Wind Energy Potential Assessment Based-on WRF Four-Dimensional Data Assimilation System and Cross-Calibrated Multi-Platform Dataset

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Abstract. Indonesia has a target of achieving 23% of renewable energy share in the total energy mix in 2025. However, Indonesia does not have accurate and comprehensive data on renewable energy potentials, especially wind energy. This article aims to assess the theoretical potential of wind speed and to visualize the wind speed by province for the entire Indonesia. Our assessment relied on the Weather Research and Forecasting (WRF) model using Four-Dimensional Data Assimilation technique, also known as Nudging Newtonian relaxation. The robustness of our analysis is confirmed by using high-resolution data from the National Centers for Environmental Prediction – Final (NCEP - FNL) and Cross-Calibrated Multi-Platform (CCMP) Reanalysis satellite data. This study shows the WRF method is a feasible option to estimate wind speed data.

1. Introduction
Wind farm is one of feasible option to decarbonize electricity sector in Indonesia [1]. Wind power resource in Indonesia has been measured by various institutions [2]. However, further reliable and high-resolution assessments of wind energy resources are crucial to improve the quality of wind energy potential data in Indonesia.

This study proposes an assessment methodology that assimilates two weather data sources (i.e., Cross-Calibrated Multi-Platform/ CCMP and the National Centers for Environmental Prediction – Final/ NCEP-FNL) to produce more accurate and higher-resolution data. NCEP data is a common data resource for wind speed assessment due to its accuracy but has a lower resolution than that of CCMP. Meanwhile, CCMP has higher spatial and temporal resolutions but has lower accuracy in high-wind speed (i.e., > 15 m/s) and rainy conditions. Previous studies mostly used data from NCEP only [3-5]. An exception is Hesty and Hadi [6] who assimilated CCMP and NCEP-FNL but their wind energy assessment was only for a specific site (microscale). The novelty of this study is the assimilation of those two-weather data to estimate wind energy in mesoscale with Indonesia as a case.

2. Literature Review
The improvement of the wind energy assessment would not have been as successful without the use of the numerical weather prediction (NWP) model. Micro-level analysis commonly uses models of MM5, Wind Atlas Analysis and Application Program (WAsP), and WindSIM [7-9]. MM5 and WAsP may produce comparable results, but MM5 has a critical advantage in that it only needs reanalysis data without requiring wind measurement data [10]. Reanalysis data is useful for wind resource assessments in a case when observational data is not available. NWP model, a software to describe atmospheric processes and changes, along with reanalysis data is the main tool to construct historical climate data in a regional grid by integrating various past observation and measurement systems. NWP models are useful to downscale reanalysis data sets while adding physical phenomena, due to their smaller spatial and temporal time scales, including the consideration of local topographical features.

The most accurate data for the wind energy simulation is ERA-Interim reanalysis for the onshore area and NCEP-R2 reanalysis for the offshore area [3, 11]. Hesty and Hadi [6] assimilated CCMP and NCEP-FNL to increase data resolution from 27 km into 3 km for wind speed assessment in West Java coast, Indonesia.

The MCP method also uses long-term reference data derived from the NWP model and the atmospheric reanalysis data set [12]. One of the most widely used NWP models is the Weather Research and Forecasting (WRF) model, which provides relatively accurate wind estimates for analysis on flat and homogeneous flat terrain [13, 14]. For higher terrain complexity, WRF requires more detailed terrain data [11]. As a mesoscale model, NWP models are commonly coupled to microscale wind flow model to obtain a higher spatial resolution and accuracy [4].

Our resource assessment lays on an assessment model built from WRF Four-Dimensional Data Assimilation System (WRF-FDDA) FNL and CCMP dataset. These two approaches could provide more accurate and higher resolution data without requiring huge computation resources. The finding of our study calls for more discussions about opportunities of wind energy investments in Indonesia as detailed out in section 5.

3. Methodology

We estimated wind energy potentials by constructing an atmospheric mesoscale model based on a regional wind map. We improved the model by measured wind resource data coupled with a data assimilation technique. For this purpose, we used the atmospheric mesoscale WRF model with a spatial resolution of 5 x 5 km to map wind resources at 50 meters (m) above ground level (agl). The outer domain has a horizontal resolution of 27 km and the resolution for the inner domain is 5 km. It has 35 vertical levels and the lowest crucial levels are at around 10, 30, 52 and 97 m agl. Initial and boundary conditions are from FNL datasets with a spatial resolution of 1 x 1°.

