An Approach to Obtain the Optimum Balance between Wind Turbine Rotor Size and Generator Power Rating to Minimize Cost of Energy

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Abstract

In addition to environmental advantage of wind turbine the modern wind turbine design is aiming to become more competitive by minimizing the cost of energy (COE).When evaluating any change to the design of a wind turbine, it is critical that the designer evaluates the impact of the design change on the system cost and performance. A typical problem when starting up wind turbine design project is to determine the optimum balance between turbine power rating and the rotor size which will minimize the COE. In this article an optimization approach is adopted using COE as objective function with the rotor size and power rating as design variable. NREL (National renewable energy laboratory) cost of energy model is adopted with modifications to include the components load level effects on the COE.

A reference blade design is introduced and used as base for evaluating the rotor performance. The blade is scaled to represent different rotor size and operating conditions for each power rating. An analysis tool is developed to consider coupled interactions between power rating and the rotor size. The Blade Element Momentum (BEM) technique is used to evaluate the effect of rotor size and power rating on the wind turbine load levels and the expected annual energy production (AEP). These are used as inputs for the proposed COE model in addition to the main parameters presenting the manufacturing technology and site conditions.

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The COE model is based on several elements such as initial capital cost (ICC), balance of station (BOS), operations and maintenance (O&M), levelized replacement cost (LRC), AEP and design load levels.

A pattern search technique is adopted for the optimization and the approach is illustrated by means of principle test examples for two types of turbines platform, representing a power rating range of 1.0-2.5MW and power rating range 5.0-8.0MW. A sensitivity analysis is presented to show the effect of rotor size and power rating on the COE.

1. Introduction

The term optimum design is a widely used expression which can go from overall system level down to each minor component in subassembly..

The NREL has developed a cost model based on market survey and financial data in addition to the expectation of the turbine size for the planned wind turbine [1]. That model was updated and the latest update was presented in 2013 [2]. There was a trial to define an approach to optimize the rotor with intensive investigation to the rotor performance and aero- elastic modelling of the blade without considering the rest of turbine components [3].

The effect of load level on the component cost was considered in [4] but it was limited to two wind turbine configurations 1.5MW and 2MW while keeping the blade size fixed and changing the rotor size by increasing the hub radius. A simpler technique was adopted in [5] to find the optimum rotor to generator size with simple cost model for only generator and rotor with fixed total cost without considering the wind turbine operation parameters and its effect on the cost.

The approach presented in this article is a generic approach to optimize the wind turbine design through cost of energy as objective. This information is vital during the preliminary design of wind turbine platform and it gives an estimate to the intended cost of the turbine and to the design driving parameters.

2. The approach description

The approach is based on developing a design tool which combines a numerical optimization algorithm with different basic calculation tool through an interface. The input to the problem is divided into the information which is required to execute the numerical optimization algorithm and the specifications for the basic calculation tools.

A. The optimization algorithm

The numerical optimization algorithm needs the following:

1. An objective function: The cost of energy that has to be minimized by changing the design variables.
2. A set of design variables: Parameters that influences cost of energy such as rotor size.

3. Constraints: Upper or lower values for the design variables and any calculable response parameter that is dependent on the design variables. The constraints bound the design space into a feasible domain in which the optimum is found.
4. Boundaries to the operation of the turbine such as tip speed limits due to noise level.
5. Finally, an initial guess on a design vector is needed.

B. The specifications for basic calculation tools.

The specifications of the basic calculation tool include the wind climate that is specified as the incoming mean velocity profile, density and shear profile. When the design tool is applied, different basic calculation tools are used:

1. Traditional aerodynamic analysis based on blade element/momentum theory is used for calculation of the power.
2. Extreme loads are determined from outputs of the aerodynamic analysis tool.
3. Weibull distribution is adopted in estimating AEP.
4. The COE. calculation model based on several elements such initial capital cost (ICC), balance of station (BOS), operations and maintenance (O&M), levelized replacement cost (LRC), AEP and design load levels.

