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Site Specific Design Optimization Of Horizontal Axis Wind Turbine Based On Minimum Cost Of Energy For Adama I Wind Farm

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Abstract

The essence of this work is to project the potential savings offered by site specific design of wind turbine. XFOIL has been used to generate profiles for S-series airfoils for blade design process and validated with experimental results from literature. Standard cost models of HAWT are scaled for cost spent on Adama I wind Farm and validated with Commercial prices globally available. The Annual Energy Production (AEP) has been evaluated by an open source HAWT optimization code, named HARP_Opt in this work. Baseline case and three scenarios have been generated to investigate the effect of airfoil profiles and turbine rated power on AEP and Cost of Energy. An increase of 12 to 28.5% in net AEP has been observed with an attendant reduction in Cost of Energy by 8.44 to 17.6%. Atmospheric turbulence effect on AEP has also been investigated and found to reduce net annual energy by1.8 % to 5.5%. For Adama I, Wind Farm with capacity of 51MW, $2.13 million savings per year has been projected.

Key words: *Horizontal Axis Wind Turbine, Site Specific Design, Blade Element Momentum Theory, Minimum Cost of Energy, Annual Energy Production.*

1.Introduction

World is changing. Energy and global warming are the most important problems in today's world. Fossil fuel prices are increasing day by day because of limited sources. Natural balance of earth is changing because of global warming. One of the main reasons of this change is burning too much fossil fuel. Kyoto Protocol [1] which is an agreement to reduce the emission of CO2 and greenhouse gases by United Nation Framework Convention on Climate Change (UNFCCC) is ratified by many countries today. Therefore, alternative energy sources are needed. These are the reasons why wind energy becomes so important. Wind source is free and clean. Wind turbine technology is growing and wind is getting to be one of the best alternative energy sources, today on the world.

EEPCo's generating capacity is largely based on hydropower reservoirs, which are significantly affected during periods of extended drought, resulting in potentially large fluctuations in availability of power. Considering the increasing power demand and capacity shortfall in the Grid system and to have a better generation mixes, wind energy was found an immediate and clean energy solution as wind power is renewable with short construction period & has significant advantage of quick result. Based on these facts, the Ethiopian Electric power corporation /EEPCo/ has planned to implement huge wind power Projects at different sites.

One of these projects is Adama I wind farm with installed capacity of 51Mw. Adama I Wind Farm is considered to be the best potential wind farm [2]. It is located around 95km south east of Addis Ababa and around 3km north east of Adama/Nazareth on an altitude range of 1836 - 1926 m. Adama/Nazareth Wind Farm is reach in wind energy. In the site area at the height of 65m, the average wind speed is 9.56m/s, the wind power density is 654.5W/m2 and the Wind direction is stable.

This thesis work is aimed to help the future Wind Energy development plans in the country by suggesting efficient and effective design system which can be implemented for other sites.

2. Literature review

Wind turbine design is a multidisciplinary design process and therefore, naturally, it is an optimization problem. The design of optimal system involves essentially aero dynamic, structural and control systems. In order to establish an optimum system that produces as much power as possible with low cost and low noise levels, the ideal case is the optimization of this design process with all of the components included. However, this is not possible all the time. This idealized procedure needs too much time and effort to produce best wind turbine geometry by using the most accurate methods for all phases. As a result, in most of the design applications, accurate design methods are used partially [3].

Site specific design optimization is the current focus of researchers in the area. This method allows optimized wind turbine for specific site. It is the design optimization of wind turbine blade for specific site wind resource characteristics. Promising results had been claimed *[4]*. The difference in the design of wind turbine for different sites depends on the difference in wind turbine loads which are a result of specific design wind conditions. Thus, it is possible to modify wind turbine design for specific wind conditions of a site. Site specific design is believed to benefit over usual design trend, which categorizes wind turbine based on wind condition [5].

To determine the optimum design parameters for horizontal axis wind turbines a specific method was investigated. The optimum values were found to be dependent on site wind regime. The results of the study indicated that it was the optimization of the relative combination of rotor diameter and rated power with respect to site mean annual wind speed that afforded significant reduction in energy production cost. The author suggested that for windier sites the energy production cost may be reduced by up to 10% through the optimization of machine rated wind speed to suit the sites [6].

