IMPACTS OF INTEGRATING SOLAR AND WIND PLANTS INTO THE POWER NETWORK OF BHUTAN

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***Abstract*—** Hydropower has been the primary source of electricity in Bhutan, and to achieve power security and sustainability, alternative renewable energy sources (RES) such as solar and wind are being explored. However, the literature reviews present that bus voltage is the most affected parameter during integration. Therefore, this paper presents the impact on the bus voltage due integration of RES into the power network of Bhutan. The measured weather and power grid parameters were used as inputs to the solar and wind farm models developed in MATLAB/Simulink. The output from Simulink was then used as input to the solar and wind model in DIgSILENT Power Factory. The existing Bhutan power grid from 33kV and above has been developed in DIgSILENT to study power flow and results were validated against relevant standards. The voltage profile at the individual bus was maintained at 0.95 to 1.05 p.u. The varying hourly load for 24 hours at the different substations was considered. A quasi-dynamic simulation was performed to study the impact on voltage stability of buses at different penetration levels with every 5% increment. It was observed that at a 25% penetration level, the voltage falls below the accepted limit of 0.95 p.u. The Levelised Cost of Energy for the wind was calculated to be Nu. 13.37/ kWh and Nu. 6.02/ kWh and Nu. 6.51/ kWh from Shingkhar and Yongtru solar, respectively.

Keywords— renewable energy sources, integration of wind and solar, penetration level, MATLAB/Simulink, DIgSILENT PowerFactory

I. INTRODUCTION

In Bhutan, hydropower is the primary source of power generation. To achieve power security, and sustainability and to broaden the country's energy mix, alternative sources are being explored. Bhutan's current electricity demand is met by 99.84% hydropower and 0.16% is contributed by the 600kW Rubesa wind farm [1]. Hydropower has been a significant share of the country's economy and had provided one-fifth of domestic revenue and one-third of export earnings in 2016. However, depending on energy sources that rely on the glacier-fed, when climate change is accelerating, raises concerns about energy security. The negative impacts of climate change such as reduced river flow, changing weather patterns resulting in frequent flooding, and in severe cases, glacial lake outburst flood (GLOF) will affect the country's existing and future hydropower development [2].

Globally, due to the depletion of fossil fuels and rising concerns about climate change, most countries invest in renewable energy technologies. China and the European Union are estimated to achieve 94% Renewable Energy (RE) share by 2050. In comparison, India and the United States of America target approximately 92% and 78% of the share respectively [3]. Bhutan is no exception, though almost 100% of electricity in the country is being generated from hydro [4], two wind turbines with 300kW each were installed at Rubesa, Wangdue as a pilot project in 2016 [5]. Nonetheless, various policies, such as the Alternative Renewable Energy Policy (AREP), 2013 have been enacted to promote renewable energies and strengthen the energy security of the country [1]. A Renewable Energy Master Plan (REMP) has been developed for strategic implementations of renewable energy technologies and addresses the cross-cutting issues and project-specific issues [1]. Therefore, Bhutan with such policies and regulations for renewable energy technologies development looks at a new horizon for the diversified energy sector.

The review on the impact of penetration level of the wind power system (WPS) [6] presented that at lower penetration the voltage stability of the network is improved. The study also concluded that when the wind power system is connected at several points in the network there is a positive effect on the voltage stability compared to a single point connection. On the other hand, [7] presented that high penetration of WPS helps in improving voltage stability. The study specified that more reactive power is contributed by turbines as the penetration increases. The investigation on small signal stability [8] on the 9-bus test system of IEEE,

presented that better damping of the inter-mode areas is achieved with DFIG wind turbines. This indicates that the length of the transmission line from the connection point of the wind farm to the network did not affect the network stability. Reference [9] specified that SGs wind turbines are more effective in damping frequency oscillations compared to SCIG wind turbines. However, the study states that DFIG wind turbines do not respond to frequency deviations as their rotor mechanical speed is decoupled from grid frequency. Reference [10] performed steady-state analysis on PV penetrations and observed that overvoltage occurred at transmission line busbars when the penetration level crossed 20%. However, during transient events, a large voltage drop was seen in line with higher penetration of PV. A comparative investigation of the effects of centralized and distributed PV systems on the system voltage stability concluded that the system voltage stability is greatly improved by distributed PV systems than that by centralised PV systems [11]. The same study showed that increased penetration levels of distributed PV systems aided in improving the transient performance of the system. A study on the effect of penetration level of PV on frequency [12] specified that frequency stability is adversely affected at 20% penetration. Reference [13] analyzed the penetration level of PV on a low voltage in Chiang Mai, Thailand. The analysis showed that network voltage rises beyond the standard of 1.1 p.u and only 30% of PV penetration is acceptable.
As the literature reviews suggest that the grid voltage is the most vulnerable parameter during the penetration of wind and solar power. Therefore, this study tries to present the impact on grid voltages through a hypothetical approach to integrating wind and solar plants into the power grid of Bhutan as the country expects the addition of more renewable sources to its energy mix in the future. Additionally, the development of such projects invites huge financial investment, making the cost per unit of energy high, and hence will further help to perform the economic analysis of such projects and determine their techno-economic feasibility altogether.

