Undergraduate Research Towards An Integrated Modeling Framework For Electric Grid Planning

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***Abstract*—This paper aims to develop an integrated modeling framework that combines generation, load, weather, and renewable sources for comprehensive electric grid analysis and simulations. Such a framework can support better forecasting accuracy and enable more accurate long-term grid planning, ultimately enhancing grid resilience and ensuring sustainable growth of the grid. This is motivated by a rise in load demand that has become increasingly unpredictable due to new types of loads such as AI datacenters, Bitcoin mining, and Electric Vehicles (EV). These loads reduce the effectiveness of traditional load forecasting methods, suggesting the development of more flexible and diverse forecasting models that consider variability under different weather conditions. Simultaneously, many industries are adopting sustainability policies for environmental benefits and lower costs by integrating renewable energy sources like wind and solar, which are inherently weather-dependent and difficult to forecast. These trends highlight the growing importance of incorporating weather analysis into both load and generation forecasting to maintain grid stability.**

***Index Terms*—Renewable Energy, Load Demand, Weather Analysis, Comprehensive Simulation Model**

I. Introduction and Motivation

Electrification is widely regarded as the most significant engineering advancement of the 20th century, fundamentally shaping modern life [1]. Electricity powers everything from household appliances to large-scale manufacturing machinery, driving rapid technological advancements and fueling the Fourth Industrial Revolution. However, this rapid progress has brought considerable environmental challenges, primarily due to the heavy dependence on fossil fuels such as natural gas and coal. Climate change, largely driven by carbon emissions from these traditional energy sources, represents the most urgent of these challenges.

In response, organizations worldwide are adopting eco-friendly policies aimed at transitioning from fossil fuels to renewable energy sources. Solar, wind, and other renewable resources provide promising alternatives, significantly reducing carbon emissions. However, renewable energy generation depends heavily on weather conditions. For instance, solar power decreases on cloudy days, and wind power is viable only when wind speeds fall within optimal ranges. This variability introduces unique challenges for integrating renewable energy into the power grid. Consequently, analyzing power grids under various weather conditions is essential for improving forecasts of generation output and ensuring grid stability. This analysis supports the development of a sustainable energy system that meets rising power demands while reducing carbon emissions and mitigating climate change impacts.

Renewable energy continues to gain importance across the United States, becoming a crucial component of power generation [3]. For instance, on February 3, 2025, at 10:29 AM, solar and wind contributed 60 percent of total power generation within the Electric Reliability Council of Texas (ERCOT), highlighting the substantial role of renewable energy in contemporary power grids [4]. As renewable energy's share grows, traditional resource adequacy studies must account for resource variability to ensure grid reliability and resilience.

Simultaneously, the adoption of Electric Vehicles (EVs) is rapidly increasing, leading to further growth in electricity demand. Therefore, power system management and planning must prioritize grid reliability and resilience, particularly during extreme weather events. Grid reliability comprises two main components: adequacy—the system's ability to consistently meet demand despite outages—and operational reliability, which refers to the grid's capacity to manage sudden disturbances without blackouts or equipment damage. Resilience involves the grid's ability to cope with and quickly recover from outages, minimizing impact and preparing for future challenges [5].

Accurate weather analysis across diverse scenarios is crucial for maintaining a dependable power system, effectively responding to outages, and preventing future disruptions. Recent efforts to improve weather forecasting accuracy include introducing the new "pww" file format [6] and developing the Power Flow Weather (PFW) model [7].

This paper presents an integrated modeling framework designed to simulate and analyze power grid performance, emphasizing wind and solar energy generation. The research leverages Energy Information Administration (EIA) 860 data to create case files and employs the PFW model to simulate various weather scenarios using the PowerWorld software tool, specifically applied to the Texas grid. By evaluating renewable power generation potential under different weather events and comparing these outputs against load data, the study assesses the ability of renewable sources to meet electricity demand. This analysis helps inform strategies for managing increased loads from EVs and other sources. Ultimately, accurate weather scenario simulations will enhance forecasting precision for both power generation and demand, thus improving grid resilience, minimizing outage risks, and ensuring a stable electricity supply despite rising demand and challenging weather conditions.