The execution of the different calculation tools is controlled by the interface that is tailored for communication between the numerical optimization algorithm and the calculation models. It generates the wind turbine configuration from the design variables. When the calculation tools have been executed, the interface evaluates the objective function and the constraints.

3. Design variables

The design variables are chosen based on the ability to be modelled in the BEM technique in addition to represent geometrical and aerodynamical characteristics of the wind turbine. From above the following design variables are chosen

1. *Generator power rating*
2. *Rotor radius*

In addition to the BEM outputs of power performance [6], [7], steady load level could be presented as in eqs. (1), (2), and (3).

$$M = M(R, P, C_p, V_w, \ldots) \tag{1}$$

$$T = T(R, P, .C_p, V_w, \ldots) \tag{2}$$

$$Q = Q(R, P, C_p, V_w, \ldots) \tag{3}$$

Where

M= blade flap moment, T = rotor thrust, Q = rotor torque

R, P, C_p, V_w = rotor radius, power, power coefficient and wind speed respectively.

A. *Changing the rotor size*

The choice of the rotor radius as design variable leads to the question about the methodology to change the rotor radius.

In this article, a scaling methodology is adopted to change the rotor size. The scaling is done by using reference blade design which is scaled to represent the change in the rotor size. The scaling is uniform to increase the rotor radius without violating the aerodynamic characteristics of each aerofoil on the blade.

Two pre-designed blades are used for the scaling. Each of them is dedicated to power rating range of the wind turbine as follows:

1. Blade design 1: 40 m blade for low to mid power turbines(1.0-2.5 MW) and wind class IECIII (mean wind speed=7.5 m/s)
2. Blade design 2: 65 m blade for mid to high power turbines(5.0-8.0 MW) and wind class IECI (mean wind speed=10 m/s)

The aerodynamic designs of the blades are based on optimizing the aerodynamic efficiency of the blade and the overall performance of the blade to maximize the AEP as in [6], [7]. The airfoils used for the aerodynamic design of the blades are

1. Riso airfoils [8].
2. Delft airfoils [9].
3. NACA airfoils[10].

B. *Changing the rated power*

Changing the rated power will lead to changes in the BEM model outputs and also to modifications of the power loss model due to the effect of increasing the torque. The loss model incorporated in this article is the same loss model as incorporated in [11] and [12] which could be expressed as in (4).

$$P_{loss} = P_{loss}(P, Q, \Omega) \tag{4}$$

4. Cost model

The formulation in eq. (1) to eq. (3) for loads is related to the main components cost as follows:

$$TC = TC(T, M, H, \ldots) \tag{5}$$
$$BC = BC(M, Q, \ldots) \tag{6}$$
$$HC = HC(Q, T, \ldots) \tag{7}$$
$$RC = RG(HC, BC, \ldots) \tag{8}$$
$$DTC = DTC(Q, P, R, \ldots) \tag{9}$$

$$FC = FC(TC, T, R, \ldots) \quad (10)$$

$$NAC = NAC(P, R, \ldots) \quad (11)$$

Where TC= tower cost, H= hub height, BC= blade cost, HC= hub cost, RC= rotor cost, DTC= drive train cost, FC= foundation cost and NAC= nacelle cost.

The other parameters defining the detail cost such as maintenance, operational and installation costs are based on the empirical formulation from NREL cost model [1] and [2].

5. The Design Tool

In order to test the approach, a MATLAB code was developed in this work. The pattern search technique is adopted for optimization. A flow chart of the developed tool is shown in Fig. 1 and a snapshot of the tool input window is shown in Fig. 2.

