Capture Costs Definitions:

There are two generally excepted formulas used to define the cost of capturing CO_2:

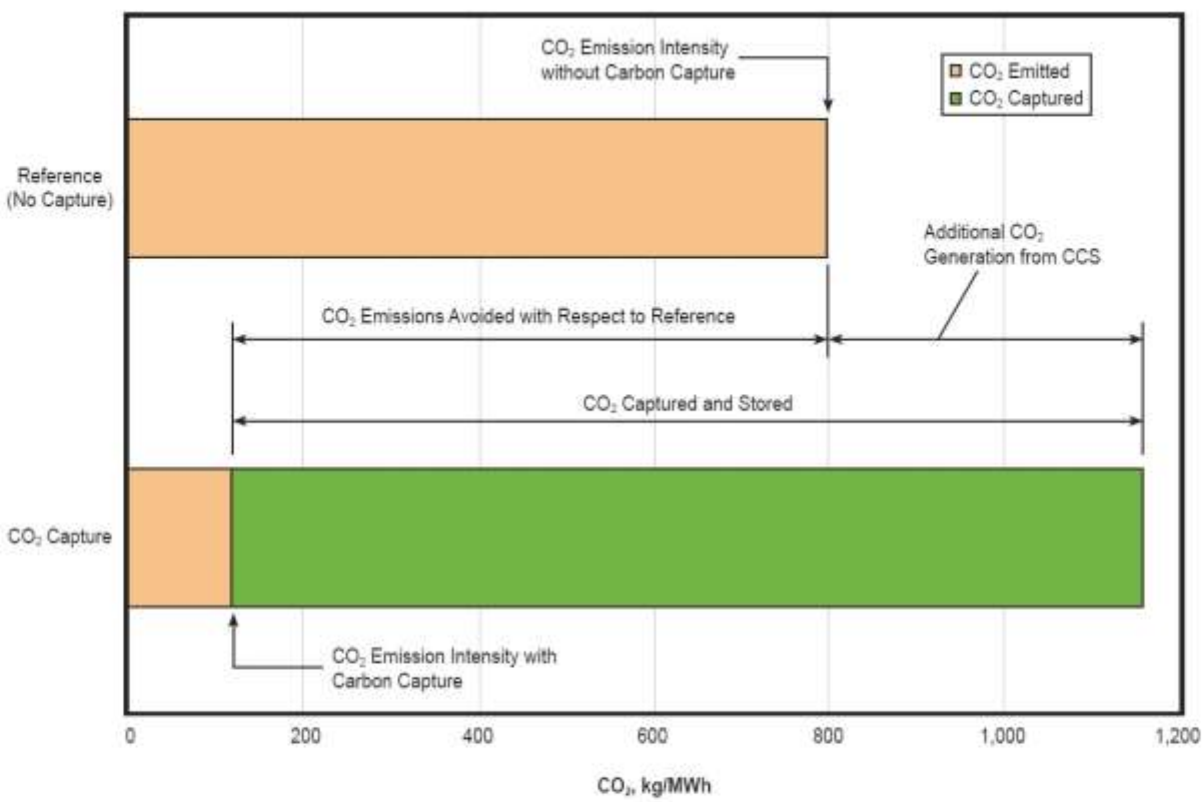
1. Cost of Capture
2. Avoided Cost of Capture

1) Cost of Capture:

The cost of capture is defined as the incremental levelized capture costs in a given year divided by the volume of CO_2 captured for a given year. It is generally expressed as the change in levelized cost of power for a year, between the capture case and the reference case, divided by the volume of CO_2 captured in a year. The standard formula is:

$$(COE_{capture} - COE_{ref}) \times MWh_{capture} / CO2_{captured}$$

However, capturing carbon dioxide requires energy which is generally produced by the combustion of a fuel. Therefore, CO_2 is created to facilitate the capture process. This additional CO_2 produced is not included in the avoided cost calculation because it is not avoided when compared to the emissions in the reference case. The following picture illustrates this point.