II. METHODOLOGIES

A. EIA 860 CASE

This study primarily focuses on generator output under various weather scenarios, making generator data a key factor having significant impact on simulation accuracy. The synthetic grid case is commonly used in power system research because it represents the key features of real power grids without revealing sensitive information [8]. However, in this study, synthetic grids are not suitable, as the generator data differs from real-world generator information. Therefore, this study uses the EIA-860 case with data from the U.S. Energy Information Administration (EIA) rather than a synthetic grid case. The EIA-860 dataset, which are publicly accessible, includes details on electrical generators with a minimum capacity of one megawatt across the United States. This dataset includes several schedules: Schedule 1 provides utility data, Schedule 2 offers plant details, including geographic coordinates, and Schedule 3 contains generator information, with further specifics on wind turbine and solar cell models [9]. Although there are also Schedule 4 and Schedule 6, we mostly utilize Schedule 1, Schedule 2, and Schedule 3. The EIA-860 data are particularly helpful because Power Flow Weather (PFW) models are used for simulations, where accurate generator data are crucial for reliable results. Furthermore, dataset's structure is split into utilities, plants, units, and by US states, allowing to align with power flow structures. The next step involves building the case for simulation in PowerWorld using this well-organized dataset. A simplified procedures can be outlined as follows: first, define areas using utility data; then create substations from plant data, establish zones, and set up buses with plant data. Generators are then added based on generator data, followed by connecting buses through transmission lines. Lastly, Power Flow Weather (PFW) models are placed using generator information. Detailed procedures for these steps are thoroughly explained in [9].

B. Power Flow Weather (PFW) Models

PFW models, like stability models, are used to represent components of the power system, such as generators, enabling analysis of the behavior of the system under various conditions. They are especially useful for integrating environmental inputs (ENI) into power system analysis, allowing for an accurate evaluation of how various conditions impact power flow across the grid. The current simulation model does not account for the characteristics of solar energy. As shown in Figure 1, two simulation results are compared using the same input data: the blue curve represents the outcome without the PFW model (the existing approach), while the other curve reflects the results when the PFW model is applied. These comparisons highlight the effect of the PFW model on generation output. In practice, solar power production follows a natural cycle—beginning around 6 AM, peaking near midday, and gradually tapering off until reaching zero after 7 PM. By contrast, the simulation without the PFW model unrealistically indicates constant high generation throughout the day. Incorporating the PFW model produces a more realistic distribution of generation output, emphasizing its importance for accurate power flow analysis.

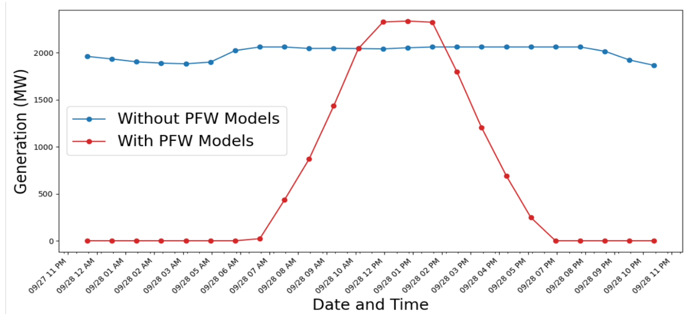

Fig. 1. Generation output graph with PFW and without PFW

Although there are numerous fuel types, this paper focuses primarily on wind and solar. Each PFW model has unique input requirements. For instance, the wind model needs six inputs: AllowTurnOff, which permits turbine shutdown; AllowTurnOn, which allows turbine turn on; MWMax, the maximum power output in megawatts; Hubsclar, a factor that adjusts the turbine's hub height for performance; DefaultWindMS, the default wind speed in meters per second; and HubHeightM, the height of the turbine hub in meters. In solar model, there are more inputs than wind, but the main inputs would be represented as Installed Capacity, which the maximum power the solar system can generate; Type of Tracking, which the mechanism for tracking sunlight(fixed or movalbe); Azimuth and Title Angle, which the orientation and angle of the solar panels; and sky diffuse, which the amount of sunlight scattered in the atmosphere. More detailed explanations can be found in [10]. Before running weather simulations with PFW models, it is essential to classify each model according to generator data. For example, as illustrated in Figure 2, the power curve varies with wind speed in wind models. In PowerWorld, there are six different wind classes, but primarily four are used: Wind Class 1 for high wind, Wind Class 2 for medium wind, Wind Class 3 for low wind, and Wind Class 4 for very low wind. In the solar model, there are only two types: SolarPVBasic1 and SolarPVBasic2. We primarily use SolarPVBasic2 as it is the most recent model.

