Chapter 3

ECONOMICS OF WIND TURBINES: A REVIEW OF LITERATURE

Wind Turbines are installed in wind farms\(^1\) to capture wind energy and convert it to electrical energy. They are considered to be renewable sources of energy with zero pollution and zero fuel costs. However, manufacturing, installation and maintenance costs for wind turbines are considerable.\(^2\) Also the technology is complex and evolving. All kinds of engineering comes into play: civil works for a foundation, mechanical for gearboxes, yaw mechanism, blades and tower, rotor; and electrical for power generation and transmission, highway engineering for transportation of wind turbine tower, nacelle and blades. As wind turbines generate electricity from blowing wind, its technology is sensitive to fluctuations in wind speeds and directions. Bigger turbines are costlier to build, transport and maintain, though they also generate more electricity. Ideally, wind turbines have to be customized as per local weather conditions, especially the wind speed and directions, wind chill and dew and moisture and rainfall. For wind turbines ‘one size fits all’ does not work.

3.1 WIND CHARACTERISTICS

Wind Turbines generate electricity from the kinetic energy of wind. Understanding wind characteristics help in selection of wind farm location, type of wind turbine and the amount of wind energy that can be generated. The costs of site preparation, installation of wind turbines, transmission lines to evacuating grid can be estimated based on wind farm location.

Freris (1992)\(^3\) says wind is caused by large-scale movements of air generated principally by differences in the temperature within the atmosphere, which is due to differential solar heating. The study of wind structure leads to the following conclusions:

- Wind speed increases with height

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\(^1\) An area of land with a group of energy-producing windmills or wind turbines.  
• There are continuous wind speed fluctuations, i.e. turbulence.
• The turbulence is spread over a broad range of frequencies
• Turbulence is random and best defined through statistical techniques.

Moving wind has Kinetic Energy. Theoretically energy

\[ E = \frac{1}{2} m v^2 \]

**Equation 3-1: Kinetic Energy**

where m= mass, v = velocity

Instantaneous power is available in a cross sectional area (A) perpendicular to a wind stream moving with velocity v (m/s) with an air density ρ.

Hence, power in wind

\[ \frac{E}{t} = P = \frac{1}{2} \rho A v^3 \]

**Equation 3-2: Power in the wind**

From the above equation it follows that wind power is proportional to the density of the air, rotor cross sectional area and cubic wind speed. For standard conditions (sea-level, 15° C) 1.225 kg/m³ is taken as the density of air.\(^5\)

Hence the wind power becomes a function of: wind power density; turbulence intensity, rotor area and wind speeds

**3.1.1 Wind power densities:**

Rehman, El-Amin, Shaahid, Ahmad, Ahmad, & Thabit (2007)\(^6\) note that air density is a function of pressure and temperature. As mentioned in Ozerdem, Ozer, & Tosun (2006)\(^7\) air density can be calculated as

\[ \rho = \frac{P}{R \times T} \]

**Equation 3-3: Air density**


where:

\[ P = \text{the surface pressure (Pa)}; \]
\[ R = \text{the specific gas constant for air (287 J/kg°K)}; \]
\[ T = \text{the air temperature in degrees Kelvin (°C+273)}. \]

And available power density (wind power available per unit area swept by the blades)\(^8\) can be written as\(^9\)

\[ P_{\text{avail}} = \frac{1}{2} \rho v^3 \]

**Equation 3-4: Power density**

where, \( \rho \) is the air density in kg/m\(^3\) and \( v \) is the wind speed. Air density is affected by elevation and high elevation has lower air density.

Wind power density is measured in watts per square metre and indicates how much energy is available at the site for conversion by a wind turbine.\(^10\)

### 3.1.2 Turbulence intensity

Zhang & Ula (2007)\(^11\) mention that wind turbulence has both positive and negative impacts on the power curves of wind turbines. In the condition of low wind speed, higher turbulence intensity can increase the output power of wind turbines because of the high power density of the air through the rotor. Under practical conditions, especially at the rated wind speed, high turbulence intensity can decrease the output power of wind turbines because the control systems hardly respond optimally to the fast and large fluctuations of the wind speed. Krohn, Morthorst, & Awerbuch (2009)\(^12\) mention if the weather is cold (high air density) the turbine will have a slightly higher output at all wind speeds. If there is high turbulence intensity (that is, very rapid shifts

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in wind speed and direction, typically in rugged terrain) power output will be lower at all wind speeds.

### 3.1.3 Rotor area

The rotor area determines how much energy a wind turbine is able to harvest from the wind. Since the rotor area increases with the square of the rotor diameter, a turbine, which is twice as large will receive \( 2 \times 2 = 4 \) times as much energy.\(^{13}\) The area, from which the power is extracted, is considered, just as in farming. The difference being the area for wind turbines is vertical and area in farming is flat on the ground.

### 3.1.4 Wind speeds

As seen in the Equation 3-2, power in the wind varies with the cube of available wind speed, hence it is important that wind speed be measured accurately. As the wind turbine is exposed to all types of weather conditions, records of site specific weather data are helpful. Liu & Rayudu (2010)\(^{14}\) describes weather station, which monitors weather, by reading, displaying and recording the weather data from external sensors. Data like temperature, humidity, wind direction and velocity, wind chill, air pressure, dew point and rainfall are measured and recorded. The measurement of wind speeds can also be done using a cup anemometer.\(^{15}\) The cup anemometer has a vertical axis and three cups which capture the wind. The number of revolutions per minute is registered electronically.

In practice the data on both wind speeds and wind directions from the anemometer(s) are collected on electronic chips on a small computer, a data logger, which may be battery operated for a long period. Every month the data can be collected from the electronic chip.\(^{16}\)

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3.1.4.1 Wind Rose

Gardner, Garrad, Hansen, Morgan, Murray, Tindal, Ignacio, Arribas & Fichaux (2009) explain ‘wind rose’ is a pictorial representation in which both: the wind speed and direction distribution are defined. An example is given in Figure 3-1: The wind rose can be thought as a wheel with spokes, spaced, in this example, at 30 degrees. For each sector, the wind is considered separately. The duration for which the wind blows in this sector is shown by the length of the spoke and the speed is shown by the thickness of the spoke.

**Figure 3-1: Wind Rose**

In Figure 3-2 the radius of the 12 outermost, wide wedges give the relative frequency of each of the 12 wind directions, i.e. how much percent of the time is the wind blowing from that direction.


The second wedge gives the same information, but multiplied by the average wind speed in each particular direction. The result is then normalised to add up to 100 per cent. This gives information about how much each sector contributes to the average wind speed at this particular location. The innermost (red) wedge gives the same information as the first, but multiplied by the cube of the wind speed in each particular location. The result is then normalised to add up to 100 per cent. This gives information about how much each sector contributes to the energy content of the wind at this particular location.

### 3.2 Site Selection and Turbine Siting

Energy yield from wind turbines have to be optimized by proper wind turbine arrangement known as micro siting on a wind farm. Wind speeds are influenced by earth’s surface roughness and obstacles, height, time of the day (morning, afternoon, evening, night) seasons, geographical locations like mountains and valleys, land breeze and sea breeze. Wind speeds are influenced by friction coefficient which depends on the surface roughness of the earth.

#### 3.2.1 Friction Coefficient

According to Prasad, Bansal, & Sauturaga (2009)\(^\text{19}\) at a height of about 1 km, wind is hardly influenced by the surface of the earth. However, in the lower layers of the atmosphere, wind speeds are affected by the friction against the surface of the earth. In general, the more pronounced roughness of the earth’s surface, the more wind speed will be slowed down. Table 3-1 presents the typical values of friction coefficient \((\alpha)\) for loosely defined terrain types.

<table>
<thead>
<tr>
<th>Terrain characteristics</th>
<th>Friction coefficient ((\alpha))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth hard ground, calm water</td>
<td>0.10</td>
</tr>
<tr>
<td>Tall grass on level ground</td>
<td>0.15</td>
</tr>
<tr>
<td>High crops, hedges and shrubs</td>
<td>0.2</td>
</tr>
<tr>
<td>Wooded countryside, many trees</td>
<td>0.25</td>
</tr>
<tr>
<td>Small town with trees and shrubs</td>
<td>0.3</td>
</tr>
<tr>
<td>Large city with tall buildings</td>
<td>0.4</td>
</tr>
</tbody>
</table>


Kubik, Coker, & Hunt (2011) mentioned two common analytical models that are used to map the wind velocity profile with height, and hence allow the calculation of horizontal wind speed at a certain elevation over the earth’s surface: the log law and the power law. In reality, the complex and dynamic nature of the atmospheric boundary layer means that one single profile will not provide a consistently reliable extrapolation of wind speed from one height to another. The variables in the log and power laws, therefore, are particularly important to consider when performing any future study.

MNRE explains the hub heights of modern wind turbines are usually 80 m or greater, but cost effective meteorological towers are only available up to 60 m in height. The power law and log law vertical shear profiles are the most common methods of extrapolating measured wind speed to hub height.

### 3.2.2 Power law

Mahbuh, Rehman, Meyer, & Al-Hadhrami (2011) write the power law exponent is a number that characterizes the wind shear, which is the change in wind speed with height above ground.

Manwell, McGowan, Rogers, Blanco, & Dua (2003) note the power law exponent is related to the “roughness” of the terrain at a given site and it can be found in the literature for different roughness heights.

Gross.R.C. & Phelan (2006) refer the change in wind speed with height as wind shear. The wind blows at a consistently higher velocity at higher elevations. One method of estimating wind shear is given Equation 3-5:

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\[ v_{hub} = v_{sensor} \left( \frac{H_{hub}}{H_{sensor}} \right)^{\alpha} \]

**Equation 3-5: Power law**

where,

- \( v_{hub} \) is the average wind speed at hub height \( H_{hub} \),
- \( v_{sensor} \) is the speed at sensor height \( H_{sensor} \) (standard 10-metre height)
- \( \alpha \) is the ground surface friction coefficient or shear factor

Bañuelos-Ruedas, Camacho, & Rios-Marcuello (2011)\(^{25}\) describe this coefficient also known as Hellman exponent as a function of the topography at a specific site and is roughly estimated to be of 1/7 value for open land. However, this parameter can vary for one place with 1/7 value during the day up to 1/2 during at night time. Equation 3-5 is also known as the power law when the value of \( \alpha \) is equal to 1/7 and is commonly referred to as the one-seventh power law.

<p>| <strong>Table 3-2: Roughness length and types of terrain</strong> |</p>
<table>
<thead>
<tr>
<th><strong>Terrain Description</strong></th>
<th>( Z ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very smooth, ice or mud</td>
<td>0.01</td>
</tr>
<tr>
<td>Calm open sea</td>
<td>0.2</td>
</tr>
<tr>
<td>Blown sea</td>
<td>0.5</td>
</tr>
<tr>
<td>Snow surface</td>
<td>3.0</td>
</tr>
<tr>
<td>Lawn grass</td>
<td>8.0</td>
</tr>
<tr>
<td>Rough pasture</td>
<td>10</td>
</tr>
<tr>
<td>Fallow field</td>
<td>30</td>
</tr>
<tr>
<td>Crops</td>
<td>50</td>
</tr>
<tr>
<td>Few trees</td>
<td>100</td>
</tr>
<tr>
<td>Many trees, hedges, few buildings</td>
<td>250</td>
</tr>
<tr>
<td>Forest and woodlands</td>
<td>500</td>
</tr>
<tr>
<td>Suburbs</td>
<td>1500</td>
</tr>
<tr>
<td>Centre of cities with tall buildings</td>
<td>3000</td>
</tr>
</tbody>
</table>


In fact, Rehman, El-Amin, Shaahid, Ahmad, Ahmad, & Thabit (2007)\(^{26}\) find the wind speed, at a given site, increases with height by the wind shear factor or coefficient. The power law exponent depends on atmospheric stability, wind speed, roughness

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length, and the height interval. The roughness length is defined as the height above ground $z$ in metres at which the wind speed is theoretically equal to zero.\(^{27}\)

### 3.2.3 Log Law

Another formula known as the logarithmic wind profile is used widely across Europe. Log Law equation as mentioned by Bañuelos-Ruedas, Camacho, & Rios-Marcuello (2011)\(^{28}\)

$$\frac{V_h}{V_{hr}} = \frac{\ln(h/z)}{\ln(hr/z)}$$

**Equation 3-6: Logarithmic wind profile law**

where,

- $V_h$ is the wind speed at height $h$;
- $V_{hr}$ is the wind speed at the reference height $hr$; and $z$ is the roughness coefficient length, which can be matched from the Table 3-2.

### 3.2.4 Diurnal variation of wind speed

Johnson (1978)\(^{29}\) indicates a lot of predictable uniform variation in wind speed when measured over the duration of a day.\(^{30}\) This is known as diurnal variation. This variation decreases with increase in height and wind turbines are installed at a considerable height, nonetheless it is important to know the variations. From the figure it is seen that the power varies from about 80% of long term average annual power in the early mornings to about 120% of long term average annual power in the early afternoon hours. Rehman, El-Amin, Shaahid, Ahmad, Ahmad, & Thabit (2007)\(^{31}\) point out that this insight into wind speed and energy production because of diurnal variation of wind speeds will be beneficial to manage the peak load demand periods.

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Figure 3-3: Average Power Density and Normalized Average Power Density at Dodge city, 1948-1971. Anemometer Height is 58 feet.