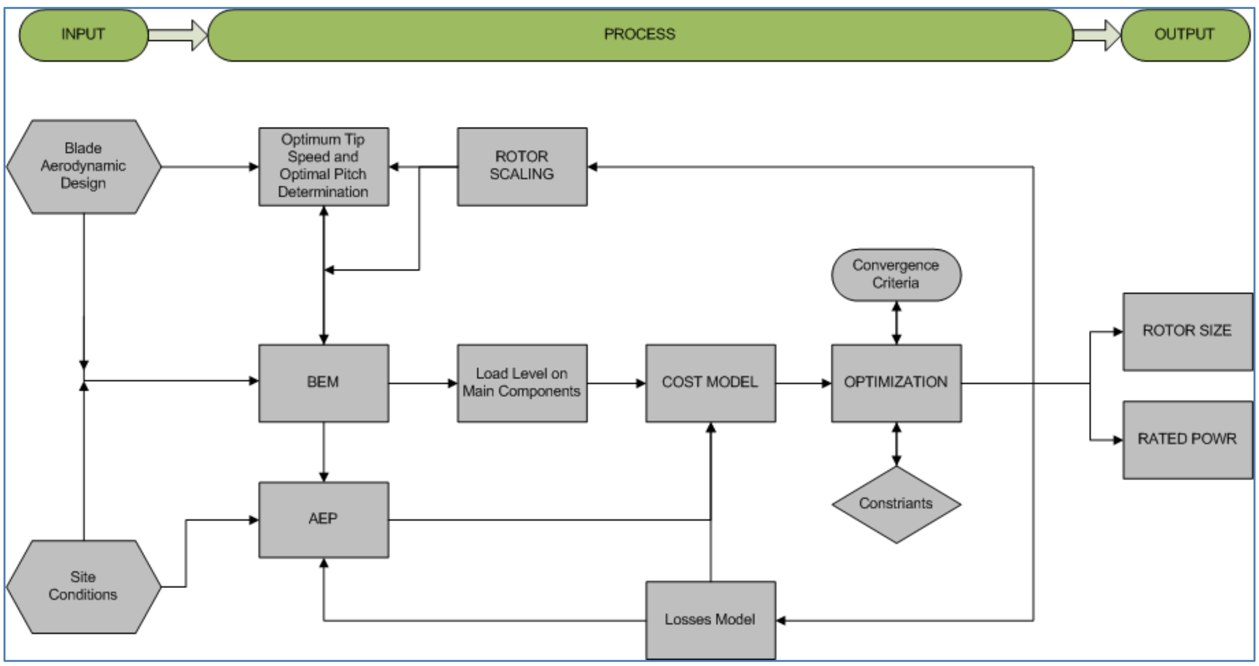

Fig.1. Cost and design optimization tool flowchart.

