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Wind turbine selection method based on the statistical analysis of nominal specifications for estimating the cost of energy

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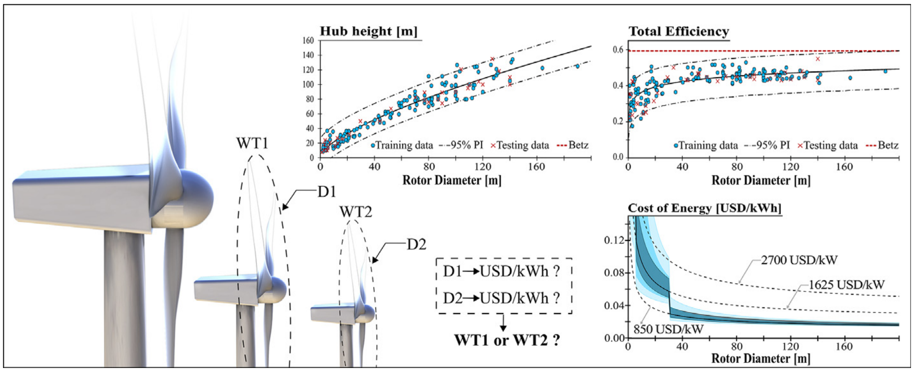
HIGHLIGHTS

- Wind turbine selection method based on easily available nominal specifications.
- Cost of energy estimation when accessible information is limited or unreliable.
- Construction of a dataset with valuable information from 176 HAWT turbines.
- Statistical models of the efficiency and hub height were proposed and validated.
- Uncertainty assessment with prediction intervals and stochastic dominance analysis.

GRAPHICAL ABSTRACT



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ABSTRACT

Wind turbine selection is a critical engineering problem in the overall cost-effectiveness of a wind project. With the wide spreading and democratization of wind energy technologies, non-expert stakeholders are being faced with the challenge of selecting among very different wind turbines. As a comprehensive indicator, the cost of energy can serve as a guide, but reportedly misleading publicity and commonly unavailable information render its calculation more inaccessible and less reliable. Accordingly, this work proposes a method to compare wind turbines, on the basis of the cost of energy, from only nominal specifications and a standard characterization of the local wind conditions. For this endeavor, it was identified that two key variables are not usually available at a preliminary stage: the total efficiency and a feasible hub height. Through a systematic statistical analysis of the trends in a constructed dataset of 176 turbines, it was possible to establish regression models for the estimation of both variables. These models were tested in a validation set and their estimations were found to correctly characterize the central trend of the data without significant deviations. The uncertainty related to the use of both models was addressed by analyzing the 95% Prediction Intervals and the stochastic rank dominance. The established statistical models were then used as the core of the proposed selection method. When the available information is limited or not trustworthy, the steps of the method can be followed as an approach to estimate the cost of energy of a given horizontal axis wind turbine in a given location.

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Nomenclature

Acronyms

CR	Certification Reports
HAWT	Horizontal Axis Wind Turbine
JM	Justus and Mikhail model for Weibull parameters extrapolation
LCOE	Levelized Cost Of Energy
ME1	Model of Efficiency where $\hat{\eta} = f_{(D)}$
ME2	Model of Efficiency where $\hat{\eta} = f_{(\eta_R)}$
ME3	Model of Efficiency where $\hat{\eta} = f_{(D,\eta_R)}$
MED	Model of Efficiency in function of Diameter
MHh	Model of Hub height where $\widehat{Hh} = f_{(D)}$
MHhD	Model of Hub height in function of Diameter
MPr	Model of rated Power
PI	Prediction Intervals
RMSE	Root Mean Square Error
SR	Spera and Richards model for Weibull parameters extrapolation
SWT	Small Wind Turbine
TB	Trusted Brands
TP	Third-Party testing studies
WT	Wind Turbine

Greek symbols

$\bar{\eta}$	mean total efficiency
η	total efficiency
η_{95high}	estimate of the upper 95% PI limit in $\hat{\eta}$
η_{95low}	estimate of the lower 95% PI limit in $\hat{\eta}$
η_R	rated efficiency
λ	used in variable transformation, such as X^{λ}
ρ	air density in [kg/m^3]

