. The package includes access to capital grants with stipulations requiring unions between organizations within identified sectors, along with sequential rollout of synthetic fuel mixture mandates for the aviation and shipping industries. Mixture adoption would begin with a 25 percent CCUS-created biodiesel and 75 percent renewable diesel blended mixture, with incremental five percent yearly shifts of the mixture towards CCUS-created biodiesel until comprising the entirety (about 15 years) for both industries. It also establishes criteria by which projects shall be held to qualify for expedited planning, simplified decision-making, and streamlined execution to quicken the incorporation and start-up time on CCUS projects.

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Artificial Intelligence-optimized Power Grids — Dublin, Ireland

Ricardo Ribeiro, Daria Tymchenko and Luna Zavalía Pángaro

Issue

The rapid growth and widespread adoption of artificial intelligence (AI)-driven data centres in Dublin is outpacing the expansion of clean electricity and grid infrastructure, which creates ethical, economic and climate governance risks as governments struggle to introduce net-zero pathways without crowding out broader decarbonization efforts.

Background

In the context of an ongoing global energy crisis characterized by rising electricity demand, supply volatility and rapid digitalization, the energy footprint of data centres has become increasingly critical. The International Energy Agency (IEA) (2025) establishes that global electricity consumption by data centres currently represents 1.5 percent of global electricity consumption. The forecasted trajectory is not different. By 2030, data centre electricity demand will more than double, and by 2035, renewables are projected to generate half of the energy required to meet data centre demand, with continued substantial growth expected. This reveals structural urgency. At present, Europe accounts for 15 percent of global data centre electricity consumption, but within Europe, Ireland and Dublin face acute local constraints due to data centre clustering.

The European Parliament (2025) identifies "FLAP-D cities" (Frankfurt, London, Amsterdam, Paris, Dublin) as hubs for industrial-scale cloud infrastructure where local grid pressure is disproportionate to national averages. Although counterintuitive, the implementation of AI-optimized power grids can help improve system efficiency and support climate mitigation by monitoring energy flows and adapting to changes in demand and supply, and additionally, assist in monitoring the variability and distributed generation of renewable energy sources and reducing system inefficiencies (International Renewable Energy Agency [IRENA] 2013; European Commission n.d. b.; Greene-Dewasmes & World Economic Forum, 2025).

The most critical matter in the current stage is the structural timing gap, where electricity demand surpasses the green supply. The AI-driven demand for data centres is growing substantially faster than the green energy supply. The IEA (2025) projects that half of the global growth in data centre demand is met by renewables, leaving substantial fossil fuel requirements. Without extraordinary, coordinated investment, AI data centres will either lock in fossil-fuel electricity (undermining climate goals) or monopolize available renewable capacity, crowding out electrification of transport, heating and industry.

The core of the issue relies on the two nodes that fuel the dynamics: the energy consumer, the AI data centre demand grows exponentially; and the AI optimization systems that enable higher renewable penetration and better demand management through grid efficiency. The tension between both accelerates investment in green energy because this offers a sustainable path, incentivizing power purchase agreements (PPAs) acquisition, driving the entire renewable transition forward. This is key because grid modernization would not be funded at its current pace without urgent data centre demand. One drives demand for the other, accelerating both infrastructure modernization and AI-enabled optimization capabilities.

These AI optimization systems yield measurable macro-level efficiency gains; recent simulations of AI-integrated smart grids explicitly report an 11.76 percent increase in energy efficiency and grid stability compared to traditional infrastructures. Noviati et al. (2024) study also found a 66.67 percent reduction in prediction errors for renewable energy generation and a 20 percent decrease in operational costs, demonstrating the tangible operational benefits of algorithmic grid management (Noviati, Maulina and Smith 2024).

Ethical Considerations

Distributional Justice

The World Economic Forum (2025) identifies the central power dynamic as fundamentally a distributional justice issue: determining who benefits and who bears the costs. Technology companies' dominance over long-term PPAs for renewable generation creates market foreclosure, explicitly generating inequality by limiting clean energy access for smaller businesses, municipalities and households while hyperscalers[1] lock in future capacity.

This network-effect monopoly leverages economies of scale to displace smaller market participants, concentrating control of renewable supply among dominant players. Consumers could bear the costs of the transition through network surcharges, while the main benefits accrue to the AI companies implementing these optimization systems. While AI-driven network optimization significantly improves system efficiency, equitable distribution of benefits requires policy intervention to prevent technology monopolies from exclusively capturing clean energy.

Power Concentration and Democratic Oversight

The growing concentration of AI capabilities among a small number of private firms poses a clear accountability risk for energy governance. Such power asymmetries could undermine public trust, highlighting the need for stronger regulatory oversight and public stewardship of AI systems used in energy governance (United Nations Educational, Scientific and Cultural Organization 2021; Organisation for Economic Co-operation and Development [OECD] 2019).

Technological Impact Assessment

AI-powered electricity grids enable real-time analysis and optimization of energy consumption, improving system efficiency and supporting climate mitigation. By enhancing demand forecasting, balancing loads and integrating variable renewable energy sources, AI can reduce reliance on fossil fuel-based peaking plants (IEA 2017). In this context, digitalization and AI act as key enablers of low-carbon power systems as renewable penetration increases (IRENA 2025, 22). A practical example can be found in Denmark, where Elværk is employing digital twins of its power grid in order to optimize their operations and better understand demand patterns, facilitating the seamless integration of renewable energy sources. (Volue n.d.; McCall 2025).

Dublin's Potential

In Dublin, AI-enabled grid optimization aligns with existing local initiatives. Dublin City Council's Smart City programme provides innovation districts where digital energy solutions can be tested and scaled in real-world conditions (Dublin City Council n.d.). The Interreg Twin for Resilience initiative has also embedded digital twin technologies within city departments, creating a foundation for integrating AI-based energy models into planning and public engagement processes (Interreg Europe n.d.). Dublin is a particularly suitable case for such deployment, given the growing pressure on its electricity system driven by rapid demand growth from data centres, alongside its established technology-forward ecosystem as one of the European Union's leading digital and innovation hubs.

When comparing AI-driven optimization with other emission reduction initiatives, it offers high leverage relative to its material footprint, relying primarily on software while taking advantage of the European Union's push for European-based data centres. As the European Union strives for carbon neutrality by 2050, AI-enabled smart grid energy management becomes central to achieving EU climate objectives while strengthening its competitiveness in clean and digital technologies (European Commission 2024).

Trade-offs

Although AI can reduce the need for additional physical infrastructure for energy generation, it still depends on extensive supporting infrastructure, including data centres, and associated buildings, as well as reliable energy and water supply. However, these infrastructure needs align with the EU's strategic objective to expand domestic data-centre

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[1] Technology company that provides massive-scale cloud computing, data storage, and networking services

capacity while meeting strict energy efficiency, renewable energy sourcing and waste-heat recovery standards (European Parliament 2022; European Commission n.d.) Consequently, AI deployment still requires significant upfront investment in digital systems, specialized skills and long-term maintenance (OECD 2025a). Scaling AI also depends on access to high-quality, interoperable data, with data fragmentation, data protection compliance and transparency posing persistent challenges across the EU energy sector (OECD 2025b). If these challenges are not approached correctly, it could lead to difficulties transitioning from experimentation to implementation.

Effective deployment of AI-powered grid optimization depends not only on technical performance, but also on coordination among key stakeholders with differing levels of power, incentives and risk exposures. While public policy makers and system operators are generally supportive due to climate, energy security and operational efficiency benefits, their ability to act is constrained by accountability and system reliability concerns. In contrast, regulators and cybersecurity authorities represent a potential bottleneck, as unresolved issues around transparency, data access, consumer protection and cyber resilience can slow approval and scaling. Conditional support from market and financial actors means that regulatory uncertainty and cost-recovery risks could stall investment, thus creating a chokepoint to scaling AI optimization.

These coordination challenges intersect with a key resource prioritization trade-off: public funding, skilled labour and political attention are limited, requiring choices between digital optimization and traditional mitigation measures such as renewable capacity expansion. However, digital solutions are complementary for physical decarbonization investments, hence misallocation could delay emission reductions if optimization proceeds without sufficient clean energy supply (IEA 2023).

Recommendations

Pilot deployment and evaluation of Dublin as a case study. As a city, Dublin is well suited as a pilot location due to its growing electricity demand driven by urban electrification and data centres, significant renewable energy penetration and regulatory capacity. This environment makes the location optimal for assessing AI-optimized grids. In terms of evaluation, an independent expert panel would evaluate project performance at two different stages: an initial review six months after implementation to assess operational and grid stability impacts, followed by a second review 18 months after implementation to evaluate emissions outcomes, cost effectiveness through a cost-benefit analysis, as well as a scalability assessment prior to further and wider replications.

Require readiness assessments from all EU member states by 2026. EU member states should be encouraged to conduct infrastructure readiness and capacity assessments evaluating grid flexibility, renewable availability, cybersecurity resilience, data governance and regulatory capacity to support AI-powered grids. Reports from the readiness assessments should be reported to the European Commission to prioritize AI-optimized grids that deliver the highest net system benefits. Overall, this approach minimizes deployment-related risks.

Commit to continuous learning and adaptive regulations. The insights from the Dublin pilot should be used to feed into an adaptive regulatory framework. This would allow EU governments to update cybersecurity requirements and energy accountability standards as evidence emerges and events occur. This approach ensures that AI-optimized grids evolve in alignment with system capacity, societal needs and climate change-related objectives.

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Volue. n.d. "Elværk Power Grid Leads in Digitalisation." Volue. https://www.volue.com/cases/elvaerk-power-grid-leads-in-digitalisation.Unlocking Mexico's Geothermal Potential to Power the Artificial Intelligence Revolution

Unlocking Mexico's Geothermal Potential to Power the Artificial Intelligence Revolution

Gabriel Evangelista-Palma, Nayely Monserrat Luna-García, Brenda Salas-Caldera and Andrea Victoria Vásquez-Cantero

Issue

To meet the explosive energy demands of artificial intelligence (AI)-scale computing, Mexico must unlock its untapped geothermal potential to provide firm, continuous baseload power, enabling a renewable transition without the inconvenience of intermittency.

Background

The rapid expansion of artificial intelligence (AI), particularly large language models (LLMs), has become a structural driver of electricity demand, as these technologies rely on continuously operating, power-intensive data centres. LLMs now follow accelerated innovation cycles, with major performance upgrades occurring every three to six months, alongside unprecedented adoption: ChatGPT alone exceeds 800 million monthly active users (Berenberg 2025). By 2025, LLM-powered applications are projected to reach approximately 750 million worldwide, while global spending on generative AI is expected to climb to US$644 billion, representing a 76 percent year-on-year increase (Pandey 2026). Within firms, AI-assisted systems already generate between 25 and 33 percent of new code in major technology companies, signalling the deep integration of AI into core productive activities. Globally, data centre electricity consumption reached approximately 460 TWh in 2022 and is projected to exceed 1,000 TWh by 2026, while installed capacity is expected to grow from around 60 GW today to 171–219 GW by 2030, with nearly 70 percent dedicated to advanced AI workloads (IEA 2024; Bhargs Srivathsan, Sorel and Sachdeva 2024).

The Real Constraint: Firm Power, Grids and Storage

In Mexico, these global trends intersect with nearshoring dynamics and a rapid expansion of data centres. Mexico is currently the eleventh-largest data centre market globally, with approximately 170 facilities and an expected investment of US$7 billion between 2022 and 2027. Over the next five years, at least 73 additional centres are expected, representing US$9.19 billion in direct investment and more than US$27.5 billion in indirect investment: potentially increasing sectoral electricity demand by up to 400 percent, to approximately 1,492 MW (Calderón 2024). Furthermore, Mexico ranks seventh globally with 976 MW of geothermal potential. The state of Queretaro serves as a strong case study, where 10 of the 21 hyperscale data centres planned for 2025 were successfully initiated, illustrating the intersection of high digital demand and geothermal viability. However, this growth is unfolding within an electricity system facing structural constraints, as documented in Mexico's "Plan de Desarrollo del Sector Eléctrico Nacional 2025–2039" (PLADESE) published by the Secretaría de Energía (SENER) (2025). Between 2010 and 2024, demand grew at an average annual rate of 2.6 percent, while generation capacity expanded more slowly with growth of only 1.7 percent in 2024; transmission bottlenecks persist, with 73 percent of 223 priority projects still in the early stages; energy losses reached 12.3 percent of net consumption; and clean technologies, despite accounting for 36.9 percent of installed capacity, generated only 26 percent of electricity in 2024, leaving Mexico below its 45 percent clean generation target for 2030 (ibid.). Under these conditions, energy policy must address both decarbonization and the rapidly rising electricity demand driven by AI-intensive digital infrastructure. For data centres (whose operations require uninterrupted power and continuous cooling), the binding constraint is not renewable potential per se, but limited access to firm, dispatchable baseload power and water-efficient cooling solutions. Facilities often rely on fossil-fuel backup systems, reinforcing emissions and price volatility (Sampedro Guamán et al. 2021), while cooling requirements create additional water-security risks, as illustrated by the suspension of a US$200 million Google data centre project in Chile due to projected water use in a drought-prone region (AP News 2024).