C. Choosing Weather Scenarios

This paper utilizes PowerWorld's "Time Step Simulation" tool to simulate various weather scenarios. For Time Step Simulation, PowerWorld requires files in either "tsb" or "pww" formats. This study uses the useful format called "pww" as

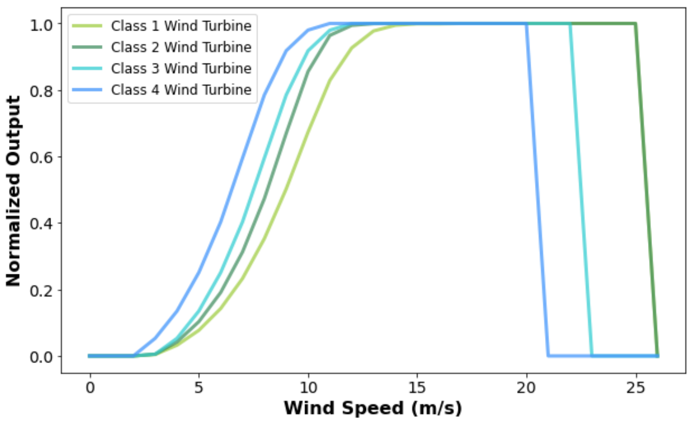

Fig. 2. Power Curves for PFW models [7]

it can be directly loaded into PowerWorld, enabling direct inclusion of weather measurements in power flow and optimal power flow analyses [6]. With this convenient and efficient file format, we can choose the weather scenarios significantly affecting electric gird. Four weather scenarios are utilized in this study. First, one of weather scenarios this paper use is drought case, more perceisly renewable drought. While drought definitions can vary, common definition is classified when resource availability remains below a certain threshold for a prolonged period [11]. In this study, we classify a drought as occurring when generator output drops below 25 percent of the average power output over the past 80 years, and we track its duration. Here is a brief overview of the data acquisition process. Our research team has historical pww files covering the years from 1940 to 2024, enabling us to simulate hourly renewable generator outputs for each day over the last 80 years. Although solar panels and wind turbines were not widely deployed in earlier decades—such as in 1945—our simulations assume that the current level of renewable energy infrastructure existed at that time. However, the generation output is based on the actual weather conditions recorded for each historical date. We then compute the average hourly output over the 80-year period and compare it to the actual output at corresponding dates and times. More details methodological details are available in [12]. If the actual output is less than 25 percent of the historical average, it is classified as a drought, and its duration is recorded. For this study, we focus on one of the longest droughts identified in Texas. Additionally, analyzing weather conditions with strong winds is crucial since wind turbines operate efficiently only within a specific wind speed range. Identifying periods of lower efficiency can provide valuable insights for managing extreme weather events, such as winter storms. Therefore, the second and third weather scenarios include simulations of winter storms “Uri” and “Elliott. The final scenario integrates a winter storm with a weather drought, this time using a 35 percent threshold, to analyze renewable energy output shortfalls during the storm.

