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Spatial modeling of wind energy potential using GIS in the Patagonian coastal plains

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Abstract

A wind turbine is only as productive as the site beneath it—and picking the right site in a region as wind-rich as Patagonia is less about finding wind than about finding wind where roads, power lines, and environmental constraints align. This research modelled wind energy potential across the Patagonian coastal plains of southern Argentina using GIS-based multi-criteria evaluation. Six suitability criteria—wind speed, elevation, road access, grid proximity, land use compatibility, and environmental sensitivity—were scored across three zones: Northern Plains, Central Coast, and Southern Steppe. Wind data from 18 meteorological stations (2010-2022) and ERA5 reanalysis products provided the resource assessment layer. The Analytical Hierarchy Process (AHP) assigned criterion weights validated by expert consensus (consistency ratio < 0.08). Results showed that 34.7% of the total area qualified as highly suitable for wind farm development, with the Southern Steppe scoring highest for wind resource (mean annual wind speed 11.4 m/s at 80 m hub height) but lowest for infrastructure access. The Central Coast offered the best balance of wind resource and grid connectivity. Estimated installable capacity across all highly suitable areas reached 8,400 MW, enough to supply roughly 6.2 million households at Argentina's average consumption rate. Monthly wind speed profiles confirmed year-round viability, with all three zones exceeding the 7 m/s minimum commercial threshold in every month. These findings provide a spatial framework for guiding wind energy investment toward sites that maximise both energy yield and development feasibility.

Keywords: Wind energy, spatial modeling, GIS, Patagonian coastal plains, renewable energy, multi-criteria evaluation, analytical hierarchy process, wind resource, suitability mapping, energy geography

Introduction

Wind turbines work like fishing nets—the best technology in the world catches nothing if you set it in the wrong spot. Patagonia has been called one of the windiest inhabited regions on Earth, with mean annual wind speeds exceeding 8 m/s across vast stretches of coastal plain^[1, 2]. Argentina's renewable energy programme targets 20% of electricity from non-conventional renewables by 2025, and Patagonian wind is expected to carry most of that load^[3].

But wind speed alone doesn't determine site suitability. A turbine needs road access for heavy equipment delivery, proximity to transmission lines to export power, terrain compatible with foundation construction, land free from environmental restrictions, and community acceptance^[4, 5]. GIS-based multi-criteria evaluation combines these factors into a single suitability score that identifies the spatial overlap between resource availability and development feasibility^[6, 7].

Earlier assessments of Argentine wind potential used coarse national-scale resource maps^[8] or focused on single provinces without integrating infrastructure and environmental constraints^[9]. This research provided the first multi-criteria suitability analysis covering the entire Patagonian coastal plain at a resolution fine enough (250 m) to guide individual project siting.

Calibration and Validation

Wind resource estimates from ERA5 reanalysis (0.25° resolution) were calibrated against 18 ground-based meteorological stations operating within the research area. Monthly mean wind speeds from ERA5 were regressed against station measurements at 10 m and 80 m heights for the period 2010-2022. The calibration yielded $R^2 = 0.89$ for monthly means and

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mean bias error of +0.34 m/s, which was subtracted as a systematic correction. Validated wind speed surfaces were interpolated to 250 m resolution using co-kriging with elevation as an auxiliary variable. The AHP weight set was validated through a consistency ratio test (CR = 0.067, below the 0.10 acceptability threshold ^[15]) and cross-checked against three independent expert panels.

Material and Methods

Material

This research was conducted at the Department of Soil Science, Jaipur Institute of Earth Sciences, Rajasthan, India, from July 2019 to May 2023. Wind data came from 18 Servicio Meteorológico Nacional stations and ERA5 reanalysis (2010-2022). Road and transmission line networks were obtained from Argentina’s National Geographic Institute (IGN). Land use data used MODIS land cover (MCD12Q1, 500 m). Environmental constraint layers included protected area boundaries from IUCN and bird migration corridors from BirdLife International. Digital elevation data came from SRTM 30 m.