2) Avoided Cost of Capture:

The avoided cost is the incremental levelized capture costs for a year divided by the difference in intensities between the reference and capture cases multiplied by the MWh produced in the capture case. The denominator is essentially the volume of CO_2 captured less the volume of CO_2 emitted by the systems required to capture the CO_2.

$$(COE_{capture} – COE_{ref}) \text{ X } (MWh_{capture}) / [(Intensity_{ref} – Intensity_{capture}) \text{ X } MWh_{capture}]$$

This formula simplifies to the standard avoided cost formula of:

$$(COE_{capture} – COE_{ref}) / (Intensity_{ref} – Intensity_{capture})$$

Numerical Examples:

A) IGCC Case:

Reference Assumptions:	IGCC Assumptions:
Energy = 4,000,000 MWh/yr	Energy = 3,000,000 MWh/yr
COE = $90/MWh	COE = $140/MWh
CO2 Emitted = 4.0 X .8 = 3.2 Mt/yr	CO2 Emitted = 4.0 X .8 – 3.2 = .48 Mt/yr
CO2 Intensity = .80 t/MWh	CO2 Intensity = .48 / 3 = .16 t/MWh
	CO2 Captured = 3.2 Mt/yr
	CO2 Produced = 3.68 Mt/yr

Capture Cost = (140 – 90) X 3,000,000 / 3,200,000 = $46.9/t

Avoided Cost = (140 – 90) / (.80 - .16) = $78.13/t

The reference case here is assumed to be a super critical coal plant. It is important to choose reference cases one would likely build.

B) Amine Case: (used for rest of document)

Reference Assumptions:	Amine Capture Assumptions:
Energy = 4,000,000 MWh/yr	Energy = 3,000,000 MWh/yr
COE = $90/MWh	COE = $140/MWh
	Capture Rate = 85%
CO2 Intensity = .80 t/MWh	CO2 Intensity = .16 t/MWh
	CO2 Captured = 4,000,000 MWh X 85% X .80 t/MWh = 2.72 Mt/yr
CO2 Emitted = 4.0X .8 = 3.2 Mt/yr	CO2 Emitted = 3 X .16 = .48 Mt/yr
	CO2 Produced = 3.2 Mt/yr

In this case the same amount of fuel is used, therefore the same amount of CO_2 is produced in each case.

Capture Cost = (140 – 90) X 3,000,000 / 2,720,000 = \$55.2/t
This is higher than the IGCC case above because less CO_2 is captured for the same cost.

Avoided Cost = (140 – 90) / (.80 - .16) = \$78.13/t

Another way to look at the avoided cost is to consider that 1,000,000 MWh worth of power must be produced by another non-CCS plant to achieve 4,000,000 MWh of production. The CO_2 produced from this extra production will be
$(MWh_{ref} - MWh_{capture}) \times CO_2\ Intensity_{ref} = CO_2$ not Avoided.

In this case it is (4,000,000 - 3,000,000) X .8 t/MWh = 800,000 t/yr. This is the CO_2 produced to provide the energy required to capture the other CO_2. This can be deducted from the CO_2 volume in the Capture Cost equation to yield,
(140 – 90) X 3,000,000 / (2,720,000 - 800,000) = \$78.13/t the avoided cost.

C) Components of Avoided Cost:

The cash costs related to capture can be expressed as

$(COE_{capture} \times MWh_{capture} - COE_{ref} \times MWh_{ref}) / CO_{2\ avoided}$

This is the difference in cash costs for all cost recovery for both plants divided by CO_2 volume avoided for a given year. One can use individual cash components here.

If a plant is derated, then as described above, the lost capacity will need to be replaced. The cost associated with replacing this capacity, with nonCCS generation, used to provide the energy required to capture the CO_2, can be expressed as

$(MWh_{ref} - MWh_{capture}) \times COE_{ref} / CO_{2\ avoided}$

Cash cost= (140 X 3,000,000 – 90 X 4,000,000) / (2,720,000-800,000) = \$31.25/t
Derate cost= (4,000,000 – 3,000,000) X 90 / (2,720,000-800,000) = \$46.9/t

This totals \$78.13/t which is the avoided cost.

