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# Exploring the "Cost - Capacity Factor" Tradeoffs Offered by the Best Performing Commercial Wind Turbines

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**Wind resources vary significantly in strength from one location to another over a wide geographical region. The major turbine manufacturers offer a family/series of wind turbines to suit the market needs of different wind regimes. The current state of the art in wind farm design however does not provide quantitative guidelines regarding what turbine feature combinations are suitable for different wind regimes, when *turbines are operating as a group in an optimized layout*. This paper provides a unique exploration of the best tradeoffs between the cost and the capacity factor of wind farms (of specified nameplate capacity), provided by the currently available turbines for different wind classes. To this end, the best performing turbines for different wind resource strengths are identified by minimizing the cost of energy through wind farm layout optimization. Exploration of the "*cost - capacity factor*" tradeoffs are then performed for the wind resource strengths corresponding to the wind classes defined in the 7-class system. The best tradeoff turbines are determined by searching for the non-dominated set of turbines out of the pool of best performing turbines of different rated powers. The medium priced turbines are observed to provide the most attractive tradeoffs – 15% more capacity factor than the cheapest tradeoff turbines and only 5% less capacity factor than the most expensive tradeoff turbines. It was found that although the "*cost - capacity factor*" tradeoff curve expectedly shifted towards higher capacity factors with increasing wind class, the trend of the tradeoff curve remained practically similar. Further analysis showed that the "*rated power - rotor diameter*" combination and the "*rotor diameter/hub height*" ratios are very important considerations in the current selection and further evolution of turbine designs. We found that larger rotor diameters are not preferred for mid-range turbines with rated powers between 1.5 - 2.5 MW, and "rotor diameter/hub height" ratios greater than 1.1 are not preferred by any of the wind classes.**

**Keywords: capacity factor, cost of energy, Rayleigh distribution, tradeoff, turbine, wind farm layout optimization**

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# I. Introduction

The *intermittency of a wind resource at a place* and the *variation of the wind pattern from place to place* present significant challenges to the full-scale development of wind energy. Appreciable work has been done (and is ongoing) (i) to account for the variation of wind conditions at a particular site (e.g. wind distribution modeling), and (ii) to address the intermittency of wind resources (e.g. energy storage technologies). In contrast, there has been limited amount of work that investigates the complex demands on wind turbine performance presented by the variety of wind patterns (e.g. different wind classes) existing in the entire market.

Available commercial turbines provide a range of feature combinations − combinations of rotor diameter, tower height, and power characteristics. A quantitative exploration of the best trade-offs between cost and energy production capacity provided by the available turbines is necessary to (i) identify most suitable turbine-feature combinations, and (ii) understand the required direction of evolution of turbines (in terms of primary features) for better performance. Additionally, an exploration how these trade-offs shift with the wind class is helpful to understand the sensitivity of turbine-array performance potential to the individual turbine features.

Chowdhury et al.[1] developed a methodology to identify the best performing turbines for differing wind regimes and quantify their performance potential (in terms of minimized Cost of Energy) as function of the wind resource strength. This paper extends the research presented by Chowdhury et al.,[1] by exploring the trade-offs between cost and capacity factor offered by the best performing turbines (for different wind regimes), and how these trade-offs are related to the turbine-feature combinations. The following subsections discuss the role of turbine selection in wind farm planning and the observed variation of wind patterns in the entire market.

## A. Role of Turbine Selection in Wind Farm Design

Post wind resource assessment of a site, the objectives of *optimal wind farm planning* are to (i) minimize the Cost of Energy (COE), expressed in $/kW.h, and/or (ii) maximize the Capacity Factor (CF). Successful accomplishment of these objectives demands a robust and flexible wind farm optimization platform that allows appropriate consideration of the following critical factors:

1. the installed capacity of the wind farm,
2. the land configuration and the placement of turbines in the wind farm,
3. the types of wind turbines to be installed.

In this paper, we are particularly concerned with the role of the third factor in wind farm performance. A turbine (or a set of turbines) that offers the most attractive trade-off between (i) its life cycle costs and (ii) its long-term energy production capacity for the predicted site conditions can be considered suitable for the concerned wind farm.

The power generation capacity of turbine at a particular site depends on the annual (long-term) average wind speed at that location. The average wind speed rating for a turbine is generally provided by the manufacturer as a component of the specified IEC Wind Turbine Class rating.[2] However, considering that each turbine operates as a part of an entire array in a commercial wind farm, the relation of its power generation performance to its average wind speed rating is seldom straightforward. In quantifying the energy production capacity of a farm, it is important to recognize and account for the wake-induced interactions among the turbines in the farm. To this end, the optimization process should simultaneously consider the farm layout and the turbine type selection.[3] Another important criterion for turbine selection is its load bearing capacity. In this context, the IEC wind turbine rating provides the compatibility of the turbine with respect to standard turbulence intensity measures. The determination of the local average wind gusts at a site and the subsequent turbulence intensity measures is a crucial part of wind resource assessment. However, such information is site specific, and long term turbulence intensity maps for an entire region is generally not available. Hence, the load bearing capacity of turbines is not considered as a compatibility criteria in this research.

In this paper, we focus on the following two important aspects of a turbine to determine its geographical compatibility.

1. Actual *energy production capacity* of a turbine (when operating as a group) based on the local wind resource;
2. Cost of the wind farm attributable to the turbines.

In this context, we define commercially available wind turbines in terms of five major features: (i) rated power, (ii) power characteristics, (iii) rotor-diameter, (iv) hub-height, and (v) drive-train type.

The decision-making regarding (i) the placement of turbines and (i) the type(s) of turbines to be installed are interdependent, and should ideally be performed simultaneously when designing optimal wind farm configurations. To this end, the Unrestricted Wind Farm Layout optimization (UWFLO)[3,4] methodology is adopted in this paper. The UWFLO method is a significant advancement of the state of the art in wind farm layout optimization.[5–10] The majority of the other methods do not explicitly account for turbine type selection during the layout optimization process. In addition, UWFLO allows the optimal selection of both a single turbine type and a combination of multiple turbine types for a wind farm.

