Analytical Models of Carbon Capture-Enabled Power Plant Configurations in GREET

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OVERVIEW

This document presents the analytical expressions used to characterize the thermal efficiency, effective power output, CO_2 emissions and CO_2 emissions intensity of utility-scale electric power plants with amine-based postcombustion carbon capture and sequestration (CCS) for implementation in the Argonne National Laboratory GREET model.[1] The analytical expressions are adopted from Supekar and Skerlos.[2] The document also includes the values of various input parameters embedded in the analytical expressions that are used in the GREET implementation, as well as key assumptions and data sources associated with those values.

CCS PLANT CONFIGURATION DESCRIPTIONS

Several CCS plant configurations are possible for both coal and natural gas combined cycle power plants based on combinations of steam and electricity sources for the capture unit, fuel used in each source, steam generation equipment and process details, and the extent of CO_2 capture. For GREET, two of the most likely configurations are chosen based on their economic viability. Details on each of these configurations including process diagrams, as well as the derivations behind the analytical expressions presented in the subsequent sections can be found in the Supekar and Skerlos[2] paper.

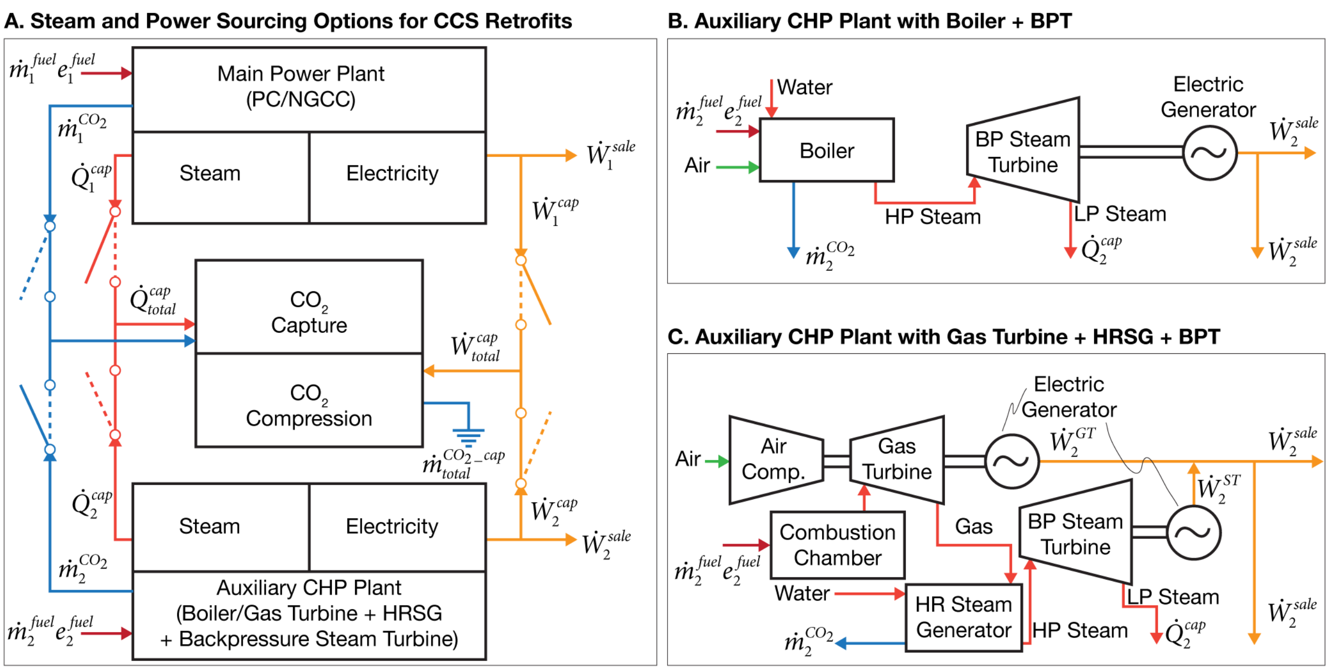

Figure 1. (A) Steam and electricity sourcing from the main and/or auxiliary combined heat and power (CHP) plants for carbon capture. Quantities associated with the main and auxiliary plants are indexed by the subscripts 1 and 2 respectively. Nomenclature explained in Table 1. Key energy and mass flows associated with (B) boiler-based auxiliary CHP plants and (C) gas turbine-based CHP plants. Figure reprinted with permission from Supekar, S. D.; Skerlos, S. J. Sourcing of Steam and Electricity for Carbon Capture Retrofits. *Environ. Sci. Technol.* **2017**, acs.est.7b01973 DOI: 10.1021/acs.est.7b01973. Copyright 2017 American Chemical Society.

