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COMPENDIUM OF GREENHOUSE GAS EMISSIONS METHODOLOGIES FOR THE OIL AND GAS INDUSTRY

CLIMATE CHANGE

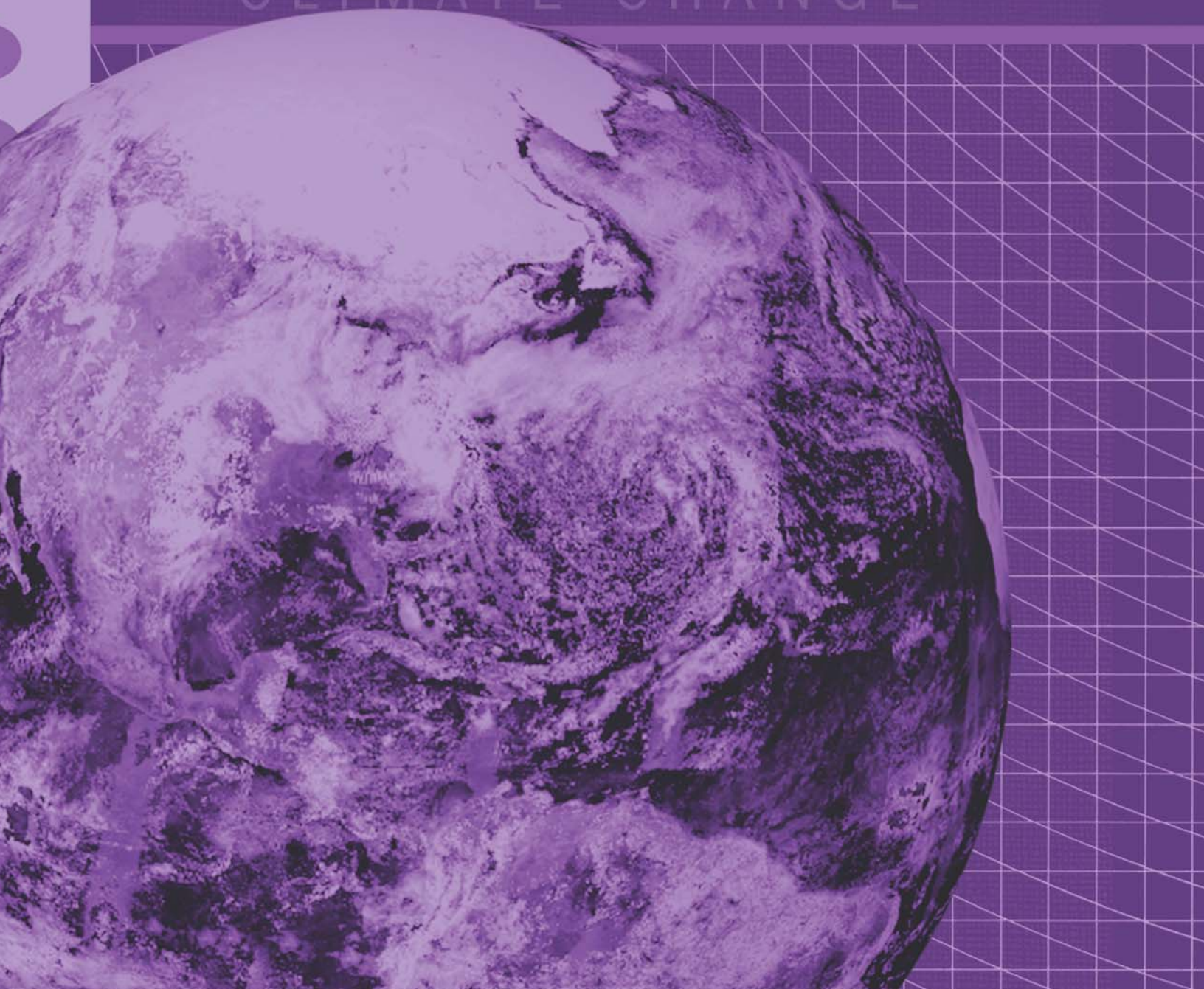

EXHIBIT 4.12: Sample Calculation for Steam (Indirect) Emissions, continued

CALCULATION METHODOLOGY:
Because the method of steam generation is unknown, the simple approach of assuming the steam was generated in a natural gas boiler with an efficiency of 92% will be used. The first step is to convert the mass of steam generated into an equivalent thermal basis using 212°F saturated water as the reference basis. Using a commonly available steam table, the enthalpy of the steam at the two conditions are:

Steam, 600 psig, 700°F = 1350 Btu/lbm
Saturated Water, 212°F = 180 Btu/lbm

Thus, the equivalent steam thermal energy is:

$$\text{Steam thermal equivalent} = (15 \times 10^6 \text{ lbm/yr})(1350 \text{ Btu/lbm} - 180 \text{ Btu/lbm}) = 1.755 \times 10^{10} \text{ Btu/yr}$$

The emissions can now be estimated using the emission factors presented in the preceding discussion:

$$CO_2: \frac{1.755 \times 10^{10} \text{ Btu}}{\text{yr}} \times \frac{0.05772 \text{ tonne}}{10^6 \text{ Btu}} = \underline{1{,}013 \text{ tonnes } CO_2/\text{yr}}$$

$$CH_4: \frac{1.755 \times 10^{10} \text{ Btu}}{\text{yr}} \times \frac{1.21 \times 10^{-6} \text{ tonne}}{10^6 \text{ Btu}} = \underline{0.0212 \text{ tonnes } CH_4/\text{yr}}$$

$$N_2O: \frac{1.755 \times 10^{10} \text{ Btu}}{\text{yr}} \times \frac{3.26 \times 10^{-7} \text{ tonne}}{10^6 \text{ Btu}} = \underline{0.0057 \text{ tonnes } N_2O/\text{yr}}$$

4.7.3 Allocation of Cogeneration Emissions

Cogeneration of electricity and steam, also known as combined heat and power (CHP), is the simultaneous production of electricity and process heat from the same fuel. In these units, the heat produced from the electricity generating process (e.g., from the exhaust systems of gas turbines or from conventional boilers with steam turbines) is captured and used for process steam, hot water heating, space heating, and other thermal needs, or to produce additional electricity. Lower emissions result from these processes because process heat is generated with little or no additional fuel usage. Note that for some processes, additional energy from a secondary combustion unit is required to generate steam. GHG emissions should also be considered from this supplemental combustion source.

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Where all or part of the electricity and/or steam/heat produced from the cogeneration facility is transferred, sold, or otherwise used by another entity, it may be necessary to divide the emissions resulting from the CHP among multiple energy streams. The UK Emissions Trading Scheme (DEFRA, 2003), the WRI/WBCSD GHG Protocol Initiative (WRI/WBCSD, 2001), and the California Climate Action Registry (CACR, 2002) have published approaches for allocating emissions between energy streams in cases where these streams are used by two or more different parties. Each of approaches partitions the total emissions resulting from fuel combustion in the cogeneration unit between the electricity and steam energy streams. As a result, the sum of the emissions assigned to the individual energy streams does not exceed the total emissions resulting from the fuel combusted to produce the energy.

These allocation methodologies are discussed further and illustrated through calculation exhibits.

Efficiency Allocation Approach - UK Emissions Trading Scheme

The UK Emissions Trading Scheme (ETS) bases its allocation on the assumption that the efficiency of heat generation is twice that of electricity generation. The approach applies to emissions associated with the direct import/export of electricity from a combined heat and power (CHP) facility (i.e., via direct contract, not supply to/from grid).

The first step is to calculate the total direct CO_2 emissions from the combustion of natural gas at the cogeneration facility. The second step is to calculate the thermal equivalent of the steam. The mass of steam generated is converted to an equivalent thermal basis using 212°F saturated water as the reference basis. A commonly available steam table provides the enthalpy of the steam at the actual and reference conditions. The third step is to apply the equation for direct electricity or steam imports/exports from cogeneration used in the UK ETS protocol. The equations are provided below.

<u>Electricity Emission Factor from Cogeneration Facility:</u>

$$\underset{(\text{lb } CO_2/\text{megawatt-hr})}{CO_2 \text{ EF from electricity}} = \frac{2 \times CO_2 \text{ direct emissions (tonnes } CO_2)}{[2 \times \text{Electricity produced (megawatt-hr)}] + \text{Steam produced (megawatt-hr)}} \quad \text{(Equation 4-5)}$$

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Steam Emission Factor from Cogeneration Facility:

$$\begin{array}{c}\text{CO}_2\text{ EF from steam}\\ (\text{lb CO}_2/\text{megawatt-hr})\end{array} = \frac{\text{CO}_2\text{ direct emissions (tonnes CO}_2)}{\left[2\times\text{Electricity produced (megawatt-hr)}\right]+\text{Steam produced (megawatt-hr)}}$$

(Equation 4-6)

This approach is illustrated in the following exhibit.

