Fuel and Carbon Dioxide Emissions Savings Calculation Methodology for Combined Heat and Power Systems

U.S. Environmental Protection Agency

Combined Heat and Power Partnership

June 2021

The U.S. Environmental Protection Agency (EPA) CHP Partnership is a voluntary program that seeks to reduce the environmental impact of power generation by promoting the use of CHP. The CHP Partnership works closely with energy users, the CHP industry, state and local governments, and other stakeholders to support the development of new CHP projects and promote their energy, environmental, and economic benefits.

The CHP Partnership provides resources about CHP technologies, incentives, emissions profiles, and other information on its website at www.epa.gov/chp. For more information, contact the CHP Partnership Helpline at chp@epa.gov or (703) 373-8108.

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1.0 INTRODUCTION

The appropriate quantification of energy and emissions savings from combined heat and power (CHP) plays a critical role in defining the value proposition of CHP for policy makers, project developers, end users, and other industry stakeholders. This paper provides the EPA Combined Heat and Power Partnership's (the Partnership) recommended methodology for calculating fuel and carbon dioxide (CO_2) emissions savings from CHP compared to conventional separate heat and power (SHP).[1] This methodology recognizes the multiple outputs of CHP systems and compares the fuel use and emissions of the CHP system to the fuel use and emissions that would have occurred with separate heat and power (SHP).

The methodology recommended in this paper is not intended as a substitute methodology for organizations quantifying and reporting GHG inventories. EPA recommends that organizations use accepted GHG protocols, such as the World Resources Institute's Greenhouse Gas Protocol [2] or The Climate Registry's General Reporting Protocol [3], when calculating and reporting a company's carbon footprint.

However, the CO_2 emissions savings amounts estimated using the methodology recommended in this paper can be reported as supplemental information in an organization's public disclosure of its GHG inventory to help inform stakeholders of the emissions benefits of CHP and to highlight the organization's commitment to energy-efficient and climate-friendly technologies.

Summary of Key Points

- To calculate the fuel and CO_2 emissions savings of a CHP system, it is necessary to account for both electric and thermal outputs of the CHP system.
- The CHP system's thermal output displaces the fuel normally consumed by and emissions emitted from on-site thermal generation in a boiler or other equipment, and the power output displaces the fuel consumed and emissions from grid electricity.
- To quantify the fuel and CO_2 emissions savings of a CHP system, the fuel use of and emissions released from the CHP system are subtracted from the fuel use and emissions that would normally occur without the system (i.e., using SHP).
- A key factor in estimating the fuel and CO_2 emissions savings for CHP is determining the heat rate and emissions factor of displaced grid electricity. Two sets of grid emissions factors are available from EPA. The choice of factors depends on the system's location and operating conditions. Appendix B provides information about these inputs.

The paper is organized as follows:

- Section 2 introduces CHP and explains the basis for fuel and CO_2 emissions savings from CHP compared to SHP.
- Section 3 presents a methodology for calculating the fuel and CO_2 emissions savings from CHP.

[1] The CEESC is available at: https://www.epa.gov/chp/chp-energy-and-emissions-savings-calculator. CHP can also reduce emissions of other greenhouse gases, such as methane (CH4) and nitrous oxide (N2O), along with criteria air pollutants. Although methane and nitrous oxide are not discussed in this paper, they are accounted for in the CHP Energy and Emissions Savings Calculator (CEESC).

[2] The Greenhouse Gas Protocol is available at: http://www.ghgprotocol.org/.

[3] The Climate Registry General Reporting Protocol is available at: http://www.theclimateregistry.org/resources/protocols/general- reporting-protocol/.

- Appendix A presents a sample calculation of fuel and CO_2 emissions savings using the EPA CHP Energy and Emissions Savings Calculator (CEESC).
- Appendix B explains methods of estimating displaced grid electricity fuel use and CO2 emissions impacts using EPA's Emissions & Generation Resource Integrated Database (eGRID) and AVoided Emissions and geneRation Tool (AVERT) as sources for two key variables in the calculation of fuel and CO_2 emissions savings from displaced grid electricity: displaced grid electricity heat rate [where the heat rate is the ratio of fuel energy input (in Btu) as heat per unit of net power output (in kWh)] and CO_2 emissions factors. It also describes how to select values for these variables.

2.0 WHAT IS CHP?

Combined heat and power (CHP) is a highly efficient method of providing power and useful thermal energy (heating or cooling) at the point of use with a single fuel source. By employing waste heat recovery technology to capture a significant portion of the heat created as a by-product of fuel use, CHP systems typically achieve total system efficiencies of 65 to 80 percent. An industrial or commercial entity can use CHP to produce electricity and thermal energy instead of obtaining electricity from the grid and producing thermal energy in an on-site furnace or boiler. In this way, CHP can provide significant energy efficiency, cost savings, and environmental benefits compared to the combination of grid-supplied electricity and on-site boiler use (referred to as separate heat and power or SHP).

CHP plays important roles both in efficiently meeting U.S. energy needs and in reducing the environmental impact of power generation. Currently, CHP systems represent approximately 7 percent of the electric generating capacity in the United States.[4] Benefits of CHP include:

- **Efficiency benefits:** CHP requires less fuel than SHP to produce a given energy output, and because electricity is generated at the point of use, transmission and distribution losses that occur when electricity travels over power lines from central power plants are displaced.
- **Reliability benefits:** CHP can be designed to provide high-quality electricity and thermal energy on site, reducing reliance on the electric grid, decreasing the impact of outages, and improving power quality for sensitive equipment.
- **Environmental benefits:** Because less fuel is burned to produce each unit of energy output, CHP reduces emissions of greenhouse gases (GHG) and other air pollutants.
- **Economic benefits:** Because of its efficiency benefits, CHP can help facilities save money on energy. Also, CHP can provide a hedge against fluctuations in electricity costs.

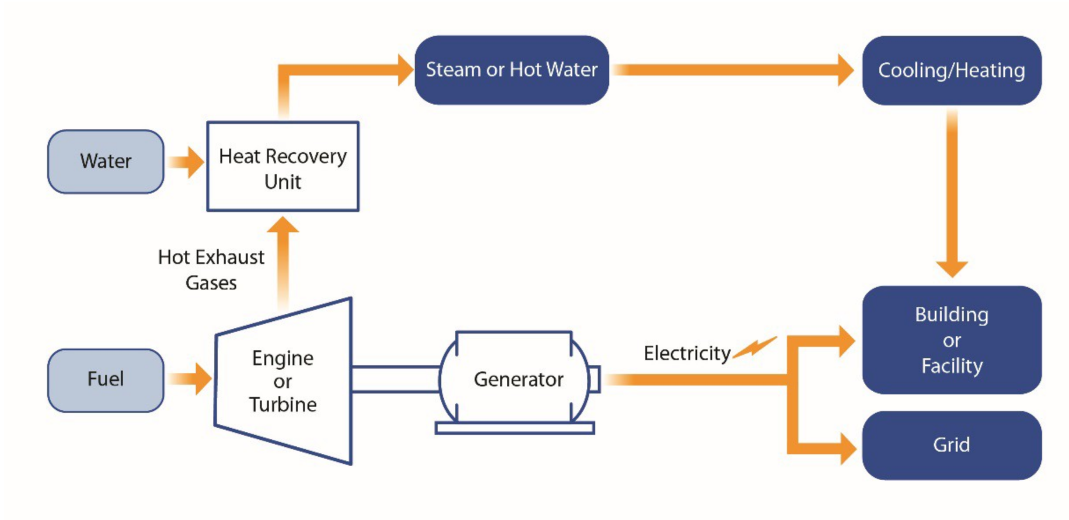
In the most common type of CHP system, known as a topping cycle (see Figure 1), fuel is used by a prime mover[5] to drive a generator to produce electricity, and the otherwise-wasted heat from the prime mover is recovered to provide useful thermal energy. Examples of the two most common topping cycle CHP configurations are:

- A reciprocating engine or gas turbine burns fuel to generate electricity and a heat recovery unit captures heat from the exhaust and cooling system. The recovered heat is converted into useful thermal energy, usually in the form of steam or hot water.
- A steam turbine uses high-pressure steam from a boiler to drive a generator producing electricity. Low-pressure steam extracted from or exiting the steam turbine is used for industrial processes, space heating or cooling, domestic hot water, or for other purposes.

[4] U.S. Department of Energy, CHP Installation Database, 2020, available at https://doe.icfwebservices.com/chpdb/.

[5] Prime movers are the devices (e.g., reciprocating engine, gas turbine, microturbine, steam turbine) that convert fuels to electrical energy via a generator.

Figure 1: Typical Reciprocating Engine/Gas Turbine CHP Configuration (Topping Cycle)



In another type of CHP system, known as a bottoming cycle, fuel is used for the purpose of providing thermal energy in an industrial process, such as a furnace, and heat from the process that would otherwise be wasted is used to generate power.

2.1 How CHP Systems Save Fuel and Reduce CO_2 Emissions

CHP's efficiency benefits result in reduced primary energy[6] use and thus lower CO_2 emissions.

Figure 2 shows the efficiency advantage of CHP compared to SHP.[7] CHP systems typically achieve total efficiencies of 65 to 85 percent compared to about 50 to 55 percent for SHP. As shown in Figure 2, CHP systems not only reduce the amount of total fuel required to provide electricity and thermal energy but also shift where that fuel is used. Installing a CHP system on site will generally increase the amount of fuel that is used at the site, because additional fuel is required to operate the CHP system compared to the equipment that otherwise would have been used on site to produce needed thermal energy.

In the example shown in Figure 2, the on-site fuel use increases from 55 units in the SHP case to 100 units in the CHP case. However, despite this increase in on-site fuel use, the total fuel used to provide the facility with the required electrical and thermal energy drops from 155 units in the SHP case to 100 units in the CHP case, a 35 percent decrease in the amount of total fuel used.[8] Using less fuel to provide the same amount of energy can significantly reduce CO_2 and other emissions compared to separate heat and power. Applying U.S. average fossil fuel emissions from eGRID, the total emissions for a 1 MW CHP engine operating at full load 8,000 hours

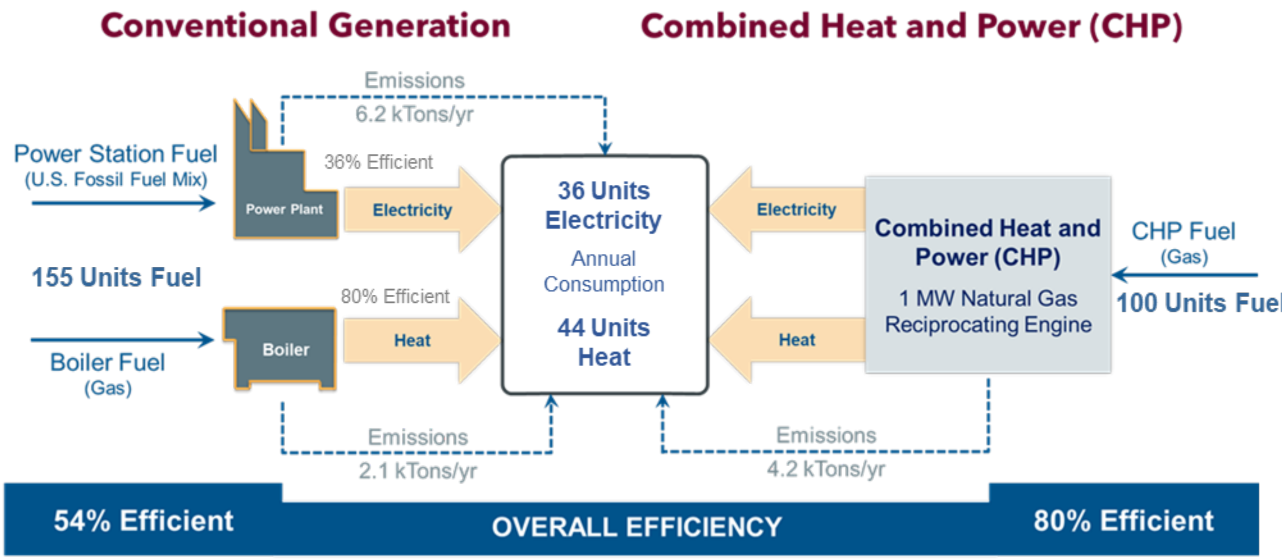
[6] Primary energy is the fuel that is consumed to create heat and/or electricity.

[7] Like Figure 1, Figure 2 illustrates the most common CHP configuration known as the topping cycle. See section 2.0 for more information.

[8] Comparison made with a 1 MW CHP engine, assumed to have a 36% electric efficiency and 80% total CHP efficiency, typical for reciprocating engines in this size range. Average efficiency for delivered grid electricity is assumed to be 36% (eGRID, see note below Figure 2), and on-site boiler efficiency is assumed to be 80%.

a year are estimated at 4,200 tons, compared to a total of 8,300 tons to deliver the same amount of electricity and thermal energy with SHP.

Figure 2: Energy Efficiency and Emissions Savings – Topping Cycle CHP Versus Separate Heat and Power (SHP) Production



***Note:** Conventional power plant delivered efficiency of 36% (higher heating value [HHV]) is based on eGRID2019 and reflects the national average all fossil generating efficiency of 38.2% and 4.88% transmission and distribution losses. Emissions estimates are based on eGRID2019 fossil fuel average. eGRID provides information on emissions and fuel resource mix for individual power plants, generating companies, states, and subregions of the power grid. eGRID is available at* https://www.epa.gov/egrid.

3.0 CALCULATING FUEL AND CO_2 EMISSIONS SAVINGS FROM CHP

To calculate the fuel or CO_2 emissions savings of a CHP system, both outputs of the CHP system—thermal energy and electricity—must be accounted for. The CHP system's thermal output typically displaces the fuel otherwise consumed in an on-site boiler, and the electric output displaces fuel consumed at central station power plants.[9] Moreover, the CHP system's electric output also displaces fuel consumed to produce electricity lost during transmission and distribution. Some CHP systems use absorption chillers to convert thermal energy into chilled water for cooling applications. This methodology document only covers traditional CHP applications.

