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Analysis of U.S. EPA's Green House Gas Equations C-8, Y-4, H-1, and C-1

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EPA's GREEN HOUSE GAS EQUATION (C-8) FOR METHANE

Methane is a crucial greenhouse gas that substantially affects the environment. And that is why there are several mentions of methane under different subparts of 40 CFR Part 98. Even though there are several different formulas to calculate the methane emission, all of those somehow represent the same approach behind them. First, the annual CH_4 emissions can be calculated for each type of fuel by using Equation C-8:

$$CH_4 = 1 * 10^{-3} * Fuel * HHV * EF \qquad (Eq. C-8)$$

$CH_4 =$ Annual CH4 emissions from the combustion of a particular type of fuel (metric tons).

Fuel = Mass or volume of the fuel combusted, either from company records or directly measured by a fuel flow meter, as applicable (mass or volume per year).

HHV = Default high heat value of the fuel from Table C-1 of this subpart; alternatively, for Tier 3, if actual HHV data are available for the reporting year, you may average these data using the procedures specified in paragraph (a)(2)(ii) of this section and use the average value in Equation C-8 (mmBtu per mass or volume).

EF = Fuel-specific default emission factor for CH_4, from Table C-2 of this subpart (kg CH4 or N2O per mmBtu).

1 × 10−3 = Conversion factor from kilograms to metric tons.

This formula is almost identical to Equation C-1 meaning that we will get exactly the same Cobb-Douglas Production Function, Marginal Product, and Isoquants as before. But unlike CO2, CH_4 has a lower number of source fuel types that are mentioned in *Table C-2 to Subpart C of Part 98 - Default CH4 and N2O Emission Factors for Various Types of Fuel* that is given in the Appendix segment of this article.

Now, emission calculation is also incorporated under 40 CFR Part 98 Subpart Y - Petroleum Refineries where the methane emissions are calculated from flared gas. From equation Y-4:

$$CH_4 = (CO_2 \times \frac{EmF_{CH4}}{EmF}) + CO_2 \times \frac{0.02}{0.98} \times \frac{16}{44} \times f_{CH4} \qquad (Eq.Y-4)$$

Where:

CH_4 = Annual methane emissions from flared gas (metric tons CH4/year).

CO_2 = Emission rate of CO_2 from flared gas calculated in paragraph (b)(1) of this section (metric tons/year).

EmF_{CH4} = Default CH_4 emission factor for "Fuel Gas" from Table C-2 of subpart C of this part (General Stationary Fuel Combustion Sources) (kg CH4/MMBtu).

EmF = Default CO_2 emission factor for flare gas of 60 kg CO2/MMBtu (HHV basis).

0.02/0.98 = Correction factor for flare combustion efficiency.

16/44 = Correction factor ratio of the molecular weight of CH_4 to CO_2.

f_{CH4} = Weight fraction of carbon in the flare gas prior to combustion that is contributed by methane from measurement values or engineering calculations (kg C in methane in flare gas/kg C in flare gas); default is 0.4.

This equation is related to CO_2 emission rate from equation Y-2:

$$CO_2 = 0.98 \times 0.001 \sum_{p=1}^{n} [\,(Flare)_p \times (HHV)_p \times EmF\,] \qquad (Eq.Y-2)$$

Where:

CO2 = Annual CO2 emissions for a specific fuel type (metric tons/year).

0.98 = Assumed combustion efficiency of a flare.

0.001 = Unit conversion factor (metric tons per kilogram, mt/kg).

n = Number of measurement periods. The minimum value for n is 52 (for weekly measurements); the maximum value for n is 366 (for daily measurements during a leap year).

p = Measurement period index.