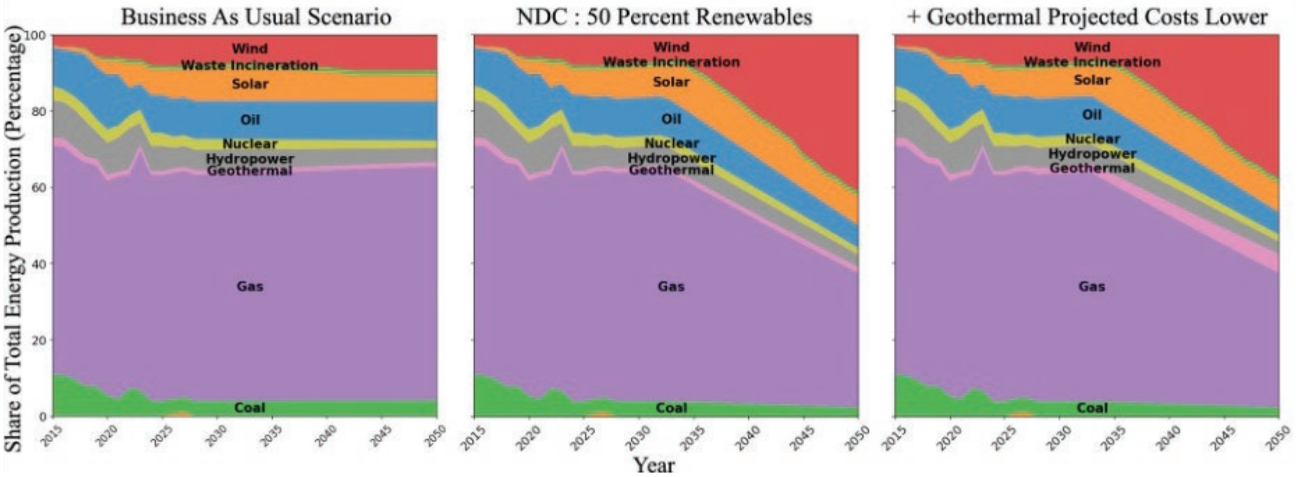
Geothermal Energy for Continuous Power, Cooling and Economic Viability

Geothermal energy is well suited to AI-driven data centres because it addresses cooling needs — around 40 percent of total energy consumption — while providing firm, continuous baseload power. Geothermal cooling systems, including ground-source heat pumps (GSHPs), can reduce power usage effectiveness (PUE) from above 1.6 to approximately 1.3, while closed-loop designs minimize risks such as aquifer depletion or contamination, making them suitable for water-stressed regions. Cascading use further improves efficiency by reusing geothermal heat for power generation, cooling and industrial applications. In Mexico, geothermal is complementary, not a substitute, to solar energy. While solar photovoltaic (PV) capacity factors are 22–26 percent, geothermal plants operate at 85–90 percent, reducing reliance on large-scale storage, backup generation, and new transmission capacity. Although geothermal has historically faced scalability constraints due to exploration and drilling uncertainty, recent advances in computational modelling, **computational fluid dynamics** (CFD) and AI-based subsurface analysis have reduced these risks, enabling wider deployment through binary-cycle and closed-loop systems. Although solar PV (US$35.1–$49.3/MWh) and wind (US$20.2–$67.1/MWh) have lower standalone levelized costs of energy than geothermal (US$39.6–$85.0/MWh), system-level analyses show geothermal is cost-competitive for continuous 24/7 industrial loads (Meza 2025). In Mexico, a 10 MW data centre case study estimates US$133/MWh for a solar-wind system with storage versus US$63/MWh for geothermal, reflecting geothermal's baseload value and avoided storage costs (ibid.). Globally, new geothermal projects average US$0.071/kWh, comparable to fossil generation (International Renewable Energy Agency [IRENA] 2023). Geothermal also offers long-term price stability due to limited exposure to fuel price volatility — an important advantage in a system where 59 percent of baseload power relies on natural gas combined-cycle plants (Meza 2025). Ongoing advances in binary-cycle, closed-loop and AI-enabled exploration are expected to further improve cost competitiveness (IRENA 2023; Meza 2025).

Environmental Considerations

Geothermal helps decarbonize baseload power, offering a renewable option that can displace fossil fuels on a continuous basis. The country's current energy mix, which relies on combined-cycle gas turbines and fuel oil, emits approximately 453 g/kWh and 906 g/kWh of $CO2$ (ibid.). To illustrate the impact of shifting this mix, a systems dynamics simulation for decarbonizing Mexican electricity production — utilizing Tecnológico de Monterrey's modelling tools — demonstrates that ambitious support for geothermal energy unlocks the greening of the rest of the grid.

Figure 1: Systems Dynamics Simulation for Decarbonizing Mexican Electricity Production



Source: Authors' elaboration using the SImulating SEctoral Pathways and Uncertainty Exploration for DEcarbonization (SISEPUEDE) model.

By projecting scenarios that include a 30 percent lower cost for geothermal alongside 50 percent nationally determined contribution fulfillment, the model suggests that introducing firm geothermal baseload reduces the overall system's reliance on fossil-fuel backups.

Binary-cycle plants with closed-loop systems, now the standard for medium-enthalpy projects, can have near-zero operational emissions, effectively decoupling continuous industrial growth from greenhouse gas (GHG) trajectories. Geothermal deployment involves localized risks, including subsidence, induced seismicity and gas releases, which can be effectively managed through established practices. In Mexico's hydrothermal systems, reinjection protocols help maintain reservoir pressure and reduce subsidence and seismic risks, while modern environmental regulation and closed-loop binary systems limit atmospheric releases of gases and trace elements,[2] protecting sensitive ecosystems (Prol-Ledesma 2024).

System-level Trade-offs in Powering Continuous Digital and Industrial Demand

The central policy trade-off lies between rapid capacity deployment and long-term operational resilience. Technologies that can be deployed quickly often rely on external system reinforcements (storage, backup generation) to meet 24/7 demand. By contrast, firm thermal resources involve higher upfront investment but drastically reduce downstream system complexity.

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[2] If not properly contained, geothermal operations can release hydrogen sulfide (H_2S) ammonia and some trace elements (for example, mercury and boron).

Table 1: Risk Dimensions of Variable Renewables versus Firm Geothermal Baseload

Risk Dimension	Variable Renewables + Storage	Firm Geothermal Baseload
System Complexity	High — requires storage, backup generation and grid reinforcement.	Low — intrinsic 24/7 supply reduces downstream system needs.
Water Stress Exposure	High in regions using evaporative cooling and thermal generation.	Low with closed-loop systems and cascading heat use.
Land Use and Spatial Constraints	High land footprint; constrained near industrial and urban hubs.	Low land footprint; high energy density.
Operational Resilience	High exposure to weather variability and storage performance.	Low-stable, climate-independent output.
GHG Emissions (Lifecycle)	Moderate — reduced operational emissions but higher lifecycle impacts from battery energy storage systems.	Low-near-zero operational and low lifecycle emissions.
Social Acceptance	Moderate — familiar technologies but recurring land and water conflicts.	Moderate — higher if poorly communicated; manageable with early engagement.
Workforce Readiness	Moderate — aligned with skills currently under development.	Moderate — requires targeted reskilling, but can use the expertise of the national petroleum agency.
Deployment Speed	Low risk — fast initial capacity additions.	Moderate — longer exploration and drilling.

Source: Authors' elaboration based on Meza (2025), Aryanfar et al. (2023), Shan et al. (2026), and García Alcaraz et al. (2025).

Land availability versus land density: Geothermal provides exceptional spatial efficiency for industrial-tech hubs. While an equivalent solar farm would require 50 times more land, a 50 MW geothermal facility occupies only a few hectares, requiring just 404 m2/GWh throughout its lifetime (Meza 2025).

Water consumption and lifecycle emissions: To mitigate water constraints in evaporative cooling, closed-loop geothermal systems utilize GSHPs and cascading heat reuse, which can even produce freshwater (up to 127.3 m3/h) via thermal desalination (Aryanfar et al. 2023; Shan et al. 2026; Sheini Dashtgoli et al. 2026). Furthermore, while battery-backed variable renewables carry high lifecycle manufacturing emissions, system-level analyses show geothermal lifecycle emissions are 400–1,000 gCO2eq/kWh lower than fossil fuel alternatives (Meza 2025).

Social impacts and employment implications: Securing a social license to operate is one of the biggest challenges for geothermal development in Mexico. Many industrial hubs are in water-stressed regions, where competition for water is a major source of conflict. Even though closed-loop geothermal systems use far less water than fossil fuel plants or evaporative cooling, concerns about resource depletion can still trigger opposition. This is compounded by Mexico's legacy of mining and industrial water use, which has eroded trust between communities and industry. Because geothermal is still unfamiliar to much of the public, clear and transparent communication is critical to distinguish it from other extractive activities. Experience shows that failure to address these concerns can stall projects for decades.[3]

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[3] The Cerritos Colorados project near Guadalajara has been stalled for decades due to sustained community opposition. Moving forward, successful projects will need to clearly demonstrate local benefits and create pathways for community participation or direct gains, such as equity stakes or access to geothermal heat, rather than treating communities simply as hosts for infrastructure serving distant users (Prol-Ledesma 2024).

Revitalizing Mexico's geothermal sector requires a targeted transformation of the workforce. Despite over 50 years of experience, sectoral stagnation between 1988 and 2015 left gaps in modern technical skills (García Alcaraz et al. 2025). Supplying industrial baseload demand will require retraining in advanced technologies, including binary-cycle systems and AI-optimized drilling, as well as multidisciplinary teams that combine geoscience and engineering with social sciences to manage both technical performance and social acceptance. Targeted financing is needed to build these integrated capabilities.

Policy and Infrastructure Strategy for Clean, Firm Digital Power

Option A: The Grid-first Approach. Mechanism: Data centres purchase geothermal power directly from the Federal Electricity Utility (Comisión Federal de Electricidad [CFE]) or legacy private plants via the National Grid (Sistema Electrico Nacional). Legal viability: The new *Disposiciones Administrativas de Carácter General para la Planeación Vinculante en la Actividad de Generación de Energía Eléctrica* (General Administrative Provisions for Binding Planning in Power Generation), issued in October 2025 (SENER 2025b), mandates "binding planning" (Planeación Vinculante). This means private projects must strictly align with the Programa de Desarrollo del Sector Eléctrico Nacional (PRODESEN). Since PRODESEN prioritizes CFE-led transmission projects (which are currently delayed), private "grid-first" projects face indefinite administrative rejection for not matching the federal plan. Economic impact: High exposure. Electricity from legacy CFE plants often exceeds MXN$1,000/MWh, while the grid mix remains 59 percent fossil-based, failing the "Green AI" mandate (Prol-Ledesma 2024).

Option B: Public Risk-sharing for Exploration. Mechanism: A state-backed geothermal risk fund to insure drilling costs for deep exploration. The reformed *Ley de Geotermia* (Geothermal Energy Law) of 2025 allows CFE to "reassign" (Reasignación) idle concessions to private partners, and a risk fund could facilitate these public-private partnerships. Constraint: The new regulation requires closer coordination with the National Water Utility (Comisión Nacional del Agua [CONAGUA]); deep geothermal drilling requires a full water concession, which in water-stressed basins can trigger a *Veda* (a government-mandated water extraction ban) and halt projects regardless of available capital. Enabling deep drilling requires amending the *Ley de Aguas Nacionales (National Water Law)* to classify fully reinjected geothermal generation as a non-consumptive use, exempting it from volume restrictions in *Veda* zones.

Option C: Targeted Eco-digital Parks (Co-location Strategy). Mechanism: Co-locating data centres with geothermal wells for "island mode" power and direct cooling, legally structured to bypass the grid. A relevant case is the San Felipe industrial complex in Baja California, which operates as an isolated system independent of the national grid, avoiding transmission congestion (Meza 2025). Legal viability: This leverages exemptions in the 2025 law, such as the *Aprovechamiento Geotérmico Exento* (projects below 100°C for cooling loops on plots under 30,000 m2 only require an *Aviso de Registro*), the *Permiso de Usos Diversos* (provides legal certainty for cascading use models) and a social impact fast-track.

Economic Value and Financial Viability: By applying cost adjustments for an "island mode" setup — which reduces transmission scope, leverages direct-use heat to prevent over-sizing and utilizes AI-enabled exploration — the financial profile of a 50 MW eco-digital park becomes highly competitive. This model provides firm baseload power at less than half the cost of an equivalent solar-plus-storage system (approximately US$63/MWh versus US$133/MWh). With an estimated initial investment of €260 million and €6 million in annual operational costs, the project offers a 10–11-year payback period while avoiding roughly 158 kt of CO_2 annually (4.7 Mt of CO_2 over its lifetime) (ibid.).

Recommendations

Mexico's industrial modernization and rapid expansion of digital infrastructure are driving demand for reliable 24/7 electricity and cooling, while grid constraints and the need to scale clean generation widen the gap between installed capacity and future needs. In this context, geothermal energy offers a continuous, low-carbon source of power and direct-use thermal applications that support mitigation and climate-resilient operations for critical loads such as data centres. Mexico must establish a comprehensive strategy to accelerate the deployment of clean geothermal energy for industrial clusters and data centres, with a focus on the following:

Geothermal energy hubs: Prioritize geothermal integration in emerging data centre corridors or zones, particularly where grid constraints or water stress limit conventional cooling. Geothermal energy can support industrial clusters and data centre hubs by supplying power or thermal cooling, reducing dependence on gas-fired generation and diesel backup, and lowering exposure to grid congestion (Ten Bosch et al. 2024). Evidence shows that geothermal-assisted cooling in data centres reduces mechanical ventilation and cooling loads, improving energy and operational efficiency.

Cascading use of geothermal energy: Deploy geothermal energy through cascading use schemes that enhance industrial productivity, regional development and emissions reduction by maximizing thermal value across multiple economic activities. Cascading use refers to the sequential application of geothermal heat, enabling direct thermal uses such as agro-industrial processing, food drying, greenhouse heating, aquaculture and industrial heat, followed where feasible by power generation or auxiliary applications, rather than limiting deployment to electricity generation alone. The *Mexico Clean Energy Report* identifies direct-use and cascading geothermal applications as an underutilized opportunity in Mexico and highlights the role of targeted public instruments, including grants and revolving funds, to unlock these industrial and agro-industrial uses (US Department of Energy 2022).