### B. Geographical Variation of Wind Patterns

The performance of a wind farm strongly depends on the variation of wind conditions at the site. Different types of turbines are expected to be suitable for different wind patterns, which calls for appropriate classification and representation of wind patterns. NREL classifies wind patterns into seven wind classes, based on the estimated average wind speed (AWS) and/or wind power density (WPD).[11] In the 7-class system, each wind class spans two values of mean wind speed and the two associated values of wind power density. The mean wind speed is based on Rayleigh speed distribution of equivalent mean wind power density.[11] Both the mean wind speed and the WPD values can be considered as measures of the *resource strength of a wind site*. Information regarding what values of mean/average wind speed are experienced in different parts of a region is often available in the form of wind maps (e.g., the US wind map[12]). However, the number of ranges of AWS need not be restricted to the seven wind classes; a finer variation of wind patterns/regimes is desirable when exploring turbines suitable for different wind patterns.

Appropriate representation of the variation of wind patterns over the entire wind energy market area is therefore the first step towards understanding the “turbine to operating-conditions” compatibility. In this paper, the compatibility of a turbine is defined by its likelihood to get chosen during wind farm layout optimization, where the objective is to minimize the cost of energy of the farm. In order to quantify the energy production (AEP) for a candidate farm design, information regarding the local long term variation of wind conditions is required. In this paper, the long term AWS is used to represent a wind resource, which has the following two advantages: (i) a 1-parameter distribution of wind speed can be readily derived from the AWS to represent the approximate variation of wind conditions at the concerned site; and (ii) the resource strength of the site can be readily related to a wind map that represents the wind resources over a region in terms of their estimate AWS.

The following section provides a brief summary of the framework developed to identify the best performing turbines for different wind regimes,[1] and the corresponding results obtained (resulting optimum turbine choices). Section III explores the performance trade-offs offered by current commercial turbines (for different wind regimes), and also investigates the sensitivity of these performance levels to the features of the turbines. Section IV presents the concluding remarks.

## II. Determination of Best Performing Wind Turbines for Different Wind Regimes

### A. Characterization of Wind Regimes

In order to determine optimal turbine choices for different wind patterns, a set of $n$ random sample wind speeds are generated based on the geographical distribution of the average onshore wind speeds. Optimization of the layout and turbine selection can then be performed for each of these sample incoming wind speeds, to yield a pool of operating-conditions compatible turbine types. An important factor to consider in this context is: *the power generated by a turbine is proportional to the third degree of the approaching wind speed. Since wind speeds vary significantly over time (days), using the linear average of the long term wind speed at a location can introduce significant errors into the estimated power generation.* To mitigate such errors, we can use a 1-parameter distribution to approximate the variation of wind speed over time at a location;

this distribution can be estimated by using the sample wind speed as its mean. In this paper, we use the Rayleigh distribution by assuming that the mean of the distribution is equal to the AWS at that location; for a location where the AWS is $s$ m/s, the parameter $\sigma$ of the Rayleigh distribution is given by,

$$\sigma = s\sqrt{\frac{2}{\pi}} \tag{1}$$

Optimizations will be performed for distributions of incoming wind speed, corresponding to each sample AWS. For illustration purposes, a set of 10 random AWS values are generated. The Rayleigh distributions corresponding to the 10 sample AWS are shown in Fig. 1. The optimization process is described in the following section.

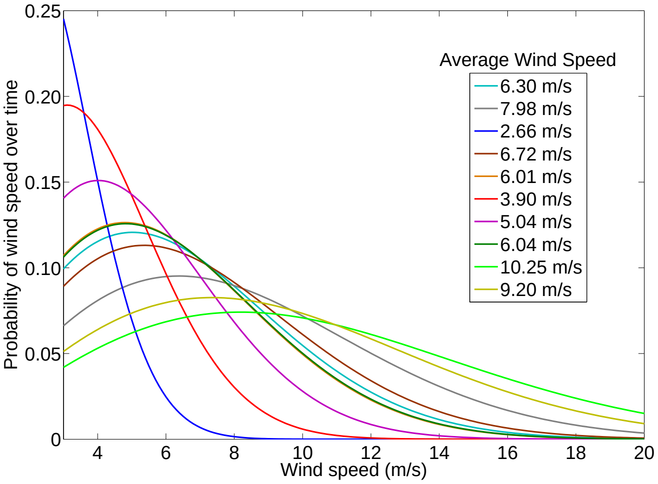


**Figure 1. Rayleigh distributions of wind speed: corresponding to specified average wind speed (AWS) values**

## B. Framework to Determine Optimal Turbine Choices

The choice of operating-conditions-compatible turbines is based on: which turbine type leads to the lowest Cost of Energy (COE) for the wind farm. In this context, the COE of a farm depends both on the cost of the turbines (installed) and on the performance of the turbines as members of the array. Hence, the minimum COE is accomplished by optimizing the selection and the placement of the turbines. The Unrestricted Wind Farm Layout Optimization (UWFLO) framework[3, 4] is an effective method to design such optimal wind farm configurations.

In the UWFLO power generation model, the incoming wind is assumed to follow a log profile.[13] The growth of the wake behind a turbine is determined using the wake growth model proposed by Frandsen et al.[14] The corresponding energy deficit behind a turbine is determined using the velocity deficit model developed by Katic et al.[15] and widely used in *wind farm power generation* estimation.[9, 10, 16] A wake superposition model, also developed by Katic et al.,[15] is adopted to evaluate the wake merging effects. The UWFLO power generation model also accounts for the possibility of a turbine being ‘partially’ in the wake of another turbine located upwind. The net power generated by the wind farm, for a given wind speed and direction, is evaluated by the sum of the powers generated by the individual turbines. The *wind farm power generation* model developed in UWFLO has been successfully validated by Chowdhury et al.[3] against published experimental data.[17]

The energy production over a defined time period is determined by integrating (numerically) the power generation function over the distribution of wind speed and direction (estimated for that time period). The *Wind Turbine Design Cost and Scaling* model, reported by Fingersh et al.,[18] is adopted to estimate the cost of the farm attributable to each turbine. The farm dimensions and the minimum distance required between any two turbines are treated as system constraints during optimization. An advanced mixed-discrete Particle Swarm Optimization[4, 19, 20] is applied to perform the optimization. The following two subsections describe how we quantify the performance of each turbine and the cost attributable to each turbine.