The displaced fuel use and CO_2 emissions associated with the operation of a CHP system can be determined by:

CHP Emission Reductions

CHP systems reduce emissions of greenhouse gases, criteria pollutants, and hazardous air pollutants by combusting less fuel to produce the same amount of energy as separate heat and grid-delivered power. The methodology presented in this paper focuses on the six pollutants in the CHP Energy and Emission Savings Calculator but can be used to calculate the reduction of other pollutants.

a) Calculating the fuel use and emissions from displaced separate heat and power (SHP) (i.e., grid-supplied electricity and on-site thermal generation such as a boiler)
b) Calculating the fuel use and emissions from CHP
c) Subtracting (b) from (a)

Equation 1 presents the recommended approach for calculating the fuel savings of a CHP system. Equation 2 presents the recommended approach for calculating CO_2 emissions savings of a CHP system.

Note: Sections 3.1 and 3.2 present the approaches for calculating the individual terms found in Equations 1 and 2. Appendix A presents a sample calculation of CO_2 savings using the EPA CHP CEESC which uses the methodology and equations outlined in this section.

[9] The thermal output from CHP can also be used to produce cooling in an absorption or adsorption chiller. Accounting for cooling introduces complexities that are not addressed in the methodology presented in this paper. However, the CEESC does account for cooling.

Equation 1: Calculating Fuel Savings from CHP

$F_S \quad = \quad (F_T + F_G) - F_{CHP}$

where:

F_S = Total Fuel Savings (Btu)
F_T = Fuel Use from Displaced On-site Thermal Production (Btu)
F_G = Fuel Use from Displaced Grid Electricity (Btu)
F_{CHP} = Fuel Used by the CHP System (Btu)

Step 1: Calculate F_T and F_G using Equation 3 (page 8) and Equation 6 (page 11), respectively.

Step 2: Calculate F_{CHP} through direct measurement or using Equations 8 (page 12), 9 (page 13) or 10 (page 13).

Step 3: Calculate F_S.

Equation 2: Calculating CO_2 Savings from CHP

$C_S \quad = \quad (C_T + C_G) - C_{CHP}$

where:

C_S = Total CO_2 Emissions Savings (lbs CO_2)
C_T = CO_2 Emissions from Displaced On-site Thermal Production (lbs CO_2)
C_G = CO_2 Emissions from Displaced Grid Electricity (lbs CO_2)
C_{CHP} = CO_2 Emissions from the CHP System (lbs CO_2)

Step 1: Calculate C_T and C_G using Equation 4 (page 9) and Equation 7 (page 11), respectively.

Step 2: Calculate C_{CHP} using Equation 11 (page 14).

Step 3: Calculate C_S.

Note on using Equations 1 and 2 for bottoming cycle CHP systems: In the case of bottoming cycle CHP, also known as waste heat to power, power is generated on site from the hot exhaust of a furnace or kiln with no additional fuel requirement. Therefore, the fuel use and CO_2 emissions for both the CHP system and displaced thermal energy (F_{CHP}, C_{CHP}, F_T, and C_T) are all zero.

3.1 Fuel Use and CO_2 Emissions from Displaced On-site Thermal Production and Displaced Grid Electricity

3.1.1 Fuel Use and CO_2 Emissions from Displaced On-site Thermal Production

The thermal energy produced by a CHP system displaces combustion of some or all of the fuel that would otherwise be consumed for on-site production of thermal energy.[10] The fuel and CO_2 emissions savings associated with this displaced fuel consumption can be calculated using the thermal output of the CHP system and reasonable assumptions about the efficiency characteristics of the equipment that would otherwise have been used to produce the thermal energy being produced by the CHP system.

Equation 3 presents the approach for calculating the fuel use from displaced on-site thermal production.

Equation 4 presents the approach for calculating the CO_2 emissions from displaced on-site thermal production. Table 1 lists selected fuel-specific CO_2 emissions factors for use in Equation 4.

Equation 3: Calculating Fuel Use from Displaced On-site Thermal Production

$$F_T = CHP_T / \eta_T$$

where:

F_T = Fuel Use from Displaced On-site Thermal Production (Btu)
CHP_T = CHP System Thermal Output (Btu)
η_T = Estimated Efficiency of the Thermal Equipment (percentage in decimal form)

Step 1: Measure or estimate CHP_T.

Step 2: Select η_T (e.g., 80% efficiency for a natural gas-fired boiler, 75% for a biomass-fired boiler).

Step 3: Calculate F_T.

[10] In certain circumstances, CHP systems are designed so that supplemental on-site thermal energy production is sometimes utilized.

Equation 4: Calculating CO_2 Emissions from Displaced On-site Thermal Production

$$C_T = F_T * EF_F * (1x10^{-6})$$

where:

C_T = CO_2 Emissions from Displaced On-site Thermal Production (lbs CO_2)
F_T = Thermal Fuel Savings (Btu)
EF_F = Fuel Specific CO_2 Emission Factor (lbs CO_2 /MMBtu)
$1x10^{-6}$ = Conversion factor from Btu to MMBtu

Step 1: Calculate F_T using Equation 3.

Step 2: Select the appropriate EF_F from Table 1.

Step 3: Calculate C_T.

Table 1: Selected Fuel-Specific Energy and CO_2 Emissions Factors

Fuel Type	Energy Density	CO2 Emissions Factor, lb/MMBtu
Natural Gas	1,028 Btu/scf	116.9
Distillate Fuel Oil #2	138,000 Btu/gallon	163.1
Residual Fuel Oil #6	150,000 Btu/gallon	165.6
Coal (Anthracite)	12,545 Btu/lb	228.6
Coal (Bituminous)	12,465 Btu/lb	205.6
Coal (Subbituminous)	8,625 Btu/lb	214.2
Coal (Lignite)	7,105 Btu/lb	215.4
Coal (Mixed-Industrial Sector)	11,175 Btu/lb	208.7

Source: 40 CFR Part 98, Mandatory Greenhouse Gas Reporting, Table C-1: Default CO_2; Emissions factors and High Heat Values for Various Types of Fuel.

3.1.2 Fuel Use and CO_2 Emissions from Displaced Grid Electricity

Grid electricity savings associated with on-site CHP include the grid electricity displaced by the CHP output and related transmission and distribution losses.

When electricity is transmitted along power lines, some of the electricity is lost. The amount of electricity delivered to users[11] is therefore less than the amount generated at central station power plants, with a 5.1 percent United States average.[12,13] Consequently, generating 1 MWh of electricity on site means that more than 1 MWh of electricity no longer needs to be generated at central station power plants to account for transmission and distribution losses.[14] Fuel and CO_2 emissions savings from displaced grid electricity are based on the corresponding amount of displaced grid electricity generated and not on the amount of grid electricity delivered (and consumed).

Equation 5 presents the approach for calculating the displaced grid electricity resulting from electricity production by on-site CHP. Once the displaced grid electricity from CHP is determined, the fuel use (Equation 6) and CO_2 emissions (Equation 7) from displaced grid electricity can be calculated.

Equation 5: Calculating Displaced Grid Electricity from CHP

$$E_G = CHP_E \ / \ (1-L_{T\&D})$$

where:

E_G = Displaced Grid Electricity from CHP (kWh)
CHP_E = CHP System Electricity Output (kWh)
$L_{T\&D}$ = Transmission and Distribution Losses (percentage in decimal form)

Step 1: Measure or estimate CHP_E.

Step 2: Select $L_{T\&D}$. (Use the eGRID transmission and distribution loss value for the appropriate U.S. interconnect power grid*)

Step 3: Calculate E_G.

* eGRID lists the estimated transmission and distribution loss for each of the five U.S. interconnect power grids (i.e., Eastern, Western, ERCOT, Alaska, and Hawaii). (eGRID Technical Support Document: http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2012_year09_TechnicalSupportDocument.pdf).

[11] For clarity, the amount of electricity generated by a central station power plant is referred to as "generated" electricity, and the amount of electricity consumed by a facility supplied by the grid is referred to as "delivered" electricity.

[12] eGRID2019 Technical Guide. February 2021. https://www.epa.gov/egrid/egrid-technical-support-document

[13] DOE Energy Information Administration. State Electricity Profiles. https://www.eia.gov/electricity/state/

[14] For example, assume a consumer without CHP requires 1.0 MWh of electricity each year and T&D losses equal 8%. The delivered electricity is 1.0 MWh/yr, and the generated electricity is 1.087 MWh/yr (= 1/(1-0.08)).

<u>Note:</u> The key factors required to calculate the fuel use and CO_2 emissions from displaced grid electricity are the heat rate and CO_2 emissions factor associated with the displaced grid electricity. The tool offers two options to estimate emissions savings: EPA's AVoided Emissions and geneRation Tool (AVERT) and EPA's Emissions & Generation Resource Integrated Database (eGRID). In this example, eGRID factors are used. The CHP fuel and CO_2 emissions savings calculations would be based on the heat rates and emissions factors of the eGRID subregion where the CHP system is located, utilizing the eGRID all fossil or non- baseload emissions factors as appropriate. See Appendix B for further information on how best to select the appropriate emission factor.

Equation 6: Calculating Fuel Use from Displaced Grid Electricity

F_G = $E_G * HR_G$

where:

F_G = Fuel Use from Displaced Grid Electricity (Btu)
E_G = Displaced Grid Electricity from CHP (kWh)
HR_G = Grid Electricity Heat Rate (Btu/kWh) for the appropriate subregion

Step 1: Determine E_G using Equation 5.

Step 2: Select HR_G for the appropriate subregion. (See Appendix B for information about appropriate values and to identify appropriate emissions factors as a source for grid electricity heat rates.)

Step 3: Calculate F_G.

Equation 7: Calculating CO_2 Emissions from Displaced Grid Electricity

C_G = $E_G * EF_G$

where:

C_G = CO_2 Emissions from Displaced Grid Electricity (lbs CO_2)
E_G = Displaced Grid Electricity from CHP (kWh)
EF_G = Grid Electricity Emissions Factor (lbs CO_2 /kWh) for the appropriate subregion

Step 1: Determine E_G using Equation 5.

Step 2: Select EF_G for the appropriate subregion. (See Appendix B for information about appropriate values and to identify appropriate emissions factors as a source for grid electricity CO_2 emissions factors).

Step 3: Calculate C_G.

3.2 Fuel Use and CO_2 Emissions of the CHP System

The energy content of the fuel consumed by the CHP system (F_{CHP} in Equation 1) can be determined through several methods listed below. Direct measurement (Method 1) produces the most accurate results but when that is not an option, the Partnership recommends the use of Methods 2, 3, or 4.

1. Direct measurement of the higher heating value (HHV) of the fuel consumed (typically in $MMBtu_{HHV}$). No calculation required.
2. Converting the fuel volume into an energy value (Btu equivalent) using a fuel-specific energy density using Equation 8.
3. Converting the fuel weight into an energy value (Btu equivalent) using a fuel-specific energy density (mass basis) using Equation 9.
4. Applying the electrical efficiency of the CHP system to the CHP system's electric output using Equation 10.

Equation 8: Calculating Energy Content of the Fuel Used by CHP from the Fuel Volume

$$F_{CHP} = V_F * ED_F$$

where:

F_{CHP} = Fuel Used by the CHP System (Btu)
V_F = Volume of CHP Fuel Used (cubic foot, gallon, etc.)
ED_F = Energy Density of CHP Fuel (Btu/cubic foot, Btu/gallon, etc.)

Step 1: Measure or estimate V_F.

Step 2: Select the appropriate value of ED_F. (See Table 1 on page 9)

Step 3: Calculate F_{CHP}.

Equation 9: Calculating Energy Content of the Fuel Used by CHP from the Fuel Weight

$F_{CHP} = W_F * ED_F$

where:

F_{CHP} = Fuel Used by the CHP System (Btu)
W_F = Weight of CHP Fuel Used (lbs)
ED_F = Energy Density of CHP Fuel – Mass Basis (Btu/lb)

Step 1: Measure or estimate W_F.

Step 2: Select the appropriate ED_F. In order to be used here, the values in Table 1 (page 9) must be converted to a mass basis using the fuel-specific density.

Step 3: Calculate F_{CHP}.

Equation 10: Calculating Energy Content of the Fuel Used by CHP from the CHP Electric Output

$F_{CHP} = (CHP_E / EE_{CHP}) * 3412$

where:

F_{CHP} = Fuel Used by the CHP System (Btu)
CHP_E = CHP System Electricity Output (kWh)
EE_{CHP} = Electrical Efficiency of the CHP System (percentage in decimal form)
3412 = Conversion factor between kWh and Btu

Step 1: Measure or estimate CHP_E.

Step 2: Determine EE_{CHP}. (This value should account for parasitic losses, and is usually available in a product specification sheet provided by the manufacturer of the equipment.)

Step 3: Calculate F_{CHP}.

The CO_2 emissions from the CHP system are a function of the type and amount of fuel consumed. CO_2 emissions rates are commonly presented as pounds of emissions per million Btu of fuel input (lb/MMBtu). Table 1 on page 9 lists common fuel-specific CO_2 emissions factors. Equation 11 presents the approach for calculating CO_2 emissions from a CHP system (inserted as C_{CHP} in Equation 2).

Equation 11: Calculating CO_2 Emissions from the CHP System

C_{CHP} = $F_{CHP} * EF_F$

where:

C_{CHP} = CO_2 Emissions from the CHP System (lbs CO_2)
F_{CHP} = Fuel Used by the CHP System (Btu)
EF_F = Fuel Specific Emissions Factor (lbs CO_2 /MMBtu)

Step 1: Measure or calculate F_{CHP} using Equations 8 (page 12), 9 (page 13), or 10 (page 13).

Step 2: Select the appropriate EF_F from Table 1 on page 9.

Step 3: Calculate C_{CHP}, the CO_2 emissions from the CHP system.

APPENDIX A CEESC EXAMPLE CALCULATION

The EPA CHP Energy and Emissions Savings Calculator (CEESC) allows users to calculate the fuel savings and emissions reductions [15] of CHP using the approach described in this guidance. The default values in the CEESC are based on the guidelines in this paper. However, the tool also allows users to input user-selected CHP system characteristics and emissions factors for CHP fuel, displaced thermal fuel, and displaced grid electricity.

The CEESC is available at: https://www.epa.gov/chp/chp-energy-and-emissions-savings-calculator.