D) Components of Capture Cost:

The cash costs related to capture can be expressed as

$(COE_{capture} \times MWh_{capture} – COE_{ref} \times MWh_{ref}) / CO_{2\ captured}$

This is the difference in cash costs for all cost recovery for both plants divided by CO_2 volume captured for a given year.

If a plant is derated, then as described above, the lost capacity will need to be replaced. The cost associated with replacing this capacity with non-CCS generation, used to provide the energy required to capture the CO_2, can be expressed as

$(MWh_{ref} - MWh_{capture}) \times COE_{ref} / CO_{2\ captured}$

Cash cost is (140 X 3,000,000 – 90 X 4,000,000) / 2,720,000 = $22.0/t
Derate cost is (4,000,000 – 3,000,000) X 90 / 2,720,000 = $33.1/t

This totals $55.1/t which is the capture cost. The addition of these two equations yields the standard capture cost formula. If the equation for the avoided CO_2 volume is deducted from the CO_2 captured term, the equation resolves to the standard avoided cost equation.

E) Breakdown of Costs:

The avoided and capture costs can be broken down into cost components such as capital, fuel and O&M for example. Simply insert the difference between the COE for the cost components into the numerator of the standard equations.

Numerical example:

	Capture COE	Ref COE	Difference
Fuel	20	10	10
O&M	40	20	20
Capex	80	60	20
Total	140	90	50

Ratio of $MWh_{Capture} / CO2_{Capture}$ = 3,000,000 / 2,720,000 = 3/2.72. Multiply this by the differences above to get the capture costs components

The difference in CO_2 intensities between the cases is .80 - .16 = .64. Divide this into the differences above to get the avoided cost components.

	Capture Cost	Avoided Cost
Fuel	11.0	15.6
O&M	22.0	31.3
Capex	22.0	31.3

Total	55.0	78.2

Slight rounding error.

F) Assume Plant is Overbuilt to Maintain Output:

For this case the plant is derated by 25% when CCS is employed. Therefore the plant capacity must be increased to 4,000,000 / (1-.25) = 5,330,000 MWh to yield a net 4,000,000 MWh of production with CCS. As a result the CO_2 captured increases to 5,330,000 X 85% X .80 t/MWh = 3.63 MT/yr.

The cash costs, for the Capture Cost becomes
(140 X 4,000,000 – 90 X 4,000,000) / 3.63 = $55.2/t
There is no derate component in for this case and it gives the same result as the standard formula.

The volume of CO_2 avoided is related to the additional 1,330,000 MWh generated. With an intensity of .8 t/MWh this provides 1,330,000 MWh X .8 t/MWh = 1.06 Mt/yr of avoided CO_2.

The cash component of the Avoided Cost calculation becomes

(140 X 4,000,000 – 90 X 4,000,000) / (3.62 – 1.06) = $78.13/t
This is no derate component for this case.

G) Derivation of Capture Costs:

As shown above the capture cost is the sum of the incremental capital costs and the costs to make up for the derate of the unit.

The cash costs related to capture can be expressed as

$(COE_{capture} \times MWh_{capture} – COE_{ref} \times MWh_{ref}) / CO_{2\ captured}$

The cost associated with replacing this capacity with non-CCS generation, used to provide the energy required to capture the CO_2, can be expressed as

$(MWh_{ref} - MWh_{capture}) \times COE_{ref} / CO_{2\ captured}$

These equations simplify to:

$COE_{capture} \times MWh_{capture} / CO_{2\ captured} – COE_{ref} \times MWh_{ref} / CO_{2\ captured}$

$MWh_{ref} \times COE_{ref} / CO_{2\ captured} – MWh_{capture} \times COE_{ref} / CO_{2\ captured}$

The middle two terms cancel leaving

$COE_{capture} X MWh_{capture} / CO_{2\ captured} – MWh_{capture} X COE_{ref} / CO_{2\ captured}$

This is simplified to

$(COE_{capture} – COE_{ref}) X MWh_{capture} / CO_{2\ captured}$

H) <u>Derivation of Avoided Cost</u>:

The denominator of the capture cost equation is reduced by the amount of CO_2 which is not avoided. It is based on the volume of CO_2 which will be produced by new capacity which must be built to replace the lost volume and for any other CO2 emitted to capture the CO2 in the capture plant. In many cases steam or power is used to capture CO2 and the emissions from the production of these utilities must be deducted from the volumes capture. It is assumed that this capacity will not have CCS. This extra CO_2 is expressed as,

$CO_{2\ ref} / MWh_{ref} X (MWh_{ref} – MWh_{capture})$

If this is deducted from the volume in the denominator of the Capture formula we get:

$(COE_{capture} – COE_{ref}) X MWh_{capture} / (CO_{2\ ref} – CO_{2\ emitted} – [CO_{2\ ref} / MWh_{ref} X (MWh_{ref} – MWh_{capture})])$

The term in the square brackets can be rearranged to give $CO_{2\ ref} – CO_{2\ ref} X (MWh_{capture} / MWh_{ref})$

This simplifies to:

$(COE_{capture} – COE_{ref}) X MWh_{capture} / (– CO_{2\ emitted} + CO_{2\ ref} x (MWh_{capture} / MWh_{ref})$

This simplifies to:

$(COE_{capture} – COE_{ref}) / (– CO_{2\ emitted}/ MWh_{capture} + CO_{2\ ref} / MWh_{ref})$

This is re-expressed as the standard formula:

$(COE_{capture} – COE_{ref}) / (Intensity_{ref} – Intensity_{capture})$

I) Avoidance Rate Calculation:

Avoidance Rate = (CO_2 ref/Energy ref – CO_2 CCS / Energy CCS) / CO_2 ref/Energy ref

This is rearranged to give us:

CO_2 ref/E export ref X Avoidance Rate = CO_2 ref/E export – CO_2 CCS / E export CCS

OR

CO_2 ref X Avoidance Rate = CO_2 ref – CO_2 CCS / E export CCS X E export ref = CO_2 Avoided

OR

Avoidance Rate = CO_2 Avoided / CO_2 ref

This formula tells us of the CO_2 in the reference case how much is avoided. That last part of this formula (/ E export CCS X E export ref) is meant to deal with the impact of derating the power plant. This term is the only one which differs from the equation for the capture rate and says that we can't take credit for CO_2 which must now be produced to replace the lost capacity somewhere else in society.

There are two ways to handle power plant derates. One is to go with the original design and allow the output to decrease with CCS. The other is to increase the size of the power plant to give the same output as the original design of the plant but with CCS. If we do this we can think of this larger plant as still being derated as before but the reference emissions become those for this new larger plant. That is the CO2 emissions from the fuel be the reference emissions. The E export ref is generally E export CCS X 1/ (1 - % Derate).

Reference Assumptions:
Energy Ref = 4,000,000 MWh/yr

CO2 Intensity = .80 t/MWh

CO2 Ref = 4.0X .8 = 3.2 Mt/yr

Amine Capture Assumptions:
Energy CCS = 3,000,000 MWh/yr

CO2 Intensity = .16 t/MWh

CO2 CCS = 3 X .16 = .48 Mt/yr

CO2 Avoided = 3.2 - .48 / 3.0 X 4.0 = 2.56 Mt/yr

Avoidance Rate = 2.56 / 3.2 = 80% Or (.8-.16) / .8 = .8

Capture and Avoided Cost Calculations:
The following shows the basic math for the calculation of the capture and avoided costs.

1. Cost of Capture:

One of the premises of the cost of capture calculation is that that the technology with CCS should have the same output as the reference case. If the CCS case has in particular a lower output then additional costs need to be included to mitigate this effect.

The generic cost of capture equation is:

Cost to Capture CO_2 / Mass of CO_2 Captured (1)

This can be expressed as

(Yearly cost to capture CO_2 + Yearly cost to mitigate derate) / Mass of CO_2 Captured (2)

The terms in the numerator of the equation above can be calculated based on the sum of incremental allocated capital, O&M and fuel costs to capture CO_2 for a given year. However it is more common to express this equation based on levelized costs of energy or some other unitized cost of output.

