Detailed Hourly Weather Measurements for Power System Applications

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***Abstract*—This paper explains how to extract and store detailed weather data measurements that are applicable for power system studies. The process of extracting high-quality, high-precision historical weather measurements dating back to 1940, for power system operation and planning is explained. A new file format is also presented for improved storing and utilizing weather data in power system studies, particularly addressing the challenges of integrating weather measurements directly into power flow and optimal power flow simulations. The file format, named pww format, offers significant storage efficiency and fast data processing capabilities of weather data for power system studies. Finally, the paper demonstrates how weather data can be effectively employed in power system simulations to enhance the accuracy, reliability, and efficiency of power grid operations. The code to create this efficient and low memory usage weather data format is available at [1].**

***Index Terms*—power system, operation and planning, resiliency studies, weather measurements, weather data, PWW, power flow**

I. Introduction

Given the escalating prominence and widespread integration of renewable energy sources in power generation, it is useful to incorporate detailed, weather-dependent aspects of these resources into planning and operational processes, recognizing their significant susceptibility to weather conditions. Renewable energy resources are progressively playing a more pivotal role in power generation. According to the U.S. Energy Information Administration form 860 (EIA-860) [2], in 2022, both nuclear and coal generation were surpassed by renewable generation in the United States. Additionally, the energy output from wind power alone surpassed hydroelectric generation by over a hundred million megawatt-hours in 2022. Thus, power generation operation and planning must incorporate an accurate forecast of available generation capacities to meet the demand at each power system node (bus) at each time.

The capability to simulate these weather conditions could offer providers a more accurate forecast of expected demand and generation. There is extensive literature on this subject, particularly on solar generation, as seen in [3] and [4], and wind generation, as discussed in [5], [6], and [7]. Billinton and Cheng's research in 1986 [8] marked an early exploration into weather's impact on power system equipment and failure rates, a topic not directly tied to load or generation effects. This focus expanded with Billington and Wenyuan's seminal 1991 publication [9], which emphasized incorporating weather conditions into composite system analyses, primarily concerning equipment failure under extreme conditions. More recent research, such as [10], delves into the role of weather in assessing the resilience of power infrastructure.

Thus, the increasing interest in integrating weather data into power system planning and operation led to the direct inclusion of weather measurements in the power flow equations in [11]. The authors in [11] utilized historical weather data from sources like the International Civil Aviation Organization (ICAO) and the World Meteorological Organization (WMO), complemented by electric utilities' real-time data [12]. However, these sources have substantial missing data and do not include all useful weather measurements for power system applications such as both 10m and 100m wind and surface solar radiation. Thus, the authors of this paper follow the recommendation of [13] to use ERA5 data to model wind power generation. However, there are many challenges including the lack of convenient access to such data by power engineers due to computational complexity for direct inclusion of detailed weather data such as ERA5 data to electric grid operation and planning.

In this work, we focus on extracting high-quality weather data that have the highest impact on power systems and storing historical weather measurements dating back to 1940 with hourly precision mainly focusing on North America in a format that needs less memory. This work stands out for its focus on providing detailed weather data for power systems planning and simulation, filling the gap in the existing literature, including [14] and [15]. We introduce the pww format, for storing data with less memory and faster extracting ERA5 data to enhance usable weather data for power flow simulations, as a useful contribution to the field, especially in addressing data challenges like missing values and limited weather parameters, such as surface wind and solar radiation measurements. The code to create this efficient and low memory usage weather data format for power system applications from ERA5 data for any other part of the world is available at [1].

II. EXTRACTING HISTORICAL WEATHER MEASUREMENTS FROM ERA5

ERA5 is the state-of-the-art (fifth generation) atmospheric reanalysis of the global climate and weather for the last eight decades, produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). “ERA” stands for “ECMWF Re-Analysis.” ERA5 provides hourly estimates of a multitude of atmospheric, land, and oceanic climate variables, combining vast amounts of historical observations into global estimates using advanced modeling and data comparison systems. It offers a comprehensive, detailed view of weather and climate, spanning several decades, and is used for various applications like climate research, meteorological forecasts, and environmental modeling. [16]