Hybrid energy systems: Enable hybrid geothermal-renewable projects through regulatory recognition, interconnection priority, and integrated planning. Geothermal energy should be deployed as part of hybrid systems that combine: Geothermal for baseload and thermal services; solar and wind for variable generation; storage and demand management to enhance flexibility. Hybrid configurations enhance system resilience, reduce curtailment of variable renewables, and improve overall capacity factors, particularly in regions with transmission constraints (ibid.).

AI-based exploration and drilling systems: Institutionalizing the use of AI and machine learning across early-stage exploration, drilling and operations can significantly reduce barriers by shortening timelines and lowering financial uncertainty. In exploration and verification, AI can reduce seismic interpretation time by up to 90 percent and lower verification drilling needs by 30 percent. During drilling, AI warning systems can detect over 95 percent of potential incidents in real time, reducing drilling costs by more than 15 percent and shortening timelines by up to 24 days through optimized rates of penetration. Once operational, AI can further improve performance: in one organic Rankine cycle plant, AI optimization increased net power output by 39.41 percent without additional infrastructure (Shan et al. 2026).

The proposed policy package is closely aligned with the core energy policy objectives set out in the *PRODESEN 2023–2037* (SENER 2023), particularly those related to security and adequacy of electricity supply, improvements in effective clean generation, and the management of regional transmission constraints. Due to its high-capacity factors, geothermal generation contributes to closing the gap between installed clean capacity and effective clean electricity production, complementing the role of variable renewables such as solar energy.

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Appendix: Glossary of Terms

AI in geothermal systems: Application of machine learning and data-driven techniques to subsurface analysis and system optimization, reducing exploration uncertainty, drilling risk and scalability constraints in geothermal projects (Al-Gaiar et al. 2024).

Baseload energy: Continuous and uninterrupted 24/7 electricity supply. Data centres, due to their nearly constant computational loads, are structurally aligned with baseload energy systems rather than variable generation sources (Chanduri 2020; IEA 2024).

Cascading use of geothermal energy: Sequential utilization of geothermal heat at different temperature levels, typically involving electricity generation followed by reuse of residual heat for cooling or industrial processes, thereby maximizing system efficiency (Chanduri 2020).

CFE: State-owned productive enterprise responsible for the generation, transmission, distribution and commercialization of electricity in Mexico.

Closed-loop geothermal systems: Configurations in which a working fluid circulates through sealed underground heat exchangers without extracting groundwater, minimizing environmental risks such as aquifer depletion or contamination (ibid. 2020).

CFD: Numerical modelling techniques used to simulate and predict subsurface thermal behaviour, improving geothermal system design and performance forecasting (ibid. 2020).

CONAGUA: Federal public agency responsible for the administration, regulation and preservation of Mexico's national water resources.

Cooling systems in data centres: Infrastructure required to dissipate heat generated by servers, accounting for approximately 40 percent of total data centre energy consumption (ibid. 2020).

Geothermal energy: Energy obtained from heat stored in the Earth's subsurface, used for electricity generation and direct thermal applications. Its reliance on stable underground temperatures enables predictable, continuous energy supply independent of weather conditions (ibid. 2020).

GSHPs: Geothermal cooling systems that transfer heat between buildings and the subsurface, improving thermal efficiency and reducing overall energy demand for cooling (ibid. 2020).

PEMEX (Petróleos Mexicanos): State-owned productive enterprise in charge of the exploration, production, refining, transformation and commercialization of hydrocarbons in Mexico.

PUE: Metric measuring data centre energy efficiency, defined as the ratio of total facility energy consumption to energy used by IT equipment. Lower PUE values indicate higher efficiency (ibid. 2020).

PRODESEN: Mexico's national electricity system development program.

SENER: Federal ministry responsible for designing, coordinating and overseeing Mexico's national energy policy.

SISEPUEDE: SImulation of SEctoral Pathways and Uncertainty Exploration for DEcarbonization is an integrated emissions modelling framework used to evaluate emissions pathways and transformations through the integration of extensive cross-sectoral dynamics (for more information, see sisepuede.readthedocs.io).

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Carbon Dioxide Removal

Closing the Measurement, Reporting and Verification Governance Gap in Carbon Dioxide Removal: Scaling Digital MRV with Accountability

Maria Grigolia and Jeeyoung Lee

Issue

Carbon dioxide (CO_2) removal (CDR) markets lack coordinated governance for measurement, reporting and verification (MRV), weakening comparability and accountability as digital MRV (dMRV) scales.

Background

The central challenge facing CDR markets is the lack of coordinated governance for MRV. At present, MRV practices for CDR rely on heterogeneous protocols, discretionary uncertainty treatment, retrospective verification and ad hoc digitalization. Internationally, no mechanism provides a common baseline of MRV principles to anchor pathway-specific requirements while remaining adaptable to technological change. At the domestic level, enforcement is uneven, and authorities make only limited use of formally approved lists of methods to manage the proliferation of protocols and to prevent regulatory arbitrage. Consequently, comparability across projects and methods remains weak, and credited tonnes are difficult to interpret across standards. Existing MRV systems often rely on *ex post* compliance checks rather than generating continuous, auditable evidence.

In this governance vacuum, dMRV is increasingly pursued as a scalability solution. However, when digitalization is layered onto fragmented rules without clear requirements for uncertainty management, independent auditing, data access and interoperability, it risks hardening fragmentation and exclusion rather than functioning as shared market infrastructure. These gaps underscore the necessity of coordinated international standards, domestically enforceable governance mechanisms and dMRV systems that integrate scaling with accountability as CDR markets grow.

Importance of dMRV

Current MRV approaches in the CDR space are in a dynamic phase of rapid iteration. While not all CDR projects view MRV costs as a barrier to scaling, for some methods, MRV can account for as much as 50 to 73 percent of total project costs, making it a potentially decisive driver of CDR's long-run marginal cost. As a result, uncertainty about future government regulation and the lack of protocol standardization remain major obstacles to estimating and reducing MRV costs (Mercer, Burke and Rodway-Dyer 2024).

In 2025 alone, 15 protocols were added across 11 methods, bringing the total number of protocols to 139 (Mercer, Burke and Chen 2025). However, as the number of protocols grows, documentation and data formats stored across registries become increasingly fragmented, making data sharing and interoperability among stakeholders more difficult. At the same time, credit issuance remains concentrated in a small number of dominant protocols, meaning that weaknesses in a leading standard can translate into market-wide over-crediting risk. Rigorous scrutiny of dominant protocols should therefore be a governance priority. Against this backdrop of high MRV cost uncertainty and an increasingly fragmented yet concentrated protocol landscape, dMRV benefits registries and CDR facilities by enabling earlier detection of underperformance, leakage or reversal risks and allowing corrective action before credits are issued. As a result, this reduces operational risk and the costs of *ex post* adjustments (Ecklu and Thomas 2025). At the same time, for credit buyers and investors, stronger data consistency, traceability and transparency make cross-project comparisons easier (Sahay et al. 2025), reducing quality uncertainty and greenwashing or reputational risks. This, in turn, lowers incentives for protocol shopping and enables clearer price differentiation based on verification quality.

Finally, transparent and auditable data trails clarify the basis of evidence and decisions on which credits are issued, thereby strengthening governance and accountability (World Bank and Carbon Markets Infrastructure Working Group 2025).

Emerging Technical Approach: dMRV

Automation and Digitalization Reduce MRV Costs and Enable Scalability

Digitalizing MRV processes (automated data collection, reporting and verification) can reduce recurring costs required to operate and maintain MRV systems over time. This will make MRV economically viable at scale and support wider deployment of CDR (Mercer, Burke and Rodway-Dyer 2024; World Bank 2022).

Standardized Digital Data Flows Improve Consistency and Auditability in MRV

By automating data capture and reporting and using standardized digital formats, dMRV systems create time-stamped data sets and traceable audit trails that support more consistent verification compared to manual, retrospective MRV approaches (ibid.; Carbonfuture 2025).

Earlier Identification of Performance Issues Supports Environmental Integrity

By moving MRV away from purely periodic, *ex post* reporting toward more continuous data collection and automated monitoring, dMRV can enable earlier identification of underperformance, leakage or potential reversal. This allows issues to be addressed before credits are issued and supports the credibility of carbon removal claims (ibid.).

Technical and Governance Challenges of dMRV

Data Governance and Interoperability Risks

dMRV depends on interoperable data standards and clear rules on data access and ownership; without coordination across platforms and jurisdictions, dMRV systems risk fragmentation and limited comparability. This complicates oversight and verification (World Bank 2022; Climate Ledger Initiative and SustainCERT 2022).

Bias and Transparency Risks in Automated MRV Systems

Increased reliance on digital tools and automated data processing can embed methodological assumptions or biases in MRV outputs if system design and data processing steps are not transparent and subject to independent verification (ibid.).

Institutional Accountability Challenges in dMRV

As MRV becomes more digitalized, responsibility for data quality and errors may be distributed across technology providers, registries and verification bodies. This creates governance challenges if accountability and oversight are not clearly defined (World Bank 2022).

Trade-offs: dMRV Introduces Additional Energy Use

dMRV relies on information and communication technologies such as data centres, networks and connected devices, which contribute to electricity consumption and associated greenhouse gas emissions; the Information and communications technology sector accounted for a measurable share of global electricity use and emissions in 2020, highlighting the need to consider the environmental footprint of dMRV systems alongside their governance benefits (Malmodin and Lundén 2023).

Recommendations

The United Nations Framework Convention on Climate Change Article 6.4 Supervisory Body should develop a reference standard, structured as a Core (common tonne-quantification rules) plus technology-specific annexes, to improve comparability across CDR pathways and safeguard market integrity. Building on its experience with methodologies, verification and registry oversight, the body is well positioned to provide a global baseline comprising shared Core principles and governance rules for annex management. This approach is well suited to CDR's rapidly evolving technology landscape. It would lock in a minimum set of widely acceptable rules and allow technology-specific requirements to be updated over time, strengthening practical effectiveness. The Core should set standards for how a tonne is calculated (covering baselines, leakage and uncertainty), permanence and reversal risk, and minimum disclosure. The annexes should specify MRV details such as what data to collect, how to measure it, how to model and validate results, quality assurance/quality control, likely failure points and how to reconcile credits after issuance.

Governments should designate a competent authority to lead CDR MRV and translate the international reference standard into domestically enforceable rules. The authority should require the use of approved protocols only and ensure that outdated versions expire after a mandatory transition period. To enable comparability across protocols, it should also mandate minimum standardized disclosure to prevent protocol shopping as the number of protocols grows. The authority should also codify the principle that higher uncertainty reduces credited tonnes as an *ex ante,* tier-based rule rather than leaving it to negotiation or discretionary judgement (for example, Tier A: 100 percent; Tier B: 90 percent with additional sampling recommended; Tier C: 70 percent with enhanced conservativeness such as larger buffers). Embedding this rule into law, fiscal subsidies and eligibility for registry issuance is one of the fastest ways to diffuse requirements across the market.

Governments and standards bodies should transition MRV toward governed dMRV, meaning standardized, interoperable and audit-ready digital systems, so that scaling up CDR does not compromise transparency, comparability or environmental integrity. Regulators and standards bodies should embed conservative uncertainty buffers (or tiered crediting adjustments), transparent documentation for automated or model-assisted components, and periodic independent audits into dMRV standards to reduce over-crediting risks and strengthen trust. In parallel, they should establish rules for cross-platform and cross-jurisdiction data access, standardization and interoperability, and clarify roles and responsibilities among registries, verification bodies, buyers and regulators to improve oversight, especially for cross-border CDR activities. International climate finance institutions and donor governments should pair dMRV requirements with training, technical support and digital infrastructure investment to prevent the exclusion of lower-capacity countries and regions, while aligning dMRV rollout with clean power availability, data-efficiency standards and broader digital governance strategies so that the infrastructure and energy demands of digital oversight do not undermine net climate benefits.

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Governing Carbon Dioxide Removal at Climate Tipping Points: South Africa as an Equity Stress Test

Seyi Agboola, Mulugeta Dinbabo, Joseph Kanyayi, Bezawork Kassa,
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Issue

While carbon dioxide (CO_2) removal (CDR) technologies involve managed interventions in the climate system, existing modes of global governance landscapes remain fragmented, voluntary and underdeveloped. This poses serious equity, environmental and governance risks for climate vulnerable countries such as South Africa.

Background

The increase in global mean temperature is likely to be more than 2°C by mid-century based on the present policy pathways (Intergovernmental Panel on Climate Change [IPCC] 2023). The chances of crossing the tipping points in the climate are also increased by this eventuality (WCRP & IPCC 2025). It is a signal for the change to more urgent and emergency climate governance instead of the gradual management of the issue. Even though many decades have passed in the mitigation of the climate change issue, the reduction has not been enough to avoid the risks of climate change. Therefore, the concept of CDR is also considered to be an option that diminishes the levels of CO_2 concentrations in the atmosphere if the mitigation options are not enough. The effectiveness and side effects of the construct are not clear but are not considered to be arguments for not experimenting with the concept. Governments can adopt CDR pilot projects with independent monitoring as an option to learn before scaling up (National Research Council 2015).

CDR differs from mitigation and adaptation because it encompasses the reduction of carbon dioxide in the atmosphere. The technologies that are used in CDR are direct air capture, afforestation, bio-energy with carbon capture and storage, and enhanced weathering (ibid.). These technologies are in the pilot phase all over the world, and no empirical evidence is available with regard to their long-term safety, effectiveness and sustainability. This is a problem of urgency and uncertainty, particularly for countries such as South Africa, which do not have well-developed regulatory frameworks.