II. MATERIALS AND METHODS

2.1 Site selection

For the purpose of the study, four potential sites identified for the development of solar and wind farms in the country were selected as the injection point. The sites are listed in Table 1, and an overview is shown in Fig 1.

TABLE 1. Selected Sites

Project Type	Case study sites	Altitude (Approx.)	Latitude	Longitude
Solar	Shingkhar (JAKAR)	3500 m	27°30'16.88"N	90°57'27.31"E
	Yongtru (WANGDUE)	3066 m	27°31'33.01"N	90°14'27.77"E
Wind	Gyeselo (WANGDUE)	1860 m	27°26'52.48"N	89°53'10.00"E
	Rubesa (WANGDUE)	1153 m	27°27'58.01"N	89°54'46.38"E

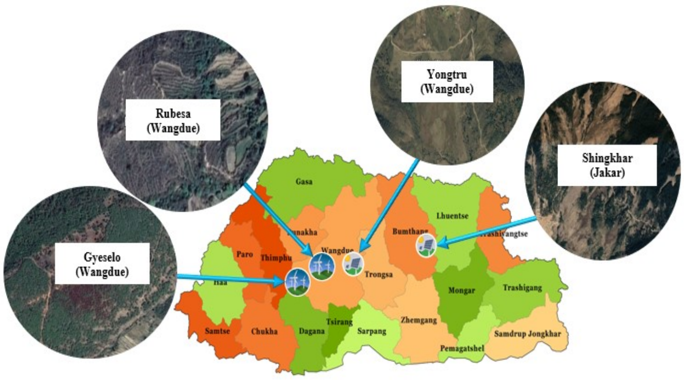


Fig. 1. Overview of the site [Image source: Google]

Shingkhar is located in the Bumthang district, at an altitude of 3500m above mean sea level. It is in the north-eastern region of the country and receives an average annual solar radiation of 5.23kWh/m^2-day at a latitude tilt [14]. To the west of Shingkhar lies Yongtru under Wangdue Phodrang district at an altitude of 3066m above mean sea level. It receives an average annual global radiation of 5.07kWh/m^2-day at latitude tilt [14].

Gyeselo and Rubesa are under Wangdue Phodrang district, at an altitude of 1860m and 1153m above mean sea level respectively. Both the sites have good wind resources and are near the main highway making them decent locations for wind farm development.

2.2 Sites resource assessment

2.2.1 Monthly average insolation

The solar data for Yongtru and Shingkhar were recorded with MS-80A Pyranometer tilted at a latitude angle, (i.e., 30°). It employs the new state-of-the-art thermopile sensor, enabling low zero offset and fast response. The irradiance was measured at an interval of 10 minutes for a rough span of 12 months for Shingkhar and Yongtru. These data were further averaged to estimate the monthly average insolation at the sites as shown in Fig 2 & Fig 3. The annual average solar insolation received at Shingkhar and Yongtru were 4.9kWh/m^2 and 4.5kWh/m^2, respectively. The solar irradiation received at the sites was adequate for solar farm design.

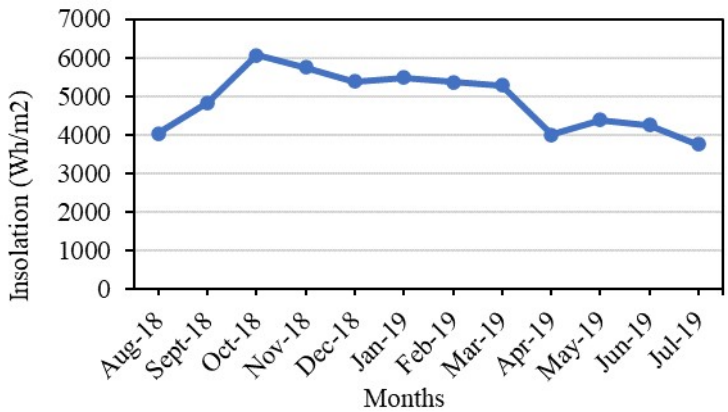


Fig. 2. Monthly Average Insolation at Shingkhar

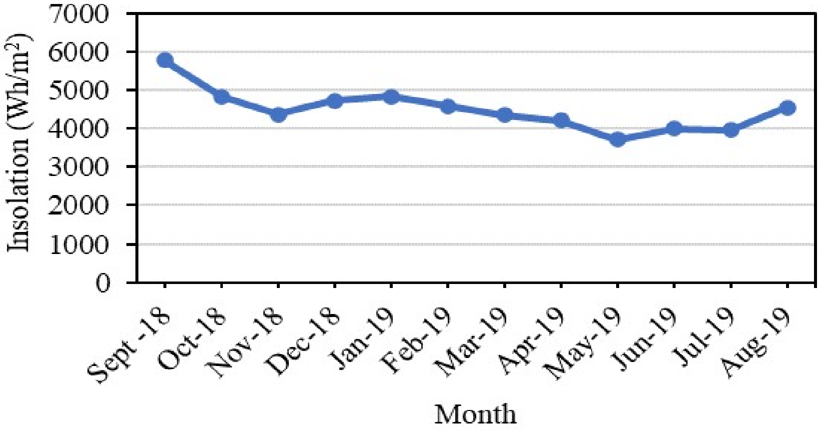


Fig. 3. Monthly Average Insolation at Yongtru

2.2.2 Weibull Distribution

Wind speed is the most critical data required to evaluate the candidate sites' wind power potential as it has a cubic relation with the power [15]. The wind constantly fluctuates with time. It is influenced by local terrain, weather system, and height above the ground. The wind data for Rubesa and Gyeselo were collected for one year, from June 2018 to September 2018. The data was recorded using Thies Anemometer First Class. The wind speed was measured at an interval of 10 minutes. These measured values were divided into wind speed classes, each comprising 1 m/s. The wind's energy content at each location is expressed by the frequency distribution of these wind speed classes. This variation in wind speeds can be best approximated by Weibull distribution as plotted in Fig 4 & Fig 5. Its two parameters, Weibull scaling factor (A) and form or shape factor (k) was used to analyze the wind characteristics at the respective sites.