For this example calculation, the CHP system is assumed to be a 5 MW natural gas-fired combustion turbine CHP system that provides heating for an industrial process at a facility located in eastern Pennsylvania. The CHP system will displace thermal energy provided by an existing natural gas boiler and will also displace grid electricity.

A.1 Calculator Inputs

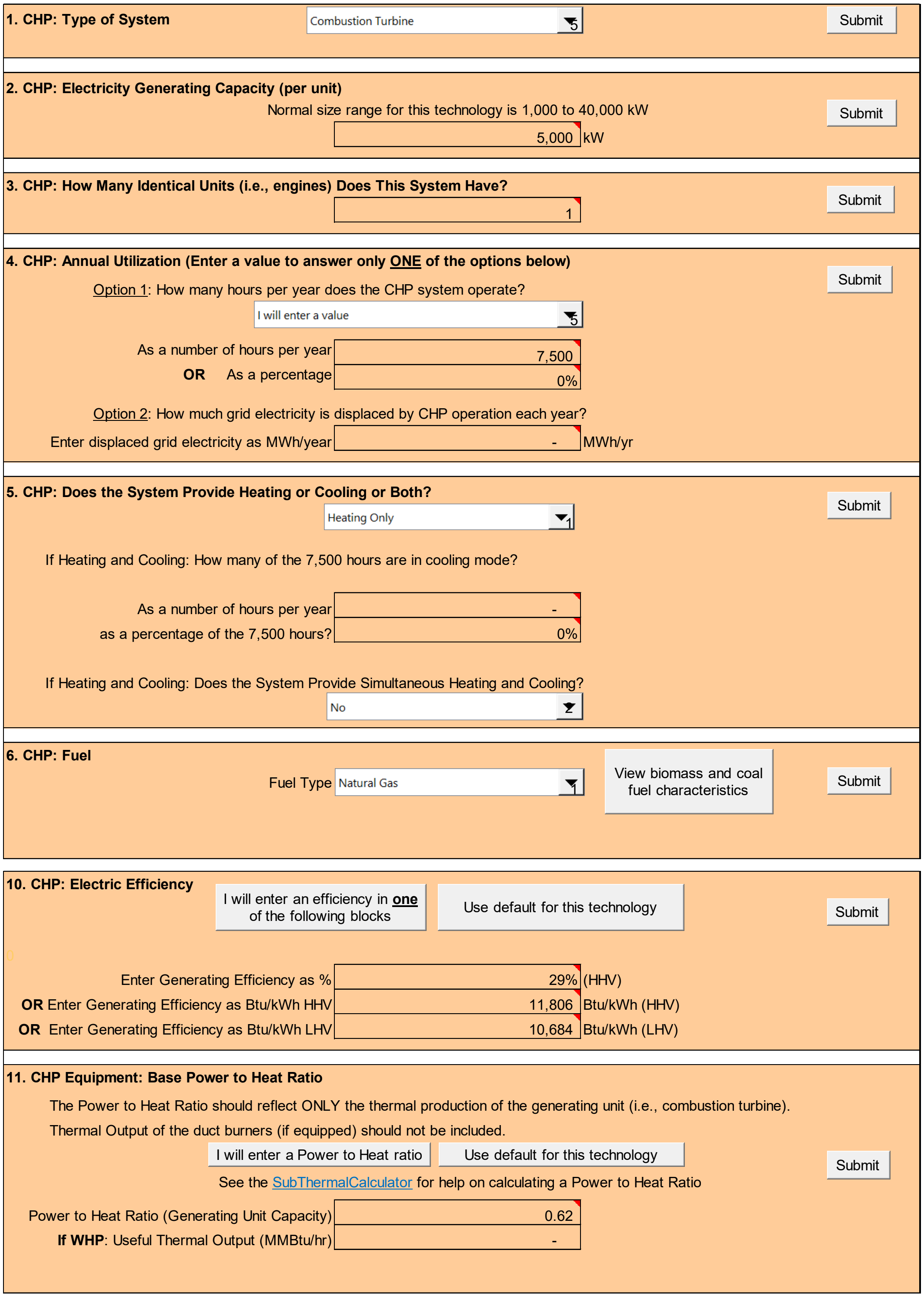
The CEESC has five main input categories to be completed sequentially:

1. CHP System Characteristics: type of system, size, fuel used, etc.
2. CHP Cooling Characteristics: if absorption chillers are used for cooling
3. Thermal Characteristics: displaced thermal equipment
4. Electricity Profile: displaced grid electricity
5. CHP & Displaced Boiler Emissions Characteristics: emissions factors for on-site fuel consumption

The input data is shown with the help of several figures, snapshots from the actual calculator, to guide the user's understanding. Figure A-1 shows the inputs related to the example CHP system. For this example, the CHP characteristics of the hypothetical system and default values for the electric efficiency and CHP power-to-heat ratio, based on the selected technology, were used.

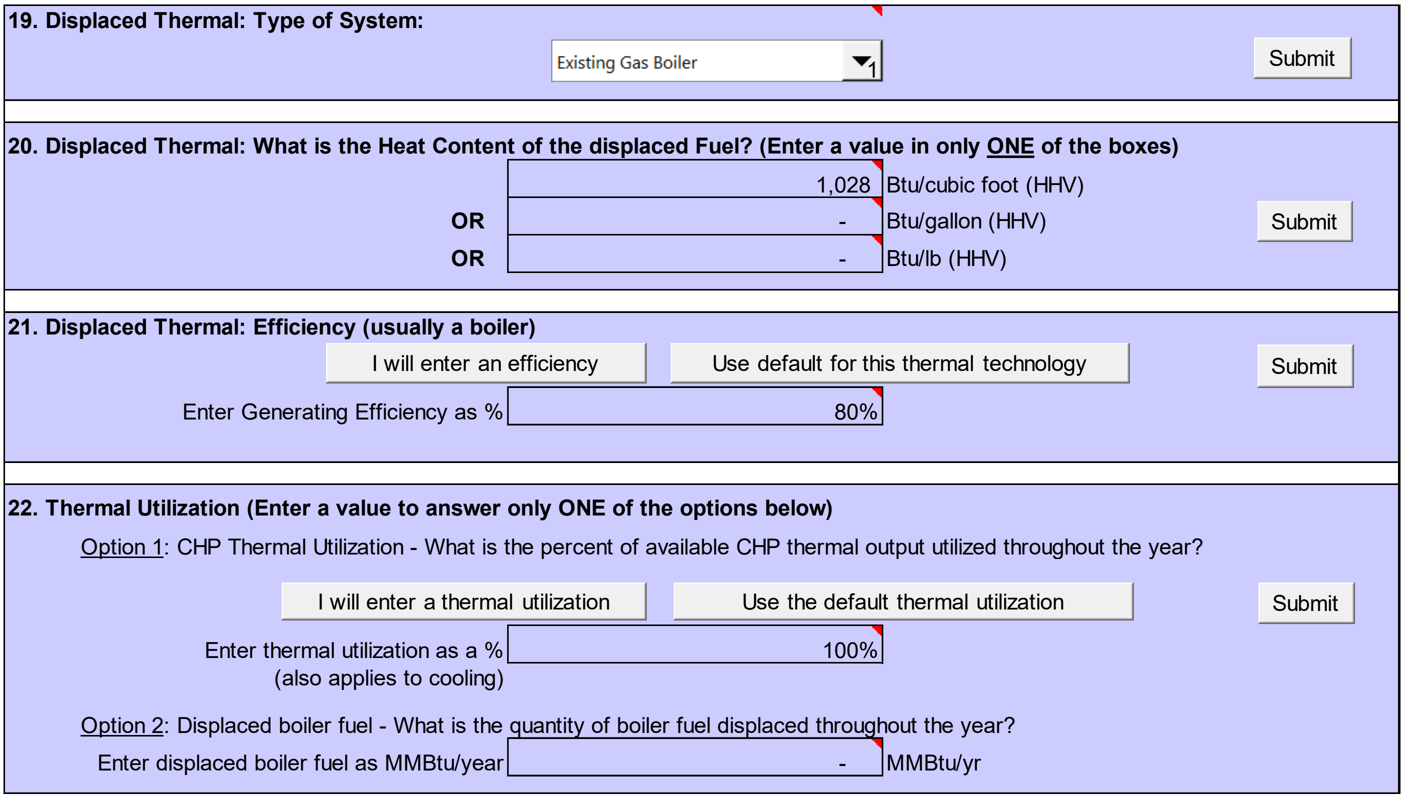
[15] The CEESC estimates changes in carbon dioxide (CO_2), methane (CH4), nitrogen oxides (NOx), nitrous oxide (N2O), sulfur dioxide (SO2), and total greenhouse gases (GHG) emissions.

Figure A-1: CHP Energy and Emissions Savings Calculator – CHP System Characteristics



In this example, CHP cooling is not being used, so the next input category is related to displaced on-site thermal energy use. This is the thermal energy produced by the CHP system and will replace thermal energy formerly produced by an on-site thermal equipment typically a boiler. In this example, 100 percent of the thermal energy from CHP is utilized by the host facility, although this factor can be adjusted. Information about the thermal equipment and the fuel used in it allows a user to calculate the displaced thermal fuel use and CO_2 emissions. Figure A-2 shows the calculator inputs on displaced thermal energy.

Figure A-2: CHP Energy and Emissions Savings Calculator – Displaced Thermal Energy



The next input category is the displaced grid electricity shown in Figure A-3 below. There are four types of displaced electricity generation profiles available: AVERT[16], eGRID[17] profiles, specific electricity generation equipment profiles, and user-defined profiles.

The AVERT profile includes the Uniform EE factor for marginal grid emissions based on AVERT region. If an AVERT emissions factor is selected, the corresponding heat rate from applicable eGRID subregion(s) will be used to calculate energy savings. More information and considerations for eGRID and AVERT emissions profiles are contained in Appendix B.

The eGRID emissions profiles include: Total Output Emissions Rate, Fossil Fuel Output Emissions Rate, Non-Baseload Output Emissions Rate, Coal Output Emissions Rate, Oil Output Emissions Rate, and Gas Output

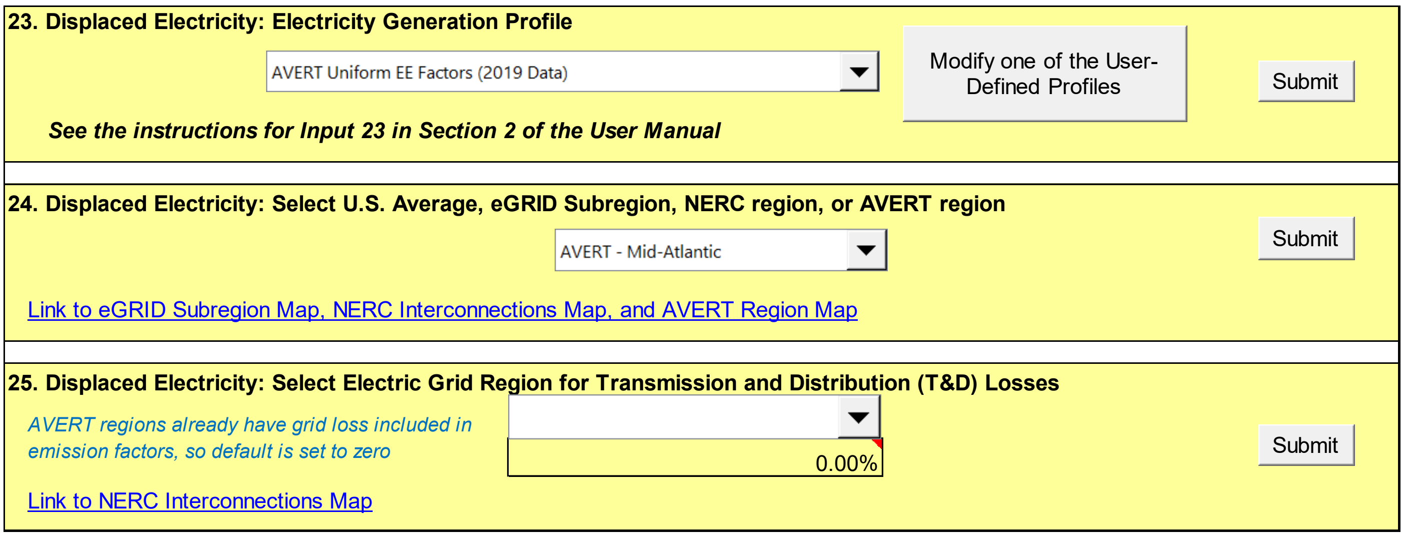
[16] https://www.epa.gov/statelocalenergy/avoided-emissions-and-generation-tool-avert

[17] https://www.epa.gov/egrid

Emissions Rate by eGRID subregion. Each eGRID emissions rate also has an associated heat rate that is used to calculate energy (fuel) savings.

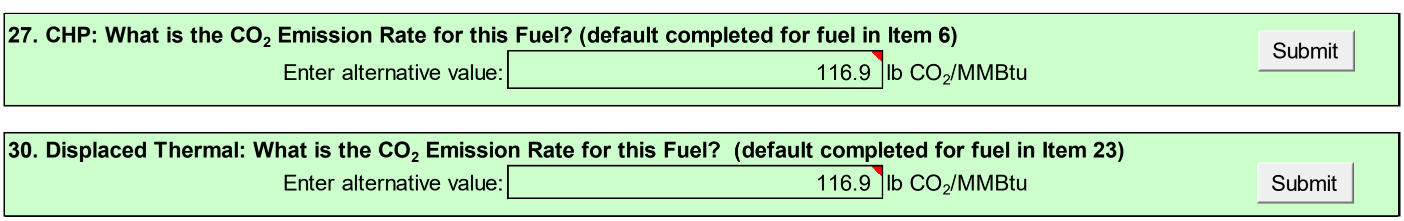
For this example, the AVERT profile was used and the system is assumed to be in the AVERT Mid-Atlantic Region (that also corresponds to the eGRID RFC East subregion).[18] AVERT factors have transmission and distribution (T&D) losses built in, so it is not necessary to fill that input. If using eGRID, the Partnership recommends using the eGRID value for grid losses from the appropriate U.S. interconnect power grid. There are five U.S. interconnect power grids (Eastern, Western, ERCOT, Alaska, and Hawaii), and the appropriate grid for this example is the Eastern grid, with average T&D losses of 5.4%.

