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Article

Evaluation of Power System Stability for a Hybrid Power Plant Using Wind Speed and Cloud Distribution Forecasts

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Abstract: Power system stability (PSS) is the ability of a system to remain in operating equilibrium which is achieved between the electric power generation and consumption. In this paper, we evaluate PSS for a Hybrid power plant (HPP) combining thermal, wind, solar photovoltaic (PV) and, hydro power generations, in Niigata City. A new method to estimate PV power generation, based on NHK cloud distribution forecast (CDF) and land ratio settings, is also introduced. Our objective is to achieve frequency stability (FS) while reducing CO₂ emission in the power generation sector. So, PSS is evaluated from the results of the frequency stability (FS) variable. 6-minutes autoregressive wind speed prediction (6ARW) support for wind power (WP). 1-hour GPV wind farm (1HWF) power is computed from the Grid Point Value (GPV) wind speed prediction data. PV power is predicted by autoregressive modelling and CDF. In accordance with the daily power curve and the prediction time, we can support thermal power generation planning. Actual data of wind and solar are measured every 10-minutes and 1-minute, respectively and the hydropower is controlled. The simulation results of the electricity frequency fluctuations are within ± 0.2 Hz of the requirements of Tohoku Electric Power Network Co. Inc., for testing and evaluation days. Therefore, the proposed system supplies electricity stably while contributing to CO₂ emission reduction.

Keywords: Wind speed; Autoregressive model; Power system stability; NHK cloud distribution forecast; Photovoltaic

1. Introduction

1.1. Background

Variable Renewable Energy (VRE) sources are non-synchronous generation technologies, and this property may require changes to how system stability is ensured, especially during periods of high shares of VRE in power generation[1]. Power system stability (PSS) is the system's ability to maintain a balance between electric power generation and consumption. From its formal definition, Power system stability (PSS) is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact[2][3][4]. In line with that, Hatziargyriou et al. (2021) introduced the converter-driven stability and, resonance stability[4]. Then, Shair et al. (2021) proposed a new power system stability (PSS) classification framework which provides wide coverage and future adaptability of the emerging stability issues[5]. Grid stability must be enhanced in light of the integration of large-scale renewable Energy sources into the grid[6]. Also, grid stability must be enhanced considering the integration of large-scale renewable energy sources into the grid[6]. Furthermore, Qin et al. (2022) pointed out that the

construction of large-scale renewable energy sources has caused challenges to frequency stability (FS) of power system, and concluded that the influence of factors such as installed locations of renewables and different renewable energy types should be further discussed[7]. The frequency stability (FS) of a power system refers to the ability to maintain a steady frequency when a disturbance is experienced that causes a significant imbalance between generation and demand. Then, Sattar et al. (2024) showed the ability of renewable energy resources and energy storage systems to participate in enhancing frequency stability (FS) through optimal coordination such that the lifetime of the latter does not deteriorate[3]. With renewable energy penetration rate increasing, the system's frequency stability (FS) will gradually deteriorate, bringing therefore challenges to frequency stability (FS) and security which causes more attention to the analysis method of FS[7]. Besides, the Conference of the Parties (COP) 28 of the United Nations (UN) climate conference underlined the importance of a methodical transition away from fossil fuels to reach net-zero carbon emissions by 2050, with goals of doubling energy efficiency and tripling renewable energy capacity by 2030[8]. So, the need to expedite the energy transition is growing as the strain from climate change increases, making the switch to clean energy an essential alternative[9]. The penetration of more renewable energy into the electrical grid is therefore needed. In fact, the power injected into the grid changes the system operation mode, power flow distribution, and operating points of the traditional equipment, which as a result affects various aspects of classical stability, including power angle, voltage, and frequency stability (FS)[5]-[10]. As, nuclear and renewable energy are low-carbon energy, it is possible to build sustainable power generation systems that are environmentally friendly. Given that, wind power (WP) and solar photovoltaic (PV) are expected to make a substantial contribution to a more secure and sustainable energy system[1], changes in the design of energy infrastructures should also be considered to support the goal of limiting global warming to 1.5 °C[11]. Bringing into the grid more renewable energy sources is one way to significantly decarbonize electricity[12]. Wei et al. (2022) concluded that CO₂ emission reduction will be achieved only with high renewable energy penetration[13]. In line with that, Kosugi et al. (2005)[14] pointed out a model to assess CO₂ emission reduction in some energy consuming sectors in Japan and realized that, a scenario where centralized power utilities are combined with decentralized systems is profitable both for consumers and the industry. The new power system that combines conventional and non-conventional power generations as a unit is called a hybrid power plant in this paper. Wind power (WP) and solar photovoltaics (PV) are crucial to meeting future energy needs while decarbonizing the power sector[1]. In February 2024, the Japanese government began issuing Japan Climate Transition Bonds to support their commitment to become carbon neutral by 2050[15]. VRE power plants can provide an increasing proportion of system services (such as frequency and voltage support services), which are relevant to ensuring the reliable operation of the power system. Interestingly, large shares of VRE (up to 45% in annual generation) can be integrated without significantly increasing power system costs in the long run, but each country may need to deal with different circumstances in achieving such a transformation. While the ability to provide such services can increase investment costs for variable renewable energy (VRE) power plants, it can be cost-effective at the system level.[1]. In March 2021, the Tohoku Electric Power Group launched the Tohoku Electric Power Group Carbon Neutral Challenge 2050, from which they want to accelerate CO₂ emissions reductions based on maximum use of renewable energy and nuclear power, decarbonization of thermal power sources and, electrification and realization of a smart society. For renewable energy 2,000 MW of new power are to be developed as early as possible by 2030 and thereafter while maintaining and improving the power generation capacity of existing sources[16]. Also, the Feed-in Tariff Scheme for Renewable Energy established by the Japanese Government obliges electric utilities to purchase electricity generated by renewable energy sources at a fixed price for a certain period of time[17]. Diversifying variable renewable resources (VRE) by combining wind, solar photovoltaic, and battery assets in a hybrid power plant (HPP) can increase renewable energy usage efficiency and improve system flexibility, particularly in distributed energy systems[18]. As renewable energy penetrations grow and existing thermal power plants retire, congested regions of both types may increase in prevalence,

Kim et al. (2024)[19]. However, many studies on integrating VRE and storage into power grids have not focused on transmission constraints[19][20][21]. Aziz et al. (2018) pointed out that the integration of wind penetration has moved the electricity grid in a transition phase to a new model where wind power plants are expected to participate in all levels of frequency regulation[22]. Ji et al. (2024) concluded that one limitation of their research is the relatively limited energy storage capacity of flywheels compared to some other energy storage technologies. Addressing this limitation is crucial for meeting the prolonged frequency regulation demands of power systems[23]. Hydropower can promote a balanced and diversified energy grid and operate complementary renewable energy generation systems[24][25]. Distributed energy resources (DERs) are elements that actively participate in the supply of renewable energy and contribute to the decarbonization of the power system[26]. Some of the already built infrastructures in hydropower systems could also be used as hidden hydro storage, especially the hydropower plants that are used only seasonally Münch-Alligné et al. (2021)[27][16]. Addressing the research limitation pointed out by Ji et al. (2024) with a hydropower plant set in Niigata city, and given that hybrid power generation system can generate more power than two standalone power plants mainly due to an increase in efficiency[28][18], and in line with the Tohoku Electric Power Group 2050 Carbon Neutral Challenge, along with the related SDG challenges[29], in this paper, a hybrid power plant (HPP) is studied and simulated for Niigata City.