South Africa is a major equity stress test for the regulation of CDR because of its vulnerability to drought, water scarcity and food insecurity, as well as high levels of socio-economic inequality. On the other hand, although not explicitly identified as a CDR hub, South Africa's industrial base and renewable energy potential suggest possible advantages for future carbon dioxide removal (CDR) deployment (International Energy Agency 2022). Unregulated development of CDR may potentially exacerbate competition for resources, particularly land and water, and may further contribute to environmental and social inequalities.

The global governance framework for CDR is still patchy, voluntary and led by developed nations and corporations (OECD 2022). This could lead to moral hazard, where large emitters depend on CDR rather than cutting their emissions, and developing nations pay the environmental and social price. There is also a possibility of double vulnerability, where South Africa is exposed to climate change impacts and technology-related risks due to the unregulated development and use of CDR. But with proper governance mechanisms such as transparency, monitoring, public engagement and shared resources, CDR could become a controlled climate risk management strategy rather than an uncontrolled technological solution. The governance of CDR in South Africa, therefore, has global implications for its fair and responsible use.

Recommendations

Link CDR to emissions reductions. Rather than displacing emission reduction, CDR should assist it. The establishment of CDR agreements tied to obligatory carbon cuts will assist in overcoming moral hazard and the commitment to the Paris Agreement. CDR should instead complement, rather than replace, emission reductions. Although CDR manages past CO_2 levels, it cannot replace the loss in new CO_2 emissions. Linking CDR agreements with binding commitments keeps South Africa's climate action aligned with the Paris Agreement, prevents moral hazard and demonstrates that high-impact technologies should not replace critical action needed to meet climate and development objectives. This ensures that emissions reduction remains the preeminent approach and that CDR is not used in lieu of it. Moreover, it aids in meeting global goals of a 43 percent cut in emissions by 2030 and net-zero emissions by 2050 (IPCC 2023), and it mitigates the danger of irreversible climate tipping points, such as ice sheet melting and ecosystems.

Implement tiered global governance with risk-based regulation. A tiered structure of governance should regulate CDR activities in the research, pilot and deployment stages according to risk levels. This global governance structure has different levels for the regulation of CDR in accordance with the identified risk in its research, pilot and deployment phases. It guarantees the inclusion of South Africa in the decision-making process at the different levels, consideration of unknown risks, avoidance of premature deployment and the required balance for promoting innovation and caution in the regulation of the unknown risks. The expected impacts include: decreasing the risk of environmental and social damage from early deployment by ensuring that projects are kept under control during the pilot stage; avoiding significant land and water resource misallocation for millions of hectares worldwide; and allowing for safe innovation while protecting at-risk populations in climate-vulnerable nations such as South Africa.

Establish a global CDR observatory for monitoring, transparency and accountability.

A global CDR observatory should monitor projects, share data and offer risk assessments. It facilitates data centralized from research and pilot projects, enabling a transparent and accountable governance system. In South Africa and other vulnerable countries, it functions as an early warning system and advice facility to create trust at a global level in CDR deployment as a safe and responsible backstop to climate change. The expected benefits include: enabling real-time monitoring of global CDR deployment capacity, projected to reach 5-10 gigatonnes of CO2 removal per year by 2050 (IPCC 2023); improving early detection of environmental risks as well as reducing governance gaps; and enhancing global trust and cooperation in climate intervention governance.

Establish a global CDR fund based on fair financing principles. High-emitting nations should fund CDR through a global CDR fund based on past emissions. CDR is an extremely expensive technology, meaning if there is no fair financing, the burden would fall on developing countries like South Africa rather than those responsible for the high levels of emissions. A global CDR fund ensures that the rich countries bear the economic burden, hence letting South Africa safely test these projects. South Africa would contribute its strategic land, scientific expertise and leadership role in equitable governance, while experimental projects promote transparency and confidence in CDR technologies across the globe; thus, counting South Africa as a global leader in equitable and safe CDR governance. The expected impacts include: mobilizing billions of dollars in climate finance to facilitate equitable deployment; avoiding financial burden transfer to developing nations such as South Africa; and assisting climate adaptation and just transition plans in developing economies.

Protect communities, water resources and food security through legal safeguards.

Legal safeguards pertaining to water resources, food security and community participation must be protected. CDR has transboundary risks, resource intensity and justice sensitivity that require global cooperation. Legal caps on water use and prioritization of food security prevent CDR from competing with basic needs in South Africa's water-scarce environment. Community participation and revenue-sharing prevent "carbon colonialism" and green grabbing, ensuring those bearing the risks also benefit. Equity and Just Transition integration is key to ensuring that interventions are not harmful in terms of exacerbating social, economic, or environmental inequality, and to promoting responsible and socially inclusive good governance, which lends legitimacy to CDR across the world. Furthermore, by safely experimenting in this field, South Africa is showing global leadership in safe, responsible and equitable CDR good governance.

The expected benefits include: conflicts between the implementation of CDR and critical water and food security infrastructure are removed; vulnerable communities are safeguarded against the negative impacts of climate change; and the protection of vulnerable communities, environmental risks, and equity and legitimacy.

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Water and Ice

Boosting Carbon Uptake in the Ocean: Electrochemical Ocean Alkalinity Enhancement as a Scalable Climate Intervention

Rozárie Haškovcová, Korbinian Johannes Benedikt Haslbeck, Alicia Prat-Baradat and Cosimo Scoccianti

Issue

Despite ambitious emission reduction plans, the world will likely surpass the 1.5°C threshold set by the Paris Agreement unless drastic emission cuts occur alongside large-scale carbon dioxide removal. Scientific consensus indicates that removing approximately five Gt of carbon dioxide (CO_2) annually by 2100 will be necessary to limit warming to 2°C (Intergovernmental Panel on Climate Change 2023).

Background

The ocean is the largest active carbon reservoir, containing over 50 times more carbon than the atmosphere and already absorbing roughly 30 percent of anthropogenic CO_2 emissions, at the cost of increasing ocean acidification. Ocean alkalinity enhancement (OAE) accelerates this natural process by increasing seawater alkalinity, thereby enabling additional atmospheric CO_2 uptake with long-term storage in the ocean (Guo et al. 2024).

OAE is considered among the highest potential marine CDR methods with modelling studies indicating it could remove gigatons of CO_2 from the atmosphere annually. Nonetheless, CO_2 removal efficiency of OAE varies significantly by location, thus resulting in some regions having higher potential than others (Zhou et al. 2025).

Unlike other marine CDR approaches, OAE directly counteracts ocean acidification by increasing pH and potentially benefitting calcifying organisms (for example, corals and shellfish) (Hartmann et al. 2023).

Two primary OAE pathways exist: mineral dissolution (adding crushed alkaline minerals), and electrochemical generation of alkalinity. The electrochemical ocean alkalinity enhancement (eOAE) approach uses electrolysis to split seawater into alkaline and acidic streams. The alkaline stream is returned to the ocean to enhance pH and CO_2 uptake. Although a few start-ups are advancing electrochemistry-based CDR at limited, non-commercial scales, these systems remain at an early technology-readiness level (Aeschlimann and Charalambous 2024).

This policy brief focuses on eOAE for four key reasons: precise control over alkalinity dispatch; no ocean pollution through dumping particles (Guo et al. 2024); hydrogen co-production and possible pairing with waste treatment and desalination facilities; and carbon neutral scalability when powered with renewable energy (National Academies of Sciences, Engineering, and Medicine [NASEM] 2022).

Financial Analysis

eOAE is capital and energy-intensive, with estimated costs ranging from approximately US$150 to US$700 per tonne of CO_2 removed, depending primarily on electricity prices and system design (ibid.). Pairing OAE plants with facilities that can use their acidic byproducts could significantly improve profitability by creating an additional source of income. For example, the acid stream produced by eOAE systems can be used to treat construction waste concrete, turning a costly waste stream into building materials and helping make carbon removal projects financially viable (Jin et al. 2025). Such couplings can even take place with desalination plants, which can reduce capital costs by 70 percent. eOAE also has the possibility of generating valuable hydrogen (H_2) as a co-product (23 kg H_2 per tonne CO_2 removed, with potential revenue of ~$46/t CO_2 at current prices) and chlorine gas (Cl_2) (1 tonne Cl_2 per tonne CO_2, ~$80/t CO_2) (NASEM 2022).

Ethical Considerations

Ethical concerns arise both from general climate intervention concerns and OAE-specific considerations. At the general level, high uncertainty regarding effectiveness and systemic ocean responses creates persistent concern for marine ecosystems and affected communities. A foundational ethical issue is whether it is acceptable to impose potential transboundary risks without consent, meaning that impacts from a deployment in one area could affect marine environments, ecosystems and communities far beyond the original location due to the interconnected nature of the ocean and international governance gaps (Boettcher et al. 2021). Furthermore, a general concern is creating a false sense of climate progress, hindering mitigation efforts.

OAE specific concerns include the low public acceptability that currently exists relative to other marine carbon dioxide removal methods, which poses political challenges (Satterfield, Nawaz and Boettcher 2023). Further, often unclear allocation of responsibility for long-term monitoring, continuation and remediation complicates legitimate deployment. Lastly, distributive justice issues arise, because benefits and burdens might be unevenly distributed, with potential socio-economic consequences for fisheries-dependent communities. Additional ethical questions relate to high energy usage and waste by-products, although circular economy approaches may reduce these impacts (Nawaz and Belotti 2025). At the same time, climate intervention may be viewed as an ethical and potentially necessary response to avert more severe and unjust climate impacts in the future (Lawford-Smith and Currie 2017).

Legal Implications

Ocean alkalinity enhancement is constrained by international environmental law, and specifically by the London Convention and London Protocol. States have binding obligations of due diligence to prevent transboundary harm and to conduct risk- and environmental-impact assessments where activities may cause environmental damage (Steenkamp and Webb 2023).

In 2013, an amendment to the London Protocol introduced a legal definition of marine climate intervention and functions as a gatekeeping list through Annex 4, prohibiting marine climate intervention activities by default unless explicitly authorized, while the new Annex 5 sets out the permitting framework for legitimate scientific research. This amendment established a precautionary, but not prohibitory, approach that allows OAE activity under strict research-only conditions (International Maritime Organization 2013).

This research-only governance has two important consequences. First, it creates a legal grey zone for scale-up and commercial deployment, which deters private investment and prevents early market formation. Second, it delays the development of robust measurement, reporting and verification (MRV) systems, since MRV frameworks will be refined only once activities move beyond small-scale research into controlled pre-commercial deployment (Steenkamp and Webb 2023).

Recommendations

Financing mechanisms and scalability. The financial viability of eOAE projects depends critically on both capital expenditure and energy inputs. As energy consumption remains the dominant operating cost, continued research and development should focus on improving electrochemical efficiency and developing less energy-intensive materials and system designs.

Early-stage financing should be mainly carried out through research and development government grants. During the scale-up phase, as the technology matures, public procurement for innovation can provide demand-side support by guaranteeing payments by the government to firms for verified carbon removal, thereby reducing market risk and securing revenues for firms. At the international level, one potential pathway for scaling deployment would be the integration of eOAE into countries' Nationally Determined Contributions under the Paris Agreement; for example, through the application of a conservative equivalency factor (for example, 1 tonne removed credited as 0.9 tonnes), ensuring that emissions reduction remains the primary objective while creating incentives for carbon removal. In parallel, the strategic integration of eOAE facilities with industrial processes capable, for example, of utilizing acidic byproducts or desalinating water should be prioritized at the project design stage. This could generate additional revenue streams, reduce waste management costs, and significantly improve the overall project's profitability. Business models incorporating multiple revenue streams should be prioritized within public procurement for innovation frameworks.

Inclusive governance. eOAE governance must prioritize project transparency. Most importantly, inclusive community engagement is crucial for legitimate and socially acceptable governance. Instruments such as regular workshops with scientists, interested and concerned stakeholders, and policy makers at prospective sites can support informed decision-making and improve public understanding and acceptance.

International legal framework. The recommendation, from an international legal perspective, is to prepare a deployment pathway for electrochemical OAE under the London Protocol. This should be done by defining eOAE as regulated "placement for a purpose" rather than operating under a legal grey zone. Additionally, Annex 5 should be amended to create an operational permitting track for controlled eOAE deployment beyond scientific research, defining scale thresholds and mandatory MRV.

Conclusion

eOAE can become a viable climate intervention: it enables durable CO_2 storage, directly counteracts ocean acidification, creates additional economic revenue via hydrogen co-production and industrial by-product use, and makes carbon removal easier to measure and verify because the alkalinity is produced and tracked inside controlled systems. Its scale-up is currently constrained by three binding factors: high renewable electricity requirements, ethical and governance challenges, including transboundary impacts and public acceptance, and legal uncertainty under the London Protocol. Governments should unlock deployment by prioritizing large-scale pilot and demonstration projects beyond current research activities, coupled with renewable energy and industrial co-benefits, while ensuring transparent governance with broad stakeholder engagement.

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Floating Photovoltaic Technology: Opportunities, Challenges and the Way Forward

Haley Flower, Chavi Ilwadhi, Ayomide Labiyi, Atreyi Mitra and Jack Richards

Issue

Floating photovoltaic (FPV) is an exciting renewable energy technology that has the potential to provide both mitigation and adaptation climate solutions at a global scale, if barriers to implementation are successfully removed.

Background

Renewable energy technologies are central to the green transition, yet most deployment strategies continue to prioritize land-based solutions such as photovoltaics and wind energy. This focus overlooks the significant potential of water surfaces as sites for clean energy generation. At the same time, climate policy pathways for mitigation and adaptation often remain siloed. FPVs offer a rare opportunity to address both of these challenges simultaneously.

Unlike conventional solar plants, which require large tracts of land, FPV systems are installed directly on water bodies, including lakes, hydropower reservoirs and irrigation canals, as well as in offshore marine environments. This technological shift is particularly relevant in regions facing land constraints alongside rising energy demand. Most existing FPV deployments are on inland water bodies, using silicon-based photovoltaic panels mounted on floating platforms with anchoring systems designed for operational lifetimes of around 25 years (Benjamins et al. 2024; Liu et al. 2024).