Figure A-3: CHP Energy and Emissions Savings Calculator – Displaced Electricity



The final inputs re related to the emission characteristics of CHP and displaced boiler fuel. With the inputs entered up to this point, it is possible to calculate energy savings, and this final set of inputs enable emissions savings to be calculated. Default emissions for sulfur, NOx, and CO_2 can be selected based on the fuel and equipment inputs. In this case, to calculate CO2 savings from CHP, the default CO2 emissions rate for natural gas (116.9 lb/MMBtu) is entered in Inputs 27 and 30 (see Figure A-4).

Figure A-4: CHP Energy and Emissions Savings Calculator – Displaced Electricity



The equations for calculating fuel use and CO_2 emissions from displaced on-site thermal energy production are:

[18] Information about eGRID subregions and grid electricity emissions is contained in Appendix B.

Fuel Use from Displaced On-site Thermal Energy Production (Equation 3):

$$F_T = CHP_T / \eta_T$$
$$257{,}964 \text{ MMBtu/yr} = 206{,}371 \text{ MMBtu/yr} / 80\%$$

where:

F_T = Fuel Use from Displaced On-site Thermal Production (Btu)
CHP_T = CHP System Thermal Output (Btu)
η_T = Thermal Equipment Efficiency (%)

CO_2 Emissions from Displaced On-site Thermal Production (Equation 4):

$$C_T = F_T * EF_F$$
$$30{,}155{,}992 \text{ lbs } CO_2 = 257{,}964 \text{ MMBtu/yr} * 116.9 \text{ lb } CO_2\text{/MMBtu}$$

where:

C_T = CO_2 emissions from displaced on-site thermal production (lbs CO_2)
F_T = Thermal Fuel Savings (Btu)
EF_F = Fuel Specific Emissions Factor (lbs CO_2/MMBtu)

The total fuel use and CO_2 emissions of displaced grid electricity are calculated using the following equations:

Displaced Grid Electricity from CHP (Equation 5):

$$E_G = CHP_E / (1-L_{T\&D})$$
$$37{,}500 \text{ MWh/year} = 37{,}500 \text{ MWh/year} / (1 - 0)$$

where:

E_G = Displaced Grid Electricity from CHP (kWh)
CHP_E = CHP System Electricity Output (kWh)
$L_{T\&D}$ = Transmission and Distribution Losses (%)

Transmission and distribution losses are not factored into this equation since AVERT emissions factors already have these losses built in. If using eGRID factors, the loss value would be selected based on the site's interconnect region.

Fuel Use from Displaced Grid Electricity (Equation 6):

$$F_G = E_G * HR_G$$
$$300{,}437 \text{ MMBtu/year} = 37{,}500 \text{ MWh/year} * 8{,}012 \text{ Btu/kWh} / 1000^*$$

*Note: numbers may not equate exactly due to rounding.

where:

F_G = Fuel Use from Displaced Grid Electricity (Btu)
E_G = Displaced Grid Electricity from CHP (kWh)
HR_G = Grid Electricity Heat Rate (Btu/kWh)

CO_2 Emissions from Displaced Grid Electricity (Equation 7):

$$C_G = E_G * EF_G$$

$$57{,}744{,}100 \text{ lbs } CO_2 = 37{,}500 \text{ MWh/year} * 1{,}539.8 \text{ lb } CO_2\text{/MWh}$$

*Note: numbers may not equate exactly due to rounding.

where:

C_G = CO_2 Emissions from Displaced Grid Electricity (lbs)

E_G = Displaced Grid Electricity from CHP (MWh)

EF_G = Grid Electricity Emissions Factor (CO_2 lb/MWh)

A.2 Calculator Results

Once the user has entered all the information on the Inputs page and clicked the “Go to Results” button, the Results page is displayed. Figure A-5 illustrates the results for this example, which shows that the CHP system reduces overall fuel consumption by 115,546 MMBtu/year and CO_2 emissions by 18,065 tons/year. The two icons show the GHG equivalency of the savings compared to the emissions from passenger vehicles and the emissions generated from electricity used for single family homes’ energy use.

CHP Results

The results generated by the CHP Energy and Emissions Savings Calculator are intended for educational and outreach purposes only; it is not designed for use in developing emission inventories or preparing air permit applications.

The results of this analysis have not been reviewed or endorsed by the EPA CHP Partnership.

Table 1: Annual Energy Savings

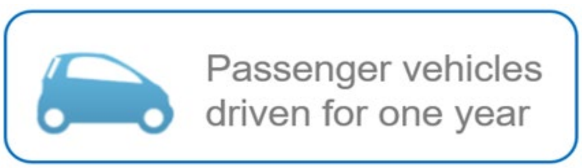
	CHP System	Displaced Electricity Production	Displaced Thermal Production	Fuel Savings	Percent Savings
Fuel Consumption (MMBtu/year)	442,855	300,437	257,964	115,546	21%
Equal to the annual energy consumption of this many passenger vehicles:				1,827	
Equal to the annual energy consumption from the generation of electricity for this many homes:				1,184	

Table 2: Annual Emissions Savings

	CHP System	Displaced Electricity Production	Displaced Thermal Production	Emissions Savings	Percent Savings
NO_x (tons/year)	20.35	13.77	51.59	45.01	69%
SO_2 (tons/year)	0.13	22.10	0.08	22.04	99%
CO_2 (tons/year)	25,885	28,872.05	15,078	18,065.17	41%
CH_4 (tons/year)	0.49	1.54	0.28	1.34	73%
N_2O (tons/year)	0.05	0.21	0.03	0.19	80%
Total GHGs (CO_2e tons/year)	25,910	28,970.92	15,093	18,153.44	41%
Equal to the annual GHG emissions from this many passenger vehicles:				3,557	
Equal to the annual GHG emissions from the generation of electricity for this many homes:				1,899	

Equal to the annual greenhouse gas emissions from 3,557 passenger vehicles.

Equal to the annual greenhouse gas emissions from the generation of electricity used by 1,899 homes.



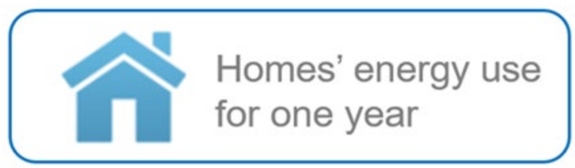


Figure A-5: CHP Energy and Emissions Savings Calculator – Fuel and Emissions Savings Results

Figure A-6 shows the outputs of the CHP system in more detail, and Figure A-7 shows the emissions rates for the CHP system as well as those from the displaced thermal production and displaced electricity generation. The equations for the relationship for total fuel savings and CO_2 savings are as follows:

Total Fuel Savings from CHP (Equation 1):

$$F_S = (F_T + F_G) - F_{CHP}$$

$$115{,}546 \text{ MMBtu/year} = (257{,}964 \text{ MMBtu/year} + 300{,}437 \text{ MMBtu/year}) - 442{,}855 \text{ MMBtu/year}$$

where:

F_S = Total Fuel Savings

F_T = Fuel Use from Displaced On-site Thermal Production

F_G = Fuel Use from Displaced Grid Electricity

F_{CHP} = Fuel Used by the CHP System

Total CO_2 Savings from CHP (Equation 2):

$$C_S = (C_T + C_G) - C_{CHP}$$

$$18{,}065 \text{ tons } CO_2 = (15{,}078 \text{ tons} + 28{,}872 \text{ tons}) - 25{,}885 \text{ tons}$$

where:

C_S = Total CO_2 Emissions Savings

C_T = CO_2 Emissions from Displaced On-site Thermal Production

C_G = CO_2 Emissions from Displaced Grid Electricity

C_{CHP} = CO_2 Emissions from the CHP System

Figure A-6: CHP Energy and Emissions Savings Calculator – CHP Outputs

Table 3: CHP Technology and Generation Profile

CHP Technology:	Combustion Turbine	
Fuel:	Natural Gas	
Unit Capacity:	5,000	kW
Number of Units:	1	
Total CHP Capacity:	5,000	kW
Operation:	7,500	hours per year
Heat Rate:	11,809	Btu/kWh HHV
CHP Fuel Consumption:	442,855	MMBtu/year
Duct Burner Fuel Consumption:	-	MMBtu/year
Total Fuel Consumption:	**442,855**	**MMBtu/year**
Total CHP Generation:	**37,500**	**MWh/year**
Useful CHP Thermal Output:	206,371	MMBtu/year for thermal applications (non-cooling)
	-	MMBtu/year for electric applications (cooling and electric heating)
	206,371	**MMBtu/year Total**

Table 4: Displaced Thermal Energy

Displaced On-Site Production for		Existing Gas Boiler
Thermal (non-cooling) Applications:	0.40	lb/MMBtu NOx
	0.00%	sulfur content
Displaced Electric Service (cooling and electric heating):		
	There is no displaced cooling service	

Table 5: Displaced Electricity

Displaced Electricity Profile:	AVERT Uniform EE Factors (2019 Data)	
eGRID/NERC Region:	AVERT - Mid-Atlantic	
Distribution Losses:	0.0%	
Displaced Electricity Production:	37,500	MWh/year CHP generation
	-	MWh/year Displaced Electric Demand (cooling)
	-	MWh/year Displaced Electric Demand (electric heating)
	-	MWh/year Transmission Losses
	37,500	**MWh/year Total**

Figure A-7: CHP Energy and Emissions Savings Calculator – Emissions Rates

Table 6: Annual Analysis for CHP

	CHP System: Combustion Turbine	Duct Burners (if applicable)	Total Emissions from CHP System
NO_x (tons/year)	20.35	-	20.35
SO_2 (tons/year)	0.13	-	0.13
CO_2 (tons/year)	25,885	-	25,885
CH_4 (tons/year)	0.49	-	0.49
N_2O (tons/year)	0.05	-	0.05
Total GHGs (CO_2e tons/year)	25,910	-	25,910
Carbon (metric tons/year)	6,400	-	6,400
Fuel Consumption (MMBtu/year)	442,855	-	442,855

Table 7: Annual Analysis for Displaced Thermal Production (non-cooling)

	Total Displaced Emissions from Thermal Production
NO_x (tons/year)	51.59
SO_2 (tons/year)	0.08
CO_2 (tons/year)	15,078
CH_4 (tons/year)	0.28
N_2O (tons/year)	0.03
Total GHGs (CO_2e tons/year)	15,093
Carbon (metric tons/year)	3,728
Fuel Consumption (MMBtu/year)	257,964

Table 8: Annual Analysis for Displaced Electricity Production

	Displaced CHP Electricity Generation	Displaced Electricity for Cooling	Displaced Electricity for Heating	Transmission Losses	Total Displaced Emissions from Electricity Generation
NO_x (tons/year)	13.77	-	-	-	13.77
SO_2 (tons/year)	22.10	-	-	-	22.10
CO_2 (tons/year)	28,872	-	-	-	28,872
CH_4 (tons/year)	1.541	-	-	-	1.541
N_2O (tons/year)	0.215	-	-	-	0.215
Total GHGs (CO_2e tons/year)	28,971	-	-	-	28,971
Carbon (metric tons/year)	7,139	-	-	-	7,139
Fuel Consumption (MMBtu/year)	300,437	-	-	-	300,437

Figure 1. Conventional Production Energy Flow Schematic

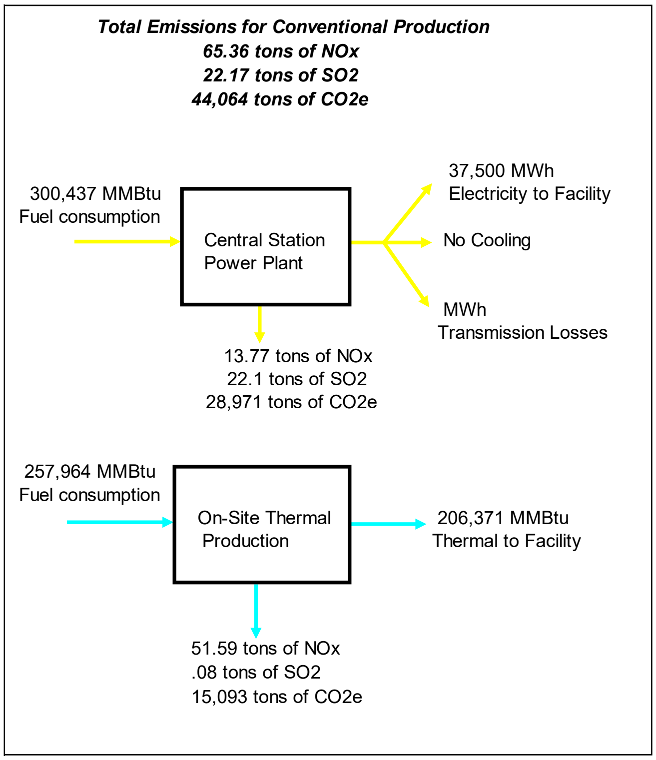
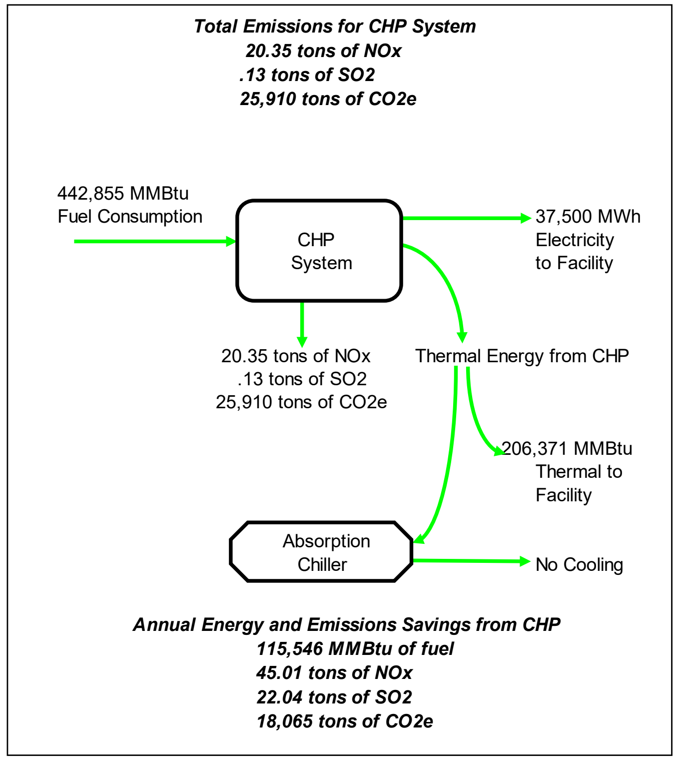


Figure 2. CHP System Energy Flow Schematic



APPENDIX B ESTIMATING DISPLACED GRID ELECTRICITY FUEL USE AND CO_2 EMISSIONS

This appendix supplements the methodology provided in Section 3.1.2, on how to estimate the displaced fuel use and CO_2 emissions from a CHP system, and provides information on how to select appropriate grid emission factors and grid electricity heat rate. The methodology can be summarized in three steps:

a) Calculate the fuel use and emissions from displaced separate heat and power (SHP) (i.e., grid-supplied electricity and on-site thermal generation such as a boiler)
b) Calculate the fuel use and emissions from CHP
c) Determine the displaced fuel use CO_2 emissions by subtracting Step (b) from Step (a)

To complete Step (a), the appropriate grid emission factor and grid electricity heat rate need to be selected. Grid-supplied electricity is generated by many sources with different fuels and heat rates and the sources that are reasonably expected to be displaced are determined to estimate the displaced fuel use and emissions. Once the grid emission factor is identified, the corresponding grid electricity heat rate is then used to determine the fuel savings from the CHP.

