LETTER

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Weather-Driven Charging Behaviors Amplify Peak Loads In EV-Integrated Grids

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Dear Editor,

Under the context of climate change, extreme weather is reshaping the intensity and distribution characteristics of urban electric vehicle (EV) charging loads. Based on the analysis of empirical data from 58 cities in China, this paper finds that meteorological factors systematically drive the non-linear evolution of total vehicle charging volume, charging behavior, and power choices. Empirical results demonstrate that charging demand significantly increases at low temperatures, while high-temperature environments tend to induce EV owners to switch to high-power charging modes. In the future, the normalization of extreme heat, cold, and heavy precipitation induced by climate change,[1] superimposed with the explosive growth of EV ownership and ultra-fast charging stations, will easily trigger highly concentrated and instantaneous bursts of massive high-power fast charging demand within specific spatio-temporal windows triggered by meteorological conditions, thereby significantly aggravating the peak pressure and scheduling control difficulties of urban power grids.

INTRODUCTION

The world is accelerating the low-carbon transition of the transportation sector through the large-scale adoption of electric vehicles. However, traditional energy scheduling schemes rely heavily on static historical load profiles, severely underestimating the impact of EV owners' charging behavior on the power grid under dynamic weather intervention. Weather fluctuations not only reconstruct residents' travel networks and risk-aversion decisions at a subjective level, but also directly restrict the vehicle's own electrical energy conversion efficiency, thereby exerting tremendous composite pressure on the power system across the dual dimensions of power and energy. Therefore, the reshaping effect of weather on charging power and volume has become an indispensable core variable in the resilience assessment of future modern power systems. To drive the transformation of power systems from traditional passive defense to active meteorological regulation, disciplinary barriers must be broken to implement synchronous innovations across multiple dimensions, including meteorological scenario forecasting, behavioral psychological decision modeling, and active load pre-control on the distribution network side.

Current research on the grid impact response of EV charging and energy evolution trends has accumulated rich achievements, which can be primarily summarized into the following three dimensions:

Effects of weather on travel behavior and charging behavior

Meteorology is a core variable driving the cross-system coupling between urban transportation and power grids. Existing studies indicate that weather changes essentially reshape users' subjective charging decisions by reconstructing residents' travel networks. Meteorological conditions such as precipitation, heatwaves, and cold spells significantly alter the structure of residents' trip chains, inducing a shift from slow-mode transportation to motorized travel, thereby reconstructing the spatio-temporal flow characteristics of vehicles.[2] At the grid level, existing literature tends to quantitatively demonstrate the energy consumption changes brought by ambient temperature variations to on-board air conditioning and thermal management systems, using this to analyze the spatio-temporal reshaping patterns of weather factors on total urban charging volume and grid base loads.

Vehicle energy consumption and climate response mechanisms

Regarding the vehicle's own operating energy consumption, the inhibitory effect of weather conditions on the inherent electrical energy conversion efficiency of EVs has been widely demonstrated. Quantitative research shows that the powertrain and thermal management systems are the most energy-consuming parts of an EV. Under extreme cold or hot conditions, the extra electricity consumption brought by the high-load operation of the air conditioning system can cause the actual driving range of EVs to plummet by up to 50%. Meanwhile, during long-distance trips exceeding 200 kilometers, EVs exhibit significantly higher sensitivity to weather conditions than traditional internal combustion engine vehicles.[3] When the ambient temperature deviates from the optimal operating window of the battery (such as below 0°C or above 25°C), the vehicle's electrical energy conversion efficiency fluctuates drastically, fundamentally altering the user's charging cycle and charging intensity.

Instantaneous impacts of spatio-temporal distribution changes in EV charging on the grid

With the iterative upgrading of charging technologies, the impact of charging loads on the grid is shifting from the continuous, low-amplitude superposition of early slow charging to the instantaneous peak shock of high-power ultra-fast charging.[4] In the dimension of spatio-temporal distribution, the concentration of users' charging decisions within specific time windows and at key spatial nodes triggers the localized, large-scale emergence of charging loads. Because this collective charging behavior is accompanied by strong travel rigidity and temporal clustering, charging demands highly coordinate and overlap in both time and space domains. Sharp fluctuations in instantaneous high-power demand can easily cause severe sudden physical overload stress and voltage instability risks on the distribution network side, constituting the most direct threat to the steady-state operation and physical security of modern urban power grids.

