APPENDIX D

METHODOLOGY FOR DETERMINING EMISSION REDUCTIONS AND COST-EFFECTIVENESS

Capture and Control System for Oil Tankers

Transportation and Toxics Division
California Air Resources Board
September 2, 2020

Cap and Trade Dollars at Work

CALIFORNIA CLIMATE INVESTMENTS

CALIFORNIA AIR RESOURCES BOARD

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ABBREVIATIONS

The following abbreviations are used in this appendix:

"AE" means annual emissions.
"AQIP" means the Air Quality Improvement Program.
"ATV" means advanced technology vehicle or piece of equipment.
"bhp-hr" means brake-horsepower-hour.
"CARB" means the California Air Resources Board.
"CCI" means California Climate Investments.
"CI" means carbon intensity.
"CO2e" means carbon dioxide equivalent.
"CNG" means compressed natural gas.
"CRF" means capital recovery factor.
"ED" means fuel energy density.
"EER" means energy economy ratio.
"EF" means emission factor.
"ER" means emission reduction.
"g/bhp-hr" means grams per brake-horsepower-hour.
"gal" means gallon.
"GHG" means greenhouse gas.
"HC" means hydrocarbon.
"hp" means horsepower.
"kg" means kilogram.
"kWh" means kilowatt-hour.
"MJ" means megajoule.
"NMHC" means non-methane hydrocarbon.
"NOx" means oxides of nitrogen.
"OGV" means ocean-going vessel.
"PM" means particulate matter.
"PM10" means particulate matter less than 10 microns in diameter.
"ROG" means reactive organic gases.
"scf" means standard cubic foot.
"WER" means weighted surplus emission reduction.
"yr" means year.

Overview

The methodology described within this appendix must be used to calculate the emission reductions and cost-effectiveness of projects proposed under this Solicitation. All calculations and assumptions made must be shown clearly and in their entirety in the application. All calculations will use the cleanest commercially available diesel-fueled engine for determining baseline emission rates of greenhouse gas (GHG) and criteria pollutant emissions for any vehicle, vessel, or pieces of equipment proposed to be used as part of the project. As an example, a baseline capture and control system would use conventional diesel fuel and not route its own emissions through the unit to control its own emissions. This baseline technique may not adequately capture the emission profiles of all the vessels or equipment included in an application; however, to ensure all applications are scored on an objective basis, this technique will be used for scoring all submitted applications.

A "well-to–wheel" analysis to quantify GHG emission reductions is required for all vessels or equipment funded under this Solicitation. The applicant is required to determine the resulting emission reductions associated with their project. All emission reductions are associated with the use of advanced technology vehicles only and not the supporting infrastructure. All calculations must be shown in their entirety and included in the application. Incomplete illustration of the mathematical processes used could result in reduced or no points being allocated for scoring criteria related to emission reductions and cost-effectiveness. If the applicant believes that the methodology for determining emission reductions and cost-effectiveness does not accurately represent the emission potential of the proposed project, the applicant may submit, in addition to using the required methodology as outlined above, an alternative methodology for determining emission benefits and cost-effectiveness to illustrate the potential emission reductions of the proposed technology or strategy that the applicant is proposing. Regardless of inclusion of an alternate methodology, the applicant must still utilize the required methodology as outlined in Appendix D and required under Appendix A, Attachment 3. Projects will only be scored based on the required methodology for determining emission reductions and cost-effectiveness. The GHG emission factors used in this appendix are excerpted from the CCI Quantification Methodology Emission Factor Database dated Augusts 27, 2020[1]. The remaining emission factors and methodology are from the approved 2017 Carl Moyer Program Guidelines (2017 Moyer Guidelines), as updated in 2017[2]. If an applicant's proposed project uses fuels or technologies that are not anticipated by this appendix

[1] CCI Quantification Methodology Emission Factor Database. https://ww2.arb.ca.gov/resources/documents/cci-quantification-benefits-and-reporting-materials
[2] 2017 Carl Moyer Program Guidelines. https://ww3.arb.ca.gov/msprog/moyer/guidelines/current.htm

the applicant may use emission factors that are found in the CCI Quantification Methodology Emission Factor Database and the Moyer Guidelines only. Please note that while emission factors may change during the Solicitation period, project applicants must use the values listed in this appendix.

The GHG Emission Calculation Section of this appendix provides the formulas that are needed to calculate the emission reductions and the cost-effectiveness for proposed projects. Please see the example calculations provided in the Example Calculations Section of this Appendix to better understand how the following formulas are used to calculate emission reduction and cost-effectiveness values. Any examples provided herein are for reference only and do not imply additional project types or categories, nor do 2017 Moyer Program funding amounts limit the amount of funding that may be available for projects funded under this Solicitation. While Carl Moyer Program guidelines may change during the Solicitation period, project applicants must use the values listed in this appendix or Appendix C of the 2017 Moyer Program Guidelines.

GHG Emission Calculations[3]

A. Well-to-Wheel GHG Emission Calculations

The amount of fuel used in the baseline vehicle must be determined. Formula 1 is used to calculate the amount of fuel that is being consumed by the baseline vehicle. The output from Formula 1 will be used in other formulas, such as Formula 2. Formula 8 can be used to modify the result of Formula 1 to account for advanced technology systems that provide an incremental improvement in vehicle efficiency.

Formula 1 should be used to determine the fuel usage for the baseline piece of equipment based on hours of operation and the fuel usage of the baseline piece of equipment.

Formula 1: Annual Fuel Usage

$$Fuel\ Usage\left(\frac{gal}{year}\right) = \left(\frac{gal}{hour}\right) * \left(\frac{hours}{day}\right) * \left(\frac{days}{year}\right)$$

Formula 2 calculates the greenhouse gas emission factor (*GHG EF*) using the carbon intensity (CI) of the fuel, the fuel's energy density, and the annual fuel usage (Formula 1) for the technology employed in the vehicle or piece of equipment.

