LETTER

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Extreme impacts on electric power systems from non-catastrophic meteorological conditions

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Dear Editor,

The rising penetration of renewables and meteorology-sensitive loads is making electric power systems more vulnerable to meteorology. Diverse weather conditions can extensively influence energy generation, demand, and transmission systems.

Both extreme weather events and non-catastrophic meteorology influence the operation of the bulk electric power system. On one hand, extreme weather events such as heatwaves and typhoons not only can exacerbate the imbalance between energy supply and demand, triggering extreme power outages, but they can also increase the failure probability of transmission lines, contributing to accidents such as tower toppling and line breaking. On the other hand, non-catastrophic meteorology can influence the electric power systems. Non-catastrophic meteorology refers to meteorological conditions that do not cause a direct catastrophic impact. However, it can create an imbalance between power sources and load within electric power systems. For example, in Xi'an, China, a city typically experiencing drought conditions, solar generation was reduced by 92.5 % due to a series of rainy days in 2016.

Researchers have explored vulnerability assessment and resilience enhancement strategies, which aim to manage and control meteorological risks to electric power systems from extreme weather events. [1] However, they have yet to fully address a critical question: How does non-catastrophic meteorology impact electric power systems? Furthermore, what strategies can effectively prevent and control the associated risks? This letter aims to answer these questions. It examines the specific impacts of non-catastrophic meteorology on electric power systems. In addition, it outlines the future directions for managing these risks.

THE IMPACTS OF NON-CATASTROPHIC METEOROLOGY ON ELECTRIC POWER SYSTEMS

We categorise non-catastrophic meteorology into three aspects: the accumulation of continuous non-catastrophic meteorology, the abrupt changes in meteorological elements, and the coupling of meteorological elements. This letter offers insights into the impacts of these aspects (Figure 1).

The accumulation of continuous non-catastrophic meteorology

Unlike abrupt and intense weather phenomena, continuous non-catastrophic meteorological conditions are characterised by persistence and moderateness. Compared to extreme weather events, continuous non-catastrophic meteorology is more susceptible to having a cumulative effect on the electrical power and energy balance of electrical power systems. For example, successive days of high temperatures ranging from 28 ℃ to 38 ℃ contribute to an abnormal increase in air-conditioning energy consumption. In 2015, Beijing, China, a total of 10.18 % of the summer electric air-conditioning energy consumption was attributed to the cumulative effect.

The abrupt changes in meteorological elements

Abrupt changes in meteorological elements are marked by rapid transitions without escalating to the level of disasters such as hurricanes. Examples include the rapid fluctuations in solar irradiance caused by cloud movement, which can change more than 300 W/m^2 within 0.1 s.

Abrupt changes in meteorological elements also impact renewables and transmission lines. For example, the quick movement of clouds can affect PV outputs, the degree of PV power fluctuations, and PV mismatch losses. The sustained and rapid changes in temperature often lead to extreme wind power ramping events. Moreover, convective weather develops quickly, which can cause serious damage to transmission lines. For example, on the windward slope, the wind promotes the warm and humid airflow to climb along the hillside to form a terrain thunderstorm, which makes transmission lines exposed to lightning threat; under the humid microclimate conditions, it is easy to form a thermal thunderstorm in the farmland pond, increasing the lightning shielding failures of transmission lines.

The coupling of meteorological elements

The coupling of multiple meteorological elements refers to the combined effects of meteorological factors. The combined impacts of multiple meteorological elements are often amplified.[2] These effects are interconnected with the whole electric energy system.

On the demand side, for example, combining the urban heat island effect with a humid environment exacerbates heat stress on urban residents, resulting in high air-conditioning energy consumption. In contrast, a dry environment may alleviate this condition because the human body may better endure high temperatures at lower humidity through perspiration.[3,4]

On the supply side, if the coupling effects are neglected, the benefits of air pollution mitigation for solar production potential may be overvalued.[5] From 2010 to 2019, controlling air pollution made solar production potential increase by 2.40 % in Central East China. However, the actual production increase was 1.24 %, primarily due to a 0.96 % counteracting impact caused by the heightened cloud-covering level. In addition, persistently high temperatures coupled with insufficient rainfall intensify the scarcity of runoff water resources, influencing hydropower generation and the cooling water supply of thermal power generation.

In integrating systems, compound events can exaggerate the imbalance between power supply and demand. For example, the late period of the cold waves is cold and windless. Despite an increase in power demand, wind power output decreases. During the daytime-nighttime hot events, solar power output decreases in the evening, while power demand continues to rise.