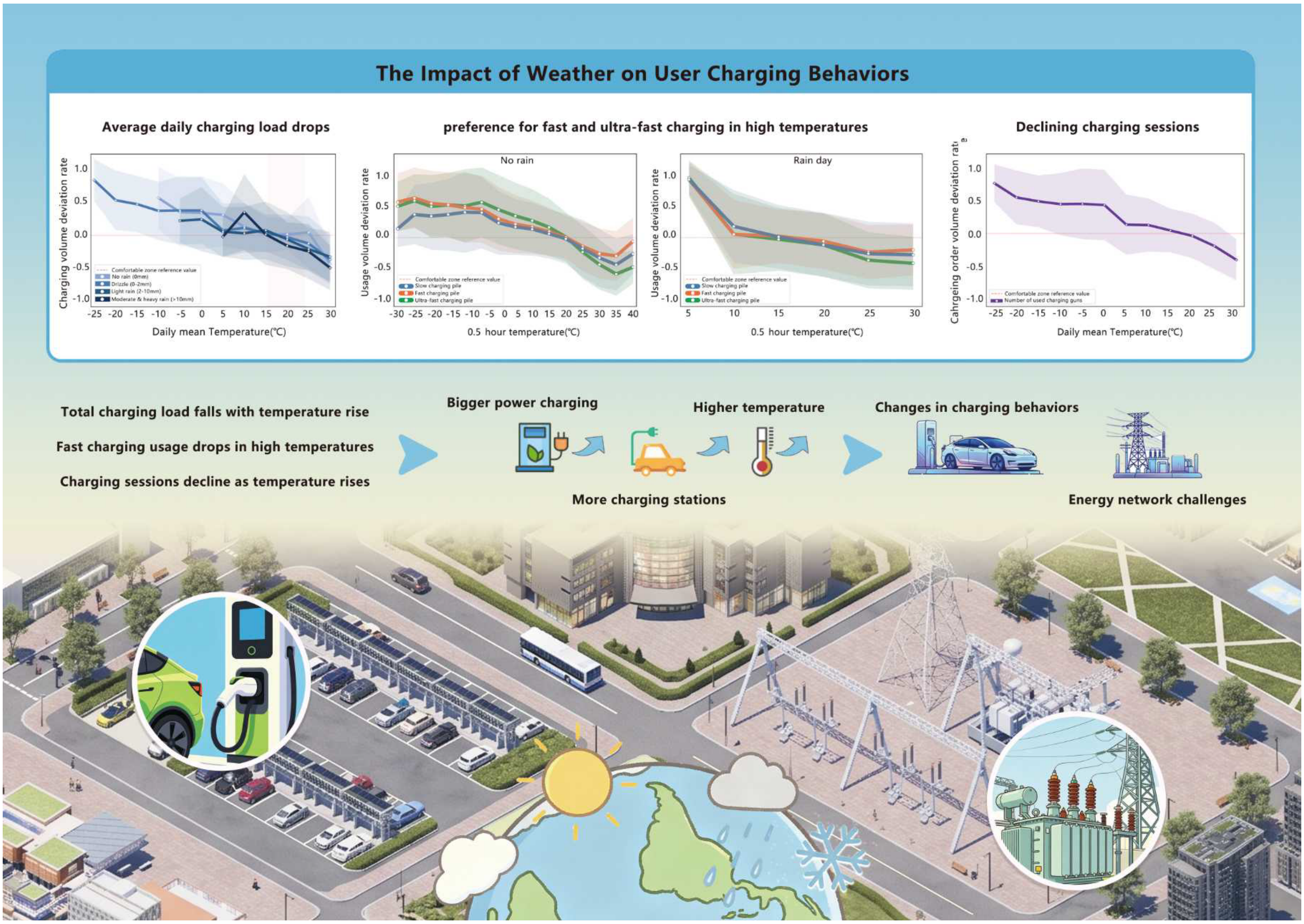

Figure 1. The impact of weather on user charging behaviors.

