Appendix I: **Efficiency Test Equation**

$$\frac{2*P+1.25*H}{F}>1$$

P = Net power output from CHP plant
H = Net thermal output from CHP plant
F = fuel use at CHP plant

1. Basis of equation:

The equation is used to determine if the combined heat and power project's efficiency is higher than the equivalent efficiency of separate heat and power. To calculate the equivalent efficiency (the efficiency that combining the sources would achieve) of separate heat and power it is assumed that electricity is supplied from a 50% efficient combined cycle gas turbine power plant and thermal output is supplied from an 80% efficient boiler. It is important to note the efficiency values are based on the higher heating value of the fuel. When the condition is true (equation > 1) the CHP plant is more efficient than what is currently considered highly efficient fossil-fired separate heat and power.

While the efficiency of CHP is compared to highly efficient separate heat and power to qualify for this guidance, the *actual* efficiency improvement from the CHP system over the *actual* separate heat and power depends on the equivalent efficiency of the units that it replaces or displaces. The actual improvement will be greater because, on average, the electric grid is 33% efficient and industrial boilers are about 75% efficient.

2. Units in equation:

The units do not matter as long as fuel, power output, and thermal output are all in the same units. This will typically require converting one or more of the units.

3. Example Calculations:

Example 1: A net 30 $MW_{electric}$ and net 300,000 lb steam/hr CHP system with a 560 mmBtu/hr higher heating value (HHV) fuel input.

First convert all values to consistent units. For this example everything will be converted to MW.[1]

$$\frac{300{,}000\text{lbsteam}}{\text{hr}}*\frac{1\text{mmBtu}}{1{,}000\text{lbsteam}}*\frac{1{,}000{,}000\text{Btu}}{1\text{mmBtu}}*\frac{1\text{kWh}}{3{,}412\text{Btu}}*\frac{1\text{MW}}{1{,}000\text{kW}}=87.9\text{MW}_{\text{ThermalOutput}}$$

$$\frac{560\text{mmBtu}}{\text{hr}}*\frac{1{,}000{,}000\text{Btu}}{1\text{mmBtu}}*\frac{1\text{MWh}}{3{,}412{,}000\text{Btu}}=164\text{MW}_{\text{Fuel input}}$$

[1] Steam value will vary slightly depending on specific conditions. Energy value in makeup water should be subtracted from the energy content of the steam.

Now that all units are consistent the equation can be used:

$$\frac{2*P+1.25*H}{F}=\frac{2*30+1.25*87.9}{164}=1.04>1.0 \qquad \text{Condition satisfied}$$

Because the value is greater than 1 the project would qualify. An alternate method would be to compare overall efficiency values. At the CHP project power to heat ratio (net power output divided by net thermal output) of 0.34 (30/87.9) the highly efficient separate heat and power equivalent efficiency (using equation 1) is 69%. Because the CHP project efficiency is 72% it would qualify for this guidance. If the actual units that the CHP project is displacing are 40% efficient electric and 75% efficient boilers, the actual improvement in efficiency is from 61% (SHP) to 72%.

Example 2: A 23 MW gas turbine producing 79 mmBtu/hr net thermal energy with a fuel input of 236 mmBtu/hr lower heating value (LHV).

First convert the lower heating value of the fuel to the higher heating value. For natural gas water vapor is approximately 10% of the energy content so the equivalent higher heating value of the fuel is 262 mmBtu/hr. For this example it is easier to convert the electrical output to mmBtu/h.

$$23MW*\frac{3.412mmBtu/hr}{1MW}=78.5mmBtu/hr$$

Using the equation,

$$\frac{2*P+1.25*H}{F}=\frac{2*78.5+1.25*79}{262}=0.98<1.0 \qquad \text{condition not satisfied}$$

Because the value is less than 1 this project would not qualify for this guidance. At this project's power to heat ratio of 1, an equivalent highly efficient separate heat and power efficiency is 62%. Because this CHP project's overall efficiency is 60% it does not meet the specified level. It should be noted that while this project does not qualify, it would still most likely have overall fuel savings since the efficiency of the more likely displaced SHP technology (40% electric and 75% thermal) is 52%.

4. Derivation of Equation:

The equivalent separate heat and power efficiency is defined by the following equation.

$$EquivalentEfficiency=\frac{1}{\frac{\%Power}{E_P}+\frac{\%Thermal}{E_{TH}}} \qquad \text{(equation 1)}$$

Where,

%Power = The percent of output from the CHP unit in the form of net electrical or mechanical output.
%Thermal = The percent of output from the CHP unit in the form of net thermal output.
E_P = Efficiency of the source of power in the separate heat and power calculation (i.e. power plant).
E_{TH} = Efficiency of the source of thermal energy in the separate heat and power calculation (i.e. boiler).

The sum of the %Power and %Thermal should equal one in all situations. The equivalent efficiency can be replaced by the sum of the power output (P) and thermal output (H) divided by the total fuel input (F). The %Power can be replaced by power output divided by the sum of power and thermal outputs. Likewise, %Thermal can be replaced by the thermal output divided by the sum of the power and thermal outputs. The following form of the equation results from the substitutions.

$$\frac{P+H}{F} = \frac{1}{\frac{\frac{P}{P+H}}{E_P} + \frac{\frac{H}{P+H}}{E_{TH}}}$$

The value (P+H) can then be divided out from each side of the equation.

$$\frac{1}{F} = \frac{1}{\frac{P}{E_P} + \frac{H}{E_{TH}}}$$

To isolate all the variables on the left side of the equation both sides are multiplied by the reciprocal of the right side of the equation. The final simplified form of the equation results and is shown below.

$$1 = \frac{\frac{P}{E_P} + \frac{H}{E_{TH}}}{F}$$

Substituting in the values for E_P (50%) and E_{TH} (80%) completes the equation. Since E_P and E_{TH} are based on assumed separate heat and power technologies values will increase as efficiencies improve. As long as the result of the equation is greater than 1 the CHP facility will use less fuel to supply the same output as separate heat and power.