[(COE capture X MWh capture – COE ref X MWh ref) + (MWh ref - MWh capture) X COE ref] / CO_2 captured (3)

The first term shows the incremental cost of capture and the second shows the cost of replacing any derated capacity. The plant may be derated to supply steam and power to capture CO_2. This capacity must be replaced. This equation assumes that this lost capacity is replaced by capacity without CCS.

These terms simplify to the standard capture cost equation:

(COE capture – COE ref) X MWh capture / CO2 captured (4)

This equation is therefore premised on the assumption that additional capacity to replace lost capacity will not have CCS or else equation 3 will not simplify to equation 4!

2. Avoided Cost:

Essentially for the avoided cost calculation we need to deduct from the mass of CO_2 captured, CO_2 which was generated to capture that CO_2. (There may be other adjustments as well.)

The denominator of equation 2, 3 and 4 above becomes Mass of CO_2 Capture – Mass of CO_2 emitted by extra capacity required to mitigate derate. This is the mass of avoided CO_2!

This can also be expressed as Mass of CO_2 ref – Mass CO_2 emitted – Mass of CO_2 emitted by extra capacity required to mitigate derate. This is also the mass of avoided CO_2!

The mass of extra CO_2 required to mitigate derate is expressed as,

CO_2 ref / MWh ref X (MWh ref – MWh capture)

Equation (4) can be rewritten as

(COE capture – COE ref) X MWh capture / (CO_2 ref – CO_2 emitted – [CO_2 ref / MWh ref X (MWh ref – MWh capture)]) (5)

This simplifies to:

(COE capture – COE ref) X MWh capture / (– CO_2 emitted + CO_2 ref x (MWh capture / MWhref)

This simplifies to:

(COE capture – COE ref) / (– CO_2 emitted/ MWhcapture + CO_2 ref / MWhref)

This is re-expressed as the standard formula:

(COE capture – COE ref) / (Intensity ref – Intensity capture) (6)

The point of all is that if the denominator of equation 5 is substituted into the denominator of equation 2 the results should be exactly the same as that for equation 6. Why, because the numerator of equation 2 has not change and is still in equation 5! Only the denominator of equation 2 has changed in equation 5.

Sometimes there is insufficient information available for the reference case to complete equation 6. Therefore a version of equation 2 must be used instead. It only works if the output for the reference and CCS cases are the same.

Yearly cost to capture CO_2 / Mass of CO_2 Avoided (7)

In order to use equation 7 the mass of CO_2 avoided must be calculated.

A) Common Calculation: The mass of CO_2 avoided is commonly expressed as the mass of CO_2 generated in the non-capture reference case less CO_2 emissions in the capture case less CO_2 which is effectively produced to capture this CO_2. The following is a definition of the mass of CO_2 avoided:

CO_2 in reference non-CCS case (CO_2 generated)
Less CCS emission

Less CO_2 associated with power used to capture CO_2

Plus CO_2 associated with waste heat boiler operating on extra heat generated by the capture process

Plus CO_2 emissions associated with reduced fuel usage

Less uncaptured CO_2 associated with steam use

However, for many cases little information may be available regarding the nature of the reference case without CO_2 capture. This may be true if the cost of the reference case is not determined and only costs associated with the incremental cost to complete capture are available.

Recall that CO_2 captured is = CO_2 in reference + CO_2 emissions associated with extra fuel used in CCS process – CO_2 emissions

OR

CO_2 in reference – CO_2 emissions = CO_2 captured - CO_2 emissions associated with extra fuel used in CCS process

B) Alternative Calculation: Therefore the first two terms listed above in definition A) can be replaced by the first two terms below. The mass of CO_2 avoided can also be expressed as:

CO_2 captured

Less CO_2 emissions associated with extra fuel used in CCS process

Less CO_2 associated with power used to capture CO_2

Plus CO_2 associated with waste heat boiler operating on extra heat generated by the capture process

Plus CO_2 emissions associated with reduced fuel usage

Less uncaptured CO_2 associated with steam use

Conclusion:

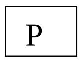
1) The standard formula represented by equation 6 above, as shown below, can be used to handle various situations including cases where the output of the process changes or additional fuel is required by the underlying process.
2) If information on the cost and GHG emission intensity of the reference case is not available for use in the standard equation it is possible to use equation 7 which requires information on incremental costs for CCS and derivations of the mass of CO_2 avoided. However, this formula is only valid if the output of the CCS case is the same as the reference case. If not then it will not be possible to calculate the adjustment required to mitigate the impact of the change in output correctly.