Integrated CCS

In an integrated carbon capture plant, the energy demand of the CO_2 capture unit is met from within the main power plant, and no additional fuel is burnt for CCS. Low-pressure (LP) steam is obtained by bleeding the crossover connection between the intermediate-pressure (IP) and LP stages of the main turbine, and electricity for the capture plant is obtained from the main generator. Depending on the design, pre-capture efficiency, and residual life of the power plant, the integrated retrofit approach can achieve significant levels of waste heat utilization through elaborate networks of heat exchangers, which would in turn govern the effective heat demand for the CO_2 regeneration step.

CCS with an Auxiliary CHP Plant

An auxiliary combined heat and power (CHP) plant can burn additional fuel in a boiler or a gas turbine to generate steam and electricity to meet the total capture heat demand, which is called heat matching, or the total capture electricity demand, which is called power matching. The CO_2 generated from the combustion of this additional fuel may or may not be captured depending on operational, environmental, and economic factors. Based on the findings reported in Supekar and Skerlos[2] for various post-CCS power plant performance metrics, a power-matched auxiliary gas turbine-based CHP plant without CO_2 capture from the auxiliary plant was chosen as the alternative option to an integrated retrofit.

The gas turbine-based auxiliary burns natural gas in a gas turbine followed by a heat recovery steam generator (HRSG) to generate high-pressure (HP) steam. HP steam is expanded through a non-condensing backpressure turbine (BPT) to obtain LP steam for the capture process. Electric power from the BPT and the gas turbine is used to meet a 100% of the carbon capture process electricity demand. LP steam from the auxiliary plant meets some of the steam demand of the capture process, with the remaining steam demand met from the main plant. The mass and energy flows in the auxiliary CHP are shown in Figure 1C. When using natural gas in the auxiliary CHP for CCS in a coal-fired power plant, flue gases from the auxiliary CHP plant are assumed to *not* be captured since the capture process is designed for flue gases from coal combustion, which have a different CO_2 partial pressure.

Performance Metrics

Analytical expressions for the following performance metrics are developed for implementation in GREET. Thermal performance metrics include overall plant efficiency and the efficiency of the main plant with CCS (only in cases where an auxiliary CHP is used), difference in power output compared to an identical plant (same heat input) without CCS, and fuel flow rates. Environmental performance metrics include effective % reduction in CO_2 emissions from the plant relative to an identical plant without CCS and the CO_2 emissions intensity of useful output power from the plant. *All performance metrics are normalized by net electric power output of the power plant.*

NOMENCLATURE, PARAMETER VALUES, AND DATA SOURCES

Table 1. Variables, parameters, and performance metrics used in the GREET implementation of the analytical expressions from Supekar and Skerlos[2] for power plants with CCS. Parameters values and their sources are also provided.

Symbol	Definition	Value	Units	Comments
η_{plant}^{noCCS}	Power plant efficiency defined as useful electric output per unit thermal input before CCS	39.3[3], 55.7[4]	%-points	Higher end for subcritical coal plants
η_{plant}^{CCS}	Power plant efficiency after CCS	Calculated	MJ_e / MJ_{th}	See eqs. (1) and (7)
$\Delta\dot{W}^{sale}$	Loss in useful power output of plant relative to power output before CCS	Calculated	%	See eqs. (2) and (11)
$\Delta\dot{C}_{eff}$	Effective reduction in overall plant CO_2 emissions	Calculated	%	See eqs. (5) and (16); this value is different from capture efficiency of the process
$\hat{c}_{eff}^{power}$	Effective CO_2 intensity of power output after CCS	Calculated	kg CO_2 / kWh	See eqs. (6) and (17)
$\bar{\dot{m}}^{fuel}$	Fuel flow rate per unit power output	Calculated	kg fuel / s / MW_e	See eqs. (3), (4), (12) – (15)
η^{cap}	Efficiency of the carbon capture process	90%[5]	MJ_e / MJ_{th}	Typical value for amine solvents; different from effective CO_2 reduction
c^{fuel}	CO_2 content of fuel	2.47 for coal and 2.65 for natural gas[1]	kg CO_2 / kg fuel	Matched with GREET values
e^{fuel}	Lower heating value of fuel	26.33 for coal and 47.13 for natural gas[1]	MJ_{th} / kg fuel	Matched with GREET values