Key Takeaways

CEESC users are recommended to use AVERT factors by default, as they use a more rigorous and sophisticated method of estimating marginal displaced grid emissions. However, for end users that meet the following criteria, eGRID may be the preferred option:

- Heat rate information is desired for energy savings calculations (heat rate data is tied to eGRID subregions).
- Grid emissions data for CH_4 and N_2O is desired (found in eGRID, used in calculating CO_2-equivalent emissions).
- End user is located in one of four AVERTs region that corresponds to multiple eGRID subregions: Central and Mid-Atlantic that have two corresponding eGRID subregions, and Midwest and New York that have three corresponding eGRID subregions.
- End user is located in Alaska, Hawaii, or Puerto Rico.

The appendix is divided in the following sections:

i. Section B.1 - An explanation of how displaced grid emissions are estimated using load duration curves and grid dispatch order.
ii. Section B.2 - An overview of different methods of estimating displaced grid emissions
   a. Sophisticated Methods
   b. Intermediate Methods
   c. Basic Methods
iii. Section B.3 - An explanation of EPA's AVoided Emissions and geneRation Tool (AVERT) and how it can be used to estimate the grid electricity emissions factor (EF_G) to calculate the CO_2 emissions associated with displaced grid electricity from CHP.

iv. Section B.4 - An explanation of EPA's Emissions & Generation Resource Integrated Database (eGRID) as a resource for the grid electricity heat rate (HR_G) and the grid electricity emissions factor (EF_G) to calculate the fuel and CO_2 emissions associated with displaced grid electricity from CHP.

v. Section B.5 - The Partnership's recommendations on appropriate grid emission factors and grid electricity heat rate for the Emissions Calculator.

B.1 Load Duration Curves and Grid Dispatch Order

In a competitive electric market, generators are dispatched based on their bid price into the market (typically a function of the variable costs of generation, fuel, other consumable items, and operation and maintenance costs[19]). Generators serving the electric grid are dispatched in order of operating cost – lowest to highest:

- The generators with the lowest operating cost (nuclear, hydroelectric, and renewable) supply electricity to the grid whenever they are available. This is illustrated in Figure B-1, which shows that these generators operate continuously over the entire year.
- Combined cycle gas plants and coal generation are typically the grid resources with the next-lowest operating cost. While these plants largely serve as baseload plants, there are periods in which power must be scaled back or turned off during periods of low demand.
- Simple cycle natural gas and oil-fired systems typically have the highest operating costs, and therefore operate the fewest number of hours. They are also well suited for intermediate and peaking loads, as simple cycle systems can ramp up and down faster than combined cycle or coal systems to meet marginal loads. The generators with the very highest operating costs are typically only used to meet peaking loads.

When a CHP system is operated as a distributed generation source at a site, electricity demand from the wholesale electricity grid is reduced commensurate with the electricity the CHP generates. Certain generation resources, those at the top of the grid dispatch order, will no longer be required to serve the total customer load. These generation resources will now be used to serve incremental customer loads as grid demand changes through the day.

Demand for electricity varies widely over the year, and different types and sizes of generators are used to meet the varying load as it changes. A load duration curve represents the electric demand in MW for a specific region or subregion for all 8,760 hours in a year, arranged in descending order.

Figure B-1 shows a representative CHP load duration curve for a hypothetical power control area (PCA). The shape of the curve is typical of electric load duration curves. Demand (in MW) is indicated on the vertical axis and the number of hours of the year the system is operated are indicated on the horizontal axis. The area under the load duration curve represents the total generation for the year. The zones defined by colored bands represent a typical generating mix and dispatch order. The dispatch order is dependent on the demand and the relative costs of serving customer loads[20].

This example shows a simplified load duration curve created for a CHP system and dispatch order for the hypothetical PCA. The PCA has a maximum demand of 10,000 MW that occurs in the first hour of the annual

[19] Electric generator dispatch depends on system demand and the relative cost of operation, accessed at https://www.eia.gov/todayinenergy/detail.php?id=7590.

[20] One example is provided by the PJM regional transmission organization. Refer to "How PJM Schedules Generation to Meet Demand" at https://learn.pjm.com/three-priorities/keeping-the-lights-on/how-pjm-schedules-generation-to-meet-demand.aspx.

operation (between 0 hours and 1 hour on the curve). During this hour, all available resources, including peaking units, are deployed. At the 8,760-hour mark (the right-most point on the chart) that corresponds to load required to meet the last hour of the annual demand for this hypothetical year, the resources below the black line are used to meet a minimum demand of 4,000 MW.

Figure B-1: Hypothetical Power System Load Duration Curve and Dispatch Order

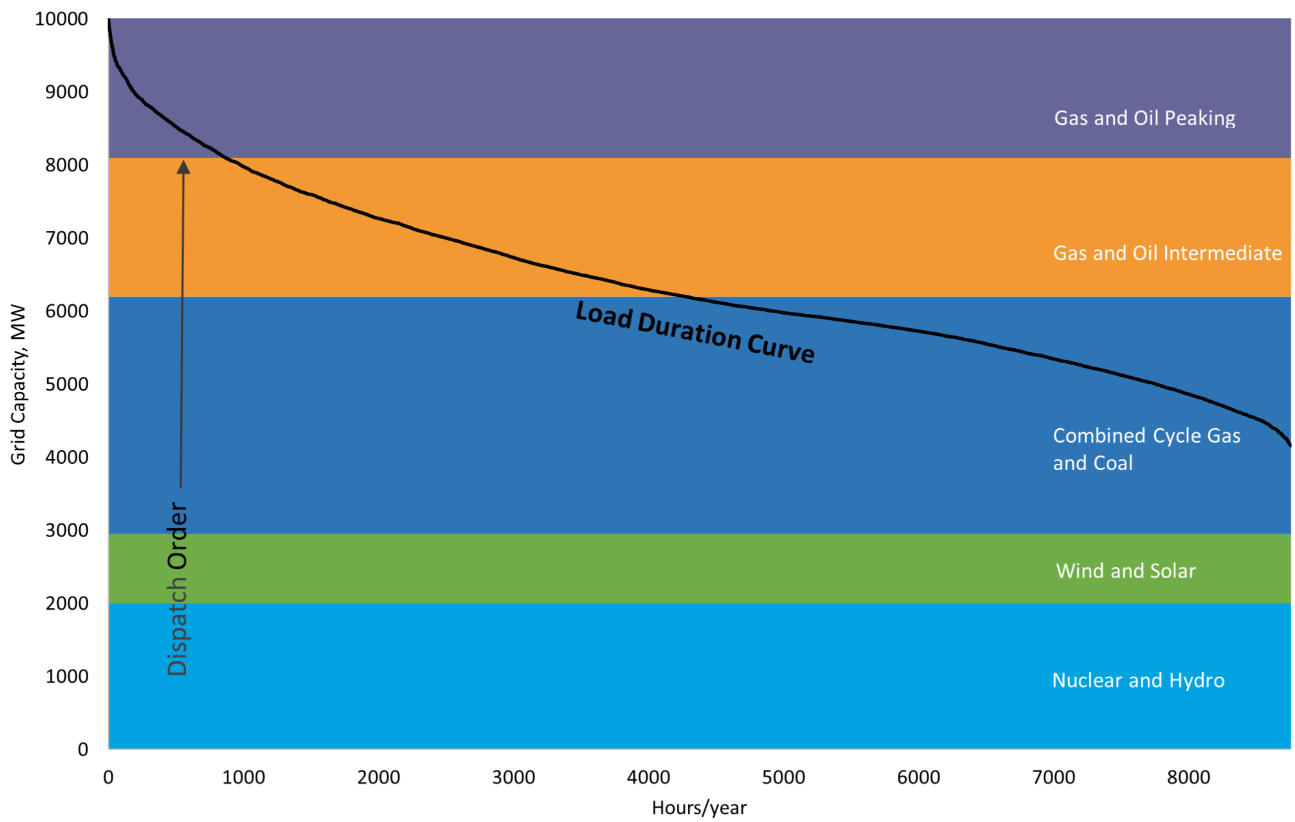


Figure B-2 illustrates the effect of CHP capacity that continuously avoids 1,000 MW of central power generation in the hypothetical PCA. For simplicity, it is assumed that the CHP system operates 24/7 for the entire year even though CHP systems may be offline for several days a year for planned or unplanned maintenance. In the figure, we observe the following:

i. Because the CHP capacity operates continuously, the load duration curve shifts downward to reflect the 1,000 MW reduction in demand for all hours of the year.

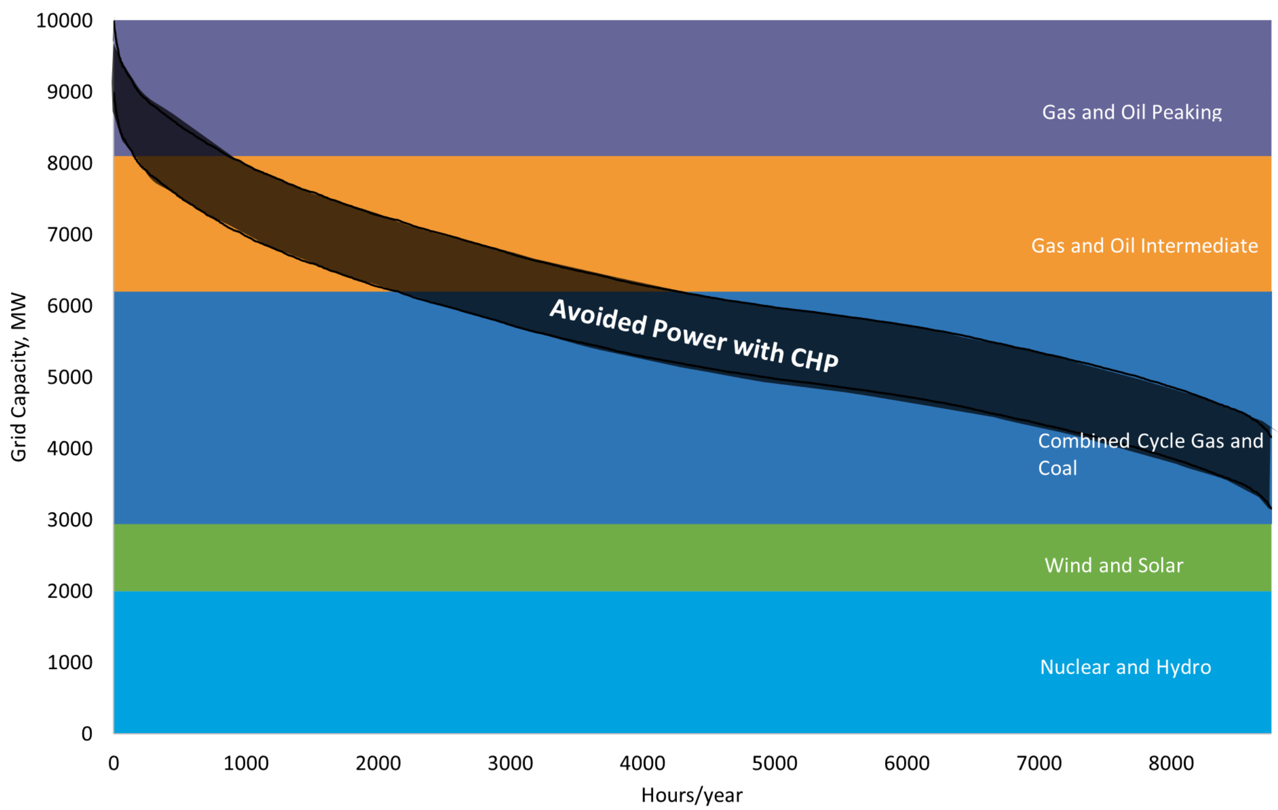
ii. Compared to the base case (the top curve), the additional CHP capacity displaces an equal amount of generation each hour that it runs, shifting the load curve down while it runs. The CHP system displaces power from the last unit of generation that would have been dispatched in each of these hours.

iii. Depending on the hour, the displaced generator could be a coal, oil, or gas steam unit, a combined cycle generator, a central station peaking turbine, or a reciprocating engine peaking unit.

iv. Generators with a lower dispatch order, such as nuclear, hydro, and renewables, are unaffected. These resources generate electricity whenever they are available so are unaffected by changes in power demand that result from CHP additions.

v. The grid generation (and corresponding emissions) displaced with CHP is therefore the output represented by the shaded area in the chart—a mix of mostly baseload and intermediate generation with some peaking generation, all from fossil fuel resources.