Please see a few numerical examples below. The mass of CO_2 avoided are calculated in accordance with definitions A) and B) above and are identified as such. The first definition of avoided cost is based on equation 7 shown above. The second definition of avoided cost is the standard on and is based on equation 6 above.

1) Base Capture Plant:

Reference:

Output = 50

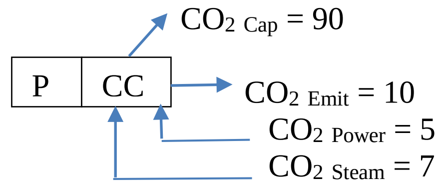


$CO_{2\ Ref}$ = 100

Yearly Cost = \$10,000

CCS Case:

Output = 50



Yearly Cost = \$16,000

A) CO_2 Avoided = $CO_{2\ Ref}$ – CO_2 emit – $CO_{2\ Power}$ – $CO_{2\ Steam}$ = 100 – 10 – 5 – 7 = 78 t/yr

B) CO_2 Avoided = $CO_{2\ Cap}$ – $CO_{2\ Power}$ – $CO_{2\ Steam}$ = 90 – 5 – 7 = 78 t/yr

1) Avoided Cost = (16,000 – 10,000) / 78 = \$76.9/t

2) Avoided Cost = (16,000/50 – 10,000/50) / [100/50 – (10+5+7)/50] = \$76.9/t

If insufficient data is available on the cost for the reference case then the numerator in equation 1 above can be adjusted to include the incremental cost of CCS. However, this is only possible if the output for the two cases is the same.

If 100% of the steam emissions are capture by the CCS plant, then CO_2 avoided becomes

A) CO_2 Avoided = $CO_{2\ Ref}$ – $CO_{2\ Emit}$ – $CO_{2\ Power}$ – $CO_{2\ Steam}$ = 100 – 10 – 5 = 85 t/yr

B) CO_2 Avoided = $CO_{2\ Cap}$ – $CO_{2\ Power}$ – $CO_{2\ Steam}$ = 97 – 5 – 7 = 85 t/yr

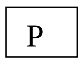
Since these steam emissions are captured, their entrance into the atmosphere is avoide.

2) <u>CCS Plant Uses Extra Fuel</u>:

An ATR may require additional fuel to produce the same amount of low carbon fuel as say natural gas used in the reference case. As a result there will be more CO_2 to capture.

Reference:

Output = 50

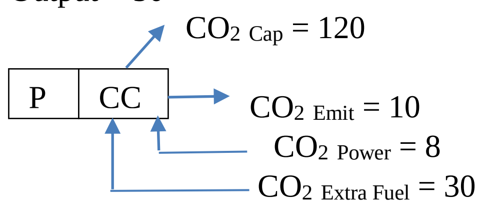


$CO_{2\ Ref}$ = 100

Yearly Cost = $10,000

CCS Case:

Output = 50



Yearly Cost = $21,000

A) CO_2 Avoided = $CO_{2\ Ref} - CO_{2\ Emit} - CO_{2\ Power}$ = 100 – 10 – 8 = 82 t/yr

B) CO_2 Avoided = $CO_{2\ Cap} - CO_{2\ Power} - CO_{2\ Extra\ fuel}$ = 120 – 8 – 30 = 82 t/yr

1) Avoided Cost = (21,000 – 10,000) / 82 = $134/t

2) Avoided Cost = (21,000/50 – 10,000/50) / [100/50 – (10+8)/50] = $134/t

If insufficient data is available on the cost for the reference case then the numerator in equation 1 above can be adjusted to include the incremental cost of CCS. However, this is only possible if the output for the two cases is the same.