EXHIBIT 4.13: Cogeneration Emissions Allocation – UK ETS Efficiency Allocation Approach

INPUT DATA:
A cogeneration facility operates three natural gas-fired combustion turbines, three heat recovery steam generators with supplemental duct firing capability, and a steam turbine. The combustion turbines and duct burners are the only material sources of GHG emissions associated with the cogeneration plant (i.e., fugitive component emissions are assumed to be negligible).

The cogeneration facility consumes 8,131,500 million Btu of natural gas, producing 3,614,000 million Btu steam and 1,100,600 megawatt-hr of electricity (gross) on an annual basis. A nearby refinery purchases 2,710,000 million Btu of steam and 206,000 megawatt-hr of electricity. The cogeneration facility itself requires 38,500 megawatt-hr to operate (Parasitic load). The net electricity (856,100 megawatt-hrs, metered at the custody transfer point) is sold to the electric grid.

This example applies the UK Emissions Trading System approach to allocating emissions between steam and electricity. Note that the UK ETS program does not currently address CH_4 and N_2O emissions, but the approach presumably applies to CO_2 equivalent emissions.

CALCULATION METHODOLOGY:

Step 1: Direct (On-site) Combustion Emissions from Cogeneration:
For the cogeneration unit, emissions are calculated based on the natural gas consumed using the emission factors in *Compendium* Table 4-1 for CO_2 and Table 4-5 (natural gas turbines) for CH_4 and N_2O:

$$\text{CO}_2:\ 8{,}131{,}500\times10^6\ \text{Btu}\times\frac{0.0531\text{ tonnes CO}_2}{10^6\text{ BTU natural gas}}=431{,}782\text{ tonnes CO}_2$$

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EXHIBIT 4.13: Cogeneration Emissions Allocation – UK ETS Efficiency Allocation Approach, continued

$$CH_4:\ 8{,}131{,}500 \times 10^6\ \text{Btu} \times \frac{3.9 \times 10^{-6}\ \text{tonnes}\ CH_4}{10^6\ \text{BTU natural gas}} = 31.7\ \text{tonnes}\ CH_4$$

$$N_2O:\ 8{,}131{,}500 \times 10^6\ \text{Btu} \times \frac{1.4 \times 10^{-6}\ \text{tonnes}\ N_2O}{10^6\ \text{BTU natural gas}} = 11.4\ \text{tonnes}\ N_2O$$

$$CO_2\ \text{Eq.}:\ 431{,}782 + \left(31.7 \times \frac{21\ \text{tonnes}\ CO_2\ \text{Eq.}}{\text{tonnes}\ CH_4}\right) + \left(11.4 \times \frac{310\ \text{tonnes}\ CO_2\ \text{Eq.}}{\text{tonnes}\ N_2O}\right)$$
$$= 435{,}982\ \text{tonnes}\ CO_2\ \text{Eq.}$$

Step 2: Steam Thermal Equivalent

The total amount of steam generated from the cogeneration facility needs to be converted from a Btu basis to a megawatt-hr basis. Table 3-2 provides the conversion factor.

The steam thermal equivalent is then:

$$3{,}614{,}000 \times 10^6\ \text{Btu steam} \times \frac{2.931 \times 10^{-4}\ \text{kilowatt-hr}}{\text{Btu}} \times \frac{\text{meagwatt-hr}}{1000\ \text{kilowatt-hr}}$$

$$= 1{,}059{,}263\ \text{megawatt-hr/yr}$$

Step 3: Calculate Electricity and Steam Emission Factors

The third step is to apply the UK ETS equations (Equations 4-5 and 4-6) for allocating emissions between the electricity and steam energy to generate emission factors.

Electricity allocation:

$$\frac{2 \times CO_2\ \text{direct emissions (tonnes}\ CO_2)}{[2 \times \text{Electricity produced (megawatt-hr)}] + \text{Steam produced (megawatt-hr)}}$$
$$= \frac{2 \times 435{,}982\ \text{tonnes}\ CO_2\ \text{Eq.}}{[2 \times 1{,}100{,}600\ \text{megawatt} - \text{hr}_{\text{Electricity}}] + 1{,}059{,}263\ \text{megawatt-hr}_{\text{Steam}}}$$

$$= 0.267\ \text{tonnes}\ CO_2\text{Eq.}/\text{megawatt-hr}$$

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EXHIBIT 4.13: Cogeneration Emissions Allocation – UK ETS Efficiency Allocation Approach, continued

Steam allocation:

$$\frac{CO_2 \text{ direct emissions (tonnes } CO_2)}{[2 \times \text{Electricity produced (megawatt - hr)}] + \text{Steam produced (megawatt - hr)}}$$

$$= \frac{435{,}982 \text{ tonnes } CO_2 \text{ Eq.}}{[2 \times 1{,}100{,}600 \text{ megawatt} - \text{hr}_{\text{Electricity}}] + 1{,}059{,}263 \text{ megawatt - hr}_{\text{Steam}}}$$

$$= 0.134 \text{ tonnes } CO_2 \text{Eq. /megawatt - hr}$$

<u>Step 4: Allocate Emissions to Electricity and Steam</u>

The final step is to apply the emission factors to allocate emissions between electricity and steam used for energy onsite (direct emissions) and the exported electricity and steam (indirect emissions).