Based on the impact on power systems, selected hourly weather measurements from 1940 to the present are downloaded from ERA5 [16]. For an automated download of the data using cdsapi toolbox in python [17] based on Conceptual Data Structures (CDS) [18], the product type is selected as Reanalysis. Then from the “Temperature and pressure” section of the website, ’2m temperature’, ’2m dewpoint temperature’, from the “Wind” section, ’10m u component of wind’, ’10m v component of wind’, ’100m u component of wind’, ’100m v component of wind’, from ”Radiation and heat” section, ’ Surface Solar Radiation Downwards’, ’ Total sky direct solar radiation at surface’, from “Clouds” section, variables ’total cloud cover’, ’high cloud cover’, ’low cloud cover’, ’medium cloud cover’ and from “Other” section, ’Geopotential’ is selected for the download request. Required dates and times with hourly precision are also selected. Note that ERA5 data is in coordinated Universal Time (UTC) ISO8601 format that can be converted to the local time of each point based on its geographic coordinates. The rectangular range of geographic coordinates is also selected. It would be more efficient if, from the geographical area section, one selects the required area for study to reduce computational complexity. For creating an initial data repository at [19], we focused on United States, Canada and parts of Mexico so the geographical range that is selected is [58, -130, 24, -60], which is North 58°, West -130°, South 24°, East -60°. The weather measurements data is available on a 0.25 degree grid of latitudes and longitudes. Figure 1 shows the geographic coordinates that are used for our data repository. Please note that any other parts of the world can also be downloaded and used for power system studies.

We have provided unique weather station identifiers as ’Latitude_Longitude’ including a leading zero for latitudes that are greater than -100, to make sorting data easier. Also, included two digits past the decimal point so the length of all weather station names are the same. For example the station at -60 West and 45 North is called “-060.00_45.00”. Also, states and countries are mapped to the weather stations based on latitudes and longitudes using geopandas toolbox [20] in python. The ”ElevationMeters” parameter is derived from the geopotential value, found in the “Others” category of ERA5 data, and represents the Earth’s surface elevation in meters. Geopotential, expressed in m^2/s^2, is the gravitational potential energy per unit mass at a specific location above sea level. It indicates the work required to lift a unit of mass from sea level to that location against gravity. To convert geopotential to the height (elevation in meters), we divided the geopotential values by the gravitational constant (9.80665 m/s^2). Geopotential height is crucial for calculating the output power of wind turbines. For the data points shown in Figure 1, the elevation is from -51 meters to 3414 meters with the average of 455 meters.

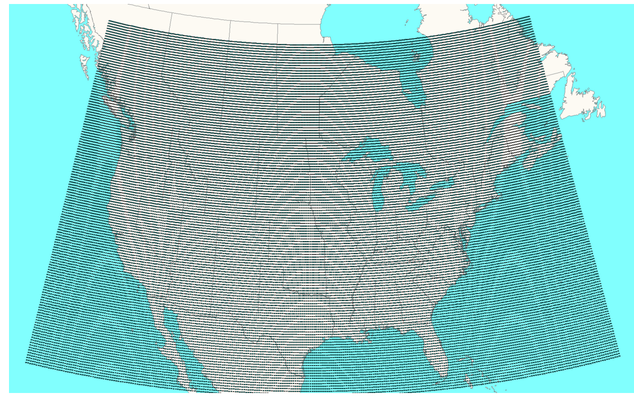

Fig. 1. Downloaded ERA5 geographic coordinates

Using ’10m u component of wind’, ’10m v component of wind’, ’100m u component of wind’, and ’100m v component of wind’ we calculated wind speed at surface (10 meters) and at wind tubie heights (100 meters) based on equation (1).

$$WindSpeed = \sqrt{U^2 + V^2} \tag{1}$$

In (1), U represents the wind’s zonal component (east-west direction) and V represents the wind’s meridional component (north-south direction). Both U and V are measured in meters per second (m/s) in ERA5 but we convert them to miles per hour. The resulting wind speed is a scalar quantity representing the total speed irrespective of its direction. We also calculate the wind direction from its U and V components and store the result in a new column within the data frame. The wind direction is measured in radians with respect to the geographic north and then converted to degrees. ERA5 ’2m temperature’, ’2m dewpoint temperature’ are in Kelvin and we convert those to Fahrenheit. Cloud coverage values are also converted to percentages. “Total sky direct solar radiation at surface” or “direct horizontal irradiance” refers to the amount of direct solar radiation (shortwave radiation) reaching the Earth’s surface, measured as radiation passing through a horizontal plane. This includes both scattered (diffuse) and unscattered (direct) solar radiation. “Surface Solar Radiation Downwards” or “global horizontal irradiance” encompasses both direct and diffuse solar radiation, representing the total solar radiation incident on the Earth’s surface. Both parameters are accumulated over a specific time period and expressed in joules per square meter