Variables

$\bar{V}$	average wind speed in [m/s]
A	swept area in [m^2]
c	Weibull scale parameter
C_E	cost of energy in [USD/W h]
C_{wt}	wind turbine's cost in [USD]
D	rotor diameter in [m]
E	energy output in [W h]
E_0	energy [W h] under the increasing section of the Power Curve
E_R	energy [W h] in the nominal region of the Power Curve
$h1$	height [m] at which the Weibull parameters are measured
h_{asl}	height above sea level in [m]
Hh	hub height in [m]
Hh_{95high}	estimate of the upper 95% PI limit in $\widehat{Hh}$
Hh_{95low}	estimate of the lower 95% PI limit in $\widehat{Hh}$
I	real rate of interest
k	Weibull shape parameter
$Life$	lifespan in [years]
m	proportion of the operating and maintenance costs in terms of the capital cost for the whole project
nR	number of Riemann rectangles
P	power output in [W]
p	air pressure in [Pa]
	rated power in [W]
r	Pearson's coefficient
R^2	coefficient of determination
T	air temperature in [K]
t	*Life* given in [h]
V	wind speed in [m/s]
V_{Δ}	width of Riemann rectangles in [m/s]
V_{in}	cut-in speed in [m/s]
V_{out}	cut-out speed in [m/s]
V_R	rated wind speed in [m/s]
WT_p	proportion of the capital cost for the whole project represented by the turbines
X	predictor variable
Y	response variable
Z_0	surface roughness in [m]

1. Introduction

Anthropogenic climate change [1], the growing urgency to reduce the world's dependence on fossil fuels, and a raising eco-friendly consciousness [2], are accelerating the democratization of renewable energies. Notably, the wind energy has experienced a steep growth rate since 1990 [3,4] in terms of implementation and research interest. This has contributed to the wind energy's transition to one of the most technologically mature renewable energies [5] and the fastest spreading energy source [6]. The main drivers of this trend are the three-bladed Horizontal Axis Wind Turbines (HAWTs). They are the most common Wind Turbines (WTs) and have more credibility in the market because of their balance regarding efficiency, cost-effectiveness, scalability, and social acceptance [7,8].

The overall cost-effectiveness of a wind project greatly depends on the WT selection in accordance with the wind conditions. As stated by Perkin et al. [9], "Poor turbine selection results in a financially sub-optimal investment". Correspondingly, a more efficient WT means that more usable energy can be extracted per cross-section area of the incident wind. This extra energy can help to outweigh the cost of investment. The overall efficiency, namely the *Total Efficiency* (η), is composed of: an aerodynamic efficiency for transforming the kinetic energy of the wind into mechanical energy in the axis of the rotor, a mechanical efficiency for transmitting this energy towards the axis of the electric generator, and an electric efficiency for ultimately generating electrical usable power.

Gipe [10] refers to a general well-known relation between the η of a WT and its size (in terms of rotor diameter and rated power), but he does not provide a full characterization of this relation. The electrical efficiency of HAWTs in the market is expected to be 96–97% for turbines rated at 2.5–3 MW (around 90–100 m in diameter), but only 60–70% for turbines rated at 0.5–10 kW (around 1–5 m in diameter) [11]. It has also been found that the bigger the rotor diameter, the bigger the Reynolds number related to the flow conditions [12,13]. Bak [14] found that a bigger Reynolds number allows a greater lift-to-drag ratio, which in turn tends to increase the aerodynamic efficiency. In agreement with these scaling implications, Bukala et al. [4] make a broad comparison from reported efficiency values: the η of modern big-scale HAWTs is around 45% while only 35% with Small Wind Turbines (SWTs).

Furthermore, Hren and Hren [15] state that, "As a general rule, wind energy becomes more cost-effective as wind turbines increase in diameter". The increment in usable energy, due to a bigger size, tends to be greater than the implications in the cost of investment and ecological footprint, which leads to more sustainable wind energy [16].

Accordingly, the global wind market is heading towards seemingly ever-bigger wind turbines, seeking a lower Levelized Cost Of Energy (LCOE) [17,18]. During 2012, the average capacity of new installed