CO_2 Equivalent emissions for electricity sold to the refinery:

$$\frac{0.267 \text{ tonnes } CO_2}{\text{megawatt - hr electricity}} \times 206{,}000 \text{ megawatt - hr} = 55{,}002 \text{ tonnes } CO_2 \text{ Eq. (Direct)}$$

CO_2 Equivalent emissions for electricity sold to the grid:

$$\frac{0.267 \text{ tonnes } CO_2}{\text{megawatt - hr electricity}} \times 856{,}100 \text{ megawatt - hr} = 228{,}579 \text{ tonnes } CO_2 \text{ Eq. (Indirect)}$$

CO_2 Equivalent emissions for steam sold to the refinery:

$$2{,}710{,}000 \times 10^6 \text{ Btu steam} \times \frac{2.931 \times 10^{-4} \text{ kilowatt - hr}}{\text{Btu}} \times \frac{\text{megawatt - hr}}{1000 \text{ kilowatt - hr}}$$

$$= 794{,}301 \text{ megawatt - hr/yr}$$

$$\frac{0.134 \text{ tonnes } CO_2}{\text{MW - hr steam}} \times 794{,}301 \text{ MW - hr} = 106{,}436 \text{ tonnes } CO_2 \text{ Eq. (Direct)}$$

Accounting for round-off error, the sum of the emissions assigned to onsite and offsite steam and electricity should equal the total direct emissions from combustion. This is summarized in Table 4-14.

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Table 4-14. Summary of Cogeneration Emissions – UK ETS Efficiency Allocation Approach

	Emissions, tonnes CO_2 Eq.
Cogeneration Facility – Direct Emissions from Fuel Consumption	435,982
Refinery Emissions	
Purchased electricity	55,002
Purchased Steam	106,410
Emissions Associated with Electricity Sold to the Grid	228,579

Efficiency Allocation Approach - WRI/WBCSD

WRI/WBCSD presents a slightly different efficiency allocation approach. The equations associated with the WRI/WBCSD efficiency allocation approach are:

$$\text{Emissions}_{\text{Heat}} = \text{Emissions}_{\text{Total}} \times \frac{\dfrac{\text{Heat Output}}{\text{Efficiency}_{\text{Heat}}}}{\dfrac{\text{Heat Output}}{\text{Efficiency}_{\text{Heat}}} + \dfrac{\text{Electricity Output}}{\text{Efficiency}_{\text{Electricity}}}} \qquad \text{(Equation 4-7)}$$

and

$$\text{Emissions}_{\text{Total}} = \text{Emissions}_{\text{Heat}} + \text{Emissions}_{\text{Electricity}} \qquad \text{(Equation 4-8)}$$

where:

$\text{Emissions}_{\text{Total}}$ = total emissions from CHP plant
$\text{Emissions}_{\text{Heat}}$ = emissions share attributable to heat production
$\text{Emissions}_{\text{Electricity}}$ = emissions share attributable to electricity production
$\text{Efficiency}_{\text{Heat}}$ = assumed efficiency of typical heat production
$\text{Efficiency}_{\text{Electricity}}$ = assumed efficiency of typical power production

Heat Output and Electricity Output are reported in the same units (Joule, Btu or kilowatt-hr).

This approach is demonstrated in Exhibit 4.14. Note that this approach is also preferred by EPA's Climate Leaders Program (EPA, 2003).

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EXHIBIT 4.14: Cogeneration Emissions Allocation – WRI/WBCSD Efficiency Allocation Approach

INPUT DATA:
For the same scenario as described in the previous exhibit (Exhibit 4.13), this example applies the WRI/WBCSD Efficiency Allocation approach

The cogeneration facility consumes 8,131,500 million BTU of natural gas, producing 3,614,000 million BTU steam and 1,100,600 megawatt-hr of electricity (gross) on an annual basis. The refinery purchases 2,710,000 million Btu of steam and 206,000 megawatt-hr of electricity. The cogeneration facility itself requires 38,500 megawatt-hr to operate (Parasitic load), with the net electricity (856,100 megawatt-hrs) is sold to the electric grid.