(Flare)p = Volume of flare gas combusted during measurement period (million (MM) scf/period). If a mass flow meter is used, you must also measure molecular weight and convert the mass flow to a volumetric flow as follows: Flare[MMscf] = 0.000001 × Flare[kg] × MVC/(MW)p, where MVC is the molar volume conversion factor [849.5 scf/kg-mole at 68 °F and 14.7 psia or 836.6 scf/kg-mole at 60 °F and 14.7 psia depending on the standard conditions used when determining (HHV)p] and (MW)p is the average molecular weight of the flare gas combusted during the measurement period (kg/kg-mole).

(HHV)p = Higher heating value for the flare gas combusted during measurement period (British thermal units per scf, Btu/scf = MMBtu/MMscf). If measurements are taken more frequently than daily, use the arithmetic average of measurement values within the day to calculate a daily average.

EmF = Default CO2 emission factor of 60 kilograms CO2/MMBtu (HHV basis).

MATHEMATICAL ANALYSIS OF EQUATION C-8

The Equation C-8 can be transformed into a **Cobb-Douglas** production function model. The Equation C-8 can be redefined as below:

$$Y = A * M^{\alpha} * T^{\beta}$$

where:

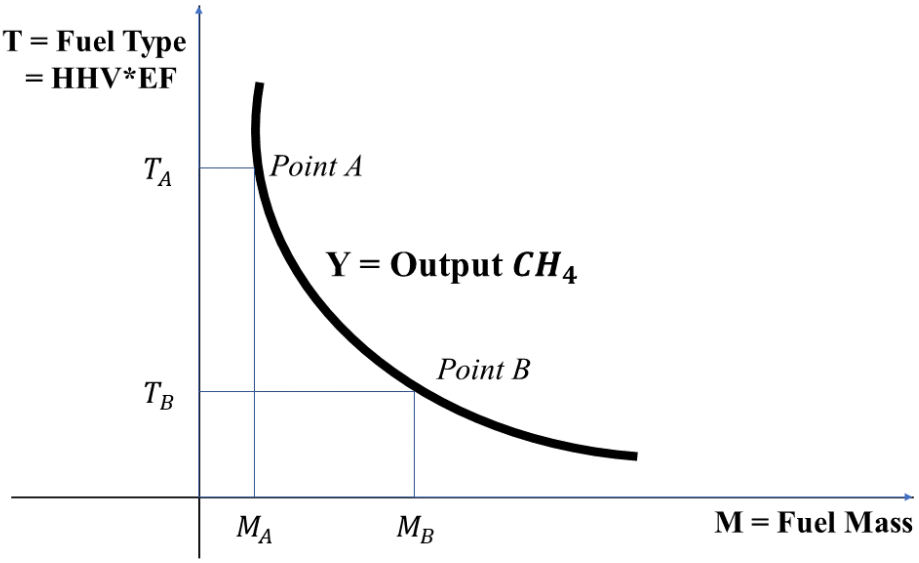
Y = Annual CH_4 emissions from the combustion of a particular type of fuel (metric tons)

M = Mass or volume of fuel combusted per year (**Based on Fuel Mass**)

T = HHV * EF (**Based on Fuel Type**)

A = $1 * 10^{-3}$

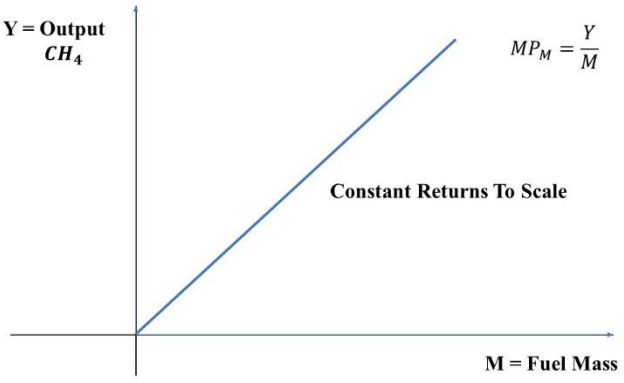
$\alpha = \beta = 1$



This gives a similar expression mentioned in 1.3 section of this article. This illustrates that the Methane emission can be transformed into a Cobb-Douglas production function model which would give us the CH_4 emission output as a function of inputs between the fuel mass and fuel type. This production function would be strictly monotonic and strictly convex.