Formula 2: GHG Emission Factor Based on Fuel Usage

$$GHG\ EF\left(\frac{metric\ \ tons\ \ CO2e}{year}\right) = CI * fuel\ energy\ density * fuel\ usage * \frac{1\ metric\ \ ton\ \ CO2e}{1{,}000{,}000\ grams}$$

$$= \left(\frac{gram\ \ CO2e}{MJ}\right) * \left(\frac{MJ}{gal}\ or\ \frac{MJ}{kg}\ or\ \frac{MJ}{scf}\ or\ \frac{MJ}{kWh}\right) * \left(\frac{gal}{year}\ or\ \frac{kg}{year}\ or\ \frac{scf}{year}\ or\ \frac{kWh}{year}\right) * \left(\frac{1\ metric\ \ ton\ \ CO2e}{1{,}000{,}000\ grams}\right)$$

Where:

- *CI* is the carbon intensity of the fuel (see Values for Calculations section).

[3] GHG emission factors are from the CCI Quantification Methodology Emission Factor Database, available at: https://www.arb.ca.gov/cc/capandtrade/auctionproceeds/cci_emissionfactordatabase.xlsx

B. Conversion from Diesel Fuel Usage to Electricity / Hydrogen / CNG Usage

Formula 3 is used to calculate the advanced technology vehicle (ATV) fuel usage based on the diesel usage of the baseline vehicle or equipment calculated from Formula 2.

Formula 3: Advanced Technology Vehicle Fuel Usage

$$ATV\ Fuel\ Usage\left(\frac{unit}{year}\right) = Baseline\ fuel\ usage * ED_{diesel} * \left(\frac{1}{ED_{replacement\quad fuel}}\right) * \left(\frac{1}{EER}\right)$$

Where:

- ***ED*** is the fuel energy density (see Values for Calculations section);
- ***EER*** is the Energy Economy Ratio value for fuels relative to diesel (see Values for Calculations section); and
- ***Unit*** is the units associated with the replacement fuel. Electricity usage is in units of kWh, hydrogen is in kg, and CNG is in standard cubic feet (scf).

C. GHG Emission Reduction Calculation

The project's GHG emission reduction value is determined by taking the difference between the GHG emissions of the baseline vehicle or equipment and the advanced technology vehicle or equipment.

Baseline vehicles or equipment are those using the cleanest engines commercially available at the time the application for funding is submitted, which for the purposes of this solicitation is a heavy-duty on-road engine certified for the 2020 Model Year, even if the actual baseline vehicle or piece of equipment used in a proposed project is a different model year. If a TRU is being proposed as part of the project, the baseline engine will be a U.S. E.P.A Tier-4 final off-road diesel engine.

Formula 4 is used to determine the annual GHG emission reductions ($GHG\ ER_{annual}$) associated with the ATV.

Formula 4: Annual GHG Emission Reductions from Advanced Technology Vehicle

$$ATV\ GHG\ ER_{annual}\left(\frac{metric\ tons\ CO2e}{year}\right) = GHG\ EF_{base} - GHG\ EF_{ATV}$$

Where:

- $ATV\ GHG\ ER_{annual}$ is the annual GHG emission reductions that are associated with the one of the proposed projects vehicles;
- $GHG\ EF_{base}$ is the GHG emissions associated with the baseline vehicle that the advanced technology vehicle is compared against; and
- $GHG\ ER_{ATV}$ is the GHG emissions that is associated with the proposed advanced technology vehicle.

D. Cost-Effectiveness Calculations for GHG

The cost-effectiveness of a project is determined by dividing the annualized cost of the potential project by the annual emission reductions that will be achieved by the project, as shown in Formula 5 below.

Formula 5 is used to determine the cost-effectiveness of the project in dollars per ton of emissions reduced.

Formula 5: GHG Cost-Effectiveness

$$Cost\text{–}Effectiveness\left(\frac{annualized\ cost\ \$}{metric\ ton\ reduced}\right) = \frac{CRF * Incremental\ Cost}{Project\ GHG\ ER_{annual}}$$

Where:

- ***Metric ton reduced*** is the amount of GHG emissions reduced for one year
- ***CRF*** is the Capital Recovery Factor (see Values for Calculations section);
- ***Incremental Cost*** is the difference between the cost of the baseline vehicle or equipment and the advanced technology vehicle or equipment (result from Formula 6);
- ***Project GHG*** ER_{annual} is the calculated annual emission reduction in metric ton of CO2e (result from Formula 4).

Incremental cost is determined by subtracting the cost of a baseline vehicle from the cost from the advanced technology vehicle. Formula 6 is used to determine incremental cost.

Formula 6: Incremental Cost of Advanced Technology Vehicle

$$Incremental\ Cost = Cost\ of\ ATV - Cost\ of\ Baseline\ Vehicle$$

E. Composite Carbon Intensity Calculations

Formula 7 below is used to determine a composite carbon intensity value in the calculations if two of the same fuel types are to be blended for use in the proposed vehicle or equipment. Use Carbon Intensities from the Values for Calculations section as inputs into Formula 7.

Formula 7: Composite Carbon Intensity

$$CI_{composite} = (fraction\ of\ total\ fuel * CI_{fuel\ 1}) + (fraction\ of\ total\ fuel * CI_{fuel\ 2})$$

F. Advanced Technology Efficiency Calculation

Technologies such as advanced aerodynamic trailers or Intelligent Transportations Systems can provide incremental decreases in truck energy usage. Formula 8 should be used to determine the amount of fuel per year necessary to operate an advanced technology vehicle or equipment that has included a technology to provide a percent efficiency improvement. Use results from Formula 1 to determine the annual fuel usage for the baseline vehicle or equipment and then use the resultant of Formula 8 as an input for Formula 2.

Formula 8: Annual Fuel Usage of Advanced Technology Vehicle with Efficiency Improvement

$$Fuel\ Usage_{ATV}\left(\frac{gal}{year}\right) = fuel\ usage * \left(1 - \frac{(X * Y\%\ improvement)}{100\%}\right)$$

Where:

- ***X*** is the fraction of the time the advanced operational efficiency technology or logistic strategy is enabled and providing emission reductions. If the advanced operational efficiency technology is always engaged and providing emission reductions, assume that X is equal to 1; and
- ***Y*** is the percentage fuel economy improvement that is gained by having the advanced operational efficiency technology or logistic strategy efficiency improvement over the baseline engine.

Criteria Pollutant Calculations

This section provides the formulas that are needed to calculate the criteria pollutant emissions results and cost-effectiveness for proposed projects, which are necessary to submit a successful application. Inputs for criteria pollutant cost-effectiveness calculations are taken from Appendix C of the 2017 Moyer Guidelines. Updates to these Guidelines may have been made since the release of this Solicitation. However, applicants may only use the information included in the 2017 Moyer Guidelines for criteria pollutant emission reduction and cost-effectiveness calculations in response to this solicitation.