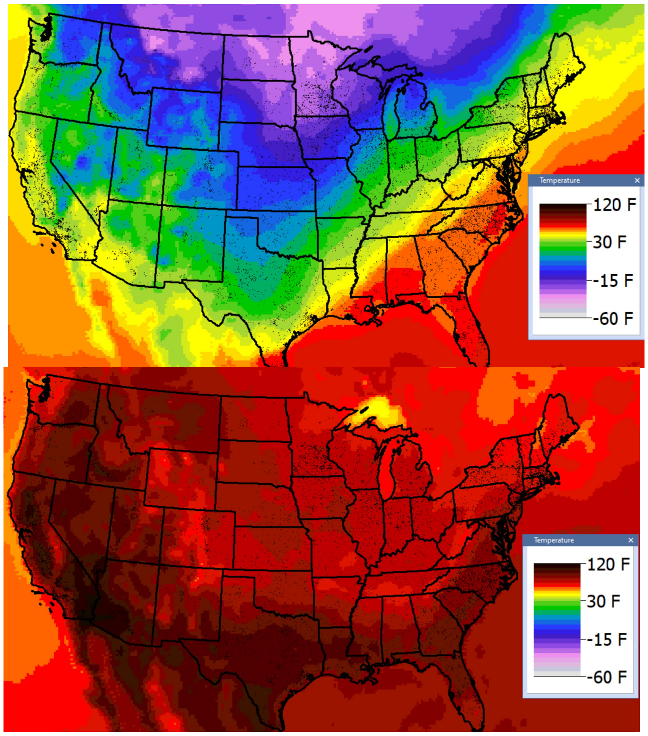

Fig. 2. Temperature contours at 7 am on January 21, 1954 (upper Figure), and 5 pm on July 21, 2023 (lower Figure)

(J/m^2). For conversion to watts per square meter (W/m^2), we divide the values by the accumulation period in seconds. These measures approximate what a pyranometer would record, although they average over a model grid box rather than representing a specific local point. The convention for these measurements is positive downwards, and when converting from J/m^2 to W/m^2 (over 3600 seconds), division by 3600 is required.

The ERA5 data is available in Network Common Data Form (NetCDF) and GRIB (Gridded Binary) formats. These formats are standard in meteorological data and are supported by various software tools for analysis and visualization. For this work, NetCDF is preferred over GRIB for experimental use and data frame conversion due to its self-describing nature, compatibility with a wide range of data analysis tools, and flexibility in representing complex datasets. NetCDF format facilitates easier data manipulation and analysis, supported by robust community and tooling, unlike the more specialized and compact GRIB format. For large data management and data manipulations, we convert NetCDF format to pandas data frames [21], [22].

III. Extracting Future Weather Measurements from ERA5

The future weather data including medium, extended, and long-range forecast data, is available at [23] from the European Centre for Medium-Range Weather Forecasts (ECMWF), which is one of the data providers of ERA5. Copernicus Climate Data Store, Climate Change Service and Europian Comission are other collaborators to gather ERA5 data. This website provides the necessary resources to download and utilize future weather data similar to the reanalysis data available from ERA5. ECMWF Forecast User Guide [24], is designed to help meteorologists make the best use of ECMWF's forecast products. This guide outlines the structure and use of the Integrated Forecasting System (IFS) and includes information on how to use the high-resolution forecast (HRES), ensemble forecast (ENS), extended-range forecast, and seasonal forecast models. The guide offers links to more detailed descriptions and ECMWF training resources for a deeper understanding of the IFS. To obtain access to ECMWF forecast datasets, one should visit the ECMWF Access to Forecasts page. This page details the various ways to obtain access to ECMWF forecast datasets and charts, depending on the status of a user. Similiar to historical weather data, ECMWF forecast datasets are also available in GRIB or NetCDF formats.