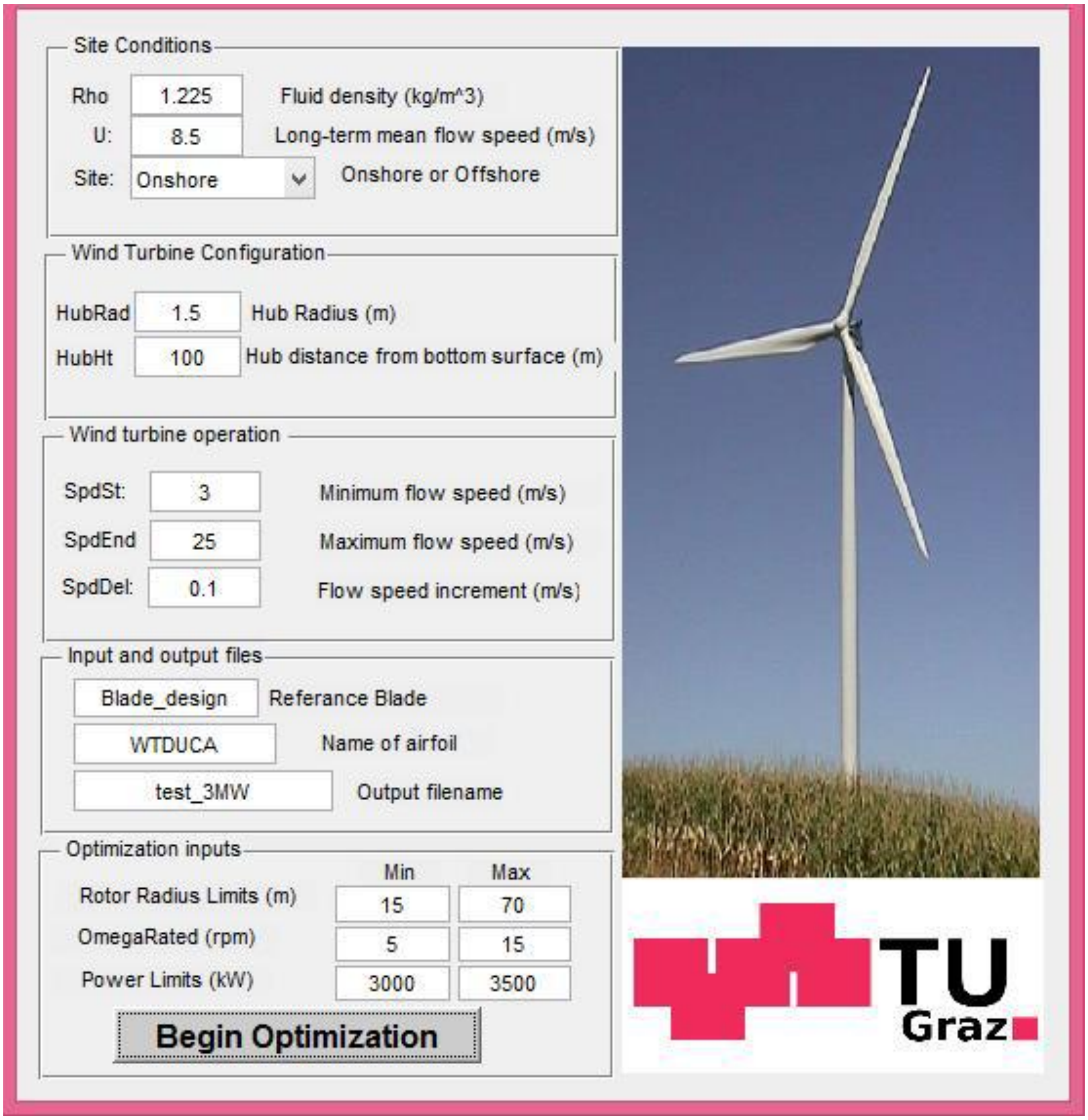

Fig.2. Snapshot from the wind turbine optimization tool

The outputs of the optimization tool are as follows:

1. Breakdown cost report of the wind turbine
2. Extreme load levels on the main components
3. The COE value
4. The optimized design variable values
5. The aerodynamic design of the blade corresponding to the optimum rotor size
6. Performance charts corresponding to the optimum design (power curve, power coefficients, thrust …etc.).

6. Test Examples

The test examples are used to test the approach. The test examples are for variable- speed pitch-regulated wind turbine. The choice of the test examples are based on representing both low and high wind sites. The characteristics of each of them are listed in the table I and table II:

Site density	1.225 kg/m3
Annual average wind speed	7.5 m/s
Hub-height	90 m
Cut in wind speed	3 m/s
Cut out wind speed	25 m/s
Rotor radius range	30-70 m
Power rating range	1.0 MW- 2.5 MW

Table I. – Low wind test example characteristics and constraints

Site density	1.225 kg/m3
Annual average wind speed	10 m/s
Hub-height	120 m
Cut in wind speed	3 m/s
Cut out wind speed	25 m/s
Rotor radius range	50-95 m
Power rating range	5.0 MW- 8.0 MW

Table II. – High wind test example characteristics and constraints

7. Results

The results are presented as cost break down, cost report and performance curves for the test examples.

A. *Low wind site example results*

The first test example is an onshore turbine constructed for low wind sites. The optimized main configuration, components cost and COE are shown in Table III.