For this example, the efficiency of steam generation is assumed to be 77% and the efficiency of the electricity generation is assumed to be 24%.

CALCULATION METHODOLOGY:

Step 1: Direct (On-site) Combustion Emissions from Cogeneration:
The total direct emissions are calculated as shown in Exhibit 4.13, resulting in 435,982 tonnes CO_2 equivalent emissions.

Step 2: Define Power and Heat Production on the Same Units
The electric power output from the cogeneration unit needs to be converted from a megawatt-hr basis to Btu. The conversion factor for is provided in Table 3-2.

$$1{,}100{,}600 \text{ megawatt-hr} \times \frac{1000 \text{ kilowatt-hr}}{\text{megawatt-hr}} \times \frac{\text{Btu}}{2.931 \times 10^{-4} \text{ kilowatt-hr}}$$
$$= 3.755 \times 10^{12} \text{ Btu (Electricity Output)}$$

Step 3: Calculate the Emissions Allocated to Steam
Estimate the emissions associated with the steam generation by applying Equation 4-7.

$$\text{Emissions}_{\text{Heat}} = 435{,}982 \text{ tonnes } CO_2 \text{ Eq.} \times \frac{\dfrac{3{,}614{,}000 \times 10^6 \text{ Btu}}{0.77}}{\dfrac{3{,}614{,}000 \times 10^6 \text{ Btu}}{0.77} + \dfrac{3.755 \times 10^{12} \text{ Btu}}{0.24}}$$

$$\text{Emissions}_{\text{Heat}} = 435{,}982 \text{ tonnes } CO_2 \text{ Eq.} \times 0.23076 = 100{,}607 \text{ tonnes } CO_2 \text{ Eq.}$$

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EXHIBIT 4.14: Cogeneration Emissions Allocation – WRI/WBCSD Efficiency Allocation Approach, continued

Step 4: Calculate the Emissions Allocated to Electricity
Applying Equation 4-8, the emissions allocated to electricity are calculated based on the difference between the total emissions and those allocated to steam.

435,982 tonnes CO_2 Eq. (Total) – 100,607 tonnes CO_2 Eq. (Heat)
= 335,374 tonnes CO_2 Eq. (Electricity)

Step 5: Allocate Emissions for Energy Exports
The total steam and electricity emissions can be estimated for exports based on the ratio of the total electricity and steam generated versus the energy sold.

CO_2 Equivalent Emissions for electricity sold to the refinery:

$$335{,}374 \text{ tonnes } CO_2 \text{ Eq. (Total Electricity)} \times \frac{206{,}000 \text{ megawatt-hr (Refinery)}}{1{,}100{,}600 \text{ megawatt-hr (Total)}}$$
$$= 62{,}772 \text{ tonnes } CO_2 \text{ Eq. (Refinery)}$$

CO_2 Equivalent Emissions for electricity sold to the grid:
335,374 tonnes CO_2 Eq. (Total Electricity) – 62,772 tonnes CO_2 Eq. (Refinery)
= 272,601 tonnes CO_2 Eq. (Grid)

CO_2 Equivalent Emissions for steam sold to the refinery:

$$100{,}607 \text{ tonnes } CO_2 \text{ Eq. (Total Heat)} \times \frac{2{,}710{,}000 \times 10^6 \text{ Btu (Refinery)}}{3{,}614{,}000 \times 10^6 \text{ Btu (Total)}}$$
$$= 75{,}441 \text{ tonnes } CO_2 \text{ Eq. (Refinery)}$$

The results for the allocation of emissions based on energy efficiency are shown in Table 4-15.

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Table 4-15. Summary of Cogeneration Emissions – WRI/WBCSD Efficiency Allocation Approach

	Emissions, tonnes CO_2 Eq.
Cogeneration Facility – Direct Emissions from Fuel Consumption	435,982
Refinery Emissions	
Purchased electricity	62,772
Purchased Steam	75,441
Emissions Associated with Electricity Sold to the Grid	272,601

California Climate Action Registry Efficiency Allocation Approach

The California Climate Action Registry (CCAR, 2003) attributes emissions to heat and electricity production based on a ratio of the energy produced for each type (heat or steam) to the total energy produced (net heat production plus electricity production), where each of the energy streams are expressed in the same units (Btu or Joules).

