Journal of Renewable and Sustainable Energy

PERSPECTIVE | DECEMBER 04 2024

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*J. Renewable Sustainable Energy* 16, 062301 (2024)
https://doi.org/10.1063/5.0231754

Journal of Renewable and Sustainable Energy PERSPECTIVE pubs.aip.org/aip/rse

# Weather as a driver of the energy transition – present and emerging perspectives of energy meteorology

Cite as: J. Renewable Sustainable Energy **16**, 062301 (2024); doi: 10.1063/5.0231754
Submitted: 2 August 2024 · Accepted: 1 November 2024 ·
Published Online: 4 December 2024

View Online Export Citation CrossMark

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## ABSTRACT

Energy meteorology is an applied research field of meteorology that focuses on the study and prediction of weather conditions and events that affect energy production and use. This field has become increasingly important as the energy industry has become more dependent on weather conditions, especially in the areas of renewable energy sources such as wind energy, solar energy, and hydropower. The following paper has been written by experts of the Committee on Energy Meteorology of the German Meteorological Society summarizing their more than 30 years of experience and lessons learnt. It gives an overview of activities in energy meteorology that are already essential for the transformation of energy systems to systems with high shares of renewable energies. Building on this, the experts have created a vision of future topics that describe the future research landscape of energy meteorology. The authors explain that work in energy meteorology in recent years has primarily been concerned with the physically based modeling of wind and solar power generation and the development of short-term forecasting systems. In future years, a significant expansion of work in the areas of energy system modeling, digitalization, and climate change is expected. This includes the detailed consideration of regionally specified spatiotemporal variability for system design, the integration of artificial intelligence skills, the development of weather-related consumption based on smart meters, and the mapping of the effects of climate change on the energy system in planning and operating processes.



## INTRODUCTION

Many energy systems worldwide will primarily rely on renewable and weather-dependent — energy technologies. Energy meteorology is an applied research field, which facilitates the operation of such energy systems. Energy meteorology sits at the interface of many disciplines that are related to energy such as meteorology, physics, ecology, engineering, computer science, and economics. The collaboration between these fields allows us to understand the interconnected nature of the energy system. Energy meteorology is the enabler of a sustainable, reliable, and economical energy system.

## STATE-OF-THE-ART IN ENERGY METEOROLOGY

Energy meteorology is a mature field that has already contributed substantially to different fields in green energy transition. The following is an overview of the main topics of energy meteorology to date.

There are many different established tools to model the production of solar and wind power plants at different sites in great detail. This detail is the result of R&D in advanced measurement technologies and advanced modeling techniques; many of which have been commercialized. These models use different methods to convert meteorological parameters such as solar irradiance and wind speed into power production with great accuracy using technology-specific models. The combination of technological expertise and meteorology is of great importance here. Meteorological models and remote sensing systems can provide relevant parameters such as solar irradiance or solar power production for specific sites or aggregated over an electric balancing area.

Weather forecasting and reanalysis data from several national weather services are available for energy system analysis and forecasting. Forecasts from numerical weather prediction are successfully combined with short-term forecasts from satellite and ground-based observation systems to enhance forecast quality. In the last few years, a major focus lies on the utilization of probabilistic forecasting to support probabilistic and risk-based analysis and decision-making in energy systems.

Operational weather services have adapted their forecasts to the requirements of the energy system operators by increasing temporal resolution and providing more types of parameters. There are many meteorological service providers and specialized consulting companies who offer meteorological data related to energy systems. Energy system operators, traders, and distribution system operators increasingly integrate products from these providers into their operations. A growing number of universities offer courses and degrees in energy meteorology and integrate the energy meteorological content into education and practical training.

## PERSPECTIVES OF ENERGY METEOROLOGY

The developers of the field of energy meteorology have always envisioned an energy system with high renewable penetration. This vision is now being realized at a breathtaking pace. The committee on energy meteorology in the German Meteorological Society (DMG) is a forum for the collaboration between researchers and practitioners from Austria, Germany, and Switzerland. The expert group relies on a more than 30 years of experience in the energy transition in Central Europe. Through this collaboration, the committee has developed the following priorities and challenges for the future research in energy meteorology. In this Perspective paper, the committee would like to support the world-wide energy transition by bringing these thoughts into international discussion. Such international discussions are typically organized within the International Energy Agency (IEA) expert task groups or the World Meteorological Organization (WMO).

Improved data and digitalization promote the modeling of complex processes, which can reduce the over-reliance on expensive hardware for grid control. Physics-based and AI-based methods as well as large datasets exist. However, the large potential of energy informatics and digitalization has yet to be fully embraced by the energy industry. For example, the growing importance of decentralized operation of distribution system could greatly benefit from digitalization. The large number of weather-dependent generators and loads requires scalable, standardized, and automated processes that could greatly benefit from energy meteorological information.

AI based modeling shows manifold advantages for different weather dependent use cases in the energy sector based on large model and measurement datasets. Especially, shortest-term forecast systems will profit from modern AI technologies.

Currently, there is a lack of dialogue between meteorologists and the energy community. The energy community consists of a large variety of different actors, e.g. from industries and acting as project developers and operators of grids and generation. Furthermore, energy users as well as power plant and storage investors, or all kinds of R&D institutions are part of the community. The energy community increasingly relies on AI for modeling and control. While AI leverages energy meteorological data, the energy community often lacks the domain knowledge for advanced quality control, preprocessing, and further data development. The lack of knowledge exchange presents a barrier to innovation and technology transfer.

In several countries, government officials who regulate and fund energy meteorology are spread over several departments and ministries. This leads to communication challenges, and interdisciplinary activities in energy meteorology then often fall through the cracks. On the other hand, the European Union and European Space Agency, for instance, are better set up to promote interdisciplinary research on energy meteorology.