Figure 3-4: Diurnal wind speed variation at different heights


3.2.5 Seasonal variation of wind speed

Johnson (1978)\(^{32}\) cites a graph (Figure 3-5) of seasonal variation of wind speed at a place Russell (Great Plains in USA). Variations in average power are about 125% in March and April to less than 90% in August, November and December. Bars show standard deviations of monthly average power. This graph clearly illustrates the difficulty with wind systems being the variability in wind speeds from month to month. Figure 3-6 shows the seasonal variation of air density at a remote village Rawdat Ben Habbas Village in Saudi Arabia. According to Musgrove (1983)\(^{33}\) the seasonal availability of wind energy in Europe correlates closely with the seasonal demand for energy, with higher wind speeds in the winter; and this positive correlation significantly enhances the value of wind-energy systems.

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Hence, considering all these factors Prasad, Bansal, & Sauturaga (2009)\(^{34}\) say that proper siting in windy locations, away from large obstructions, enhances a wind turbine’s performance. It is vital to assess the wind power potential of a site with as much accuracy as possible, taking into account diurnal, seasonal as well as yearly variations in the local wind climate. Mahbuh, Rehman, Meyer, & Al-Hadhrami, (2011)\(^{35}\) suggest knowledge of monthly variation of wind speed provides confidence on the availability of energy in different months of the year. The annual mean wind speeds build up a confidence on the amount of energy that could be generated and also provide future trends on energy generation.

The design of a wind farm is dependent on the shape of the wind rose. For micro siting of wind turbines there are additional factors to be considered: wake effect, park effect, tunnel effect, hill effect.


3.2.6 Wake effect and Park effect

Hoeven (2013)\textsuperscript{36} addresses the wake effect (\textit{i.e.} influence of one turbine on the airflow incident on another turbine) by the siting optimisation of wind turbines. He says this is a poorly understood phenomenon in wind power. Gardner, et al. (2009)\textsuperscript{37} emphasise it is necessary to determine how the individual turbines affect one another – the wake effects. If a turbine is working downstream of another (in its wake), then it will see less wind than it would if it were in the free stream.

In fact, Wang, Liu & Zeng (2009)\textsuperscript{38} write when the wind passes through the turbine, the rotating blades will absorb some amount of wind energy and cast wind in the downwind direction, increasing wind turbulence and the reduction of the wind speed, which is called the wake effect. After that, the wind speed would be gradually recovered, and the recovered value of the wind speed is related to the distance between the upstream and the downstream wind turbines. Therefore, if wind turbines were too dense, the wind speed is unable to adequately recover when reaching the downstream wind turbine, which reduces or stops the output of the downstream wind turbine. In this case, the benefit of power generation is smaller and the investment cost of average unit output is larger. On the contrary, if wind turbines in wind farm were too scattered, the total installed capacity of the whole wind farm is very small, and the investment cost of average unit capacity and the operation maintenance fee are, obviously, high. Therefore, according to the specific condition of the local wind energy of wind farm, once the capacity of wind turbine is selected, the number of the wind turbines and corresponding placement scheme is most important to improve the economy of the wind farm.

Lu & Feng (2010)\textsuperscript{39} quote wind turbine arrangement depends on wind turbine wake flow, which is a result of wind speed, wind direction, temperature, humidity, atmospheric pressure and geographic location. Wake flow effects can be reduced by

proper spacing of wind turbines and make full use of geographical resources on the wind farm.

**Figure 3-7: wind turbine wake effect**

According to Zhang & Ula (2007)\(^{40}\) layout of wind turbines in the wind farm is about optimization of technical, economic, legal, environmental and social aspects. A general conclusion can be drawn with minimum one year data of wind speeds and direction. As each wind turbine will slow down the wind leaving it, the space between turbines should be as far as possible in the prevailing direction. Here the wind rose becomes extremely useful. There should be fewer obstacles and smoother terrain in prevailing wind directions. Based on experience wind turbines are usually spaced between 5 to 9 rotor diameters apart in the prevailing wind direction and between 3 to 5 rotor diameters apart in the direction perpendicular to the prevailing winds. Prasad, Bansal, & Sauturaga, (2008)\(^{41}\) refer this as park effect.


3.2.7 Hill and Tunnel effect

Abdelaziz, Mekhamer, & Mohamed (2012)\textsuperscript{42} write on hills wind speeds are higher than in the surrounding area. As a result, wind turbines are commonly placed on hills or ridges overlooking the surrounding landscape. If the hill is steep or has uneven surface, significant amounts of turbulence occur and the advantage of higher wind speeds may be lost. The air becomes compressed on the windy side of hills or mountains, and its speed increases considerably between obstacles. This is known as "the tunnel effect". Placing a wind turbine in a natural tunnel is one way of obtaining higher power outputs. To obtain a good tunnel effect the tunnel should be "softly" embedded in the landscape. Rough and uneven hills produce wind turbulence that may negate the wind speed advantage; the changing winds may inflict a lot of useless tear and wear on the wind turbine.

3.2.8 Weibull distributions

Muhamad Razali & Hashim (2009)\textsuperscript{43} emphasize the importance of accurate wind resource assessment for harnessing wind power. Wind resources are rarely consistent and vary with time, season, terrain type, height above ground, and from year to year, thus necessitate thorough investigation before any exploitation. Understanding of wind potential will facilitate estimation of how much energy will be produced. Knowledge of the wind-speed frequency distribution plays an important role, especially in evaluating the economic feasibility of the site.

In their study Samantaray & Patnaik (2010)\textsuperscript{44} observe evaluation of wind farm takes place by several methods first of which is wind speed forecasting methods which estimate the wind speed distribution with Weibull distribution curve. The wind speed is measured by anemometers and the Weibull parameters are estimated which gives accurate distribution of wind speed. Using this methodology the energy density of a place can be determined and consequently energy that can be produced in a year.

Freris (1992)\textsuperscript{45} advises when assessing a site for wind energy exploitation it is essential to establish the wind potential as accurately as possible. This is usually done through anemometric measurements at the site, preferably over one year. Local published meteorological data is also used plus computer models to predict regional wind flows as shown in Figure 3-9. All this data is processed and a histogram of the probability of a wind speed occurring within a bin of 1 m/s wide is plotted against wind speed, as shown in Figure 3-10. It has been found that a continuous mathematical function known as the Weibull distribution, as shown in Figure 3-10, can be made to fit closely the data at any site by appropriate selection of factors within the function. Having established the 'shape' and scale' factors of the Weibull distribution it can be used to assess the site wind energy potential.

Figure 3-9: Measured wind speeds


Each graph shows the measured wind speed over the time period indicated. Vertical axis is wind speed, 0-20 m/s [Reproduced from the European Wind Atlas, I. Troen and E. L. Peterson, 1989]

Figure 3-10: Wind Statistics: The Weibull distribution

Liu X. (2010)\textsuperscript{46} writes the relation between wind power $P$ and wind speed $v$ is highly nonlinear. ‘$v$’ is the wind speed (m/sec), which is a \textit{random variable}.

According Albadi & El-Saadany (2008)\textsuperscript{47} wind speed variation is normally described using Weibull Probability Density Function (PDF) because it gives a good representation to the observed wind speed data at the surface and in the upper air. The Weibull PDF is\textsuperscript{48}:

$$
    f(v) = \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left[ -\left( \frac{v}{c} \right)^k \right]
$$

\textbf{Equation 3-7: Probability density function of wind speed}

$$
    F(v) = 1 - \exp \left( \frac{v}{c} \right)^k
$$

\textbf{Equation 3-8: Cumulative distribution function}

where

- $v$ is the wind speed in m/s,
- $k$, is a shape parameter at hub height, and
- $c$ is a scale parameter at hub height

Sadeghi, Gholizadeh, Gilanipour, & Khaliliaqdam (2012)\textsuperscript{49} characterize the Weibull parameters $k$ and $c$, for estimating the wind potential of the region under study. Basically, the scale parameter, $c$, indicates how ‘windy’ a location under consideration is, whereas the shape parameter, $k$, indicates how peaked the wind distribution is (i.e. if the wind speeds tend to be very close to a certain value, the distribution will have a high $k$ value and is very peaked)


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Gardner, et al. (2009)\textsuperscript{50} relate the Weibull ‘scale’ parameter, to the mean wind speed, and the ‘shape’ parameter, to the width of the distribution. This approach is useful since it allows both the wind speed and its distribution to be described in a concise fashion. The shape factor $k$ is related to the variance\textsuperscript{51} of the wind speed and therefore, is location specific. When $k=2$, the Weibull PDF is called Rayleigh PDF and is demonstrated in the following relation:

$$f(v) = \left(\frac{2v}{c^2}\right) e^{\left[-\left(\frac{v}{c}\right)^2\right]}$$

Equation 3-9: Rayleigh Probability distribution function

In this case, the scale factor $c$ can be found using the mean wind speed as follows:

$$v_m = \frac{\sqrt{\pi}}{2} c \quad \text{&} \quad c \approx 1.128 v_m$$

Equation 3-10: To find scale factor $c$

If the shape parameter is exactly 2, as in the graph (Figure 3-11), the distribution is known as a Rayleigh distribution write Borowy & Salameh (1996)\textsuperscript{52}. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution.

Figure 3-11: Rayleigh Distribution


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3.3 POWER IN THE WIND

3.3.1 Betz’s studies

Rand\textsuperscript{53} writes actually all the wind power cannot be captured by the rotor or air would be completely still behind rotor and not allow more wind to pass through. Betz theoretically proved that maximum\textsuperscript{54} $16/27 =0.5926$ portion of the total kinetic energy of the air that goes through wind turbine can be effectively captured. There will be no wind coming out of the wind turbine if entire energy is consumed.\textsuperscript{55}

Theoretically, the maximum power that can be extracted from a wind turbine\textsuperscript{56} is 59.3\% of the power contained in the wind. In practice, this value is around 45\% for large turbines. The power output of a wind turbine is given as follows:

$$P = \frac{1}{2} C_p \rho A v^3$$

\textbf{Equation 3-11: Power output of a wind turbine}

where, \(P\) is a wind turbine output power and \(C_p\) is the coefficient of performance of the turbine, \(A\) is the rotor cross sectional area and \(v\) is the wind speed. As suggested by the above equation, the power extracted from the wind is highly speed-dependent. Doubling the wind speed increases the power output by a factor of eight.\textsuperscript{57}

de Campos & Penteado (2004)\textsuperscript{58} explain for each wind velocity, there is a rotation (or angular speed) that will provide a better power performance (higher \(C_p\)). Coefficient \(C_p\) is a nonlinear function of two magnitudes: Pitch angle (\(\beta\)) of rotor blades and Tip speed ratio \(\lambda\) which is the quotient between the tangential speed of the rotor blade tips, given by:

\begin{itemize}
\item \textsuperscript{53} Rand, J. Wind Turbine Blade Design. The Kidwind Project joe@kidwind.org 877-917-0079
\end{itemize}
\[ \lambda = \frac{R \times \omega_r}{V} \]

Equation 3-12: Tip speed ratio

where

- \( R \) is the rotor radius, measured to the tip of the blade,\(^{59}\)
- \( \omega \) is the rotational speed and \( V \) is the wind speed well upstream.

Kiani, Torregrossa, Simoes, Peyraut, & Miraoui (2009)\(^{60}\) state that if the value of \( C_p \) is maximized, the power generated by the turbine for a given wind speed is maximized too. For the given turbine the optimal value of the tip speed ratio is equal to seven. The correspondent maximum value of power coefficient is equal to 0.45 as in Figure 3-12.

![Figure 3-12: Evolution of power coefficient](image)


As shown in Figure 3-13 kinetic energy of wind gets converted to mechanical energy via the rotor model and gear box, which in turn gets converted to electricity energy in the generator. This electrical energy is then transmitted to the grid.


Figure 3-13: Block diagram of wind energy conversion system


Johnson (1978)\(^{61}\) writes the power in the wind \(P_w\) is converted to mechanical power with an efficiency (coefficient of performance) \(C_p\), which is transmitted to the generator through a mechanical transmission with efficiency \(\eta_m\) and which is converted to electricity with an efficiency \(\eta_g\).

The electrical power output is then

\[
P_e = C_p \eta_m \eta_g P_w W
\]

Equation 3-13: Electrical power output

Optimistic values for these efficiencies are \(C_p = 0.4\), \(\eta_m = 0.9\) and \(\eta_g = 0.9\), which give an overall efficiency of 32%. Actual experimental values will probably be no more than 25% to 30%. This will vary with wind speed, with the type of wind turbine, and with the nature of the load. For a given system, \(P_w\) and \(P_e\) will vary with wind speed as shown in Figure 3-14.

Figure 3-14: Variation of power with wind speed


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As wind speed increases from a low value, the turbine is able to overcome all mechanical and electrical losses and start delivering electrical power to the load at the cut-in speed $V_c$. The rated power output of the generator is reached at rated wind speed $V_R$. Above that speed, some wind power is spilled to maintain constant power output. At the furling speed $V_F$, the machine is shut down to protect it from high winds.

### 3.3.2 Power curve: Wind speed vs. wind power

Power output of the machine as a function of wind speed is defined as the wind-turbine power curve by Hanane Dagdougui (2010)\(^6^2\)

Lu, McElroy, & Kiviluoma (2009)\(^6^3\) explain the turbine power curve to be the result of turbine design efficiency with which kinetic energy intercepted at any given wind speed is converted to electricity by the turbine.