Wind speed distribution function to specific wind site, to satisfy the maximum annual energy output was investigated by using Extended Compact Genetic Algorithm (ECGA) and tested on 1.3MW stall controlled wind turbine. As a result, the designed blades were observed to have a better aerodynamic performance for specific site [7].

Cost of energy reduction by site specific design on small wind turbine was studied [8]. The optimization was done by Multi-Disciplinary Design Feasible (MDF) approach and blade aero-structural analysis and aerodynamic analyses were performed using a Blade Element Momentum (BEM) method. The result indicated that optimal design depends on wind distribution. It was verified on two specific sites and 3 to 4% output increase was achieved.

Design optimization methodology based on minimizing the Cost of Energy (COE) of a HAWT to be operated at a specific wind site. For the calculation of the Cost of Energy, the Annual Energy Production (AEP) model neglecting atmospheric turbulence and the total cost of that turbine were used. The AEP was calculated using the BEM theory for wind turbine power and the Weibull distribution for the wind speed characteristics of selected wind sites. And promising results were found [9].

2. 1 Problem statement

Wind power in Ethiopia is taken as an immediate renewable energy resource with short gestation period which has been given attention for complimenting Hydropower. This huge investment requires support form research side to make it effective and efficient.

Usually, in wind farm development wind turbine Generators are selected by classifying site resource as per IEC61400-1standard. In classifying Wind site resource, always there is rounding off the actual site characteristics to the nearest IEC categories. Compromising the actual site characteristics for the standard category penalizes either maximum AEP or Investment cost and as a result CoE is affected. The emerging trend at present is to implement site specific wind turbine design optimization which addresses these problems. This work is aimed to help the future Wind Energy development plans in the country by suggesting efficient and effective design system.

2.2 Scope

This work deals with the aerodynamic design of wind turbine blades. By predicting optimized system AEP, the cost of energy is minimized. Atmospheric turbulence effect on annual energy production is also explored. Design optimized system performance is compared with system installed at Adama I wind park in terms of AEP and CoE.

3. Materials and Methods

HARP_Opt Code: It is the main tool used to perform Design optimization process. In the code, the Genetic Algorithm optimization routine fitness function is coupled with Wind Turbine Rotor Performance predictor. Five span wise locations are predefined and optimizations of parameters are performed on these locations by GA routine. The fittest individuals of the geometric population within the defined constraints are used in performance prediction. The code has alternative objective functions of Annual energy Production and turbine efficiency prediction. The later combines AEP and power output optimizations. In combining the two functions, the optimization parameters are rated power, Chord and twist distributions. In the former optimization function, optimization parameters are twist and chord distributions. Both alternatives are used in this study for different scenarios.

XFOIL9.96: it is an interactive zonal approach viscous/in viscid code used either for designing new airfoil or analyzing available airfoils. Here, it is used to analyze existing airfoil performance data for wind turbine blade design optimization process. It is recommended for angle of attack just above stall angle. **AirfoilPrep_V2.P2**: It is an excel spread sheet developed to extrapolate airfoil performance data for large angle of attack between -180 and +180 deg.

3.1 Methodology

Site Wind resources and technical data of wind turbines installed have been collected. Data of commercial wind turbines with the same size and rating have taken from literatures to get detail turbine information and later use in optimization as base line reference. Aerodynamic data of selected NREL S-series airfoils have been numerically generated and validated with confidential literature. Data are generated at different turbulence environments.

Life Cycle cost of wind turbine is assessed by scaling Horizontal Axis Wind Turbine cost prediction models to the cost spent at Adama I Wind Farm. The scaled cost models are compared to actual price on the market.Three scenarios and base line cases are generated to investigate effects of airfoils shape and rated power on cost of energy. In all scenarios, two cases; considering and neglecting atmospheric turbulence are investigated.

3.1.1.Blade Element Momentum Theory. The BEM theory, generally attributed to *Betz and Glauert (1935)*, originates from two different theories: blade element theory and momentum theory [10]. It is basically aims to model the axial and tangential induction factors by equating the force and torque relations derived from each blade element and momentum theories. The total force acting on the annular radius is calculated by both blade element theory and momentum theory independently.

