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Integrating AI into Energy Systems: The approach of the Global Climate Hub

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Abstract

Energy systems are facing multiple complex challenges, related to factors such as environmental, climate change, social, economic and market, variations in supply and demand patterns, and infrastructure, to name a few. The Global Climate Hub (GCH) is a research-led initiative operating within the United Nations Sustainable Development Solutions Network framework, and mobilizes nine research units to deliver holistic, equitable, and context-specific energy solutions. These units leverage advanced modelling tools, participatory frameworks, and Open Science principles to support resilient, equitable, and sustainable energy transitions. The integration of new technologies in energy systems planning is key to facilitate the workflows of the GCH, and support a sustainable energy transition. This chapter explores the integration of Artificial Intelligence (AI) in the GCH's transdisciplinary approach to energy systems planning. AI offers transformative capabilities, enabling efficient data analysis, predictive modelling, resource optimization, stakeholder engagement and Open Science. We describe how the major advantages of AI can be integrated in existing approaches developed by the GCH, including climate scenario development, decarbonization pathways design, participatory approaches, and digital applications. While AI's integration into GCH processes is ongoing, the chapter presents a foundational framework for AI-enabled energy planning and invites collaboration to advance global sustainability goals through innovative, inclusive, and scalable solutions.

Keywords: Energy Systems; Artificial Intelligence; Global Climate Hub; Sustainability; Energy Transition.

1. Introduction

Energy systems are at the heart of modern infrastructure, evolving rapidly in response to the pressing need for sustainability, resilience, and efficiency. Historically centered around centralized generation and supply, they are now transforming to encompass a broader range of decentralized, renewable energy sources, smart grids, and demand-side management strategies.[1] This transition reflects a shift from purely technical approaches to more transdisciplinary frameworks that integrate environmental, social, economic and technological dimensions, along with pressing decarbonization goals. Challenges such as climate change, extreme phenomena, resource limitations, the need for decarbonization, and increasing energy demands necessitate the adoption of advanced technologies and tools.[2] Artificial Intelligence (AI) is an example, as it can enable innovative solutions by analyzing big and complex data, optimizing operations, and supporting predictive modelling, making it an indispensable tool for modern energy systems planning. AI is a collection of algorithms and computer systems that have been created to perform tasks that require human cognitive abilities. It has widely influenced development in planning, operation, and innovative approaches to energy systems.[3] The big challenge of our times, decarbonized energy systems, is a task that can be supported by AI tools needed to support system reliability, improve the efficiency of operations, and integrate larger shares of renewable resources in an affordable and fair manner.

In this chapter, we explain how AI can support energy systems under the research actions of the Global Climate Hub (GCH). The GCH is developed under the UN Sustainable Development Solutions Network (UN SDSN) and is an international, research-driven initiative designed to address modern sustainability challenges, including those related to energy systems.[4] Leveraging diverse expertise across disciplines such as climate science, economics, and social systems, the GCH delivers actionable pathways through integrated models, resilience assessments, and stakeholder participation. Its transdisciplinary approach bridges science and society, ensuring solutions are holistic, equitable, socially acceptable, and tailored to local contexts.[5]

First, we outline AI's revolutionary role in energy systems through current applications in decision-making, scenario development, resource optimization, and policy formulation. Next, we describe the GCH research approach. Finally, we discuss more specific examples of AI-supported processes within the GCH's approach for energy planning, towards a sustainable, resilient, and inclusive energy future.

2. How AI Enhances Energy Systems

AI holds transformative potential for energy systems across multiple dimensions, including enhanced data integration, predictive modelling, resource optimization, and accelerated climate action. Below, we outline some main relevant fields where AI can support energy systems planning processes.

Data Processing and Analysis

Advanced electrical grid systems generate and utilize large volumes of data from high-frequency grid measurements such as PMUs, smart meters, weather forecasts, and economic indicators, often exceeding the capacity of traditional analytics. AI, particularly machine

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learning (ML), processes this complexity by identifying patterns and anomalies with increasing accuracy over time. It can integrate neural networks, among other statistical learning methodologies, to improve data quality and accuracy, or satellite imagery and remote sensing data to assess land-use changes affecting renewable resource availability or grid infrastructure.[6] Examples of such AI-supported processes include forecasts by the U.S. National Renewable Energy Laboratory (NREL), enhancing solar and wind predictions, and European grid operators using AI to integrate weather-dependent renewables more securely and cost-effectively.[7,8]