OUTLOOK

With the rising penetration of meteorology-sensitive power sources and loads, electric power systems face more meteorological risks: The impacts of non-catastrophic meteorology on electric power systems are intensifying and posing a negative effect on energy sustainability and security. Furthermore, smart grid is gradually translating into the cyber-physical-social system in energy. Non-catastrophic meteorology influences the social behaviors of electric vehicles and distributed energy resources, affecting the hierarchical energy management of electrical networks. Continuous non-catastrophic meteorology mainly has a cumulative effect on meteorology-sensitive loads and behaviors of residents. Renewable energy generation is greatly influenced by short-term meteorological fluctuations: Cloud coverings affect solar power generation capacity, while sharp fluctuations in temperature and rapid changes in wind speed are associated with wind power generation. Compared with single meteorology, compound meteorology brings superposition and offset impacts, which are most likely to cause integrating system risks. Based on the three perspectives discussed here, we prioritize future research avenues: (1) map the non-catastrophic meteorology database for electric power systems; (2) conduct electric power systems' risk assessment and management under non-catastrophic meteorology scenarios.

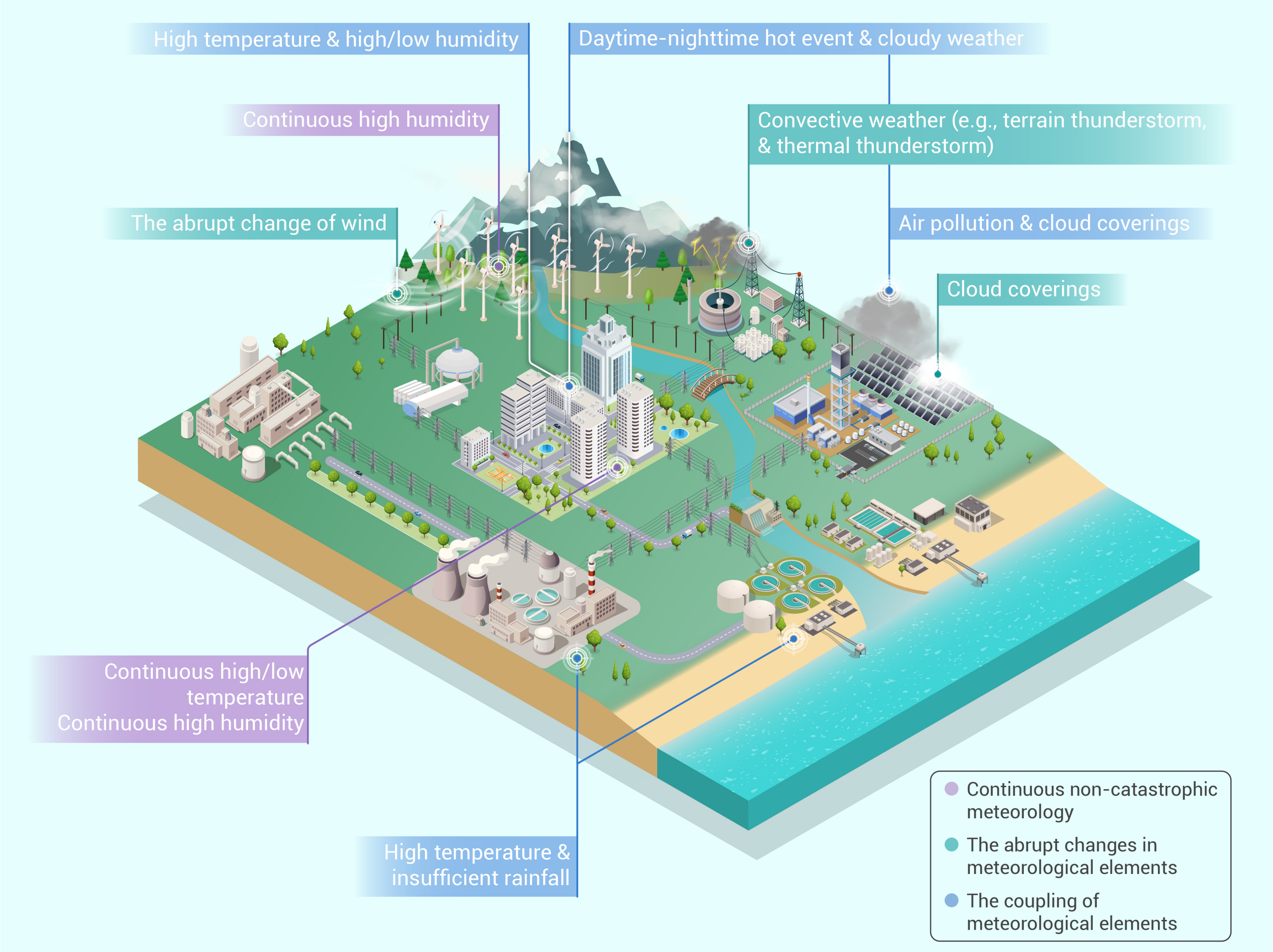

Figure 1. The illustration of non-catastrophic meteorology Three types of non-catastrophic meteorology that can affect the electric power systems are illustrated: continuous non-catastrophic meteorology, which affects wind power generation and load; the abrupt changes in meteorological elements, influencing the wind power generation, solar power generation, and transmission lines; and the coupling meteorology, which impacts load, solar power generation, and integrating systems.