Johnson & Solomon (2010)\(^6^4\) note the power output of a potential turbine can be determined by fitting the data from a wind speed histogram to the energy output of a specific turbine’s power curve. A very general rule of thumb is that the average power output of a wind turbine must be at least 25 to 30% of the rated output for the turbine to be profitable.

**Figure 3-15: Power curve and wind frequency distribution**


Manwell, McGowan, Rogers, Blanco, & Dua, (2003)\textsuperscript{65} note the basic components of the most commonly used horizontal axis wind turbine are: the rotor, the drive train, the electrical system and the power control system. The power available from wind is 

\[ P = \frac{1}{2} \rho A v^3 \]

where \( \rho \) denote density of air, \( A \), the area of the rotor and \( v \), the air velocity. In practice, the power available from a wind turbine can be shown by a machine power curve. A typical power curve is shown in Figure 3-16 and Figure 3-17. These curves, which can be obtained from the turbine suppliers, are based on test data. Three characteristic velocities are illustrated on the curve:

• The cut-in speed – the wind speed at which the turbine starts to generate power.
• The rated velocity – the wind velocity at which the turbine reaches the rated power.
• The cut out velocity – the wind speed at which the turbine is shut down to keep loads and generator power from reaching damaging levels.

Figure 3-16: Typical Wind Turbine Power Curve

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{wind_turbine_power_curve.png}
\caption{Typical Wind Turbine Power Curve}
\end{figure}


Figure 3-17 Regions of Wind Turbine Power Curve

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{wind_turbine_power_regions.png}
\caption{Regions of Wind Turbine Power Curve}
\end{figure}


de Campos & Penteado (2004)\textsuperscript{66} explain the rated power of the unit (wind rated velocity point) is reached for wind velocities over the average annual velocity, which might be at least 5.5 to 7.0 m/s for the system to be economically feasible.

Figure 3-16 also shows hypothetical values of ‘minimum speed’ ($V_{\text{min}}$), ‘nominal or rated speed’ ($V_{\text{nom}}$), & and ‘maximum speed’ ($V_{\text{max}}$). It can be seen that there are four operation regions to be considered as in Figure 3-17:

The first one goes from zero to minimum speed of generation (from 2.5 to 4.5 m/s). Within this range of speed, there is no electrical power generation.

The second one goes from $V_{\text{min}}$ to $V_{\text{nom}}$ (usually between 10 and 15 m/s), determined through studies on the site winds where the system will be installed. Within this range, the extracted electrical power varies proportionally to the cube of wind velocity. It is within this operating range that a good wind turbine control system has a great importance. If it is equipped with a pitch control system, in this region, the system tries to keep the pitch angle (p) in such way to optimize the curve $C_{p} \times \lambda$. If the turbine is equipped with speed control, it will try, according to the wind velocity, to obtain the best speed to reach the best tip speed ratio value ($\lambda$) to maximize the power coefficient value ($C_{p}$).

The third region is that of the system rated power, which goes from $V_{\text{nom}}$ to $V_{\text{max}}$. An increase in the wind velocity in this region does not mean an increase in the extracted electrical power; on the contrary, within this range, the difference between the obtained wind power and the generated electrical power shall be “wasted”. For this purpose, either the stall regulated blades or the pitch regulated blades (variation of the angle $\beta$) are utilized. $V_{\text{max}}$ is determined by the system mechanics. It is the speed (usually between 25 and 30 m/s) including a security margin, with a possibility of damages to the system in case it is exceeded.

The fourth and last region is that of the speeds over the maximum value, for which an intervention is necessary (mechanical brake, turbine reorientation out of the wind or others) in order to obtain the mechanical protection of the system.

Camacho, Garcia-Sanz, & Hiskens (2011)\(^{67}\) show a generic qualitative power curve for a variable-speed pitch-controlled wind turbine in Figure 3-18. Four zones and two areas are indicated in the figure. The rated power \(P_r\) of the wind turbine (that is, the actual power supplied to the grid at wind speeds greater than \(V_r\)) separates the graph into two main areas. Below rated power, the wind turbine produces only a fraction of its total design power, and therefore an optimization control strategy needs to be performed. Conversely, above rated power, a limitation control strategy is required.

**Figure 3-18: Power curve of a wind turbine and control zones**

![Power curve of a wind turbine and control zones](image)


Overall, Liu X. (2010)\(^{68}\) notes the relation between the input wind power and the output electric power relies on several factors, such as the efficiencies of generator, wind rotor, gearbox, and inverter, depending on what kind of turbine is investigated.

### 3.3.3 Capacity factor

Ditkovich, Kuperman, Yahalom, & Byalsky (2012) mark since the wind is seldom consistent, the wind turbine rarely operates at its rated power. The concept of capacity factor (CF) is usually employed to evaluate the expected amount of energy delivered

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by a wind turbine. In order to calculate the CF, wind probability distribution function (PDF) and turbine power performance curve are required. A majority of wind sites may be characterized by Weibull PDF, while the turbine power curve is usually provided by the turbine manufacturer.\textsuperscript{69}

As mentioned in Bhattacharyya.S.C. (2011)\textsuperscript{70} and Karki (2008)\textsuperscript{71} capacity factor is the ratio of the actual output of a power plant over a period of time and its output if it had operated continuously at full capacity during that time period. A high percentage of capacity factor means that the running condition of wind turbines is closer to the rated condition. Albadi & El-Saadany (2007)\textsuperscript{72} have defined capacity factor as the ratio of the average output power over the rated output power.

$$CF = \frac{P_{ave}}{P_{rated}}$$

\textit{Equation 3-14: Capacity factor}

The annual capacity factor is given by

$$CF = \frac{E_a}{P_{rated} \times 8760}$$

\textit{Equation 3-15: Annual capacity factor}

where $E_a$ is the annual energy produced by the wind turbine.

The annual energy is calculated by multiplying the power output of the turbine at a certain speed by the probability of having that speed in a year as shown in Equation 3-16:

$$E_a = 8760 \times \sum_{v_1}^{v_2} f(v)P(v)$$

\textit{Equation 3-16: Annual energy produced by the wind turbine}


where

- \( v_1 \) and \( v_2 \) are the cut-in and cut-out speed, respectively;
- \( P(v) \) is the power output at speed \( v \);

\( f(v) \) is the Rayleigh PDF (Probability Density Function) value at \( v \). Figure 3-19 illustrates how to calculate the annual energy yield given turbine power curve and wind probability distribution function. By plotting both wind PDF data and the turbine's power curve, one can easily calculate the annual energy produced at each wind speed value.

**Figure 3-19: Annual gross energy calculation**


Albadi & El-Saadany (2008)\(^7\) write it is worth mentioning that the capacity factor calculated above is over estimating the annual energy yield of wind turbines. To get a more realistic value of the annual factor, energy yield should be corrected by multiplying the gross energy yield by an adjustment loss factor. Components of this factor include wake loss, air density, blade soiling, electrical losses, and availability.

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3.4 EVOLUTION OF WIND TURBINE TECHNOLOGY

Union of concerned scientists (2012)\textsuperscript{74} in their website mentions that wind power is both old and new. From the sailing ships of the ancient Greeks, to the grain mills of pre-industrial Holland, to the latest high-tech wind turbines rising over the Minnesota prairie, humans have used the power of the wind for millennia.

In the United States, the original heyday of wind was between 1870 and 1930, when thousands of farmers across the country used wind to pump water. Small electric wind turbines were used in rural areas as far back as the 1920s, and prototypes of larger machines were built in the 1940s. When the New Deal brought grid-connected electricity to the countryside, however, windmills lost out. Interest in wind power was reborn during the energy crises of the 1970s.

3.4.1 Traditional windmill

In his conference proceedings paper Musgrove writes (1983)\textsuperscript{75} the traditional windmill, most commonly had four blades which, in their simplest form, provided a lattice framework over which the miller could spread the canvas sails. For many centuries, the only practicable alternative (unless one lived alongside a substantial river, which could provide water power) was the muscle power output of people or animals. But a man needs to work hard all day to deliver 1 kWh of useful work. The traditional windmill could, therefore, do the work of a hundred men, or more than a dozen oxen or horses; hence its importance for so many centuries.

3.4.2 Wind Energy Conversion

Smith, et al. (2009)\textsuperscript{76} have observed over the past 20 years, average wind turbine ratings have grown almost linearly (Figure 3-20), with the majority of machines installed in 2007 rated at 1.5 MW. With each new generation of wind turbines, the size has increased and reductions in the life-cycle cost of energy have been achieved through economies of turbine scale and a larger rotor to increase energy capture.

However, there are constraints to this continued growth in size; at some point, it will cost more to build a larger turbine than the benefit of increased energy is worth. In addition, land transport restrictions and cost, as well as crane requirements, can impose size limits for wind turbines installed on land. While there is no “big breakthrough” on the horizon for wind technology, many evolutionary steps executed with technical skill can cumulatively result in a 30–40% improvement in the cost effectiveness of wind technology over the next decades. Capacity factor can be increased over time using enlarged rotors on taller towers.

**Figure 3-20: The development path and size growth of wind turbines.**


Blaabjerg, Chen, Teodorescu, & Iov (2006)\(^77\) write wind turbines capture power from wind by means of aerodynamically designed blades and convert it to rotating mechanical power. The number of blades is normally three. As the blade tip-speed typically should be lower than half the speed of sound the rotational speed will decrease as the radius of the blade increases. For multi-MW wind turbines the rotational speed will be 10-15 RPM. The most weight efficient ways to convert the

low-speed, high-torque power to electrical power is using a gear-box and a standard fixed speed generator as illustrated in Figure 3-21.

**Figure 3-21: Converting wind power to electrical power in a wind turbine**

The gear-box is optional as multi-pole generator systems are possible solutions. Between the grid and the generator a power converter can be inserted. The possible technical solutions are many and Figure 3-22 shows a technological roadmap starting with wind energy/power and converting the mechanical power into electrical power. It involves solutions with and without gearbox as well as solutions with or without power electronic (PE) conversion. The electrical output can either be AC or DC. In the last case a power converter will be used as an interface to the grid.

**Figure 3-22: Road-map for wind energy conversion**

3.4.3 Wind Turbine Power Rating

Lewis & Muller (2007)\textsuperscript{78} wonder if value of efficiency in a wind turbine could be questioned, since the source of energy is free. However a more efficient generator will generate more sales revenue from the same power at the turbine blades. There is an economic balance between the amounts of energy generated by the turbine over its lifetime against the capital cost of the turbine. However, if an efficiency gain can be obtained without a corresponding increase in the capital cost of the turbine, it offers an advantage.

Kang, Zhang & Lang (2007)\textsuperscript{79} report wind turbine technology has undergone a dramatic transformation using the newest technology in power electronics, aerodynamics, and mechanical designs. In order to decrease the cost per megawatt and to increase the efficiency of the wind power conversion, the power rating of wind turbines has been continuously growing. The development of wind turbine power rating during the last 30 years is shown as Figure 3-23.

![Figure 3-23: The development of wind turbine power rating](image)


3.4.4 Generations of Wind Turbines

Ma K. (2013) chronicles the dramatic change in the technologies used for Wind Turbine System (WTS) for the last 30 years with four to five generations emerged. Up until now the existed or existing wind turbine configurations can be generally categorized into four concepts. The main differences between these concepts locate on the types of generator, power electronics, speed controllability and the way in which the aerodynamic power is limited.

A. Fixed Speed Wind Turbines (Type A)

This configuration corresponds to the “Danish concept” that was very popular in 80’s. The wind turbine is equipped with asynchronous Squirrel Cage Induction Generator (SCIG) and smoother grid connection can be achieved by incorporating a soft-starter.

B. Partial Variable Speed Wind Turbine with Variable Rotor Resistance (Type B)

This concept is also known as OptiSlip (VestasTM) emerged in the mid 1990’s. It introduces the variable rotor resistance and thus limited speed controllability of wind turbines. The Wound Rotor Induction Generator (WRIG) and corresponding capacitor compensator are typically used, and the generator is directly connected to the grid by a soft-starter.

C. Variable Speed Wind Turbine with partial-scale power converter (Type C)

This concept is the most established solution nowadays and it has been used since 2000’s. A back-to-back power electronic converter is adopted in conjunction with the Doubly-Fed Induction Generator (DFIG). The stator windings of DFIG are directly connected to the power grid, while the rotor windings are connected to the power grid by the power electronics converter with normally 30% capacity of the wind turbine.

D. Variable Speed Wind Turbine with Full-scale Power Converter (Type D)

Another promising concept that is becoming popular for the newly installed wind turbines introduces a full-scale power converter to interconnect the power grid and stator windings of generator, thus all the generated power from the wind turbine can be regulated. The asynchronous generator, Wound Rotor Synchronous Generator

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80 Ma, K. (2013). Power Electronics for the Next Generation Wind Turbine System. Aalborg University, Department of Energy Technology. Entire portion 3.4.4 taken from this source.
(WRSG) or Permanent Magnet Synchronous Generator (PMSG) has been reported to be used in this concept.

3.4.5 Role played by power electronics

Blaabjerg & Rodríguez (2014)\(^{81}\) comment in the last few decades power electronics gradually has become more and more advanced and has brought significant performance improvements for the renewable energy production by improving energy capturing efficiency and also enabling the whole renewable system to act as a controllable electrical power generation unit in order to be better integrated with the power grid. As shown Figure 3-24 power electronics converter has already achieved 100% power coverage in the wind turbine system since 2005, actually in most of the newly established wind turbines, power electronics converters have become essential components carrying all of the generated power up to multi-MW.