MAIN CONFIGURATION OF THE TURBINE	
Machine Rating (kW)	**1,356.50**
Rotor Diameter (m)	**94.99**
CAPACITY FACTOR	**0.48**
INITIAL CAPITAL COST (ICC=BOS+TCC)	**1,899,581.14**
AEP (kWh)	**5,649,969.69**
COE ($/kWh)	**0.0458127**

Table III.-Low wind site turbine results

Fig.3. Low wind site turbine cost breakdown

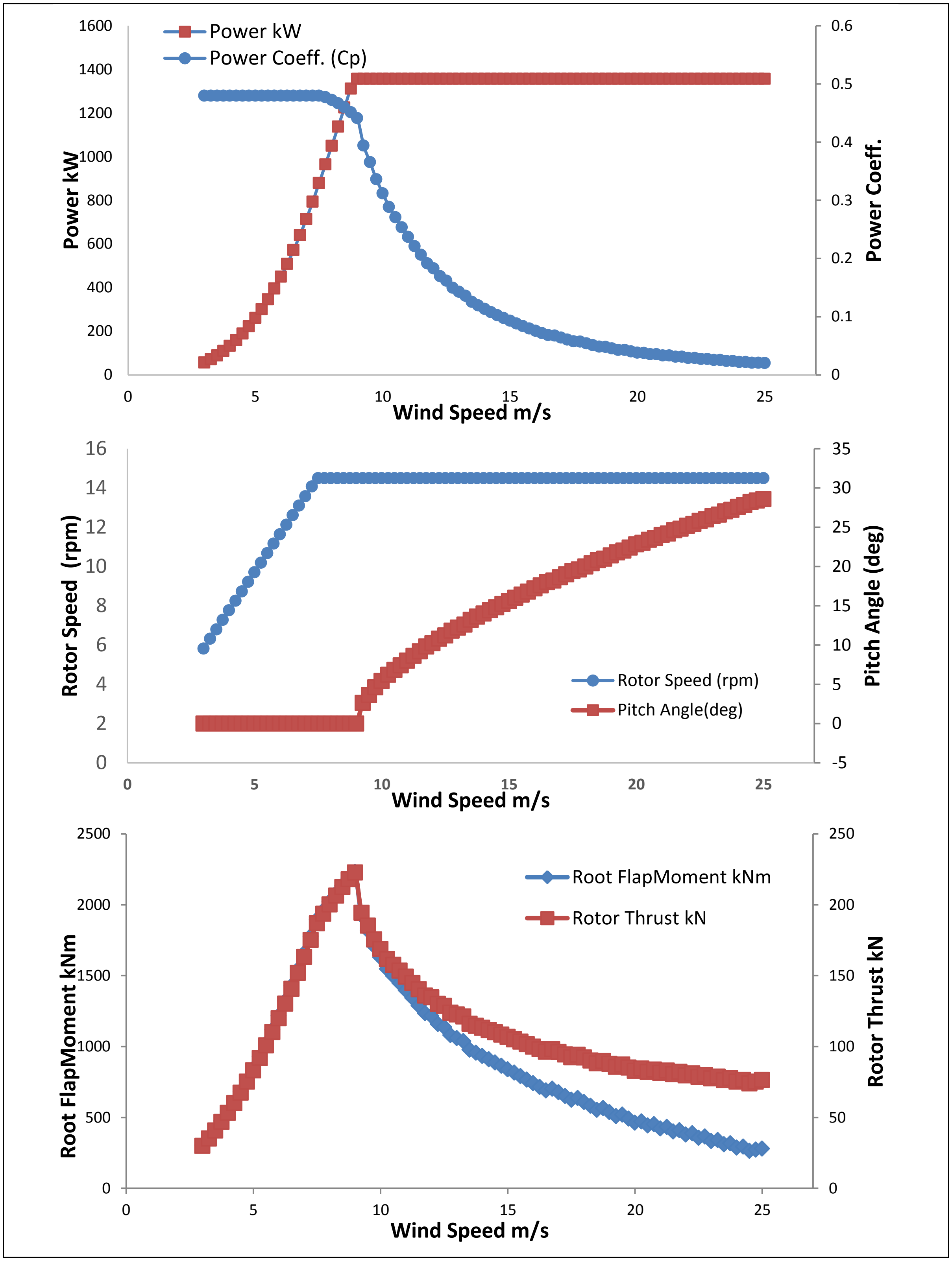

Fig.4. Low wind site turbine performance curves

The drive train and nacelle account for almost 35% of the turbine. A second important contribution results from the balance of station (BOS) cost, which is the summation of foundation, erection, transport and installation costs. The BOS represents almost 30%.