The equations associated with is approach are:

$$\text{Emissions}_{\text{Heat}} = \text{Emissions}_{\text{Total}} \times \frac{\text{Net Heat Production}}{\text{Net Heat Production} + \text{Electricity Production}}$$

(Equation 4-9)

and

$$\text{Emissions}_{\text{Electricty}} = \text{Emissions}_{\text{Total}} \times \frac{\text{Electricity Production}}{\text{Net Heat Production} + \text{Electricity Production}}$$

(Equation 4-10)

where:

$\text{Emissions}_{\text{Total}}$ = total emissions from CHP plant in tonnes
$\text{Emissions}_{\text{Heat}}$ = emissions share attributable to heat production in tonnes
$\text{Emissions}_{\text{Electricity}}$ = emissions share attributable to electricity production in tonnes

Net heat production refers to the useful heat that is produced in a CHP less the heat that returns to the boiler as steam condensate. Electricity production is the electrical energy output reported on the same units basis, either Btu or Joules, as heat production.

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This approach is similar to the WRI/WBCSD energy efficiency allocation method, accept that the California approach assumes the efficiency is the same for both net heat production and electricity production. An example is provided in Exhibit 4.15.

EXHIBIT 4.15: Cogeneration Emissions Allocation – California Climate Action Registry Efficiency Allocation Approach

INPUT DATA:
For the same scenario as described in the previous exhibits, this example applies the California Climate Action Registry approach.

The cogeneration facility consumes 8,131,500 million BTU of natural gas, producing 3,614,000 million BTU steam and 1,100,600 megawatt-hr of electricity (gross) on an annual basis. The refinery purchases 2,710,000 million Btu of steam and 206,000 megawatt-hr of electricity. The cogeneration facility itself requires 38,500 megawatt-hr to operate (Parasitic load), with the net electricity (856,100 megawatts) sold to the electric grid.

CALCULATION METHODOLOGY:

Step 1: Direct (On-site) Combustion Emissions from Cogeneration:
The total direct emissions are calculated as shown in Exhibit 4.13, resulting in 435,982 tonnes CO_2 equivalent emissions.

Step 2: Define Power and Heat Production on the Same Units
The electric power output from the cogeneration unit needs to be converted from a megawatt-hr basis to Btu. The conversion factor is provided in Table 3-2.

$$1{,}100{,}600\ \text{megawatt-hr} \times \frac{1000\ \text{kilowatt-hr}}{\text{megawatt-hr}} \times \frac{\text{Btu}}{2.931 \times 10^{-4}\ \text{kilowatt-hr}}$$
$$= 3.755 \times 10^{12}\ \text{Btu (Electricity Output)}$$

Step 3: Calculate the Emissions Allocated to Steam
Estimate the emissions associated with the steam generation by applying Equation 4-9.

$$\text{Emissions}_{\text{Heat}} = 435{,}982\ \text{tonnes}\ CO_2\ \text{Eq.} \times \frac{3{,}614{,}000 \times 10^6\ \text{Btu}}{3{,}614{,}000 \times 10^6\ \text{Btu} + 3.755 \times 10^{12}\ \text{Btu}}$$

$$\text{Emissions}_{\text{Heat}} = 435{,}982\ \text{tonnes}\ CO_2\ \text{Eq.} \times 0.49 = 213{,}820\ \text{tonnes}\ CO_2\ \text{Eq.}$$

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EXHIBIT 4.15: Cogeneration Emissions Allocation – California Climate Action Registry Efficiency Allocation Approach, continued

Step 4: Calculate the Emissions Allocated to Electricity
The emissions allocated to electricity are calculated based on Equation 4-10.

$$\text{Emissions}_{\text{Electricity}} = 435{,}982 \text{ tonnes } CO_2 \text{ Eq.} \times \frac{3.755 \times 10^{12} \text{ Btu}}{3{,}614{,}000 \times 10^{6} \text{ Btu} + 3.755 \times 10^{12} \text{ Btu}}$$

$$\text{Emissions}_{\text{Electricity}} = 435{,}982 \text{ tonnes } CO_2 \text{ Eq.} \times 0.51 = 222{,}162 \text{ tonnes } CO_2 \text{ Eq.}$$

Step 5: Allocate Emissions for Energy Exports
The total steam and electricity emissions can be divided among onsite and offsite usage based on the ratio of electricity and steam used onsite versus the energy sold for use offsite.