**Figure 3-24: Evolution of wind turbine size and the power electronics**

from 1980 to 2018 (Estimated) Blue circles indicate the power coverage by power electronics

As per Ma K. (2013)\(^{82}\) besides the quick growth in the total installed capacity, the size of individual wind turbine is also increasing dramatically in order to reduce the price per generated kWh. In 2011 the average turbine size delivered to the market is 1.7 MW, among which the average offshore turbine size achieves 3.6 MW. The growing

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trends of the emerging turbine size between 1980 and 2018 are shown in Figure 3-24, it is noted that the cutting-edge 8 MW wind turbines with a diameter of 164 m have already shown up in 2012. Right now most manufacturers are developing products in the range of 4.5-8 MW, and it is expected that more and more large wind turbines with multi-MW power level, even up to 10 MW, will be present in the next decade - driven mainly by the considerations to lower down the cost of energy.

3.4.6 Rotors

Just like in farming there is an area which is farmed, with a wind turbine it is much the same scene, though in wind farming it is harvesting wind energy from a vertical area instead of a horizontal one. The area of the circle covered by the rotor determines how much energy can be harvested in a year. Figure 3-25 shows theoretical power production of a wind turbine with a given rotor diameter. Actual power generation will be influenced by many factors like the wind speed and direction, the efficiency of the wind turbine, elevation of wind turbine location and other design characteristics of the wind turbine.

![Figure 3-25: Theoretical power production](http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm)

For Small wind turbines at wind speeds 10 m/s.

For normal size wind turbines at wind speeds 15 m/s.

Source: [http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm](http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm)


84 [http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm](http://www.omafra.gov.on.ca/english/engineer/facts/03-047.htm)
Schubel & Crossley (2012)\textsuperscript{88} notes over the centuries, many types of design have emerged, and some of the more distinguishable are listed in Figure 3-26.

\textbf{Figure 3-26: Modern and historical rotor designs}

<table>
<thead>
<tr>
<th>No.</th>
<th>Design</th>
<th>Orientation</th>
<th>Use</th>
<th>Propulsion</th>
<th>Peak Efficiency*</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Savonius rotor</td>
<td>VAWT</td>
<td>Historic Persian windmill to modern day ventilation</td>
<td>Drag</td>
<td>16%</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Cup</td>
<td>VAWT</td>
<td>Modern day cup anemometer</td>
<td>Drag</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Dutch Windmill</td>
<td>HAWT</td>
<td>16(^{th}) century, used for grinding wheat</td>
<td>Lift</td>
<td>27%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>American farm windmill</td>
<td>HAWT</td>
<td>18(^{th}) century to present day, farm use for pumping water, grinding wheat, generating electricity</td>
<td>Lift</td>
<td>31%</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Darrieus Rotor (egg beater)</td>
<td>VAWT</td>
<td>20(^{th}) century, electricity generation</td>
<td>Lift</td>
<td>40%</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Modern Wind Turbine</td>
<td>HAWT</td>
<td>20(^{th}) century, electricity generation</td>
<td>Lift</td>
<td></td>
<td>Blade Qty</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
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<td></td>
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<td></td>
<td>2</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>

*Peak efficiency is dependent upon design, values quoted are maximum efficiencies of designs in operation.


They further add in practice rotor designs suffer from the accumulation of minor losses resulting from: tip losses, wake effects, drive train efficiency losses and blade

shape simplification losses. Therefore, the maximum theoretical efficiency has yet to be achieved.

3.4.7 **Blades**

Tangler (2000)\(^{86}\) quotes evolution of rotor and blade design is a balanced integration of economic, aerodynamic, structural dynamic, noise, and aesthetic considerations. The design of a modern rotor includes choices of blade number, airfoils, chord and twist distributions, and materials. These choices include conflicting considerations that need to be prioritized like thick or thin airfoils. Thick airfoils provide greater blade stiffness and thin airfoils are desirable for their high lift-to-drag ratios and are roughness tolerant.

Schubel & Crossley (2012)\(^{87}\) emphasise the aesthetics involved with the rotation of blades. Faster one and two bladed designs have a jerky motion, three bladed designs appear smoother and also appear more orderly in stationary position. The three blade turbine has been widely adopted as the most efficient design to meet environmental, commercial and economic constraints and therefore dominates today’s large scale wind turbine industry. Manufacturers seek greater cost effectiveness through increased turbine size. This may change as larger models face construction, transport and assembly issues.

3.4.8 **Gearbox**

Frank & Toliyat (2009)\(^{88}\) observe turbine designs need improvements not only to increase generation capacity but also reduce maintenance needs. One method is moving from purely mechanical components to electromechanical ones like direct drive generators. Majority of wind turbines have a gearbox to take the high-torque, low-speed output from the hub and transfer it into a high-speed, low-torque input to the generator. A small but growing segment is using direct drive generators. Directly driven wind turbines have heavier tower heads due to large generators. Gear manufacturers readily admit that wind turbines are the most demanding applications

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which they supply, one in which the loads are variable and arduous to predict. One of the common causes of a wind turbine failure is due to gearbox failure, bearings being a key instigator. In order for bearings to reduce their failure rate, load prediction is a key issue which must be solved. Progress is slow however due to the proprietary nature among bearing and gearbox manufacturers.

3.5 ECONOMICS OF WIND ENERGY – COSTS AND BENEFITS

There is no single answer to economic viability to wind turbines. Wind turbine itself consists of about 8000 components. Other costs are land cost where the turbine is to be installed and the electricity connection to the grid. Wind Turbines are mammoth machines which need to be transported to the site and installed there. There are considerable costs associated with these operations. And then there are annual operations and maintenance costs.

3.5.1 Costs of Wind Turbines

Cost of wind energy depends on a number of factors over and above the cost of wind turbines. Location of wind turbine is a key consideration for two reasons: location determines the nature of the wind resource that is available, as well as the cost of connecting to the grid. To perform a detailed analysis of the economic viability of particular wind energy investment following estimates are required:

• the initial cash outlay,
• the annual operating and maintenance expenses over the life of the investment,
• the revenue stream from power sales, and
• the cost of capital.

Cost of wind energy also depends on the size of the project. In addition to the economics of wind turbine size, use of multiple wind turbines at a site offers smoothing of the normally fluctuating power from a single large wind turbine.

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90 These costs pertain to wind generation alone. There are substantial costs associated with connecting to the grid that are also incurred and obviously vary depending upon site specific factors.
3.5.1.1 Cost Structure of a Wind Turbine

The main components of a wind turbine and their share of the overall turbine cost for a 5 MW wind turbine as mentioned in *The Economics of Wind Energy* by Krohn, Morthorst, & Awerbuch (2009)⁹³

A typical wind turbine will contain up to 8,000 different components. This guide shows the main parts and their contribution in percentage terms to the overall cost. Figures are based on a MM92 turbine with 45.3 metre length blades and a 100 metre tower.

**Tower (26.3%)**: Range in height from 40 metres up to more than 100 m. Usually manufactured in sections from rolled steel; a lattice structure or concrete are cheaper options.

**Rotor blades (22.2%)**: Varying in length up to more than 60 metres, blades are manufactured in specially designed moulds from composite materials, usually a combination of glass fibre and epoxy resin. Options include polyester instead of epoxy and the addition of carbon fibre to add strength and stiffness.

**Rotor hub (1.37%)**: Made from cast iron, the hub holds the blades in position as they turn.

**Rotor bearings (1.22%)**: Some of the many different bearings in a turbine, these have to withstand the varying forces and loads generated by the wind.

**Main shaft (1.91%)**: Transfers the rotational force of the rotor to the gearbox.

**Mainframe (2.80%)**: Made from steel, must be strong enough to support the entire turbine drive train, but not too heavy.

**Gearbox (12.91%)**: Gears increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator

**Generator (3.44%)**: Converts mechanical energy into electrical energy. Both synchronous and asynchronous generators are used.

**Yaw system (1.25%)**: Mechanism that rotates the nacelle to face the changing wind direction.

**Pitch system (2.66%)**: Adjusts the angle of the blades to make best use of the prevailing wind.

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Power converter (5.01%): Converts direct current from the generator into alternating current to be exported to the grid network.

Transformer (3.59%): Converts the electricity from the turbine to higher voltage required by the grid.

Brake system (1.32%): Disc brakes bring the turbine to a halt when required.

Nacelle housing (1.35%): Lightweight glass fibre box covers the turbine’s drive train.

Cables (0.96%): Link individual turbines in a wind farm to an electricity sub-station.

Screws (1.04%): Hold the main components in place, must be designed for extreme loads.

### 3.5.1.2 Cost structure of a wind farm

Wind turbines are laid out in wind farms to take advantage of economies of scale in terms of substation and electrical infrastructure, operations and maintenance personnel, civil work, site management. The wind characteristics of that place also need to be studied, as the wind turbine technical specifications need to match those of the prevailing site conditions to yield optimum power from wind. J. Serrano González (2009)\(^\text{94}\) presents wind turbine costs’ percentages in a wind farm.

<table>
<thead>
<tr>
<th>Item</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind turbines</td>
<td>65-75</td>
</tr>
<tr>
<td>Substation and electrical infrastructure</td>
<td>10-15</td>
</tr>
<tr>
<td>Inner electrical distribution installation</td>
<td>6-9%</td>
</tr>
<tr>
<td>Substation and evacuation line</td>
<td>4-6%</td>
</tr>
<tr>
<td>Civil work</td>
<td>5-10</td>
</tr>
<tr>
<td>Component installation</td>
<td>0-5</td>
</tr>
<tr>
<td>Other</td>
<td>5</td>
</tr>
<tr>
<td>Overall wind turbine cost (€/kW)</td>
<td>800-1100</td>
</tr>
</tbody>
</table>


### 3.5.1.3 Operations and maintenance costs

Gsanger, Sawyer, & Januario (2012)\(^\text{95}\) write the fixed and variable operations and maintenance (O&M) costs are a significant part of the overall LCOE of wind power. O&M costs typically account for 20% to 25% of the total LCOE of current wind power.


power systems. Actual O&M costs from commissioned projects are not widely available. Even where data are available, care must be taken in extrapolating historical O&M costs given the dramatic changes in wind turbine technology that have occurred over the last two decades.

They further add the data are widely distributed, suggesting that O&M costs, or at least their reporting, are far from uniform across projects. However, since the year 2000 O&M costs appear to be lower and to be more uniform across projects than was the case prior to 2000. These declines in O&M costs may be due to the fact more recent projects use larger, more sophisticated turbines and have higher capacity factors (reducing the fixed O&M costs per unit of energy produced). Another important consideration for wind energy is the fact that O&M costs are not evenly distributed over time. They tend to increase with the age of wind turbine.

Gardner, et al. (2009) mention after commissioning, the wind farm will be handed over to the operations and maintenance crew. A typical crew will consist of two people for every 20 to 30 wind turbines in a wind farm. For smaller wind farms there may not be a dedicated O&M crew but arrangements will be made for regular visits from a regional team. Typical routine maintenance time for a modern wind turbine is 40 hours per year. Non-routine maintenance may be of a similar order.

Byon & Ding (2010) suggest one of the key factors for enhancing the marketability of wind energy is to cut its operations and maintenance (O&M) costs, the contribution of the O&M costs to the total energy production cost is 10%–20% for a wind farm. Since wind turbines are subject to irregular loading, the deterioration progress of turbine components vary considerable from each other. Scheduled maintenances might be unfruitful. Hence to handle unexpected failures condition-based maintenance is carried out. Condition-based monitoring, equipped with sensors inside a wind turbine, provides diagnostic information regarding the health condition of the turbine components. Based on the information, one can estimate the deterioration progress that may lead to a major failure or consequential damage. Wind farm operators can


plan maintenance tasks in advance before the problem escalates and develops into major failures or critical malfunctions.

3.5.1.4 Cost of Capital

As documented in IRENA (2015)\textsuperscript{98} the key factor that determines the cost of capital is risk. A project with greater risk (\textit{e.g.} of non payment of electricity sales, currency risk, inflation risk or country risk) will require a higher rate of return. Capital can come in the form of equity and loans, while the project may be structured in a variety of ways. Equity is more expensive than secured loans, all else being equal, because it carries more risk in the eventuality that the project underperforms or goes bankrupt.

The report further writes the key benchmark for assessing the relative cost of risk is the ‘market risk premium’, which is the difference between the average market expected rate of return and the risk-free rate (\textit{e.g.} government bonds). The cost of capital for renewable projects is affected by the nature of the market, government policy, technological maturity and capacity factors. Policy risk is scrutinised by investors and can render computations of risk investments highly variable. Countries with lower perceived political and country risk, a proven track record and respected institutions benefit from more generous terms and are more likely to be able to attract private investors and arrange commercial loans. Efforts to minimise the sources of risk (Table 3-4), wherever possible, will help to reduce the cost of capital and improve the project economics. The financial structure of renewable generation projects and the cost of capital vary widely by technology, country, project developer and region.

Also is added in the report the situation can be very different in developing countries, as various risks can often make it difficult for project developers to mobilise the funds necessary to bring a project to fruition, or if they can, the financing costs mean the economics of the project will not be sufficient to provide an adequate return on equity.