1.2. Objective and Method

Our objective is to evaluate the hybrid power plant (HPP) grid integration based on the frequency stability (FS) variable requirements of Tohoku Electric Power Network Co. Inc. The proposed hybrid power plant (HPP) is a system that combines thermal power generation with wind power, solar photovoltaic (PV) power and, hydropower generations.

In Niigata prefecture the frequency is 50 Hertz and, Figure 1 highlights the distributed grid in the next-generation network[29]. Depending on the geographical location, clouds may affect solar photovoltaic systems grid-connected or standalone. So, we introduce a new mesh method to effectively estimate solar photovoltaic (PV) power generation output of the proposed hybrid power plant (HPP) with a different approach, compared to our previous research[30]. Given that at least 1-year dataset is recommended to evaluate Power system issue, we assume in the simulations, the autumn datasets same as those of spring, due to the similarity of their weather in Niigata City. As weather affects clouds and wind, GPV (Grid Point Value) data provided by the Japan Meteorological Agency (JMA) and calculated with the Global Spectral (GSM) and Meso Scale (MSM) models[31], generate weather maps.

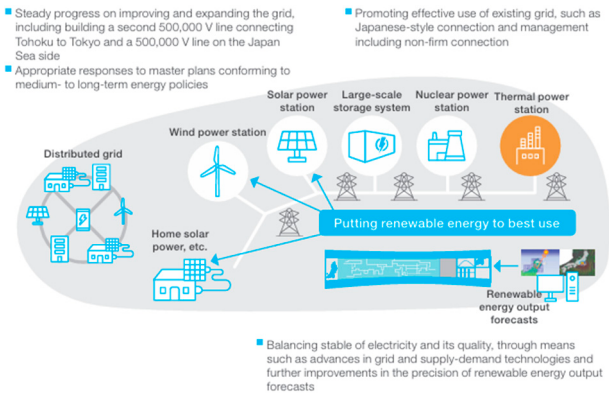


Figure 1. Next-generation network with distributed grid[29][32].

This research is simulated-based under MATLAB, Python, and Excel platforms. In section 2, we predict photovoltaic power. In section 3, the prediction of wind power (WP) is also presented in

details, and section 4 is about the power balance along with, the simulation results and discussion. The prediction times are 6-minutes, 1-minute, and 1-hour respectively, for the start-up time of the hydrogenator, the data logger collection time for PV panel at Niigata University and converted actual wind speed data from JMA, and planned power generation of VRE except hydro, respectively. The evaluation of power system stability (PSS) is presented and discussed within ± 0.2 Hz of the electricity frequency fluctuations range of Tohoku Electric Power Network Co. Inc., to verify the proposed system’s grid integration.

2. Prediction of Photovoltaic Power

PV power is predicted by autoregressive modelling and CDF. Actual data from a 30 Wp solar photovoltaic panel at Niigata University are measured every minute from a data logger and converted to a PV power plant set at 93 MWp for Niigata City. 6-minutes autoregressive PV power prediction (6ARP) is performed on this measured data using Python. NHK cloud distribution forecast (CDF)[33] data are collected online from the NHK website[33] for 1-hour NHK prediction (1HP) that, contribute to estimate the 93 MWp PV power plant planned power generation. The CDF data are collected from the NHK website every hour, to get a 24 hours CDF image dataset. Basically, under the “mesh” section in the NHK website, 1-hour NHK prediction (1HP) images results are available every hour for 12 hours. From this principle the rest of the CDF data are collected accordingly in 2 or 3 steps to complete the 24 hours dataset. Excel PivotTable converts photovoltaic minutes data to hourly data.

2.1. Mesh Design for PV Power Estimation

In this paper, mesh[34][33] referring to the CDF data is the topology of a network whose components are all connected directly to every other component. Also, it is the number of regular openings per linear inch or centimeters, that are digitally drawn on Google Drawings as shown from Figures 2–4. A mesh covers the 726.45 km² of Niigata City inhabited by 505,272 people in 2024[35], and is put on the NHK cloud distribution forecast (CDF)[33] data in Google Drawings. Figures 2–4 show examples for winter, spring, summer, and autumn 2024 at 1 PM. As mentioned in section 1, the dataset of autumn is considered same as those of spring in this paper as a setting. In our previous research[30] we did not set any land distribution ratio based on CDF data like in this research, and even the proposed mesh method is different.

- * The picture is taken from the CDF data and Google Maps;
- * A mesh is designed on the picture to cover Niigata City.

The scale of the picture is 1:20 km both for the CDF data and Google Maps. Therefore, we can draw in Google Drawings the blue line which represents Niigata City, along with the 7x7 rectangles that form a mesh with the red, yellow, and grey lines as shown in Figures 2–4. Each rectangle is identified by a number to complete the entire mesh counted from 1 to 49. The rectangles completely inside the shape of Niigata City are indicated in red while others are in yellow and grey colors. The CDF data with orange, grey, dark blue, clear green and white colors, stand for sunny, cloudy, rainy, rainy with snow, and snowy clouds, respectively.