III. Results

A. *One Of The Longest Drought Period In Texas*

The first case examines the impact of the longest drought recorded in Texas over the past 80 years. This drought period was identified using the methodology outlined above, which leverages historical weather data to pinpoint extended periods of minimal generation. To evaluate how such extreme conditions affect power generation, Time Step Simulation were conducted in PowerWorld using the EIA-860 case for the corresponding year. The generated graph, shown in Figure 3, provides a visual representation of generator output during this prolonged drought event. To quantify the effects of the drought on electricity generation, historical generator output data from the same dates over the past 80 years was used as a baseline for comparison. As expected, generator output during the drought was significantly lower than the long-term historical average. Notably, during the drought, the maximum generator output reached only 5601.5 MW. The minimum recorded output dropped to just 1758.83 MW, demonstrating the severe limitations in power production during these extreme conditions. This substantial variability in electricity generation suggests that droughts can pose a serious risk to grid stability, potentially leading to power shortages if proper mitigation measures are not in place. These findings emphasize the need for improved energy storage solutions, diversified generation sources, and enhanced grid flexibility to compensate for generation losses during prolonged droughts.

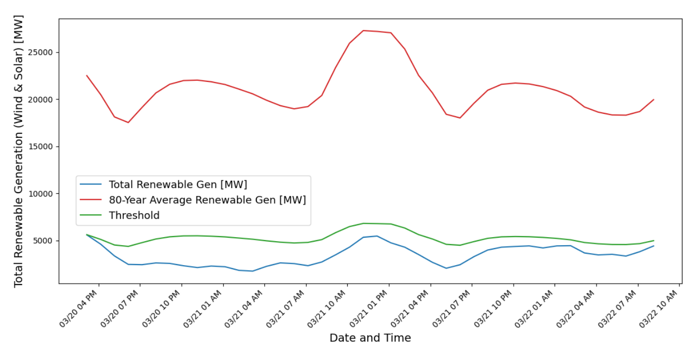

Fig. 3. Renewable Generation Output During One Of The Longest Drought Period In Texas

B. *Winter Storm “Uri”*

The following case study analyzes the impact of winter storm ”Uri,” which struck Texas in February 2021 and caused widespread power outages. This simulation follows the same methodology as the previous case but with the PWW file corresponding to the ”Uri” period, which occurred from February 13 to 17, 2021. The resulting data, illustrated in Figure 4, offers a clear visualization of the performance of generation resources under extreme winter conditions. As expected, generator output varied significantly throughout the duration of the storm. During the peak of ”Uri,” the maximum recorded generator output reaches 22,666.35 MW. However, during the most extreme conditions, the minimum output is 3,187 MW. This drastic fluctuation had severe implications for grid stability, as Texas's electricity demand remained high while generation capacity fluctuated. The disparity between available generation and actual demand likely contributed to widespread blackouts, leaving millions without power for extended periods. This analysis underscores the challenges that renewable energy sources such as wind and solar are particularly vulnerable to severe winter storms due to factors like frozen wind turbine blades and reduced solar irradiance. The findings highlight the necessity of enhancing grid resilience through improved infrastructure, increased energy storage capacity, and better forecasting models.

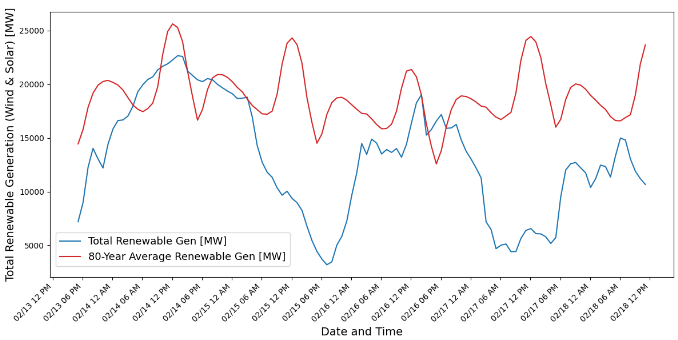

Fig. 4. Renewable Generation Output During Winter Storm "Uri"

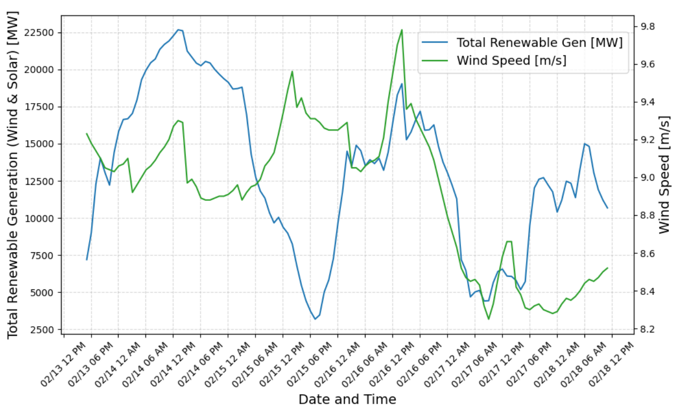

Fig. 5. Effect of Wind Speed On Wind Turbine Generation During Winter Storm "Uri"