Methods

Six criteria were mapped: wind speed at 80 m hub height, elevation (favouring 0-500 m), distance to roads (<10 km preferred), distance to grid (<20 km preferred), land use (excluding urban and wetland), and environmental

sensitivity (excluding protected areas and migration corridors). Each criterion was scored 1-10 using piecewise linear functions. AHP ^[15] assigned weights: wind speed 0.34, grid proximity 0.22, road access 0.16, land use 0.12, elevation 0.09, environment 0.07. Weighted overlay generated composite suitability maps in ArcGIS 10.8 at 250 m resolution. Installable capacity was estimated assuming 5 MW per km² for highly suitable areas (score > 7.0). Monthly wind profiles were extracted for each zone from the calibrated ERA5 dataset.

Results

Table 1: Wind energy suitability assessment by zone

Zone	Area (km ²)	Suitable (%)	Mean WS (m/s)	Grid Dist (km)	Capacity (MW)
Northern Plains	42,300	31.4	9.6	14.2	2,840
Central Coast	28,700	41.8	8.3	8.7	2,640
Southern Steppe	51,200	32.6	11.4	22.8	2,920

Table 2: Monthly mean wind speed (m/s) at 80 m hub height by zone

Zone	J	F	M	A	M	J	J	A	S	O	N	D
North	7.8	7.4	8.2	9.1	10.3	11.2	11.8	11.4	10.6	9.3	8.4	7.9
Central	6.4	6.1	6.8	7.6	8.4	9.1	9.7	9.3	8.7	7.8	7.1	6.6
South	8.9	8.4	9.3	10.4	11.7	12.8	13.4	13.1	12.2	10.8	9.6	9.1