Symbol	Definition	Value	Units	Comments
q^{cap}	Heat demand per unit of CO_2 captured	3.0[5] for coal and 3.2[6] for natural gas CCS plants	MJ_{th} / kg CO_2	This value depends on the type of capture process and solvent chosen, and the extend of heat recovery feasible without diverting or changing any heat flows that would affect the pre-capture efficiency of the plant; these values are latest values for MEA
w^{cap}	Electricity demand per unit of CO_2 captured	0.355[5,7] for both coal and natural gas CCS plants	MJ_e / kg CO_2	Assumes multistage compression from 2 bar to 150 bar
α	Power equivalence factor defined as the ratio of electric output lost per unit of thermal energy bled from the turbine in the form of steam	0.22[8]	MJ_e / MJ_{th}	–
η_2^{GT}	Efficiency of auxiliary gas turbine in converting heat from combustion gases to electricity from the gas turbine alone	38.3[9]	%-points	Siemens SGT 800 turbine selected based on MW_e size required for power-matched auxiliary CHP plant
f	Air to fuel ratio in the combustor	46.5[9]	kg air / kg fuel	Calculated based on rated output and exhaust gas flow rate in the turbine specifications
$h_2^{gas_{GT_{exit}}}$	Enthalpy of combustion flue gas at the exit of the auxiliary gas turbine	0.842[9]	MJ_{th} / kg gas	Based on gas temperature of 544 °C as per specifications for SGT 800
$h_2^{gas_{HRSG_{exit}}}$	Enthalpy of gas at the outlet of the HRSG in auxiliary plant	0.312[10]	MJ_{th} / kg gas	Calculated assuming 37.7 °C temperature of HRSG outlet gas
η_2^{HRSG}	Efficiency of HRSG at converting input heat from combustion gases to heat in HP steam in auxiliary plant	79%[10]	%-points	Calculated assuming an inlet water at 0.6 bar and 32 °C, and a gas-to-steam ratio of 8

Symbol	Definition	Value	Units	Comments
$h_2^{steam_{HP}}$	Enthalpy of HP steam in the auxiliary plant	3.497[6,11]	MJ_{th} / kg steam	HRSG steam output temperature required is 544 °C at 80 bar based on Siemens SST 800 backpressure turbine specifications
$h_2^{steam_{LP}}$	Enthalpy of LP steam in the auxiliary plant	2.748[12]	MJ_{th} / kg steam	Assumes 5 bar saturated steam needed for CO_2 regeneration
h_2^{cond}	Enthalpy of condensate in the auxiliary plant	0.134	MJ_{th} / kg water	Based on inlet water conditions of 0.6 bar and 32 °C
η_2^{BPT}	Efficiency of non-condensing backpressure turbine in the auxiliary plant	75%[13]	%-points	Value adjusted for feedwater pump losses
β	Binary parameter representing whether or not CO_2 from auxiliary plant is captured	0 or 1	Dimensionless	0 implies no CO_2 capture from auxiliary plant, and 1 implies CO_2 from auxiliary plant is captured

ANALYTICAL EQUATIONS FOR PERFORMANCE OF POWER PLANT WITH CCS

Equations for Integrated CCS

Overall plant efficiency (%-points)

$$\eta_{plant}^{CCS} = \eta_{plant}^{noCCS} - \left(\eta^{cap} \left(\frac{c_1^{fuel}}{e_1^{fuel}} \right) \left(w_1^{cap} + \alpha q_1^{cap} \right) \right) \tag{1}$$

Power plant derating (%)

$$\Delta \dot{W}^{sale} = \eta^{cap} \left(\frac{c_1^{fuel}}{e_1^{fuel}} \right) \frac{\left(w_1^{cap} + \alpha q_1^{cap} \right)}{\eta_{plant}^{noCCS}} \tag{2}$$

Fuel flow rates (kg fuel / s / MW_e electric output *without* CCS)

$$\bar{\dot{m}}_1^{fuel} = \frac{1}{\eta_{plant}^{noCCS} e_1^{fuel}} \tag{3}$$

Fuel flow rates (kg fuel / s / MW_e electric output *with* CCS)

$$\bar{\dot{m}}_1^{fuel} = \left(\frac{1}{\eta_{plant}^{noCCS} e_1^{fuel} - \eta^{cap} c_1^{fuel} \left(w_1^{cap} + \alpha q_1^{cap} \right)} \right) \tag{4}$$