Figure B-2: Marginal Displaced Generation due to 1,000 MW of CHP

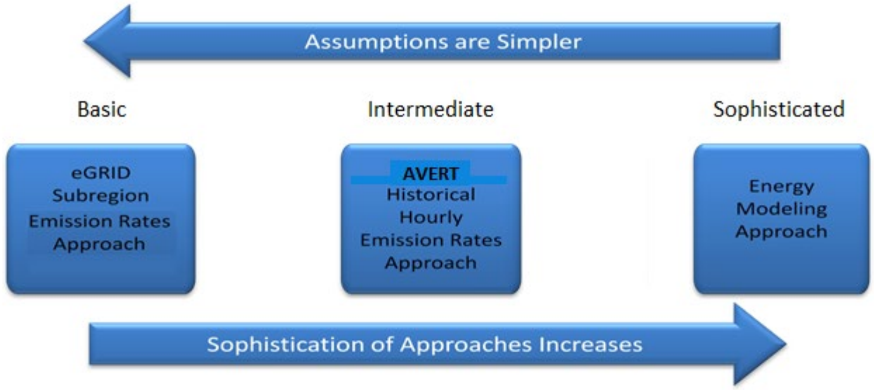


B.2 Methods for Estimating Displaced Grid Emissions

There are different methods that can be used to quantify emissions reductions from displaced grid generation, each answering different analytical questions with varying levels of rigor, assumptions, resource requirements, data needs, and temporal and spatial scales of emission outputs. Each method is intended to quantify the avoided or displaced emissions from grid system generation due to energy efficiency, renewable energy, or distributed energy resources (such as CHP) that displace grid electricity. The level of sophistication of each grid emissions quantification approach is inversely related to the complexity of assumptions in each approach. Figure B-3 below shows how the level of sophistication of the approaches increases as you go from basic straightforward emissions calculations to complex modeling.[21]

[21] U.S. EPA, Quantifying the Emissions and Health Benefits of Energy Efficiency and Renewable Energy, Part Two, Chapter 4, https://www.epa.gov/sites/production/files/2018-07/documents/mbg_2-4_emissionshealthbenefits.pdf

Figure B-3: Methods for Estimating Displaced Grid Emissions[22]



- ***Sophisticated methods*** use energy-related models that represent the interplay of futuristic assumptions within the electricity or energy system to determine emission impacts. To calculate the effects on emissions, these methods provide detailed forecasts of regional supply and demand in relation to multiple factors such as emissions controls, fuel prices, dispatch sequences and associated changes, and new generation resources. Sophisticated dispatch models result in more rigorous estimates of emissions impacts as compared to basic-to-intermediate methods, but these models and methods are resource intensive.
- ***Intermediate methods*** use hourly load profiles to reflect time-of-day impacts throughout the year and use electric generating unit (EGU)'s dispatch patterns to assess impacts. EPA's AVoided Emissions and geneRation Tool (AVERT) factors are derived taking this approach. By taking into account time-of-day impacts, intermediate methods can use historical data to capture the impact of current and certain future activities. Analysts have been known to use these methods to compare the emissions impacts of existing or planned energy efficiency and renewable energy policies and programs from the county to the state level such as agency staff and state air quality planners interested in assessing emission benefits incorporated into Clean Air Act plans to meet the National Ambient Air Quality Standards.
- ***Basic methods*** assume consistent energy savings throughout the year and assign marginal emissions rates or specific emissions rates for proxy unit types based on historical data rather than accounting for hourly load profiles for the year or considering dispatch patterns. EPA's Emissions & Generation Resource Integrated Database (eGRID[23]) factors are derived taking this approach. These methods offer a simplified analysis of capturing complex data and can be used to support activities where a snapshot of different emission factors are necessary. For example, eGRID data can be used for greenhouse gas registries and inventories, carbon footprinting, consumer information disclosure and analysis of changing power markets.

The CEESC is a location-specific tool that can use either AVERT or eGRID emissions factors to estimate displaced grid emissions and offer a preliminary analysis of emission reductions from CHP. The rest of this Appendix provides a better understanding on how both sets of emissions factors can be used in the CEESC.

[22] https://www.epa.gov/statelocalenergy/avoided-emissions-and-generation-tool-avert
[23] https://www.epa.gov/egrid

B.3 EPA's AVoided Emissions and geneRation Tool (AVERT)

EPA's AVoided Emissions and geneRation Tool (AVERT) is a web-based tool that uses an intermediate method to estimate the fine particulate matter ($PM_{2.5}$), carbon dioxide (CO_2), nitrogen oxides (NO_X), and sulfur dioxide (SO_2) emissions avoided at electric power plants by energy efficiency and renewable energy policies, programs, and projects. AVERT uses historical hourly emissions rates based on recent EPA data on EGUs' hourly generation and emissions reported through EPA's Acid Rain Program.[24] This method combines historical hourly generation and emissions with the hourly load profiles of energy resources to determine hourly marginal emissions rates and hourly changes in emissions.

Emissions and Heat Rate Data

When using AVERT, users receive the following outputs:

- NO_X emissions reductions
- SO_2 emissions reductions
- CO_2 emissions reductions
- Marginal Emissions Rates
- Emissions associated with power generation in the United States.

AVERT utilizes data collected by the EPA Clean Air Markets Division (CAMD) on fossil-fuel electric generating units subject to 40 CFR 75,[25] comprised of units greater than 25 MW and other units subject to the rule. Data collected and reported by CAMD includes the following:

- Plant
- State
- Electric generating company (EGC)
- Gross Generation
- Heat Input
- Emissions of NOx, SO_2, & CO_2

AVERT consists of historic sets of recent data compiled annually and enables analysis in near term future years. The generation data and related data categories provided by AVERT are based on consumed electricity and include the impact of transmission and distribution (T&D) losses (see Section 3.1.2 and Equation 5 for more information on T&D losses).

The AVERT data is aggregated into 14 regions (see Figure B-4), which are based on one or multiple balancing authorities. Each AVERT region consists of at least one balancing authority, with most encompassing multiple balancing authorities. AVERT regions generally represent sections of the grid that have similar resource mix and emissions characteristics and are similar to the regional assignments from EIA's 930 dataset. Alaska and Hawaii are not included in AVERT regions or analysis since there is limited data on units from the two states in the CAMD data.

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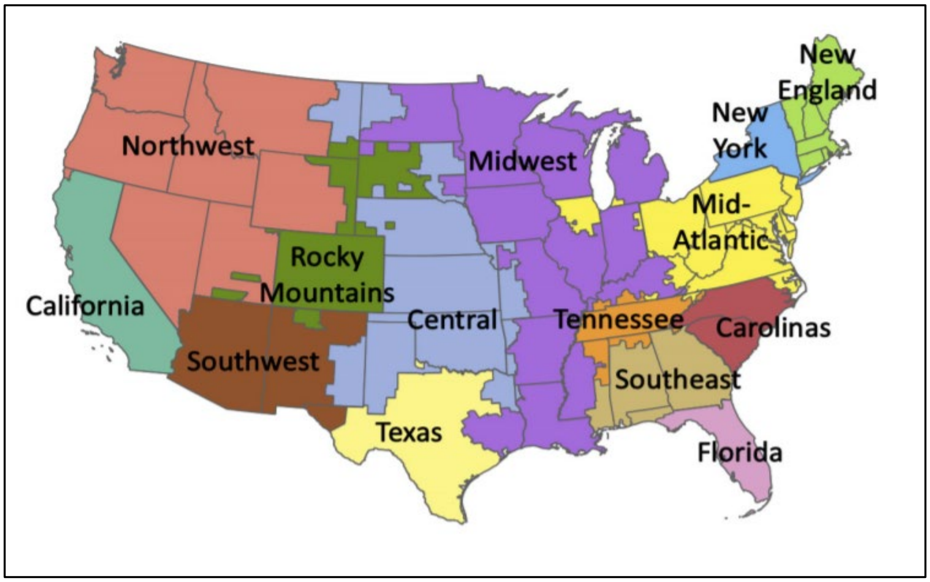
[24] See EPA's Power Sector Emissions Data at https://ampd.epa.gov/ampd/

[25] 40 CFR 75 accessed at https://www.ecfr.gov/cgi-bin/text-idx?SID=f2e2623eb620fa4e165b39dd865ff713&mc=true&node=pt40.18.75&rgn=div5#se40.18.75_12

Figure B-4: AVERT Region Map



AVERT Emissions Data

AVERT collects usage data at an hourly level from EGUs to understand which power plants are generating energy at a given time and how that impacts emissions. AVERT outputs displaced marginal grid emissions based on energy efficiency programs and improvements by estimating how they displace individual fossil fuel EGU in a region. AVERT provides displaced emissions data for CO_2, SO2, NOx, and PM2.5 emissions.

AVERT does not provide heat rates. For the purpose of the CEESC, when using the AVERT emission factors, heat rates are calculated by using eGRID Fossil Fuel Output heat rate values. AVERT regions that encompass multiple eGRID regions use a calculated heat rate proportional to the eGRID regions that comprise the AVERT region.

Selecting the Appropriate AVERT Emissions Factor

The AVERT tool can estimate specific emissions reductions based on user-supplied hourly kWh data for detailed planning and custom analysis that accounts for seasonal and time-of-day variations. However, EPA has also developed emissions factors for AVERT based on pre-defined load patterns and assuming a 0.5% displacement of the existing demand in each of AVERT's 14 regions. These regional emissions factors, estimating displaced grid emissions in units of pounds per MWh, are divided into six categories: wind (onshore and offshore), photovoltaic (PV) (utility and distributed), portfolio EE, and uniform EE. EPA recommends that these emissions factors be used for general estimates of avoided emissions from renewable energy or energy efficiency programs, policies, or projects.[26,27] A summary description of these factors are provided below and more details can be found in the AVERT manual.

- **Wind.** Both AVERT wind emissions factors are based on load patterns for wind farms following typical generation profiles with respect to wind resource availability in each region.

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[26] EPA, "Emissions Factors from AVERT", https://www.epa.gov/sites/production/files/2019-05/documents/avert_emission_factors_05-30-19_508.pdf

[27] EPA, "AVERT User Manual: Version 3.0", https://www.epa.gov/sites/production/files/2020-09/documents/avert_user_manual_09-12-20_508.pdf

- **PV.** AVERT PV emissions factors focus on the impact of rooftop and utility PV on grid emissions reductions. Each AVERT region has unique solar emissions factors based on the region's solar insolation and grid fossil fuel generation.
- **Portfolio EE.** Portfolio EE emissions represent avoided emissions for a typical portfolio of energy efficiency resources, incorporating seasonal and time-of-day differences in energy efficiency savings and comparing to grid fossil fuel generation.
- **Uniform EE.** Uniform EE factors are used for programs that provide consistent energy savings in the form of constant load reductions over the course of a year compared to grid fossil fuel generation.

Wind and PV factors represent highly variable loads that are not representative of CHP generation. Between the Portfolio EE and Uniform EE factors, Uniform EE factors more closely resemble CHP operation as they represent a constant non-variable reduction in grid electricity requirements. Most CHP systems operate consistently at or near full capacity, producing the same constant reduction in grid electricity. In Figure B-5, the load duration curve illustrates the approximate constant load reductions on the grid marginal emissions with AVERT's Uniform EE factors.

While Uniform EE factors most closely represent a system that is operating 24/7, they also provide a close representation of avoided emissions from CHP systems that primarily operate during day and evening hours. The Partnership conducted an analysis in 2018 to assess the difference between 24/7 operation and typical commercial operating regimes for daytime/evening CHP. The analysis showed that avoided grid emissions from CHP tracked closely to the Uniform EE factor for both operating regimes. Results of the analysis are summarized in Table B-1.

Figure B-5. Marginal Emissions Estimated with AVERT Uniform EE Factor

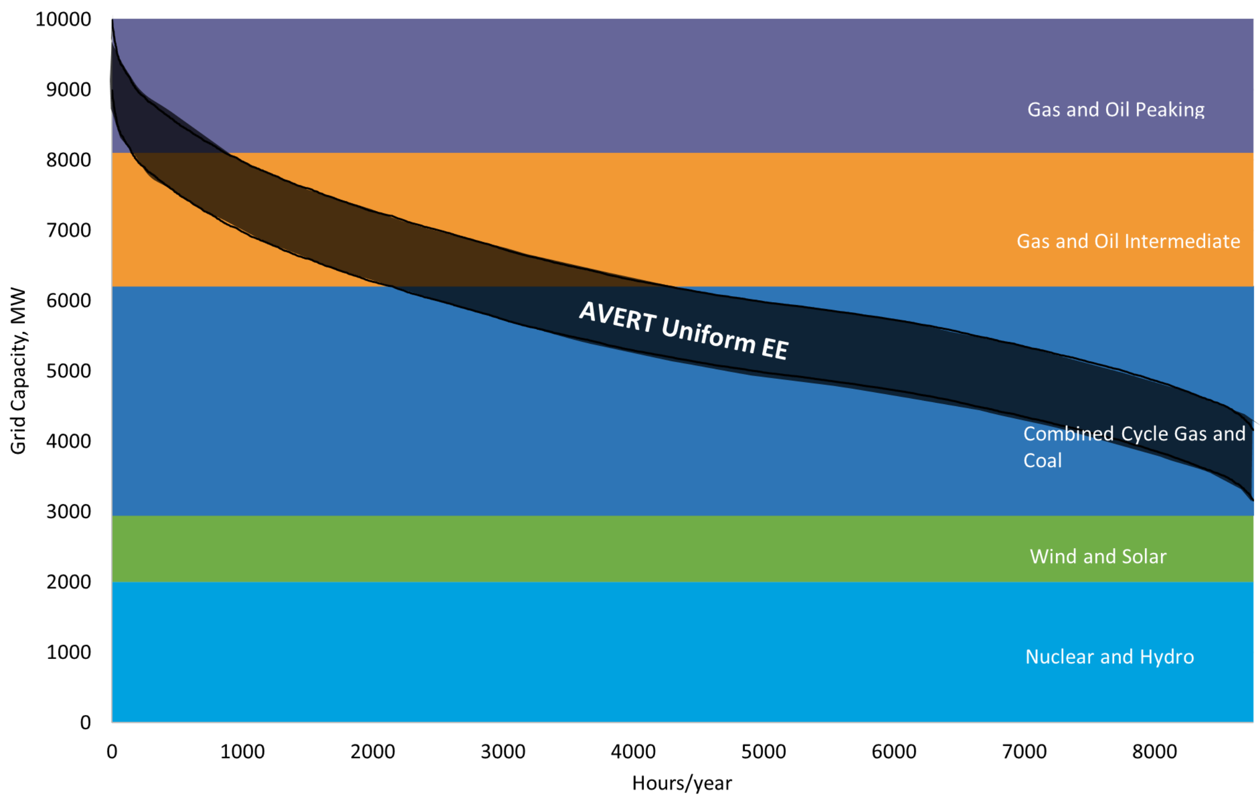


Table B-1. 2018 Analysis Comparing AVERT Uniform EE Factors to AVERT-Generated CHP Emissions Factors

AVERT Region	Uniform EE	CHP 24/7 Baseload	CHP Commercial
Northeast	1,231	1,201	1,226
Great Lakes/Mid-Atlantic	1,903	1,832	1,829
Southeast	1,630	1,613	1,619
Lower Midwest	1,897	1,857	1,835
Upper Midwest	2,013	1,971	1,944
Rocky Mountains	1,998	1,852	1,789
Texas	1,498	1,498	1,509
Southwest	1,354	1,306	1,290
Northwest	1,691	1,622	1,644
California	1,148	1,112	1,119

Table B-2 summarizes the latest uniform EE emissions factors for CO_2, NO_X, SO_2, and $PM_{2.5}$ in all AVERT regions.