CO_2 Equivalent Emissions for electricity sold to the refinery:

$$222{,}157 \text{ tonnes } CO_2 \text{ Eq. (Total Electricity)} \times \frac{206{,}000 \text{ megawatt - hr (Refinery)}}{1{,}100{,}600 \text{ megawatt - hr Total}}$$
$$= 41{,}581 \text{ tonnes } CO_2 \text{ Eq. (Refinery)}$$

CO_2 Equivalent Emissions for electricity sold to the grid:
222,157 tonnes CO_2 Eq. (Total Electricity) – 41,581 tonnes CO_2 Eq. (Refinery)
= 180,576 tonnes CO_2 Eq. (Grid)

CO_2 Equivalent Emissions for steam sold to the refinery:

$$213{,}815 \text{ tonnes } CO_2 \text{ Eq. (Total Heat)} \times \frac{2{,}710{,}000 \times 10^{6} \text{ Btu (Refinery)}}{3{,}614{,}000 \times 10^{6} \text{ Btu Total}}$$
$$= 160{,}332 \text{ tonnes } CO_2 \text{ Eq. (Refinery)}$$

The results for the allocation of emissions based on energy efficiency are shown in Table 4-16.

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Table 4-16. Summary of Cogeneration Emissions – California Climate Action Registry Efficiency Allocation Approach

	Emissions, tonnes CO_2 Eq.
Cogeneration Facility – Direct Emissions from Fuel Consumption	435,982
Refinery Emissions	
Purchased electricity	41,582
Purchased Steam	160,335
Emissions Associated with Electricity Sold to the Grid	180,580

Work Potential Allocation Approach

This approach assigns the emissions to the energy streams in proportion to their contribution to the total work potential, or exergy. The work potential for steam is calculated from the specific enthalpy (H) and specific entropy (S) of the stream. This approach sums the work potential of all streams and allocates the total emissions to the individual streams.

As with the UK ETS method, the first step is to calculate the total direct CO_2 emissions from the combustion of natural gas at the cogeneration facility. The second step is to calculate the work potential of the steam, using 212 °F (100 °C) saturated water as the reference basis, and 700°F (371 °C) and 600 psia (4,137 kilo Pascal) for the process steam. The enthalpy and entropy of the steam can be determined from a steam table at the reference and actual conditions. The work potential of the steam is calculated using the following equations.

In US units:

$$\text{Steam work potential (Btu/lb)} = (H_i - H_{ref}) - (T_{ref} + 460) \times (S_i - S_{ref}) \qquad \text{(Equation 4-11)}$$

and in SI units:

$$\text{Steam work potential } (10^9 \text{ J/tonne}) = (H_i - H_{ref}) - (T_{ref} + 273) \times (S_i - S_{ref}) \qquad \text{(Equation 4-12)}$$

where:
H_i = specific enthalpy of the process steam (BTU/lb or 10^3 J/kilogram)
H_{ref} = specific enthalpy at the reference conditions (BTU/lb or 10^3 J/kilogram)
T_{ref} = reference temperature (R or K)
S_i = specific entropy of the process steam (BTU/lb R or 10^3 J/kilogram K)
S_{ref} = specific entropy at the reference conditions (BTU/lb R or 10^3 J/kilogram K)

The third step is to allocate the total emissions from the cogeneration facility in proportion to their work potential, as shown in Equation 4-13.

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$$CO_2 \text{ EF from electricity or steam (tonnes } CO_2\text{/megawatt - hr)} = \frac{CO_2 \text{ direct emissions (tonnes } CO_2\text{/yr)}}{\left[\text{Work potential}_{\text{steam}}\left(\frac{\text{megawatt - hr}}{\text{yr}}\right) + \text{Work potential}_{\text{electricity}}\left(\frac{\text{megawatt - hr}}{\text{yr}}\right)\right]}$$

(Equation 4-13)

This allocation approach is demonstrated in the following exhibit.

EXHIBIT 4.16: Cogeneration Emissions Allocation –Work Potential Allocation Approach

This example applies the WRI/WBCSD Work Potential approach to allocating emissions between steam and electricity for the same facility described in Exhibit 4.13.

The cogeneration facility consumes 8,131,500 million Btu of natural gas, producing 3,614,000 million Btu steam at 700 °F and 600 psia and 1,100,600 megawatt-hr of electricity (gross) on an annual basis. The refinery purchases 2,710,000 million Btu of steam and 206,000 MW-hr of electricity. The cogeneration facility itself requires 38,500 megawatt-hr to operate (Parasitic load), with the net electricity (856,100 megawatt-hrs) sold to the electric grid.

CALCULATION METHODOLOGY:

Step 1: Direct Emissions from Cogeneration:
Direct emissions are calculated as shown previously, resulting in 435,982 tonnes CO_2 Eq. emissions.

Step 2: Steam Work Potential
Steam work potential requires the enthalpy and entropy of the steam at both actual and reference conditions. These values can be determined using a steam table.