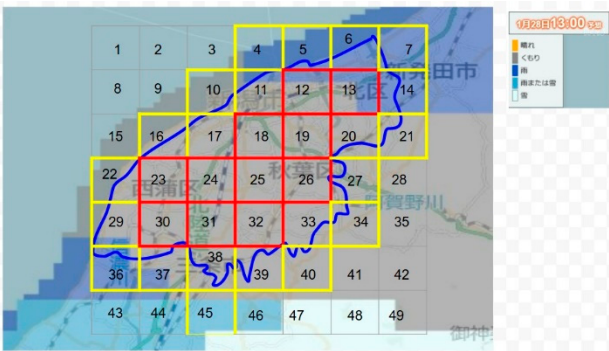
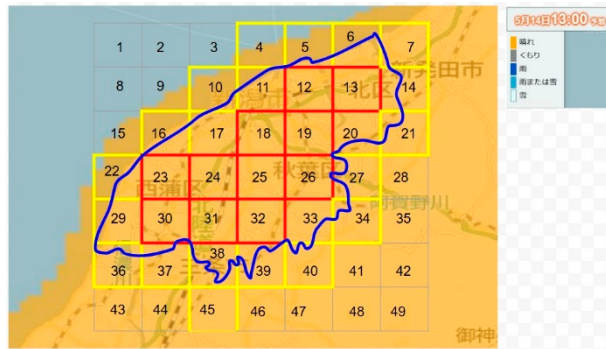
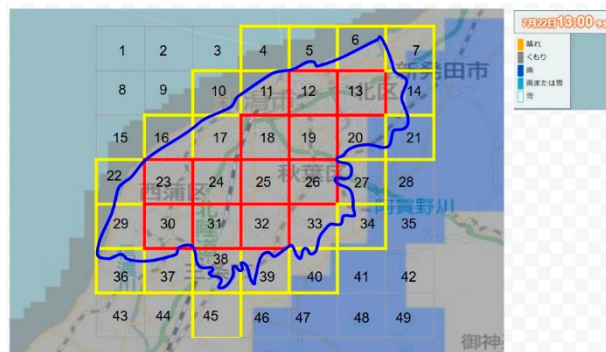


Figure 2. Mesh on CDF data (28/Jan/2024).**Figure 3.** Mesh on CDF data (14/May/2024).**Figure 4.** Mesh on CDF data (22/July/2024).

To get the Photovoltaic estimated power (PVE), each rectangle is set to have both a CDF and land coverage percentage. Supported by NASA (The National Aeronautics and Space administration), NOAA (The National Oceanic and Atmospheric Administration), Table 1 relates power generation with the CDF settings[36][37], while referring to Figure 5, Table 2 elaborates more about the PVE by clarifying in details the land coverage settings. The entire mesh is formed by 49 rectangles represented in column 1 of Table 2, and each rectangle is identified by a number. Furthermore, in column 1, line 2 of Table 2, rectangles 1-3, 8, 9, 15, 28, 35, and 41-49 are, referring to the blue line of Figure 5, not in Niigata City.

Concerning column 2 of Table 2, we set for each rectangle a land distribution ratio based on the CDF data. Assuming that, the inside of the blue line representing the shape of Niigata City is full of land, we can for further illustration purposes, set rectangles 12, 13, 18, 19, 23-26, 31 and 32 land distribution value at 1 each, which means full of land. But, for rectangles 1-3, 8, 9, 15, 28, 35, and 41-49, there is no connection with the blue line meaning that we can set their respective land distribution to 0 which means no land. Then, as the blue line covers parts of rectangles 4 -7, 10-14, 16-27, 29-34, and 36-40, we can accordingly set their land distribution value to 0, 0.17, 0.65, 0.08, 0.15, 0.7, 1, 1, 0.4, 0.4, 0.95, 1, 1, 0.8, 0.2, 0.4, 1, 1, 1, 1, 0.27, 0.75, 0.99, 1, 1, 0.8, 0.1, 0.21, 0.17, 0.56, 0.32, and 0.08, respectively. These values are fixed and not related to the daily weather, time, CDF, or season of the year. Equations 1 and 2 support for the AC solar photovoltaic (PV) generation output by the inverter.

$$P_t(W) = \frac{90}{100} \times 93 \times 10^6 \times \left[\frac{CSP}{30} \times \frac{\sum_1^{49} LCI}{\sum_1^{49} RLR} \right] \quad (1)$$

where P_t , is the Alternating Current (AC) solar photovoltaic (PV) generation output by the inverter, and CSP, LCI, RLR stand for Clear Sky Power, Land and Cloud Impacts, and Related Land Ratio, respectively.

$$LCI = RLR \times [(SA \times 1 + CA \times 0.3 + RA \times 0.1)]$$

(2)

where SA, CA and RA mean Sunny Cloud Amount, Cloudy Cloud Amount, and Rainy Cloud Amount in Table 1. The ratio of rainy with snow, as well as of snowy clouds are not considered in Equation 2 because a shown in Table 1, their generation capacity is set to zero. Equation 2 is developed to calculate the corresponding land and cloud impacts for every rectangle counted from 1 to 49, and the results are shown in column 3 of Table 2.

Besides, the clear sky data are collected over a period of 24 hours (00 AM-11 PM) and in column 4 of Table 2, we show the temporal clear sky power results. In fact, we have used the Bird model which is a model that estimates clear sky conditions based on the location settings (latitude, longitude, etc.). The clear sky days are assumed for a leap year[38], and for each day of the year, the Bird model provides (in W/m²), data of the direct beam, the direct horizontal irradiance, and of the diffuse horizontal irradiance as well. Among these, the global horizontal irradiance has been used in the current study and it is assumed in the simulations that the maximum irradiance is achieved at the solar panel rated power, i.e. 30Wp at 12 AM, for the winter, spring, and summer cases as we can see from the green curves in Figures 6–8. The values presented in column 4 of Table 2 are for the 30 Wp solar panel at Niigata University, but converted to 93 MWp when plotting. After converting, we assume an inverter efficiency of 90 %, to get $P_t(W)$. In July 21st, 2024 we obtain $P_{2PM}(MW) = 39.1$, as shown in the last line of Table 2. The photovoltaic module type used at a laboratory level of Niigata University is 0.172 m², model#893TGM500-24V72 for 24 volts rechargeable battery & appliance.

Table 1. Settings on clouds and power.

Coverage type	Amount	Generating power
Sunny	0	1
Cloudy	0.7	0.3
Rainy	0.9	0.1
Rainy with snow	1	0
Snowy	1	0

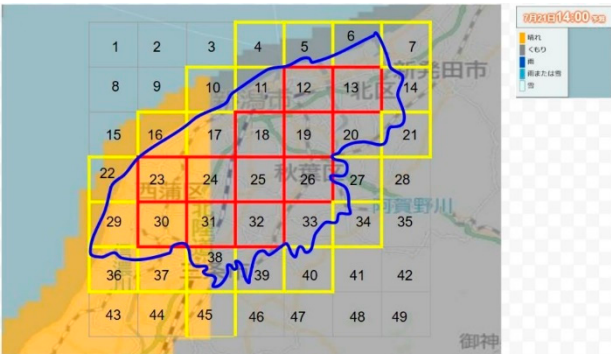


Figure 5. Mesh on CDF data (21/Jul./2024).

Table 2. Power estimation method.