CORE FINDINGS

The analysis results based on empirical charging data from 58 cities in this paper demonstrate that weather factors can significantly alter EV charging demand and charging power choices. In terms of total volume and frequency, compared to the baseline condition of a daily average temperature of 21°C and 0 mm of precipitation, when the daily average temperature is -15°C, the daily average charging volume significantly increases by 20.6%, whereas at 30°C, the daily average charging volume decreases by 65.0%. In the dimension of charging power selection, under rain-free scenarios, the utilization rate of each charger type generally shows a fluctuating decline as the temperature rises. However, during extreme high-temperature weather, car owners tend to select high-power charging methods such as fast charging and ultra-fast charging. Nationwide charging data reveal that at a normal temperature of 21°C, the utilization shares of slow, fast, and ultra-fast charging are 36.3%, 27.2%, and 36.5%, respectively; under the low-temperature condition of -30°C, the utilization shares shift to 50.9%, 45.5%, and 3.2%, respectively; while under the high-temperature condition of 38°C, a distinct upward turn is observed, with shares evolving to 7.4%, 59.8%, and 32.8%, which objectively mirrors the strong sensitivity of users to charging efficiency and time costs in high-temperature environments. In the dimension of precipitation impacts, data results show that precipitation exerts no significant interference on the hourly charging frequency, but exhibits a weak inhibitory effect on the total daily charging volume.

The above phenomena indicate that the impact of weather on charging behavior stems not only from the inherent physical energy consumption changes of vehicles, but also indirectly acts on charging demand by altering users' travel decisions and charging strategies. In low-temperature environments, the surge in on-board heating demand and the degradation of battery efficiency led to a shortened actual driving range, which consequently heightens users' range anxiety, behaviorally driving up both charging frequency and total charging volume. In high-temperature environments, car owners pay closer attention to time costs and environmental comfort, tending to shorten their outdoor stay during charging, thus exhibiting a significant preference for high-power charging methods such as fast and ultra-fast charging. Under rainy weather, emergency and temporary centralized charging behaviors increase, causing charging demand to display greater dispersion and volatility.

DISCUSSION

According to CMIP6 future climate scenario projections, the frequency and intensity of extreme cold spells, heatwaves, and heavy precipitation events show an upward trend.[5] Concurrently, urban transportation and energy systems are witnessing explosive growth in EV ownership, the scale of public charging stations, and high-power ultra-fast charging infrastructure. More severe meteorological fluctuations will trigger the range and time anxiety of the car owner population more frequently and extensively, thereby inducing the charging load to shift toward ultra-high-power nodes on the demand side. Once this instantaneous electricity peak—deeply catalyzed by abrupt weather changes and spontaneously initiated by the subjective risk-aversion choices of massive vehicle fleets—resonates in the same direction as the urban base electricity load, it will constitute an unavoidable and most destructive system-level challenge in future system resilience assessments.

CONCLUSION

Based on large-scale empirical data from 58 Chinese cities, this paper systematically reveals the non-linear reshaping mechanism of meteorological conditions on EV charging behavior. The study indicates that the spatio-temporal evolution of charging loads under the influence of weather is not only constrained by the decay of the vehicle's underlying physical energy efficiency, but is fundamentally and more deeply driven by the shift toward high-power, high-frequency charging decisions under users' risk-aversion psychology. Facing the future normalization of extreme climate and the explosive expansion of ultra-fast charging networks, localized severe load fluctuations and instantaneous ultra-high-power shocks triggered by meteorological fluctuations will become systemic normalcies. This finding portends that future distribution networks must break through the traditional static scheduling framework and evolve toward active defense and resilient scheduling that integrates meteorology-behavior-grid thereby confidently addressing climate uncertainty challenges in the process of the deep decarbonization of electrified transportation.[6]

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DECLARATION OF INTERESTS

The authors declare no competing interests.