Baseline vessels or equipment for the purpose of this Solicitation contains the cleanest engines commercially available at the time the application for funding is submitted. Further, for the purpose of this solicitation a baseline capture and control system would be powered by a US EPA Tier-4 final off-road conventionally diesel fueled engine with emission from that engine not being routed through the capture and control system.

A. Calculating Emission Reductions

Criteria pollutant emissions are determined by multiplying the emission factor found in the Values for Calculations section of this appendix by the amount of fuel that is being consumed by the baseline vehicle. The criteria pollutant emissions from the advanced technology vehicle or piece of equipment is then subtracted from the baseline vehicle's emissions to determine the criteria pollutant emission reduction from the advanced technology vehicle. Criteria pollutant emissions are determined on a tank-to-wheel basis; therefore, zero-emission tailpipe technologies have no criteria pollutant emissions.

Fuel usage from Formula 1 Annual Fuel Usage, is multiplied by the Criteria Pollutant Emission Factors given in the Values for Calculations Section of this appendix and converted from metric to standard units.

Formula 9 is used to determine the annual emission reductions for each of the three criteria pollutant species that are required to be included in an application for funding.

Formula 9: Estimated Annual Emissions based on Hours of Operation

$$AE_{critieria} = EF * usage * horsepower * load\ factor * \left(\frac{1\ ton}{907{,}200\ g}\right)$$

Alternatively, to calculate emissions from ocean-going vessels (OGV), use Formula 10 for each of the three criteria pollutant species.

Formula 10: Annual Criteria Emissions from Baseline OGVs at Berth for Known Engine and Boiler Effective Power

$$E_{OGV,Criteria} = \frac{ED}{D} \times AA \times \frac{\left(EF_{AuxEng} * FC_{AuxEng} * EP_{AuxEng} + EF_{Boiler} * FC_{Boiler} * EP_{Boiler}\right)}{EER_i}$$

Where:

- $E_{OGV,Critieria}$ is the annual criteria emissions of the baseline OGV at berth or shore power system (g/yr);
- EF_{AuxEng} is the emission factor of the baseline OGV auxiliary engines at berth (g/MJ);
- EF_{Boiler} is the emission factor of the baseline OGV boilers at berth (g/MJ);
- *ED* is the energy density of diesel (MJ/gal);
- *D* is the density of diesel (g_{dsl}/gal);
- *AA is the* annual activity of the shore power system (hr/yr);
- FC_{AuxEng} is the fuel consumption rate of the baseline OGV auxiliary engines (g_{dsl}/kWh);
- EP_{AuxEng} is the effective power of the baseline OGV auxiliary engines (kW);
- FC_{Boiler} is the fuel consumption rate of the baseline OGV boilers (g_{dsl}/kWh);
- EP_{Boiler} is the effective power of the baseline OGV boilers (kW); and
- EER_i is the energy economy ratio of the baseline or shore power system relative to diesel.

The amount of annual emission reductions is then determined using Formula 11.

Formula 11: Annual Emission Reductions

$$Criteria\ AE = AE_{base} - AE_{advanced\ \ technology}$$

B. Calculating the Weighted Emission Reduction

Annual weighted emission reductions (WER) are determined by taking the sum of the project's annual criteria pollutant reductions following Formula 12 below, using the result of Formula 11. While NOx and ROG emissions are given equal weight, emissions of PM carry a greater weight in the calculation.

Formula 12: Annual Weighted Surplus Emission Reductions

$$WER = NOx\ Reductions\ \left(\frac{tons}{year}\right) + ROG\ Reductions\ \left(\frac{tons}{year}\right) + \left(20 *\ PM\ Reductions\ \left(\frac{tons}{year}\right)\right)$$

C. Calculating Cost-Effectiveness

The cost-effectiveness of a potential project is determined by dividing the annualized cost of the project by the annual weighted emission reductions that will be achieved by the project, as shown in Formula 13 below.

Formula 13: Cost-Effectiveness of Weighted Surplus Emission Reductions

$$Cost\ Effectiveness\ \left(\frac{\$}{WER\ ton}\right) = \frac{CRF * Incremental\ Cost}{WER}$$

Where:

- ***WER ton*** is a ton of weighted emission reductions of criteria pollutant emissions on an annual basis;
- ***CRF*** is the Capital Recovery Factor (see Values for Calculations);
- ***Incremental Cost*** is the result from Formula 6; and
- ***WER*** is the calculated annual emission reduction in ton of criteria pollutant (result from Formula 12).

Example Calculations

Example calculations are provided to illustrate the typical calculations that staff expects may be included in an application for funding. Example calculations are included for three scenarios, providing the ten values that are needed for a complete application. Those required values are:

- GHG annual emission reductions from each proposed piece of equipment or vessel;
- Criteria pollutant and toxic air contaminant annual pollutant emission reductions for each proposed piece of equipment or vessel;
- GHG reduction cost-effectiveness for a two-year life during the time of the proposed project for each piece of equipment or vessel;
- GHG reduction cost-effectiveness for a 10-year life, two years after the end of the proposed project for each piece of equipment or vessel, assuming the technology being proposed is fully commercialized and integrated into the marketplace at numbers described in the application;
- Criteria pollutant and toxic air contaminant reduction cost-effectiveness for a two-year life during the time of the proposed project;
- Criteria pollutant and toxic air contaminant reduction cost-effectiveness for a 10-year life, two years after the end of the proposed project for each piece of equipment or vessel, assuming the technology being proposed is fully commercialized and integrated into the marketplace at numbers described in the application;
- GHG reduction cost-effectiveness for an entire proposed project, during the time of the proposed project, assuming a two-year life;
- Criteria pollutant and toxic air contaminant reduction cost-effectiveness for an entire proposed project during the time of the proposed project, assuming a two-year life;
- GHG reduction cost-effectiveness for an entire proposed project, during the time of the proposed project, assuming a ten-year life, assuming the technology being proposed is fully commercialized and integrated into the marketplace at numbers described in the application; and
- Criteria pollutant and toxic air contaminant reduction cost-effectiveness for an entire proposed project during the time of the proposed project, assuming a ten-year life, assuming the technology being proposed is fully commercialized and integrated into the marketplace at numbers described in the application.