In this section the equations used to perform the iteration process of BEM theory used is summarized. Wind turbine performance analysis with BEM theory is the prediction of induction factors, angle of attacks and thrust for each blade element separately. To do this, induction factors are needed to be calculated first which is an iterative process.

Assuming that the inflow angle ϕ is small (sinϕ ≈ ϕ), the tangential induction a′is zero, the tip and hub-loss corrections F are one, the drag coefficient Cd is zero, the lift coefficient, Cl= 2πα, and finally, α =ϕ−β. After some rearranging, we arrive at the initial estimate of the axial induction factor:

$$a = \frac{1}{4}\left[2 + \pi\lambda_r\sigma' - \sqrt{4 - 4\pi\lambda_r\sigma' + \pi\lambda_r^2\sigma'(8\beta + \pi\sigma')}\right] \qquad \text{….. (1)}$$

Where; ϕ-is inflow angle, a’-tangential induction factor, Cd-drag coefficient, Cl-lift coefficient, α-attack angle, β-blade pitch angle, a-axial induction factor, σ’-local solidity and λr-local tip speed ratio. From here we can estimate the inflow angle using an initial assumption of zero for the tangential induction, a′ and

$$\tan\varphi = \frac{U_\infty(1-a) + v_{e-op}}{\Omega r(1+a') + v_{e-ip}} \qquad \text{……… (2)}$$

Next, the BEM tool determines the thrust coefficient for the element using the following:

$$C_T = \left[1 + \frac{\sigma'(1-a)^2(C_l\cos\varphi + C_d\sin\varphi)}{\sin^2\varphi}\right] \qquad \text{…. (3)}$$

Then, the tip- and hub-loss corrections are calculated as follows:

$$F_{tip} = \frac{2}{\pi}\cos^{-1} e^{-\frac{B}{2}\frac{R-r}{r\sin\varphi}} \qquad \text{……….. (4)}$$

$$F_{hub} = \frac{2}{\pi}\cos^{-1} e^{-\frac{B}{2}\frac{r-R_{hub}}{r\sin\varphi}} \qquad \text{………. (5)}$$

The combination of tip and hub loses is given by:

$$F = F_{hub}F_{tip}\,. \qquad \text{……. (6)}$$

Now, if CT> 0.96F, the element is highly loaded and the modified Glauert correction will be used to determine the new axial induction factor:

$$a = \frac{18F - 20 - 3\sqrt{C_T(50-36F) + 12F(3F-4)}}{36F-50}\,. \qquad \text{……… (7)}$$

If CT ≤0.96F, the standard BEM theory is used to calculate the axial induction:

$$a = \left[1 + \frac{4F\sin^2\varphi}{\sigma'(C_l\cos\varphi + C_d\sin\varphi)}\right]^{-1}. \qquad \text{……. (8)}$$

The tangential induction factor is calculated using

$$a' = \left[-1 + \frac{4F \sin\varphi \cos\varphi}{\sigma' (C_l \sin\varphi - C_d \cos\varphi)} \right]^{-1} \qquad \ldots\ldots (9)$$

And finally, the effect of skew is included using the skewed wake correction factor:

$$a_{skew} = a \left[1 + \frac{15\pi}{32} \frac{r}{R} \tan \frac{\chi}{2} \cos\psi \right] \qquad \ldots\ldots\ldots (10)$$

During the iteration process, lift and drag coefficients are given as input to the program. For each blade element, airfoil information is required with chord and twist values. Lift and drag coefficients have to be given according to different angle of attack values. The iteration and power calculation procedure explained here is coded by using FORTRAN90 programming language. BEM analysis tool predicts the performance of wind turbines according to the given geometrical variables. This tool is also used for calculating wind turbine power production during the optimization loop.