Rectangles (1-49)	Related land ratio	Land and cloud Impacts	Temporal clear sky power (Wp)
1-3, 8, 9, 15, 28, 35, 41-49	0	0	0
4	0	0	0
5	0.17	0.04539	0
6	0.65	0.195	0
7	0.08	0.024	0
10	0.15	0.07875	0

11	0.7	0.21	3.139
12	1	0.3	9.202
13	1	0.3	15.327
14	0.4	0.12	20.884
16	0.4	0.4	25.402
17	0.95	0.6175	28.521
18	1	0.3	30
19	1	0.3	29.7254
20	0.8	0.24	27.72
21	0.2	0.06	24.132
22	0.4	0.34	19.25
23	1	1	13.46
24	1	0.65	7.273
25	1	0.3	1.463
26	1	0.3	0
27	0.27	0.081	0
29	0.75	0.75	0
30	0.99	0.99	0
31	1	0.65	
32	1	0.3	
33	0.8	0.24	
34	0.1	0.03	
36	0.21	0.21	
37	0.17	0.17	
38	0.56	0.364	
39	0.32	0.096	
40	0.08	0.024	
$P_{2PM}(MW)$		39.1	

Since we used the Bird model for PV clear sky power estimation at Niigata City[38]-[30], Figures 6–8 highlight in green the clear sky data for the 93Wp PV power plant for the winter, spring, and summer cases, respectively. Then, from Equations 1 and 2, we compute the DC power in Excel, i.e., to get the PVE before the inverter highlighted with red color, and in orange, is the converted measured data from the 30 Wp solar panel of Niigata University.

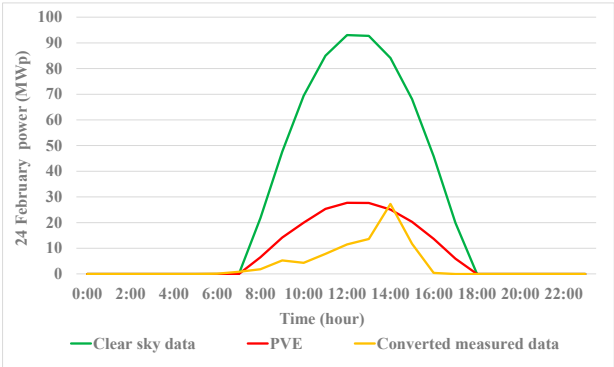


Figure 6. Power of the 93 MWp PV plant (24/Feb./2024).

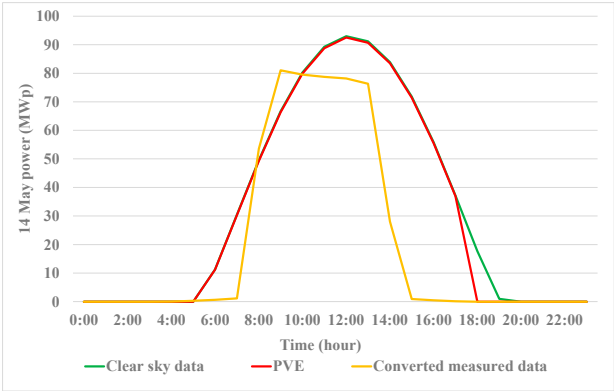


Figure 7. Power of the 93 MWp PV plant (14/May/2024).

Due to the influence of temperature on solar panels, the 30 Wp solar panel’s measured value can sometimes be higher than the rated value, which justifies why in Figure 7, the converted measured data, are higher than the clear sky data at 8 and 9 AM. The impact of this error is checked from the simulations results of the electricity frequency fluctuations.

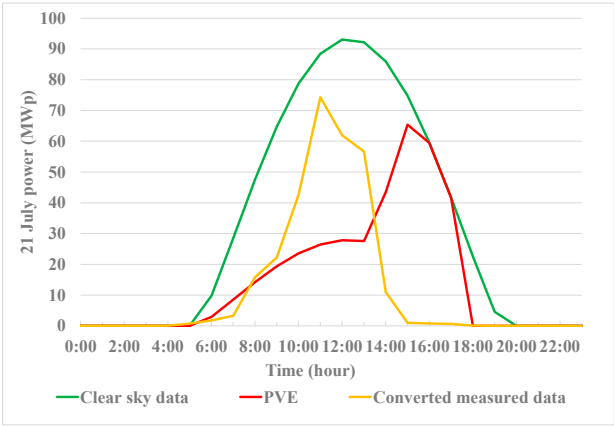


Figure 8. Power of the 93 MWp PV plant (21/Jul/2024).

2.2. Niigata City Daily Power Curve

The Tohoku Electric Power Network Co. Inc., supplies 7 prefectures in Japan including Niigata, and Figure 9 highlights the grid settings along with the power stations locations defined in the 2024 Tohoku Electric Power group integrated report[29]. The daily power curve data are available online at the power company webpage, then the value is apportioned to fit the Niigata City population. MATLAB interpolation table converts daily power curve hourly data into 1-minute data by the spline interpolation.

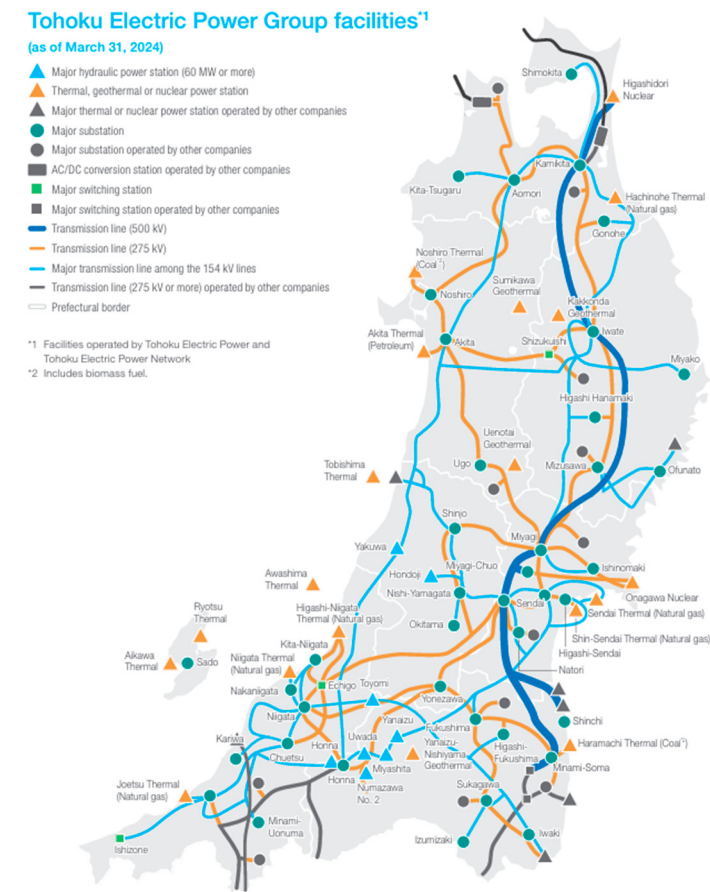


Figure 9. Grid specifications and power station locations[29][32].