### C. Turbine Characterization Model

Every turbine is defined in terms of the five primary features that influences its power generation performance: (i) rated power, (ii) rated speed, (iii) rotor-diameter, (iv) hub-height, and (v) performance characteristics. The rotor-diameter and the hub-height of a turbine determines which part of (and what extent of) the wind profile the turbine will be subject to. They also regulate the dimensions of the wake produced by the turbine. Hence, for an array of turbines, the rotor-diameter and the hub-height play an important role in regulating the overall mutual shading effects and the subsequent energy availability within the farm. The specification of these two features is readily available for most commercial wind turbines.

The rated power, the rated speed, and the power characteristics on the other hand determine what power can be generated by the turbine for any given incoming wind. These three properties are implicit to the power curve, if available. However, information regarding the "power vs. wind speed" variation is not readily available for all commercial turbines; generally the rated power and the rated speed are specified by the manufacturer. Hence, a generalized power curve ($P_n$) is developed using the data for a popular turbine type: GE 1.5 MW xle.[21] To this end, a $5^{\text{th}}$ degree polynomial is fitted to the data, as shown in Fig. 2. As it is seen from this figure, the power generated ($P$) and the incoming wind speed ($U$) are normalized with respect to the rated power ($P_{rated}$) and rated speed ($U_{rated}$), respectively.

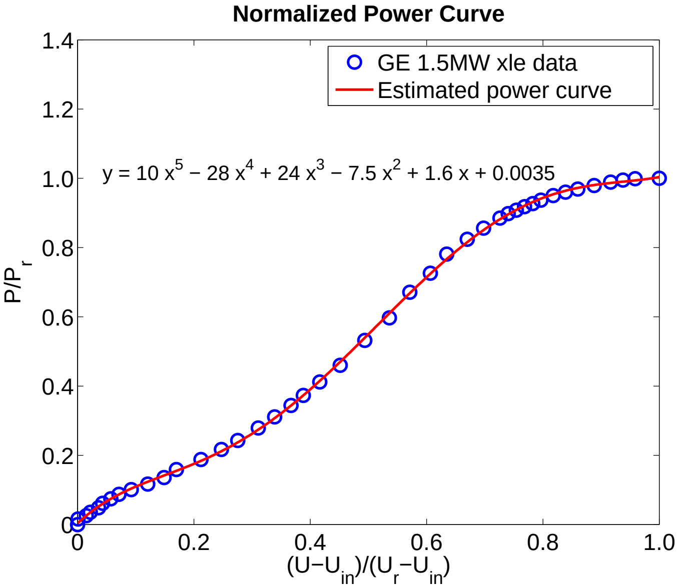


**Figure 2. Normalized power curve for GE 1.5 MW xle turbine**

Using this generalized power curve ($P_n$), along with the rated power and the cut-in, cut-out and rated speed specifications, the actual power curve of any other turbine can be approximated as:

$$\frac{P}{P_r} = \begin{cases} P_n \dfrac{U - U_{in}}{U_r - U_{in}}, & \text{if } U_{in} < U < U_r \\ 1, & \text{if } U_r < U < U_{out} \\ 0, & \text{if } U_{out} < U \text{ or } U < U_{in} \end{cases} \tag{2}$$

where $P_n$ represent the polynomial fit for the normalized power curve. This generalized power characteristics estimation strategy has been used for ready implementation purposes; if the power response data is available for a particular wind turbine, a unique power curve specific to that turbine should ideally be determined and used.

### D. Wind Turbine Cost Model

Since the mid-1990s, wind turbine design configurations have become more standardized. As a result, a generic model could be developed to estimate the cost of wind turbine components. Around this time, the

Department of Energy (DOE) started the Wind Partnership for Advanced Component Technology (WindPACT) projects. The aim of these projects was to investigate how to reduce the cost of wind turbine production.[22] Fingersh et al.[18] extended the WindPACT projects by preparing a *Wind Turbine Design Cost and Scaling Model* (WTDCS) for then modern wind turbine configurations, in terms of 2002 US dollars. In this model, the turbines are assumed to be three bladed, upwind, pitch-controlled, variable-speed with active yaw, and mounted on steel tubular towers.

According to the WTDCS model, the cost of a farm attributed to one turbine, $\mathrm{C_{FT}}$, can be expressed as

$$C_{\mathrm{FT}} = C_{\mathrm{MF}} + C_{\mathrm{BS}} + C_{\mathrm{LR}} + C_{\mathrm{OM}} \tag{3}$$

where $C_{\mathrm{MF}}$ ,$C_{\mathrm{BS}}$ ,$C_{\mathrm{LR}}$,and $C_{\mathrm{OM}}$ represent the total manufacturing cost, the balance-of-station cost, the levelized replacement cost (LRC), and the operation and maintenance (O&M) cost, respectively. Further details of the WTDCS cost formulation can be found in Figersh et al.[18] The general configuration of the wind turbines have not changed significantly since 2006. Hence the cost model developed by Fingersh et al.[18] is practically applicable to compare costs of commercial turbines currently available in the market.

## E. Pool of Optimal Turbine Choices for Differing Wind Regimes

For each sample average wind speed (AWS) value in the range 3.5 - 10.0 m/s (at 80 m height above the ground), wind farm optimization is performed to minimize the Cost of Energy (COE). The COE for a candidate farm is given by

$$COE = \frac{N \times C_{\mathrm{FT}}}{E_{farm}} \tag{4}$$

where $N$ is the number of turbines; the annual energy production (AEP), $E_{farm}$, is estimated by numerically integrating the UWFLO power generation model over the *Rayleigh distribution of wind speed* associated with the concerned average wind speed (AWS) value. The Monte Carlo integration technique is employed[4] using a set of 20 random wind speed values in the range 3.0 - 25.0 m/s. Other specified details of the generic wind farm is given in Table 1.

**Table 1. Specified properties of the generic wind farm site**

| Property | Value |
|---|---|
| Nameplate capacity | 25.0 MW |
| Radius of the circular farm | 964.0 m |
| Average terrain roughness | 0.1 m (grassland) |
| Density of air | 1.2 kg/m$^3$ |

For a given installed capacity of the farm, the number of turbines in the farm is automatically determined by the choice of the turbine rated power. In the UWFLO method, simultaneous optimization of turbine selection and placement involves $2N+1$ design variables - $2N$ turbine coordinates, and 1 turbine type indicator. Hence, differing choice of rated powers yields candidate farm designs with differing *numbers of design variables*. Such candidate designs with different variable space dimensions cannot be typically optimized together. Therefore, for each sample AWS, optimization has to be separately run to test the performances of commercial turbines with differing rated powers. In this paper, we test 131 globally available commercial turbines from the following manufacturers: GE, Vestas, Enercon, Siemens, Goldwind, Suzlon, and Gamesa. Table 2 lists what rated-power turbines (and how many variants) are considered. It is important to note that the effective installed capacity of the farm is fixed at $25 \pm 1$ MW, to allow a realistic *whole number* of turbines for each rated-power class.