Table B-2: 2019 AVERT Uniform EE Emissions Factors (lb/MWh)

AVERT Subregion	Avoided CO2 Rate	Avoided NOx Rate	Avoided SO2 Rate	Avoided PM 2.5 Rate
National	1,550	0.85	0.92	0.11
California	1,061	0.27	0.06	0.04
Carolinas	1,664	1.00	0.64	0.12
Central	1,800	1.29	1.36	0.08
Florida	1,087	0.35	0.23	0.08
Mid-Atlantic	1,540	0.73	1.18	0.13
Midwest	1,860	1.26	1.67	0.16
New England	1,104	0.20	0.09	0.03
New York	1,090	0.36	0.17	0.05
Northwest	1,636	1.15	0.75	0.09
Rocky Mountains	1,904	1.05	0.58	0.04
Southeast	1,563	0.83	0.34	0.09
Southwest	1,544	0.95	0.29	0.08
Tennessee	1,479	0.56	0.74	0.10
Texas	1,282	0.54	0.65	0.06

B.4 EPA's Emissions & Generation Resource Integrated Database (eGRID)

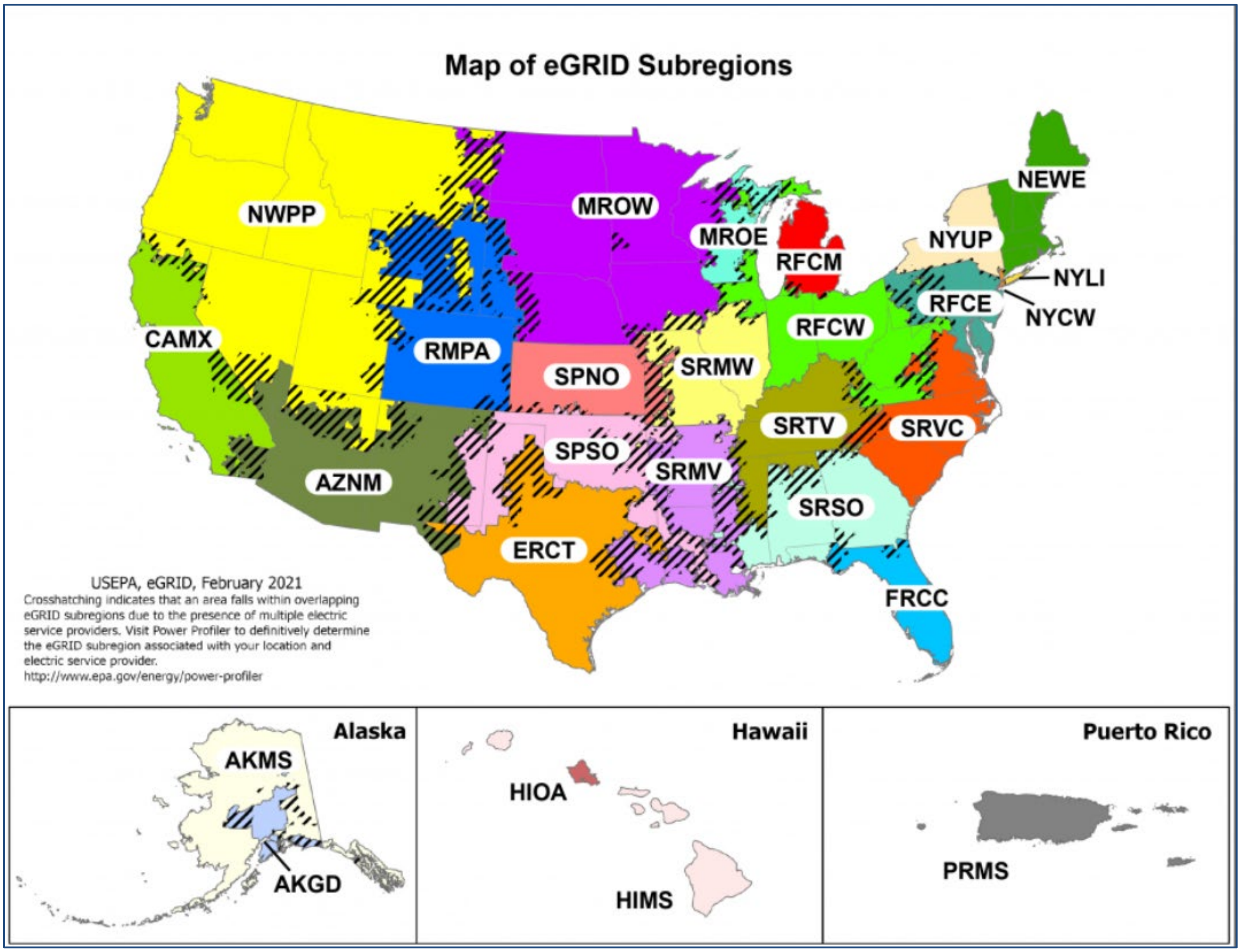
EPA's eGRID[28] provides an emission profile of almost all grid-connected power plants in the United States. The data is provided at the combustion unit and generator levels and then combined at the plant level. The plant level data are then aggregated to state, U.S. total, and three types of power grid regions: balancing authority area (generally smaller regions of the power grid in which all power plants are managed to balance power system demand and supply); eGRID subregion; and NERC region, as designated by the North American Electric Reliability Corporation (plus Alaska, Hawaii, and Puerto Rico).

[28] EPA has generated and published detailed information on electricity generation and emissions since 1998. The most recent edition of eGRID was released in 2021 and contains data collected in 2019. More information is available at https://www.epa.gov/egrid.

eGRID data is based on data from the DOE's Energy Information Administration (EIA) Forms EIA-860 and EIA-923, and EPA's Power Sector Emissions Data. Emission data from EPA is integrated with generation data from EIA to produce data in pounds of emissions per megawatt-hour of electricity generation (lb/MWh) that allow direct comparison of the environmental attributes of electricity generatione. GRID provides data on generation (MWh), fuel use, plant heat rate, resource mix (e.g., generation from coal, gas, nuclear, wind, solar), and emissions associated with power generation in the U.S. eGRID consists of historic sets of recent data; it does not include future projections of the operating characteristics of generating units. The generation data and related data categories provided by eGRID are based on generated electricity, not consumed (i.e., delivered) electricity and therefore do not include the impact of transmission and distribution (T&D) losses (see Section 3.1.2 and Equation 5 for more information on T&D losses).

The eGRID data is aggregated to a subregion level based on NERC regions, balancing authorities, and transmission systems. There are 27 eGRID subregions (see Figure B-6) in eGRID2019. eGRID subregions generally represent sections of the grid that have similar resource mix and emissions characteristics.

Figure B-6: eGRID Subregion Map[29]



Emissions and Heat Rate Data[30]

eGRID presents the heat rate of each listed plant, and emissions data aggregated by fuel type and by generation source category (e.g., all fossil fuels). eGRID also presents emissions data for several pollutants—carbon dioxide (CO_2), nitrogen oxides (NO_X), sulfur dioxide (SO_2), methane (CH_4), nitrous oxide (N_2O) and mercury (Hg)—in the form of emissions rates on an electricity output basis (lb/MWh) and on a fuel input basis (lb/MMBtu).

[29] Many of the boundaries shown on this map are approximate because they are based on transmission systems rather than on strict geographical boundaries.

[30] Notes on Terminology. For the sake of clarity and consistency, eGRID emission rates (lb/MWh) are referred to in this appendix as emissions factors. Also note that, because this document addresses how to calculate avoided CO2 emissions, all subsequent references to eGRID emissions data in this appendix refer to CO2 emissions only.

Three types of eGRID generation rates are discussed in this appendix[31]:

- **Total Output**

  The Total Output rates are based on data for all power generation regardless of energy source (i.e., fossil, nuclear, hydro, and renewables) within a defined region or subregion. One CO_2 emissions factor (lb/MWh) and one heat rate (Btu/kWh) value are associated with each region or subregion.

- **Fossil Fuel Output**

  The Fossil Fuel Output rates are based on data for power generation from fossil fuel-fired plants within a defined region or subregion. One CO_2 emissions factor (lb/MWh) and one heat rate (Btu/kWh) value are associated with the category for each region or subregion. EPA characterizes this emissions factor as "an estimate to determine how much emissions could be avoided if energy efficiency and/or renewable energy displaces fossil fuel generation." [32] The EPA CHP Partnership recommends the emissions factor and heat rate from this category to determine emissions and fuel use from displaced grid electricity when evaluating CHP systems.[33]

- **Non-baseload Output**

  The term "baseload" refers to generating plants that supply electricity to the grid even when demand for electricity is relatively low. Baseload plants are usually brought online to provide electricity to the grid regardless of the level of demand and they generally operate continuously except when undergoing routine or unscheduled maintenance.

  eGRID calculates non-baseload factors by weighting each plant's emissions and generation according to its capacity factor (a plant's annual generation divided by its *potential* annual generation at full capacity). The generation and emissions from plants that operate most of the time (that is, baseload plants with annual capacity factors greater than 0.8) are excluded. All the generation and emissions from fuel-based plants that operate infrequently during the year (for example, peaking units with capacity factors less than 0.2) are included. A portion of the emissions and generation from the remaining fuel-based plants (i.e., those with capacity factors between 0.2 and 0.8) are included, with higher portions used for plants with lower capacity factors and lower portions used for plants with higher capacity factors.

eGRID also provides emissions factors by specific fossil fuel type (i.e., for coal-, natural gas-, and oil-fired generating plants). These emissions factors are useful in assessing the different impacts of fossil fuels but they are rarely used to evaluate the relationship between CHP and displaced grid electricity emissions. Table B-3 provides the latest 'all generation', 'all fossil', and 'non-baseload' emissions factors from eGRID.

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[31] In addition to the three eGRID generation categories listed here, eGRID also includes an "annual combustion output" category. This category is not discussed in this appendix since it was primarily developed to estimate NO_x and SO_2 emissions from combustion generating units that are dispatched to respond to marginal increases in electricity demand, and thus not applicable to CO2 calculations involving CHP.

[32] EPA eGRID Technical Support Document. February 2021. https://www.epa.gov/egrid/egrid-technical-support-document

[33] The CEESC is available at: https://www.epa.gov/chp/chp-energy-and-emissions-savings-calculator

Selecting the Appropriate eGRID Aggregation Level

When selecting the appropriate grid electricity emissions factor (EF_G) and heat rate (HR_G) required by Equations 6 and 7 in Section 3.1.2, the aggregation level is based on the electricity supplied to the site where the CHP system is located. The Partnership therefore recommends using the eGRID emissions factor and heat rate for the eGRID subregion where the CHP system is located. The Partnership bases this recommendation on the following factors:[34]

- In general, eGRID subregions represent sections of the grid that have similar resource mix and emissions characteristics, operate as an integrated entity, and support most of the demand in the subregion with power generated within the subregion.
- State-level aggregation omits generation that is imported into the state and does not account for generation that is exported to other states. State-level aggregation is no longer provided as an option in the CEESC.
- Emissions factors and heat rates by aggregated by NERC region (or the U.S. average) do not reflect significant regional variations in emissions from generation and therefore do not accurately reflect the fuel use and emissions impacts of generation displaced by a specific CHP system.

Selecting the Appropriate eGRID Emissions and Heat Rate Category

When selecting the eGRID emissions and heat rate category, it is important to select the category that contains generator level data representative of those that are displaced by CHP systems. At first glance, each of the eGRID categories mentioned above (i.e., total output, fossil fuel output, and non-baseload) may seem like reasonable choices for HR_G in Equation 6 and EF_G in Equation 7 of Section 3.1.2; however, the Partnership recommends using the following factors:

- the eGRID fossil fuel output emissions factor and heat rate for the eGRID subregion where the CHP system is located for baseload CHP (i.e., greater than 6,500 annual operating hours), and
- the eGRID non-baseload emissions factor and heat rate for the eGRID subregion where the CHP system is located for CHP systems with relatively low annual capacity factors (i.e., less than 6,500 annual operating hours) and with most generation occurring during periods of high system demand.

Estimating the energy and emissions displaced by CHP requires an estimate of the nature of generation displaced using power produced by the CHP system. Accurate estimates can be made using a power system dispatch model to determine how emissions for generation in a specific eGRID subregion are impacted by the shift in the system demand curve and generation mix resulting from the addition of CHP systems. However, these models are complex and costly to run.