A. Example 1: Barge-Based Capture and Control System

Potential GHG emission reductions are determined on a well-to-wheel basis, while criteria pollutant emission reductions are determined on a tank-to-wheel basis. This example assumes that an OGV capture and control system is set up on a barge to be towed by a tugboat to an oil tanker. The oil tanker is moored at the discharge wharf. In this example, a tugboat is used to position the barge at the start of the off-load and after the off-load is completed. The tugboat is a conventionally fueled vessel and therefore no emission reductions will be attributed to it, however its emissions and costs must be determined. The off-loading will take 40 hours.

Example Oil Tanker Monroe:

- Oil Tanker – VLCC size
    - Auxiliary engines are IMO-Tier-1
- Fuel Usage: Distillate with a 0.1% Sulfur content
- Spends 40 hours off-loading cargo at typical ports

Capture and Control System Operation:

- 80% criteria pollutants control efficiency
- Diesel fueled generator USEPA Tier-4 final, 500 hp
- Will use renewable diesel which costs 0.25$ per gallon more than conventional diesel
- Consumes 8 gallons per hour of operation
- Will be used 41 hours per off-loading event for a total of 290 hours per year servicing 7 vessel off-loads
- Each off-loading event takes 40 hours with 30 minutes of warm up and cool down before and after each operation (totaling 41 hours)
- Load factor for an off-road generator is 0.34
- Cost of baseline system and advanced technology system are equal at $7,000,000 during the proposed project
- Cost of baseline system and advanced technology system are equal at $6,500,000 two years after the end of the project

Tugboat:

- Two 800 hp main engines US EPA Tier-3
- 350 hp auxiliary engine US EPA Tier-3
- Consumes 40 gallons of diesel per hour of barge operations
- Costs for tugboat usage is $1000 per hour of operation
- Tugboat will be used for 8 hours for each vessel off-load event, equaling 168 hours of operations per year
- Load factor for a tugboat is 0.50

Variables Used in Calculation:

Carbon Intensity

From Values for Calculations section

CI = Carbon Intensity

$$CI_{diesel} = 100.45 \frac{g\ CO2e}{MJ}\ ;\ CI_{renewable\ \ diesel} = 34.62 \frac{g\ CO2e}{MJ}$$

Energy Density

From Values for Calculations section

ED = Energy Density

$$ED_{diesel} = 134.47 \frac{MJ}{gal\ diesel}\ ; ED_{renewable\ \ diesel} = 129.65 \frac{MJ}{gal\ diesel}\ ; ED_{electricity} = 3.60\ \frac{MJ}{kWh}$$

Tugboat:

A tugboat is required to position the barge system alongside the oil tanker and to remove the barge system at the end of the off-load event. It is estimated that the tugboat will be used for a total of 8 hours for each off-load event. Emissions from the tugboat will be determined, however, there are no emission reductions associated with the tugboat in this example. If a project proposes to use an advanced technology tugboat or a self-propelled barge, the emissions from the advanced technology tugboat or self-propelled barge would be subtracted from the baseline tugboat emissions using the example below.

First, the amount of fuel consumed by the tugboat during barge operations needs to be determined.

Step 1: Calculate the tugboat's annual fuel usage using Formula 1:

Formula 1: Annual Fuel Usage

$$Fuel\ Usage\ \left(\frac{gal}{year}\right) = \left(\frac{gal}{hour}\right) * \left(\frac{hours}{day}\right) * \left(\frac{days}{year}\right)$$

$$Fuel\ Usage_{tug\ ,baseline} = \left(\frac{40\ gallons}{hour}\right) * \left(\frac{8\ hours}{day}\right) * \left(\frac{21\ days}{year}\right) = 6720\ \frac{gallons\ diesel}{year}$$

Step 2: Determine the GHG emissions that are attributed to the tugboat. Using Formula 2 and the variables identified above.

Formula 2: GHG Emission Factor Based on Fuel Usage

$$GHG\ EF\left(\frac{metr\ ic\ tons\ CO2e}{year}\right) = CI * fuel\ energy\ density * fuel\ usage * \frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}$$

$$= \left(\frac{gram\ CO2e}{MJ}\right) * \left(\frac{MJ}{gal}\ or\ \frac{MJ}{kg}\ or\ \frac{MJ}{scf}\ or \frac{MJ}{kWh}\right) *$$

$$\left(\frac{gal}{year}\ or\ \frac{kg}{year}\ or\ \frac{scf}{year}\ or \frac{kWh}{year}\right) * \left(\frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}\right)$$

$$GHG\ EF = 100.45\frac{g\ CO2e}{MJ} * 134.47\frac{MJ}{gal\ diesel} * 6720\ \frac{gallons\ diesel}{year} * \frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}$$

$$GHG\ EF_{tug} = 91\frac{metric\ tons\ CO2e}{year}$$

Step 3: Determine the annual criteria and toxic pollutant emissions that are associated with the tugboat. The tugboat has two 4,000 horsepower Tier-3 engines installed. The tugboat is conventionally fueled and contains no advanced technologies to reduce emissions. Thus, there are no emission reductions associated with the tugboat.

Use Formula 9 to calculate the criteria pollutant emissions from the tugboat based on usage.

Formula 9: Estimated Annual Emissions based on Hours of Operation

$$AE_{criteria} = EF * usage * horsepower * load\ factor * \left(\frac{1\ ton}{907{,}200\ g}\right)$$

For a Tier-3 marine engine, the following emission factors are used for criteria pollutants:

$$NOx = 4.14\frac{g\ NOx}{bhp-hr}\ ;\ ROG = 0.49\frac{g\ ROG}{bhp-hr}\ ;\ PM10 = 0.085\frac{g\ PM10}{bhp-hr}$$

$$AE_{tug\ ,NOx} = 4.14\frac{g\ NOx}{bhp-hr} * 168\frac{hours}{year} * (2 * 800\ hp) * (0.50) * \left(\frac{1\ ton}{907{,}200\ g}\right) = 0.61\ \frac{ton\ NOx}{year}$$

$$AE_{tug\ ,ROG} = 0.49\frac{g\ ROG}{bhp-hr} * 168\frac{hours}{year} * (2 * 800\ hp) * (0.50) * \left(\frac{1\ ton}{907{,}200\ g}\right) = 0.073\frac{ton\ ROG}{year}$$

$$AE_{tug\ ,PM} = 0.085\ \frac{g\ PM}{bhp-hr} * 168\frac{hours}{year} * (2 * 800\ hp) * (0.50) * \left(\frac{1\ ton}{907{,}200\ g}\right) = 0.0013\frac{ton\ PM10}{year}$$

Capture and Control System Operation:

Step 4: Determine the GHG emissions associated with using the capture and control system. GHG emission reductions from the capture and control system itself is only coming from the use of renewable diesel fuel. The capture and control system will also capture and control the emissions from the system at an 80% control efficiency.

