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Economically optimal configuration of onshore horizontal axis wind turbines

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ABSTRACT

During the recent years, the use of new materials and enhanced production processes led to successively increasing sizing parameter – namely rotor diameter, rated power and hub height – of wind turbines as well as decreasing initial and running costs. The thereby risen market share shows that wind energy projects are an interesting field for financial investors. In this connection the question arises, how investors benefit from the mentioned technical developments. Regarding the utility maximization of investors in turbine projects, goal of this survey is to determine the economically optimal turbine configuration in contrast to the technically feasible by maximizing the net present value. For this purpose, a generalized approximation of the power curve of three-bladed, direct-driven, variable speed horizontal axis wind turbines is applied. For estimation of the economic parameters, a complex mass-cost-model is used for determination of the initial costs as a function of the sizing parameter. Thereby, a method is shown for adjustment of this model to several differences in price levels of the different turbine components. Furthermore, detailed relationships for running costs as well as the estimation of the cost of equity capital are shown. Due to the current importance of feed-in tariff, revenues for electricity sale depend on the German "Renewable Energy Act". The calculation of economically optimal sizing parameter first is done for a reference site in conjunction with a sensitivity analysis to determine the most influential sizing parameter with respect to economic viability. Afterwards, a range of typically onshore wind speeds in Germany is considered.

1. Introduction

Over the past two decades, wind energy has rapidly evolved to the renewable energy with the highest market share worldwide [1] and an installed capacity of nearly 319 GW (2013) [2]. During this development, technological innovations in production processes and the use of new materials enabled turbine manufacturer to gradually enlarge the design properties of horizontal axis wind turbines (HAWT), namely rotor diameter, rated power and hub height, that are associated with the extraction of energy from the wind [3,4]. Actual, the most powerful available onshore turbine (2014) has a rotor diameter of 127 m with a hub height of 135 m and a rated power of 7.580 kW [5]. For offshore utilization, there exist prototypes with rated powers up to 8 MW and rotor diameters of 164 and 171 m, respectively [6,7]. However, the UpWind project even showed that a 20 MW turbine with a diameter of about 252 m is technically feasible in theory [8]. Besides upscaling of turbines, significant improvements in turbine efficiency could be observed during recent years, especially occurring in turbines designed for onshore utilization [9]. This development partly is a result of the long-term energy policy of several countries in Europe. Investors were offered incentives in form of subsidy programs, such as the German "Renewable Energy Act (EEG)"; the thereby generated market growth was accompanied by the technical progress mentioned above as well as the implementation of measures to reduce the costs for turbine manufacturing and operation. As a result, achievable annual energy production (*AEP*) of single turbines rose in context with decreasing production costs, enabling costs of energy production (COE) of large onshore HAWT that are now competitive with those of fossil fuels [1]. To summarize, by upscaling of HAWT up to the technical limitation, investors can expect higher remunerations from electricity sale. Since initial and

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List of parameters and mathematical symbols

Parameter	Symbol	Unit	Value/Range
Swept area	A	m^2	
Annual energy production	AEP	kWh	
Annual energy production (EEG reference)	AEP_{ref}	kWh	
Pitch angle	β	°deg	0
Equity beta	β_i		
Cash flow	CF_t	EUR	
Additional investment costs	c_{adInv}	EUR	
Administration costs	$c_{Administration}$	EUR	
Insurance costs	$c_{Insurance}$	EUR	
Investment costs	c_{Inv}	EUR	
Operation and maintenance costs	c_{OM}	EUR	
Coefficient of performance	$c_{P,max}$	–	0.48
Rental costs	c_{Rental}	EUR	
Running costs	c_{Run}	EUR	
Rotor diameter	D	m	[20,200]
Return on market portfolio	$E(r_m)$	%	
Incoming payments	E_t	EUR	
Adjustment factor	f_{adjust}	–	
Cost factor	f_{cost}	–	
Generator to rotor ratio	GRR	kW/m	[20,60]
Hub height	h, h_2	m	[20,200]
EEG reference height	h_0	m	30
Height to diameter ratio	HDR	–	
Annual rate of inflation	i	%	
Tip speed ratio	λ	–	opt. 8
Net present value	NPV	EUR	
Design angular speed of turbine	ω_d	s^{-1}	
Kinetic energy at hub height at vi	P_i	10^{-3} kW	
Producer Price Index	PPI	–	
Rated power	P_r	kW	[100,10000]
Air density	ρ_{Air}	kg/m^3	1.225
Cost of equity	r_{coe}	%	
Exchange rate	$r_{exchange}$	–	
Return of risk-free asset	r_f	%	
Return of market portfolio	r_M	%	
Tax rate	s	%	
Time of feed-in tarif	t	a	1 – 20
Time	T	h	8760
Time of initial rate	t_{ini}	a	
EEG reference wind speed in height h_0	v_0	m/s	5.5
Average wind speed at hub height	v_2	m/s	
Cut-in wind speed	v_{ci}	m/s	2
Cut-out wind speed	v_{co}	m/s	25
Rated wind speed	v_r	m/s	12
Rated tip speed	v_{ts}	m/s	80
Roughness length	z_0	m	0.1

running costs rise in the same time, however, there exists an economic optimum in contrast to the technically feasible turbine design. Since assessment of investment decision usually is done with net present value (*NPV*), the goal of this paper is to identify that combination of rotor diameter, hub height and rated power which is maximizing *NPV* with respect to the average wind speed.

Evolved from the development of airplane propellers, previous research in optimization of HAWT can be divided into two main groups: the first generation of investigations considered the optimization of aerodynamic performance, usually by applying blade element momentum (BEM) theory [10]. Here, aerodynamically optimal geometric shape of the rotor is determined for a single design wind speed or, more important, for the maximization of the annual energy output of the turbine [11,12]. However, this method disregards the increasing loads and the costs thereby incurred. The second generation of optimization models therefore includes functional relations between loads (or mass) of single turbine components and costs [13]. By including fatigue and extreme loads, such a calculation can be used to optimize geometric shape and thickness of rotor blades, resulting in better aerodynamic performance simultaneously with reducing weight and costs [14]. However, these considerations are more helpful for turbine development instead of being an investment decision support.

Other papers discuss the so called micro-siting and the optimized location of wind energy plants within a wind farm [15–17]. Differences in investment costs are estimated by single properties like rotor diameter [15], by relation to rated power [16] or by selection of given turbine types with hub height and location of single turbines [17]. Just two papers exactly discuss the question of economical turbine configuration, aimed in this paper [18,19], but the results do not allow a general appliance due to an outdated cost model [18] and the rotor diameter as the only viewed design parameter [19], respectively.

Nearly all existing studies regarding this topic focus on minimization of the COE. In contrast, economical optimum is found by maximization of *NPV* in this paper. Furthermore, most authors neglect adjustment of the underlying mass-cost-model in [13], or use simple estimations for initial costs, thereby ignoring important relations of costs to turbine components. In this study, a large number of possible combinations of diameter, rated power and height of a three-bladed, pitch controlled, variable speed and direct driven HAWT is viewed, since this type of turbine is one of the most utilized onshore wind turbines worldwide [1]. However, to refrain from manufacturer data, a general description of the turbine