7.10 The 101-m Siemens turbines in Table 7.5 come with either a 2300 or a 3000 kW generator. Using the approach based on Equation 7.63:

a. Find the energy (kWh/yr) each will deliver in an area with 5.7 m/s average wind speed.

b. Determine the optimum generator size for these winds. Check to be sure it does better than the standard size generators.

c. At what wind speed would the 3000 kW generator begin to outperform the 2300 kW generator? Check to see that the two generator outputs are the same at that wind speed.

\[ CF = 0.087 \bar{V} - \frac{P_r}{D^2} \]  
(RAYLEIGH WINDS)

\[ CF = \frac{\text{ENERGY DELIVERED}}{\text{ENERGY @ FULL POWER}} \]
\[ CF = \text{CAPACITY FACTOR} \]
\[ \bar{V} = \text{AVG WIND SPEED} \]
\[ P_r = \text{RATED POWER} \]
\[ D = \text{ROTOR DIAMETER} \]

2300 kW:

\[ CF = 0.087(5.7) - \frac{2300}{(101)^2} = 0.4959 - 0.2245 = 0.2713 \]
\[ \Rightarrow 2.2713(2300) \times 8760 = 5,466 \text{ MWh/yr} \]

\[ CF = 0.087(5.7) - \frac{3000}{(101)^2} = 0.4959 - 0.2940 = 0.2019 \]
\[ \Rightarrow 0.2019(3000) \times 8760 = 5,284.9 \text{ MWh/yr} \]

⇒ SMALLER GENERATOR MAY DELIVER MORE POWER.

b) EQU 7.65 Computes Max Energy

\[ \frac{dE}{dP_r} = d \left[ \frac{P_r \times 8760 \times CF}{2P_r} \right] = d \left[ \frac{P_r \times 8760 \times 0.087 \bar{V} - \frac{P_r}{D^2}}{2} \right] \]

\[ = 8760 \times 0.087 \bar{V} - \frac{2P_r}{D^2} = 0 \]
\[ \Rightarrow P_r = \frac{0.087 \bar{V} D^2}{2} \]
\[ \Rightarrow P_r = \frac{0.087 \times (5.7)(101)^2}{2} = 2529 \text{ kW} \]

\[ 2529 \times 8760 \times 0.087 \bar{V} - \frac{2529}{(101)^2} = 5493.8 \text{ MWh which is greater than 2300 and 3000 kW generators.} \]
C) AT WHAT SPEED DO THE GENERATORS HAVE EQUAL ENERGY

\[ P_1 = 3000 \quad P_2 = 2300 \]

\[ P_1 \left( 0.087 \frac{\vec{V} - P_1}{(101)^2} \right) = P_2 \left( 0.087 \frac{\vec{V} - P_2}{(101)^2} \right) \]

\[ 0.087 \vec{V} P_1 - \frac{P_1^2}{(101)^2} = 0.087 \vec{V} P_2 - \frac{P_2^2}{(101)^2} \]

\[ 0.087 \vec{V} (P_1 - P_2) = \frac{(P_1^2 - P_2^2)}{(101)^2} \]

\[ \vec{V} = \frac{(P_1^2 - P_2^2)}{(P_1 - P_2)(101)^2(0.087)} = \frac{3000^2 - 2300^2}{(3000 - 2300)(101)^2(0.087)} \]

\[ = 5.971 \text{ m/s} \]

CHECK:

\[ P_1 : \quad E = P_1 \cdot CF = 3000 \left( 0.087 \left( 5.971 \right) - \frac{3000}{(101)^2} \right) \]

\[ = 3000 \left( 0.5174 - 0.30 \right) = 676 \quad \text{MATCH!} \]

\[ P_2 : \quad E = P_2 \cdot CF = 2300 \left( 0.087 \left( 5.971 \right) - \frac{2300}{(101)^2} \right) \]

\[ = 2300 \left( 0.5174 - 0.23 \right) = 676.04 \]
7.11 Consider the design of a home-built wind turbine using a 350-W permanent magnet DC motor used as a generator. The goal is to deliver 70 kWh in a 30-day month.