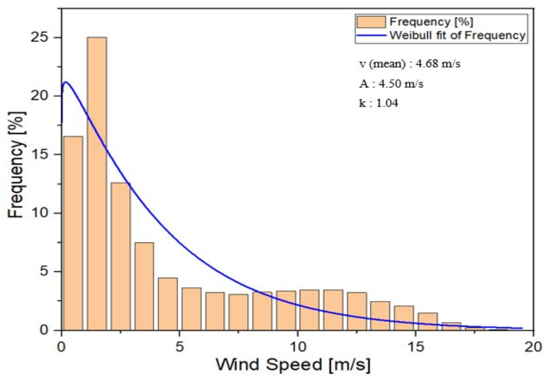


Fig. 4. Weibull distribution of Rubesa site

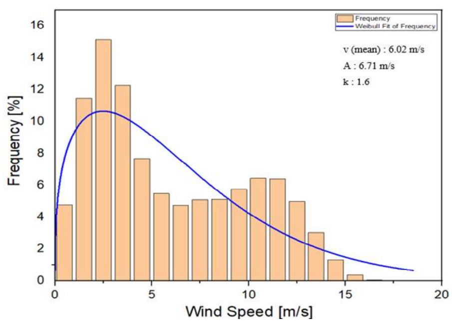


Fig. 5. Weibull distribution of Gysaelo site

From the respective plot it is observed that with k =1.04, Rubesa experiences no wind or a gentle wind most of the days. The site has a mean wind velocity of 4.05m/s. Whereas, Gyeselo almost represents the typical Weibull distribution curve with k =1.6 indicating that more days have speeds slower than the mean speed with few days having high wind. The mean speed at Gyeselo is 6.02m/s.

2.3 Modelling of solar and wind farms in MATLAB/Simulink

Simulink is a graphical modelling and simulation environment for dynamic systems in MATLAB software. It assists the user to use the blocks to represent different components of a system. This environment was used to model the solar and wind farm. The main input variables for the solar model are solar panels' efficiency, an area covered by the photovoltaic (PV) farm, and irradiance in Watt per meter square. The product of which gives the generated power from the solar farm. For typical crystalline silicon PV cells, the commercial cell efficiency ranges from 16-18% [16], and an average of the range was considered in the model (Fig 6).

In contrast, the nominal power generated by the wind farm is the result of a linear relationship with nominal wind speed as shown in Fig 7. When wind velocity is between nominal and maximum value, the power generated is fixed to 1 p.u. The wind velocities were measured at three different heights, 30m, 40m, and 50m. From the past experiences, one of the main factors that affected the wind turbine size for the 600kW Rubesa wind farm was curvy with smaller width roads [1] & [17]. This not only made transportation expensive but also limited the size of the blade. Since there has not been a great change to this factor, the same wind turbine size with a hub height of 41.5m was considered in this study. Therefore, for the potential study, the wind speed at a new height, 41.5m was calculated. The nominal wind speed, 11.5m/s and the maximum wind speed, 25m/s of a 300kW turbine at Rubesa were set for of the modelled wind farm.

The power output from the model is taken as input for the wind and solar generators injected into the existing Bhutan power network grid from the selected site.