### Table 3-4: Categorisation of Energy Sector Project Risk Factors

<table>
<thead>
<tr>
<th>Phase</th>
<th>Pre construction</th>
<th>Construction</th>
<th>Operation</th>
<th>Country risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risks</td>
<td>• Technology risk • Project design • Debt and equity financing</td>
<td>• Construction delays • Cost overruns • Environmental mitigation plans • Social mitigation plans</td>
<td>• Operation and maintenance plans • Output quality/volume • Resource fluctuations • Electricity sales payments – PPA (Power purchase agreements) contracts, etc.)</td>
<td>• Currency devaluation • Currency convertibility/transfer • Political force majeure • Environmental force majeure • Regulatory risk</td>
</tr>
</tbody>
</table>


IRENA report adds for instance, a reasonable weighted average cost of capital for African projects is 15-20%, except where strong guarantees are in place. This is significantly higher than the average cost of capital for renewable energy projects in Organisation for Economic Co-operation and Development (OECD) countries, typically between 6% and 12%. Bringing down these costs will dramatically improve the economics of renewable power generation projects in Africa. Benefits in wind generation occur in economic, environmental and social forms.

Economic benefits are in revenue and savings form. Revenue streams are generated from sale of electricity. In India State Electricity Regulatory commissions offer feed-in-tariff and Central electricity Regulatory commission offers Generation Base Incentives.

#### 3.5.2 Economic benefits from Wind Turbines

#### 3.5.2.1 Renewable Energy Sources (RES) Support Schemes

As rightly said by Chanapan Kongnam (2009) renewable energy equipments are quite capital intensive though the fuel is free. Hence, in order to generate interest and investment in renewable energy technology different types of support mechanisms are introduced by various governments as quoted by Morthorst, Aeur, Garrad, & Blanco (2015). There are direct and indirect policy instruments as shown in Table 3-5. Direct policy measures aim to stimulate the installation and indirect instruments focus

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on improving long term framework conditions. Besides regulatory instruments, customers’ willingness to pay premium rates for green electricity is a voluntary approach. It is also important to note whether policy instruments address price or quantity and whether they support investments or generation.

Table 3-5: Types of RES Support mechanism

<table>
<thead>
<tr>
<th></th>
<th>Direct</th>
<th>Indirect</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regulatory</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment-focused</td>
<td>Investment incentives</td>
<td>Tendering system for investment grant</td>
</tr>
<tr>
<td></td>
<td>Tax credits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low interest / soft loans</td>
<td></td>
</tr>
<tr>
<td>Generation-based</td>
<td>Fixed feed-in tariffs (FIT)</td>
<td>Tendering system for long-term contracts: Tradable Green Certificate system (TGC)</td>
</tr>
<tr>
<td></td>
<td>Fixed premium system</td>
<td></td>
</tr>
<tr>
<td><strong>Voluntary</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investment-focused</td>
<td>Shareholder programmes</td>
<td>Voluntary agreements</td>
</tr>
<tr>
<td></td>
<td>Contribution programmes</td>
<td></td>
</tr>
<tr>
<td>Generation-based</td>
<td>Green tariffs</td>
<td></td>
</tr>
</tbody>
</table>


It is also necessary to review and evaluate the support schemes and their success can be measured by the criteria

- **Effectiveness**: was the RES support program/s effective enough to lead to a significant increase in deployment of capacities?
- **Economic efficiency**: what was the absolute support level compared to the actual generation costs of RES generators and what was the trend in support over time?

Chanapan mentions regardless of whether a national or international support system is concerned, a single instrument is not usually enough to stimulate the long-term growth of RES. Since, in general, a broad portfolio of RES technologies should be supported; the mix of instruments selected should be adjusted accordingly. Whereas investment grants are normally suitable for supporting immature technologies, FITs are appropriate for the interim stage of the market introduction of a technology. A premium, or a quota obligation based on TGC, is likely to be the most relevant choice when:

- Markets and technologies are sufficiently mature;
- The market size is large enough to guarantee competition among the market actors;
• Competition on the conventional power market is guaranteed. These are fiscal measures used either to reduce the cost of production or increase the payment received from the production.  

3.5.2.2 Revenue

Generation based incentives given by Government. Under the scheme, a GBI will be provided to wind electricity producers @ Rs. 0.50 per unit of electricity fed into the grid for a period not less than 4 years and a maximum period of 10 years with a cap of Rs. 100 Lacs per MW. The total disbursement in a year will not exceed one fourth of the maximum limit of the incentive i.e. Rs.25.00 Lacs per MW during first four years in parallel with accelerated depreciation on a mutually exclusive manner so that companies can avail either accelerated depreciation or GBI, but not both.

Feed in Tariffs: Tariffs are the price paid by the Utilities to the renewable energy producers per kWh of electricity generated or sent to the electric grid. FIT mechanism involves the obligation on the part of a Utility to purchase electricity generated by renewable energy producers in its service area paying a tariff determined by Public Authorities and guaranteed for a specific time period. In Gujarat the FIT is 4.15 INR/kWh (without accelerated depreciation).

Renewable energy certificates: One REC corresponds to 1 MWh of electricity generated from eligible renewable energy sources. There are two categories of RECs: solar and non-solar. A ‘floor’ and forbearance’ price has been notified by the CERC. The prices, effective from 2012 and valid until 2016-17, are stated in the table below.
Table 3-6: Price of RECs notified by CERC\textsuperscript{107}

<table>
<thead>
<tr>
<th>Type of REC</th>
<th>Floor price (INR/MWh)</th>
<th>Forbearance price (INR/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>9,300</td>
<td>13,400</td>
</tr>
<tr>
<td>Non-Solar</td>
<td>1,500</td>
<td>3,300</td>
</tr>
</tbody>
</table>


The REC mechanism, and any preferential tariff availed of, are mutually exclusive, i.e., renewable power is either sold at a preferential tariff, or sold at regular (non-preferential) local tariffs and the associated REC.\textsuperscript{108}

3.5.2.3 Savings

- **Accelerated depreciation**\textsuperscript{109}: The main reason for the growth of wind power has been the availability of Accelerated Depreciation (AD), providing the facility to offset taxes on income from other sources. 80% accelerated depreciation for investors if the project is commissioned before 30 September of the same financial year; or 40% if the project is commissioned before 31 March of the same financial year.
- **Concession on import duty** on specified wind turbine components\textsuperscript{110}
- **100% exemption from excise duty** on certain wind turbine components\textsuperscript{111}
- **10 year income tax holiday** for wind power generation projects\textsuperscript{112}
- **Loans at a lower rate**: Indian Renewable Energy Development Agency (IREDA) was created in 1987 to disburse required financial loans\textsuperscript{113}. It offers ‘soft’ loans to wind farm developers with interest rates that are lower than those offered by commercial banks\textsuperscript{114}. The National Clean Energy Fund (NCEF) has been created by the Government of India to support clean technologies, including renewable ones. Projects are eligible to receive support in the form of a loan or viability gap

\textsuperscript{110} ibid
\textsuperscript{111} ibid
\textsuperscript{112} ibid
funding to the tune of 40% of the total project cost wherein a minimum financial commitment of not less than 40% of the total project cost has to come through project organization.\textsuperscript{115} To build the corpus of NCEF, a clean energy cess of Rs.400 per tonne is levied on indigenous as well as imported coal in the budget for financial year 2015-26.\textsuperscript{116}

The current applicable interest rates for loans are as given below\textsuperscript{117} (w.e.f 1.11.2015)

<table>
<thead>
<tr>
<th>Borrower/Sector</th>
<th>Grade I*</th>
<th>Grade II</th>
<th>Grade III</th>
<th>Grade IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Energy</td>
<td>10.20%</td>
<td>10.95%</td>
<td>11.10%</td>
<td>11.40%</td>
</tr>
</tbody>
</table>


*Grades are based on risk assessment

- **Value Added Tax**: Gujarat and Maharashtra offer 5% VAT for all renewable components (MNRE, 2012d)\textsuperscript{118}
- **Research and Development**: The income tax department provides for a weighted deduction for an in house R&D activity, which entitles wind turbine manufacturers to claim 200% of the expenditure (other than expenses on land and building) incurred for in-house R&D activity.\textsuperscript{119}

### 3.5.3 Economic feasibility

Sangpanich, Ault, & Lo (2009)\textsuperscript{120} describe techniques of project evaluation used to assess the economic feasibility of wind farm as a net present value (NPV), a benefit cost ratio (BCR) or profitability index (PI), an internal rate of return (IRR) and a payback period (PBP). It measures the productivity of capital investment and the


flows of costs and returns over the life time of wind farm. The profitability criteria for decision are shown in Table 3-8.

Table 3-8 : The Profitability Criteria of Decision for the Project Investment

<table>
<thead>
<tr>
<th></th>
<th>Payback period</th>
<th>NPV</th>
<th>IRR</th>
<th>BCR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worthiness</td>
<td>&lt;life time</td>
<td>&gt;0</td>
<td>&gt; discount rate</td>
<td>&gt;1</td>
</tr>
<tr>
<td>No worthiness</td>
<td>&gt;life time</td>
<td>&lt;0</td>
<td>&lt; discount rate</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Indifferent case</td>
<td>=life time</td>
<td>=0</td>
<td>= discount rate</td>
<td>=1</td>
</tr>
</tbody>
</table>


Payback Period\(^{121}\) is the time in which the initial cash outflow of an investment is expected to be recovered from the cash inflows generated by the investment. The formula depends on whether the cash flows per period is even or uneven. In case they are even, the formula to calculate payback period is:

\[
PBP = \frac{Initial\ Investment}{Cash\ Inflow\ per\ Period}
\]

\textbf{Equation 3-17: Payback Period: even cash flows}

When cash inflows are uneven, cumulative net cash flow for each period is calculated and then following formula can be used

\[
Payback\ Period = A + \frac{B}{C}
\]

\textbf{Equation 3-18: Payback Period: uneven cash flows}

- A= last period with a negative cumulative cash flow;
- B=absolute value of cumulative cash flow at the end of the period A;
- C=total cash flow during the period after A

Net Present Value (NPV) of a project is the potential change in an investor’s wealth caused by that project while time value of money is being accounted for.

\[
NPV = \left[ \frac{R_1}{(1 + i)^1} + \frac{R_2}{(1 + i)^2} + \frac{R_3}{(1 + i)^3} + \cdots \right] - Initial\ Investment
\]

\textbf{Equation 3-19: Net Present Value}

where
- \( R \) = net cash inflow expected to be received in each period
- \( i \) = the required rate of return per period
- \( n \) = the number of periods during which the project is expected to operate and generate cash inflows

Internal Rate of Return (IRR) is the discount rate at which the net present value of an investment becomes zero, thus NPV=0 or PV of future cash flows - Initial Investment = 0;

\[
\left[ \frac{R_1}{(1 + r)^1} + \frac{R_2}{(1 + r)^2} + \frac{R_3}{(1 + r)^3} + \ldots \right] - \text{Initial Investment} = 0
\]

**Equation 3-20: Internal Rate of Return**

where
- \( R \) = net cash inflow expected to be received in each period
- \( r \) = the internal rate of return (which is to be guessed and calculated by iterations)
- \( n \) = the number of periods during which the project is expected to operate and generate cash inflows

Benefit-cost ratio (BCR) or Profitability Index is an investment appraisal technique calculated by dividing the present value of future cash flows of a project by the initial investment required for the project.

\[
BCR = \frac{PV \ of \ Future \ Cash \ Flows}{Initial \ Investment}
\]

**Equation 3-21: Benefit-Cost Ratio**

### 3.5.4 Other Benefits and Costs of Wind Energy to Society

Martin & Ramsey (2009)\(^ {122} \) write as is often the case with large scale infrastructure projects, there are benefits and costs to society that are not captured by the businesses that participate in the industry. Wind power is no exception.

#### 3.5.4.1 Positive Externalities

Environmental and social benefits

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Denny (2007)\textsuperscript{123} quotes carbon-dioxide is generated by the combustion of fuels containing carbon. The amount of carbon dioxide released is in direct relationship with the amount of carbon in the fuel and the quantity of fuel burnt. The following expression was used to calculate the CO\textsubscript{2} emissions of a combustion plant.

\[
\frac{CO_2}{MWh} = \left( \frac{E}{CV} \right) (CO_2/kg_{fuel})
\]

\textbf{Equation 3-22: CO\textsubscript{2} emissions of a combustion plant}

where

- \(E\) represents the generator’s energy consumed in mega joules (MJ) per MWh and
- \(CV\) is the calorific value of the fuel in MJ per kilogram.
- \(CO_2/kg\) fuel represents the amount of \(CO_2\) emissions released per kilogram of fuel burnt.

The expression used to calculate sulphur dioxide emissions is the same as that given in Equation 3-22 substituting \(SO_2\) for \(CO_2\) (Kesgin, 2003 cited in Denny).

Pollin (2008)\textsuperscript{124} mentions the major cause of global warming to be the emission of carbon into the atmosphere resulting from energy produced through burning fossil fuels—oil, coal, and natural gas. It is clear that to fight global warming, we have to dramatically reduce our reliance on these three fossil fuels, building support for conservation and renewable energy.

Piementel, Herz, Glickstein, Zimmerman, Allen, Becker, Evans, Hussain, Sarsfeld, Grosfeld & Seidel (2002)\textsuperscript{125} have expressed concern as global warming reduces agricultural production and causes other biological and social problems. Reducing fossil fuel consumption may slow the rate of global warming.