Figure 10 shows the required power at Niigata City on January 28th, May 13th, and July 17th 2024 for the winter, spring, and summer cases.

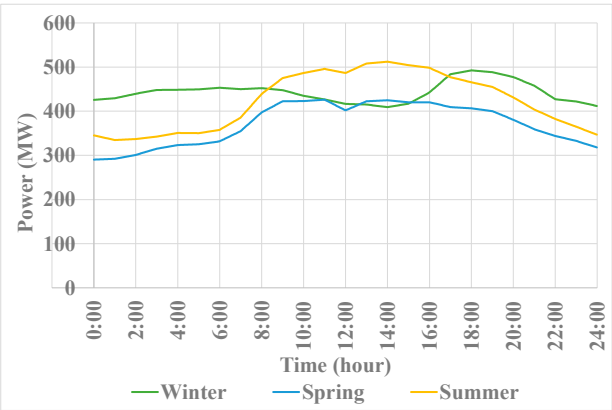


Figure 10. Daily power curves.

3. Prediction of Wind Power

Wind power is predicted from wind speed, using 6-minutes autoregressive wind speed prediction (6ARW). The 1-hour GPV wind farm (1HWF) is the planned power generation obtained from the GPV wind speed prediction data by Excel computation.

Due to the geographical wind distribution, the output of a wind farm with 10 turbines is not the same as the multiplied output of a single turbine. For example, Figure 11 highlights the wind farm arrangement with lines A and B. The first line includes turbines A1, to A5, which are vertical to the

wind direction and, in parallel with line B made by turbines B1 to B5. For example, we assume that the wind observed in line A will reach line B after 2 minutes, and that the distance between these 2 lines is 1km. Similarly, the distance between turbines A1 and A2, is 1 km same as the distance between A2 and A3, A3 and A4, A4 and A5, A1 and B1, B1 and B2, B2 and B3, B3 and B4 and, B4 and B5, as arranged in Figure 11. Furthermore, the power performance of the aerodynamics of double rotor vertical axis wind turbine (VAWT) array is significantly influenced by the relative rotational direction and positioning, ~8% in power coefficient (CP), while it is marginally dependent on relative phase lag[39]. However, the influence of geographical wind distribution in the calculation of wind farm power is considered as part of the limitations of this paper.

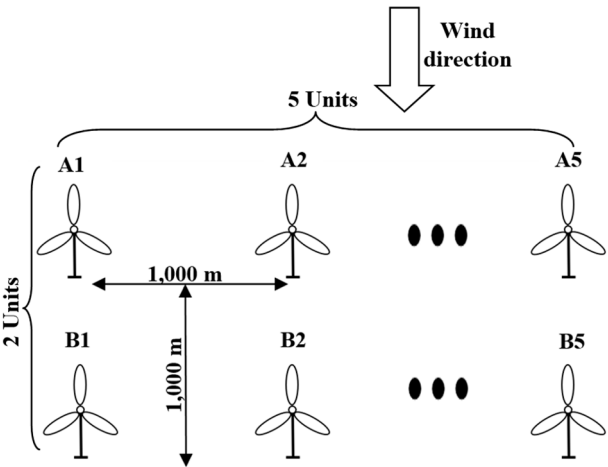


Figure 11. Arrangement example of the wind farm.

We set testing and evaluation days chosen randomly in all seasons to perform the simulations. The power system control in this research is created by using testing days data and, evaluated by evaluation days data. So, testing day and evaluation days in winter are January 28th, and February 22nd and 24th, respectively. In spring, testing days are May 13th and 15th while evaluation days are May 14th and 16th. Then in summer, July 17th and 21st are the testing days, and July 18th and 22nd, the evaluation days. We set wind farm capacity at 20 MW by combining 2 MW Vestas wind turbines[40]. Basically, the theoretical power available for hydro is calculated with Equation 3, but it is assumed in this research a hydropower capacity (HC) of 20 MW.

$$P_{hydro}(kW) = \rho \times Q \times g \times h \times \eta \tag{3}$$

where P_{hydro} , is the theoretical power available, ρ the water density is 1,000 kg/m³, Q the water flow in m³/s, g the acceleration of gravity is 9.81 m/s², $h(m)$ the falling height or head and, η the efficiency usually ranges between 0.75 to 0.95.

The Start-up test results of a vertical-shaft, single-wheel, single-flow Francis Turbine of the Okumen Power Station (rated power 34.5 MW) performed under the jurisdiction of Niigata Enterprises Bureau for reference purposes, show in Table 3, that the starting time of the hydroelectric generator is 347 seconds. From this, a cut-off time of 360 seconds or 6 minutes is set as the starting time of the hydro generator. That is why to prevent lack of electricity generation, we perform 6-minutes autoregressive wind speed prediction (6ARW). MATLAB interpolation table converts wind speed GPV hourly data and, actual wind speed 10-minutes data into 1-minute data by the spline interpolation.

Table 3. Starting characteristics of hydro generators.

Time since start-up operation (s)	
To the end of bypass valve opening	21

Until the end of the main valve opening	156
Waterwheel start-up	160
Up to excitation	206
Until the automatic synchronization system is activated	233
Up to synchronous parallelism	245
Up to a given load	347

Wind speed is also predicted by autoregressive modelling. In fact, an autoregressive model is a type of time series model that assumes the current value of a variable depends on its previous values. In other words, what happened in the past can give us a clue about what might happen in the future. It is like using historical data to forecast upcoming trends. Autoregressive models (AR) provide valuable insights into time series forecasting by leveraging a variable’s own past values. This simple yet effective approach helps us make informed predictions about future trends and patterns. Autoregressive (AR) models serve as fundamental tools in time series analysis and forecasting, enabling us to make more accurate and data-driven decisions[41].

Figure 12 shows the actual wind speed in Niigata City on February 22nd, May 15th, and July 18th, 2024.

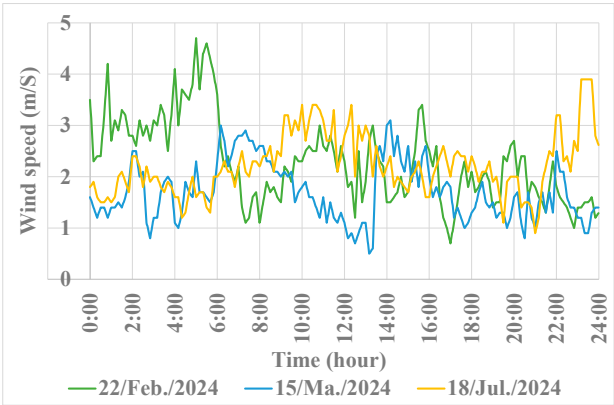


Figure 12. Actual wind speeds.