Figure 5 shows the relationship between generation output and wind speed. Up to a wind speed of 9.30 m/s, the wind turbine generates electricity efficiently, allowing the output to reach the 80-year renewable generation level presented in Figure 4. However, once wind speed exceed 9.30 m/s, the generation output drops sharply to around 3000 MW. As the wind speed continues to rise, the output decreases again, following a similarly steep decline observed during the strongest winds of the winter storm. Given that most wind classes in this case are Wind Class 2 and Wind Class 3—where the average wind speeds at hub height are 8.5 m/s and 7.5 m/s, respectively—the trend of Figure 5 aligns with expectations, as the turbine often operates above these average speeds in the simulation. While other factors also affect wind generation output, wind speed is a critical factor, highlighting the importance of analyzing how much wind turbines can withstand and operate efficiently during extreme weather conditions with strong winds.

C. Winter Storm "Elliot"

The third case analyzes the impact of a different winter storm, "Elliot", which occurred in 2022. As in the previous cases, the analysis involved using the pww file for the "Elliot" period. The resulting graph, presented in Figure 6, visually illustrates generator output during this extreme weather event. As anticipated, the generator output varied significantly during most of the storm, with a maximum output of 36,023.48 MW and a minimum output of 1,644.36 MW. According to ERCOT's report [13], the peak demand on December 22, 2022, reached 73,685 MW, recorded on August 20, 2024. Comparing these values reveals that the maximum output in the simulation is nearly half of the peak load demand reported by ERCOT.

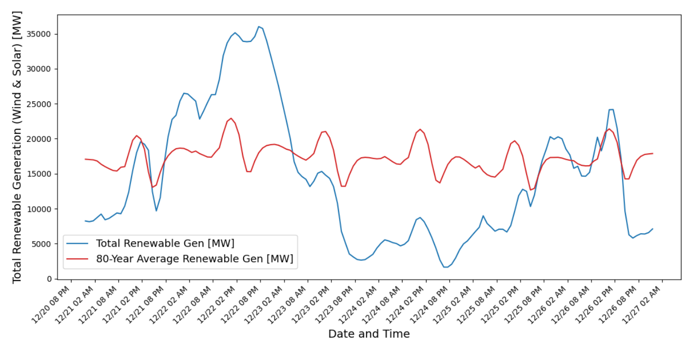

Fig. 6. Renewable Generation Output During Winter Storm "Elliot"

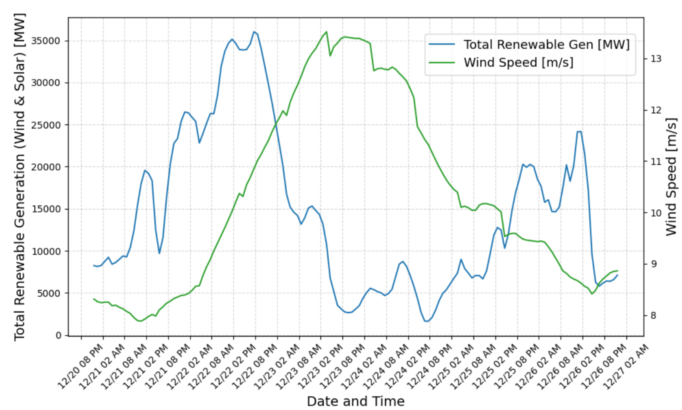

Fig. 7. Effect Of Wind Speed On Wind Turbine Generation During Winter Storm "Elliot"