Figure 3-27 \textsuperscript{126} shows the annual increase of carbon dioxide since 1960. Carbon dioxide is the most long-lived global warming gas, and once emitted by burning fossil fuels such as coal and oil, it can remain in the atmosphere for hundreds of years.

\begin{footnotesize}
\textsuperscript{123} Denny, E. (2007). \textit{A Cost Benefit Analysis of Wind Power.} National University of Ireland, School of Electrical, Electronic and Mechanical Engineering.
\textsuperscript{126} http://www.climatecentral.org/news/the-last-time-co2-was-this-high-humans-didnt-exist-15938
\end{footnotesize}
Figure 3-27: Atmospheric CO₂ at Mauna Loa Observatory

Source: http://www.climatecentral.org/news/the-last-time-CO₂-was-this-high-humans-didnt-exist-15938
Retrieved Sep 3, 2016

Gellings & Howard (2009) have tabulated the emission reduction per MW of electricity generation per year from wind generation in Table 3-9. Other benefits sometimes cited include water savings, reductions in natural gas prices and increases in employment.

Table 3-9: Emissions reductions from wind generation

<table>
<thead>
<tr>
<th>Emissions</th>
<th>Annual Reduction per MW Wind</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂⁴</td>
<td>2050 ton/year</td>
</tr>
<tr>
<td>SO₂⁵</td>
<td>1.4 ton/year</td>
</tr>
<tr>
<td>NO₅⁶</td>
<td>0.7 ton/year</td>
</tr>
<tr>
<td>Mercury⁷</td>
<td>0.2 pound/year</td>
</tr>
</tbody>
</table>

(a) Based on 5,000 MW of wind energy, where wind displaces 80% gas and 20% coal. “Analysis of Transmission Alternatives for Competitive Renewable Energy Zones in Texas,” (ERCOT 2006A).
(b) Department of Energy and Energy Information Administration.

On a positive note Sawyer, Teske, & Rave (2014) write all of the CO₂ emissions related to the manufacturing, installation, servicing and decommissioning of a turbine are generally ‘paid back’ after the first 3 to 9 months of operation. For the rest of its 20 year design lifetime, the turbine operates without producing any of the harmful greenhouse gases which are already disrupting life on earth. The benefit obtained from wind power in relation to CO₂ emissions depends entirely on what sort of power plant it displaces. If it displaces hydro or nuclear power, the benefit is small; but if it

---

replaces coal or gas, then the benefit is enormous. Emissions from fossil fuel plants range from around 500g CO₂/kWh up to 1200g CO₂/kWh or more for the dirtiest fuels.

Sovacool & Watts (2009)¹²⁹ observe renewable power plants are the least carbon dioxide-intensive forms of electricity supply currently available. When emissions from the entire lifecycle are taken into consideration, along with opportunity costs (such as long planning times and construction delays) and the risk of accidents and leakage, wind farms, hydroelectric power stations, solar PV and solar thermal power plants, bioelectric facilities, and geothermal units all emit the equivalent of between a mean of 5.1 and 59.6 grams of carbon dioxide per kWh as in Table 3-10.

**Table 3-10 Lifecycle Equivalent Carbon Dioxide Emissions (grams of CO₂/kWh) for Selected Generators**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Lifecycle</th>
<th>Opportunity Costs</th>
<th>Risk of Leakage, Accident and Disruption</th>
<th>Total</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>2.8 to 7.4</td>
<td>0</td>
<td>0</td>
<td>2.8 to 7.4</td>
<td>5.1</td>
</tr>
<tr>
<td>Concentrated solar power</td>
<td>8.5 to 11.3</td>
<td>0</td>
<td>0</td>
<td>8.5 to 11.3</td>
<td>9.9</td>
</tr>
<tr>
<td>Geothermal</td>
<td>15.1 to 55</td>
<td>1 to 6</td>
<td>0</td>
<td>16.1 to 61</td>
<td>38.6</td>
</tr>
<tr>
<td>Solar PV</td>
<td>19 to 59</td>
<td>0</td>
<td>0</td>
<td>19 to 59</td>
<td>39.0</td>
</tr>
<tr>
<td>Hydroelectric</td>
<td>17 to 22</td>
<td>31 to 49</td>
<td>0</td>
<td>48 to 71</td>
<td>59.5</td>
</tr>
<tr>
<td>Nuclear</td>
<td>9 to 70</td>
<td>59 to 106</td>
<td>0 to 4.1</td>
<td>68 to 180</td>
<td>124.0</td>
</tr>
<tr>
<td>Clean coal with CCS</td>
<td>255 to 442</td>
<td>51 to 87</td>
<td>1.8 to 42</td>
<td>308 to 571</td>
<td>439.0</td>
</tr>
</tbody>
</table>


Reduced dependence on foreign oil

Gardner, et al. (2009)¹³⁰ write integrating wind power into grid leads to lesser dependence on fossil fuel generated energy. This leads to energy independence and climate change mitigation.

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Reduced water usage

Wind energy\textsuperscript{131} releases no pollution into the air or water, and does not contribute to global warming. And unlike most other electricity sources, wind turbines do not consume water.

3.5.4.2 Negative Externalities

Birds and Bats

There are reports of avian collision and resulting death due to wind turbines. Swisher, Christine, & Clendenin (2001)\textsuperscript{132} caution to avoid any Altamont Pass type anomaly; industry and other experts now recommend that a thorough evaluation of prospective wind energy sites be carried out before wind turbines are installed so that sites that may be problematic can be avoided. Butler, (2009)\textsuperscript{133} suggests wind farm developers to work carefully to minimize harm to birds and other wildlife via detailed environmental impact assessments and consideration of the habitats and migration routes that a development could threaten.

Visual pollution

Butler (2009)\textsuperscript{134} finds people oppose wind turbine construction due to their ‘aesthetically unpleasing’ nature. Aesthetic judgments vary among well-intentioned individuals, and although some view wind turbines as elegant alternatives to coal and gas power plants, many others find them unattractive. Martin & Ramsey (2009)\textsuperscript{135} feel not everyone is happy to have a nuclear power plant, hydro electric dam, or wind tower in their back yard. Wind farms can have a detrimental effect on the views of nearby residents that can lead to a decrease in their property values. This is particularly true in more heavily populated areas; however, most high wind zones are concentrated in very sparsely populated regions of the country.

\textsuperscript{131}http://www.pawindenergynow.org/wind/benefits.html Retrieved Sep 15, 2016
\textsuperscript{134}ibid
Noise pollution

Martin & Ramsey (2009)\textsuperscript{136} caution noise generated by wind turbines is also a potential problem for nearby residents. The American Wind Energy Association documented the noise level of a modern wind farm at a distance of 750 to 1,000 feet and found that it was 50 decibels. This compares to whispering which is 25 decibels or falling leaves at 15 decibels. Advances in the technology of rotor blades, vibration damping and improved design have reduced noise levels significantly. Butler (2009)\textsuperscript{137} describes noise produced by wind turbines as ‘buzzing, whooshing, pulsing, and even sizzling’. Piementel, et al. (2002)\textsuperscript{138} mentions the noise caused by rotating wind turbine blades is unavoidable. However, beyond 2.1 km, the largest turbines are inaudible even downwind. At a distance of 400 m, the noise level is about 56 decibels, corresponding roughly to the noise level of a home air conditioning unit.

3.5.5 Previous studies of economic viability

Swisher, Christine, & Clendenin (2001)\textsuperscript{139} say that when optimising the economics of wind energy, there are two primary factors that influence the cost of wind energy: the wind resource at the site and the size of the project. The power in the wind is determined using the following formula:

\[
P = \frac{1}{2} \times \text{efficiency} \times \text{air density} \times \text{swept rotor area} \times (\text{wind speed})^3
\]

Equation 3-23: Power in the wind

Some first generation projects were developed with inadequate wind resource data. When the projects did not perform as expected, projects sometimes lost money. Subsequently, developers learned to invest money upfront in intensive wind resource monitoring. Because the formula for calculating the power in the wind involves the cubic function of the wind speed, even small variations in wind speed make a major

\textsuperscript{139} \text{Swisher, R., Christine, R., \& Clendenin, J. (2001). Strong Winds on the Horizon: Wind Power Comes of Age. IEEE, 89, pp. 1757-1764.}
difference in power output. For example, a 12 mph (miles/hour) wind has 70% more power than a 10 mph wind.

Figure 3-28 demonstrates the difference in expected cost per kWh for a 51 MW project at three different wind speeds. As the figure reveals, a difference of slightly more than 2 m/s results in an 84% increase in the cost of energy. Hence, assuming the same size project, the better the wind resource, the lower will be the cost.

The other critical factor in regard to the cost of energy from wind projects is the size of the project. There are economies of scale from developing large projects. The two projects that are compared in Figure 3-29 are 51 MW and 3 MW in size, but both projects will bear many of the same transaction costs. With a larger project 51 MW the cost of electricity generation is less $0.035/kW-hour compared to a small project 3 MW, where the cost of electricity $0.059/kW-hour.

**Figure 3-28: Impact of wind speed on cost per kWh**

![Cost of energy and wind speed](image)

**Figure 3-29: Impact of project size on cost per kWh**

![Cost of electricity](image)


The larger project, with substantially more output, simply has many more kWh of production over which to spread those costs, resulting in electricity that is 64% less expensive than the smaller project.

Falconett & Nagasaka (2007)\(^{140}\) add in windy locations or high wind turbine capacity, the use of the environmental benefits (like CO\(_2\) benefits) in the NPV calculation is

\(^{140}\)Falconett, I., & Nagasaka, K. (2007). A stochastic model to analyze the economic competitiveness of wind power projects within a restructured electricity industry. *The 8th International Power Engineering Conference (IPEC 2007)*, (pp. 30-35).
more profitable than the governmental grants, allowing renewable energy
technologies to compete with conventional power production. In less windy location, 
the small wind power projects are still depending on the governmental support.

Hoffman & Molinski (2009)\textsuperscript{141} list the economic viability of wind power as dependent 
upon the following factors:

- available wind resource,
- installed capital costs and cost of capital,
- operation and maintenance costs,
- wind integration costs,
- transmission line interconnection and grid upgrade costs,
- value of available subsidies or incentives, and
- willingness of customers to pay a premium for wind energy.

Roy (1997)\textsuperscript{142} describes the major advantages of using very large WECS concern the 
economy of \textit{space required} by the installations. It is possible, by installing such units, 
to obtain a high energy output per unit area of land. Further, in regions where available land area is restricted, generation of energy by WECS may become viable only if units of very large capacity are employed. It follows that when choosing economically viable WECS of very high power rating, one may judiciously examine the advantages in view of the \textit{reduced number of units} that need to be installed.

Ragheb M. (2015)\textsuperscript{143} writes the cost of wind power has fallen from about 30 cents per kWh in early 1980s to less than 5 cents kWh.

He further writes in wind energy production there is no such thing as a point price. This is because annual electricity production depends on the wind available at a given wind turbine site. Thus, there is no single price, but a price interval or range, depending on wind speeds. Figure 3-30 shows the change in cost of electricity with annual production of energy. It must be noted that wind speeds at 50 metre hub height will be 28-35 percent higher, for roughness classes in the range 1-2, than the nominal

10 metres height used for meteorological observations and wind speed reporting at different locations. For instance a wind speed of 5 m/s at 10 metre-height in the roughness class 1 will correspond to 6.5m/s at a 50 metre hub height. It can be noticed that at high wind speeds over 9 m/s, the cost of electricity is about the same at the 10 or 50 metres heights as in Figure 3-31.

The price/kW of rated power is not a good guide in wind energy project. What really matters is the price per square metre of rotor swept area. This is analogous to farming where the price per acre of farmland is the relevant capital expenditure in addition to the price of the machinery and farm structures. The reason being the annual production depends much more on the rotor diameter than the generator size.

Figure 3-30: Cost of electricity for a 600kW wind turbine as a function of its power output

Figure 3-31: Cost of electricity at a 50 m hub height (lower graph) and at the meteorological nominal 10 m height (upper graph)


Wind energy is a resource extraction technology. There is no average cost of wind energy because wind turbine prices vary due to transportation costs, different tower heights, different rotor diameters, different generators size and the grid connection costs. A unique aspect of wind energy production is that its productivity and costs depend on the price of electricity and not vice versa as in other energy systems.


144
Wang, Yeh, Lee, & Chen (2009)\textsuperscript{145} employ various economic analysis methods like simple payback period, cost, cost of energy method and discounted cash flow method to study the benefit analysis of wind turbine generators. Energy generated by wind turbines is a cubic function of its wind speed and wind speed varies with height and location. Hence, it is important to select proper rated wind speed and wind turbine capacity than raising hub height. Suitable scale parameter and shape parameter, and wind turbine capacity are important factors in selection of good wind farms for wind turbines installation.

### 3.5.6 Cost comparisons from different sources

Yang & Bai (2010)\textsuperscript{146} compares various costs like investment cost, fuel cost, Operations and maintenance cost, carbon cost and social costs with different types of technologies: wind, coal, nuclear and natural gas.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Investment cost</th>
<th>Fuel</th>
<th>O*M</th>
<th>Carbon cost</th>
<th>Social cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>Medium to high</td>
<td>None</td>
<td>Low</td>
<td>None</td>
<td>Very low</td>
</tr>
<tr>
<td>Coal</td>
<td>Low</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Nuclear</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Natural gas</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>


From Table 3-11 it can be observed that though wind does have a high investment cost, other costs like fuel, O & M, carbon and social are ‘low to none’ compared to coal, nuclear and natural gas. A look at the above table shows wind to be a clear winner.