Predictive Modelling for Scenario Analysis

Energy markets are dynamic and influenced by a myriad of factors—policy changes, technological breakthroughs, consumer behavior shifts, and climate variability. AI-driven predictive modelling allows stakeholders to explore a wide range of "what-if" scenarios, revealing often hidden connections and patterns among diverse datasets. [9]

Optimization of Resources

AI plays a critical role in optimizing resource allocation in increasingly complex energy systems dominated by variable renewables like wind and solar. Algorithms, ranging from linear programming to advanced reinforcement learning, optimize dispatch schedules, manage battery storage, and implement dynamic pricing to shift peak loads. This improves economic efficiency and environmental performance. According to the IEA, AI integration reduces renewable curtailment, lowers emissions, and minimizes overall system costs.[10,11]

Resilience to Hazards

Energy infrastructure, such as power lines and substations, is vulnerable to hazards like severe weather, vegetation growth, and environmental degradation. Early detection is crucial for enhancing grid resilience. AI-powered tools, including satellite imagery and LiDAR remote sensing, enable operators to monitor tree growth near power lines, identify landslide-prone areas, and assess infrastructure at risk from storms.[12,13]

Real-Time Monitoring

AI has a large potential in real-time monitoring of energy systems by analyzing data streams from sensors, smart meters, and grid devices. It enables rapid detection of anomalies, such as equipment malfunctions or cyber threats, and provides insights for immediate corrective

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actions.[14] AI-powered tools also optimize system performance, balancing loads and improving energy efficiency while ensuring grid stability under dynamic conditions.

Supporting Decisions

Grid modernization and climate resilience require significant investment, with policymakers balancing costs against long-term benefits like reduced emissions and improved reliability. AI enhances cost-benefit analysis by rapidly evaluating scenarios and identifying least-cost strategies. For instance, AI models can compare preventive measures—reinforcing lines, installing sensors, enhancing cybersecurity—against recovery costs from climate disruptions.[15,16] Supported by organizations like the World Bank, AI helps policymakers prioritize high-impact interventions, advancing low-carbon and climate-resilient infrastructure while meeting sustainable development goals.

Stakeholder Engagement

Energy transitions are shaped by public opinion, community priorities, and stakeholder feedback, making it essential to ensure policies are equitable, accepted, and enduring.[17,18] AI-driven Natural Language Processing (NLP) enables policymakers to analyze social media, public comments, and surveys to gauge sentiment on proposed projects or policies.[19,20]

Open Science

The principles of Open Science imply having data and models publicly available, to enhance transparency, reproducibility, and collaboration. AI-powered tools can support this by automating metadata creation, anonymizing sensitive data, and facilitating safe data exchanges.[21]

3. The Approach of the Global Climate Hub for Energy Systems Planning

The GCH, developed under the UN Sustainable Development Solutions Network (UN SDSN), is a research-driven initiative addressing sustainability challenges, including energy transitions. It employs transdisciplinary science to provide actionable pathways for resilient and equitable energy systems by combining advanced modelling, stakeholder participation for solutions' co-development, and Open Science principles.[22]

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The GCH's approach is structured around five key and interconnected innovations, which are also used for assessments of the energy sector:

- Integrated Models: Application of advanced cross-sectoral mathematical models, analyzing the dynamics of energy, water, land, climate, etc. systems.
- Digital Infrastructure: Tools for managing big data and creating digital twins improve the connection of different models and insights.
- Socio-Economic Narratives: Tailored analyses integrate economic models and stakeholder perspectives to design sustainable, robust, and equitable policies.
- Participatory Frameworks: Stakeholders actively participate in co-design solutions along with the modelling insights, ensuring community ownership and social acceptance.
- Open Science: Publicly accessible data and tools promote transparency and global collaboration.