For a set of $n$ random AWS values and the allowed 13 different turbine rated powers (Table 2), wind farm optimization has to be run $13n$ times, which can be computationally expensive. Through numerical experiments we found that a sample size of $n = 25$ provides an acceptable representation of the pertinent range of AWS, while keeping the overall computational expense of the $13n$ optimization reasonable. In the case of each sample AWS, the results of the optimizations corresponding to the 13 different turbine rated-power classes are compared to determine the best turbine choice.

**Table 2. Major commercial turbine choices in the US onshore market**

| Rated-power class (MW) | No. of available choices | No. installed in the farm |
|---|---|---|
| 0.60 | 3 | 42 |
| 0.80 | 7 | 31 |
| 0.85 | 13 | 29 |
| 0.90 | 3 | 28 |
| 1.25 | 6 | 20 |
| 1.50 | 16 | 17 |
| 1.60 | 5 | 16 |
| 1.80 | 10 | 14 |
| 2.00 | 36 | 13 |
| 2.30 | 14 | 11 |
| 2.60 | 3 | 10 |
| 2.75 | 4 | 9 |
| 3.00 | 11 | 8 |

Figure 3 shows the variation (with AWS) of the *minimum COE accomplished by the best performing turbines from each rated-power type* (through wind farm optimization). Detailed discussion of the results shown in this figure is provided in the paper by Chowdhury et al.[1] In this paper, we focus on the exploration of the "cost - capacity factor" tradeoffs provided by the best performing turbines (for different wind regimes).

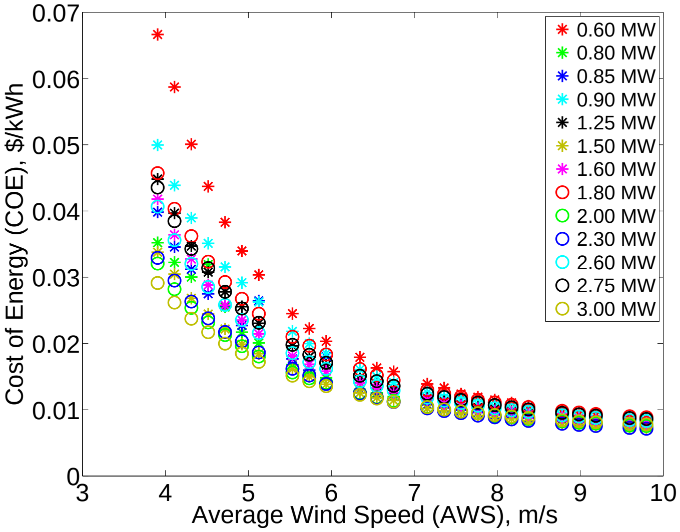


**Figure 3. The minimized COE given by the best performing turbines (of each rated-power type) for each sample AWS value[1]**

# III. Performance Tradeoffs Offered by Current Commercial Turbines

## A. Turbine Tradeoffs for Different Wind Regimes

Turbines were selected for different wind regimes based on the minimum cost of energy accomplished by them, when operating in an optimized layout. However, it is also important to understand the tradeoffs between the energy production capacity (capacity factor) and the cost offered by the best performing turbines. A subsequent investigation of what feature combinations provide the best tradeoffs is useful to identify what range(s) of turbine-feature combinations are likely to have greater market acceptability. Hence, out of the pool of best performing turbines (of different rated power classes) for each wind regime, we determine the turbines that provide the best tradeoffs between capacity factor and average annual cost ($/kW installed). The best tradeoffs are determined by searching for the non-dominated solutions, based on the principles of weak dominance. These solutions can be called Pareto solutions; however, it is important to note that the Pareto solutions in this case are determined as a post process after a single objective optimization problem.

In this paper, wind farm optimization (optimum turbine selection) is performed for 25 different AWS values. For tractable exploration purposes, we illustrate and discuss the best tradeoff solutions corresponding to the six AWS values that are closest to those defining the 7 wind class system. NREL provides the range of AWS and WPD spanned by each wind class,[11] defined at the 10 m and 50 m heights above the ground. The specified 50 m wind speeds separating each wind class are extrapolated to 80 m (using the 1/7 power law), and the sample AWS values closest to the extrapolated values are identified. The figures represent the tradeoff solutions for the six selected AWS values (wind regimes) in terms of the wind class they are closest to. Figures 4 shows the best tradeoff solutions for different wind regimes (colored based on the wind class).