We assimilated ocean surface wind data provided from the CCMP satellite data by coupling numerical model with the Newtonian relaxation technique. The CCMP data contains high-resolution wind data generated from the integrations of wind measurements from Remote Sensing Systems (REMSS) satellites and Variational Analysis Method (VAM). The CCMP surface winds dataset contains 0.25° gridded ocean surface wind. We then added prognostic equations nudging the predicted variables toward available observation data (interpolated in each model grid). The nudging equation:

$$\frac{\partial \theta_m}{\partial t} = \frac{(\theta_{obs} - \theta_m)}{\tau}$$

(1)

where $\theta_m$ is the variable of prognostic model, $\theta_{obs}$ is the measured variable, and $\tau$ is the time scale of a relaxation. The spatial variation of nudging is:

$$f(r) = e^{-r/r_0}$$

(2)

where $r$ is the distance from the measuring point, and $r_0$ is a reference distance representing the nudging range. The weight of the nudging is obtained by multiplying Equations (1) and (2). As a result, the selected optimal relaxation time scale is one hour and the selected nudging radius is 25 km. We then convert the estimated wind speed data into wind energy potentials by assuming that a 1 MW wind
turbine is for one hectare of land with wind speed above 6 m/s and a 100-kW wind turbine is for one hectare of land with wind speed between 4 – 6 m/s.

4. Results

Fig. 1 shows the modelled annual mean wind speed at 50 m agl by using the Geographic Information System (GIS). We classified the wind speed into eight speed classes from below 3 m/s (i.e., the lowest class) represented by green colour to higher than 9 m/s (i.e., the highest class) represented by red colour. Wind resources in coastal areas are extremely high exceeding 5 m/s, which is the average cut-in wind speed for many commercial wind turbines [15, 16]. Furthermore, Fig. 1 shows that the wind speed in several west parts of Indonesian offshore areas is over 7 m/s.

Fig. 1. Indonesia global wind speed at 50 m height - resolution 5 km.

We evaluated the model by using wind measurement data from three meteorological masts (met masts) in University of Cendrawasih (Uncen) - Jayapura, Tamanjaya - West Java, and Bantaeng - South Sulawesi. The met masts observed climatological and weather conditions at a height of 50 m agl. Table 1 summarize the sites of met mast and the measuring period. Fig. 2 compares the average hourly data between the measured data (i.e., blue line) and the modelling results (i.e., red line). The average measured wind speeds are 2.33 m/s in Jayapura, 6.70 m/s in Sukabumi, and 4.66 m/s in Bantaeng. Meanwhile the modelled wind speeds are 2.78 m/s in Jayapura, 7.20 m/s in Sukabumi, and 5.44 m/s in Bantaeng.

Table 1. The coordinate of met mast and measuring periods

| Site     | Coordinate | Measuring periods                  |
|----------|------------|-----------------------------------|
| Jayapura | -2.58249   | 140.6575                          |
|          |            | October 2005 to December 2006     |
| Sukabumi | -7.2688    | 106.5288                          |
|          |            | January to December 2008          |
| Bantaeng | -5.5825    | 120.0475                          |
|          |            | June to December 2006             |

Table 2 summarizes statistical parameters of bias, root mean square error (RMSE), and correlations between the modelled- and observed- wind data. The bias is below 0.5 m/s for all sites or lower than the maximum bias (i.e., + 0.5) proposed by Emery, Tai and Yarwood [17]. The RMSE for Bantaeng is the highest among the other sites while the correlations for all sites are between 0.6 and 0.7. The WRF model produces overestimated results at low wind speeds and underestimated results at wind speed above 9 m/s for all sites.
Fig 2. Measured wind speed (blue color) and modelled wind speed (red color) at 50 m agl in three sites.
Comparing geographical characteristics on different sites can identify terrain effects on wind distribution data. Wind speed distributions and their Weibull-fits of the observed and modelled wind speed at 50 m agl for each mast are different for each location. Sukabumi data has the widest range of wind speeds while the lowest range of wind speed is in Jayapura site. The channeling in Sukabumi is clearly visible; however, the modelled wind speeds are lower than in the observations. One of the possible causes is that terrain model is too smooth. In Bantaeng, most observed data is low wind speed while the modelled data is mostly high wind speed. The WRF model cannot precisely replicate wind directions in Bantaeng even though the terrain is flat. The observation data has higher wind speeds and more northerly component than the modelled data. The deviation is due to the inaccurate representations of surface roughness elements like forests and buildings. Therefore, the representation in numerical weather models should be improved for this specific site. The application of a roughness length alone is not enough to characterize the interaction of atmospheric flows with the surface. The modelled wind speed for Jayapura is stronger than the observed data, but the wind direction in both modelled and observed data is similar. The modelled data appears to capture the directional wind distribution of observation data quite well.