Unlike other case, the graph shows that during the storm, generator output briefly exceeded the 80-year average—likely due to strong winds boosting wind energy production. However, once wind speeds surpassed turbine limits, output dropped sharply due to shutdowns or damage. This illustrates how extreme winds can both enhance and disrupt renewable energy systems. Figure 7 shows a similar trend to Winter Storm "Uri": when wind speeds exceed 10.85 m/s, output drops sharply to around 1600 MW, remaining below the 80-year average thereafter. Notably, while peak output during "Elliot" was over 14,000 MW higher than during "Uri", the minimum was nearly twice as low. This suggests "Elliot" had stronger winds that often exceeded optimal turbine ranges, causing performance drops. These findings highlight the operational challenges wind turbines face in extreme weather and the need to ensure resilience to avoid outages like those seen in "Uri" and "Elliot".

D. Renewable energy drought during winter storm

The final case examines the extreme case scenario, which occurs during one of the longest drought periods coinciding with the winter storm "Uri". In this extreme situation, a higher threshold of 35 percent was used, rather than the previous 25 percent threshold, to better capture the severity of the conditions. By identifying one of the most extended drought periods during the winter storm, the analysis was conducted similarly to the Winter Storm "Uri" case but with the adjusted threshold to reflect the extreme nature of the combined event. The resulting graph, shown in Figure 8, visually represents the generator performance during this extreme case. As seen in the graph, the maximum generator output in this case reached 6557.16 MW, while the minimum output plummeted to 4408.88 MW. This drastic reduction in generation output highlights the vulnerability of the power grid under such combined extreme weather conditions. These output levels would have put immense stress on the grid, especially considering its heavy reliance on wind and solar renewable energy sources. The absence of dispatchable backup sources left grid operators with few options, increasing the risk of widespread outages. This situation highlights the need for a diversified energy mix, resilient infrastructure, and better planning to address the combined challenges of high demand and renewable intermittency.

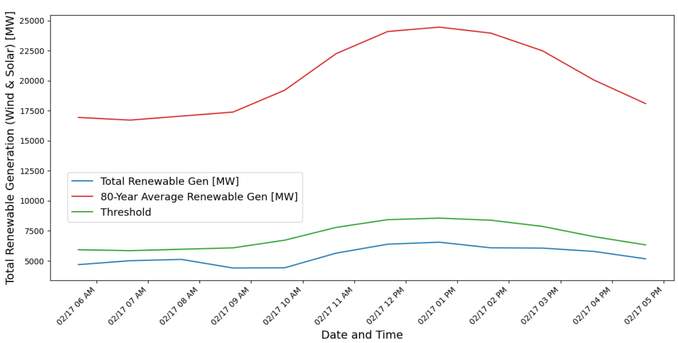

Fig. 8. Renewable Generation Output During Extreme Case Scenario

E. Comparing generation output with historical load demand

After evaluating the substantial influence of weather on the electric grid, the next step involves analyzing how much of the load demand can be met by the renewable generation output with copper plate model. This analysis utilizes historical load data from ERCOT, specifically from 2002 to 2024, as the study focuses on the Texas electric grid. Given the annual increase in load demand, it is essential to account for load inflation. This is done by calculating the average load for each year and determining the inflation ratio by dividing each year's average load by the average load in the latest year, which are 2024 in this study. Each load value is then adjusted using this inflation ratio. This approach ensures that the comparison between past and present conditions remains accurate, preventing underestimation of future electricity needs.

With the necessary data gathered, two typical cases are chosen, and the first scenario under examination is a renewable drought. This period represents conditions where renewable generation is at its lowest, directly impacting the grid's ability to meet demand. Figure 9 illustrates the share of renewable energy in meeting the load demand during a prolonged drought scenario. The data reveals that renewable sources contributed an average of approximately 8.5 percent, with a peak of around 13 percent and a low of about 5 percent. These low contribution levels highlight a significant shortfall in generation capacity relative to demand, underscoring the challenges posed by the variability of wind and solar resources. As renewable adoption continues to expand, ensuring grid reliability will require the need for complementary solutions, such as long-duration energy storage and flexible, dispatchable generation, compensating for such deficits during extreme weather conditions.

