EnergAIze

Combining climate and weather models with physics-informed AI to tackle the energy transition - a feasibility study

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Projektbeschreibung

Der sich vollziehende Klimawandel und seine Auswirkungen auf Mensch und Infrastruktur werden immer bedrohlicher - und damit zu einer Klimakrise. Um eine Zukunft voller extremer Klimaereignisse zu verhindern, muss die Eindämmung des Klimawandels das wichtigste globale Ziel sein. In diesem Sinne hat die Europäische Union den Green Deal ins Leben gerufen und erklärt, bis 2050 klimaneutral zu sein, und unternimmt erhebliche Anstrengungen, um dieses Ziel zu erreichen. Österreich hat sich zum Ziel gesetzt, bis 2040 klimaneutral zu sein, und daher werden derzeit verschiedene Strategien für die emissionsintensivsten Sektoren entwickelt oder wurden bereits entwickelt. Einer der wichtigsten Hebel zur Erreichung der Klimaneutralität liegt in der Energiewende, weg von fossilen Brennstoffen und hin zu erneuerbaren Energien. Daher wurden große Anstrengungen unternommen, um diesen Übergang zu ermöglichen und zu fördern.
In den letzten Jahren wurden verschiedene Studien durchgeführt, die das Potenzial der erneuerbaren Energiequellen in Österreich ermitteln, wie z.B. das Potenzial von Sonnenkollektoren, Windkraftanlagen oder Wasserfahrzeugen. Diese Studien berücksichtigen die beobachteten und prognostizierten Wind-, Sonnenenergie- oder Wassermengen und den verfügbaren Platz für die erforderliche Infrastruktur und kombinieren diese Informationen, um abzuschätzen, wie viel des derzeitigen Bedarfs gedeckt werden könnte. Darüber hinaus wurden die Auswirkungen des Klimawandels auf die Verfügbarkeit erneuerbarer Energien in früheren Projekten im Hinblick auf Wettermuster eingehend untersucht, z. B. Hitzeperioden mit hohem Energiebedarf, aber geringen Windgeschwindigkeiten und hohen Temperaturen, die sich negativ auf die Effizienz von Solarzellen auswirken. Der Schwerpunkt liegt dabei auf der Gefahr, dass aufgrund der vorherrschenden Wettersysteme nicht genügend Energie zur Verfügung steht. Abgesehen von spezifischen Wettermustern können auch extreme Ereignisse, die die bestehende Infrastruktur beschädigen, ein Problem darstellen und müssen berücksichtigt werden.
Um all die oben genannten Aspekte zu berücksichtigen, sind numerische Wettervorhersagen und regionale Klimamodelle von entscheidender Bedeutung. Sie sind jedoch sehr rechenaufwändig und daher nur teilweise verfügbar. Um diese Einschränkungen zu überwinden, schlagen wir vor, einen physikalisch informierten Ansatz der künstlichen Intelligenz (KI) mit hochauflösender Klimamodellierung zu kombinieren, um hochauflösende Datensätze auf eine rechnerisch effiziente Weise zu erhalten. Das übergeordnete Ziel von energAIze ist die Entwicklung neuer physikalisch motivierter KI-Algorithmen zur Abschätzung der verfügbaren Menge an erneuerbarer Energie mit Hilfe von hochauflösenden Klima- und Wetterprojektionen in Österreich und Mitteleuropa.

Abstract

The occurring climate change and its impact on human and infrastructure is increasingly threatening – thereby becoming a climate crisis. To prevent a future full of extreme climate events, climate mitigation needs to be the number one global goal. In this sense, the European Union has set up the Green Deal, declaring to be climate neutral by 2050 and putting considerable efforts into realizing this goal.

Austria has stated to be climate neutral by 2040 and therefore various strategies concerning the most emitting sectors are currently being or have been developed. One of the major levers to achieve climate neutrality lies within energy transition, away from fossil fuel and towards renewable energy. Consequently, a lot of effort has been taken to enable and to boost this transition.

Over the past years there have been various studies defining the potential of renewable energy sources in Austria, such as defining the solar panel, wind, or watercraft potential. These studies consider the observed and predicted wind, solar energy or water and available space for the required infrastructure and combine this information to estimate how much of the current demand could be met. Further, the impact of climate change on the availability of renewable energy has been investigated in detail in previous projects with respect to weather patterns, for instance hot spells with high energy demand, yet with low wind speeds and high temperatures, which negatively impact the efficiency of solar panels. Thereby focusing on the threat of not having enough energy available due to prevailing weather systems. Apart from specific weather patterns, extreme events that damage prevailing infrastructure can pose a problem and needs to be considered.