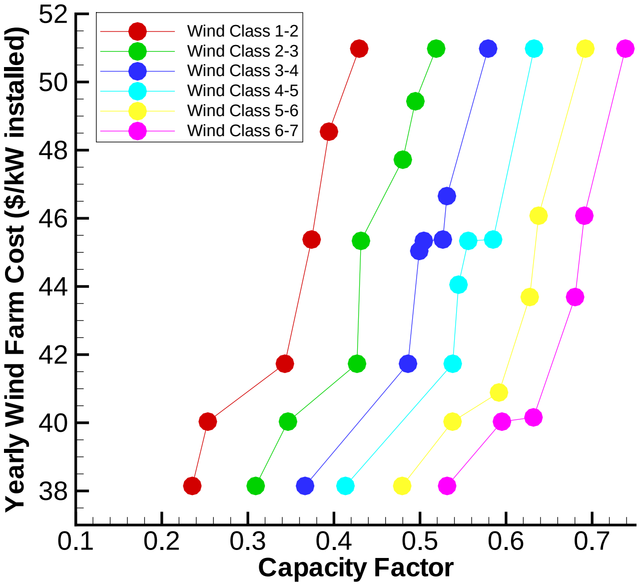
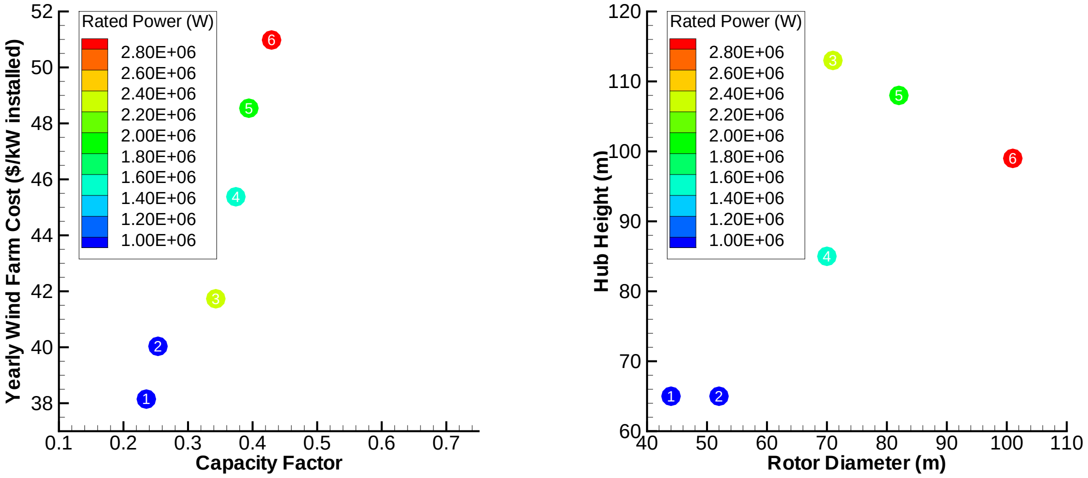


**Figure 4. Best trade-offs between wind farm capacity factor and cost ($/kW installed) for different wind classes**

Expectedly, with increasing wind class, the best tradeoffs shift towards higher capacity factors – more energy being available. It is however interesting to note (from Fig. 4) that the best tradeoff curves/fronts for different wind classes have a similar trend. For an increase of $13/kW installed in average annual cost, the increase in farm capacity factor is approximately 20% for each wind class (where *100% capacity factor* would represent continuous operation at rated/nameplate capacity). Therefore, owing to the higher increase in relative capacity factor, using the more expensive turbines might be attractive for the lower wind classes. It is also observed from Fig. 4 that the initial $7/kW installed increase in annual cost (starting from $38/kW) yields a significantly higher (14-15%) increase in capacity factor; thereafter, the rate of *capacity factor appreciation with cost* decreases (only 5% for the next $6/kW cost increase). This observation indicates that the medium priced turbines likely offer more attractive tradeoffs than than their counterparts. The overall feasibility of wind energy projects (with any turbine choice) would however also depend on other financial factors (e.g., payback time and local energy prices) and environmental impact assessment (e.g., noise and impact on surrounding ecosystem).

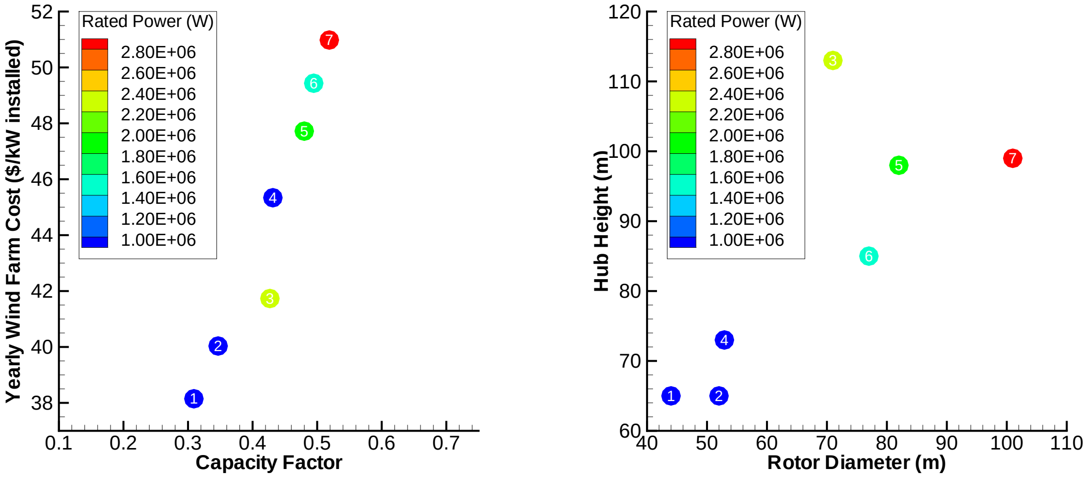
The following six pairs of figures (Figs. 5(a) - 10(b)) show the best "capacity factor - cost" tradeoffs and the features of the corresponding turbines, for the different wind classes. To readily relate the "capacity factor - cost" tradeoffs in the left-side figures to the "rotor diameter - hub height" combinations in the right side figures, they are labeled with identifying numbers. The colors of the circles represent the corresponding turbine rated power.



(a) Trade-offs between capacity factor and yearly cost

(b) Rotor diameters and hub heights of the best trade-off turbines

**Figure 5. Trade-offs offered by the best performing turbines (of different rated powers) for Class 1-2 winds**



(a) Trade-offs between capacity factor and yearly cost ($/kW installed)

(b) Rotor diameters and hub heights of the best trade-off turbines

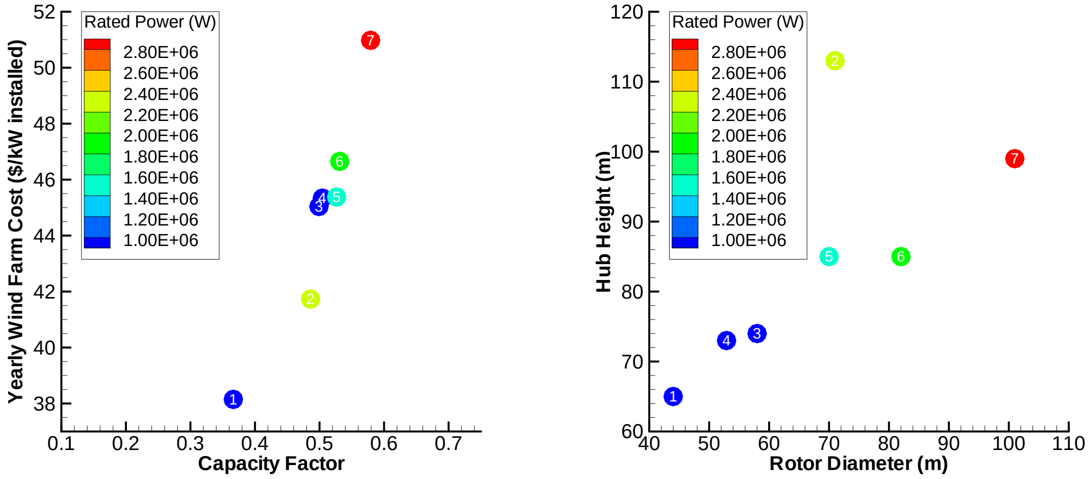
**Figure 6. Trade-offs offered by the best performing turbines (of different rated powers) for Class 2-3 winds**