a. What capacity factor would be needed for the machine?

b. If the average wind speed is 5 m/s, and Rayleigh statistics apply, what should the rotor diameter be if the CF correlation of Equation 7.63 is used?

c. How fast would the wind have to blow to cause the turbine to put out its full 0.35 kW if the machine is 20% efficient at that point?

d. If the TSR is assumed to be 4, what gear ratio would be needed to match the rotor speed to the generator if the generator needs to turn at 600 rpm to deliver its rated 350 W?

\[ a) \quad CF = \frac{\text{ENERGY DELIVERED}}{\text{ENERGY @ FULL POWER}} = \frac{\text{[470,000/720] HR/MON}}{350} = \frac{0.78}{1} \approx 27.8\% \]

\[ b) \quad \text{EQN 7.63: } \frac{C_F}{0.87} = \frac{D}{D} = \frac{0.78 - (0.87)(5)}{D} = \frac{-350}{D^2} \]

\[ D^2 = \frac{-350}{(0.78 - 0.87)} \]

\[ D = \frac{1.49}{\text{m}} \quad \text{ANS.} \]

\[ c) \quad \frac{P_r}{\eta} = \frac{C_F}{0.87} \quad \frac{A}{V^3} \]

\[ V^2 = \frac{2P_r}{\eta A} = \frac{2(350)}{0.87(1.225)(1.743)} = 1220.7 \]

\[ V = \sqrt{\frac{850}{214}} = \frac{11.78}{\text{m/s}} \quad \text{wind speed} \]

\[ \eta = 0.2 \quad \text{ANS.} \]

\[ d) \quad \text{TSR} = 4 \]

\[ \Rightarrow \text{tip speed} = 4 \times \text{(wind speed)} = 4 \times 11.78 \text{ m/s} = 47.12 \text{ m/s} \]

\[ \text{tip speed circumference} = 2\pi R = \pi (1.49) = 4.68 \]

\[ 47.12 \text{ m/s} \Rightarrow 10.066 \text{ Hz} \Rightarrow \frac{10.066 \text{ rev/s}}{4.68} = \frac{604}{\text{rev/min}} \quad \text{ANS.} \]
d) (cont)

\[ \text{GEAR RATIO} = \frac{\text{GENERATOR RPM}}{\text{ROTOR RPM}} = \frac{600}{604} \approx 1 \Rightarrow 1:1 \text{ Aug} \]

\text{GEAR RATIO}
7.12 Consider the perspective of a landowner being offered the following three choices by a wind developer. Compare the options.

a. A flat $20,000/yr per turbine
b. 0.5¢ for each kWh generated
c. $500/yr per acre (4047 m²/acre) of array (turbine corner to turbine corner) plus $100/yr per acre of buffer zone.

The proposal is for thirty 1.6-MW, 80-m turbines with 3D (side-by-side) and 10D (row-to-row) spacing plus a 5D buffer zone. Winds are modeled with Rayleigh assumptions at an average wind speed of 7 m/s. Wind-farm losses (wake loss, interconnects, blade bugs) are estimated at 15%.

9) \( 30 \times 20k = 600k/yr \)

b) Using Eqn 7.64.

\[
\text{ANNUAL ENERGY} = 8760 \times \frac{Pr(\text{KW})}{\text{yr}} \left( \frac{0.087 \sqrt{\text{m/s}}}{\text{yr}} - \frac{Pr(\text{KW})}{D(\text{m})} \right)
\]

\[
= 8760 \times 1600 \left( \frac{0.087 \sqrt{7}}{80} \right) \times \{1 - 0.15\}
\]

\[
= 4276 \text{ MWh/yr}
\]

\[
\$ = 30 \times 4276 \text{ MWh/yr} \times 0.005\$
\]

\[
= 644,150/yr
\]