From the above we can also interpret that, in order to reduce the COE for low wind sites, the rotor size shall be increased for low rated power.

B. *High wind site example results*

The test example is given by an onshore turbine constructed for high wind sites. The optimized main configuration, component cost report and COE are given in Table IV.

MAIN CONFIGURATION OF THE TURBINE	
Machine Rating (kW)	5,000.00
Rotor Diameter (m)	134.93
CAPACITY FACTOR	0.52
INITIAL CAPITAL COST (ICC=BOS+TCC)	7,793,792.96
AEP (Kwh)	22,821,943.76
COE ($/kWh)	0.0459944

Table IV.-High wind site turbine results

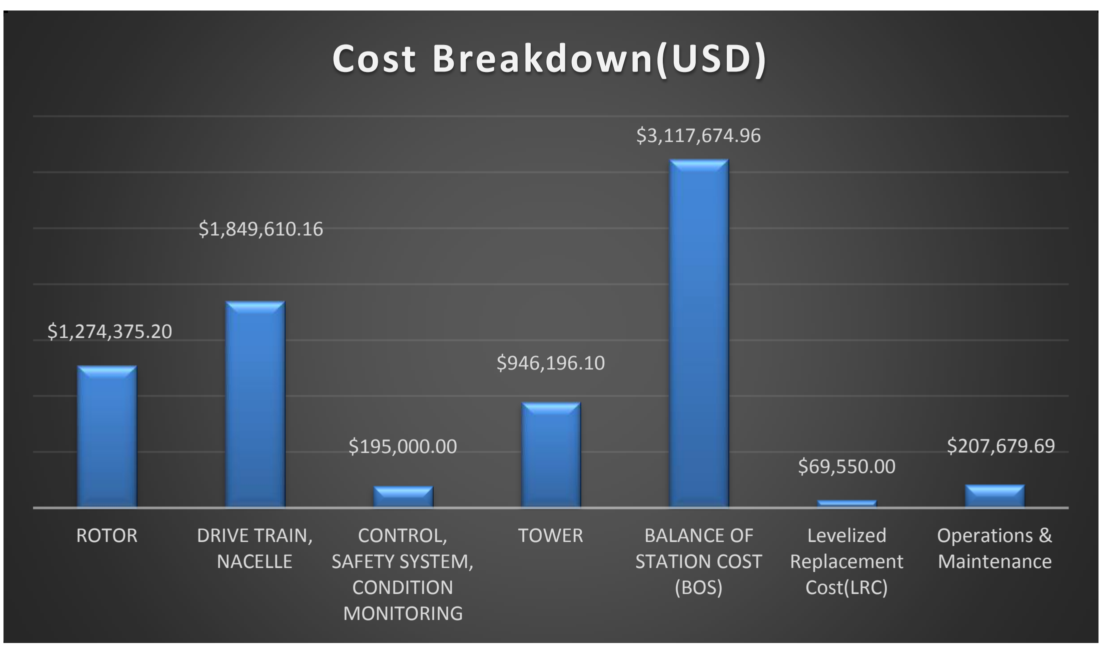

Fig.5. High wind site turbine cost break down

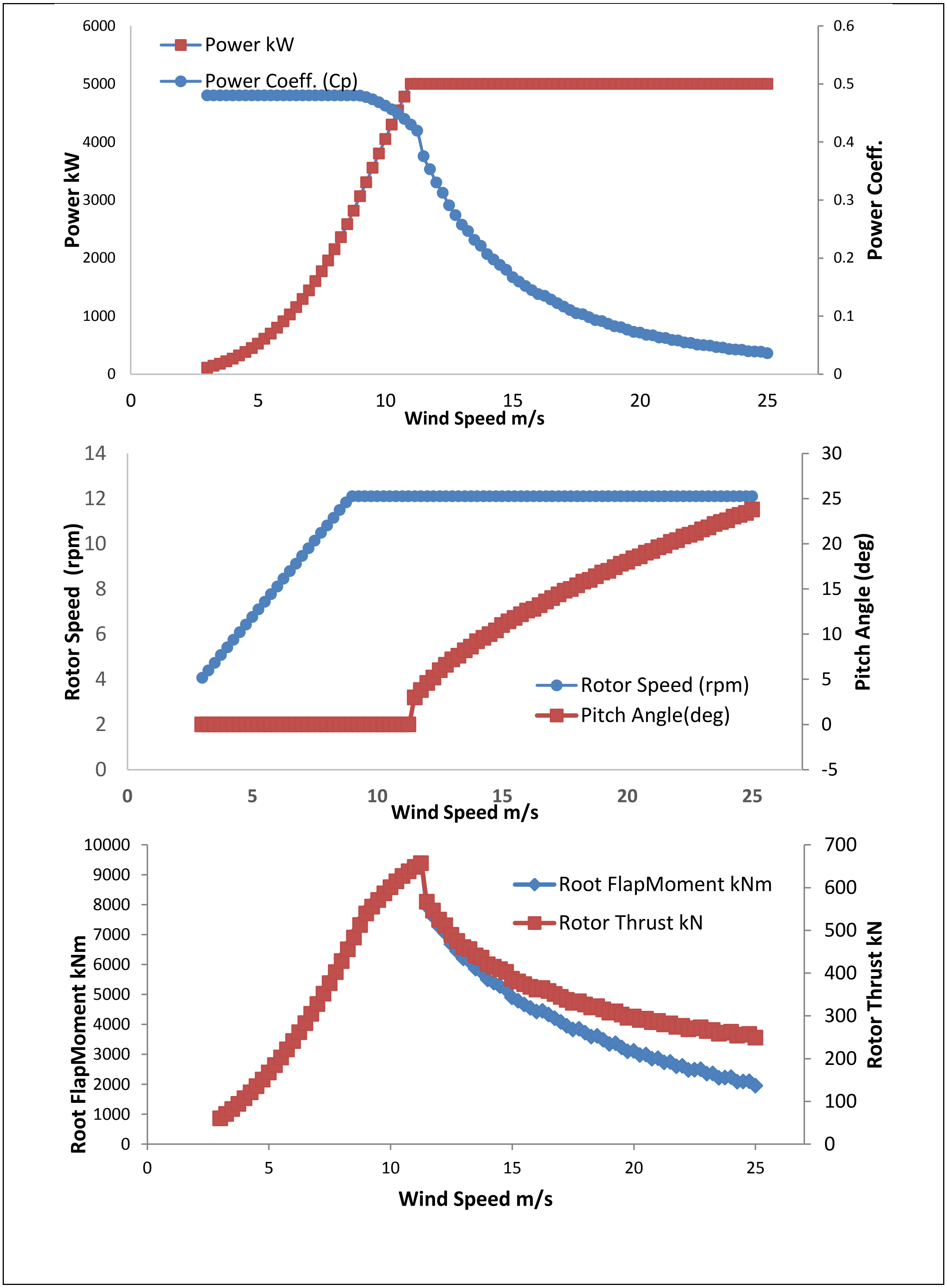

Fig.6. High wind site turbine performance curves

For this case, the drive train and nacelle account for almost 25% of the turbine while the balance of station cost represents almost 40%. Here, the main cost driver is the nacelle cost and BOS (Balance of Stations) cost.

The examples indicate that increasing the rotor size is not the key driver of COE for high wind sites, but the nacelle and drive train costs with consideration to BOS cost play the major roles in COE.

8. Sensitivity analysis

The methodology adopted for sensitivity analysis is OAT (one at time method) to see the effect of this parameter on the output. It is done by:

- Moving one input variable, keeping others at their baseline (nominal) values, then,
- Returning the variable to its nominal value, and then repeating for each of the other inputs in the same way.