3.1.2.Annual Energy Production. The Annual Energy Production (AEP) Model calculates the total energy generated by a specific wind turbine in a specific wind site per year. The AEP is calculated by equation 11[9].

$$\text{Net AEP} = \text{Egen} * \mu * \text{Availability} \left[\frac{\text{KWh}}{\text{yr}}\right] \qquad \ldots (11)$$

Where μ-is the efficiency of the wind turbine defined as,

$$\mu = (1 - \text{soiling loss}) * (1 - \text{Array loss}) \quad ..(12)$$

Where, soiling loss=4%, array loss=4% and availability 98%. Soiling and array losses are low because of special airfoil used. E_{gen-} is the total energy that can be produced in a year and is defined as;

$$\text{Egen} = \sum_{\text{Vcutin}}^{\text{Vcutout}} \text{P(vi)} * \text{Weibull(vi)} * \frac{8760}{1000} \left[\frac{\text{KWh}}{\text{year}}\right] \qquad \ldots\ldots\ldots\ldots (13)$$

Where, $P_{(vi)}$ is the power output of the turbine at a specific wind speed calculated through BEM analysis and Weibull (vi) is the probability density function of the wind speed calculated using the user defined parameters of a selected wind site. 8760 is the total number of hours in a year's period.

3.1.3.Airfoils in Wind Turbines. Airfoils generate the aerodynamic forces on a wind turbine blade. Power of a wind turbine is related to aerodynamically and geometrical properties of its airfoils. The net force acting on an airfoil is divided into two components as lift force and drag force. Lift force is the component of the net force on an airfoil perpendicular to flow direction. Drag force is the component of the net force on an airfoil parallel to flow direction. Moment which is acting on quarter chord is called as pitching moment. The equations of these forces are given in equation (14) below.

$$\begin{aligned} Lift &= l = C_l \tfrac{1}{2} \rho U^2 c \\ Drag &= d = C_d \tfrac{1}{2} \rho U^2 c \qquad \ldots\ldots\ldots (14) \\ Moment &= m = C_m \tfrac{1}{2} \rho U^2 c r \end{aligned}$$

where Cl -is airfoil lift coefficient, Cd-is airfoil drag coefficient, Cm-is airfoil moment coefficient, c -is the chord length, ρ-air density and U-airflow speed. Flow passing on the surface of an airfoil is not always the same. These effects are represented by a non-dimensional number which is called as *Reynolds Number* given by:

$$Re = \frac{UL}{\nu} = \frac{\rho UL}{\mu} = \frac{Inertia\ forces}{Viscous\ forces} \qquad \ldots\ldots\ldots\ldots (15)$$

3.1.4. NREL S-series airfoil. National Renewable Energy Laboratory (NREL), USA developed series of airfoils known as ***S-series*** for wind turbine application [11].NREL was able to increase total energy produced by 15%. By designing airfoils specific to a span wise location on the blade (airfoil family), NREL obtained optimized airfoils with respect to Reynolds number. This optimization has resulted in an increase in performance about 3 to 5 %.

3.2. XFoil results of analyzed airfoil

Here a numerical result of S818, one of the airfoils used in optimization, is presented. Turbulence intensity set to 11.6%, Chord Reynolds number is 0.7E6 and Panel number of the solver is 200.

3.2.1 AirfoilPrep_V2.P2 extrapolation result. It takes airfoil information for limited angle of attack range and extrapolates the data between -180 and +180 degrees. The extrapolation of airfoil data is done by Viterna method in AirfoilPrep V2.P2. Veteran's method is a kind of correlation between the post-stall characteristics of wind turbine, the airfoils. and Aspect Ratio of wind turbine for which post stall characteristics of airfoils are close to experimental data [12].