5. Policy Implications

We convert the average wind speed data into wind energy potentials. The potential data is then used by RUEN [18]. The largest potentials are in electricity systems of Java, Madura, and Bali (JAMALI) (24,011 MW) and East Nusa Tenggara (10,188 MW). RUEN has expected to build wind farms with total capacity for 716 MW and 266 MW in those regions respectively [18]. Yet, the feasibility of wind farm should consider at least two other factors that are grid flexibility and electricity tariffs. The JAMALI system is the largest electricity grid system with total electricity supply 149.9 TWh in 2019. Currently, the main electricity supply in the JAMALI system is mainly coal-fired power plants and combined cycle gas turbine (CCGT) for 70.3% and 22.6% of respectively [19]. The JAMALI system does not have neither solar farms nor wind farm yet; however, PV rooftop in the system is growing with installed capacity 4,849 kWp in December 2019 [20]. Moreover, RUEN [18] also expects that the JAMALI system will have wind farms with total capacity 716 MW by 2025. However, wind farm investment in JAMALI system is less interesting since the average generation cost of the State-owned Electricity Company (PLN) in the JAMALI system is only 6.91 ¢ US$/ kWh, which is the ceiling price for PLN to buy renewable-based electricity from independent power producers (IPP). The regulation of Minister of Energy and Mineral Resources (MEMR) No. 53 /2018 [21] and No. 50 /2017 [22] sets PLN regional generation cost in previous year as the ceiling price for regions with generation costs lower than the PLN’s average national generation cost, i.e., 7.86 ¢ US$/ kWh in 2019. In contrast, East Nusa Tenggara systems have average regional generations costs (i.e., 17.58 ¢ US$/ kWh) higher than the average national generation cost. East Nusa Tenggara actually has several separated grid systems with different generation costs. The largest system (and the generation cost in 2019) are Sumba system (20.81 ¢ US$/ kWh), Timor system (18.17 ¢ US$/ kWh), West Flores (17.58 ¢ US$/ kWh), and East Flores (21.28 ¢ US$/ kWh). The generation costs for smaller systems in Nusa Tenggara reached 21.34 ¢ US$/ kWh in 2019. For such regions, MEMR [21] and MEMR [22] allow PLN to buy renewables-based electricity at maximum 85% of regional electricity production costs. It means that the ceiling tariff will be between 14.94 and 18.14 ¢ US$/ kWh, which are higher than average levelized cost of energy (LCOE) of wind power plants around the world, i.e., 4.6 to 9.9 ¢ US$/ kWh in 2019 [23]. However, by assuming VRE only can supply 20% of total electricity productions, East Nusa Tenggara only can take 200 GWh electricity generated from wind turbine. If

| Site    | Bias | RMSE | Correlation |
|---------|------|------|-------------|
| Jayapura| 0.324| 2.300| 0.734       |
| Sukabumi| 0.368| 2.373| 0.736       |
| Bantaeng| 0.324| 2.870| 0.667       |

Table 2. Bias, RMSE and Correlation of Model Results and Actual Data
the capacity factor of wind turbine is 35% [23], total capacity of wind farms that could be installed in East Nusa Tenggara is around 65 MW. Beyond the attractive ceiling tariff, the Indonesia government offers three incentives that are:

a. Import duty exemptions for two years that can be extended for one year [24];
b. Tax holiday up to 20 years [25];
c. Tax allowance [26].

6. Conclusions
This study uses WRF and GIS models to estimate theoretical wind energy resources in Indonesia. The modelled data is then validated by using empirical data measured by three met masts in Jayapura, Bantaeng and Sukabumi. As results, the WRF model is reliable to estimate mean wind speeds in all Indonesia provinces. The wind speeds, presented in a GIS map, are useful information for wind energy planning in national and regional levels. It is the first map for Indonesia context and it also has been used officially by the General National Energy Plan [18]. Our WRF model validated by three measurement data is the initial stage to provide more robust wind maps for the entire of Indonesia. In general, the modelling slightly overestimates the wind speed and the deviations are related to local topographical feature and at low-high wind speed.

This analysis emphasizes that the model outputs have realistic meteorological patterns. Once more data is available, future studies should conduct spatial analysis by points by using other prominent methods such as Inverse Distant Weight and Kriging in GIS environment. Moreover, wind energy potential data should be extended to offshore wind energy potentials.

7. References
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