There is a need to better integrate university courses and programs in meteorology, physics, engineering, computer science, and economics. Especially, programs in control systems and power systems and courses such as renewable power plant design and distribution system design and operation should integrate energy meteorology content into their programs. Likewise, meteorology programs should teach about the basics of energy systems to enable students to understand the requirements for meteorological data and to contribute properly to decision processes in the industry.

There are many research results, e.g., on reducing costs of energy by optimizing energy storage systems or the spatiotemporal complementarity of renewable generation due to weather. These research results are very relevant for an optimization of electricity grid operations. More systematic knowledge transfer of these research results to governments and the private sector is needed.

Processes for weather-dependent capacity assumptions (dynamic line rating) and operations of transmission lines have to be tested and moved into operation. Improved operation of transmission lines is critical to reduce congestion of existing lines and avoid the construction of new transmission lines.

Improved methods of load forecasting and demand response should also be transferred to operators. Consumer and load behavior is affecting the load curve through electric vehicles, heat pumps, and energy storage. The joint operation of these systems with renewable energy requires efficient and coupled forecasting and modeling tools.

Reducing energy consumption in the building sector is a centerpiece of the energy transition. Modeling the effects of the meteorology on energy consumption of buildings is a hot topic. Building energy management systems for heating and cooling that integrate predictive information are starting to be commercialized, but they require continued improvements. The dynamic behavior of buildings, their users, and the effects of distributed optimization of loads on electricity, heat, and gas networks should be considered.

In a world with high penetrations of distributed energy generation, the accuracy and spatial and temporal resolution of meteorological models and earth observation systems require further improvement to enable accurate local control. For solar radiation, the Meteosat Third Generation (MTG) satellite system will enable these improvements as well as the new generation of HIMAWARI and GOES satellites. For wind speed — especially for distant offshore wind power plants as well as wind power plants at 500 m nacelle heights — LiDAR technologies could be applied.

The design of renewable power plants should be adapted to the climatic conditions and their changes in response to global warming. Of particular concern are extreme conditions during heat and cold waves as well as variability, e.g., due to atmospheric turbulence, soiling, or the spectral composition of solar radiation. The impact of largely extended wind energy usage on local and regional climate needs to be monitored for environmental as well as economic reasons, e.g., between neighboring wind parks.

There is a renewed interest in the performance of materials and technologies for energy systems in different climate zones and in regions with different spatiotemporal meteorological variability. In specific, do different energy storage and power-to-X technologies perform differently in different regions?

Seasonal forecasts of up to 6 months ahead are of growing importance especially to identify periods of prolonged low solar radiation, winds (dunkelflaute), or water levels. Early warnings of such conditions will contribute to reducing risks and costs for reliable energy supply.

So far climate models have focused primarily on temperature, wind speed in 10 m height, and precipitation. The modeling of clouds, solar radiation, and wind speeds in heights of more than 100 m in climate models needs to be further improved. Climate models should be evaluated from the perspective of their fitness for modeling energy systems. Moreover, standards for pre-processing and utilization of climate model data for energy system modeling are needed. These evaluations and standards would build the confidence for energy systems modelers to leverage "big data" from climate models.

There are several open questions as to how energy systems will need to adapt to climate change. How will solar and wind resources change? How will conventional generators be affected? How will the cooling demand change? How will the global generation distribution change? How will change in spatiotemporal generation affect European transmission lines? Which infrastructure needs to be adapted to climate change and how? How does climate change affect the design of new infrastructure?

## CONCLUSION

After more than 30 years of R&D, energy meteorology has established itself in recent years as an independent field of research. Within energy systems based on high shares of weather-dependent energy sources models for determining the feed-in of such volatile energy sources are indispensable for planning and operational management processes. However, a wide range of issues and challenges are also expected in the future, for which the expertise of energy meteorology will be required. In summary, the following key aspects can be mentioned as lessons learnt, which will have an overriding relevance in energy meteorology in the future:

- Energy meteorology will have to rapidly expand its interdisciplinarity, in order to be able to answer increasingly important weather-related questions. On the one hand, this includes fundamental expertise in the areas of digitalization, AI, and climate research, but, on the other hand, also application-specific knowledge that extends across the electricity, heating, and transport sectors, including energy storage and sector coupling technologies.
- The aforementioned aspect puts emphasis on the need for cross-domain thinking. This includes not only a general understanding but also —and especially in the context of advancing digitalization — the ability to correctly interpret, process, and make use of new and unknown data.
- Deterministic short-term forecasts of wind and solar are already established. The upcoming need lies primarily in the development of (1) small-scale, cross-sectoral forecasts of consumption and flexible services, (2) longer-term to seasonal forecasts for issues of security of supply, and (3) fundamental probabilistic modeling to estimate uncertainties and extreme scenarios.

There are many open questions. While some answers exist, there are and will be additional challenges in modern energy meteorology. Increased collaboration from all parties in the energy system is an urgent necessity. Energy meteorology will remain a critical enabler of the success of the energy transition worldwide.

## ACKNOWLEDGMENTS

We thank all members of the Committee on Energy Meteorology of the German Meteorology Society for the provision of valuable feedback.

## AUTHOR DECLARATIONS

### Conflict of Interest

The authors have no conflicts to disclose.

### Author Contributions

**Marion Schroedter-Homscheidt:** Conceptualization (equal); Writing – original draft (lead). **Jan Dobschinski:** Writing – original draft (supporting); Writing – review & editing (equal). **Stefan Emeis:** Writing – review & editing (equal). **Detlev Heinemann:** Writing – review & editing (equal). **Stefanie Meilinger:** Writing – review & editing (equal).

## DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.