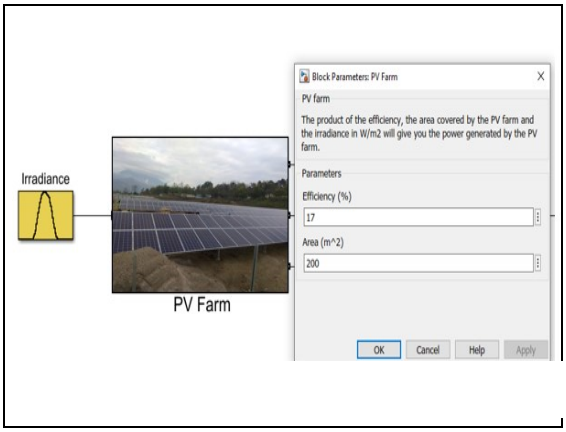


Fig. 6. Solar Farm Model in Simulink

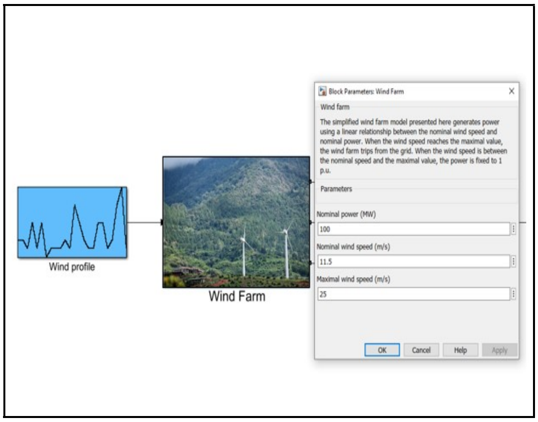


Fig. 7. Wind Farm Model in Simulink

2.4 Steady-state and quasi-dynamic simulation in DIgSILENT PowerFactory

Bhutan's transmission network is extended across all 20 districts with about 1611.484km of line length and 29 sub-stations (1620.5MVA), including one switching station at Chumdo. The transmission grid voltage levels in Bhutan are 400kV, 220kV, 132kV, and 66kV, and voltage levels 33kV and below are deemed distribution voltages. The power network of Bhutan is modelled in DIgSILENT PowerFactory (APPENDIX A-1). PowerFactory offers a platform for modelling and simulation of generation, transmission, distribution, and industrial systems.

The steady-state and quasi-dynamic simulation of the modelled Bhutan power grid without integration with RES was considered the base case. This was carried out to determine the extent of deviation of the network voltage. The voltage violation in the nodes followed the ANSI standard [18] and Grid Code Regulation 2008 [19] as shown in Table 2.

TABLE 2. Bus Voltage Conditions

Bus Voltage	Voltage Condition
> 1.05 p.u	Overvoltage
0.95 p.u - 1.05 p.u	Stable
< 0.95 p.u	Undervoltage

2.5 Determination of Penetration level (PL) of Renewable Energy Sources (RES)

The penetration level of wind and solar power was calculated with (1), adapted from [20];

$$\text{Penetration Level } (PL) = \frac{Power_{RES}}{Power_{Load}} \times 100\% \qquad (1)$$

Here,

$Power_{RES}$ is the amount of power demand met by RES technologies.

$Power_{Load}$ is the total load of the network. A PL of 0% represents load demand is totally met by the grid and 100% PL represents RES technologies entirely supply load demand.

Since four different sites are considered, PL is equally divided into these sites. This is because other than the location, author did not know the availability of the space allocated for the sites. The PL was started from 5% of the total load and is subsequently increased with every 5%. The PL for the individual site is in Table 3.

TABLE 3. Defined Penetration Levels at different sites

Penetration level(%)	Penetration level (MW)	Wind Farms (MW)	Rubesa Windfarm (MW)	Gyeselo Windfarm (MW)	Solar Farms (MW)	Yongtru Solarfarm (MW)	Shingkhar Solarfarm (MW)
5	19.4	9.7	4.8	4.8	9.7	4.8	4.8
10	38.7	19.4	9.7	9.7	19.4	9.7	9.7
15	58.1	29	14.5	14.5	29	14.5	14.5
20	77.4	38.7	19.4	19.4	38.7	19.4	19.4
25	96.8	48.4	24.2	24.2	48.4	24.2	24.2
30	116.1	58.1	29	29	58.1	29	29
35	135.5	67.7	33.9	33.9	67.7	33.9	33.9
40	154.8	77.4	38.7	38.7	77.4	38.7	38.7
45	174.2	87.1	43.5	43.5	87.1	43.5	43.5
50	193.5	96.8	48.4	48.4	96.8	48.4	48.4
55	212.9	106.4	53.2	53.2	106.4	53.2	53.2
60	232.2	116.1	58.1	58.1	116.1	58.1	58.1
65	251.6	125.8	62.9	62.9	125.8	62.9	62.9
70	270.9	135.5	67.7	67.7	135.5	67.7	67.7

75	290.3	145.1	72.6	72.6	145.1	72.6	72.6
80	309.6	154.8	77.4	77.4	154.8	77.4	77.4
85	329	164.5	82.2	82.2	164.5	82.2	82.2
90	348.3	174.2	87.1	87.1	174.2	87.1	87.1
95	367.7	183.8	91.9	91.9	183.8	91.9	91.9
100	387.03	193.5	96.8	96.8	193.5	96.8	96.8

The wind and solar farms were injected at 11kV and 33kV buses. The low voltage side was selected as the point of injection due to the location of the sites. It was found that these voltages levels were nearest to the candidate sites. The Shingkhar solar farm, Gyeselo wind farm and Rubesa wind warm were injected at Garpang (GAR_11kV) bus, Gyeselo (GYE_11kV) bus and Rubesa (RUB_11kV) bus respectively. The Rubesa wind farm however was injected at Rubesa (RUB_33kV) bus (APPENDIX A-2).

2.6 Results and Analysis

2.6.1 Assessment of Bhutan power network at a different RES penetration levels

A quasi-dynamic simulation was performed with a different penetration level of RES. As highlighted in various literature, voltage violation was a major indicator of grid network stability when the grid is integrated with RES. With the integration of RES into the grid, at a 30% penetration level, low voltage buses reached the alert state. On further increasing the penetration levels, violation of voltage at a greater number of buses was observed. The overview of the impact on the network is shown in Table 4. The occurrence of technical violation is indicated by the alphabet letters Y representing Yes, and N representing No. The number in the bracket indicates the number of elements deviating from the standard.

