United Nations University
Institute for Water, Environment and Health

POLICYBRIEF
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Employing Domain-Informed AI for Energy Planning and Decarbonization under Uncertainty

Key Messages

1. Renewable energy is a critical part of climate change mitigation but is also more susceptible to adverse climate conditions than fossil fuel-based energy generation.

2. The electricity grid is further stressed by growing demand and the expansion of power-intensive end-uses (e.g., data centers and EVs) whose growth trajectory already exceeds the anticipated capacity expansion needs.

3. Current long-term planning of electric grid upgrades and expansion generally relies on historical weather and climate trends that are unlikely to remain stable in the coming decades.

4. In the past, the complexity of large-scale climate downscaling has inhibited deeper integration of climate projections and energy planning models. Failing to integrate climate projections exposes public infrastructure to severe physical and fiscal risk.

5. Domain-informed AI can be used as a complement to existing tools to provide forward-looking information on the impacts of climate change on renewable energy integration, informing decarbonization policies.

6. Unregulated AI data centers consume massive amounts of electricity, directly straining the grid. Policymakers should mandate that this computational infrastructure of AI operates primarily on verifiable renewable energy.

Context

Decarbonizing the energy sector through increased renewable energy integration is a central instrument for successful climate change mitigation. Yet, the intermittency of renewable energy sources means that climate change is likely to impact their generation potential, creating a feedback loop in which the primary means of mitigating climate change becomes increasingly less reliable as climate change intensifies. Simultaneously, climate change is increasing the demand for electricity through increased use in different sectors (e.g., more groundwater pumping in drier conditions and more air conditioning at higher temperatures). Additionally, growing economies and emerging end-uses, such as increased number of electric vehicles (EVs), exponential growth of artificial intelligence (AI), and the resulting proliferation of power-hungry data centers, create larger demand for electricity.

Ironically, the push for decarbonization is colliding with surging global electricity demand and uncertainty in the reliability of renewable energy resources under climate change. Without intervention, this conflict will overwhelm existing grid capacity. Balancing this trade-off will require a deep understanding of how climate change is likely to impact renewable energy integration, as well as how current and emerging demands will shift in an uncertain future. AI data centers consume massive amounts of electricity, directly straining the grid. Yet, regulated AI also offers the computational power necessary to integrate renewable energy safely and securely. The policy question is not whether to deploy AI for grid resilience, but under what guardrails.

This brief directs national regulators and climate-finance institutions managing long-term grid infrastructure. It synthesizes peer-reviewed climate science with applied AI. The resulting framework delivers actionable safeguards to enforce forward-looking climate risk assessments during capacity planning. These directives secure AI governance and support acceleration of decarbonization targets through 2030.

Problem Statement

Currently, the global energy system relies predominantly on fossil fuels, but the share of renewable energy is growing. In fact, the renewable energy sector is projected to nearly triple in size by 2030 [1]. This trend towards a low-carbon energy system is crucial for mitigating climate change and reducing emissions. However, the growth in renewable energy technologies is concurrent with increasing demand for electricity, creating a situation where our energy systems need to generate more electricity than in previous years while we work to shift that generation towards cleaner sources to aid climate change mitigation.

A primary barrier to securing a resilient energy grid is the failure of long-term capital planning to account for forward-looking climate risk. This failure creates severe macroeconomic exposure. Deploying capital based on stationary historical data for infrastructure with 15- to 20-year lifespans results in the accumulation of stranded assets as physical climate risks materialize. To date, there have been advancements in assessing the potential impacts of climate change on renewable energy [2]. However, there remain gaps in the implementation of these research findings into practice, particularly within the regulatory agencies responsible for long-term capacity planning [3]. Often, these agencies rely on historical weather data to account for possible spikes in demand, which ignores the shifting weather conditions caused by climate change. Historical reliance on inflexible physics-based models creates an information bottleneck. This lack of flexibility limits the transfer of critical knowledge from research to practice, effectively creating gaps in the resilience of the world's energy systems.

Solution Overview

Applying domain-informed AI is one of many necessary solutions to solving the challenge of integrating renewable energy in a way that is reliable and resilient to the changing climate. Domain-informed AI refers to a class of algorithms that are more transparent in terms of training, as well as tailored to the specific application area (e.g., energy systems). These methods differ from large language models (LLMs) and other deep learning approaches, as they are easier for stakeholders to understand and integrate into their existing planning processes. By focusing on tailoring the algorithms to specific application areas, these methods will often perform better than their more general-purpose counterparts. These transparent, tailored AI algorithms can be used to improve existing energy system planning tools and processes. Domain-informed AI algorithms can provide fast, reliable estimates of future extreme events, project future energy needs, and improve energy system modeling for generation and transmission planning under climate change.