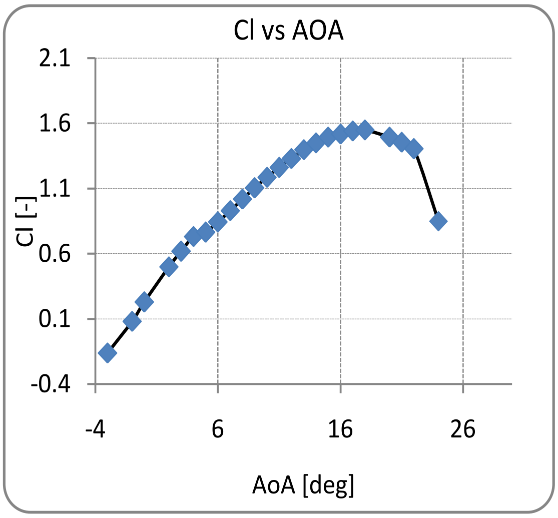

Figure 1 lift coefficient curve

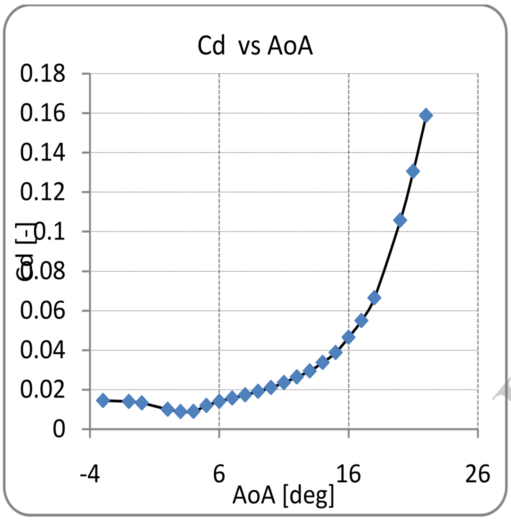

Figure 2 Drag coefficient curve

Figure 3 pressure distribution of S818

3.3 Design Optimization Process

The design optimization is based on different aerodynamic performance and economics, using Cost of Energy (COE).

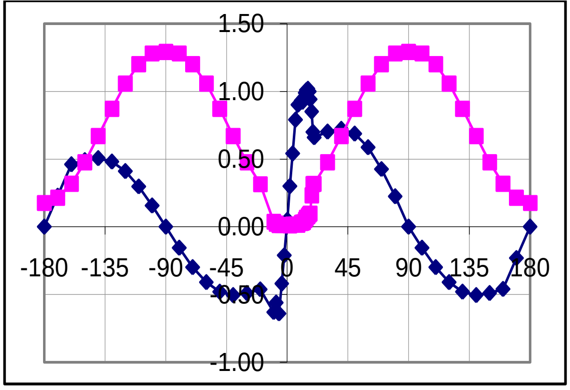

Figure 4 Extrapolated Cl & Cd result

$$\mathbf{CoE} = \frac{\mathbf{FCR*ICC+AOE}}{\mathbf{Net\ AEP}} \quad \text{………} \ (16)$$

Cost components are made of ICC, FCR and AOE. ICC is the Initial Capital Cost of the wind turbine in American dollars ($) that covers wind turbine costs and Balance of Station costs. FCR is the Fixed Charge Rate that is the annual rate of money that should be paid to cover ICC. FCR is dimensionless and depends on the amount of year that ICC is covered and taken as 0.0544 [13]. AOE is the Annual Operating Expenses in American dollars ($), which covers the fees that are paid annually as Operating & Maintenance and land rental fees (particularly for this work land rental fees is taken to be zero). ICC and AOE are computed as a function of the rotor diameter, the hub height, the rated power and Annual Energy Production.

3.3.1. Optimization objectives. HARP_Opt code has two optimization objectives which are: AEP and Maximum turbine efficiency. In this work, both optimization objectives are used in different scenarios. When turbine efficiency is activated, parallel annual energy production can be optimized by using rated power as optimization parameter. User-Defined Distribution function is used to describe the flow speed distribution of the site. Using the selected flow distribution, the code maximizes the AEP directly and turbine efficiency indirectly. User defined distribution is formatted as per the file format of the code input file flow data folder and used as input for optimization.

3.3.2. Wind Turbine Optimization Problem. For the genetic algorithm based optimization, an open source MATLAB code written by Danny [14] is used in this work. The optimization code inputs are related with the efficiency of Genetic Algorithm and they are used as proposed by references [15 and 16]. Fitness function in the optimization code is replaced with BEM analysis code which is developed by Marshall. Each member produced in every generation is analyzed with BEM analysis tool for power output. When a member has a high power production, its optimization variables are kept for next generations for better power production.

3.3.3.Objective Function. Maximum power output, minimum Cost of Energy, maximum Annual Energy Production are typical objective functions for wind turbine designs. In this study maximizing AEP and turbine efficiency are selected, which ultimately minimizes CoE.