First, calculate the amount of diesel fuel that will be used by the generator system that is supplying power to the capture and control system. Since the off-load event can span more than one day and with the understanding that the system will be used for 290 hours per year, Formula 1 can be modified by combining the usage per day and the number of days of usage per year to give the number of hours of usage per year.

Formula 1: Annual Fuel Usage

$$Fuel\ Usage\ \left(\frac{gal}{year}\right) = \left(\frac{gal}{hour}\right) * \left(\frac{hours}{day}\right) * \left(\frac{days}{year}\right)$$

$$Fuel\ Usage_{C\&C,baseline} = \left(8\ \frac{gallons}{hour}\right) * \left(290\ \frac{hours}{year}\right) = 2{,}320\ \frac{gallons\ diesel}{year}$$

Step 5: Calculate the amount of GHG emissions that are associated with the baseline capture and control system using Formula 2.

Formula 2: GHG Emission Factor Based on Fuel Usage (Baseline)

$$GHG\ EF\left(\frac{metric\ tons\ CO2e}{year}\right) = CI * fuel\ energy\ density * fuel\ usage * \frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}$$

$$= \left(\frac{gram\ CO2e}{MJ}\right) * \left(\frac{MJ}{gal}\ or\ \frac{MJ}{kg}\ or\ \frac{MJ}{scf}\ or\ \frac{MJ}{kWh}\right) *$$

$$\left(\frac{gal}{year}\ or\ \frac{kg}{year}\ or\ \frac{scf}{year}\ or\ \frac{kWh}{year}\right) * \left(\frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}\right)$$

$$GHG\ EF_{C\&C,baseline} = \left(100.45\frac{g\ CO2e}{MJ}\right) * \left(134.47\frac{MJ}{gal\ diesel}\right) * \left(2{,}320\ \frac{gallons\ diesel}{year}\right) * \left(\frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}\right)$$

$$GHG\ EF_{C\&C,baseline} = 31.3\ \frac{metric\ tons\ CO2e}{year}$$

Step 6: Calculate the amount of GHG emissions that are associated with the proposed capture and control system using Formula 2 and the CI and ED for renewable diesel fuel found in the Values for Calculations section.

Formula 2: GHG Emission Factor Based on Fuel Usage (Advanced Technology)

$$GHG\ EF\left(\frac{metric\ tons\ CO2e}{year}\right) = CI * fuel\ energy\ density * fuel\ usage * \frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}$$

$$= \left(\frac{gram\ CO2e}{MJ}\right) * \left(\frac{MJ}{gal}\ or\ \frac{MJ}{kg}\ or\ \frac{MJ}{scf}\ or\ \frac{MJ}{kWh}\right) * \left(\frac{gal}{year}\ or\ \frac{kg}{year}\ or\ \frac{scf}{year}\ or\ \frac{kWh}{year}\right) * \left(\frac{1\ metric\ ton\ CO2e}{1{,}000{,}000\ grams}\right)$$

$$GHG\ EF_{C\&C,ATV} = \left(34.62\frac{g\ CO2e}{MJ}\right) * \left(129.65\frac{MJ}{gal}\right) * \left(2320\frac{gal\ diesel}{year}\right) * \left(\frac{1\ metric\ ton}{1{,}000{,}000\ g}\right)$$

$$GHG\ EF_{C\&C,ATV} = 10.4\frac{metric\ tons}{year}$$

Step 7: Determine the amount of GHG emission reductions that are associated with the use of the proposed capture and control system.

Formula 4: Annual GHG Emission Reductions from Advanced Technology Piece of Equipment

$$Project\ GHG\ ER_{C\&C,annual} = GHG\ EF_{C\&C,baseline} - GHG\ EF_{C\&C,ATV}$$

$$Project\ GHG\ ER_{C\&C,annual} = \left(31.3\frac{metric\ tons\ CO2e}{year}\right) - \left(10.4\frac{metric\ tons\ CO2e}{year}\right)$$

$$= 20.9\frac{metric\ tons\ CO2e}{year}$$

Therefore, the use of the capture and control system with renewable diesel fuel would provide 20.9 metric tons of GHG in emission reductions over the course of one year of operation.

Step 8: Determine the criteria pollutant emissions that are associated with the baseline capture and control system without routing the emissions through the capture and control system. There is a Tier-4 final diesel off-road engine that is being used to supply electricity to the capture and control system, therefore:

Formula 9: Estimated Annual Emissions based on Hours of Operation

$$AE_{C\&C,critieria} = EF * usage * horsepower * load\ factor * \left(\frac{1\ ton}{907{,}200\ g}\right)$$

For a Tier-4 off-road engine, the following emission factors are used for criteria pollutants:

$$NOx = 0.26\frac{g\ NOx}{bhp-hr}\ ;\ ROG = 0.05\frac{g\ ROG}{bhp-hr}\ ;\ PM10 = 0.009\frac{g\ PM10}{bhp-hr}$$

A diesel fueled generator has a typical load factor of 0.34.

$$AE_{C\&C,NOx} = 0.26 \frac{g\ NOx}{bhp-hr} * 290 \frac{hours}{year} * (500\ hp) * (0.34) * \left(\frac{1\ ton}{907{,}200\ g}\right) = 0.014\ \frac{ton\ NOx}{year}$$

$$AE_{C\&C,ROG} = 0.05 \frac{g\ ROG}{bhp-hr} * 290 \frac{hour\ s}{year} * (500\ hp) * (0.34) * \left(\frac{1\ ton}{907{,}200\ g}\right) = 0.0027 \frac{ton\ ROG}{year}$$

$$AE_{C\&C,PM} = 0.009\ \frac{g\ PM}{bhp-hr} * 290 \frac{hours}{year} * (500\ hp) * (0.34) * \left(\frac{1\ ton}{907{,}200\ g}\right) = 0.00049 \frac{ton\ PM}{year}$$