These innovations work together, in collaboration and complementary, in order to address any sustainability problem holistically. The work of the GCH is carried out by Nine Research Units (RUs), combining the necessary mix of diverse expertise, and is funded by competitive research grants. The nine RUs are (Fig.1):

1. Data, Platforms and Digital Applications: Manages Open Science and digital applications for big data handling, model coupling, and online platforms sharing data and models.
2. Atmospheric physics and Climatology: Develops climate scenarios, downscaled projections, and analyzes extreme events.
3. Systems Modelling: Simulates physical systems, e.g. land-water-food-biodiversity, and natural resources. Key modelling tools include the FABLE Calculator[23], the WaterReqGCH model [24], etc.
4. Energy-Emissions: Simulates energy-fuel-emissions systems of various sectors and scales, to designs decarbonization pathways, using advanced models like Balmorel [25], LEAP (Low Energy Analysis Platform) [26], and the MaritimeGCH model [27,28]. [27,28]
5. Climate, Environment and Health: Assesses health impacts of energy policies.
6. Innovation and Acceleration: Focuses on implementing sustainable solutions.
7. Socio-Economic narratives: Builds economic models, social assessments, and develops robust financial mechanisms and policy frameworks for feasible and just energy transitions.
8. Transformative Participation: Stakeholder engagement and participation to co-design solutions.

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9. Education and Training: Develops and provides education and training to communities and stakeholders to sustain the designed long-term solutions.

Each RU has its own head and they are working complementarily in an integrated way. Thus, the GCH delivers holistic solutions that are adaptable across contexts and scales, driving sustainable energy transitions globally.

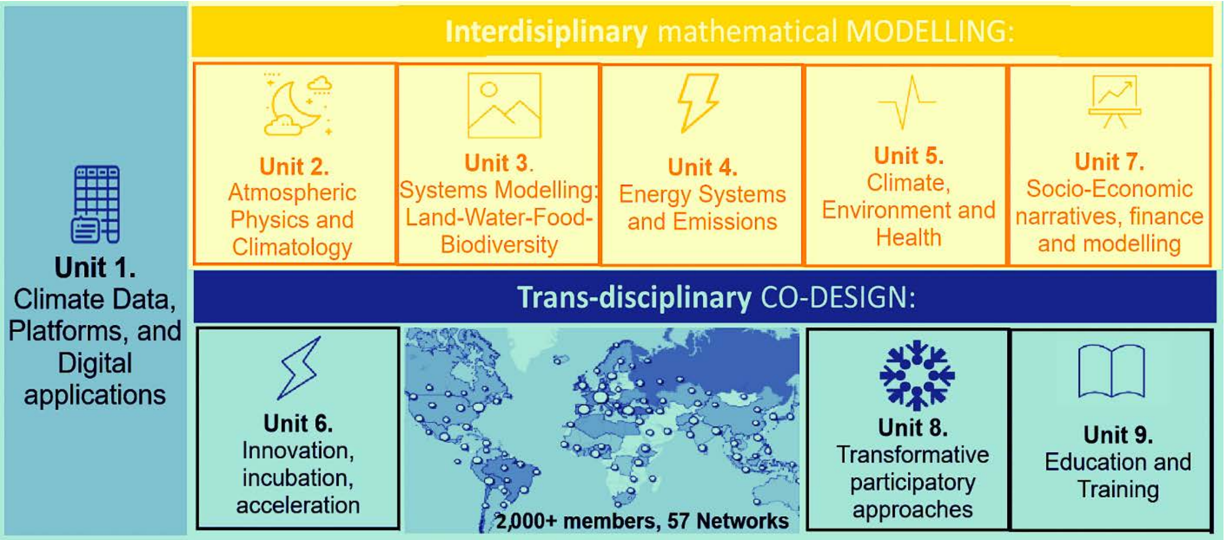

Figure 1. The nine RUs of the GCH. They work complementarily, according to the five innovations (principles) of the GCH, and they cover: the modelling (first row), and the development of solutions, pathways, their implementation, and training required to sustain them in the long run (second row).

4. The role of AI in the Global Climate Hub's Energy Systems Planning

As one can imagine, the potential fields where AI has the potential to assist modern energy systems (as outlined in section 2), can find multiple applications within the scope of GCH (section 3). Table 1 describes the role of AI in the GCH's energy systems planning approach, explaining specifically how it can support the workflow of each unit.

Table 1. The role of AI in supporting the nine RUs of the GCH for holistic and sustainable energy systems planning.