To tackle all of the above mentioned aspects numerical weather prediction and regional climate models are crucial. However, they are computationally time consuming and therefore only partly available. To overcome these limitations, we suggest combining a physics-informed artificial intelligence (AI) approach with high-resolution climate modeling to obtain superresolution datasets in a computationally efficient way. The overall aim of energAIze is to develop new physics-informed AI algorithms for estimating the available amount of renewable energy with the help of high-resolution climate and weather projection in Austria and Central Europe.

Endberichtkurzfassung

The EnergAIze project aimed to enhance the planning, integration, and resilience of renewable energy systems by harnessing artificial intelligence (AI) to improve high-resolution climate data products and renewable energy resource assessments. Recognizing that actionable climate information is crucial for effective energy system transformation, the project explored the feasibility of physics-informed AI techniques to overcome spatial, temporal, and computational limitations of conventional climate modeling, especially within complex terrains like the Alpine region.

A central focus of the project was the development and evaluation of novel AI-based downscaling methods as well as traditional dynamical and statistical empirical models. These techniques translate coarse-resolution global climate model (GCM) outputs into locally relevant information, enabling improved resource assessments in complex terrains like the Alpine region with the AI-methods, once trained, being superior in terms of computational costs esp. for downscaling of longer periods. EnergAIze successfully demonstrated the computational efficiency of physics-informed AI downscaling, achieving multi-year output within seconds. However, the current generation of AI-based downscaling algorithms still faces challenges in reproducing fine-scale precipitation structures and extreme event intensities, especially in mountainous regions. As such, they are not yet ready to replace classical dynamical nesting approaches in numerical weather prediction or climate modeling chains.

To ensure practical relevance, EnergAIze conducted a comprehensive data inventory and gap analysis, evaluating widely used reanalysis, analysis, and climate projection datasets (e.g., ERA5, COSMO-REA6, CERRA) , identifying their strengths, limitations, and suitability for various renewable energy applications. Practical guidelines were created to assist stakeholders in selecting appropriate datasets, ensuring that renewable energy infrastructure can be better planned to withstand extreme events such as storms and prolonged periods of low wind and solar production ("Dunkelflaute"). Tailored recommendations were issued for different renewable energy use cases (wind, solar, hydro), with particular attention to Austrian and Alpine-specific requirements. The project also compiled and published a benchmark dataset containing high-resolution, energy-relevant climate parameters, now openly available via Zenodo to support future modeling, comparison, and planning efforts.

A second major innovation was the development of an AI-based method for ensemble generation and hybrid model weighting. Rather than relying on a single deterministic forecast, EnergAIze introduced a multivariate, spatio-temporal ensemble method that reflects realistic meteorological variability at different scales. This approach allows users to quantify uncertainty and generate physically plausible scenarios critical for infrastructure resilience and investment planning. Although still experimental, the method complements classical ensembles and offers a scalable alternative for actors with limited access to high-performance computing.

The project also tested the applicability of state-of-the-art AI weather prediction models (e.g., Pangu-Weather, Aurora, GraphCast) for replacing one or more downscaling steps in traditional model chains. While promising in speed and spatial refinement, these models are currently constrained by input/output requirements and limitations in reproducing all necessary variables, precluding their direct use for regional climate model initialization.

By improving the usability, speed, and resolution of climate data products, EnergAIze directly supports sustainable energy transition planning. It enables better infrastructure siting, adaptation to climate variability, and planning for compound events such as “Dunkelflaute” (low wind and solar production periods). The project’s AI-enhanced workflows require up to 100 times less computational resources than conventional dynamical modeling, contributing to environmentally sustainable data generation. Furthermore, the shared datasets and best-practice guides facilitate broader access, knowledge transfer, and scientific reproducibility.

Economically, the project's outcomes help minimize investment risks and infrastructure vulnerability, fostering a more resilient energy sector. Socially, the improved reliability of renewable energy systems contributes to energy security, particularly in regions vulnerable to climate extremes. Overall, the EnergAIze project successfully demonstrated how AI and advanced modeling techniques could substantially contribute to sustainable development and climate resilience, highlighting both achievements and areas for ongoing innovation.

Projektkoordinator

- AIT Austrian Institute of Technology GmbH

Projektpartner

- GeoSphere Austria - Bundesanstalt für Geologie, Geophysik, Klimatologie und Meteorologie