Arora, Busche, & Cowlin (2010)\textsuperscript{147} opine for on-grid application of renewable energy, growth depends on grid infrastructure improvements and the continued reduction of renewable energy costs. Currently, wind, small hydro, and biomass are the most cost-competitive renewable options. Solar technologies, including concentrated solar power (CSP) and photovoltaic (PV), are the least competitive, but offer the greatest opportunity for growth because of the high potential. It therefore receives the most

financial support in terms of government incentives. Table 3-12 is a summary of generation costs across different energy types in India.

<table>
<thead>
<tr>
<th>Energy Type</th>
<th>Electricity Generation Costs in INR/kWh (USD/kWh)*</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>1-2 (0.02-0.04)</td>
<td>McKinsey-Powering India</td>
</tr>
<tr>
<td>Nuclear</td>
<td>2-3 (0.04-0.06)</td>
<td>McKinsey-Powering India</td>
</tr>
<tr>
<td>Large Hydro</td>
<td>3-4 (0.06-0.08)</td>
<td>McKinsey-Powering India</td>
</tr>
<tr>
<td>Gas</td>
<td>4-6 (0.08-0.12)</td>
<td>McKinsey-Powering India</td>
</tr>
<tr>
<td>Diesel</td>
<td>10+ (0.20+)</td>
<td>McKinsey-Powering India</td>
</tr>
<tr>
<td>Wind (onshore)</td>
<td>3-4.5 (0.06-0.09)</td>
<td>Industry experts</td>
</tr>
<tr>
<td>Small Hydro</td>
<td>3-4 (0.06-0.08)</td>
<td>Industry experts</td>
</tr>
<tr>
<td>Biomass</td>
<td>4-5 (0.06-0.10)</td>
<td>Industry experts</td>
</tr>
<tr>
<td>Solar (CSP)</td>
<td>10-15 (0.20-0.30)</td>
<td>Industry experts</td>
</tr>
<tr>
<td>Solar (PV)</td>
<td>12-20 (0.24-0.40)</td>
<td>Industry experts</td>
</tr>
</tbody>
</table>


*over 25 years

3.5.7 Trends influencing the cost of Wind Power

Morthorst, Aeur, Garrad, & Blanco (2015)\(^{148}\) add three major trends have dominated the development of grid-connected wind turbines in recent years:

- Turbines have become larger and taller – the average size of turbines sold on the market has increased substantially.
- The efficiency of turbine production has increased steadily.
- In general, the investment costs per kW have decreased, although there has been a deviation from this trend in recent years.

3.5.7.1 Factors affecting generation costs

AWEA (2002)\(^{149}\) has listed down the factors which affect generation costs:

- The mean wind speed at a given project (Figure 3-32)
- Improvements in turbine design bring down costs
- Size of a wind farm: a large wind farm is more economical than a small one.
- Optimal configuration of the turbines taking advantage of micro-features on the terrain


• As wind energy is capital-intensive, the cost of financing constitutes a large variable in a wind energy project’s economics.

• The reliability and availability of the wind turbines.

**Figure 3-32: Costs of wind produced power as a function of wind speed (number of full load hours) and the discount rate.**


Note: Installed cost of wind turbines is assumed to be 1,225 /kW

### 3.5.7.2 Reduction in Cost/kWh

IRENA (2015)\(^{150}\) remarks wind turbine prices have fluctuated with economic cycles and with the price of commodities such as copper and steel, which can make up a sizeable part of the final cost of a wind turbine. In 2009, the cost of wind turbines peaked. The cost increase was driven by rising costs of materials, labour and civil engineering and tight supply. Manufacturers earned higher profits. But as technology improved; wind turbine manufacturers introduced larger, more expensive turbines, with higher towers and more capital intensive foundations, but which also achieved higher capacity factors. The turbine technology had improved significantly due to larger rotor diameters and higher towers, allowing for higher electricity output. The 2008-2009 slow down in the economy has meant lesser pressure on commodity prices. With the decline in wind turbine price competition has increased in the market, and it has become more of a buyer’s market. Emerging markets from China have added to this downward pressure as policy makers in China are favouring investments in renewable energy. In China the wind turbine prices, which were USD 1,036/kW in 2007, went down to USD 628/kW in 2011 and increased to USD 676/kW in 2014.

Even India has deployed a large number of small wind farms of up to 5 MW. Figure 3-33 presents data for commissioned small wind farms in India for the period 2000 to 2013. The average cost of these projects is around USD 1,344/kW. There is some evidence of economies of scale even for these small wind projects.

**Figure 3-33: Total installed costs of commissioned small wind farms in India (<5 MW) 2000-2013**

![Figure 3-33: Total installed costs of commissioned small wind farms in India (<5 MW) 2000-2013](image)


According to a research by financial advisory and asset management firm Lazard (2014) the wind costs are falling as shown in Figure 3-34.

**Figure 3-34: Wind costs falling (levelised costs of wind energy)**

![Figure 3-34: Wind costs falling (levelised costs of wind energy)](image)


Regarding the cost of generation Zhe, et al (2009) write on-grid price of wind power is usually between 0.6 and 0.7 Yuan/kWh, and 1.2 at the maximum, much

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higher than the price of coal power. The cost of wind power is 1.7 times of coal power. Wind power equipments usually account for 80% of the total cost of wind power.

Smith J. (2009)\(^{153}\) says the technology advances saw the cost of wind energy drop by an order of magnitude, from around 40 cents/kWh to about 4 cents/kWh, and then start to rise again in the middle of this decade with the increased commodity prices and improved operating margins, to an unsubsidized cost of 6–8 cents/kWh today.

Kane (2009)\(^{154}\) remarks wind energy to be a zero carbon solution. Aggressive global targets have been made by Kyoto protocol, European Union, United States, China and India. There is no geopolitical risk and no fuel price volatility. It is socially, ecologically and economically sustainable. Energy demand is increasing. If the cost/kWh of wind power generation is reduced to USD 0.03-0.06, it can directly compete with conventional power. 30% of the world population has no grid connection. Wind power generation can be developed as a non grid stand alone system which can meet the demand of the deprived world.

As mentioned by Swisher, Christine, & Clendenin (2001)\(^{155}\) reasons behind surge in wind energy market is due to reduction in wind-generated electricity cost, competition amongst electricity suppliers to provide for green electricity, increased availability of wind turbines as technology has matured, production tax credits, stable price and favourable state policy. The cost of wind-generated electricity is reducing due to increase in wind turbine size, reduction in wind turbine weight which lowers the cost due to reduction of raw materials requirement, manufacturing economies of scale, improvements in power electronics and control systems and improvements in blade design.

Mohammed & Nwankpa (2000)\(^{156}\) observes this increased interest in wind power has reduced the cost of wind-generated electricity to less than 5 cents per kilowatt-hour, a hundred percent decrease from the early 1980’s.

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3.5.7.3 **PESTEL Analysis**

MNRE, Ministry of New and Renewable Energy (2011)\(^{157}\) provides a summary of the external factors that will impact the renewable energy sector through a PESTEL analysis as illustrated in Table 3-13 below.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Opportunities</th>
<th>Threats</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Political</strong></td>
<td>Conducive Policy and Regulatory Framework for Renewable Energy, domestically</td>
<td>Non availability of financial resources for supporting RE.</td>
</tr>
<tr>
<td></td>
<td>Availability of funds for renewable energy</td>
<td>Political support at the State Government level institutions vary widely</td>
</tr>
<tr>
<td></td>
<td>Regulatory developments in grid and market integration of RE</td>
<td>Lack of interest to support such resources by other Ministries</td>
</tr>
<tr>
<td></td>
<td>Growing private sector interest in RE</td>
<td></td>
</tr>
<tr>
<td><strong>Economic</strong></td>
<td>Possibility of significant reduction in costs of solar technologies</td>
<td>Continuation of high subsidies for diesel, kerosene, cooking gas</td>
</tr>
<tr>
<td></td>
<td>Increasing energy demand-supply gap</td>
<td>Readiness of financial institutions to take on risks</td>
</tr>
<tr>
<td></td>
<td>Increasing pressure on availability of conventional fuel sources such as coal</td>
<td>Ability to maintain cost competitiveness vis-à-vis international markets</td>
</tr>
<tr>
<td></td>
<td>Several regions in the country with no access to grid power</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increasing price of oil</td>
<td></td>
</tr>
<tr>
<td><strong>Socio Cultural</strong></td>
<td>Significant potential of employability</td>
<td>Resistance from local community/end-users towards use of certain technologies (e.g. waste to energy)</td>
</tr>
<tr>
<td><strong>Technological</strong></td>
<td>Development of storage technology</td>
<td>Inadequate transmission system capacity</td>
</tr>
<tr>
<td></td>
<td>New technology breakthrough for example second generation biofuel technology breakthrough</td>
<td>Infrastructure bottlenecks</td>
</tr>
<tr>
<td></td>
<td>Technology breakthrough in solar</td>
<td></td>
</tr>
<tr>
<td><strong>Environmental</strong></td>
<td>Decreasing domestic coal allocations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increasing awareness of climate change concerns</td>
<td></td>
</tr>
<tr>
<td><strong>Legal</strong></td>
<td>Conducive legal framework-Electricity Act, National Energy Policy, National Tariff Policy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>National Action Plan on Climate Change</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Kyoto Protocol and new Global Climate Protocol</td>
<td></td>
</tr>
</tbody>
</table>


3.5.7.4 Economic Impact

Stannard & Bumby (2006)\textsuperscript{158} list a number of factors that could change in the near future to allow the economic pendulum to swing in favour of small-scale wind generation:

- If the uptake of small-scale wind turbine systems increases, the price per unit would fall significantly
- The cost of fossil fuels may continue to rise.
- Grid supply may become less reliable (due to aging infrastructure or security problems with the fuel supply)
- The Government may increase the grant and incentive schemes.
- Power companies may be forced to reflect the true environmental impact of fossil fuelled power generation in their price-perhaps through a carbon trading system.

If any (or all) of these scenarios play out, small-scale wind generation may well see a sudden upsurge in popularity.

3.5.8 Levelised cost of energy

The levelized cost of electricity (LCOE)\textsuperscript{159} is a measure to compare different methods of electricity generation. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. It can also be regarded as the minimum cost at which electricity must be sold in order to break-even over the lifetime of the project.

Gsanger, Sawyer, & Januario (2012)\textsuperscript{160} explain the levelised cost of energy (LCOE) is the primary metric for describing and comparing the underlying economics of power projects. For wind power, the LCOE represents the sum of all costs of a fully operational wind power system over the lifetime of the project with financial flows discounted to a common year. The principal components of the LCOE of wind power systems include capital costs, operation and maintenance costs and the expected


annual energy production Figure 3.35. Assessing the cost of a wind power system requires a careful evaluation of all of these components over the life of the project.

**Figure 3.35: The cost of wind energy**

3.5.8.1 **LCOE Sensitivities**

Tegen, Lantz, Hand, Maples, Smith, & Schwabe (2013)\(^\text{161}\) write the input parameters described above reflect the reference wind project as these parameters are subject to considerable uncertainty. As a result, it is beneficial to investigate how this variability may impact LCOE. The sensitivity analysis shown in Figure 3.36 focuses on the basic LCOE inputs: 1) capital cost, 2) operating cost, 3) capacity factor (a substitute for Annual energy production AEP), and 4) FCR (Fixed charge rate), although in Figure 3.36, FCR is broken into its principal elements: discount rate and operational lifetime. (ICC~installed capital costs, AOE~annual operating expenses)

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### Figure 3-36: Sensitivity of land-based wind LCOE to key input parameters

<table>
<thead>
<tr>
<th>Key Parameters for LCOE Sensitivity Analysis</th>
<th>Reference LCOE = $72/MWh</th>
<th>LCOE ($/MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICC ($/kW)</td>
<td>$1,400</td>
<td>$2,098</td>
</tr>
<tr>
<td>AOE ($/MWh)</td>
<td>$9</td>
<td>$11</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>63%</td>
<td>37%</td>
</tr>
<tr>
<td>Discount Rate (nominal, after-tax)</td>
<td>6%</td>
<td>8%</td>
</tr>
<tr>
<td>Operational Life (years)</td>
<td>30</td>
<td>25</td>
</tr>
</tbody>
</table>


Note: The reference LCOE represents the estimated LCOE for the NREL reference plant. Changes in LCOE for a single variable can be understood by moving to the left or right along a specific variable. Values on the X-axis indicate how the LCOE will change as a given variable is altered, and assuming that all others are constant. For example, as capacity factor decreases toward 18%, the LCOE shown on the X-axis will increase accordingly to more than $100/MWh. As the operational life for the reference project moves toward 30 years, the LCOE will decrease to nearly $60/MWh.

Lazard (2014)\(^{162}\) an international financial advisory and asset management firm in their study summarises the cost components of 16 different energy technologies: 10 of them are alternative (which includes mainly low-carbon, renewable technologies) and six are conventional (which includes fossil fuel sources and nuclear) as in Figure 3-37.

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Figure 3-37: Components of levelised cost of energy

Lantz (2014)\textsuperscript{163} tracks LCOE analysis trends in cost of energy with a consistent methodology and standardized assumptions as per Office of Energy Efficiency and Renewable Energy (EERE) guidance and allows assessment of progress towards Programmatic Goals.