Step 9: Determine the criteria pollutant emission reductions that are associated with routing the off-road engine emissions through the capture and control system. Since the capture and control system has an 80% criteria pollutant control efficiency, the emissions from the baseline capture and control system should be multiplied by the fraction of emissions that are captured by the system.

$$ER_{C\&C,NOx} = 0.014 \frac{tons\ NOx}{year} * 0.80\ control\ efficiency = 0.011 \frac{tons\ NOx}{year}\ reduced$$

$$ER_{C\&C,ROG} = 0.0027 \frac{tons\ ROG}{year} * 0.80\ control\ efficiency = 0.0022 \frac{tons\ ROG}{year}\ reduced$$

$$ER_{C\&C,PM} = 0.00049 \frac{tons\ PM}{year} * 0.80\ control\ efficiency = 0.00039 \frac{tons\ PM}{year}\ reduced$$

Step 10: Determine the weighted annual surplus emission reductions that are associated with the proposed project, using the results from Step 9 above as inputs into Formula 12.

Formula 12: Annual Weighted Surplus Emission Reductions (tons/yr)

$$WER = NOx\ Reductions\ \left(\frac{tons}{year}\right) + ROG\ Reductions\ \left(\frac{tons}{year}\right) + \left(20 * \ PM\ Reductions\ \left(\frac{tons}{year}\right)\right)$$

Therefore, using the results from Step 9 above and Formula 12:

WER is the Weighted Emission Reductions

$$WER_{C\&C} = \left(0.011 \frac{tons\ NOx}{year}\right) + \left(\ 0.0022\ \frac{tons\ ROG}{year}\right) * 20 \left(0.00039 \frac{tons\ PM}{year}\right) = 0.021\ tons$$

Therefore, $WER_{C\&C} = 0.021 \frac{tons\ weig\ hted\ criteria\ \ pollutants\ \ reduced}{year}$

Step 11: Determine the incremental cost of the proposed barge system technology using Formula 6 and the equipment costs for a baseline capture and control system. Cost-effectiveness is to be calculated for two scenarios: for two years during the proposed project and for 10 years (two years after the completion of the proposed project).

Baseline capture and control equipment:

- Cost of baseline system and advanced technology system are equal at $7,000,000 during the proposed project.
- Cost of baseline system and advanced technology system are equal at $6,500,000 two years after the end of the project.

Advanced Technology:

- Will use renewable diesel which costs $0.25 per gallon more than conventional diesel.
- Cost of baseline system and advanced technology system are equal at $7,000,000 during the proposed project.
- Cost of baseline system and advanced technology system are equal at $6,500,000 two years after the end of the project.

There is no difference in cost between the baseline capture and control system and the advanced technology capture and control system. The only difference in operational costs is the use of renewable diesel fuel. Determine the increased cost in using renewable diesel fuel by using the result from Step 4.

$$Renewable\ Diesel\ Fuel\ Cost = \left(2{,}320\ \frac{gal\ diesel}{year}\right) * \left(0.25\frac{dollars}{gal}\right) = 580\frac{dollars}{year}$$

$$Two\ years\ of\ fuel = 580\frac{dollars}{year} * 2\ years = \$1{,}160$$

$$Ten\ years\ of\ fuel = 580\frac{dollars}{year} * 10\ years = \$5{,}800$$

The results from the calculation below will be used as the incremental cost of the advanced technology capture and control system.

Step 12: Determine the GHG emission reduction cost-effectiveness for the proposed capture and control system using the results calculated above as inputs into Formula 13.

Formula 13: Cost-Effectiveness of Weighted Surplus Emission Reductions

$$Cost\ Effectiveness\ \left(\frac{\$}{WER\ ton}\right) = \frac{CRF * Incremental\ Cost}{WER}$$

Where:

- **CRF** is the Capital Recovery Factor:
    - CRF_2 = 0.508 per Values for Calculations section (2-year life)
    - CRF_{10} = 0.106 per Values for Calculations section (10-year life)

Therefore,

GHG C/E is the GHG Cost-Effectiveness

$$GHG\ C/E_{2\ years} = \left(\frac{\frac{(0.508 * \$1{,}160)}{year}}{\frac{20.9\ metric\ \ tons\ \ CO2e}{year}}\right) = \frac{\$28}{metric\ \ tons\ \ CO2e\ reduced}$$

$$GHG\ C/E_{10\ years} = \left(\frac{\left(\frac{(0.106 * \$5{,}800)}{year}\right)}{\frac{20.9\ metric\ \ tons\ \ CO2e}{year}}\right) = \frac{\$29}{metric\ \ tons\ \ CO2e\ reduced}$$

Step 13: Determine the criteria pollutant cost-effectiveness for the proposed technology. Use the results calculated above to populate Formula 13.

$$Criteria\ Pollutant\ C/E_{2\ years} = \left(\frac{\frac{(0.508 * \$1{,}160)}{year}}{\frac{0.021\ tons\ \ WER}{year}}\right) = \frac{\$28{,}000}{tons\ \ criteria\ \ pollutants\ \ reduced}$$

$$Criteria\ Pollutant\ C/E_{10\ years} = \left(\frac{\frac{(0.106 * \$5{,}800)}{year}}{\frac{0.021\ tons\ \ WER}{year}}\right) = \frac{\$29{,}300}{tons\ \ criteria\ \ pollutants\ \ reduced}$$

<u>Example Oil Tanker Monroe</u>:

Next determine the emissions that are associated with the oil tanker. Only criteria pollutant emissions will be considered since the proposed capture and control system does not reduce GHG emissions.

Step 14: Determine the criteria pollutant emissions associated with the oil tanker, using Formula 10.

Formula 10: Annual Criteria Emissions from Baseline OGVs at Berth for Known Engine and Boiler Effective Power

$$E_{OGV,Criteria} = \frac{ED}{D} \times AA \times \frac{(EF_{AuxEng} * FC_{AuxEng} * EP_{AuxEng} + EF_{Boiler} * FC_{Boiler} * EP_{Boiler})}{EER_i}$$

The vessel that is utilizing the capture and control system is a VLCC size vessel. The following variables are associated with this vessel.