Enthalpy: Steam, 600 psia, 700 °F = 1,350 Btu/lb (H_i);
Saturated Water, 212 °F = 180 Btu/lb (H_{ref})

Entropy: Steam, 600 psia, 700 °F = 1.5872 Btu/lb-R (S_i);
Saturated Water, 212 °F = 0.31213 Btu/lb-R (S_{ref})

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EXHIBIT 4.16: Cogeneration Emissions Allocation –Work Potential Allocation Approach, continued

The work potential of the steam is then calculated using these values:

$$\text{Steam work potential (Btu/lb)} = (H_i - H_{ref}) - (T_{ref} + 460) \times (S_i - S_{ref})$$

$$= (1{,}350 - 180)\frac{\text{Btu}}{\text{lb}} - \left[(212 + 460)\text{R} \times (1.5872 - 0.31213)\frac{\text{Btu}}{\text{lb - R}}\right] = 313.2 \text{ Btu/lb}$$

In addition, the steam needs to be expressed on a mass basis to apply the work potential equations.

$$3{,}614{,}000 \times 10^6 \text{ Btu steam} \times \left(\frac{\text{lb steam}}{1{,}350 \text{ Btu}_{\text{steam conditions}} - 180 \text{ Btu}_{\text{reference conditions}}}\right)$$

$$= 3.089 \times 10^9 \text{ lbs steam}$$

Next, the mass of steam and the steam work potential are combined and converted to megawatt-hrs:

$$3.089 \times 10^9 \text{ lbs steam/yr} \times \left(\frac{313.2 \text{ Btu}}{\text{lb steam}}\right) \times \frac{2.931 \times 10^{-4} \text{ kilowatt - hr}}{\text{Btu}} \times \frac{\text{megawatt - hr}}{1000 \text{ kilowatt - hr}}$$

$$= 283{,}567 \text{ megawatt - hr/yr}$$

<u>Step 3: Calculate Electricity and Steam Emission Factors</u>
The third step is to apply Equation 4-13 for allocating emissions between the electricity and steam energy to generate emission factors.

Allocation =

$$\frac{\text{CO}_2 \text{ direct emissions (tonnes CO}_2\text{/yr)}}{\left[\text{Work potential}_{\text{steam}}\left(\frac{\text{megawatt - hr}}{\text{yr}}\right) + \text{Work potential}_{\text{electricity}}\left(\frac{\text{megawatt - hr}}{\text{yr}}\right)\right]}$$

$$= \frac{435{,}982 \text{ tonnes CO}_2 \text{ Eq.}}{283{,}567 \text{ megawatt - hr}_{\text{steam}} + 1{,}100{,}600 \text{ megawatt - hr}_{\text{electricity}}} = 0.315 \text{ tonne CO}_2 \text{ Eq./megawatt - hr}$$

<u>Step 4: Apply Emission Factor to Estimate Emissions</u>
The emissions associated with exported electricity and steam are determined by applying the appropriate MW-hrs to this emission factor.

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EXHIBIT 4.16: Cogeneration Emissions Allocation –Work Potential Allocation Approach, continued

CO_2 Equivalent Emissions for electricity sold to the refinery:

$$\frac{0.315 \text{ tonnes } CO_2}{\text{megawatt - hr electricity}} \times 206{,}000 \text{ megawatt - hr} = 64{,}890 \text{ tonnes } CO_2 \text{ Eq. (Refinery)}$$

CO_2 Equivalent Emissions for electricity sold to the grid:

$$\frac{0.315 \text{ tonnes } CO_2}{\text{megawatt - hr electricity}} \times 856{,}100 \text{ megawatt - hr} = 269{,}672 \text{ tonnes } CO_2 \text{ Eq. (Grid)}$$

CO_2 Equivalent Emissions for steam sold to the grid:

$$2{,}710{,}000 \times 10^6 \text{ Btu steam} \times \frac{283{,}567 \text{ megawatt - hr/yr}}{3{,}614{,}000 \times 10^6 \text{ Btu steam}} = 212{,}636 \text{ megawatt - hr/yr}$$

$$\frac{0.315 \text{ tonnes } CO_2}{\text{megawatt - hr steam}} \times 212{,}636 \text{ megawatt - hr} = 66{,}980 \text{ tonnes } CO_2 \text{ Eq. (Indirect)}$$

Table 4-17 summarizes the results for the work potential method.

Table 4-17. Summary of Cogeneration Emissions – Work Potential Allocation Approach

	Emissions, tonnes CO_2 Eq.
Cogeneration Facility – Direct Emissions from Fuel Consumption	435,982
Refinery Emissions	
Purchased electricity	64,890
Purchased Steam	66,980
Emissions Associated with Electricity Sold to the Grid	269,672

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