3.3.4.Optimization Parameters. As defined before, optimization parameters are the variables of the design that are used to generate new configurations. In this study, chord, twist distributions and the rated power are selected as optimization parameters. The constraints are

$\mathbf{c(r)} > c(r+1)\ for\ eac\ blade\ element$

$\Phi_r > \Phi_{r+1}$ for each blade element

$$Barea_{min} < Barea < Barea_{max} \qquad \ldots\ldots.(16)$$

Where, C(r) is chord length at r radial location, Φ_r is twist angle at r radial location and Barea is blade element area.

3.3.5. Airfoil family distribution. Optimization chooses airfoil family for each individual. Before the optimization, every member in the family should be assigned to blade elements, properly.

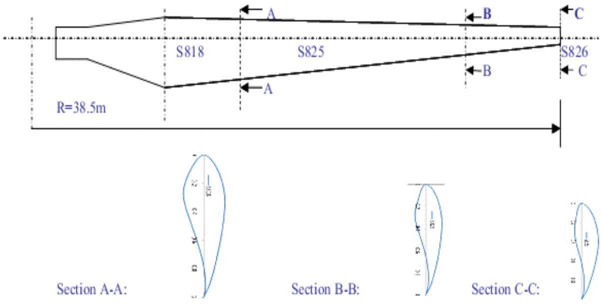

Figure 5. Airfoil family distribution

3.4 Prediction of Wind Turbine Life Cycle Cost

The Life Cycle Cost (LCC) is the total cost of a wind turbine that covers initial investment cost and annual operational expenses. In this study I used the life cycle cost model developed by USA National Renewable Energy Laboratory in 2006 [17] and [18]. The site specific cost is improved from this standard model.The model is constructed by using existing commercial wind turbine data. It is applicable for three-bladed, variable speed, variable pitch, and upwind turbine configurations. Large scale wind turbine data are used in developing the NREL model and it is preferred to apply for diameters larger than 40m in design optimization.

The LCC model is comprised of many algebraic equations that are functions of the rotor diameter, hub height, rated power and the Annual Energy Production (AEP) [17]. And it is given by:

$$\mathrm{LCC}\ [\$] = \mathrm{FCR} * \mathrm{ICC} + \mathrm{AOE} \qquad \ldots\ldots.(17)$$

where; FCR-is fixed charge rate, ICC-is initial capital cost and AOE-is Annual Operational expense

4. Results and Discussion

The baseline design performance which is taken from wind turbines installed at Adama I wind farm is compared with the selected scenarios.

Wind resource, wind turbine; configuration (Horizontal Axis Upwind), size and rated power are kept the same as Baseline (with turbine system installed at Adama I Wind Park). The scenarios are to investigate the effects of optimization parameters (twist, chord distribution and optimizing rated power) and objective function (here AEP and Turbine efficiency are maximized) on the COE. Three different optimization scenarios are investigated and for the best potential savings projection. For each scenario, two cases, including and neglecting atmospheric turbulence in the analysis are investigated. But in this paper the result with atmospheric turbulence is presented.

The optimization limits of optimization parameters are taken to be ±50% of Base line values to increase under relaxation. The optimized values will be expected to be between lower and upper limit.

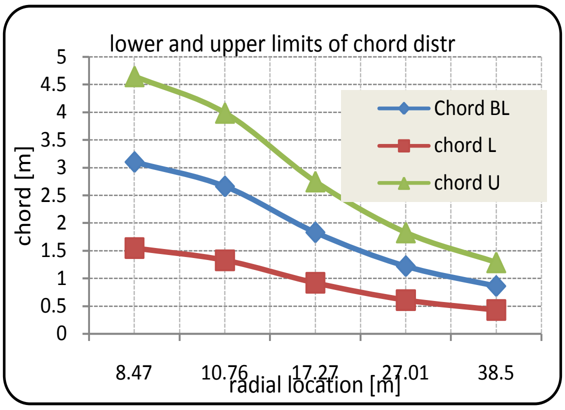

Figure 6. Limits of chord distribution

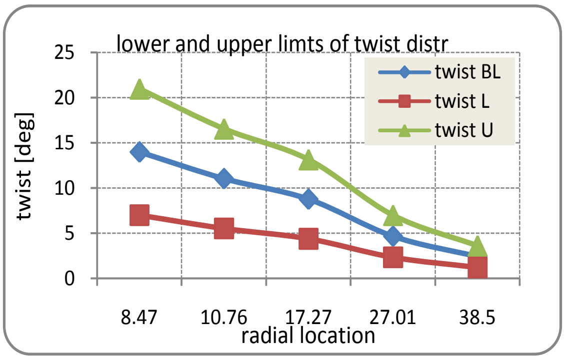

Figure7. Limits of twist distribution

4.1 Scenario 1 (S1)

S1 tries to find optimum chord and twist at control points (8.47m, 10.76m, 17.27m, 27.01m and 38.5m). The S818 airfoil is used at all blade sections except root and transition part.