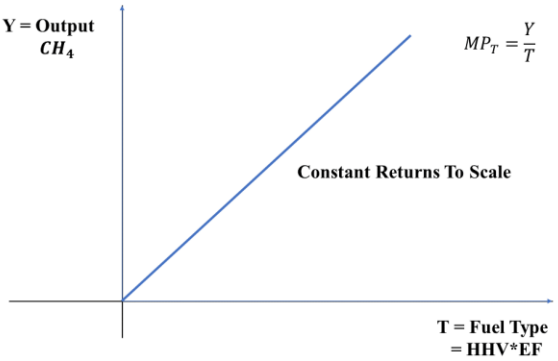
So, the Marginal Product of Fuel Mass,

$$MP_M = \frac{dY}{dM} = A * T$$
$$= \frac{A * T * M}{M}$$
$$= \frac{Y}{M}$$



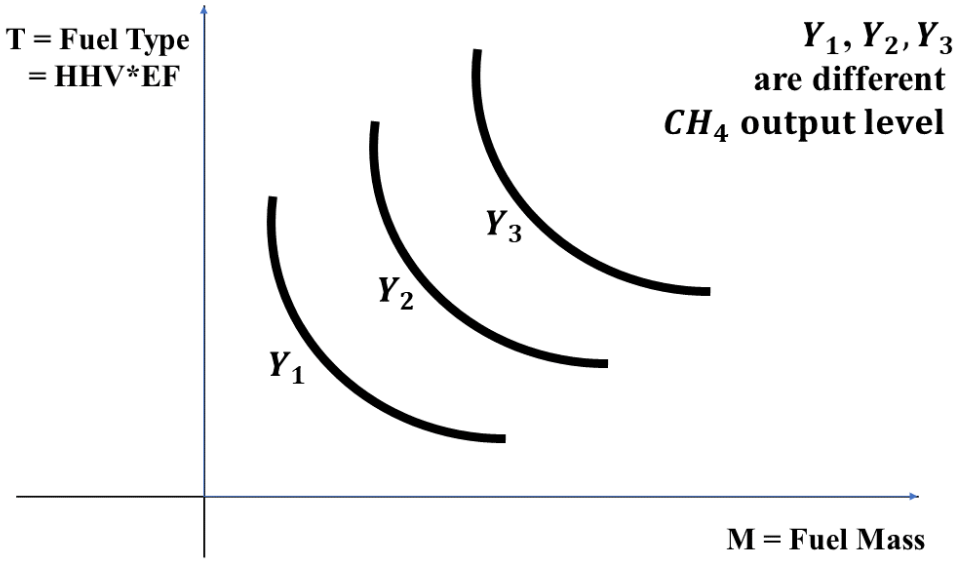
Again, the Marginal Product of Fuel Type,