The Japan Meteorological Agency (JMA) provides wind speed data at sea level, and for Niigata city it is 15.1 meters in height[42]. We need to bring the actual and GPV wind speed prediction data to both the site, and Vestas’s wind turbine specifications. We call it wind speed correction in this research in accordance with the Hellmann exponential formula[43], and to perform the correction, Table 4 [44] provides the required coefficients. From the Niigata City topography, we divide the ratio of the sea in the vicinity location by the coast on windward location to obtain the required wind speed ratio to compute the correction. Figures 13–15, show the related wind speed predictions together with the GPV wind speed results for the 3 seasons of the year 2024, as examples. The GPV corrected wind speed used to calculated the planned power generation is represented in green while the actual corrected wind speed is represented with the red color.

Table 4. Carruthers wind speed ratios[44].

Location	Ratio
On the sea	0.60
Low-lying Island	0.55
Coast on windward side, low land in the vicinity	0.50

Downwind side of the coast, low land, or sea in the vicinity	0.40
Open land with few obstructions	0.40
Shielded land and cities	0.30

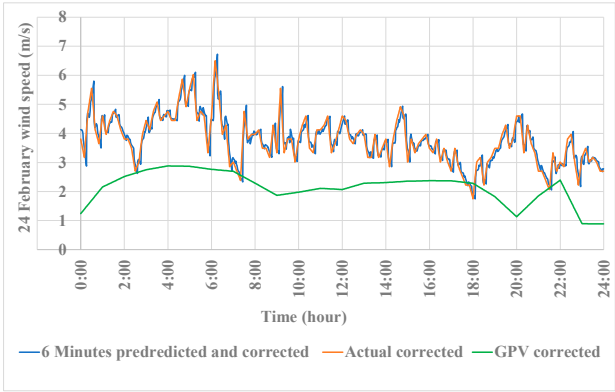


Figure 13. Wind speed forecasts (24/Feb./2024).

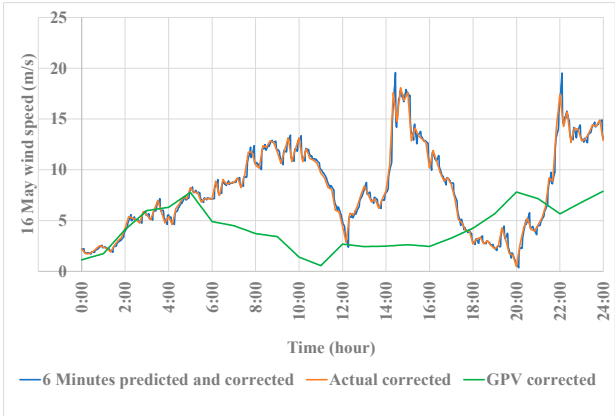


Figure 14. Wind speed forecasts (16/May/2024).

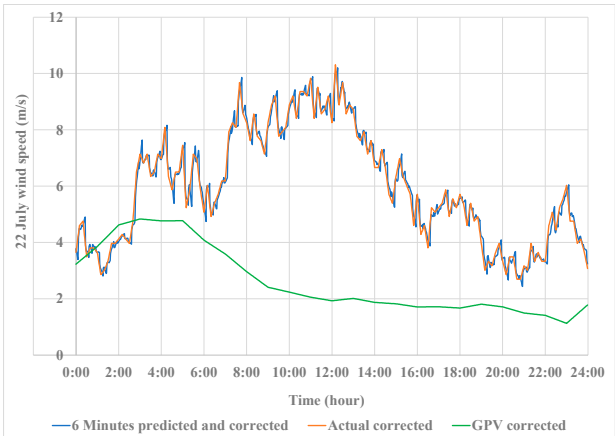


Figure 15. Wind speed forecasts (22/Jul./2024).

Since the power system control in this research is created by testing days data and, evaluated by evaluation days data, chosen randomly, the simulations were made for many different days in the same season and are also chosen randomly for presentation in this paper, which explains why the dates in the Figures are sometimes different for the same season of the year.

The wind turbine power curve is highlighted in Figure 16. In fact, by choosing a couple of points (power, wind speed) on the technical datasheet of the Vestas V80-2.0MW wind turbine, we set the polynomial order at 5 in Excel and using the Excel LINEST function, we get -10.151, +836.342, -25696.743, +352324.215, -1909204.441, and 3481877.384, respectively as the equation’s coefficients. By replacing the variable of this polynomial equation with wind speed taken from 0-25 m/s, and computed in an Excel “IF function” with conditions based on the cut-in (4 m/s), rated (16 m/s), and cut-out (25 m/s) wind speeds that are defined in the datasheet, we get the result as shown in Figure 16.

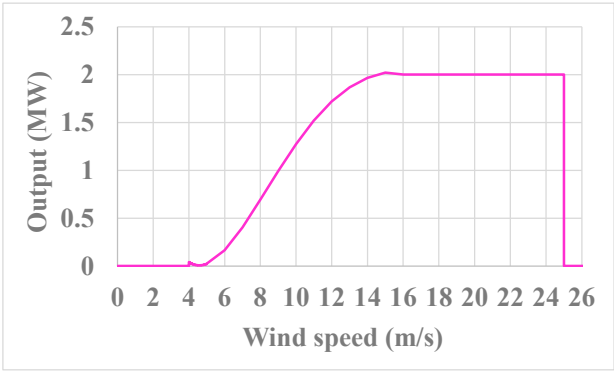


Figure 16. Wind turbine power curve[40].

4. Power Balance Simulation

Hydro is added up to 20 MW to get $\Delta P=0$. When hydro power generator is in operation, variable output control with an assumed rate of 10 %/minute is performed[45]. In the case of a shutdown state, it takes 6-minutes to start up, so wind speed prediction after 6-minutes is required, and the system is controlled to eliminate the difference with the daily power curve. We can only increase hydro at a maximum rate of 10 %/min. Figure 17 elaborates more about the power balance.