The sole effect of both rated power and rotor radius on the COE are shown in Fig 7

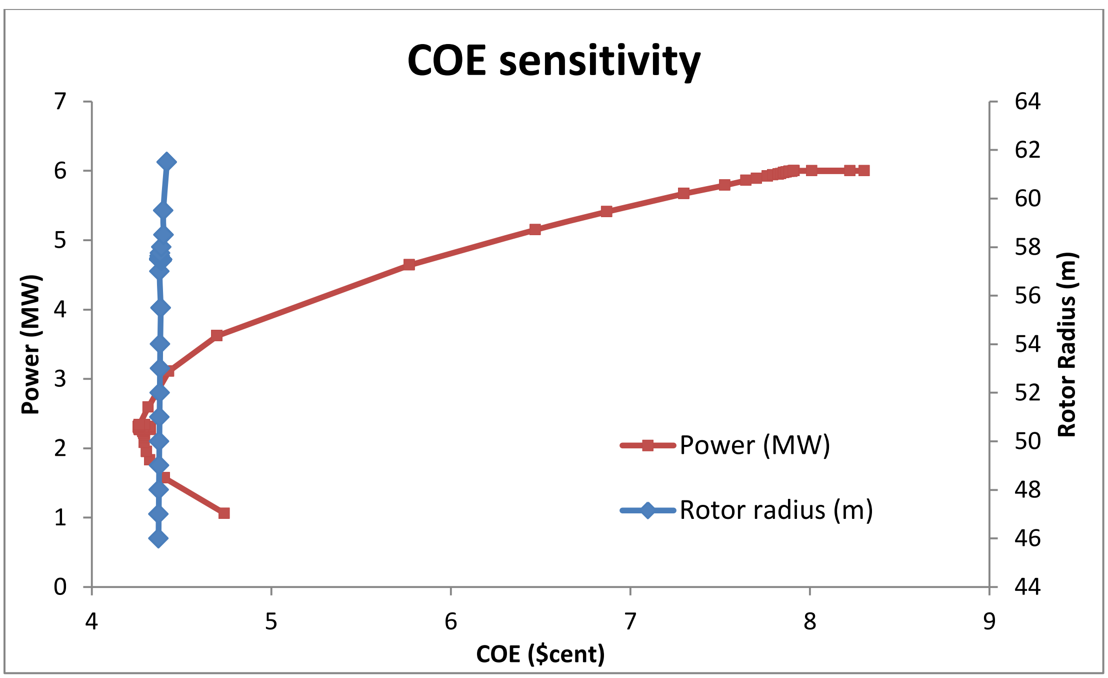

Fig.7. COE sensitivity to rotor radius and rated power

From Fig.7 we can see that, for given rotor radius the COE is very sensitive to changing the rated power of the turbine. Changing the rotor radius will change the AEP of the turbine but this change will be compensated by changing load level and increase the relevant costs due to rotor size change.

9. Conclusion

In this article an approach has been presented to optimize the cost of energy by utilizing cost of energy as objective function. The approach has adopted the complex cost model in addition to account for the load level effect on cost.

The approach can give an initial estimate of the COE for newly developed wind turbine without going into details of the sub components specification or design. The cost model can easily be changed and adopted to the changes based on the updated market price, financial inputs, labour hour cost, markets of interests, etc.

The optimum balance between generator power rating and rotor size to optimize COE is determined. The approach can present the initial estimate of aerodynamic performance for the optimized turbine configuration.

The approach has shown that, increasing the rotor size with reducing the rated power will reduce COE for onshore turbines at a low wind site.

Comparing the high wind site turbines with low wind site turbines shows that, for low wind turbine the nacelle and drive train play the major role in the turbine cost and consequently the COE. For high wind sites with high power rating turbines the BOS cost is the dominant in determine the COE.

Comparing the test examples we can conclude that, increasing the power and rotor radius for high wind sites can lead to the same COE level of small size turbines in low wind sites.

The COE is more sensitive to the rated power than the rotor radius. The rotor radius change shows that, it has almost neutral effect on the COE for given rated power.

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