For the specific variables it is required to specify the variables, time and dates and geographical coordinates similar to historical data when accessing the datasets. Accessing future datasets requires registration or adherence to specific terms of use. By following these steps and utilizing the resources provided by ECMWF, one can access and download forecast data for the specific meteorological variables and geographical coordinates of interest.

IV. Creating a Manageable Data Format

The pww file format, presents convenient and fast access to the weather data from ERA5 [16] for power system applications. The pww format is storage-efficient, with file sizes roughly a third of those in the ERA5 NetCDF format with the same data. This reduced file size not only conserves storage space but also facilitates faster data loading into PowerWorld software [25], thus enabling quicker simulation runs. These benefits make the pww format an appealing choice for integrating weather data into power flow simulations, offering both efficiency and speed enhancements. Also, weather data stored in pww format can be loaded to PowerWorld software [25] for direct inclusion of weather measurements in power flow and optimal power flow studies. [26]

Since ERA5 data are available hourly, for writing ERA5 data to pww format, we only save the start date and end date to save memory. Also, to make the file memory usage smaller all measurements are converted to integers and saved as bytes. If the integer value is larger than 256 for a byte, like Global Horizontal Irradiance and Direct Horizontal Irradiance with a maximum of 1270 W/m2, the values are divided by five for storing in bytes. Surface (10m) wind direction is also stored by degrees and can exceed the value of 256 so the values in degrees are divided by 5 degrees for storing as bytes. After the data was written to the pww file as bytes, for reading a PWW file to retrieve weather data, the data fields that were divided by five are multiplied by five to obtain the original data. Also for surface (2 meters) temperatures and dew points 115 units are added for saving data as bytes (valid range is from -115° F to 139° F) and subtracted when reading the data. A detailed explanation of PWW data format is available at [1]. Over eighty-three years of ERA5 data (1940-present) have been converted to pww file format and are available at [19]. The code to translate ERA5 data to pww format for any other location is available at [1]. Also, to further reduce computation complexity, it is possible to limit the dates and geographical coordinates from pww files.

V. Mapping Weather Data to the Power Systems and Modelling Renewable Outputs

The second goal of this study is to correlate meteorological data with electrical grid components. Historically, power flow datasets lacked geospatial data for substations, but this trend is changing due to the increased use of geographic information systems, advanced visualization techniques [27], and the necessity of geospatial data for studying geomagnetic disturbances [28]. NERC regions now often require geospatial data submissions [29], [30], and large-scale synthetic electric grids provide this information [19], [31], [32]. Most current power flow models already possess or can access the required geospatial data. Integrating weather into power flow analysis involves having geospatial data at grid components like generators and transmission lines. With the widespread availability of weather stations, weather data is generally accessible near grid locations. For estimating values at specific grid locations, 2D scattered data interpolation methods, such as Delaunay triangulation or using the nearest station with valid data, are effective.

Also, the strategy in [11] is used for generator models to calculate the outputs of renewable generators based on the detailed availaibility of renewable resources and update the outputs of thermal units based on temperatures. The paper presents a methodology for large-scale grid analysis, focusing on integrating weather information with grid components. It utilizes six models to simulate the impact of weather on electric generators' real power output, each based on different aspects such as wind speed and solar PV generation, referencing [33]–[37]. The models consider factors like wind turbine classes, cloud cover, and temperature variations, with data validation from sources like [38]–[40]. The approach emphasizes geographic location knowledge of each generator and employs interpolation methods for precise weather data mapping at grid locations. The average distance of each EIA-860 generator to the closest weather station data point is 0 km, with the average of 1940 km, a standard deviation of 832 km and a maximum of 4297 km in Canada.

VI. Results and Analysis

As the weather data have been extracted and using the generator's data from EIA-860 data as explained in [41], Texas A&M synthetic test cases at [42], which are created based on EIA-860 data or any other real case with available geographic coordinates of generators, a range of simulations can be conducted, including integrating weather data as outlined in [11]. Employing actual generator data provides benefits for various analyses, such as calculating emissions [43].