$$MP_T = \frac{dY}{dT} = A * M$$
$$= \frac{A * T * M}{T}$$
$$= \frac{Y}{T}$$

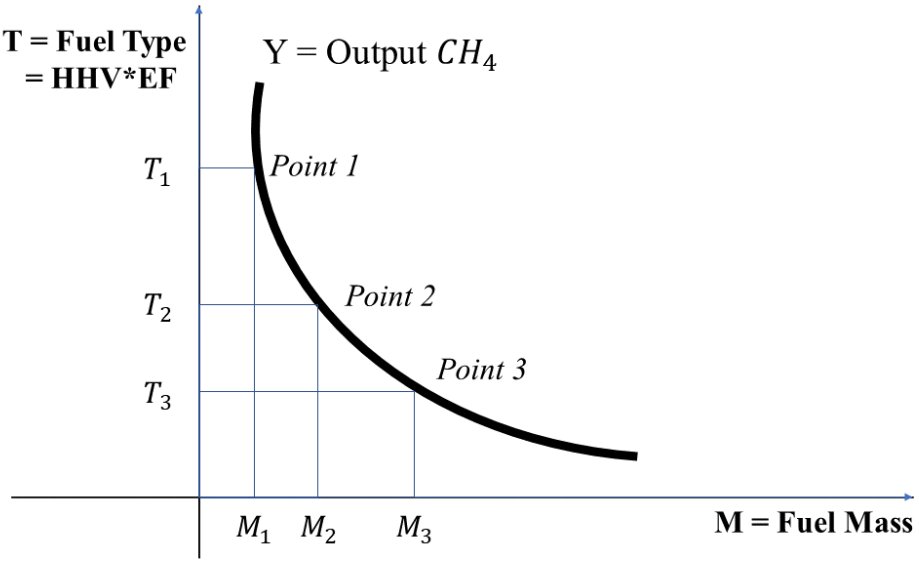


GRAPHICAL REPRESENTATION OF EQUATION C-8

Here, Y_1, Y_2, Y_3 represents different amount/mass of emitted CH_4 from the stationary fuel combustion source. In order to produce the same level of CH_4 that is Y_1, if the mass of the fuel, M decreases then T (that is the multiplication of HHV * EF) must increase.



From the production function, we can see that a falling T always be replaced with more and more M for a particular level of CH_4 output.



From the graph below, we can see that, when we move along the same output level of CH_4 from Point 1 to Point 2, as T decreases, M increases. Here, T indicates HHV * EF that is based on fuel type.

CRTICAL ANALYSIS OF EQUATION C-8

In accordance with Equation C-1, which is for measuring CO2 output, Equation C-8 exhibits similar kinds of challenges while measuring the output Methane level. New research works are being conducted to develop effective methods to capture methane (Jihan Kim, 2013) which is a bit more critical as methane is completely non-polar and interacts very weakly with most materials. The octet rule is a chemical rule of thumb that reflects the theory that main-group elements tend to bond in such a way that each atom has eight electrons in its valence shell, giving it the same electronic configuration as a noble gas. Electrons are shared differently in ionic and covalent bonds. In Ionic Bonds, one element donates another element electron so that both elements can reach octet or duplet state. And in this process, they create one positive ion and one negative ion. This makes compounds created by ionic bonds much stronger towards reactions. Covalent bonds are the bonds where elements share electrons so that they can both reach octet and duplet states

which is different from ionic bonds. And as the elements don't completely donate their electron to another element, no positive or negative ion gets created. But the problem is that some elements are more electronegative than others. electro-negative elements try to shift the shared electrons to their nucleus and that creates polarization. Most compounds, however, have polar covalent bonds, which means that electrons are shared unequally between the bonded atoms. Electronegativity determines how the shared electrons are distributed between the two atoms in a polar covalent bond. The more strongly an atom attracts the electrons in its bonds, the larger its electronegativity. Electrons in a polar covalent bond are shifted toward the more electronegative atom; thus, the more electronegative atom is the one with the partial negative charge. The greater the difference in electronegativity, the more polarized the electron distribution and the larger the partial charges of the atoms. In polarization, positive and negative poles get created as one element is forcing the electron cloud to its side making it a negative pole and the other side of the element as a positive pole. Covalent bonds can be non-polar or polar and react to electrostatic charges. This creates a similar scenario for the covalent bonds to the ionic bonds (LibreTexts Project, 2022).

Now, oxygen has a higher electronegative characteristic than carbon and while sharing electrons in covalent bonds with carbon, it shifts the electron cloud to its own nucleus creating positive and negative poles in the carbon dioxide compound. And that makes carbon dioxide stronger towards new reactions.