Beyond electricity generation, FPV can support climate adaptation in water-stressed regions by reducing evaporation losses from reservoirs. Uncovered reservoirs can lose up to 40 percent of stored water through evaporation, particularly in hot and arid climates (Sahu, Yadav and Sudhakar 2016). Modelling suggests that covering just 30 percent of global reservoirs with FPV could reduce annual water losses by approximately 106 km3, highlighting the technology's potential contribution to water security (Jin et al. 2023).

Technological innovation is further expanding the scope of FPV deployment. Emerging developments include solar tracking systems that can increase energy yields by 15 to 25 percent, hybrid configurations that integrate floating solar with offshore wind or aquaculture and designs adapted for saltwater conditions in marine environments (Ramanan et al. 2024; Liu et al. 2024).

FPV systems also offer socio-economic benefits. Co-location with hydropower infrastructure can enhance grid stability, reduce fuel costs and support energy storage. At the local level, FPV can strengthen energy security and generate employment opportunities. By limiting sunlight penetration, FPV installations may also improve water quality by reducing harmful algal blooms, delivering indirect public health benefits (Rocha et al. 2024). While installation costs are currently estimated to be 10 to 25 percent higher than those of land-based solar — particularly for offshore systems — FPV installations can generate between 0.6 and 4.4 percent more electricity due to cooling effects, partially offsetting higher upfront costs (Liu et al. 2024; Ramanan et al. 2024).

The environmental profile of FPV is generally favourable but not without risks. Life-cycle assessments indicate a rapid energy payback time of approximately 1.3 years and low greenhouse gas emissions of around 11 kilograms of CO_2 equivalent per MWh (Liu et al. 2024). Concerns regarding impacts on aquatic ecosystems have been raised, particularly in relation to reduced light penetration and altered thermal stratification. However, evidence suggests that limiting surface coverage to between 10 and 20 percent of a water body minimizes ecological disruption (Karpouzoglou et al. 2020; Liu et al. 2023; Ilgen et al. 2025). Other risks, such as nutrient loading from bird droppings, can be mitigated through regular maintenance (Karim et al. 2023). In some contexts, reduced surface temperatures may even lower greenhouse gas emissions from reservoirs, creating additional climate co-benefits (Rocha et al. 2024).

Despite these advantages, significant uncertainties continue to constrain FPV investment and deployment. Long-term environmental impacts remain poorly understood, as most studies assess effects over periods of only one to two years. Regulatory frameworks for FPV are also underdeveloped, creating uncertainty for investors and slowing large-scale deployment. Addressing these gaps will require comprehensive policy guidance that accounts for both established and emerging FPV technologies (International Energy Agency 2025; Bredeweg et al. 2025). Finally, social acceptance and governance are critical. Evidence from marine and renewable energy projects consistently shows that early and meaningful stakeholder engagement is a key determinant of public acceptance and long-term project viability (Bax et al. 2022; World Bank Group 2019).

Technological Impact Assessment

From a technological performance perspective, floating solar systems offer notable advantages. Solar panels typically lose efficiency at higher temperatures, but installing them over water allows them to benefit from natural cooling. Evaporative cooling helps maintain lower operating temperatures, improving energy output and extending panel lifespan. Evidence suggests that FPV systems can outperform land-based installations under similar conditions, strengthening their technical viability (ibid.).

Furthermore, FPV not only offers local energy security, but also scalability to become a global climate solution. Gang Liu et al. (2024) show that if 10 percent of the water bodies larger than 1 km2 in China were to install FPV, more than 900 million tons of CO2 emissions can be reduced through clean energy substitution and about 5 billion m3 water can be saved by evaporation reduction.

An illustrative example of both the potential and governance challenges associated with floating solar technology can be found in Singapore's Tengeh Reservoir project. As a land-constrained city-state with ambitious renewable energy targets, Singapore has turned to its reservoirs as platforms for solar power generation. The Tengeh floating solar installation, set to be one of the world's largest, is expected to generate enough electricity to power approximately 16,000 households while offsetting around 32 t of carbon emissions annually (Chong 2021). At the same time, the project has attracted public scrutiny due to concerns about ecosystem impacts and recreational use of the reservoir. In response, developers undertook extensive environmental impact assessments and stakeholder consultations, demonstrating the importance of transparency and public participation in managing uncertainty.

Operating in aquatic environments also introduces technical challenges related to long-term durability and system reliability. Floating solar installations must withstand fluctuating water levels, wave action and prolonged exposure to the environment. The lack of standardized design specifications further increases complexity, as anchoring and mooring systems are often tailored to local conditions. The World Bank Group (2019) therefore emphasises the importance of site-specific engineering and environmental assessments to effectively manage these risks. Corrosion represents an additional limitation, particularly in saltwater environments, where accelerated material degradation can raise costs and affect economic viability (Cazzaniga et al. 2018).

The future impact of floating solar technology depends on how effectively these technical, environmental and governance challenges are managed. In a best-case scenario, continued research, improved design standards and growing industry experience enable wider adoption. Higher efficiency, longer system lifespans, and cost savings from avoided land acquisition and reduced civil works could enhance competitiveness over time (ibid.; World Bank Group 2019). In a worst-case scenario, unresolved durability issues, ecological concerns and governance failures could lead to project setbacks, regulatory resistance, public opposition, reduced investor confidence and a reluctance to deploy the technology at scale.

FPV thus has significant promise but is not universally applicable and is context specific. Success depends on careful site selection, robust technical design, inclusive governance and strong environmental safeguards. When deployed under appropriate conditions, floating solar technology demonstrates how innovative use of existing spaces can contribute meaningfully to a more sustainable and resilient energy future.

Trade-offs

FPV systems complement rather than replace land-based renewables by expanding clean energy capacity without additional land or transmission infrastructure. At Brazil's Sobradinho hydropower dam (1,050 MW), a pilot 1 MW FPV installation used existing grid infrastructure and increased overall energy output by about 76 percent, improving system efficiency with minimal additional emissions (Farfan and Breyer 2018).

FPV also strengthens climate resilience by diversifying energy supply during droughts and reducing reliance on fossil-fuel backup generation. At Sobradinho, FPV helped offset hydropower losses and reduced reservoir evaporation, which supported water security under climate stress (*Power Magazine* 2021; Farfan and Breyer 2018). These combined mitigation and adaptation benefits make FPV a climate-efficient complement to other renewable pathways, instead of a competing technology.

From a least-cost perspective, floating solar is not the most cost-effective option in the short term. FPV has higher upfront costs than ground-mounted solar or other shading methods because it requires floating platforms and anchoring systems. The advantages of FPV are thus most economically impactful in contexts where alternative options are constrained. FPV is primarily justified in contexts of land scarcity, environmental sensitivity or where existing infrastructure such as grid connections, substations and access roads can be reused to lower deployment costs. For example, The SsangYong open-pit limestone mine in South Korea demonstrates how FPV can become a cost-efficient solution by generating around 971 MWh per year on flooded mine pits, avoiding land acquisition costs while contributing to site rehabilitation (Song and Choi 2016).

Policy makers should assess onshore FPV based on system-wide value and not existing grid access alone. To increase cost-effectiveness, priority should be given to sites where existing water and energy infrastructure reduce costs, such as hydro power reservoirs or industrial water bodies. Onshore FPV should also be prioritized in land-constrained locations that preclude the possibility for land-based photovoltaics, even in the absence of existing grid access. Deployment in environmentally sensitive waters should proceed cautiously where higher upfront costs are not matched by clear climate or land-use benefits.

Recommendations

Prioritize optimal sites for best practice installation. These include hydropower reserves; abandoned mines; locations where land use is limited; and where existing infrastructure grants grid access. Onshore FPV should be initially prioritized over offshore FPV. FPV installation should target sites in regions with optimal climates for photovoltaic energy generation.

Implement environmental safeguards to address stakeholder uncertainties about environmental impact to gain trust and overcome barriers to scalability. This should occur through comprehensive environmental site assessment before installation; limiting onshore FPV to 10 percent coverage, and offshore FPV to 20 percent coverage; ensuring all installed FPV is self-cleaning or regularly maintained; continuous monitoring of all sites to assess long-term environmental impact; creating legal frameworks to regulate and reinforce this; and publishing annual environmental impact reports to ensure transparency.

Increase social acceptance. Build trust with local communities, for example through public participation in planning and installation processes, clear governance arrangements and transparent decision-making processes that value local knowledge and include local residents. Strict health and safety regulations must be enforced during installation. Local communities should enjoy cheaper energy generated by local FPV. Installation regulations must ensure that FPV does not conflict with socio-economic water-based activities and broader sustainable development goals.

Optimize financing. Due to the higher upfront costs of FPV and significant long-term financial return, governments must provide short-term financing to bridge the gap to land-based photovoltaic affordability. This financing needs to price in improvements to water security gained through evaporation prevention to reflect the environmental benefits of FPV. Barriers restricting FPV integration with other energy systems must be removed. Innovation and research must also be funded to create opportunities for technology development and increased efficiency.

Create best practice frameworks for installation and regulation. While FPV impacts and benefits are highly site specific, best practice frameworks should be created to guide installation and regulation processes across diverse sites. These should include the policies mentioned above and should be integrated into existing national renewable energy policy guidance. This ensures that FPV does not conflict with existing renewable infrastructure policy and allows for efficient use of existing national governmental structures.

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Stabilizing the Arctic: Governing Sea Ice Thickening to Reduce Climate Risk

Alexander M. Michael Handal, Caroline Szawlowski, Manuela Garzon and Meena Sabeeh

Issue

The rapid loss of Arctic sea ice is heightening climate volatility and global environment risk, requiring an innovative and governable climate response technology that also supports the prevention and escalation of conflicts in the Arctic region.

Background

The rapid decline of Arctic sea ice is a central driver of global climate instability. The Arctic is warming nearly four times faster than the global average, weakening one of the Earth's most powerful natural cooling systems and amplifying heat absorption across the planet (Rantanen et al. 2022). As seawater freezes, ice forms from the bottom of glaciers and the top white layer acts as an insulator to slow the rate of melting. However, as global temperatures continue to increase, the ice has been melting at a faster rate, causing sea levels to rise. Sea ice thickening is an emerging green technology designed to make Arctic sea ice stronger by making it thicker. The technology uses small, autonomous pumps placed inside the ice and pulls seawater from the ocean to spread across the surface, allowing the water to freeze in the cold air from above. This process adds new layers of ice, while also thickening the existing layers. The pumps run on renewable energy so they can function in remote Arctic areas without fuel.

Sea ice thickening devices operate over a limited surface area, making mass scaling essential to desired results. Existing model structures suggest that tens of millions of units would be required to stabilize a significant portion of Arctic sea ice coverage (Desch et al. 2017). These earlier models assumed high material intensity, but ongoing innovation is actively reducing per-unit costs and material requirements, creating opportunities for more efficient production and development pathways. The majority of proposed designs rely on autonomous, ice-embedded pumping systems that pull seawater from beneath the ice and disperse it across the surface during winter, where it refreezes and gradually thickens the ice. During winter operations, these devices are capable of pumping approximately 1,000 L of seawater per minute across the ice surface (Poynting 2024).

In addition, the process of sea ice thickening is challenged by operational issues. As an isolated region with limited infrastructure, equipment may be deployed and maintained using icebreakers, air support and limited seasonal windows (Gunnarsson and Lasserre 2023). This is due to the installation, repair and repositioning that must take place in ice-covered waters without permanent ports or road access, and only for brief periods of time when the ice conditions allow safe mechanical and human intervention. Risks such as mechanical failure, ice drift, corrosion and storm damage necessitate a strong design and continuous monitoring (Pauling and Bitz 2021). These challenges position sea ice thickening as an ongoing Arctic infrastructure system. Sustained deployment would need long-term capital investment, reoccurring maintenance cycles and institutional accountability for failure and environmental risk as opposed to a one-time climate intervention. Large-scale deployment would require cooperation among Arctic states to align regulatory frameworks, environmental standards and operational oversight.

Seeking an Opportunity through Technological Solutions

Being a climate intervention tool, sea ice thickening raises ethical concerns primarily related to Indigenous rights, community consent and decision-making authority over interventions in Arctic environments. When Indigenous communities are included as partners in monitoring and governance, and when free, prior and informed consent is secured, ethical concerns are significantly reduced. Evidence from community engagement shows that Indigenous partners are open to climate interventions that align with their values and do not harm natural resources, livelihoods or cultural practices (Williams and John 2025). This demonstrates that ethical risks are not inherent to this technology itself, but rather to how it is governed and implemented.

Sea ice thickening raises environmental considerations related to its potential effects on the Arctic ecosystems, particularly under-ice biological communities. Ice thickness influences light penetration, nutrient exchange and habitat conditions, which can affect microalgae growth beneath the ice — a foundational component of Arctic marine food webs (Lund-Hansen et al. 2024). Current expert assessments indicate that environmental risks are low and manageable. Scientific leadership on a field trial in Nunavut stated that the research is unlikely to cause environmental harm, and regulatory review bodies have similarly concluded that work to date is unlikely to result in adverse environmental or social impacts (Nunavut Impact Review Board 2024). As the technology advances, it is expected to continue to undergo formal environmental assessment, and governance frameworks require that deployment cease if negative effects emerge (Williams and John 2025). This precautionary, science-based approach ensures that environmental protection remains central to implementation. Compared to the accelerating and irreversible ecological harms caused by continued Arctic ice loss, the environmental risks of sea ice thickening are proportionate and responsibly governed.

