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Assessment of seismic noise induced by Next-Generation Wind Turbines in the Fulgatore Area, NW Sicily

The detection of gravitational waves with large-scale laser interferometers such as LIGO and VIRGO has opened a new era in physics, and the scientific community is now planning to build the Einstein Telescope (ET), a next-generation detector with significantly higher sensitivity. These instruments are highly sensitive to seismic noise from natural and anthropogenic sources. In particular, the seismic noise generated by wind turbines may have a pernicious effect on gravitational waves detectors. Understanding the implications of the seismic noise generated by wind farms is crucial for mitigating the potential impact that this source of noise poses on their operational performance. For this reason, one of the candidate site to host the ET is located in Sardinia (Italy), one of the quietest seismic sites worldwide. However in this area next-generation wind turbines might be installed in the near future, hence assessing their impact in terms of seismic noise is essential.

To assess the potential impact of next-generation wind farms on the potential ET site, we analyzed the seismic noise generated by a new class of wind turbines (taller and heavier than older models) operating at Fulgatore (TP), Sicily. A one-month seismic acquisition was carried out using six broadband three-component seismometers: four installed at the base of different turbines in Fulgatore and 2 deployed at the archaeological park of Segesta, located about 12–13 km away. To correlate seismic records with wind farm activity, we used turbine operational data at 10-minute resolution provided by EDP Renewables, together with hourly wind data from SIAS. Turbine-induced seismic noise was mainly confined to the 0.1–10 Hz frequency band. For each station, power spectral densities (PSD) were computed on 10-minute waveform segments and compared with turbine operating regimes defined by rotor speed intervals. At the Fulgatore array, PSDs consistently showed narrow spectral peaks across all channels (HHZ, HHE, HHN). Spectrograms confirmed that below 2 Hz the dominant signal corresponds to the Blade Passing Frequency (BPF), ranging from 0.30 to 0.54 Hz depending on rotor speed, and its harmonics. In the 2–10 Hz band, stable peaks were observed at about 2.45 Hz and 5.25 Hz, along with an additional peak at 8.60 Hz restricted to the HHZ channel.

To investigate near-field ground motion polarization, we applied Principal Component Analysis (PCA) based on the singular value decomposition of data covariance matrices. The results indicate that the Blade Passing Frequency (BPF) and its harmonics generate predominantly linear oscillations with dips below 30°, consistent with the stronger amplitudes observed in the HHN and HHE power spectral densities. The spectral peak at 5.25 Hz exhibits linear polarization with an average incidence angle of ~60° and maximum amplitude in the HHZ channel, whereas the 8.60 Hz peak shows vertical linear polarization with dips of ~85°, explaining its exclusive presence in the HHZ spectra. Furthermore, the azimuth of the dominant polarization directions varies with the nacelle orientation, which rotates in response to changes in wind direction.

After characterizing the spectral features of the wind turbines, we extended the analysis to the Segesta site to identify correlations with the wind farm's operation. Results show that the wavefield radiated from the wind farm is attenuated and not detectable at 12–13 km under the local geological and noise conditions. During maximum turbine activity, PSD values at Segesta are approximately 40–60 dB lower than those at Fulgatore in the 2–10 Hz band. Instead, in the band below 2 Hz the difference is lower because all PSDs are affected by the secondary microseismic peak at 0.22 Hz.

Finally, we derived a source time function to represent the vertical motion of a single turbine, constructed from four sinusoids at 0.54 Hz, 1.08 Hz, 2.45 Hz, and 5.25 Hz. Each component was assigned a random phase and an amplitude estimated from RMS ground velocity statistics during maximum operational conditions. Cross-correlation analysis between station pairs at the Fulgatore array showed that phase relationships among different sources are random and exhibit no temporal coherence. Based on these findings, we employed a spectral element method together with the extracted source time function to simulate the propagation of turbine-induced seismic waves. The resulting models provide a basis for future studies at the Sardinian site, enabling predictions of wind farm-generated wavefields under realistic geological conditions.

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