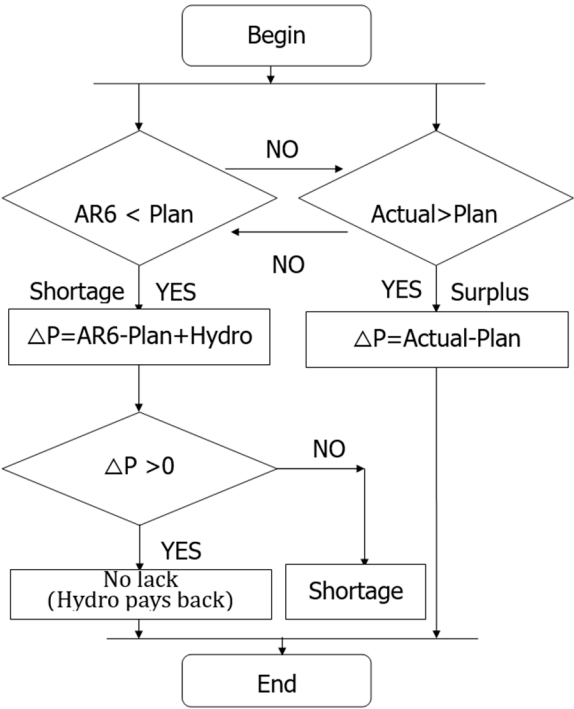


Figure 17. Power balance flow chart.

In Figure 17, AR6 means 6-minutes autoregressive wind farm prediction plus, 6-minutes autoregressive PV power prediction output (6ARP), Plan means 1-hour GPV wind farm (1HWF) plus 1-hour NHK prediction (1HP), then Actual means, Wind farm actual power (WFA) plus photovoltaic estimated power (PVE).

animals or humans, and other studies that require ethical approval, must list the authority that provided approval and the corresponding ethical approval code.

4.1. Simulation Results

From these wind speeds, we can simulate the power generation curves as shown in Figures 18–20.

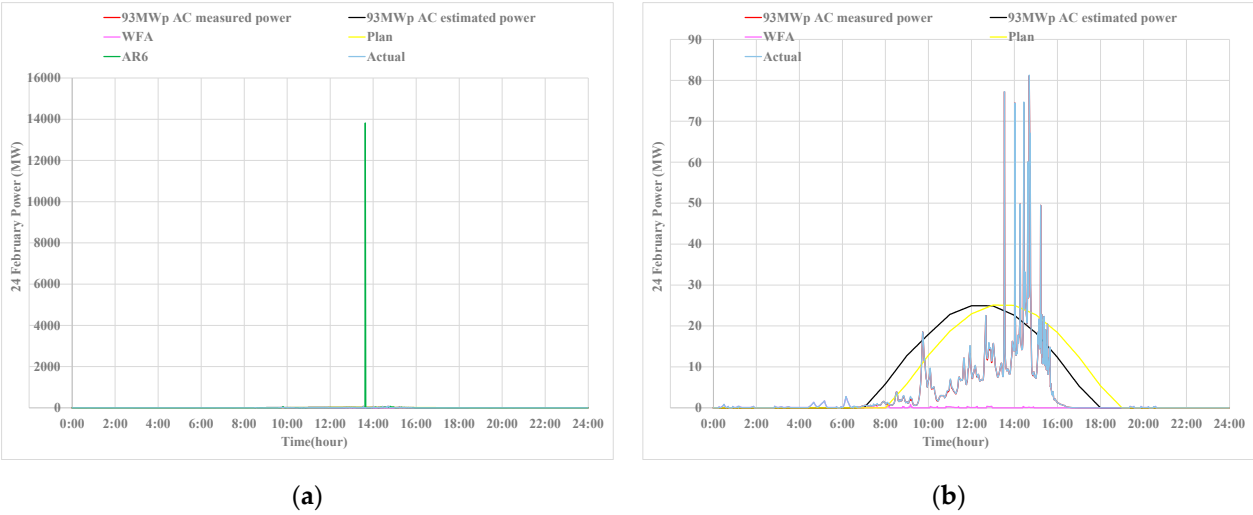


Figure 18. Power generation change example (24/Feb./2024).

The 6-minutes autoregressive PV power prediction (6ARP) from Python unexpectedly gave 13,814MW at 13:38 PM in Figure 18a, which is very high compared to other power curves values, preventing them to be fully seen. The error might be related to the Python autoregressive model (AR) simulation and its Influence on the frequency stability results is discussed in the latter section. However, by isolating AR6 of Figure 18a, we can obtain Figure 18b showing other power curves in detail.

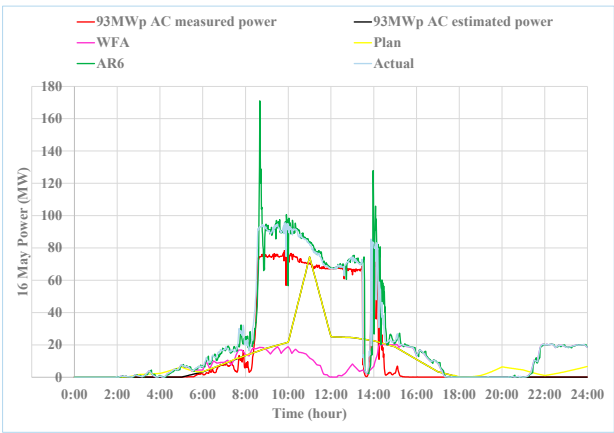


Figure 19. Power generation change example (16/May/2024).

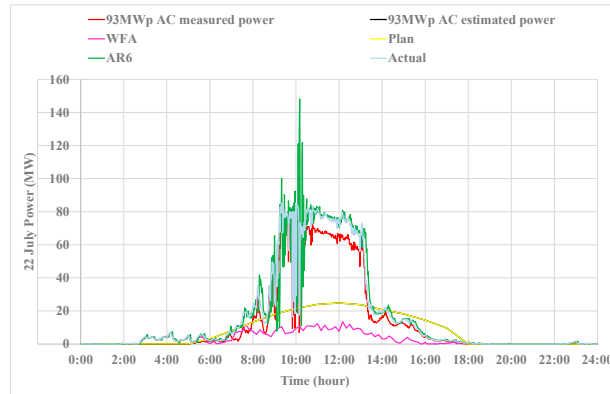


Figure 20. Power generation change example (22/Jul./2024).

Equation 4 support the frequency fluctuations of electricity calculation. We set in Excel a curve smoothing factor of 0.2. So, the frequency fluctuation Δf (Hz) at the power grid is,

$$\Delta_f = \frac{\Delta_P / P}{K} \quad (4)$$

where P (MW) represents all the generated output power same as the daily power curve, and Δ_P (MW) the difference between the predicted photovoltaic and wind farm outputs. Then K (%MW/Hz) represents the frequency characteristic. Considering the worst-case scenario, we use a K value of 10 in this research. Figures 21–23 highlight accordingly the change in the frequency of electricity.