Effective CO_2 reduction (%)

$$\Delta \dot{C}_{eff} = \eta^{cap} \tag{5}$$

Effective CO_2 intensity of electric power output (kg CO_2 / kWh)

$$\hat{c}_{eff}^{power} = \frac{\left(1 - \eta^{cap} \right) \left(\frac{c_1^{fuel}}{e_1^{fuel}} \right)}{\eta_{plant}^{noCCS} - \left(\eta^{cap} \left(\frac{c_1^{fuel}}{e_1^{fuel}} \right) \left(w_1^{cap} + \alpha q_1^{cap} \right) \right)} \times 3.6 \times 10^6 \tag{6}$$

Equations for Power-Matched CCS with Auxiliary CHP Plant

Overall plant efficiency (%-points)

$$\eta_{plant}^{CCS} = \frac{\eta_{plant}^{noCCS} - \dfrac{\alpha\Psi}{e_1^{fuel}}}{1 + \left(\dfrac{e_2^{fuel}}{e_1^{fuel}}\right)\left(\dfrac{1}{\Theta}\right)} \tag{7}$$

Here, Θ and Ψ are defined as follows. Note that Θ has units of MJ_{th} / MJ_e, and Ψ has units of MJ_{th} / kg fuel.

$$\Theta = \frac{1}{\eta^{cap} w_1^{cap} c_1^{fuel}} \left(\begin{array}{l} e_2^{fuel}\eta_2^{GT} + \left(\dfrac{h_2^{steam_{HP}} - h_2^{steam_{LP}}}{h_2^{steam_{HP}} - h_2^{cond}}\right)\left(h_2^{gas_{GT_{exit}}} - h_2^{gas_{HRSG_{exit}}}\right)(1+f)\eta_2^{BPT}\eta_2^{HRSG} \\ -\beta\eta^{cap} w_2^{cap} c_2^{fuel} \end{array} \right) \tag{8}$$

$$\Psi = \eta^{cap} c_1^{fuel} q_1^{cap} + \frac{\beta\eta^{cap} c_2^{fuel} q_2^{cap}}{\Theta} - \frac{1}{\Theta}\left(\frac{h_2^{steam_{LP}}}{h_2^{steam_{HP}} - h_2^{cond}}\right)(1+f)\left(h_2^{gas_{GT_{exit}}} - h_2^{gas_{HRSG_{exit}}}\right)\eta^{HRSG} \tag{9}$$

Efficiency of the main plant

$$\eta_{main\_plant}^{CCS} = \eta_{plant}^{noCCS} - \frac{\alpha\Psi}{e_1^{fuel}} \tag{10}$$

Power plant derating (%)

$$\Delta \dot{W}^{sale} = \frac{\alpha\Psi}{\eta_{plant}^{noCCS} e_1^{fuel}} \tag{11}$$

Fuel flow rates (kg fuel / s / MW_e electric output *without* CCS)

$$\bar{\dot{m}}_1^{fuel} = \frac{1}{\eta_{plant}^{noCCS} e_1^{fuel}} \tag{12}$$

$$\bar{\dot{m}}_2^{fuel} = \frac{1}{\Theta}\left(\frac{1}{\eta_{plant}^{noCCS} e_1^{fuel}}\right) \tag{13}$$

Here, Θ is given by eq. (8).

Fuel flow rates (kg fuel / s / MW_e electric output *with* CCS)

$$\bar{\dot{m}}_1^{fuel} = \left(\frac{1}{\eta_{plant}^{noCCS} e_1^{fuel} - \alpha\Psi}\right) \tag{14}$$

$$\bar{\dot{m}}_2^{fuel} = \frac{1}{\Theta}\left(\frac{1}{\eta_{plant}^{noCCS} e_1^{fuel} - \alpha\Psi}\right) \tag{15}$$

Here, Θ is given by eq. (8) and Ψ is given by eq. (9).

Effective CO_2 reduction (%)

$$\Delta\dot{C}_{eff} = \eta^{cap} - \left(\frac{1}{\Theta}\left(\frac{c_2^{fuel}}{c_1^{fuel}}\right)\left(1 - \beta\eta^{cap}\right)\right) \tag{16}$$

Effective CO_2 intensity of electric power output (kg CO_2 / kWh)

$$\hat{c}_{eff}^{power} = \frac{\left(1-\eta^{cap}\right)\left(\frac{c_1^{fuel}}{e_1^{fuel}}\right) + \left(1-\beta\eta^{cap}\right)\left(\frac{c_1^{fuel}}{e_1^{fuel}}\right)\left(\frac{1}{\Theta}\right)}{\eta_{plant}^{noCCS} - \frac{\alpha\Psi}{e_1^{fuel}}} \times 3.6 \times 10^6 \tag{17}$$

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