Sea ice thickening functions as a climate change reduction method and a strategic legal tool to aid Canada in recognizing Indigenous rights, supporting Canada's sovereignty claims and promoting environmental stewardship. Currently, Canada's sovereign position remains contested, as international powers deny parts of Canada's Arctic as international waters, the Northwest Passage (NWP) being one example. Under the United Nations Convention on the Law of the Sea (1982), the legal meaning of maritime spaces is not fixed but rather contested, as states actively interpret, stretch and selectively apply treaty provisions to advance their own political and strategic goals (Van Aaken 2019). This flexibility highlights the dispute: Canada claims the NWP as their internal waters based on the historic title claim and Inuit use, while other states fail to recognize this claim. Climate change has intensified this dispute, as ice has declined 12 percent per decade since 1979, widening the nautical mile distance of the Passage from Canadian land, which weakens Canada's territorial claim (Lindsey and Simmon 2022). However, sea ice thickening maintains ice conditions that support Canada's historic title claims, since Canada has a duty to protect the Indigenous groups. The importance of maintaining sovereignty over the Arctic is further reinforced by the United Nations Declaration on the Rights of Indigenous Peoples, as denying Inuit historical use of the NWP would create a failure to recognize Indigenous rights and Canada's reconciliation commitments, even if it does not clearly violate international law (Gioia 2018).

Regional Cooperation through the Arctic Council

The Arctic Council was established in 1996, and it serves as the principal global governance institution that supports inter-state coordination, interaction and cooperation within the Arctic region (Arctic Council Secretariat 2025). The initiative, the Sustained Arctic Observing Networks (SAON), has been stewarded by the Arctic Council and the International Arctic Science Committee. The SAON establishes objectives that align with environmental interests of Arctic states. Response mechanisms to environmental state changes in the Arctic requires stable and continuous cooperation from the Arctic states. By supporting operating networks of instruments that observe, assess and synthesize data for research reports, Arctic states can utilize this data to inform policy-making processes that strengthen regional cooperation (Berkman 2015). It is important to identify indicators that signal potential detrimental changes to the Arctic region (ibid.). This can support the implementation of technological responses that align with regional cooperation objectives, such as sea ice thickening mechanisms that foster economic community-informed growth opportunities.

Private-sector initiatives such as Real Ice have publicly stated that individual units may be produced for US$5,000, equivalent to CDN$6,900, as the devices are powered with renewable energy (Hay 2025). Fieldwork in Cambridge Bay, Canada, yielded optimistic results as the flooded areas were consistently thicker than the control areas. The flooded areas flooded were ~30 cm thicker than the control areas.

Compensating for 50 years of ice thinning (Howell et al. 2016), the flooded areas flooded once were ~17 cm thicker than the control.

A targeted investment of CDN$7 billion would enable the deployment of one million units, establishing the first regional-scale sea ice thickening network across the Arctic. Field testing has shown that pumping 10 in. of seawater onto the ice boosts growth from below, thickening it by another 20 in. (Hay 2025). This level of investment would move the technology beyond pilot stages into climate intervention, generating significant impacts to the region while producing the data required for broader Arctic deployment.

Looking at the Future and Recommendations.

Sea ice thickening represents one of the remaining climate interventions capable of actively restoring Arctic ice and offers governments a credible opportunity to fill the policy gap left by the absence of Arctic adaptation tools. Investing in this green technology enables states to shape governance standards, ensure ethical implementation and position themselves as leaders in climate intervention. This policy window represents a critical decision point for translating scientific innovation into durable Arctic governance.

Integrate the technology into national climate and infrastructure strategies. Canada should invest in sea ice thickening as part of its Arctic infrastructure and climate resilience strategy, supporting Indigenous communities, strengthening its ties to the region and reinforcing Arctic governance and sovereignty, while being aligned with climate commitments.

Coordinate deployment through existing Arctic institutions. Arctic states, non-governmental and governmental stakeholders should coordinate through existing institutions (for example, the Arctic Council) to guide sea ice thickening research, standards and deployment. This coordination should support the development of shared regulatory standards, binding agreements, environmental oversight mechanisms and data-sharing protocols for sea ice thickening research and deployment. States can collaborate with leading research organizations such as Real Ice and other multi-sector stakeholders, to ensure that deployment is safe and adaptive to evolving Arctic conditions.

Establish a fund for regional cooperation. Create a multilateral fund with Arctic states for financial support in climate change mitigation technologies related to the Arctic. This fund will be extended to non-Arctic states that wish to participate.

Embed Indigenous co-governance. Canada should prioritize sea ice thickening as part of its constitutional duty to Indigenous peoples whose livelihoods, food systems, cultures and territorial sovereignty depend on stable ice. All research, testing and deployment must be governed with Indigenous peoples and within their frameworks to ensure free, prior and informed consent, the protection of their livelihoods and support Indigenous leadership on their traditional lands and water.

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Agriculture

Precision Agriculture as Climate Action: Addressing the Incentive and Equity Problem

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Issue

Climate change poses unprecedented risks to livelihoods, ecosystems and the planet. While integrating green technology for climate adaptation is a vast topic, the agricultural sector remains one of the world's most climate-exposed sectors, and smallholder farmers face the greatest concentration of risk. This brief examines precision agriculture as a dual climate strategy that simultaneously mitigates resource-driven emissions and enables farmers to adapt to accelerating climate impacts.

Background

Agriculture's Position as a Climate-exposed Sector

Agricultural yields today are increasingly determined by extreme weather conditions as climate-related hazards such as droughts, floods, unpredictable rainfall and heat stress are increasing in frequency and in severity. Drought-induced drop in yields is expected to sharply reduce income and food availability, and rising temperatures are projected to intensify water scarcity even in irrigated systems. The agriculture sector's inefficient use of water, fertilizers and pesticides contributes significant carbon emissions while depleting soil fertility, placing further stress on farmers that are already struggling to adapt to increasingly variable temperature and precipitation patterns.

Global food value chains are responsible for 30 percent of the greenhouse gas emissions contributing to climate change; this includes agricultural processed of growing, harvesting, processing, land use and transportation of produce and livestock. The Intergovernmental Panel on Climate Change (2022)estimates that 37 percent of the world's greenhouse gas emissions come from the food systems, so for the purposes of scope, this brief will focus on crop growth and harvesting. With the current dominant large-scale conventional farming process of monocropping, where overuse of fertilizer and pesticides leads to dependency, it also decreases soil fertility, offering a vicious cycle of agriculture vulnerability to climate change unless addressed at grassroot levels.

Recent policy experience demonstrates that these input-intensive systems can shift when incentives change with a targeted approach. McKinsey reports that in China, fertilizer subsidy reforms in pilot counties reduced chemical fertilizer use by over 100 kg per hectare, with estimates suggesting potential reductions of up to 30 percent compared to prior rates (Frost *et al.* 2023). This illustrates how policy-supported adjustments to input use can reduce emissions while maintaining productivity in agricultural processes.

These conditions require real time, localized climate and soil monitoring systems, but small farmers often cannot access reliable weather forecasts, soil data, early warning systems or pest diagnostics. Most smallholder farmers rely on delayed or generalized climate information, which does little in addressing these immediate risks. While precision tools exist in some capacity, they remain inaccessible due to cost, digital literacy barriers and limited infrastructure. This causes a gap in regionally integrated data sharing systems and increases vulnerability as farmers operate in informational isolation.

This brief seeks to bridge the divide between large-scale and smallholder farmers by examining how technology is socially embedded within agricultural systems and identifying pathways for equitable implementation by leveraging pre-existing infrastructure to extend precision agriculture's benefits to those who need them most, in an effort to address climate change on ground.

Landscape of Agricultural Actors

Small farmers lack the resources to acquire precision farming tools, while **commercial farms** lack the mechanisms to share implemented precision agriculture systems with small farmers. According to a US Department of Agriculture news release (2025), small family farms make up about 85 percent of all US farms and manage nearly 40 percent of farmland, yet they generate only 14 percent of total production value. On the other hand, large-scale family farms, represent fewer than four percent of farms but they produce more than half of national agricultural output.

Regional farmer cooperatives (RFCs) are producer organizations that bring together farmers in the same region to coordinate input use, align production practices and jointly market their products. RFCs can help farmers adopt climate-smart practices, manage weather-related risks and access resilience building services such as improved seed varieties, irrigation systems and early warning information. RFCs reduce costs, strengthen bargaining power and improve farmers' ability to participate in low carbon and climate resilient value chains by pooling resources. For example, the Food and Agriculture Organization (FAO) reported in 2021, that in Burundi, the Confederation of Agricultural Producers for Development supported 39 cooperatives in registering over 14,000 farmers, enabling bulk purchasing of inputs, improved access to agricultural credit and coordinated marketing of thousands of tons of crops. This demonstrates how cooperative-level data systems can strengthen resilience and regional coordination.

Regulatory bodies may include a steering committee, working groups and task teams, and a support structure, which can be based in a neutral organization or independent entity. While establishing a governance structure, managing biases, ensuring inclusiveness, crafting decision-making processes, achieving consensus and managing operations should all be considered.

Overseeing bodies such as the United Nations Framework Convention on Climate Change (UNFCCC) and the FAO play a role in climate adaptation by mobilizing climate finance and providing policy frameworks through the Paris Agreement and Kyoto Protocol. These organizations also serve as a platform for knowledge exchange, particularly FAO's Global Network of Digital Agriculture Innovation Hubs, enabling successful regional projects to be adapted across different countries.

Operational Definitions of Proposed Technologies

The proposed technologies aim to narrow the gaps in data access between large and small farms. By utilizing technology implemented on large farms, data can be shared regionally with small farms to inform decision making, therefore reducing unnecessary water use. Presently, the agricultural sector accounts for more than 70 percent of global freshwater. Reports cite instances in Vietnam where water sensors have proven to reduce freshwater use by 13–20 percent compared to conventional irrigation methods use (Gupta *et al.,* 2023).

Wireless sensory networks (WSNs) are comprised of a series of Internet of Things (IoT) devices. Connected sensors, including dielectric sensors, provide real-time data on soil moisture and nutrients. These sensors serve as tools to provide data to end users regionally.

Complementary digital advisory systems further demonstrate how climate data can be translated into practical decision making. The United Nations Development Programme (2021) reported that in Odisha, India, the mobile-based advisory service "Ama Krushi" reaches over one million farmers with localized, crop- and season-specific guidance during the monsoon season, illustrating how regionally tailored information systems can support adaptation at scale.

Moving Forward

A concern for any technological strategy is lifecycle, and relevancy over time, or the risk of obsoletion. Precision agriculture is an opportunity to optimize recycling of equipment, such as reusing parts. Sensors, drones and data infrastructure are becoming more cost effective, lighter and more efficient with every generation. The need to cut water, fertilizer and pesticide waste in agriculture will create an ongoing demand for equipment and technology that can ensure this goal, which is why precision agriculture is a proposal with longevity.

Ethical considerations for data should also be made. With any intelligence gathered from censors, data security must always be a priority. Similarly, with sensor technologies such as drones, there must be worker protections overseen by regional cooperatives to prevent surveillance from equipment companies or employers.

Critically, adoption decisions must come from farmers themselves through bottom-up processes rather than top-down mandates. Technology integration should complement and enhance farmers' existing skills and knowledge rather than seek to replace them (Duncan *et al.* 2021). A crucial future consideration is data compensation by establishing mechanisms through which farmers receive value for the ground-level data they generate, restoring agency rather than allowing continuous extraction by developers. Without standardized, user-friendly tools, even well-intentioned equipment risks becoming either economically infeasible or chronically underused, ultimately failing the farmers it was designed to serve.

Recommendations

Parties to the UNFCCC, multilateral climate funds and development finance institutions should prioritize financial support for climate-smart agricultural monitoring technologies for smallholder farmers. Funding under the Green Climate Fund (GCF), Adaptation Fund, World Bank, and regional development banks should support:

- targeted subsidies, concessional loans and cooperative leasing models to reduce upfront costs of WSNs and precision tech to incentivize participation of large farms;
- bundled service delivery, including installation, maintenance and technical training to ensure sustained and effective use; and
- market safeguards and procurement standards to prevent monopolization and ensure fair pricing in emerging agriculture-tech supply chains.

National governments can integrate these financing models into national adaptation plans (NAPs) to align agricultural resilience investments with international climate finance streams.

Parties to the UNFCCC should incorporate cooperative-led climate data systems into their climate information strategies, with support from international climate finance and technical assistance programs. Governments should:

- formally delegate to RFCs and producer organizations as local climate-data intermediaries responsible for aggregating and sharing hyperlocal environmental data;
- ensure national regulations also clarify data ownership, consent, privacy and cybersecurity, ensuring farmer-generated data are protected and transparently managed; and
- make certain international organizations such as the World Meteorological Organization provide technical standards, data sharing frameworks and data governance guidance.

Integration into national meteorological and early warning systems can improve regional accuracy of climate services, strengthen early warning delivery, support more targeted adaptation planning and finance allocation.

Parties to the UNFCCC and international adaptation finance providers should support the expansion of farmer-centered climate education and digital literacy systems as a core component of agricultural adaptation. Through NAPs, implementation funding, GCF readiness programs and bilateral development assistance, governments should:

- develop national training frameworks that translate climate forecasts and sensor data into practical agricultural decisions;
- partner with cooperatives, extension services and local institutions to deliver training on irrigation timing, heat stress response, pest and disease risk interpretation, and crop diversification;
- train local youth, women and extension officers as climate information intermediaries; and
- use regionally accessible communication channels (SMS, voice messaging, radio, in-field demonstrations) to reach farmers with limited digital access.

Embedding these systems within national adaptation strategies ensures that investments in climate data and monitoring technologies translate into focused and actionable resilience, and reduced vulnerability toward the path of equitable access among smallholder farmers.

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Governing Smart Water Technologies for Drought-resilient Agriculture

Coralie Cazzola, Wendi Gjata and Ivan Gligorov

Issue

Drought is the most destructive climate hazard affecting agriculture, accounting for 82 percent of all disaster-related agricultural impacts between 2008 and 2018 (Food and Agriculture Organization 2021).