From Table 4, voltage violation as per Table 2, is observed when the RES penetration is at 30%. At 30% penetration bus voltage reaches 0.95 p.u beyond which nodes experience Undervoltage violation, i.e. less than 0.95 p.u. In the considered scenario, the network can be said to be stable till 25% of penetration.

TABLE 4. Overview of Violation on voltage bus at a different Penetration level of RES

Technical Violation	RES Penetration Levels									
	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%
Voltage Stability										
11kV (No.)	N	N	N	N	N	Y (1)	Y (3)	Y (3)	Y (9)	Y (11)
33kV (No.)	N	N	N	N	N	Y (1)	Y (4)	Y (7)	Y (10)	Y (10)
66kV (No.)	N	N	N	N	N	N	Y (5)	Y (10)	Y (15)	Y (19)
132kV (No.)	N	N	N	N	N	N	N	N	N	Y (1)
220kV (No.)	N	N	N	N	N	N	N	N	N	Y (14)

2.6.2 Impact on Voltage Profile – Steady-state flow

The steady-state load flow at different penetration levels illustrates a gradual decrease of voltage at individual buses. A significant voltage drop at 30% penetration was observed in SEMTOKHA_11kV and D-CHOLING_33kV (Dechencholing_33kV) buses as shown in Fig 8 & Fig 9 respectively. A cascading impact on buses was seen as the penetration level was increased. Buses directly connected from wind and solar farm substations got impacted first, followed by buses at distance.

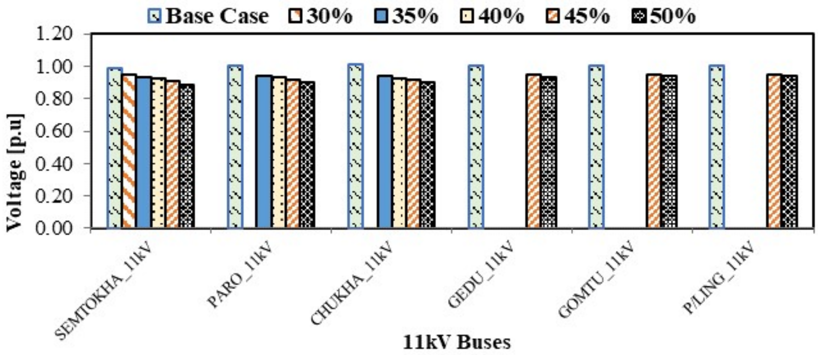


Fig. 8. Voltage profile of 11kV Buses at different RES PL

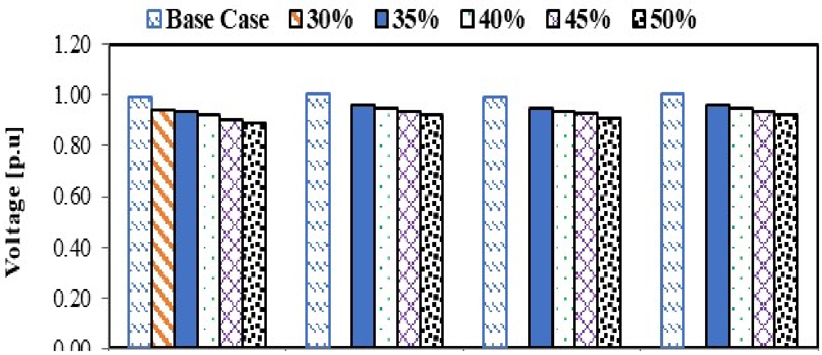


Fig. 9. Voltage profile of 33kV Buses at different RES PL

The decrease in the voltages is due to the lack of reactive power compensator employed in the power network and high injection of only active power from wind and solar farms. The lack of enough reactive power results in voltage drops, line overheating and in a worse scenario, it can cause a total blackout of the networks [21]. Moreover, the sudden connection of wind generators consumes a large amount of current to magnetize the generator [22], this further decreases the voltage in the network.

2.6.3 Impact on Voltage Profile- Quasi-dynamic

Analysis of the impact of node voltage with the integration of wind and solar power is presented with a quasi-dynamic voltage profile at 35% of SEMTOKHA_11kV bus plotted for 24 hours, in Fig 10. The bus voltage starts to deviate from its base case (normal) voltage at 7:00:00 hours, which corresponds to the power injection to the grid from Yongtru solar farm (SF). The bus voltage further deteriorated at 8:00:00 hours and 10:00:00 hours, when power was injected from Rubesa wind farm (WF) and Gyeselo wind farm (WF). The maximum deviation of bus voltage was observed at 13:00:00 hours, corresponding to maximum wind power (33.7MW each) injection for the day from both the wind farms and 93% of maximum solar power (31.6MW).