Figures 5(a) - 10(b) indicate that some of the best tradeoff turbines (rotor diameter - hub height combinations) are common across the different wind classes, particularly the 0.9MW-44m/65m and the 3.0MW-101m/99m turbines. The higher wind classes are observed to promote shorter turbines (smaller hub heights). Some of the taller turbines are observed to be less expensive and yield lower capacity factors compared to turbines with shorter towers but similar rotor sizes (mid-size rotors of approximate 70 m diameter) – e.g.,

i. turbines numbered 3 and 4 in Figs. 5(a) - 5(b);

ii. turbine numbered 2 and 5 in Figs. 7(a) - 7(b);

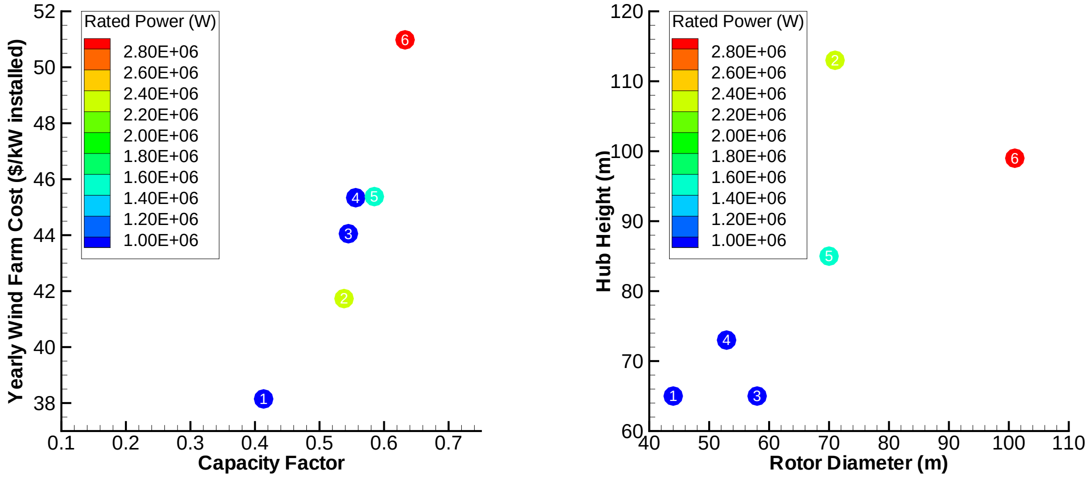
iii. turbine numbered 2 and 5 in Figs. 8(a) - 8(b)



(a) Trade-offs between capacity factor and yearly cost ($/kW installed)

(b) Rotor diameters and hub heights of the best trade-off turbines

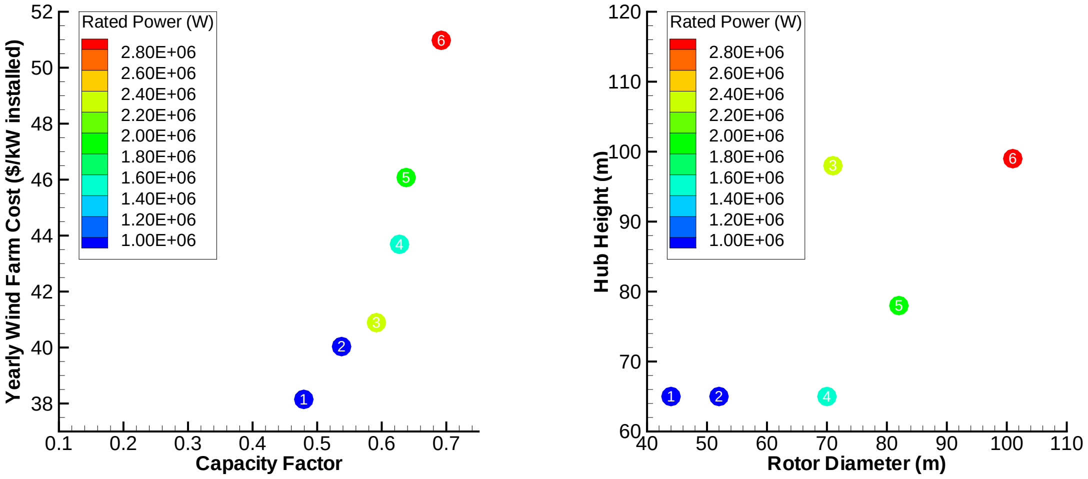
**Figure 7. Trade-offs offered by the best performing turbines (of different rated powers) for Class 3-4 winds**



(a) Trade-offs between capacity factor and yearly cost ($/kW installed)

(b) Rotor diameters and hub heights of the best trade-off turbines

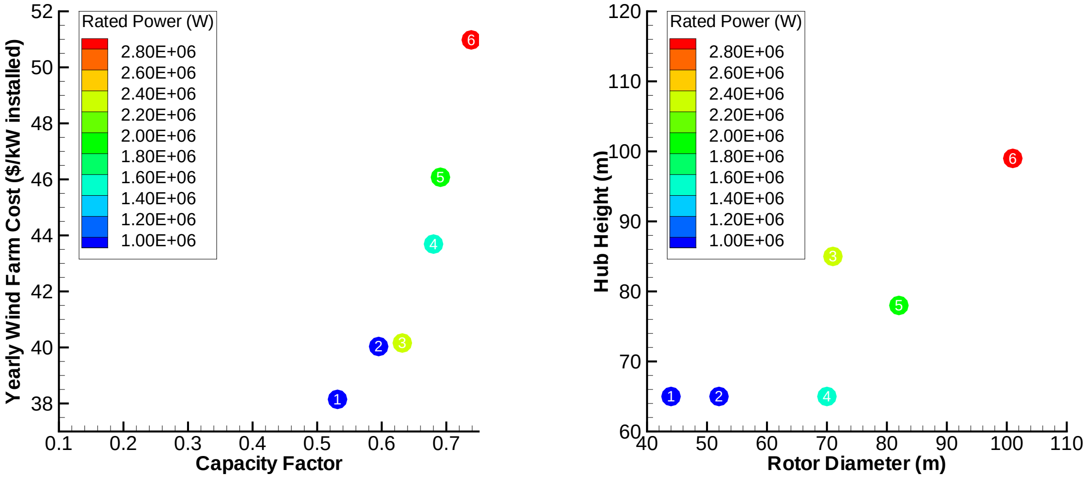
**Figure 8. Trade-offs offered by the best performing turbines (of different rated powers) for Class 4-5 winds**