RUs Description	AI's role
Data Infrastructure (Unit 1): This unit manages data, models, and tools following Open Science principles to ensure accessibility and transparency.	AI enhances data management by automating integration of data and models, and improved visualization. The GCH builds AI-powered platforms to improve model interoperability and facilitate the development of digital twins for testing energy scenarios.
Climatology (Unit 2): This unit generates climate change scenarios downscaled to specific regions, exploring their impacts on energy demand and consumption, such as changes in heating and cooling	AI can enhance these processes by improving downscaling techniques, identifying patterns in historical weather data, and integrating diverse datasets for more accurate forecasting. AI models can also predict the frequency and

requirements. It also analyzes extreme phenomena like floods and storms to test energy system resilience.	intensity of extreme events under different climate scenarios, aiding in resilience planning.
Systems Modelling (Unit 3): This unit simulates natural and physical systems, including land use changes, urbanization, and water resource availability, which affect energy demand and renewable resource potential.	AI can optimize land-use simulations using spatial algorithms and machine learning to predict urban growth patterns or agricultural productivity. AI also improves hydrological modeling by analyzing real-time remote sensing data to better estimate water availability for hydropower and cooling.
Energy (Unit 4): Focused on energy and emissions modelling, this unit develops decarbonization pathways across economic sectors using tools like Balmorel for cross-sector coupling and LEAP for demand and policy analysis.	AI can optimize energy dispatch strategies, improve demand forecasting accuracy, and identify cost-effective decarbonization options by analyzing extensive energy and emissions datasets. Reinforcement learning can further enhance grid management and storage solutions.
Public Health (Unit 5): This unit assesses the health impacts of energy policies, focusing on emissions-related consequences and mitigation strategies.	AI supports this work by analyzing large health datasets to correlate air quality with health outcomes and model the public health benefits of different energy policy scenarios. Machine learning can also identify vulnerable populations and predict the effectiveness of mitigation strategies.
Innovation and Acceleration (Unit 6): This unit focuses on the deployment of designed solutions by mobilizing governance, technology holders, and investors.	AI accelerates innovation by identifying the most promising technologies, automating project evaluation, and analyzing market readiness. Predictive algorithms can optimize investment strategies and identify barriers to adoption for emerging energy solutions.
Economics (Unit 7): This unit develops socio-economic narratives, conducts environmental valuation, and creates financial models, to account for holistic economic assessments for a just transition.	AI can streamline economic modelling by automating cost-benefit analyses, integrating real-time market data, and simulating economic impacts of policy decisions. AI tools can also quantify non-market values, such as ecosystem services, and predict investment needs for different energy pathways.
Transformative Participation (Unit 8): This unit engages stakeholders in co-designing sustainable energy solutions, ensuring policies are equitable and widely accepted.	AI can facilitate participatory processes by using natural language processing (NLP) to analyze stakeholder feedback, identify common concerns, and simulate policy outcomes to foster informed decision-making. Virtual reality tools powered by AI are used in GHC's living labs, enhancing stakeholder workshops by creating realistic simulations of proposed energy systems.
Education (Unit 9): This unit develops training programs to build local capacity and ensure long-term sustainability of energy solutions.	AI can personalize educational content by analyzing learner data and tailoring training to specific needs. AI-driven platforms can also simulate energy system operations, offering

	interactive learning experiences for professionals.
Open Science: It is an explicit principle of the GCH, and one of its key innovations.	Opening the modelling approaches and data of the GCH democratizes access, fosters creativity, and more equitably diffuses the benefits arising from the use of AI tools supporting this, to advance the SDGs and a just transition to a low-carbon economy.

5. Concluding Remarks

AI’s implications for energy systems are profound, offering a path to work more efficiently for developing robust, resilient, and sustainable energy futures. By integrating diverse data streams, improving scenario modelling, enabling resource optimization, AI can support the work of the GCH in delivering tangible benefits, such as reduced emissions, more reliable grids, lower costs, through economically beneficial and socially acceptable solutions.

This chapter presented our vision for integrating AI into the holistic workflow of the GCH, as a powerful tool for advancing sustainable energy planning. While we are still in the process of developing and integrating AI-driven solutions, this chapter provides a preliminary framework for how AI can enhance the GCH’s approach to energy system modelling, resilience, and stakeholder engagement. Although there are no completed projects to showcase at this stage, we believe this approach holds great potential for addressing global sustainability challenges. We invite other researchers and practitioners in the field to join us in this journey of bridging new ideas and new technologies, as we work toward creating more resilient, efficient, and inclusive energy systems. We are optimistic that, through collaboration and the continuous development of models, engagement of stakeholder, and integration of new technologies (such as AI tools), the GCH will contribute to the long-term transformation of energy planning worldwide.