C) Compute the Wind Farm Area

\[
\text{ARRAY} = 50D \times 12D = 600D^2 = 600(80^2) = 3,840,000 \text{ m}^2
\]

\[
\text{ACRES} = \frac{3,840,000 \text{ m}^2}{4,047 \text{ m}^2/\text{acre}} = 948.5 \text{ ACRE}
\]

\[
\text{BUFFER} = 60D \times 22D - \text{ARRAY}
\]

\[
= (600 \times 220^2 - 3,840,000)
\]

\[
= 84,480,000 - 3,840,000 = 4,608,000
\]
(cont) \[ \text{acre} = \frac{4608.000}{4017} = 1.135 \text{ acre} \]

\[ S = (98.5)(\$500 \text{ acre}^{-1} \text{ yr}^{-1}) + (1136)(\$100 \text{ acre}^{-1} \text{ yr}^{-1}) \]

\[ = \$588,112 \text{ per year} \]

Thus most $ produced by option (b) which

REIMBURSES BASED UPON WHA'T PRODUCED \iff \text{ BUT MOST RISKS BECAUSE IT DEPENDS ON WIND TURBINE AVAILABILITY.} \iff \text{ BEST OPTION IS FLAT RATE PER TURBINE MARKET DEMAND.} \iff \text{ BEST OPTION IS PER ACRE RATE.} \]
7.13 The 2013 “low wind” turbine pricing in Table 7.6 uses a 1.62 MW turbine with an installed cost of $2025/kW with a 100-m rotor diameter.

a. At a site with 6 m/s Rayleigh winds at 50-m, estimate the energy this turbine would deliver at a hub height of 100 m assuming the usual 1/7th wind-shear factor. Assume 15% losses.

b. Assuming a nominal 9% financing charge with a 20-year term along with annual O&M costs of $60/kW, find the levelized cost of electricity. Does it agree with Figure 7.48?

Table 7.6

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>2002</th>
<th>2009</th>
<th>2013 Turbine Pricing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Type</td>
<td>Standard</td>
<td>Standard</td>
<td>Standard</td>
</tr>
<tr>
<td>Rated power (MW)</td>
<td>1.5</td>
<td>1.5</td>
<td>1.62</td>
</tr>
<tr>
<td>Hub height (m)</td>
<td>65</td>
<td>85</td>
<td>30</td>
</tr>
<tr>
<td>Rotor diameter (m)</td>
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<td>77</td>
<td>82.5</td>
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<tr>
<td>Installed capital cost (S/kW)</td>
<td>1300</td>
<td>2150</td>
<td>1600</td>
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<tr>
<td>Operating (and SAWS)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Interest rate (%)</td>
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<td>15</td>
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<tr>
<td>Financing term (y)</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

![Fig. 7.48](image)

\[ V = V_0 \left( \frac{H}{H_0} \right)^{1/7} = 6 \left( \frac{100}{50} \right)^{1/7} = 6.624 \text{ m/s} \]

\[ E = CF (1 - Losses) \times 8760 \times P_{\text{rated}} \times \frac{1}{40} \text{ kWh} \]

\[ A = \frac{1.62 \times 8760 \times \text{kWh}}{15 \times 20} \]

\[ A = 1095 \times 2025 \times \text{$/kWh}$, $1620 \text{kWh} = \$359,327 \]
LCOE (Levelized Cost of Energy) = \( \frac{\text{Annual Fixed Cost + Annual Variable Cost}}{\text{Annual Output}} \)

Operating Cost ($/kWh) = $60 \/ kWh \cdot 1620 = $97,200

\[
LCOE = \frac{391,367 + 97,200}{4,997 \times 10^6} = 0.0914 \$/\text{kWh}
\]

This LCOE does agree with P162.48 (at 6 m/s, 50 m)

Ans.