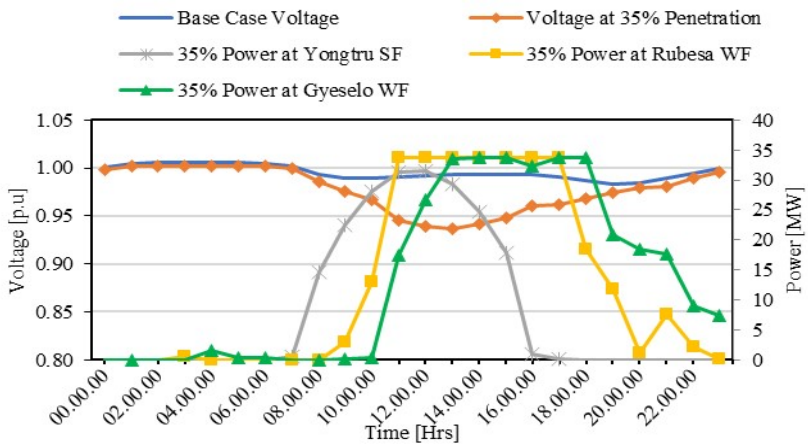


Fig. 10. Voltage violation at 35% PL at 11kV SEMTOKHA_11kV bus

As solar power starts to drop post noon, the voltage begins to rise. However, no significant improvement in voltage is observed as wind power is dominant at those hours. At 16:00:00 hours when solar power is almost zero and a sudden drop in wind power from Gyeselo WF due to irregularity of wind, a spike of voltage improvement is noticed, from 0.948 p.u to 0.960 p.u. The bus voltage gets better towards the late evening when the solar farm has completely stopped generating power and the wind farms are at their lowest generation point.

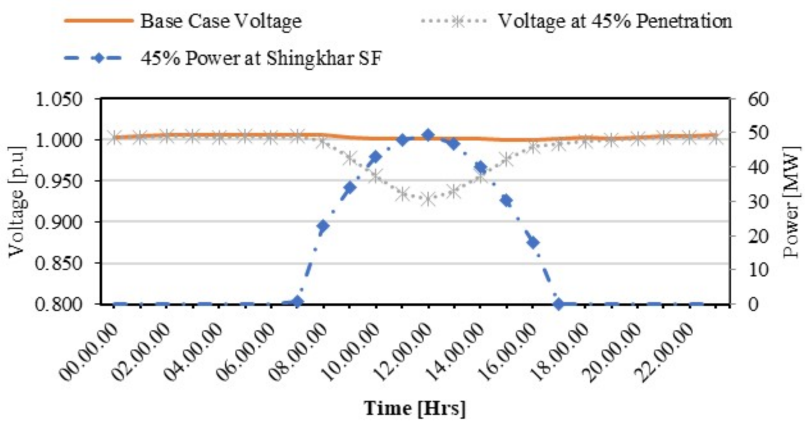


Fig. 11. Voltage violation at 45% PL at 33kV YURMO_33kV bus

Similarly, YURMO_33kV the bus (Fig 11) saw a voltage deviation starting at 7:00:00 hours. At noon when Shingkhar SF injects its maximum power (49.23MW) for the day, the bus voltage reaches as low as 0.929 p.u forcing the bus into severe instability. However, the voltage starts improving, corresponding to a decrease in solar power production. Subsequently, at 17:00:00 hours when there is no sun, the bus voltages rise back to normal.

2.7 Technical and Economic Analysis

Development and investment in renewable energy sources are feasible for Bhutan due to the great potential for wind and solar power, which opens windows of opportunities. This section presents an overview of the feasibility of developing the four studied RES projects, Rubesa WF, Gyeselo WF, Yongtru SF, and Shingkhar WF, on the ground of assumed penetration level.

2.7.1 Technical Aspects

For wind farms, with a wind turbine size of 300kW, a total of 81 numbers is required to generate 24.4MW. Though a higher rating of the wind turbine is available in the market, JICA in their report titled "Data Collection Survey on Renewable Energy in the Kingdom of Bhutan", in 2013, has detailed that mountainous terrains and narrow roads are reasons for limiting the choice to 330kW. This limitation affects the size of the turbine and questions the availability of land area to accommodate 81 numbers of wind turbines and 162 numbers considering wind farms. Such a mega wind farm would be accompanied by its inherent limitations such as wake effects. Wake effects are the aggregate influence on wind farm energy production, which results from the changes in wind speed caused by the impacts of turbines on each other [23]. Most wind turbines in Bhutan are expected to be located on the ridges in the valley without the second rows and with a clear prevailing wind direction uphill [1]. This makes the power stability and evacuation issue a secondary matter to consider in the assumed scenario.

In the case of solar farms, the total system output and total array area can be determined with the following equations [18]:

$$\text{Total system output (kW)} = \text{Rated output per PV panel} \times \text{installation nos.of PV Panel} \qquad (2)$$

$$\text{Total array } (m^2) = \text{Photovoltaic panel size} \times \text{installation numbers of the photovoltaic panel} \qquad (3)$$

Considering this method and considering the space required for facilities such as power conditioning systems (PCS), transformers and administration buildings, a 1MW mega solar system requires a land area of 15,000m^2 [17]. This value is closely related to that of the thumb rule method, where a 1MW solar system requires an area of 4 acres (16187.2m^2), inclusive of all the accessories [24]. Hence, it is befitting to take the average of these two values as the estimated area required for a 1MW solar farm.

Therefore, in the assumed scenario, a total area of 377365.12m^2 is needed at each site to develop a 24.2MW solar farm. The actual availability of the area was not known due to the lack of land survey. The limitation due to transportation is eliminated as both the sites are near the access point. These sites are located in the region where human settlements are less. Therefore, power evacuation from the site to the load centre becomes the primary aspect.