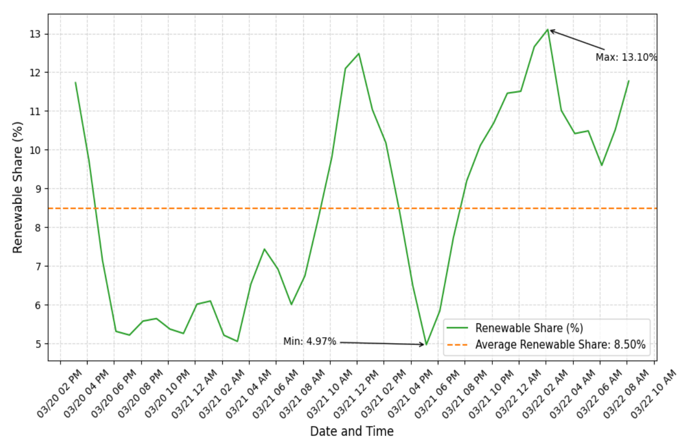

Fig. 9. Renewable Generation Output During Extreme Case Scenario

The next case to examine is the "Uri" case, shown in Figure 10. It presents the share of renewable energy in meeting load demand during winter storm "Uri". On average, renewables supplied approximately 21.37 percent of the load, with the lowest contribution dropping to around 6 percent. While this performance is notably better than during the drought scenario, the data still reveals a substantial gap between renewable output and actual demand. These results highlight the limitations of relying solely on wind and solar, particularly during extreme weather events. To address this, long-term solutions are needed beyond simply increasing renewable capacity or depending on EV batteries during emergencies [14]. A more sustainable strategy includes investing in large-scale energy storage, expanding transmission infrastructure to move power from resource-rich areas to where it's needed most, and adopting advanced forecasting methods. Together, these enhancements can improve system resilience and ensure a stable, reliable energy supply even during severe disruptions like Winter Storm "Uri".

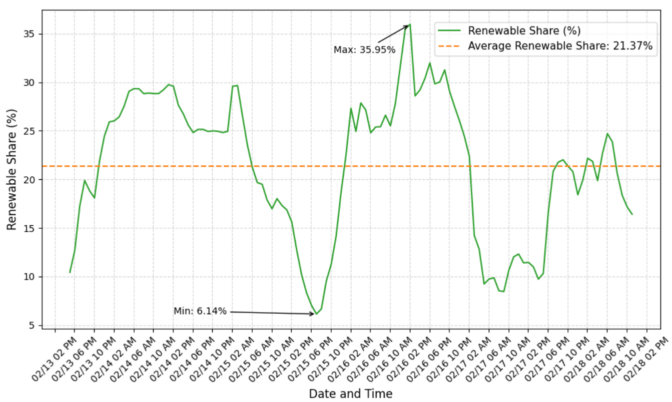

Fig. 10. Renewable Generation Output During Extreme Case Scenario

IV. Conclusion and Future Work

With the advent of the fourth industrial revolution and the transition from traditional energy sources to renewable energy, weather analysis has become increasingly essential for the successful integration of renewable energy into electric grid planning. As anticipated, renewable energy sources, particularly wind and solar, are highly dependent on weather conditions, making it crucial to forecast generation output under different weather scenarios and assess whether it can meet load demand. This study leverages EIA 860 data, Power Flow Weather Models, and extreme weather scenarios, including renewable droughts, to provide a comprehensive modeling framework for simulating and analyzing electric grid performance, with a focus on Texas. The simulation results, compared to historical load data, show that weather variations have a significant impact on the Texas electric grid. Rather than relying on short-term solutions like increasing the number of solar panels and wind turbines, the study emphasizes the need for long-term solutions in grid planning such as large-scale battery storage, enhanced transmission networks, and improved grid flexibility.

Future work will focus on identifying days based on weather conditions, such as those with high or low renewable generation or extreme load levels, rather than selecting specific historical dates. This method better reflects grid operation planning by focusing on high-load, low-renewable scenarios rather than solely depending on historical storm dates. By doing so, the analysis will become more data-driven and realistic, capturing actual worst-case scenarios for grid stress, as weather conditions can vary significantly across different years.

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