(a) Trade-offs between capacity factor and yearly cost ($/kW installed)

(b) Rotor diameters and hub heights of the best trade-off turbines

**Figure 9. Trade-offs offered by the best performing turbines (of different rated powers) for Class 5-6 winds**



(a) Trade-offs between capacity factor and yearly cost ($/kW installed)

(b) Rotor diameters and hub heights of the best trade-off turbines

**Figure 10. Trade-offs offered by the best performing turbines (of different rated powers) for Class 6-7 winds**

iv. turbine numbered 3 and 4 in Figs. 9(a) - 9(b);

v. turbine numbered 3 and 4 in Figs. 10(a) - 10(b)

Since taller towers are generally more expensive and allow greater energy capture, the above observation is counterintuitive. A careful investigation of the rated powers and of the general cost variation with hub height and rated power for these turbines (with mid size rotors) can explain the seemingly counterintuitive observation.

The taller turbine in each of the above-listed cases is of a higher rated power (2.5 MW vs. 1.5 MW), and hence are expected to have higher rated speed rating (or overall lower power coefficient) than the corresponding shorter turbine, since they have similar rotor diameters. The classical turbine power generation formula given below further elucidates this scenario.

$$P = k_g k_b C_p \left(\frac{1}{2}\rho\pi\frac{D^2}{4}U^3\right) \tag{5}$$

In the above equation, $P$ represents the power generated by a turbine corresponding to a uniform incoming velocity, $U$; parameters $k_g$, $k_b$, $C_p$ and $D$ are respectively the generator efficiency, the gearbox efficiency, the power coefficient, and the rotor diameter of the turbine; and $\rho$ represents the air density. Figure 11 shows the variation of average annual farm cost with the rated power and hub height of the turbines installed, assuming their rotor diameters to be 70 m. It is readily observed from Fig. 11 that the cost variation is more sensitive to the rated power than to the hub height, for the specified ranges. In other words, *the rate of cost reduction with increasing rated power is more than that with decreasing hub height.* Since the taller turbines come with higher rated powers in the five listed cases (rotor size remaining the same), they are significantly cheaper.

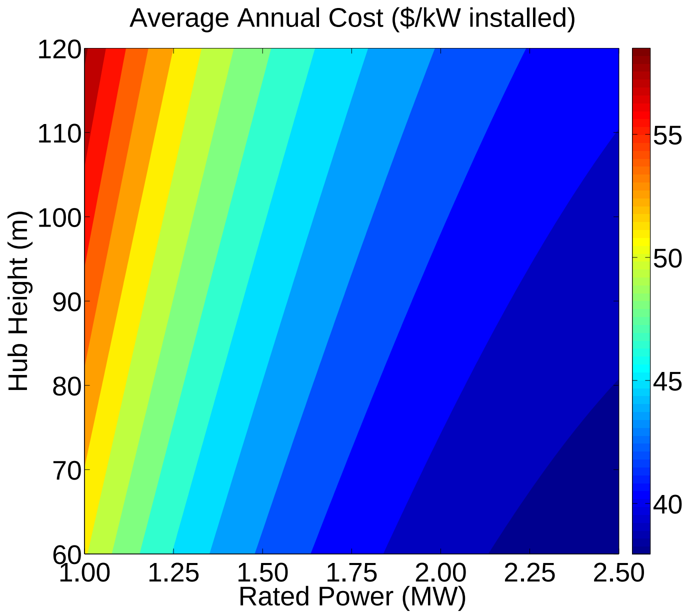


**Figure 11. Contour plot of the average annual wind farm cost (in $/kW installed) with respect to the rated power and hub height of turbines, assuming a 70 m rotor diameter**

## B. Feature Analysis of the Best Tradeoff Turbines

In this section, we compare the feature combinations of the best trade-off turbines to that of the other dominated turbines (available commercially). The objective of this illustrative comparison is to investigate why certain range(s) of currently available turbine-feature combinations are more desirable across different wind classes. In this case, desirability is based on the ”capacity factor - cost” tradeoffs offered by the turbines when operating as an optimized array.

Figure 12 shows the "rated power - rotor diameter" combinations of the best trade-off turbines for all wind classes (represented by circles) and the other commercial turbines (represented by triangles). Both the circles and the triangles are colored in terms of the average annual cost expressed in \$/kW installed.

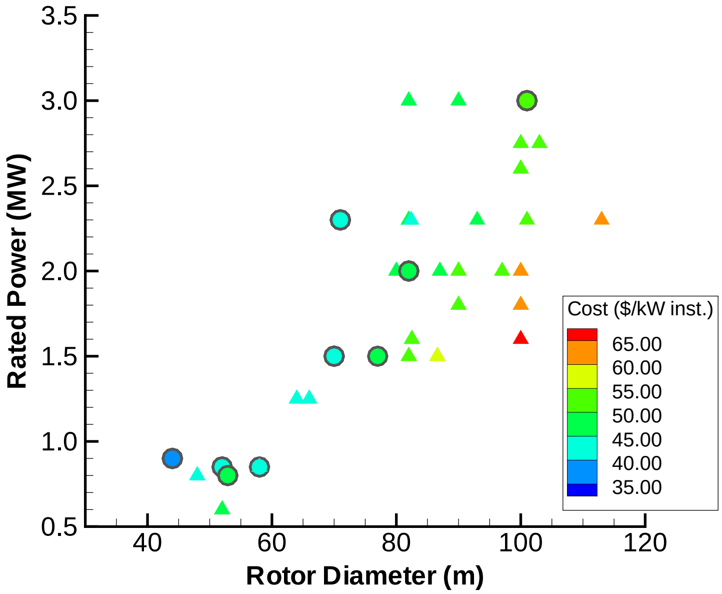


**Figure 12. Rated powers and rotor diameters of the best trade-off turbines (circles) and other available commercial turbines (triangles)**