Background

Drought refers to prolonged deficits in precipitation that reduce soil moisture and surface and groundwater availability, with cascading impacts on ecosystems and human activities (United Nations Office for Disaster Risk Reduction and International Science Council2025). The latest Intergovernmental Panel on Climate Change (IPCC) report concludes with high confidence that anthropogenic warming is significantly altering the water cycle, increasing the frequency, intensity and duration of droughts (IPCC 2023).

Drought is no longer an episodic risk but a structural threat to global food systems. Its consequences are multidimensional: crop losses, income shocks and food price volatility disproportionately affect households in low- and middle-income countries, compounding the risk of food insecurity and malnutrition (Ziadat et al. 2025).

Smart Irrigation Systems

Smart irrigation systems are data-driven irrigation management systems that optimize the timing and volume of water application by aligning irrigation decisions with real-time soil, crop and climatic conditions rather than fixed schedules (Sharma et al. 2025). More precise timing and targeting of irrigation produces three interrelated outcomes:

- It improves water-use efficiency by reducing over- and under-irrigation and minimizing losses from runoff, percolation, and evaporation.
- It supports yield stability and crop quality by keeping soil-moisture conditions within optimal ranges and reducing crop stress.
- It reduces consumption of water, energy and production inputs such as fertilizers, lowering costs and environmental impacts.
- Beyond field-level control, smart irrigation supports water governance by making water use attributable and verifiable. Continuous monitoring enables performance-linked compliance and more adaptive allocation decisions than conventional reporting allows (Khanna et al. 2024).

Technical Architecture

Smart irrigation systems operate across three technical layers: Wireless Sensor Networks (WSNs), the Internet of Things (IoT) and cloud computing. The WSN layer consists of networked field devices that continuously measure water flows within the irrigation system, including how much water enters, moves through and leaves the field. The IoT layer manages device connectivity, data transmission and basic processing, converting sensor readings into standardized data streams. The cloud computing layer aggregates, stores and analyzes irrigation and environmental data, combining sensor readings with weather information, historical records and forecasting models to inform irrigation decisions.

Cost Structure

Upfront Capital Costs

Deploying a smart irrigation layer requires upfront investment in field sensing, control hardware, connectivity and an IoT gateway, including soil-moisture sensors (typically one per irrigation zone), system-level flow and pressure monitoring, and automated valves or controllers where not already present. Indicative upfront capital costs (smart layer only): €2,500–€6,500 per 10-acre farm. Costs vary primarily with the level of automation: manual-operation decision-support systems fall at the lower end, fully automated systems at the upper.

Annual Operating Costs

Annual costs are driven by connectivity subscriptions, data platform services and basic system maintenance (sensor calibration, replacements, and technical support). Indicative annual operating costs: €300–€1,000 per 10-acre farm. Variation reflects differences in connectivity requirements, platform services and maintenance intensity rather than computing or data-transmission costs. Despite their technical potential, smart irrigation systems face barriers to adoption and scaling that are primarily financial and governance-related, not technological.

High Upfront Investment Costs

Even where pressurized or drip irrigation infrastructure already exists, deploying a smart irrigation “layer” requires substantial initial capital outlays for field sensors, control hardware, connectivity and system integration. For small- and medium-scale farms, these costs represent the primary barrier to adoption, limiting uptake under market-led deployment alone.

Infrastructure and Connectivity Gaps

Smart irrigation systems depend on reliable electricity and digital connectivity to operate continuously. In rural regions, limited broadband access constrains performance and increases maintenance costs. The farms most exposed to drought are often least equipped with the connectivity, human capital and data infrastructure these systems require, an inverse relationship between adaptive need and deployment readiness (Tzachor 2020). Adoption is further constrained by technology aversion: farmers often resist delegating irrigation decisions to systems they cannot interpret or override (Khanna et al. 2024).

Current Policy Landscape

Three observations emerge from the analysis of the current policy landscape around smart irrigation.

Current Stakeholder Perceptions and Barriers

A survey of five Mediterranean countries (Toscano et al. 2025) reveals a significant gap between awareness and adoption. Among the 238 farmers surveyed, 87.9 percent acknowledge that smart irrigation reduces water consumption and 75.7 percent believe it increases yields, yet only 25.9 percent currently use smart water technologies. While 64.6 percent of irrigating farmers express a willingness to invest, two major barriers stand in the way: high initial costs (cited by 66.3 percent) and a lack of technical training (cited by 70 percent). From the policymaker side, the picture is equally telling: 92 percent identify low farmer awareness of benefits as the main challenge, while 75.6 percent report no legal barriers to adoption and 61.1 percent claim familiarity with digital agriculture tools. On effective levers, policy makers rate economic incentives highest (3.9/4), followed by training programs (3.1/4). Taken together, these findings confirm that smart irrigation is primarily a technology governance challenge, not a technological one.

Irrigation in Current Drought Policies

Irrigation is increasingly embedded in national drought policy frameworks. All 35 of the National Drought Plans (NDPs) reviewed reference a national irrigation policy or strategy, and 72 additional countries have expressed interest in developing such plans (United Nations Convention to Combat Desertification 2019). However, smart irrigation technologies remain only partially addressed: just 13 of the 35 NDPs (approximately 35 percent) include specific policies for smart irrigation, and 11 of those acknowledge major challenges hindering the adoption or scaling. This points to a structural gap between the recognition of irrigation as a drought-resilience tool and the governance frameworks needed to support its digital transformation.

Current Policy Challenges

Two interrelated challenges undermine the effectiveness of existing irrigation policies. First, efficiency gains do not automatically translate into water savings: a dynamic known as Jevons' paradox. A case study from China’s Tianshan region illustrates this: despite two decades of drip irrigation policy, agricultural water use increased by 114.79 percent, driven by crop mix changes toward more water-intensive varieties (Wang et al. 2020). Second, governance fragmentation compounds this problem. Agricultural agencies typically promote irrigation expansion to boost production, while water and environment ministries warn of aquifer depletion with no coordinating mechanism to reconcile these objectives (Molle and Sanchis-Ibor 2019). Smart irrigation technologies, if deployed without clear governance conditions, risk reproducing and accelerating these same dynamics.

Recommendations

Modernize physical irrigation infrastructure before digitization. Prioritize the repair and upgrade of deteriorated irrigation canals and structures, then fund low-cost, low-energy IoT sensors that provide continuous flow and soil-moisture data.

Foster regulated public-private partnerships (PPPs) for financial resilience. Use PPPs to overcome the high upfront capital costs of smart irrigation systems, with the public sector subsidizing sensors and connectivity while private technology providers operate data platforms and maintenance services (Moreddu 2016). Contracts should clearly define performance targets, allocate risks to the actors best able to manage them and ensure transparency to safeguard the public interest.

Policy makers should apply Organisation for Economic Co-operation and Development (OECD) best practices adapted to smart water technologies: define clear and shared objectives (for example, enhancing drought resilience); ensure transparent and competitive partner selection by promoting open, interoperable architectures; establish robust data governance frameworks that treat water and environmental data as public-interest assets while protecting farmers' data; and embed monitoring, evaluation and exit mechanisms through performance indicators, periodic reviews, and adaptive or termination clauses (OECD 2025).

Mandate a standardized, interoperable and open IoT architecture. Condition public funding for smart irrigation technologies on the adoption of open data models (for example OGC SensorThings API) and connector-based middleware, ensuring interoperability between heterogeneous devices while preventing vendor lock-in (Roccatello et al. 2025).

Public authorities should support international standardization efforts that define shared technical rules (protocols, data models, interfaces and exchange formats) enabling devices and platforms to communicate seamlessly and interpret data consistently. Standardized middleware based on connectors should decouple data production (sensors) from data consumption (applications), allowing legacy and proprietary systems to integrate at lower transition costs and making standardization both politically and economically viable (ibid.).

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Addressing Canada's Agricultural Methane Emissions by Advancing the Accessibility of Anaerobic Digesters

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Issue

As per the Global Methane Pledge, Canada — one of the top 10 greenhouse gas emitters — has committed to reducing methane emissions by 30 percent by 2030 (Government of Canada 2022). Methane has a near-term global warming potential 84 times greater than carbon dioxide, making it a significant contributor to rising temperatures (ECCC 2026). Globally, the agricultural sector is the largest source of anthropogenic methane emissions (ibid.). Although mitigation technologies such as anaerobic digesters (AD) can reduce methane emissions, implementation remains limited. This brief considers ADs and provides recommendations to improve farmers' access to the technology and to reduce methane emissions within Canada's agricultural sector.

Background

The Intergovernmental Panel on Climate Change (IPCC) estimates that methane has contributed 0.5°C of the observed global surface warming since pre-industrial times (IPCC 2021). Anthropogenic activities account for roughly 60 percent of global methane emissions, and this percentage will continue to rise (ibid). In Canada, 86 percent of agricultural methane emissions are a result of enteric fermentation with the remainder attributed to manure management (Government of Canada 2024). Without targeted policy interventions, manure-related emissions will continue to impede the country's progress toward its international climate commitments.

ADs offer a promising path forward. While other agricultural methane mitigation technologies exist, such as feed additives and selective breeding, ADs go beyond mitigation and contributes to adaptation and resilience. Needing a minimum of 0.5 acres of land, the mechanical components include digester tank(s), feed, mixing and heating systems, gas collection, gas storage and a digestate outlet (University of Missouri 2019). ADs use bacteria to break down organic matter (feedstock) such as manure to produce renewable electricity, heat, fuel and digestate, all while reducing methane emissions that would otherwise be released, by up to 90 percent (Rodriguez et al. 2024). However, the technology requires high upfront capital costs and technical expertise, and not all projects perform as expected. Technical failures and extreme weather conditions can lead to underperforming or financially stranded assets, exposing farmers to significant economic risk (International Energy Agency [IEA] 2020). However, with proper financial and policy support, these risks can be mitigated. Indeed, Germany has decades of proven success with thousands of AD systems set up throughout the country's agricultural, industrial, waste and biomethane sectors (Lebuhn, Munk and Effenberger 2014).

However, despite its potential, ADs have received limited policy attention in Canada. Despite decades of research, farmers seeking to adopt this technology continue to face significant challenges.

Key Challenges

Challenge 1: High Upfront Capital Cost and Lack of Funding

ADs incur high upfront capital costs that are prohibitive for medium- and small-scale farms, with installation costs upwards of CDN$2 million (Mashhadi, Noori and Carlo 2021). Farmers have few targeted funding programs and face uncertainty over long-term revenue. Without secure offtake agreements or purchase power agreements, lenders perceive these projects as high risk, making it difficult for farmers to access the money they need to get their projects off the ground (Canadian Biogas Association 2022a).

Challenge 2: Grid Connection and Injection

Biomethane, the end product of AD, is a purified biogas that can be blended with natural gas networks to be used for electricity generation and transportation (European Biogas Association 2024). The process of injecting biomethane into existing gas grids can be expensive due to grid connection costs, with metering systems and injection fees approximating CDN$3 million to $4 million dollars (Government of Alberta 2006). Grid connection and heat distribution can add an additional 70 percent to the costs of a biogas project (IEA 2025).

In Canada, the potential use of biomethane is 809 PJ — yet only 155 PJ can be achieved due to logistical and financial limits of grid connection (Stephen et al. 2020). Furthermore, the majority of biogas projects are based in Ontario and Quebec, with limited use in rural, agricultural provinces such as Manitoba and Saskatchewan (Canadian Biogas Association 2022a). Farms even 1.5 kilometres away from existing natural gas grids require millions of dollars to finance grid connection and injection (Canadian Gas Association 2024). Limited access to grids results in biogas being flared rather than used, reducing economic viability and emissions reduction outcomes (Stephen et al. 2020).

Challenge 3: Lack of Feedstock Diversification

Only 14 percent of the current Canadian feedstock capacity is being used through AD (Canadian Biogas Association 2025). Quebec, for example, allows only 25 percent of off-farm waste to be among the feedstock mix, the rest must have on-farm origins, while British Columbia limits that amount to 49 percent (Canadian Biogas Association 2022a). This has the effect of favouring large facilities at the expense of smaller farms since the former have access to more on-farm waste. It also restricts site selection to only agricultural land where big farms operate. Strict regulations also apply to off-farm waste, specifically regarding contamination risks and odour management. While such guidelines are necessary for health and environmental protection, many are incompatible with a typical anaerobic process. Research shows that different types of bio-waste with varying chemical components (such as food waste or slaughterhouse waste) can be co-digested with manure for excellent results (Rehman et al. 2019; Xu et al. 2018). Indeed, in provinces like New Brunswick, 30,000–40,000 metric tonnes of waste are processed every year thanks to diversification strategies allowing feedstock to be collected from not only farms but also surrounding food processors (Canadian Biogas Association 2022a). Strategies to diversify feedstock could produce almost 200 PJ of renewable natural gas that would help Canada decarbonize (ibid.).

Challenge 4: Patchwork Policy Making

In Canada, farmers must contend with poorly defined and highly intensive regulatory processes. Concretely, biogas projects face one to two years regulatory timelines, a lack of policy awareness and overlapping regulatory requirements (ibid.). For example, British Columbian producers must navigate a minimum of three regulatory processes for any given project, whereas Ontario has defined three clear regulatory pathways for biogas production via the Nutrient Management Regulation (ibid.) While government policies regarding AD adoption have primarily been enacted at provincial and municipal levels, the lack of centralized policy instruments at the federal level has resulted in patchwork policy implementation across provinces, hampering essential market signalling required to spur investment.