But in methane, both carbon and hydrogen have similar types of electronegative characteristics, and that's why the polarization isn't strong as the carbon dioxide compound. That means that in methane, the elements are in a more stable form which makes it weaker towards new reactions because the electrons are already in stable conditions. And that's why it becomes difficult to engage methane in chemical reactions with other materials to capture it compared to carbon dioxide (Jihan Kim, 2013, p. 1).

Thus, Equation C-8 has a similar issue just like Equation C-1 where the focus is only regarding how much methane was produced but not how much methane was finally released in the environment. It is important that policymakers encourage new GHG capture and absorption technologies because, in order to reach net-zero emission, these technologies will play a vital role.

In addition to knowing how much methane from general stationary fuel combustion sources are producing, it's also important to understand what kind of technologies those plants are

using, their operation process, and the most important fact would be how effectively they are running those plants. Because two plants might be producing the exact same amount of methane annually, but one might be working in a low efficient technology and the other might be working in higher efficiency. The former might generate a higher amount of methane if they plan to match the main production of the latter.

MATHEMATICAL ANALYSIS OF EQUATION Y-4

From Equation Y- 4:

$$CH_4 = (CO_2 \times \frac{EmF_{CH4}}{EmF}) + CO_2 \times \frac{0.02}{0.98} \times \frac{16}{44} \times f_{CH4} \qquad (Eq.Y-4)$$

Or, $CH_4 = CO_2 \left[\frac{EmF_{CH4}}{EmF} + \left(\frac{0.02}{0.98} \times \frac{16}{44} \times f_{CH4}\right)\right]$

Or, $CH_4 = CO_2 \left[A_1 \times EmF_{CH4} + A_2\right]$

Where both A_1 and A_2 are constants.

$A_1 = \frac{1}{EmF}$

$A_2 = \frac{0.02}{0.98} \times \frac{16}{44} \times f_{CH4}$

Now, the equation can be further transformed into a **Cobb-Douglas** production function model. The Equation C-8 can be redefined as below:

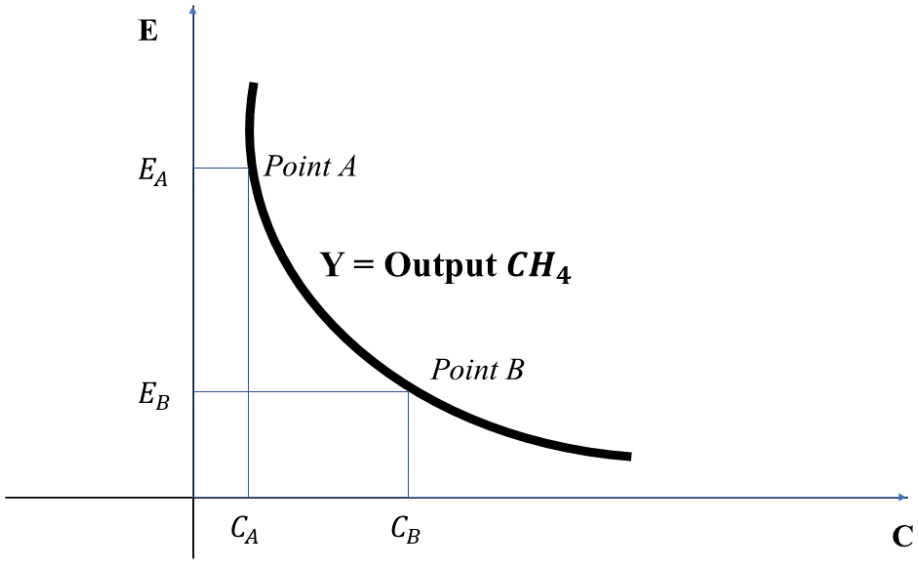
$$Y = C \times E$$

where:

Y = Annual CH_4 emissions from the combustion of a particular type of fuel (metric tons)