[34] Rothschild, S. et al., "The Value of eGRID and eGRIDweb to GHG Inventories", https://www.epa.gov/sites/production/files/2015-12/documents/thevalueofegrid.pdf

Table B-3: eGRID Ninth Edition CO_2 Emissions factors and Heat Rates by NERC Region and eGRID Subregion (2019-year data)

NERC Region and Subregions	All Generation		All Fossil Average		Non-Baseload	
	Heat Rate (Btu/kWh)	CO_2 Emission Factor (lb/MWh)	Heat Rate (Btu/kWh)	CO_2 Emission Factor (lb/MWh)	Heat Rate (Btu/kWh)	CO_2 Emission Factor (lb/MWh)
Alaska Systems Coordinating Council	6,738	1,008	9,682	1,448	9,526	1,424
ASCC Alaska Grid	7,848	1,114	9,428	1,353	9,287	1,333
ASCC Miscellaneous	3,646	549	10,141	1,526	10,102	1,520
FRCC All	6,677	861	7,629	1,005	7,812	1,030
Hawaiian Islands Coordinating Council	9,800	1,605	10,134	1,743	9,814	1,688
HICC Miscellaneous	8,058	1,186	10,253	1,686	9,421	1,549
HICC Oahu	10,192	1,695	10,097	1,761	9,770	1,704
Midwest Reliability Organization	5,790	1,034	9,789	1,770	9,462	1,710
MRO East	8,490	1,503	9,676	1,775	8,600	1,578
MRO West	5,647	1,098	10,030	1,977	9,165	1,807
Northeast Power Coordinating Council	3,852	425	7,462	893	7,766	929
NPCC Long Island	10,209	1,209	9,385	1,130	10,802	1,301
NPCC New England	4,627	489	7,050	841	7,043	840
NPCC NYC/Westchester	4,665	554	7,640	910	8,536	1,016
NPCC Upstate NY	2,088	232	7,163	865	7,372	890
PR – Puerto Rico	9,893	1,537	10,131	1,574	10,219	1,588
PRMS- Puerto Rico Miscellaneous	9,893	1,537	10,131	1,574	10,219	1,588
Reliability First Corporation	5,851	965	8,877	1,490	9,869	1,657
RFC East	4,918	695	8,012	1,155	8,585	1,238
RFC Michigan	7,033	1,189	9,046	1,577	10,138	1,767
RFC West	6,092	1,068	9,324	1,653	10,334	1,832

NERC Region and Subregions	All Generation		All Fossil Average		Non-Baseload	
	Heat Rate (Btu/kWh)	CO2 Emission Factor (lb/MWh)	Heat Rate (Btu/kWh)	CO2 Emission Factor (lb/MWh)	Heat Rate (Btu/kWh)	CO2 Emission Factor (lb/MWh)
Southeast Reliability Corporation	6,025	912	8,470	1,317	8,542	1,328
SERC Midwest	7,989	1,584	10,045	1,996	9,869	1,961
SERC Mississippi Valley	5,919	807	7,858	1,099	8,584	1,200
SERC South	6,556	969	8,572	1,315	9,061	1,390
SERC Tennessee Valley	5,493	950	9,197	1,603	8,978	1,565
SERC Virginia/Carolina	4,708	675	8,320	1,248	8,995	1,349
SPP North	5,579	1,070	10,137	1,949	10,190	1,959
SPP South	6,537	1,002	9,494	1,473	9,952	1,544
Texas Regional Entity	5,821	870	8,275	1,243	8,539	1,283
TRE All	5,827	869	8,262	1,238	8,521	1,277
Western Electricity Coordinating Council	4,912	769	9,001	1,450	8,567	1,380
WECC California	3,876	453	7,461	941	7,642	964
WECC Northwest	4,209	715	9,491	1,651	9,295	1,617
WECC Rockies	6,949	1,243	10,020	1,800	8,791	1,579
WECC Southwest	6,162	952	9,041	1,407	9,285	1,445

As stated previously, eGRID provides two rates that can be used to estimate the mix of generation that is displaced using clean energy technologies such as CHP: the fossil fuel output rates and the non-baseload output rates. Use of the total output rates is not appropriate since it includes a substantial amount of baseload generation that is not offset by CHP projects.

Figures B-7 and B-8 show the eGRID fossil fuel and non-baseload resources mapped onto the hypothetical load duration curve. The fossil fuel resources contain a large amount of combined cycle and coal plants that primarily produce baseload power.

Figure B-7: eGRID Fossil Fuel Resources Mapped onto Hypothetical Load Curve

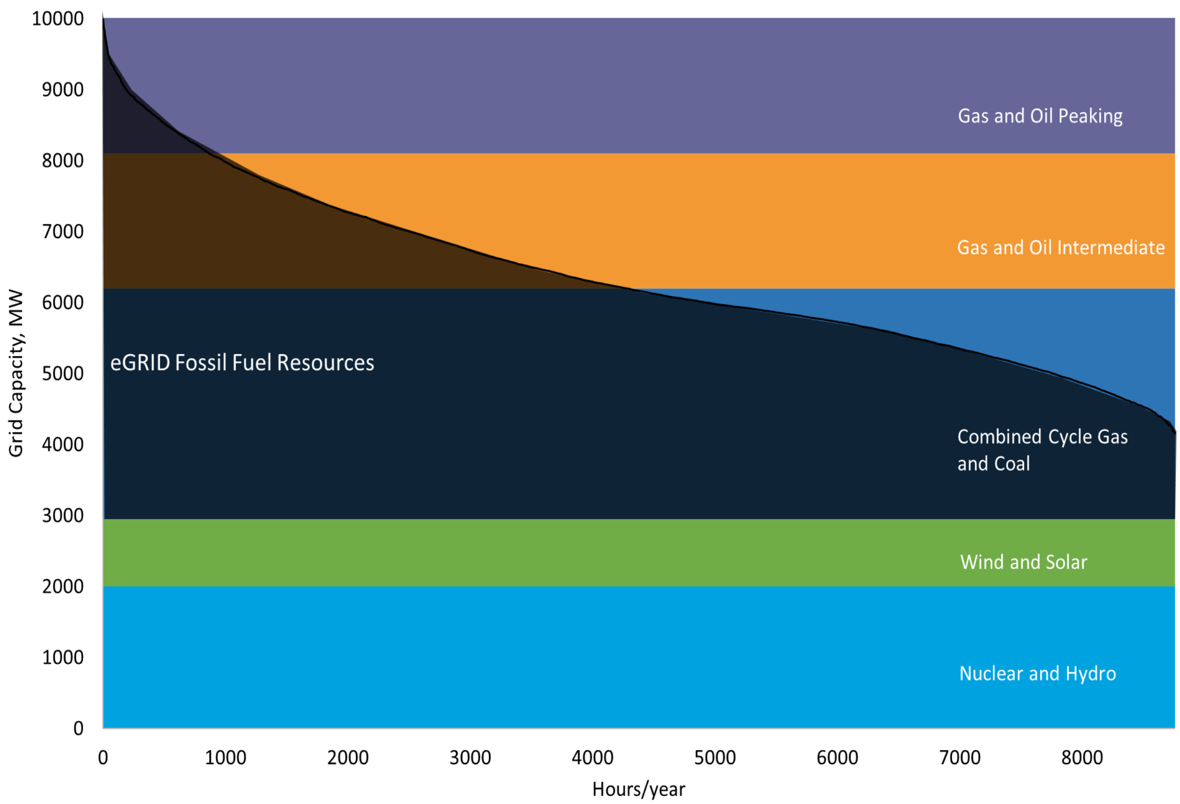
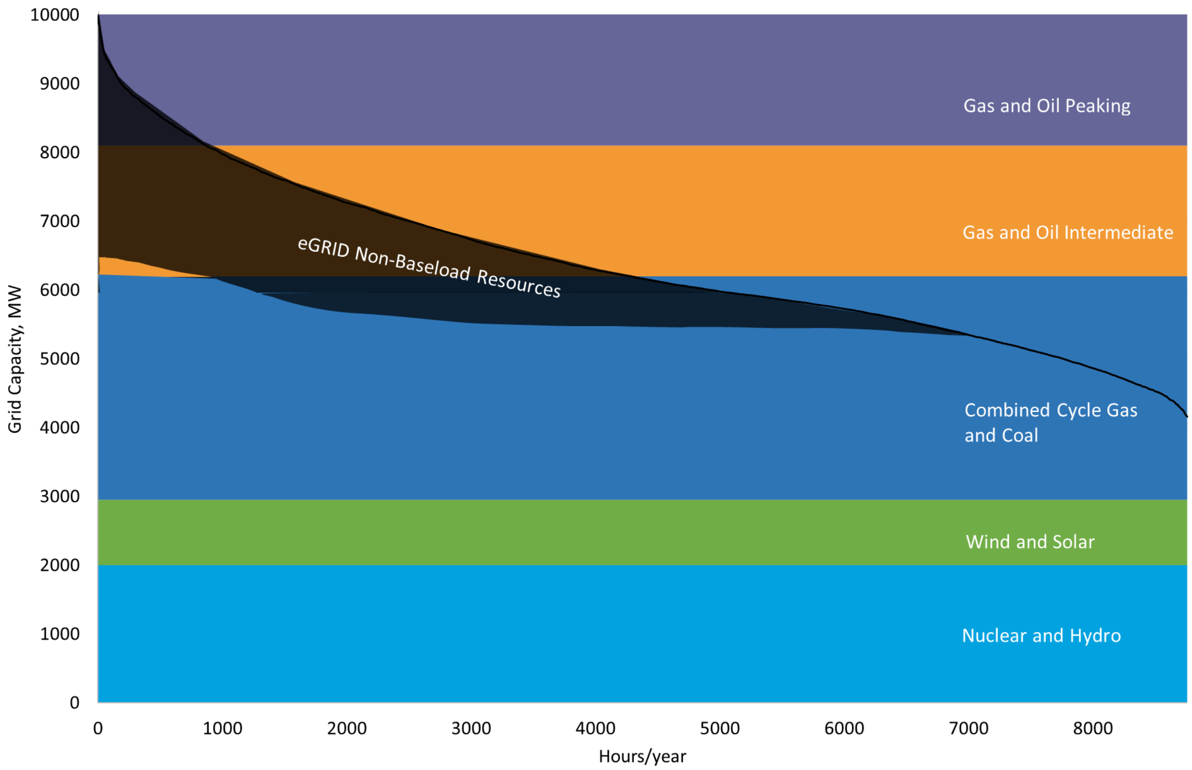


Figure B-8 shows an approximation of the eGRID non-baseload resources. This curve more closely represents displaced grid emissions from CHP systems that are primarily operating during peak day and evening hours, typically around 5,000 hours/year.

Figure B-8: eGRID Fossil Fuel Resources Mapped onto Hypothetical Load Curve



B.5 Recommendations

CEESC users have the option to select either AVERT or eGRID emissions factors. For the purpose of the CEESC, the differences between AVERT and eGRID emission factors do not result in a significant difference in the final estimate. There are variations for a few regional levels. Some AVERT regions map with multiple eGRID subregions and for a CHP system located in this regions, a user will see variations in generation sources and associated emission factors. The key differences between eGRID and AVERT emissions factors, and how they are used in the CEESC, are summarized in Table B-4.

Table B-4: Comparison of eGRID and AVERT Emissions Factors for Estimating CHP Energy and Emissions Savings with CEESC

Tool Characteristics	eGRID	AVERT
Regions	27 subregions including Alaska, Hawaii, and Puerto Rico	14 regions, continental United States
Emissions Factors Used	Fossil Fuel or Non-Baseload	Uniform EE
T&D Losses	Select from menu of options	Included in AVERT factors
Heat Rate	Included for both factors	Estimated using eGRID subregion heat rates
Pollutants	NO_X, SO_2, CO_2, CH_4, N_2O	NO_X, SO_2, CO_2 (others estimated with eGRID data)

The Partnership compared the difference in emissions factors and associated grid emission estimates between eGRID2019 factors (2019 data with T&D losses added) and 2020 AVERT factors (2019 data with T&D losses built in). The analysis showed that while there are some regional differences, the three factors – eGRID All Fossil, eGRID Non-Baseload, and AVERT Uniform EE – all track relatively close to each other on average across the U.S. Table B-5 shows a comparison of AVERT and eGRID carbon emission factors, both using 2019 data.

Both AVERT and eGRID emission factors provide estimates for displaced grid emissions that can be used to help approximate the energy and emissions savings associated with CHP installations.

CEESC users are recommended to use AVERT factors by default, as they use a more rigorous and sophisticated method of estimating marginal displaced grid emissions. However, for end users that meet the following criteria, eGRID may be the preferred option:

- Heat rate information is desired for energy savings calculations (heat rate data is tied to eGRID subregions).
- Grid emissions data for CH_4 and N_2O is desired (found in eGRID, used in calculating CO_2-equivalent emissions).
- End user is located in one of four AVERTs region that corresponds to multiple eGRID subregions: Central and Mid-Atlantic that have two corresponding eGRID subregions, and Midwest and New York that have three corresponding eGRID subregions.
- End user is located in Alaska, Hawaii, or Puerto Rico.

Table B-5. Comparison of AVERT Uniform EE Factors with Corresponding eGRID Subregion Factors

		eGRID 2019 with T&D losses (lb/MWh CO_2)								
AVERT Emission Factors (lb/MWh CO_2, 2019)		eGRID2019 Subregion Match			eGRID2019 Subregion Match (if more than 1 eGRID subregion)			eGRID2019 Subregion Match (if more than 2 eGRID subregion)		
AVERT Region	Uniform EE	eGRID subregion	Fossil-Fired	Non-baseload	eGRID subregion	Fossil-Fired	Non-baseload	eGRID subregion	Fossil-Fired	Non-baseload
California	1,061	CAMX	992	1,016	-	-	-	-	-	-
Carolinas	1,664	SRVC	1,319	1,426	-	-	-	-	-	-
Central	1,800	SPNO	2,060	2,070	SPSO	1,473	1,544	-	-	-
Florida	1,087	FRCC	1,063	1,088	-	-	-	-	-	-
Mid-Atlantic	1,540	RFCE	1,221	1,309	RFCW	1,653	1,832	-	-	-
Midwest	1,860	SRMW	2,110	2,073	MROW	1,977	1,807	SRMV	1,099	1,200
New England	1,104	NEWE	889	888	-	-	-	-	-	-
New York	1,090	NYUP	914	941	NYLI	1,130	1,301	NYCW	910	1,016
Northwest	1,636	NWPP	1,746	1,710	-	-	-	-	-	-
Rocky Mountains	1,904	RMPA	1,896	1,664	-	-	-	-	-	-
Southeast	1,563	SRSO	1,390	1,469	-	-	-	-	-	-
Southwest	1,544	AZNM	1,483	1,523	-	-	-	-	-	-
Tennessee	1,479	SRTV	1,695	1,655	-	-	-	-	-	-
Texas	1,282	ERCT	1,305	1,346	-	-	-	-	-	-
U.S. Average	1,558	U.S. Average	1,476	1,497	-	-	-	-	-	-