4.2Scenario 2 (S2)

Scenario 2 tries to optimize wind turbine blade by using airfoil family. The NREL S-series airfoil family (S818, S825 and S826) are used as recommended by [17]. This family is designed for medium turbine, but by modifying trailing edges of airfoils they are effectively used for large wind turbine blades. Except airfoils used for optimization, the other concepts are the same as scenario 1.

4.3Scenario 3 (S3)

Design optimization parameters for the S3 are selected as rated power, chord and twist distributions. The objective function is AEP and turbine efficiency. Fixing turbine configuration similar to baseline, maximization of AEP is observed. Airfoil used is similar to scenario 2, which is NREL S-series airfoil family (S818, S825 and S826) for the blade sections.

4.4 Summary of optimization output

In this section optimized shape distribution along radial location and performance parameters are presented in tables and figures given below.

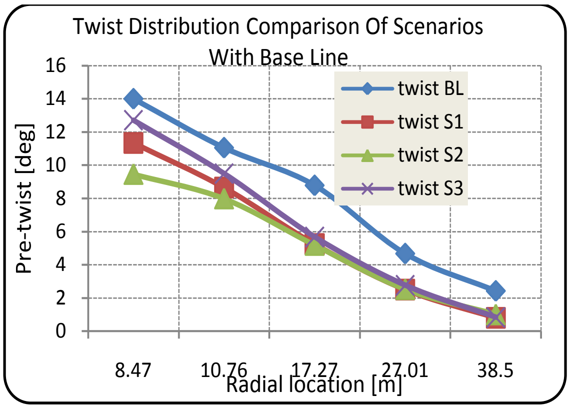

Figure 8. Twist distribution comparison of BL and scenarios

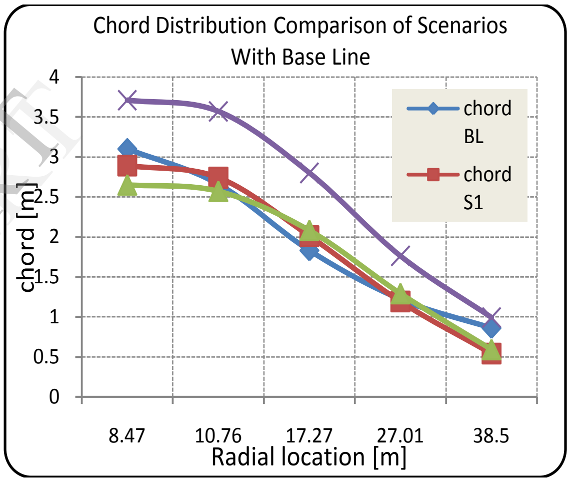

Figure 9. Chord distribution comparison of BL **and S1**

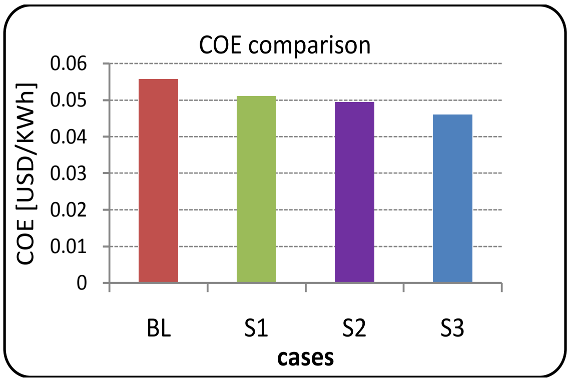

Figure 10. CoE comparison of optimization results

Table 1. Design Scenario Summary

baseline	scenarios 1 (s1) design			scenarios 2 (s2) design			scenarios3 (s3) design		
Airfoil	Opt. Para	Opt obj	airfoil	Opt Para	Opt Obj	Airfoil	Opt Para	Opt obj	Airfoil
Unknown	twist	AEP	S818	twist	AEP	S818	twist	Turbine efficiency	S818
	chord			chor		S825	chord		S825
						S826	Prate		S826