Emission factors for the example ship's auxiliary engine and boiler are below; however, the emission factors need to be converted to a MJ base. To convert the emission factors to the format used in the formula, it must be converted from grams per kWh to grams per MJ. There are 3.6 MJ per kWh.

Auxiliary Engine Emission Factors:

$$EF_{AuxEng,NOx} = 12.200 \frac{g\ NOx}{kWh} * \frac{kWh}{3.6\ MJ} = 3.39 \frac{g\ NOx}{MJ}$$

$$EF_{AuxEng,ROG} = 0.520 \frac{g\ ROG}{kWh} * \frac{kWh}{3.6\ MJ} = 0.144 \frac{g\ ROG}{MJ}$$

$$EF_{AuxEng,PM} = 0.182 \frac{g\ PM}{kWh} * \frac{kWh}{3.6\ MJ} = 0.506 \frac{g\ PM}{MJ}$$

$$Auxiliary\ engine\ fuel\ consumption\ rate = 217 \frac{g\ diesel}{KWh}$$

$$Auxiliary\ engine\ effective\ power = 1171\ kW\ for\ discharge$$

Boiler Emission Factors:

$$EF_{Boiler,NOx} = 1.995 \frac{g\ NOx}{kWh} * \frac{kWh}{3.6\ MJ} = 0.554 \frac{g\ NOx}{MJ}$$

$$EF_{Boiler,ROG} = 0.110 \frac{g\ ROG}{kWh} * \frac{kWh}{3.6\ MJ} = 0.0306 \frac{g\ ROG}{MJ}$$

$$EF_{Boiler,PM} = 0.164 \frac{g\ PM}{kWh} * \frac{kWh}{3.6\ MJ} = 0.0456 \frac{g\ PM}{MJ}$$

$$Boiler\ fuel\ consumption\ rate = 300 \frac{g\ diesel}{kWh}$$

$$Boiler\ effective\ power = 6000\ kW\ for\ discharge$$

Other variables used:

The density of the fuel being used on this vessel is:

$$Fuel\ Density = 3368 \frac{g\ diesel}{gallon}$$

The energy density of diesel is:

$$ED_{diesel} = 134.47 \frac{MJ}{gal\ diesel}$$

Since the control system is being powered by diesel, the EER is equal to 1.

Therefore, populating Formula 10 to determine the NOx emissions for the oil tanker while at berth and discharging its cargo:

$$E_{OGV,Criteria} = \frac{ED}{D} \times AA \times \frac{(EF_{AuxEng} * FC_{AuxEng} * EP_{AuxEng} + EF_{Boiler} * FC_{Boiler} * EP_{Boiler})}{EER_i}$$

$$E_{OGV,NOx=} = \frac{134.47 \frac{MJ}{gal\ diesel}}{3368 \frac{g\ diesel}{gallon}} \times 290 \frac{hours}{year} \times \frac{\left(3.39 \frac{g\ NOx}{MJ} * 217 \frac{g\ diesel}{kWh} * 1171\ \text{kW} + 0.554 \frac{g\ NOx}{MJ} * 300 \frac{g\ diesel}{kWh} * 6000\ \text{kW}\right)}{1}$$

$$E_{OGV,NOx} = 21{,}520{,}015 \frac{g\ NOx}{year} * \frac{1\ ton}{907{,}200\ g} = 23.7 \frac{tons\ NOx}{year}$$

Next, perform the calculation for ROG:

$$E_{OGV,ROG} = \frac{134.47 \frac{MJ}{gal\ diesel}}{3368 \frac{g\ diesel}{gallon}} \times 290 \frac{hours}{year} \times \frac{\left(0.144 \frac{g\ ROG}{MJ} * 217 \frac{g\ diesel}{KW-hr} * 1171\ \text{kW} + 0.0305 \frac{g\ ROG}{MJ} * 300 \frac{g\ diesel}{KW-hr} * 6000\ \text{kW}\right)}{1}$$

$$E_{OGV,ROG} = 1{,}061{,}415 \frac{g\ ROG}{year} * \frac{1\ ton}{907{,}200\ g} = 1.17 \frac{tons\ ROG}{year}$$

Next, perform the calculation for PM:

$$E_{OGV,PM=} = \frac{134.47 \frac{MJ}{gal\ diesel}}{3368 \frac{g\ diesel}{gallon}} \times 290 \frac{hours}{year} \times \frac{\left(0.506 \frac{g\ PM}{MJ} * 217 \frac{g\ diesel}{KW-hr} * 1171\ \text{kW} + 0.0456 \frac{g\ PM}{MJ} * 300 \frac{g\ diesel}{KW-hr} * 6000\ \text{kW}\right)}{1}$$

$$E_{OGV,PM} = 2{,}439{,}100 \frac{g\ PM}{year} * \frac{1\ ton}{907{,}200\ g} = 2.69 \frac{tons\ PM}{year}$$

Step 15: Determine the emission reductions associated with using the capture and control system on an oil tanker. The capture and control system has a control efficiency rate of 80%; therefore, 80% of the tankers criteria pollutant emissions are ultimately captured and controlled. Therefore, multiplying the emissions from the oil tanker by the control efficiency rate will give the emission reductions associated with using the capture and control system on the tanker vessel.

Therefore, taking the results from above:

$$ER_{OGV,NOx} = 23.7\frac{tons\ NOx}{year} * 0.80\ control\ efficiency = 19.0\frac{tons\ NOx}{year}\ reduced$$

$$ER_{OGV,ROG} = 1.17\frac{tons\ ROG}{year} * 0.80\ control\ efficiency = 0.94\frac{tons\ ROG}{year}\ reduced$$

$$ER_{OGV,PM} = 2.69\frac{tons\ PM}{year} * 0.80\ control\ efficiency = 2.2\frac{tons\ PM}{year}\ reduced$$

Step 16: Determine the WER for the capture and control system using Formula 12 and the results from the above calculation.