C = Emission rate of CO_2 from flared gas

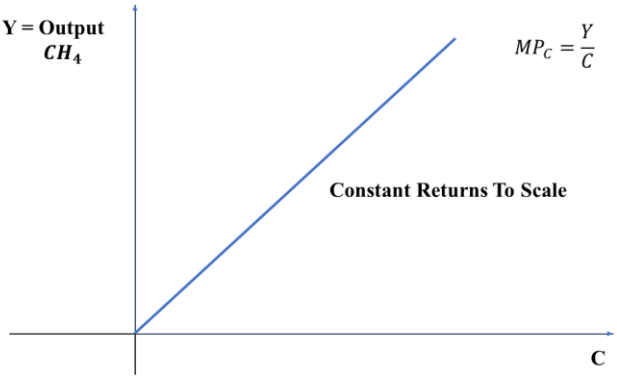
$E = \left[A_1 \times EmF_{CH4} + A_2\right]$; which is a parameter dependent on default CH_4 emission factor for any "Fuel Gas"



The final expression here can also be interpreted as a Cobb-Douglas production function model which would give us the CH4 emission output as a function of inputs between the variable C and E. Furthermore, the production function would be strictly monotonic and strictly convex that is similar to the 1.3 section of this article.

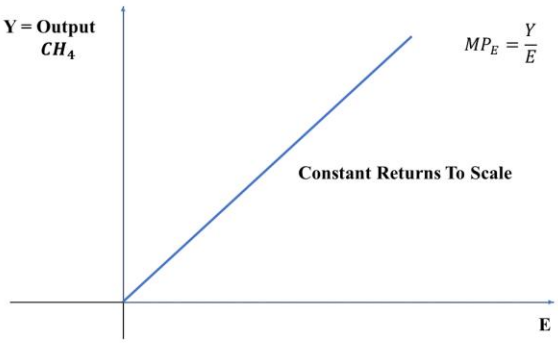
So, the Marginal Product of C,

$$MP_M = \frac{dY}{dC} = E$$
$$= \frac{C * E}{E}$$
$$= \frac{Y}{E}$$



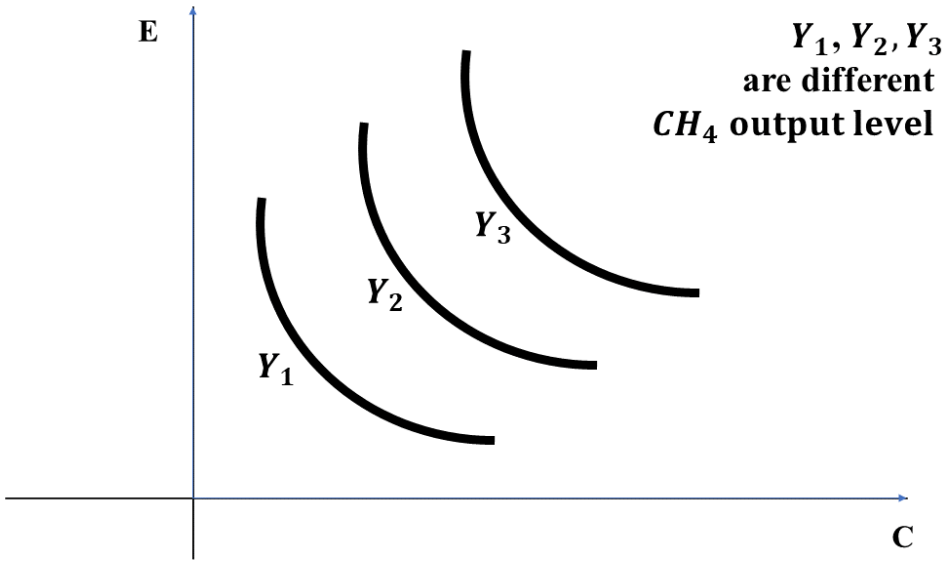
Again, the Marginal Product of E,

$$MP_E = \frac{dY}{dE} = C$$
$$= \frac{C * E}{E}$$
$$= \frac{Y}{E}$$

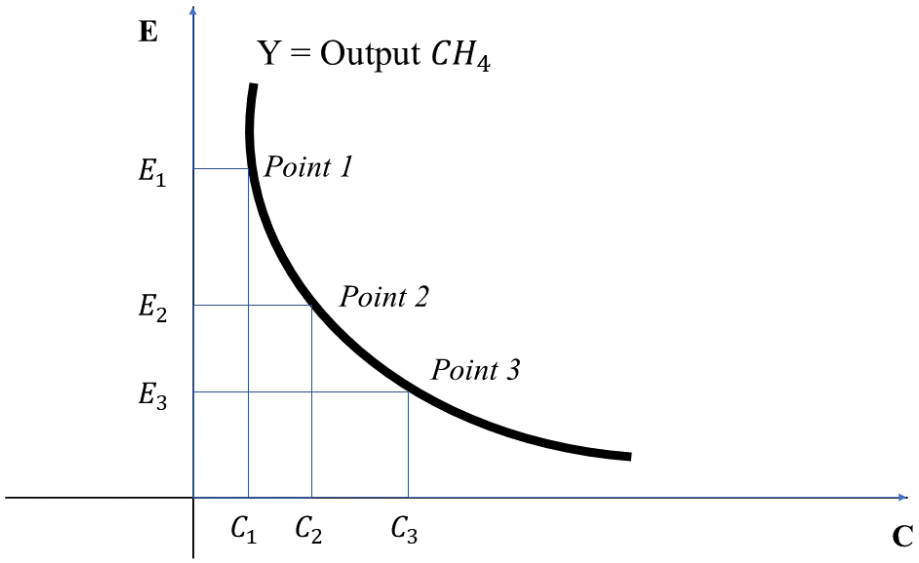


GRAPHICAL REPRESENTATION OF EQUATION Y-4

Here, Y_1, Y_2, Y_3 represents different amount/mass of emitted CH_4 from the stationary petroleum refineries. In order to produce the same level of CH_4 that is Y_1, if the E decreases, then C must increase.



From the production function, we can see that a falling E always be replaced with more and more C for a particular level of CH_4 output.



From the graph below, we can see that, when we move along the same output level of CH_4 from Point 1 to Point 2, as E decreases, C increases. Same statement is valid when we move further from Point 2 to Point 3.

CALCULATING GHG EMISSION FROM CEMENT PRODUCTION

The cement production source category consists of each kiln and each in-line kiln/raw mill at any portland cement manufacturing facility including alkali bypasses and includes kilns and in-line kiln/raw mills that burn hazardous waste. CO_2 process emissions from all kilns at the facility using Equation H-1 of this section:

$$CO_{2\,CMF} = \sum_{m=1}^{k} CO_{2\,Cli,m} + CO_{2\,rm} \qquad (Eq.H-1)$$

Where:

$CO_{2\,CMF}$ = Annual process emissions of CO_2 from cement manufacturing, metric tons.

$CO_{2\,Cli,m}$ = Total annual emissions of CO_2 from clinker production from kiln m, metric tons.

$CO_{2\,rm}$ = Total annual emissions of CO_2 from raw materials, metric tons.

k = Total number of kilns at a cement manufacturing facility.