2.7.2 Economic Aspects

Shingkhar Solar Farm and Yongtru Solar Farm produce approximately 91 GWh and 84 GWh of energy annually Table 5. It is seen that average solar irradiance is a driving factor for energy yield. As per [25], the average installed cost of utility-scale solar PV projects was USD 793/ kW and for onshore wind farms, the average installed cost was USD 1200/ kW in India in 2018. For the economic analysis, the cost of the Indian market has been taken into account since India is the closest market.

TABLE 5. Total Investment cost of RES

Renewable Source	Installed capacity [kW]	Total installed cost [$/ kW]	CAPEX [$]	OPEX (30% of CAPEX) [$]	Annual Generation [GWh/a]
Rubesa Wind	24.2×10^3	1200	29,040,000	8,712,000	64.00
Gyeselo Wind	24.2×10^3	1200	29,040,000	87,12,000	64.00
Shingkhar Solar	24.2×10^3	793	19,190,600	5,757,180	91.00
Yongtru Solar	24.2×10^3	793	19,190,600	5,757,180	84.00

TABLE 6. LCOE for solar and wind

Renewable source	Discount rate *(i)*	Capacity factor	Lifetime *(n)*	Capital Recovery Factor (CRF)	Total investment per annum ((CAPEX × CRF) + OPEX) [$]	Annual Generation [GWh/a]	LCOE [$/ kWh]
Rubesa Wind	10%	0.3	20	0.12	12,123,027.5	64.00	0.191
Gyeselo Wind	10%	0.3	20	0.12	12,123,027.5	64.00	0.191
Shingkhar Solar	10%	0.18	30	0.11	9,351,485.306	91.00	0.086
Yongtru Solar	10%	0.18	30	0.11	9,351,485.306	84.00	0.093

The cost is converted into Bhutan Ngultrum (Nu. or BTN) at an exchange rate of 70 Nu. per USD [26]. With this exchange rate, the Levelised Cost of Energy (LCOE) for wind is Nu.13.37/kWh, and Nu.6.02/kWh & Nu.6.51/kWh for Shingkhar and Yongtru solar farms respectively as presented in Table 5.

Currently, the weighted average domestic generation tariff stands at Nu.1.5/kWh [27], this low tariff for hydro becomes a limiting factor for power generation from renewable energy for the said scenario solar and wind are 5 and 10 times more expensive.

III. CONCLUSION

This study aimed to analyze the techno-economic impacts when RES was integrated into Bhutan's electric power network. This was supported by assuming various penetration levels of RES for steady-state and quasi-dynamic load flow. The voltage parameter of the system primarily defined the impact. Further, a short discussion was completed to evaluate the feasibility of the technical and economical point of view for the development of RES in the country.

The penetration limit of renewable energy sources into the current network of Bhutan was 25%, which is equivalent to 96.8MW. Further increase in penetration experienced a severe deviation of the voltage from the said standard. Since the study was on the whole network, cascading impacts on various buses' voltages were witnessed. The overloading of transformers and lines was seen as early as a 5% penetration level. These overloading corresponded to the varying characteristics of solar and wind power.

It was interpreted that though 25% of solar and wind saw clear technical feasibility through quasi-dynamic simulation, the limiting factor became the availability of areas for the development of such mega projects. This was mainly due to the unfavourable geographical features of the country. It was calculated that LCOE for the wind was Nu.13.37/ kWh, and Nu.6.02/ kWh and Nu.6.51/ kWh for Shingkhar and Yongtru solar farms.

REFERENCES

[1] DRE, "Renewable Energy Master Plan 2017-2032.Thimphu," Department of Renewable Energy (DRE), Thimphu, 2016.
[2] IRENA, "Renewables Readiness Assessment: Kingdom of Bhutan," International Renewable Energy Agency (IRENA), Abu Dhabi, 2019.
[3] IRENA, "Global Energy Transformation: A Roadmap to 2050," International Renewable Energy Agency (IRENA), Abu Dhabi, 2018.
[4] NEC, "Intended Nationally Determined Contribution," National Environmental Commission (NEC), Thimphu, 2015.
[5] BBS. (2016, Jan. 26). Bhutan gets its first wind turbine [Online]. Available: URL http://www.bbs.bt/news/?p=56637

[6] I.S. Naser, A. Garba, O. Anaya-Lara, *et al.*, "Voltage stability of transmission network with different penetration levels of wind generation," *45th International Universities Power Engineering Conference UPEC2010*, pp. 1-5, 2010.

[7] R.R. Londero, CdM. Affonso, and J.P.A. Vieira., "Long-term voltage stability analysis of variable speed wind generators," *IEEE Transactions on Power System*, pp. 1-9, 2014.

[8] T. Ayodele, Jimoh, J. Munda, *et al*., "The influence of wind power on the small-signal stability of a power system," *International Conference on Renewable*, pp. 244-249, 2011.

[9] U.B. Qureshi and S.J. Iqbal., "Impact of large-scale wind penetration on power system frequency stability," *2017 Second International Conference on Electrical, Computer and Communication Technologies (ICECCT)*, pp. 1-6, 2017.

[10] S. Eftekharnejad, V. Vittal, G.T. Heydt, *et al*., "Impact of increased penetration of photovoltaic generation on power systems," *IEEE Transactions on Power* Systems, pp. 1-8, 2012.

[11] B. Tamimi, C. Cañizares, and K. Bhattacharya., "System stability impact of large-scale and distributed solar photovoltaic generation: The case of Ontario, Canada," *IEEE Transactions on Sustainable Energy*, pp. 1-9, 2013.