Formula 12: Annual Weighted Surplus Emission Reductions (tons/yr)

$$WER = NOx\ Reductions\ \left(\frac{tons}{year}\right) + ROG\ Reductions\ \left(\frac{tons}{year}\right) + \left(20 * \ PM\ Reductions\ \left(\frac{tons}{year}\right)\right)$$

Therefore, using the results from Step 15 above:

WER is the Weighted Emission Reductions

$$WER_{OGV} = \left(19.0\frac{tons\ NOx}{year}\right) + \left(0.94\ \frac{tons\ ROG}{year}\right) * 20\left(2.2\frac{tons\ PM}{year}\right) = 63.9\text{ tons WER}$$

Therefore, $WER_{OGV} = 63.9\frac{tons\ \ weig\ hted\ riteria\ \ polluta\ nts\ reduced}{year}$

Step 17: Determine the emission reductions that are associated with the whole project. The total project cost includes the cost of the capture and control system, use of the tugboat, and all other costs associated with the project such as project administration, data collection and analysis, and operational costs. For this example, the cost of the capture and control system is $7,000,000 and the balance of the costs for the project is $5,500,000, giving a total cost of the project of $12,500,000.

Emission Reductions:

- 20.9 metric tons CO2e per year from capture and control system
- 0.021 tons annual WER from capture and control system
- 63.9 tons annual WER from use of capture and control system on oil tanker

Annual GHG emission reductions from the project all come from renewable diesel fuel use in the capture and control system which was calculated above.

Step 18: Determine the total criteria pollutant emission reduced, which is equal to the sum of the emission reductions from the capture and control system and from the use of the system to reduce emissions from the tanker.

$$WER_{Total} = 0.021 \frac{tons\ WER}{year} + 63.9 \frac{tons\ WER}{year} = 63.9 \frac{tons\ WER}{year}$$

Use Formula 5 and 13 to determine the cost-effectiveness for both GHG and criteria pollutant emissions.

Formula 5: GHG Cost-Effectiveness

$$Cost\ Effectiveness\ \left(\frac{\$}{metric\ \ ton}\right) = \left(\frac{\frac{CRF * (\$\,Total\ \ Project\ \ Cost)}{year}}{\frac{metric\ \ ton\ \ emissions\ \ reduced}{year}}\right)$$

Where:

- **CRF** is the Capital Recovery Factor:
  - CRF_2 = 0.508 per Values for Calculations section (2-year life)
  - CRF_{10} = 0.106 per Values for Calculations section (10-year life)

Therefore,

GHG C/E is the GHG Cost-Effectiveness

$$GHG\ C/E_{2\ years} = \left(\frac{\frac{(0.508 * \$12{,}500{,}000)}{year}}{\frac{20.9\ metric\ \ tons\ \ CO2e}{year}}\right) = \frac{\$300{,}000}{metric\ \ tons\ \ CO2e\ reduced}$$

$$GHG\ C/E_{10\ years} = \left(\frac{\left(\frac{(0.106 * \$12{,}500{,}000)}{year}\right)}{\frac{20.9\ metric\ \ tons\ CO2e}{year}}\right) \frac{\$63{,}000}{metric\ \ tons\ \ CO2e\ reduced}$$

Step 19: Determine the criteria pollutant cost-effectiveness for the proposed technology. Use the results calculated above to populate Formula 13.

Formula 13: Cost-Effectiveness of Weighted Surplus Emission Reductions

$$Cost\ Effectiveness\ \left(\frac{\$}{WER\ ton}\right) = \frac{CRF * Incremental\ \ Cost}{WER}$$

$$Criteria\ Pollutant\ C/E_{2\ years} = \left(\frac{\frac{(0.508 * \$12{,}500{,}000)}{year}}{\frac{63.9\ tons\ \ WER}{year}}\right) = \frac{\$99{,}000}{tons\ \ criteria\ \ pollutants\ \ reduced}$$

$$Criteria\ Pollutant\ C/E_{10\ years} = \left(\frac{\frac{(0.106 * 12{,}500{,}000)}{year}}{\frac{63.9\ tons\ \ WER}{year}}\right) = \frac{\$21{,}000}{tons\ \ criteria\ \ pollutants\ \ reduced}$$

Values for Calculations

GHG Emission Factors

The following emission factors apply when calculating emission reductions and cost-effectiveness for Capture and Control System for Oil Tankers project applications. Values are from the California Climate Investments Quantification Methodology Emission Factor Database, dated August 27, 2020. This database is the only approved source of GHG emission factors for use in calculations.

Fuel Energy Density Values

Diesel: 134.47 MJ/gal

Renewable Diesel: 129.65 MJ/gal

Electricity: 3.6 MJ/kWh

Hydrogen: 120.00 MJ/kg

Fuel Carbon Intensity Values

Diesel: 100.45 gCO2e/MJ

Renewable Diesel: 34.62 gCO2e/MJ

Hydrogen: 111.61 gCO2/MJ

Hydrogen from zero-emission sources: 0.0 gCO2e/MJ

Electricity: 82.92 gCO2/MJ

Electricity from zero-emission sources: 0.0 gCO2e/MJ

EER Values for Fuels Used in Heavy-Duty Truck Applications

Diesel: 1.00

Electricity: 5.0

Hydrogen: 1.9

Criteria Pollutant Emission Factors[4]

For a Tier-3 marine engine, the following emission factors are used for criteria pollutants:

$$NOx = 4.14\frac{g\ NOx}{bhp-hr}\ ;\ ROG = 0.49\frac{g\ ROG}{bhp-hr}\ ;\ PM10 = 0.085\frac{g\ PM\ 10}{bhp-hr}$$

For a Tier-4 final off-road engine, the following emission factors are used for criteria pollutants:

$$NOx = 0.26\frac{g\ NOx}{bhp-hr}\ ;\ ROG = 0.05\frac{g\ ROG}{bhp-hr}\ ;\ \mathrm{PM10} = 0.009\frac{g\ PM\ 10}{bhp-hr}$$

If additional emission factors are needed, use the 2017 Moyer Guidelines Appendix C as the source of those values.

[4] 2017 Carl Moyer Guidelines Appendix D.
https://ww3.arb.ca.gov/msprog/moyer/guidelines/2017gl/2017_gl_appendix_d.pdf

Capital Recovery Factor (CRF) for Various Project Lives

At a 1% Discount Rate

Project Life	CRF
1	1.010
2	0.508
3	0.340
4	0.256
5	0.206
6	0.173
7	0.149
8	0.131
9	0.117
10	0.106
11	0.096
12	0.089
13	0.082
14	0.077
15	0.072
16	0.068
17	0.064
18	0.061
19	0.058
20	0.055