Map the non-catastrophic meteorology database for electric power systems

The impacts of non-catastrophic meteorology present new challenges to electric power systems' meteorological data requirements. Nowadays, the meteorology sector mainly provides forecasting and monitoring data for extreme weather events, which cannot meet the data requirements of the energy sector. The lack of complete information will influence the utilization of renewable energy and the operation of electric power systems. Consequently, it is necessary to construct a non-catastrophic meteorology database for electric power systems.

There are two perspectives to mapping non-catastrophic meteorological data for electric power systems. First, the temporal and spatial resolution of meteorological data should be improved. Nowadays, the temporal-spatial resolution of meteorological databases still needs to be better calibrated for electric power systems. For example, abrupt meteorological changes have an impact on electric power systems at the minute and second levels. Rapid changes in meteorological characteristics are outside the scope of geostationary satellites and reanalysis datasets. Approaches such as remote sensing and temporal dynamic satellite observations may facilitate further increases in the temporal-spatial resolution of non-catastrophic meteorology.[6] Second, the evolution process of non-catastrophic meteorology should be forecasted. NWP methods such as the ECMWF Integrated Forecasting System (IFS) are accurate prediction systems with a stable improvement in resolution. However, the computational cost of NWP increases almost twelve times if the resolution is doubled. Recently, artificial intelligence methods such as FourCastNet and Pangu-Weather have shown potential for accelerating high-resolution weather forecasting.[7] For example, FourCastNet with a sub-km resolution can exceed six orders of magnitude in speed compared to the sub-km resolution of NWP.

Risk assessment and management of non-catastrophic meteorology

The dynamic mechanisms of extreme weather events such as hurricanes and storms have been studied. However, there is a noticeable gap in considering the risks associated with non-catastrophic meteorology scenarios. To improve the resilience of electric power systems, future studies should focus on reliability assessment and enhancement of electric power systems under the influence of non-catastrophic meteorology.

The scarce samples for non-catastrophic meteorology scenarios pose challenges to the precise modeling of meteorology-related random variables utilising observational records or historical simulations. Especially, the required samples for compound meteorological events are much larger than those needed for analyses of univariate meteorological events.[8] Further representation of non-catastrophic meteorology-related uncertainties is possible thanks to approaches including probabilistic modeling of meteorological processes, sample migration and generation, and making the most of inadequate data sets. Constructing the probabilistic meteorological factors through shifting and adjusting the probability distribution can reduce the dependence of the characterization process on the number of samples. Obtaining the data based on sample migration (e.g., TrAdaBoost) and generation model (e.g., variational autoencoder and generative adversarial network), can realize the data enhancement. Also, strategies that unite statistical algorithms and machine learning methods have been developed. They aim to discover extreme events with less data. For example, combining Bayesian experimental design with deep neural operators can reduce the number of input samples required to characterize extreme phenomena. It effectively represents the scenarios and probability of extreme events.[9]

The risks to the electric power systems from non-catastrophic meteorology may be misrepresented if the assessment fails to incorporate the combined supply and demand impacts of non-catastrophic meteorology. Especially, the integration of electric vehicles and distributed renewables has improved the connection among source, grid, load, and storage in the distribution network, challenging the reliability assessment of non-catastrophic meteorological risk.[10] However, the order of the electric power system model grows exponentially with increased uncertainty, which affects the efficiency of operational reliability evaluation. Two efficiency-enhancement approaches are state reduction and fast analysis. The combination of deep learning algorithms and the Internet of Things (IoT) can be adopted. Deep reinforcement learning-enabled approaches outperform mixed integer linear programming methods by two or three orders of magnitude in terms of computational performance. The application of IoT technology makes remote control and real-time monitoring possible.

Further, innovative optimization techniques such as ant lion optimizer (ALO), grasshopper optimizer (GHO), elephant herding optimizer (EHO), and whale optimization (WO) can be utilized to manage non-catastrophic meteorological risk in electric power systems. These optimization techniques have strong global search capability and excellent adaptability, which can adapt to changing weather conditions. They can be applied to cloud-edge-device collaboration, energy dispatch optimization, reserve capacity configuration, and equipment maintenance plans, enhancing the reliability of electric power systems.

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DECLARATION OF INTERESTS

The authors declare no competing interests.