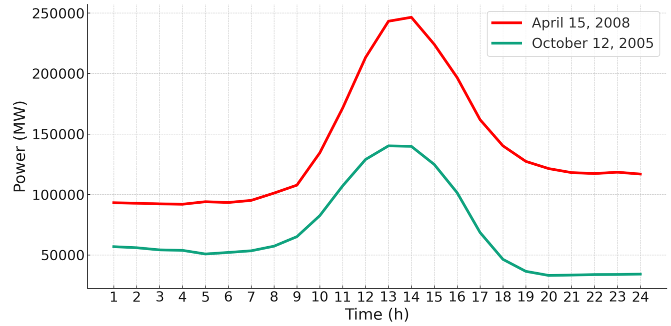

Fig. 3. Comparison of renewable generation in two days

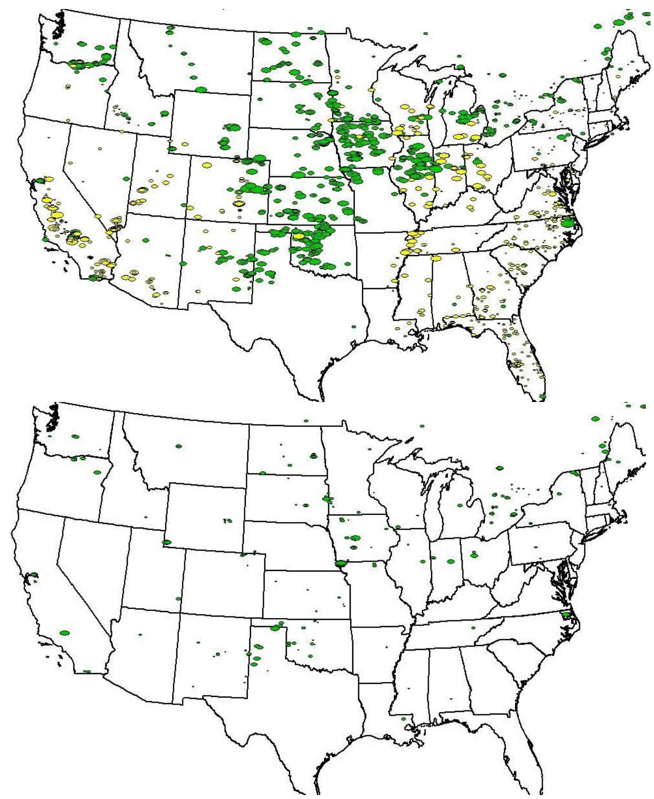

Fig. 4. Renewable generation at 1 pm of April 15, 2008 (upper Figure), and 8 pm of October 12, 2005 (lower Figure)

Sample portions of the converted data to applicable weather data for power system analysis is visualized in this section. For improved visual examination of power grid functioning, several effective tools are available. These include the Geographical Data View (GDV) [44], contour mapping techniques [45], and expansive visualizations of the transmission grid [46]. The application of these tools enhances the understanding and awareness of grid conditions across various situations and time frames [47], [48]. Figure 2 shows contours of temperatures at 7 am on January 21, 1954 (upper Figure), and 5 pm on July 21, 2023 (lower Figure).

One of the most important weather measurements that impacts power systems with increased penetration of renewable