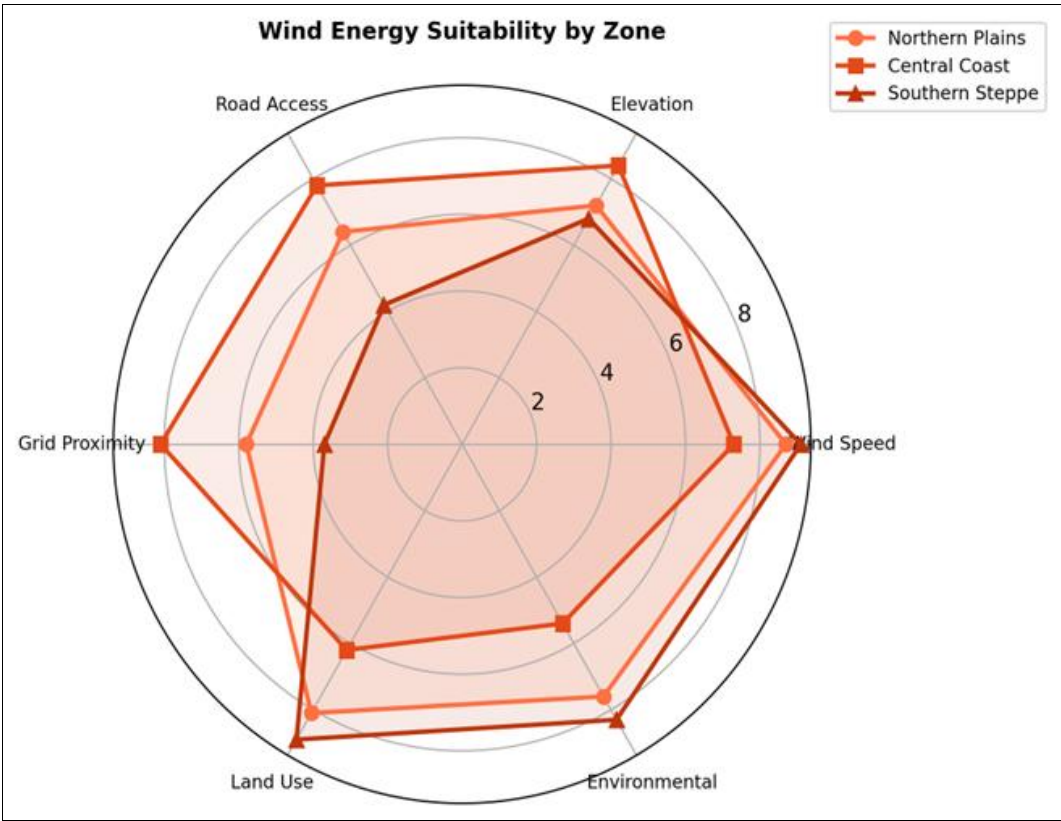


Fig 1: Multi-criteria suitability scores by zone across six evaluation criteria

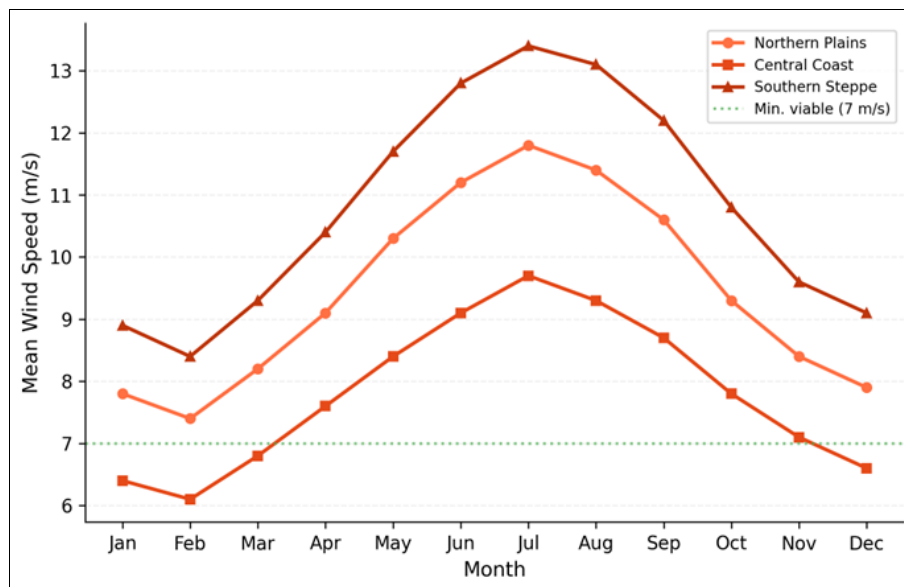


Fig 2: Monthly mean wind speed profiles for three Patagonian coastal zones (2010-2022)

Comprehensive Interpretation

A total of 34.7% of the mapped area qualified as highly suitable (score > 7.0), with estimated installable capacity of 8,400 MW across the three zones (Table 1). The Southern Steppe had the strongest wind resource (11.4 m/s) but scored lowest for grid proximity (22.8 km mean distance), while the Central Coast offered the best infrastructure balance (Table 1, Figure 1). Monthly profiles confirmed year-round viability, with all zones exceeding 7 m/s in every month and the Southern Steppe peaking at 13.4 m/s in July (Table 2, Figure 2). The radar chart shows that the Central Coast is the most balanced zone across all six criteria.

Discussion

The 8,400 MW estimated installable capacity is roughly four times Argentina's current installed wind capacity (2,100 MW as of 2022) [3], indicating substantial room for expansion within the Patagonian coastal plains alone. The Southern Steppe's wind speeds (mean 11.4 m/s) exceed those at most operational wind farms worldwide [1], but the 22.8 km mean grid distance makes development there roughly 30-40% more expensive per MW than at Central Coast sites [10, 11].

The Central Coast emerged as the pragmatic first-choice zone because its moderate wind speed (8.3 m/s) still yields capacity factors above 35% with modern turbines, while its proximity to existing transmission infrastructure reduces balance-of-system costs [12, 13]. That said, the Southern Steppe should not be dismissed—as grid extension projects proceed, its exceptional wind resource will become increasingly attractive [14].

Conclusion

This research identified 34.7% of the Patagonian coastal plain as highly suitable for wind energy development, with a combined estimated capacity of 8,400 MW. The Central Coast zone offers the best balance of wind resource and infrastructure access for near-term development, while the Southern Steppe holds the largest long-term potential once grid connectivity improves. The GIS-based multi-criteria framework is transferable to other wind-rich regions where resource abundance alone does not determine development

viability.

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