In addition, AD technologies are less cost competitive against more established fossil-fuel equivalents (Canadian Biogas Association 2022b). However, due to a lack of policy awareness, the environmental benefits of AD technologies are not fully realized, leading to disproportionately low prices when farmers try to sell their biogas to grid distributors, as is the case for British Columbia and Newfoundland (Canadian Biogas Association 2022a). To incentivize AD technology development, government policies that accurately reflect their value are necessary to correct market failures and increase their viability/profitability.

Recommendations

Reduce uncertainty and improve funding access for farmers. To address farmers' concerns of securing funding, the federal and provincial governments could implement a coordinated financial support framework that reduces capital risk while improving the bankability of long-term projects. Targeted federal capital grants, investment tax credits and loan guarantees can significantly reduce upfront costs, making the technology more accessible. This approach, paired with formal recognition of AD as a priority climate solution, could help attract private equity funding, opening access to both public and private financing. The expansion of long-term offtake approaches such as well-structured power purchase agreements found in Ontario for biogas-based electricity and biogas offtake could ensure more stable revenue streams that lenders require for long-term projects (Timmins 2025). Altogether, capital support and long-term certainty can strengthen access to AD as well as waste-management outcomes.

Improve access to grids and markets. The process and costs of grid connectivity remain a barrier to small and medium sized farms. To counter these issues, Canada could facilitate a national right-to-connect framework, including cost-sharing strategies between federal, provincial and municipal levels and agricultural biogas producers. This formula could be modelled after Germany's highly successful Gas Network Access Ordinance, which has fed 1.4 billion m3 of biomethane into the national gas grid (Fachverband BIOGAS 2025). Costs for the grid connection are borne by the grid operator (75 percent) and biogas feeder (25 percent) on a pro-rata basis up to 10 km of connecting pipeline (Deutsche Energie-Agentur n.d.). Grid operators are obliged to give priority to connecting systems to the gas grid immediately upon request (ibid.). This operation establishes an implementation schedule for the establishment of grid connection, which is federally supervised (ibid).

Expand feedstock availability through integrated waste management policy. Reducing regulation is critical to increasing feedstock availability through the incorporation of off-farm feedstock. Simultaneously, stricter regulations on composting and landfilling are needed to ensure a sustained feedstock supply. In Denmark, landfilling biodegradable waste was banned in 1997 as part of an integrated strategy to maximize the energy potential of such wastes (Edwards, Othman and Burn 2015). European Union directives such as the Integrated Pollution Prevention and Control Directive mandates producers to have adequate waste treatment strategies, either through barrel composting or shipping waste for AD, ensuring that feedstock is well-managed and their energy values are maximized (ibid.) British Columbia has taken steps in the right direction in implementing organic disposal bans on food waste, ensuring that such resources are reserved for renewable energy production via AD (Canadian Biogas Association 2022a).

Enhancing policy capacity and sending strong signals to industry. To support the adoption of biogas projects across Canada, expanding Canadian policy implementation for the sector is critical. It is proposed that the federal government chairs a regulatory working group with related ministries, provincial governments and private producers to explore best practices in biogas policy and support the industry in navigating regulatory processes. As well, through the amendment of the Clean Fuel Regulations, to introduce a federal minimum renewable content requirement for gaseous fuels, the government could send a strong market signal for AD as a priority climate solution. This has the crucial result of reflecting the environmental benefits of AD in the energy market. The United Kingdom's Renewable Transport Fuel Obligation (2022) strategy demonstrates a successful emissions saving model, reducing emissions by 82 percent (Department for Transport 2023). Modelling for Canada suggests that a federal minimum would result in an additional 82 percent reduction in greenhouse gas emissions by 2030, compared to the current emissions rate (Canadian Biogas Association 2022b).

Conclusion

AD has considerable potential in supercharging Canada's net-zero ambition through renewable processes that capture methane and use it to produce energy, thereby promoting the phasing out of fossil fuels. There is also significant potential for the wider application of AD in the agricultural sector, one of the highest emitting sectors with ample feedstock availability. By lowering financial barriers and improving access to grids and feedstock, Canada can unleash AD's full potential not only in emissions reduction but also towards realizing its renewable energy future.

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Reclaiming Biomass as a Climate Asset: Biochar as a Strategic Lever for Canada's Climate Goals

Emily Millie Hannan, Ekamjot Dhillon, Ganiyat Sadiq and Maham Naweed

Issue

Canada can more productively use its abundant biomass generated across forest, agricultural and production systems. With such resources, Canada has significant potential for carbon sequestration and for strengthening food security and climate resilience, particularly for rural communities. By reframing biomass as a strategic climate asset and prioritizing biochar as a sustainable climate technology, Canada can align its emissions targets with commitments to Indigenous self-determination, national food security and global climate action.

Background

Canada has committed to ambitious Nationally Determined Contributions (NDCs) to reduce emissions by 45-50% below 2005 levels by 2035 under the framework of the United Nations Framework Convention on Climate Change (UNFCCC) (Canada, 2025). To date, however, Canada has largely fallen short of its emissions reduction targets, relying mainly on extractive technologies and promises of green transitions. This highlights the need to invest in climate technologies rooted in existing land-use systems that integrate twenty-first-century advancements with traditional environmental practices. One such technology has been used for over 2,500 years across diverse Indigenous agricultural contexts and provides an opportunity for such bridging. Biological charcoal or "biochar" is a durable solid that can be applied to soils in support of long-term carbon sequestration and nutrient enrichment. Biochar production involves the combustion of biomass that would otherwise decompose and release carbon dioxide (CO2), then heating it in an oxygen-free environment, with applications ranging from individual households to large-scale biochar production through a process called pyrolysis. This process involves the co-production of syngas and biofuels, making it self-sustaining while also producing alternative fuel sources. This distinguishes biochar from slightly more profitable, but intensive climate approaches (Fergerson and Sievert 2024). As a mitigation tool, biochar functions as a negative-emissions technology by removing carbon from the atmosphere over time. As an adaptation measure, biochar has a porous microstructure that improves soil structure, water retention and nutrient availability, increasing resilience to drought, flooding and declining agricultural productivity (ibid.). As an intervention, biochar can be integrated into agricultural and forest management systems to mitigate soil degradation, without introducing new dependencies and reducing reliance on chemical fertilizers (Zhang et al. 2023). Biochar can be produced from a variety of biomass sources, many of which are abundant in Canada, such as dead wood, wood waste and agricultural waste, making it an extremely versatile technology. (Bird 2025). Moreover, biochar can be used alongside other climate-friendly agricultural practices, such as floating or vertical gardens, to enhance agricultural security and sustainability (Francis 2025).

Best Practices

This versatile technology has already been implemented in international contexts, such as Norway, where the large-scale conversion of biomass into biochar is among the most promising mitigation activities, capable of sequestering up to 0.96 Tg of CO2 per year (Hagenbo et al. 2024). Similarly, Denmark has integrated biochar into its national strategy, committing €1.3 billion in subsidies to support pyrolysis, aiming for two million tonnes of carbon storage annually by 2030 (ibid.). Both nations use a diverse range of local biomass, demonstrating that these low-value materials can effectively be transformed into stable carbon sinks. These precedents are important benchmarks for Canada, demonstrating successful navigation of similar boreal-climate contexts while establishing biochar as a cornerstone of their national strategies. Additionally, an increasing number of pyrolysis companies are emerging within and beyond North America, highlighting the growing value and market for biochar production, even at the local level, where pyrolysis processes such as the Kon-Tiki kiln are used in 80 countries to produce carbon sinks (Ithaka Institute n.d.). This is critical, as estimates suggest that biochar could offset approximately 12 percent of current greenhouse gas emissions, while also complementing other technologies and strategies across spheres of climate mitigation, adaptation and intervention (Woolf et al. 2010, 1–3).

Stakeholders

The successful implementation of biochar solutions requires coordinated engagement across multiple sectors. Domestically, Indigenous communities are central stakeholders, contributing long-standing knowledge of biochar practices, acting as agricultural end users and advancing food security objectives within their communities. Forest industry actors are the primary suppliers of biomass feedstocks and manage supply, while farmers and end users are key consumers who can demonstrate biochar's economic viability through improved soil productivity (Keske et al. 2020). Provincial governments play a coordinating role between forest management and agricultural users, and local municipalities are crucial for managing biomass waste streams away from landfills and towards biochar production (Rodriguez-Franco et al. 2023). There are also technology providers developing mobile pyrolysis systems that may enable decentralized processing, particularly in remote or northern regions, and agro-processing industries can further support circular economy models by supplying feedstocks and using biochar in waste treatment (Page-Dumroese, Coleman and Thomas 2016; Dahal, Acharya and Farooque 2020). Internationally, global climate institutions, international financial institutions and carbon market actors will shape the recognition, financing and credibility of biochar as a versatile climate technology.

Economic Consideration

Biochar has high production costs and may be difficult to scale through market forces alone. Production requires pyrolysis equipment, a steady biomass supply, transport, and ongoing operating costs, all of which increase production costs. Currently, most estimated commercial production costs range from US$571 to $1,455 per tonne, making initial profitability uncertain without policy support (Nematian, Keske and Ng'ombe 2021, 470–72). Risk for producers seeking to recoup costs or plan long-term investments may arise, as biochar demand and markets remain small and fragmented, leaving producers unable to sell biochar at prices that reflect its environmental value, increasing reliance on subsidies or public programs (ibid. 471). Farmer incentivization is also constrained, as biochar application will be difficult under current carbon pricing regimes, necessitating pricing below EU Emissions Trading System carbon prices or subsidies that exceed them (Jokubė et al. 2025, 3-4). These are important considerations as biochar competes with lower cost, more readily scalable mitigation options for limited public funding.

Environmental Considerations

Despite its versatility, biochar has environmental limitations in the Canadian context, particularly regarding the availability of sustainable biomass. Although biochar can store carbon in soils for extended periods, its climate benefits depend on biomass being harvested without undermining food security, soil health or ecosystems. Biochar's effectiveness also varies by feedstock type, production conditions, soil characteristics and climate. Although some contexts show clear soil benefits, others demonstrate limited or uncertain gains, requiring attention to targeted programming rather than broad policy mandates. Moreover, large-scale deployment of biochar can intensify pressure on land and biomass resources, creating foreseeable trade-offs with other environmental or economic goals (Fuss et al. 2018, 7–9). However, given successful scaling in other countries, the overall climate benefit may depend more on careful management and realistic assumptions about permanence and scale.

Social Considerations

Large-scale uptake of biochar could intersect with Indigenous land rights, governance and cultural traditions, particularly where biomass sourcing and development happen without free, prior and informed consent. Similarly, farmer participation cannot be assumed without clear incentives, upfront support and protections against market volatility, requiring avoiding risks associated with favouring large agribusiness over small stakeholders. Uneven access to infrastructure, knowledge and financing may further concentrate benefits among already-resourced actors. Addressing these social dimensions requires recognizing Indigenous knowledges, inclusive governance, targeted incentives and rights-based frameworks to ensure biochar contributes to equitable and politically durable climate action.

Policy Analysis

Canada's governance of biochar as a climate technology must align domestic climate objectives with international commitments. Domestically, biochar supports Canada's emissions-reduction goals by transforming biomass waste into a stable, largely self-sustaining form of carbon sequestration, thereby advancing circular economy priorities. Its co-benefits, such as enhanced soil productivity, rural development and Indigenous collaboration, strengthen the political stability of climate policy by linking long-term climate action to tangible outcomes and social sustainability. Internationally, biochar interacts with Canada's obligations under the UNFCCC and the Paris Agreement. Fulfilling Canada's commitments under these agreements requires credible mitigation, adaptation and intervention pathways, such as the use of biochar, which offers a profound opportunity for collaboration and innovation in the name of sustainable climate action.

Recommendations

Establish a federal biochar incentive program. Canada should establish targeted, time-bound incentives to support biochar production and application, prioritizing community scaling, Indigenous-led and regionally appropriate projects. These incentives should address high upfront capital costs associated with pyrolysis equipment, transport and verification, which currently constrain adoption despite clear public benefits. Rather than creating a standalone funding stream, biochar incentives should be integrated into existing agri-environmental, forestry and waste-diversion programs, embedding biochar within established policy architectures and reducing administrative complexity. This is an essential step, particularly as biochar can sequester up to 12 percent of current greenhouse gas emissions. The Canadian government should work with emerging tech companies such as Carbonity, which estimates biochar production at 350,000 tonnes by 2035 (Ranevska 2025). Such partnerships can help to ground biochar policy design in the Canadian context.

Implement a public procurement process. To address uncertain demand, the federal government should introduce public procurement guarantees or minimum uptake quotas for biochar within publicly funded land-use activities, including forest restoration, mine reclamation, degraded agricultural lands and municipal green infrastructure projects. Under this approach, a defined portion of biochar production would be allocated to public climate and land stewardship objectives, while the remaining production could be sold commercially. This dual-track model provides predictable demand, reduces market volatility and lowers investment risk without requiring permanent subsidies.

Prioritize Indigenous governance and collaboration. Given its traditional use, biochar policy should be designed to advance Indigenous self-determination, not solely participation. Public funding and regulatory approval should involve Indigenous leadership, free, prior and informed consent, and long-term benefit sharing, particularly where biomass sourcing or land-use impacts affect Indigenous communities. This approach reduces the risk of benefit capture, strengthens legitimacy and aligns biochar deployment with Canada's reconciliation commitments. This can also be linked to the growing International Biochar Initiative to ensure that best practices and regulations align with international standards (International Biochar Initiative n.d.).

Regulate biomass use to protect ecological integrity. Biochar policy should include clear sustainability thresholds for biomass sourcing to prevent ecological harm. Only waste biomass and residues that do not compromise soil health, biodiversity or food security should qualify for public support or carbon accounting. Federal guidelines should require region-specific assessments of feedstock availability, soil conditions and climate suitability prior to approval. These safeguards prevent over-deployment and reinforce biochar's role as a targeted, context-specific intervention rather than a universal solution.

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