Table.2. Performance Optimization

	AEP [MWh]	Change AEP [MWh]	COE [$/KWh]	AEPi /AEP$_{BL}$ [-]	LCCi /LCC$_{BL}$ [-]	COEi/ COE$_{BL}$ [-]
BL	4785.29	0	0.0557	1	1	1
S 1	5366.02	580.73	0.0510	1.12	1.03	0.918
S 2	5593.73	808.44	0.0494	1.17	1.04	0.887
S 3	6149.5	1364.2	0.0459	1.29	1.06	0.825

5. Conclusion

The main focus of this thesis initiative is to highlight the merits of Site specific Aerodynamic design optimization of Horizontal Axis Wind turbine on Cost of Energy.

The airfoils used are NREL-S series, which are developed and tested by USA National Renewable Energy Laboratory for wind turbine application. The polars or aerodynamic performance characteristic of these airfoils are not available in open literatures except for S809. Therefore, the performance data of airfoils used in this study are generated numerically and validated with experimental data from literature. *XFOIL* numerical code is used for polar data generation of attack angle just above stall-angles and extrapolated for larger attack angles by *AirfoilPrep* excel spread sheet and presented.

The standard wind energy system cost models developed by National Renewable Energy Laboratory of USA have been scaled for Adama I Wind Farm based on the Actual cost found from the project document.

Three different scenarios and a baseline case (Wind Turbines installed at Adama I) have been generated and their effects on Cost of energy are investigated. Baseline case has been generated for comparison with the site specific design scenarios. It is taken from Wind turbines installed at Adama I Wind Farm and the same size commercial wind turbine (i.e. 1.5MW size). In these scenarios the effect of airfoil and rated power on AEP and CoE has been investigated. In addition, the effect of atmospheric turbulence on AEP has been analyzed for all scenarios. The conclusions from this study are as follows:

- In the first scenario (S1), the objective function is AEP and optimization parameters are twist and chord distributions along span locations with single airfoil. NREL S818 airfoil has been used for the whole blade length except circular and cylindrical root and transition sections by varying thickness and aspect ratio of the airfoil from root to tip. For the analyzed Wind farm site, Annual Energy Production has been found to increase by 12.14% per turbine and Cost of Energy for the Farm to reduce by 8.44% (from \$0.0557/KW-hr to \$0.0510/KW-hr) when compared with base case.

- The second scenario (S2) is similar to scenario 1 except the airfoil profile used. Here, NREL series airfoil family of S818, S825 and S826 has been employed at 0.22, 0.3 and 0.75 normalized radial locations respectively. Root and transition sections are circular and cylindrical shapes. For the same site resource, annual energy production has been found to increase by 16.9% per turbine and cost of energy for the farm reduced by 11.3% comparing with baseline case.

- Third scenario (S3) is the same as S2 by airfoil used and span wise distributions, but the objective function being turbine efficiency with optimization parameters as rated power, twist and chord distributions on radial locations. Annual energy has been found to increase by 28.5% per turbine and Cost of energy for the Farm reduced by 17.6% when compared with base case.

- Atmospheric turbulence decreases annual energy production by 1.8%, 2.4% and 5.5% for scenario 1, scenario 2 and scenario 3, respectively. This reduction increases with annual energy production.

- Generally for Adama I Wind Farm, if the best scenario (S3) is applied, net annual energy production has been found to increase from 162.7GWh to 209.083GWhr per annum. Cost of energy has been found to decrease from \$0.0557 per KWh to \$0.0459 per KWh. If site specific design were applied, 2.13 million USD per year could be saved.

5.1 Future Works

- Airfoil shape used in this work is only NREL S-series and extension of Airfoil group used for blade design makes the work complete
- Including economies of scale into cost prediction model so as to assess the penalty on initial capital cost front.
-

6. References

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