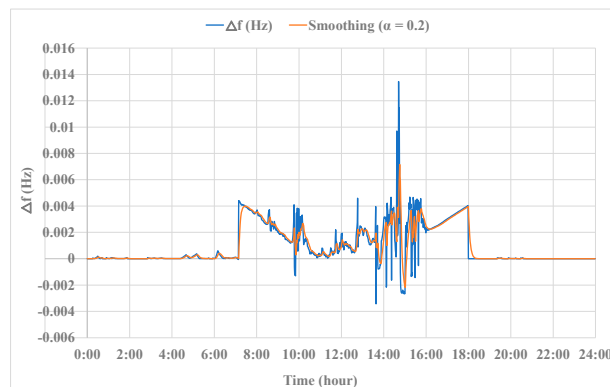


Figure 21. Frequency fluctuation example (24/Feb./2024).

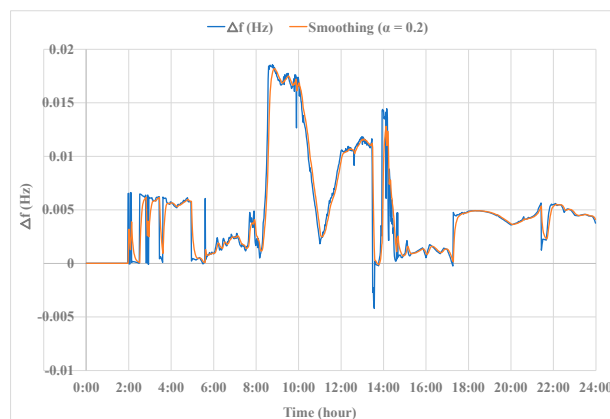


Figure 22. Frequency fluctuation example (16/May/2024).

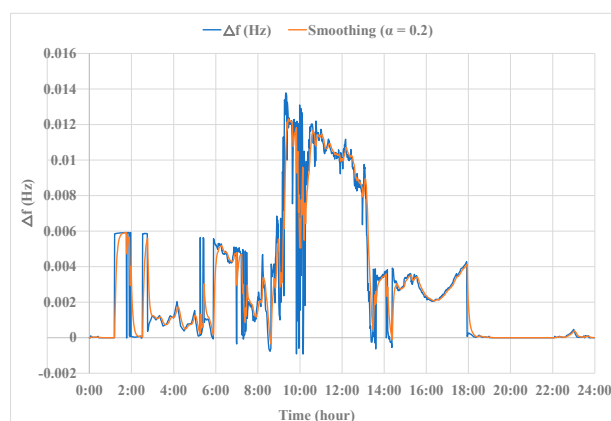


Figure 23. Frequency fluctuation example (22/Jul./2024).

4.2. Results and Discussions

The power system stability of the proposed Hybrid Power Plant (HPP) is evaluated from the frequency stability (FS) simulation results. Tohoku Electric Power Network Co. Inc., provides electricity at 101 V - 50/60 Hz, with permissible limits of ± 6 Volts and ± 0.2 Hz for voltage and frequency fluctuations, respectively. i.e., if the proposed HPP's simulation results of electricity frequency fluctuations for testing and evaluation days are within these ± 0.2 Hz, power system stability is achieved. The proposed Hybrid Power Plant (HPP) includes a 93 MWp solar photovoltaic (PV) power plant set at Niigata City, a thermal power plant provided by the Tohoku Electric Power Network Co. Inc., through the daily power curve, and a 20 MW wind power plant supported by a 20 MW hydropower plant. After seasonal simulations, we reach the maximum value of +0.013 Hz at 14:42 PM and the minimum value of -0.003 Hz at 13:38 PM in winter, then in spring, a maximum value of +0.018 Hz at 08:46 AM and a minimum value of -0.004 Hz at 13:34 PM. In summer, we get -0.00092 Hz at 10:09 AM as the minimum value and +0.0138 Hz at 09:20 AM for the maximum value, which are all within ± 0.2 Hz of the permissible limits of the Tohoku Electric Power Network Co. Inc., and confirm the proposed system grid integration. Despite the error in Figure 18a, the Frequency stability (FS) results are excellent.

5. Conclusions

The simulations results for testing and evaluation days are within ± 0.2 Hz as requested by the Tohoku Electric Power Network Co. Inc. So, the proposed Hybrid power plant (HPP) supplies electricity stably to residents of Niigata City, and increases decarbonization. Further to Ji et al. (2024), hydropower is very important in power balance. Renewable energy has successfully shown its relevance in reducing CO₂ emission in the power generation sector. The new mesh method based on NHK cloud distribution forecast (CDF) and land ratio settings, has successfully estimated the PV power plant generation output. This with the autoregressive modelling are part of our research benefits. As, some countries are making efforts to reduce the effects of global warming, and given that, it has been pointed out that CO₂ emission reduction will not be achieved with short renewable energy grid penetration, this research is clearly in the trend for a sustainable planet. However, in this paper, the following limitations should be addressed in future works. First, a numerical model with mesh size optimization is necessary to improve on the proposed PV output power results. Also, the influence of geographical wind distribution on wind farm power output should be considered in the calculations in future research. The calculation method and results on how much CO₂ is reduced from the proposed HPP should be presented in future works, as well.

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A.SUGAWARA, T.D.TCHOKOMANI MOUKAM, Y.LI and Y.BELLO; investigation, T.D.TCHOKOMANI MOUKAM, A.SUGAWARA, Y.BELLO, and Y.LI; resources, T.D.TCHOKOMANI MOUKAM, Y.LI, and Y.BELLO; data curation, T.D.TCHOKOMANI MOUKAM, Y.LI, and Y.BELLO; writing—original draft preparation, T.D.TCHOKOMANI MOUKAM; writing—review and editing, T.D.TCHOKOMANI MOUKAM, A.SUGAWARA, and Y. BELLO; visualization, T.D.TCHOKOMANI MOUKAM, A.SUGAWARA; supervision, A.SUGAWARA; project administration, A.SUGAWARA; funding acquisition, A.SUGAWARA.

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Nomenclature

PV	Solar photovoltaic;
HC	Hydropower capacity;
6ARW	6-minutes autoregressive wind speed prediction;
6ARP	6-minutes autoregressive PV power prediction;
1HWF	1-hour GPV wind farm;
1HP	1-hour NHK prediction;
WFA	Wind farm actual power;
PVE	Photovoltaic estimated power;
PSS	Power system stability;
FS	Frequency stability;
HPP	Hybrid power plant;
JMA	Japan Meteorological Agency;
CDF	NHK cloud distribution forecast;
SDG	Sustainable development goals;
WP	Wind power;
GPV	Grid Point Value;
NHK	Japan Broadcasting Corporation;
DERs	Distributed energy resources;
COP	Conference of the parties;
UN	United Nations;
VRE	Variable renewable energy.

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