Policy Recommendations

1. **Mandate adaptive regulatory frameworks for proactive resilience planning**

   A challenge with integrating climate change into long-term planning is the uncertainties associated with projections of climate change, socioeconomic shifts, and population growth trajectories, which limit investments into mitigation policies that require significant upfront economic and political costs. To account for this uncertainty, regulators should institutionalize adaptive governance frameworks based on adaptation pathways [4] that would provide the necessary flexibility within long-term planning, while also moving towards a more resilient future. This regulatory structure requires regular check-ins to evaluate how the climate, socioeconomic standing, and technology, alongside the models used to generate these projections, have evolved. Regulators would update the policies to align with this evolution. Through this process, regulatory bodies can call for smaller changes that align with larger goals over the long-term planning period, adapting as necessary to shifting conditions and protecting past investments.

2. **Institutionalize interdisciplinary expertise to develop critical solutions**

   To adequately prepare the energy system for climate change while also integrating more renewable energy technology, there is a need for a variety of expertise across industries and sectors. To prepare the energy system for climate change, energy system modelers must work closely with climate scientists to figure out what specific outputs are needed from future climate simulations, including variables and spatiotemporal scale [5].

   Further, energy systems do not exist within an infrastructure vacuum, making it imperative that long-term energy system plans also account for other interconnected sectors, such as water, information and communications technology (ICT), including AI, and transportation. Research has shown that energy systems can be better represented predictive models if there is consideration for multiple interdependent systems [6]. Regulators should mandate integrated modeling that explicitly accounts for structural vulnerabilities among interconnected infrastructure networks.

3. **Explore non-traditional techniques for climate change impact assessment**

   Current state-of-the-art climate change impact assessment tools often rely on large-scale general circulation models (GCMs) that are not only difficult to integrate into existing systems but also have a plethora of issues when trying to downscale to relevant spatial scales and obtaining variables of interest to energy systems modelers [5]. Domain-informed AI has the potential to be instrumental in solving this challenge [7] through climate emulation and other projection-based models.

   Infrastructure managers should work towards the integration of domain-informed AI climate emulators, which are rapidly progressing in accuracy [8], directly into official capacity planning workflows. Domain-informed AI models already deliver highly accurate short- and long-term renewable forecasts [2,9]. The immediate policy task involves translating this proven capability into an enforceable standard for long-term grid approval, governed by strict transparency rules.

4. **Ensure transparency and safety of AI-driven work**

   Research has shown that the lack of interpretability of deep learning algorithms can limit the effectiveness of such work in sectors where domain knowledge is critical [10]. Utility operators require absolute clarity to act on automated system alerts. Regulators should classify opaque deep learning models as severe operational hazards. Enforcing interpretable, domain-informed AI guarantees accountability when directing physical infrastructure interventions.

   If AI algorithms are being used to aid decision-makers, it is critical that these algorithms are not only safe and secure for themselves, but also that the public understands and trusts the results. Focusing on explainable or domain-informed AI, as well as developing better regulations on the use of AI in critical sectors, can help to develop this trust. To this end, the AI algorithms should also include sufficient guardrails to limit any bias that may be introduced to the training process. Policymakers need to develop and implement regulatory policies that provide transparency and maintain public safety, particularly in sectors that are so completely integrated into modern life.

5. **Mandate low-impact AI infrastructure**

   The immense power demands of data centers actively destabilize the grids they aim to protect. Agencies deploying AI for grid resilience need to enforce strict energy consumption limits. Policymakers should mandate that supporting data centers operate primarily on verifiable renewable energy.

Final Remarks

The energy system around the world is currently dominated by fossil fuels, contributing to further climatic changes. Decarbonizing the electricity sector requires more than simply building new renewable capacity. It demands immediate integration of dynamic climate-risk modeling. This task alone is a challenge, but it is further complicated by the feedback loop that exists between climate and renewable energy, as well as the emergence of power-hungry end-uses, such as EVs, AI, and data centers. However, there is an opportunity to make use of the AI revolution to develop science-informed policies around renewable energy integration under climate change. These AI algorithms can provide fast, accurate modeling results that can be of great use to decision-makers that are working to expand our electricity grid and ensure that all people have access to this service that is critical to modern life. However, to ensure that these algorithms are used in a way that is both transparent and safe, it is critical that we work to implement regulations to encourage efficient use of electricity in the data centers that train these models, as well as provide transparent explanations of how AI is being used in these critical infrastructure systems. Without these policies in place, there is likely to be a continued mistrust of AI-driven models and processes, which will lead to limited uptake by public management agencies. Rejecting domain-informed AI in renewable energy integration might lead to delayed decarbonization of the electricity sector. Failing to modernize capacity planning accumulate stranded assets and lead to catastrophic infrastructure failures as climate extremes intensify.

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