Life Cycle Assessment and Economic Analysis of Wind Turbines Using Monte Carlo Simulation

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The United States depends heavily on nonrenewable energy to generate electricity. Using renewable energy sources, such as wind, could reduce air emissions and fossil fuel dependency. Previous studies have examined the life cycle costs and environmental impacts of using wind to generate electricity, but results have varied due to inconsistent modeling assumptions. This research uses Monte Carlo simulation to conduct an economic payback analysis and life cycle assessment of 11 modern, utility-scale wind turbines (>500 kW). Monte Carlo simulation allows factors such as the energy content of wind turbine materials or electricity prices to be assigned probability distributions, rather than single values. In this way, the variability is considered and the results are computed as a probability of occurrence.

The input and output of materials and energy for each wind turbine (including support structure) are included in this study. Routine wind turbine maintenance is also considered. The power distribution system beyond the turbine (battery or electrical grid) and disposal are not evaluated in this study. The most economically preferred wind turbine was selected for more detailed analysis. Hourly meteorological data was used to compute the wind turbine outputs in 239 U.S. locations. The hourly weather data are averaged across 30 years of historical data. The power output from the wind turbine is calculated from the average wind speed, humidity, and air temperature combined with the turbines power curve at each hour through the year.

A sensitivity analysis of the data reveals that the variance in the model output is primarily caused by differences in location-specific climate data (wind speed, air density). Depending on the location, the median economic payback periods ranged from 2 to 132 years. 41% of

locations had median payback periods less than 10 years, and 63% less than 15 years. Considering a typical turbine lifespan of 15-30 years, wind turbines are not economically viable at all locations. At locations with favorable wind resources, wind turbines are likely to be superior to electricity production using natural gas or coal.

For the preferred wind turbine, the median life cycle energy intensities at all 239 locations ranged from 0.05-0.54 (KWh energy inputs/KWh outputs), compared to 2.3 for natural gas and 2.6-3.5 for coal-fired electricity generation. The median CO_2 (eq) intensity values range from 13-156 g-CO_2 (eq)/kWh for the preferred wind turbine, compared to 585 g-CO_2 (eq)/kWh for natural gas and 757-1042 g-CO_2 (eq)/kWh for coal-fired power plants. SO_x and NO_x intensity values range from 0.04-0.50 g-SO_x/kWh and 0.05-0.66 g-NO_x/kWh for the preferred wind turbine, compared to 0.32 g-SO_x/kWh and 0.57 g-NO_x/kWh for natural gas and 0.72-6.70 g-SO_x/kWh and 0.54-3.35 g-NO_x/kWh for coal power plants.