MATHEMATICAL ANALYSIS OF EQUATION H-1

The Equation H-1 can be transformed into a **Perfect Substitute** production function model. The Equation H-1 can be redefined as below:

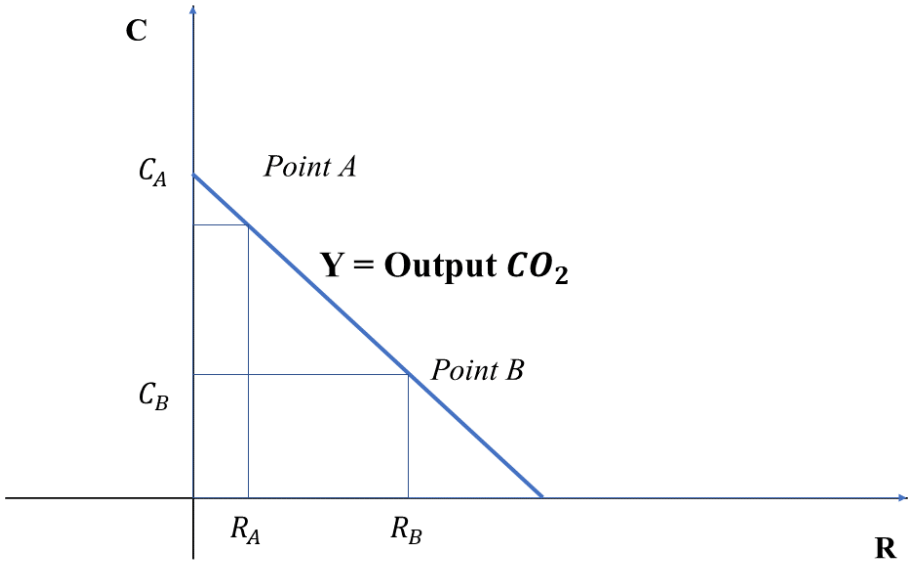
$$Y = C + R \qquad (Eq.\ 3.1)$$

Where:

C = Total annual emissions of CO_2 from clinker production from all kilns

Y = Annual process emissions of CO_2 from cement manufacturing

R = Total annual emissions of CO_2 from raw materials



So, representing the Equation H-1 in a Perfect Substitute production function model would give us the CO_2 emission output as a function of inputs between clinker production and production from raw materials. These two inputs would decide the output level of CO_2. Now, as a Perfect Substitute production function, the Equation C-1 is **strictly monotonic** but **weakly convex**. Here, Both C and R are Perfect Substitutes regarding producing CO_2.

GHG EMISSION FROM ETHANOL

Title 40 Chapter I Subchapter C Part 98 Subpart C focuses on General Stationary Fuel Combustion Sources. As Ethanol is used as fuel for combustion sources, it is important to understand how it impacts the GHG emission level. Stationary fuel combustion sources are devices that combust solid, liquid, or gaseous fuel, generally for the purposes of producing electricity, generating steam, or providing useful heat or energy for industrial, commercial, or institutional use, or reducing the volume of waste by removing combustible matter. The CO2 mass emissions can be calculated by using Equation C-1 (Subpart C - General Stationary Fuel Combustion Sources, 2022):

$$CO_2 = 1 * 10^{-3} * Fuel * HHV * EF \qquad (Eq. C - 1)$$

where:

CO_2 = Annual CO_2 mass emissions for the specific fuel type (metric tons).

Fuel = Mass or volume of fuel combusted per year, from company records as defined in § 98.6 (express mass in short tons for solid fuel, volume in standard cubic feet for gaseous fuel, and volume in gallons for liquid fuel).

HHV = Default high heat value of the fuel, from Table C-1 of this subpart (mmBtu per mass or mmBtu per volume, as applicable).

EF = Fuel-specific default CO2 emission factor, from Table C-1 of this subpart (kg CO2/mmBtu).

1×10^{-3} = Conversion factor from kilograms to metric tons.

Now for Ethanol:

HHV = 0.084

EF = 68.44

And we can re-write the variable "$Fuel$" as the "$Ethanol$". Then we can rewrite Equation C-1 as following:

$$CO_2 = 1 * 10^{-3} * Ethanol * 0.084 * 68.44$$

$$CO_2 = 5.74896 * 10^{-3} * Ethanol$$

Where,

$Ethanol$ = Ethanol Mass or volume of fuel combusted per year, from company records.