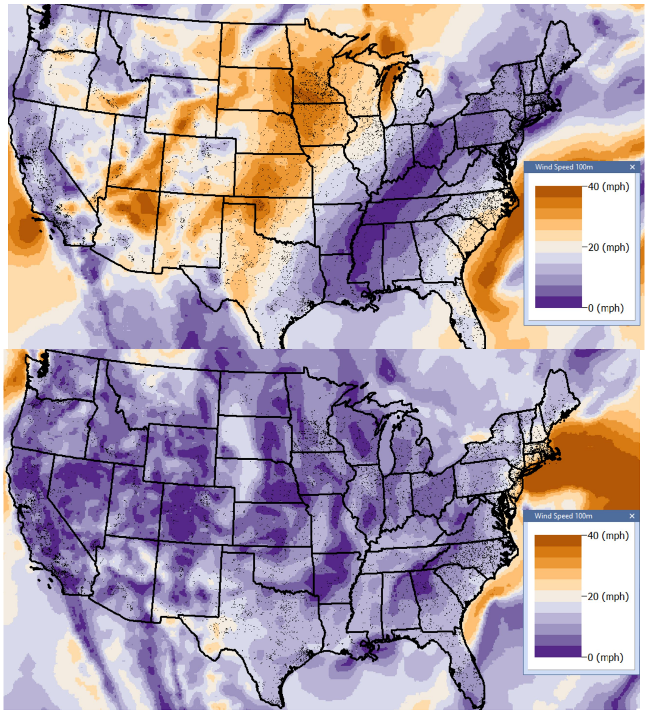

Fig. 5. Wind speed at 100 meters height at 1 pm of April 15, 2008 (upper Figure), and 8 pm of October 12, 2005 (lower Figure)

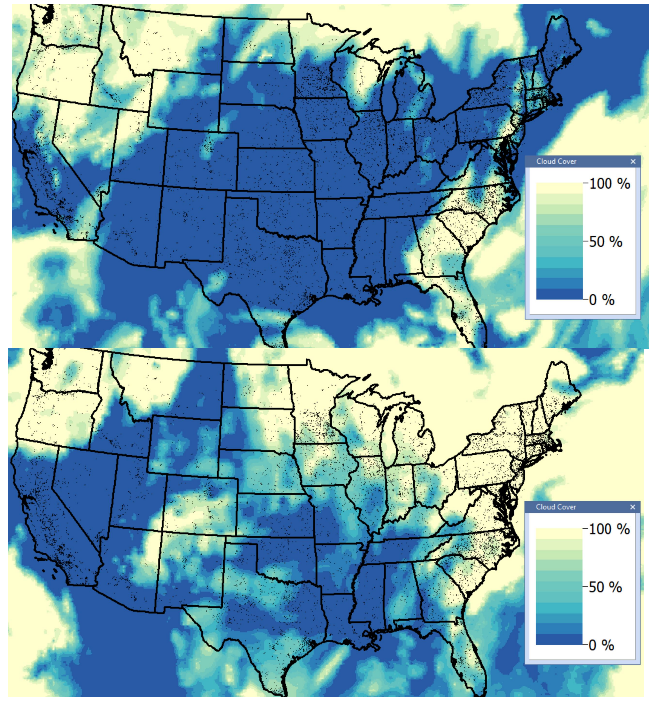

Fig. 6. Wind speed at 100 meters height at 1 pm of April 15, 2008 (upper Figure), and 8 pm of October 12, 2005 (lower Figure)

resources is wind speed. For the purpose of visualization, a day with high availability of wind (April 15, 2008) and a day with low availability of wind (October 12, 2005) is selected. Figure 3 compares the overal generation of renewable energy in two selected days with high and low availability of wind and solar resources. The US generation data of the end of 2022 with 360 GW overall renewable capacity based on EIA 860 data is used for this simulation [2]. Figures 4 visualize the renewable generation of Eastern and Western Interconnects based on EIA 860 generation data at the end of 2022, at two different time points with a large and low availability of renewable resources at the selected dates where the size of the ovals are proportional to the generation capacity, green refers to the wind turbines output power and yellow refers to the solar cells power based on their availability. Figure 5 for the same times shows the wind speed at 100 meters height and Figure 6 shows the cloud coverage for the same time as Figure 4.

VII. Conclusion

This paper presents a useful approach to extracting the weather variables useful for power systems studies from the publicly available ERA5 reanalysis weather dataset, and storing the data in a useful data format that loads faster and takes less storage memory. The extracted weather measurements are integrated into power system analysis by enabling the calculation of weather-dependent generators such as wind and solar resources. This enables studies that emphasize the critical role of accurate weather forecasting in enhancing the reliability and efficiency of power grid operations.

Visualizations are used to show the application of weather measurements in power generation and demand as well as to validate data. Future work will focus on power system simulations using this weather data, exploring the integration of renewable energy sources, and further enhancing the operational decision-making processes. This research contributes to the broader goal of creating more resilient and sustainable power systems, capable of adapting to the challenges posed by climate change and increasing energy demands. The weather data created in this efficient and low-memory usage format is available at [19]and the code to create the pww data format from ERA5 is at [1].

VIII. Acknowledgements

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