[12] T. Alquthami, H. Ravindra, M.O. Faruque, *et al*., "Study of photovoltaic integration impact on system stability using custom model of PV arrays integrated with PSS/E," *North America Power Symposium 2010*, pp. 1-8, 2010.

[13] P. Kerdouma and S. Premrudeepreechacharn, "Analysis of PV penetration level on low voltage system in Chiang Mai Thiland," *The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019)*, pp. 754-760, 2019.

[14] P. Gilman, S. Cowlin, and Heimiller, "Potential for Development of Solar and Wind Resource in Bhutan," National Renewable Energy Laboratory (NREL), Golden, 2009.

[15] M.R. Patel. Wind and Solar Power System. 2nd edn. Boca Raton: CRC Press, 2006.

[16] T. Saga, "Advances in crystalline silicon solar cell technology for industrial mass production," *NPG Asia Materials*, pp. 96-102, 2010.

[17] JICA, "Data Collection Survey on Renewable Energy in the Kingdom of Bhutan," Japan International Cooperation Agency: Tokyo Electric Power Co., Inc (TEPCO), Tokyo, 2013.

[18] H.V. Padullaparti, P. Chirapongsananurak, S. Santoso, *et al*. Edge-of-grid voltage control: Device modeling, strategic placement, and application consideration. *IEEE Power and Energy Technology Systems Journal*, vol.4, pp. 106-114, 2017.

[19] BEA, "Grid Code Regulation, 2008," Bhutan Electricity Authority (BEA), Thimphu, 2008.

[20] A. Ogunjuyigbe, T. Ayodele, and O. Akinola, "Impact of distributed generators on the power loss and voltage profile of sub-transmission network," *Journal of Electrical Systems and Information Technology*, 2015.

[21] A. Robb. (2019, Jan. 25). Grid inertia: Why it matters in a renewable world [Online]. Available: URL https://www.renewableenergyworld.com/baseload/grid-inertia-why-it-matters-in-a-renewable-world/

[22] A. G. Abo-Khalil, "Impacts of Wind Farms on Power System Stability", in Modeling and Control Aspects of Wind Power Systems. London, United Kingdom: IntechOpen, 2013 [Online]. Available: https://www.intechopen.com/chapters/43156 doi: 10.5772/55090

[23] WindEnergytheFacts. Technology-Wake effects. [Online]. Available: URL https://www.wind-energy-the-facts.org/wake-effect (22 December 2020, date last accessed).

[24] Narasimhan. Area required for Solar PV power plants [Online]. Available: URL http://www.suncyclopedia.com/en/area-required-for-solar-pv-power-plants/ (December 2020, date last accessed)

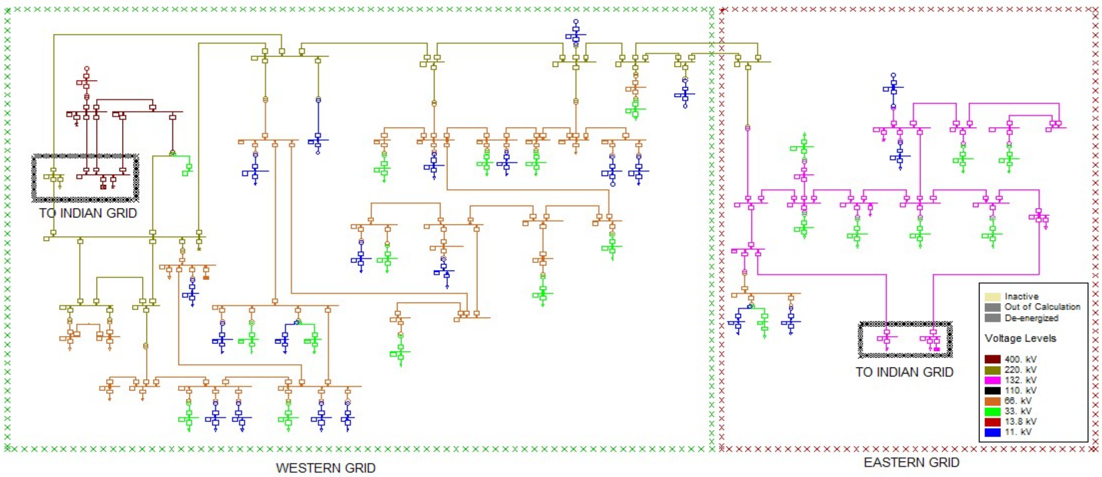
[25] IRENA. "Renewable Power Generation Costs in 2018," International Renewable Energy Agency (IRENA), Abu Dhabi, 2019.

[26] Bank of Bhutan. (2020). [Online] Available: URL https://www.bob.bt/forexnew/ (December 2020, date last accessed)

[27] Bhutan Electricity Authority. (2020). Approved Generation Tariff. [Online] Available: URL http://bea.gov.bt/approved-tariff/ (December 2020, date last accessed)

APPENDIX

A. A-1 Modelled Bhutan Network in DIgSILENT



B. A-2 SLD of Gyeselo Windfarm, Rubesa Windfarm and Yongtru Solarfarm at Lobesa sub-station (LEFT); SLD of Shingkhar Solar farm at Garpang sub-station (RIGHT)