Figure 12 shows that the best tradeoff turbines (circles) span almost the entire range of rotor diameters (except a 113 m one) and rated powers. We observe that, for mid-range turbines with rated powers between 1.5 - 2.5 MW, larger rotor diameters have not been preferred. Such preference can be attributed to the significantly higher cost per kW installed associated with larger rotor sizes. It is seen from Fig. 12 that the best tradeoff turbines (circles) annually cost less than \$50/kW installed, whereas the 1.5-2.5 MW turbines (triangles) with relatively larger rotor diameters annually cost $50-65$ per kW installed. Although, larger rotor sizes generally allow greater energy capture, they can also increase the wake effects within the farm; the advantage of larger rotor diameters, from a capacity factor perspective, thus decreases when operating as a group. However, further investigation is necessary to fully understand the impact of rotor size on the energy production capacity of optimized wind turbine arrays.

Figure 13 shows the "rotor diameter - hub height" combinations of the best trade-off turbines for all wind classes (represented by circles) and the other commercial turbines (represented by triangles). Both the circles and the triangles are again colored in terms of the average annual cost expressed in \$/kW installed. The grey solid lines correspond to the maximum and minimum "*rotor diameter/hub height*" ($D/H$) ratios among the best tradeoff turbines, and the black dashed lines correspond to the maximum and minimum $D/H$ ratios among all the 131 commercial turbines considered in this analysis.

It is readily observed from Fig. 13 that the shortest tower heights, i.e., below 65 m, are not preferred by any of the wind classes (from the "cost - capacity factor" standpoint). Shorter tower heights allow lower energy capture (owing to the wind profile), leading to such preferences; at the same time for small-midsize towers, an increase in tower height is not associated with a significant increase in cost per kW installed. Another important observation is the preference of "*rotor diameter/hub height*" ratios smaller than $D/H = 1.1$, although available commercial turbine offer $D/H$ ratios as high as 1.5. This observation indicate that "cost - energy output" tradeoffs do not promote high $D/H$ ratios.

The pursuit of larger turbines has been reported to be the right direction of turbine evolution, towards increasing performance of wind energy projects.[23] The observations from Figs. 12 and 13 indicate that such pursuit should involve careful consideration of the "rated power - rotor diameter" combination and the $D/H$ ratio, in context of the best "cost - energy output" tradeoffs obtained when operating as a group (and not

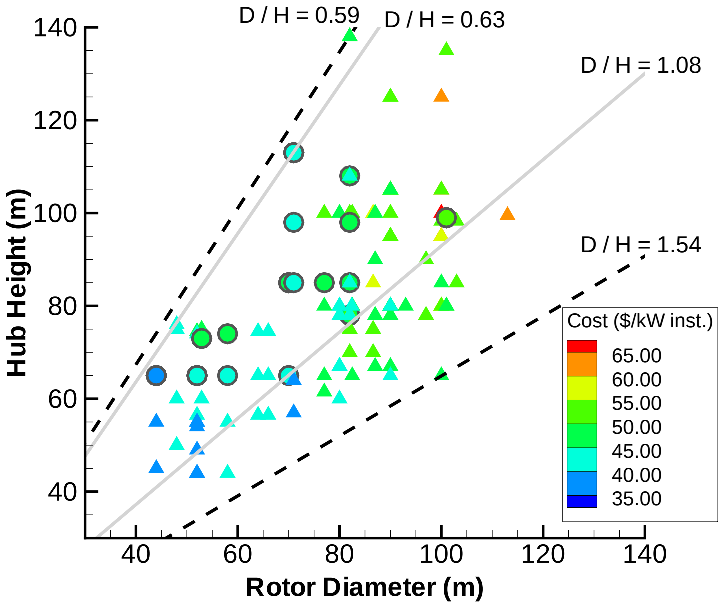


**Figure 13. Rotor diameters and hub heights of the best trade-off turbines (circles) and other available commercial turbines (triangles)**

a single independent entity).

## IV. Conclusion

This paper explores what types of turbines provide the best tradeoffs between cost and energy production capacity for various wind regimes. Wind regimes in this case are defined in terms of the average wind speed (AWS). A set of 25 sample AWS values (at 80 m height) are generated; optimum turbine selection (and placement) is performed for each AWS value, with the objective to minimize the cost of energy of an array of turbines. To this end, we used the Unrestricted Wind Farm Layout Optimization method. A Rayleigh distribution of wind speed, estimated from a sample AWS value, is used for each optimization. A set of 131 commercially available turbines of 13 different rated power classes are used to create the selection pool. The turbines that offer the best "cost - capacity factor" tradeoffs for each wind regime are identified by searching for the non-dominated/Pareto solutions among the best performing turbines (determined by optimization) for that wind regime.

We perform extensive explorations of the "cost - capacity factor" tradeoffs and how they are related to the turbine features. It was found that in general the medium priced turbines provided the most attractive tradeoffs – they offered 15% more capacity factor than the cheapest tradeoff turbines and only 5% less capacity factor than the most expensive turbines (that generated maximum energy). Interestingly, it was observed that some of the turbines with mid-size rotors and taller towers were less expensive and yielded less energy than the turbines with shorter towers and similar sized rotors; this observation is attributed to the significantly higher power rating of the former (leading to lower price per kW installed and lower power coefficients). Further analysis showed that for mid-range turbines with rated powers between 1.5 - 2.5 MW, larger rotor diameters are not preferred. We also found that "rotor diameter/hub height" ($D/H$) ratios greater than 1.1 were not preferred by any of the wind regimes. These observations indicate that larger rotors might not guarantee better performance of future turbines (performance when operating as a group), unless they are designed for appropriate power rating, and are combined with reasonable tower heights.

The analyses and the conclusions in this paper are however based on current turbine design technology and available component materials. As turbine technology advances, and new materials become available, the cost and performance variation with turbine features might change significantly – opening up new directions of evolution of wind power generation technology.

## V. Acknowledgements

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