Figure 3-38: Trends in Wind LCOE

3.5.8.2 Economic Index

Doddamani & Jangamshetti (2008) introduced the concept of economic index. Its value is used to identify the best-suited wind turbine generator at a potential wind site. It considers the performance of wind turbine generator as well as the related economic factors. Economic Index of a wind turbine generator is defined as the ratio of cost of energy produced per kWh at the rated wind speed of the wind turbine generator (CoE\textsubscript{R}) to the actual cost of energy produced per kWh (CoE\textsubscript{a}) and is given by

\[ EI = \frac{CoE_R}{CoE_a} \]

Equation 3-24: Economic index of a wind turbine

CoE\textsubscript{R} and CoE\textsubscript{a} in equation are given by,

\[ CoE_R = \frac{Cc \times FCR + C_{O&M,L}}{E_{a,WR}} = FCR \times \frac{Cc}{E_{a,WR}} + \frac{C_{O&M,L}}{E_{a,WR}} \]

Equation 3-25: Cost of energy produced per kWh at the rated wind speed of the wind turbine generator

where \( C_c \) is installed capital cost, \( FCR \) is Fixed Charge Rate including utility debt and equity costs, state and federal taxes, insurance and property taxes, \( C_{O&M,L} \) is levelised annual operation & maintenance cost. And

\[ CoE_a = \frac{Cc \times FCR + C_{O&M,L}}{E_{a,W}} = FCR \times \frac{Cc}{E_{a,W}} + \frac{C_{O&M,L}}{E_{a,W}} \]

Equation 3-26: Cost of the actual cost of energy produced per kWh

where \( E_{a,WR} \) is annual energy yield at rated wind speed of wind turbine generator, and \( E_{a,W} \) is actual annual energy yield of wind turbine generator. And \( C_{O&M,L} \) is levelised cost of operation & maintenance per unit of energy

\[ \frac{C_{O&M,L}}{L_{fom} + L_{vom}} \]

Equation 3-27: Levelised cost of operation & maintenance per unit of energy

where $L_{fom}$ is levelised fixed O & M per kWh

$$L_{fom} = \frac{f_{O&M}}{E_{akW}} (LF)$$

**Equation 3-28: Levelised fixed O & M per kWh**

where $f_{O&M}$ is fixed O & M cost (year 0) per kW per year and $E_{akW}$ is annual energy produced per kW of rating. $L_{vom}$ is levelised variable O & M cost per kWh given

$$L_{vom} = v_{O&M} * (LF)$$

**Equation 3-29: Levelised variable O & M cost per kWh**

where $v_{O&M}$ is variable O & M cost per kWh and LF is levelising factor.

3.5.9 **Economic challenge**

REN21. (2013)\(^{165}\) reports a fundamental difference between renewables and fossil and nuclear is the cost ratio between capital and operating costs. Marginal costs of most renewables are low and often prevail over conventional power generation on spot markets. Wind and solar can significantly reduce electricity prices, benefiting industrial and residential consumers. Because of low prices it becomes increasingly difficult to recover costs and earn a reasonable return on investment. In order to provide continuous electricity supply, conventional power plants have to be up and running, but give priority or guaranteed grid access to renewable energy and thus are operated with decreasing capacity factors and therefore reduced profitability. Discussions are going on regarding how to best design flexibility-driven capacity mechanisms e.g. grid infrastructure, storage capacity, demand side management (DSM) and highly flexible power plants.

3.6 **THE OTHER VIEWS**

Sweet (2013)\(^{166}\) Germany has pushed low-carbon and renewable energy technology harder than any other European country. Last year it produced 22 percent of its energy from ‘green’ sources. But the costs of these green advances are proving to be unsustainably high. Developers of green technologies are guaranteed specific rates of return well into the future but, these subsidies get distributed amongst the rate payers.


nationwide. Industry believes its threatening economic growth. The chief executives of energy companies called for an end to subsidies for wind and solar power and develop a reward system for companies that maintain standby reserves to compensate for power shortfalls when the wind doesn’t blow or sun doesn’t shine.

3.6.1 Economic Impact Studies Can Be Very Misleading

Lesser (2008)\textsuperscript{167} argues spending $100 billion to build new wind turbines may indeed create thousands of jobs, but so might spending that money on new coal and nuclear plants, or even spaceships. An RPS that mandates development that would not otherwise take place is a tax. And taxes do not create jobs.

He adds critics may argue that such taxes are “worth the price” if we are to achieve broader environmental and social goals, such as reducing dependence on foreign oil or reducing CO\textsubscript{2} emissions in Kansas. But nobody should be under the illusion that banning coal plants—or any other type of fossil fuel generation—and replacing them with renewable resources will provide economic manna from heaven. Renewables have risks, too, and costs that must be considered. And what happens when wind does not blow?

3.6.2 How "green" are Industrial Wind Turbines?

Trentowsky.W.D. (2011)\textsuperscript{168} raises doubt over how “green” and eco friendly are industrial wind turbines?

He suggests considering the reinforced concrete foundation base used to anchor a turbine into the soil. A typical base can contain 250 to 650 cubic metres of concrete. The size of the base depends on the turbine height, the mass of the blades and gearing systems, and the foundation engineering requirements of the turbine. That is a staggering amount of resources. All of this material is extracted, mined, processed and transported using machinery that is either powered by diesel fuel, coal or electricity. Cement kilns are monster consumers of coal and natural gas. The bulldozers, crushers, screeners, trucks, railway cars and ships used to create and move this stuff all gobble countless thousands of litres of fuel.


Trentowsky adds the quarries needed to produce the cement and aggregates are stripped off their vegetation, and then they are rehabilitated (more fuel and energy consumed in that process). Not to mention the construction roads and construction activity to ‘access’ and develop all wind farm sites; and the energy and efforts required to create a new electrical grid that is necessary to connect all wind farm sites into the existing power supply grid.

He says there are a finite amount ‘prime’ aggregate sources. Will there be any left for our existing roads, bridges, public buildings, homes, factories and farms? If so, how much will be left and at what premium will we have to pay to use it? The wind turbines will be ‘competing’ for these same ‘prime’ aggregate sources. Replacing coal plants with industrial wind turbines substitutes one set of air pollutants for another set of air / sound and ground pollutants. So, how ‘green’ is all of this after all?

As remarked by Marques & Fuinhas (2011) the literature on the empirical link between restraining emissions of carbon dioxide (CO₂) and economic growth has shown some unexpected results. Menyah & Wolde-Rufael, (2010) found no causality running from renewable energy to CO₂ emissions. The econometric evidence seems to suggest that nuclear energy consumption can help to mitigate CO₂ emissions, but so far, renewable energy consumption has not reached a level where it can make a significant contribution to emissions reduction. In the same way, Apergis Payne, Menjay, & Wolde-Rufael (2010) conclude that the renewable energy consumption does not contribute to reducing CO₂ emissions.

Marques & Fuinhas (2011) explain the problem is in storing energy, as well as the intermittent characteristic of renewables. The failure to store energy, for example from wind or solar sources, requires the simultaneous use of established sources of energy, such as natural gas or even the highly polluting coal. This scenario leads to two effects on the installed capacity and on energy dependency. On the one hand, it implies the maintenance and even the enlargement of productive capacity that

becomes idle for long periods, which generates economic inefficiencies. On the other hand, the intermittency may not even contribute to the reduction of a country’s energy dependence goal. Using the statistics, it is found that the share of renewables in total energy supply is not having the desired effect, as far as economic growth and wealth creation are concerned. Ultimately, with the current state of affairs, the decision to invest in renewable energy remains essentially political.

Frondel, Ritter, & Vance (2009) \(^{173}\) comment although renewable energies have a potentially beneficial role to play as part of Germany’s energy portfolio, the commonly advanced argument that renewables confer a double dividend or “win-win solution” in the form of environmental stewardship and economic prosperity is disingenuous. It is further argued that Germany’s principal mechanism of supporting renewable technologies through feed-in tariffs, in fact, imposes high costs without any of the alleged positive impacts on emissions reductions, employment, energy security, or technological innovation.

Once again for Germany Vance (2012)\(^ {174}\) says the promotion of renewable energies reduces the emissions of the electricity sector but, by lowering demand for CO\(_2\) allowances from this sector, thereby lowers their price. Other sectors in the Emissions Trading Scheme can thus buy allowances more cheaply so that they reduce less. This leaves the total amount of emissions unchanged, rendering the Feed-In-Tariff a completely ineffective measure for reducing CO\(_2\).

Simmons, Yonk & Hansen (2015)\(^ {175}\) comment wind energy is said to be clean and free and perpetual but the true cost is what consumers and society as a whole pay to purchase wind-generated electricity and also to subsidize wind energy industry through taxes and government debt. True costs need to include costs of construction, operation and maintenance of the power plant, cost of transmitting power to consumers and also hidden costs like opportunity costs. Because wind power is unreliable, conventional generators must be kept on backup to meet demand when


wind is unable to do so. This drives up the cost of electricity for consumers, as two plants are kept running to do the job of one. Billions of taxpayer dollars are used to subsidize the wind industry. Allowing consumers to pick which energy to use, based on price, would result in greater economic efficiency than allowing government to decide how the resources of consumers should best be allocated.

Hansen, Simmons, & Yonk (2016)\textsuperscript{176} in their analysis for the year 2012 find wind energy represented 43 percent of all new electricity-generating capacity, more than any other type of energy. Environmentalists and wind industry lobbyists tout these numbers as indications of great success and as a path to America's renewable energy future. The growth of wind energy, however, comes at a substantial cost to taxpayers and competitors in the energy marketplace. Government subsidies and state mandates, enacted to help the wind power industry get on its feet, are responsible for the rapid growth in wind installations over the past decade.

\textbf{Figure 3-39: Federal Electricity subsidies and electricity generation by source}\textsuperscript{177}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{chart.png}
\caption{Federal Electricity subsidies and electricity generation by source}
\end{figure}


Note: The data for this chart were taken from Table ES4 and Table ES5. The numbers may not sum to 100 percent because of independent rounding.

They further add, unfortunately, subsidies, tax breaks, and other incentives do not seem to be generating substantial returns in terms of electricity. In fiscal year 2010, for example, wind energy received 42 percent of direct federal subsidies for energy,

\begin{footnotesize}
\begin{enumerate}
\item \textsuperscript{176} Hansen, M., Simmons, R., & Yonk, R. (2016). \textit{The unseen costs of wind-generated electricity}. Institute of Political Economy, Utah State University. Logan, Utah: Strata Policy.
\end{enumerate}
\end{footnotesize}
more than any other type of electricity generation. Despite this, wind produced only 2 percent of the nation's total electricity. In 2013 that number grew to 4 percent, while still receiving 37 percent of direct federal subsidies for energy. As Figure 3-39 shows, however, the generation of electricity from wind remained insignificant compared to generation from coal, nuclear, natural gas, and hydropower.

3.7 THE WAY AHEAD

Moors (2012)\textsuperscript{178} states environment would benefit from renewable energy. But renewable sources have hefty implementation prices—there are few incentives to adopt these technologies. While the wider introduction of renewable sources with increased economics of scale will bring down generating costs, it seems these alternatives will remain more expensive for some time. Wind power generation has seen tremendous growth in the last two decades, by increasing power generating capacity from Kilowatts to Megawatts.

Sovacool & Watts (2009)\textsuperscript{179} argue that a completely renewable electric utility sector where wind farms, solar systems, bio-electric power stations, hydroelectric facilities, and geothermal power plants generate 100 percent of electricity is possible using today's technology. It is not the technology that is lacking, but the political will, institutional inertia, and social awareness needed to bring it forward.

Nissen (2009)\textsuperscript{180} predicts that wind turbines of future will likely follow the current trend of increasing energy output to multi megawatt machines, ensure optimal performance in a range of environments, and have an operational lifetime reaching or exceeding 30 years. One recent innovation is a 2.5 MW horizontal axis wind turbine (HAWT) having four generators that are engaged selectively depending on the wind-speed, thus increasing the operational range of wind-speeds and energy output for all sites that experience varying wind speeds. While this will likely increase the capital equipment costs, it has the potential to increase the plant’s capacity factor beyond the


40% ceiling that plants currently are limited to in practice; this will increase the cumulative energy generated and hence, improve the feasibility.

Mallet (2001)\textsuperscript{181} opines the essence of wind energy lies in its *decentralized nature* and the ability to supply remote areas with electricity. These areas may be connected in a local area grid (LAG), much like a Local Area Network, or LAN, in computer systems, so that power lines from rural areas do not need to be constructed to the remote area. Also, wind pumps have great potential - not for electricity production, but for pumping of water for irrigation or for drinking water. This is especially important in rural areas where access to clean drinking water or irrigation water is a huge public health problem. These pumps can power wells that reach deep into the ground to tap into ground water. This decentralized nature is an aspect of wind energy that spurred Indian policy-maker’s adoption of the technology and this philosophy needs to be remembered by other governing bodies in the developing world.

In his article Freris (1992)\textsuperscript{182} concludes by saying that material scientists are looking at improved blade construction techniques to increase fatigue life. Aerodynamicists endeavour to better understand the complex flows over blades in general and during yaw in particular and to devise improved stall regulated blades and novel drag devices for over speed control. They are also concerned with reduction of noise emission from the blades. Mechanical engineers are attempting to understand more fully the complex forces experienced by blades and hence to assess the fatigue loads on blades and the drive train. Meteorologists are developing techniques for reliable prediction of the resource. Electrical and control engineers are looking critically at the various control options and their effect on energy capture and blade stresses. They are also developing novel low-speed electrical generators for direct coupling to the turbine and other electrical interfaces to enhance performance and quality of supply. They are also setting up autonomous wind/diesel supplied systems with energy-storage components and are devising control policies to crack the most difficult system problem of 100% wind energy penetration.