3) <u>CCS with Derate</u>:

Notice that the value of $CO_{2\ steam}$ is zero now since steam is no longer being supplied by a standalone boiler but is now being supplied by the process incorporating CCS.

<u>Reference</u>:

Output = 50

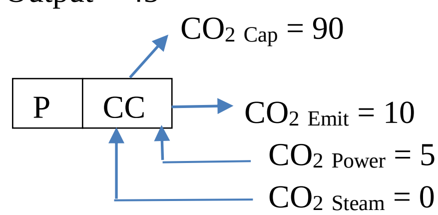
P

$CO_{2\ Ref}$ = 100

Yearly Cost = $10,000

<u>CCS Case</u>:

Output = 45



Yearly Cost = $18,000

A) CO_2 Avoided = $CO_{2\ Ref}$ – $CO_{2\ Emit}$ – $CO_{2\ Power}$ – $CO_{2\ Mitigate\ Derate}$ = 100 – 10 – 5 – (50-45)/50 X 100 = 78 t/yr

B) CO_2 Avoided = $CO_{2\ Cap}$ – $CO_{2\ Power}$ – $CO_{2\ Mitigate\ Derate}$ = 90 – 6 – (50-45)/50 X 100 = 74 t/yr

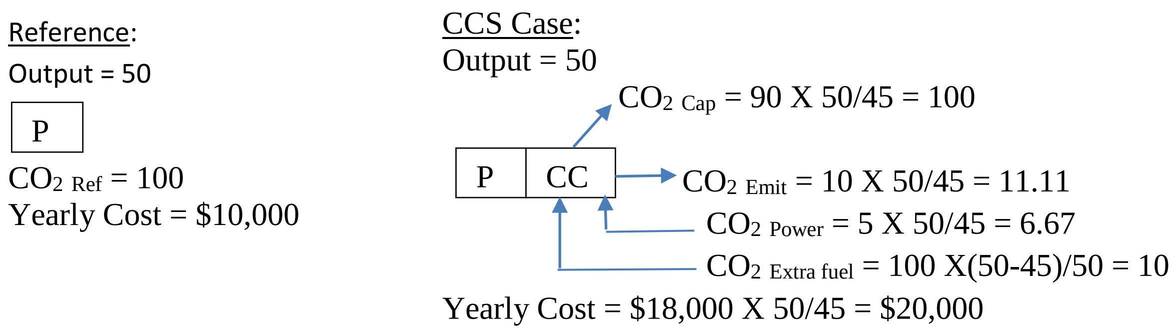
1) Avoided Cost = (18,000 – 10,000 + (50-45)/50 X 10,000)/ 78 = $121.6/t

2) Avoided Cost = (18,000/45 – 10,000/50) / [100/50 – (10+6)/45] = $121.6/t

Notice, that when the last two terms in the numerator of equation 3 are considered, essentially the size of the reference case is normalized down to an output of 45. (10,000 - (50-45)/50 X 10,000). The CO_2 to Mitigate Derate term was described earlier in this document.

4) CCS with Larger Unit:

If for instance steam is taken from an NGCC or a boiler to supply the CCS unit, the NGCC or boiler may be oversized to yield the same amount of output as the reference case. The values here are based on example 3 above.



A) CO_2 Avoided = $CO_{2\ Ref}$ – $CO_{2\ Emit}$ – $CO_{2\ Power}$ = 100 – 11.11 – 6.67 = 88.22 t/yr

B) CO_2 Avoided = $CO_{2\ Cap}$ – $CO_{2\ Power}$ – $CO_{2\ Extra\ fuel}$ = 100 – 6.67 –11.11 = 82.22t/yr

1) Avoided Cost = (20,000 – 10,000)/ 88.22 = $121.6/t

2) Avoided Cost = (20,000/50 – 10,000/50) / [100/50 – (11.11+6.67)/50] = $121.6/t

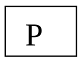
This example yields the same avoided cost as that shown in example 3. In example 3 the CO_2 to mitigate the derate is equal to the extra fuel actually consumed in this example.

5) <u>CCS with Increase in Output without Extra Fuel</u>:

With some technologies the underlying plant is able to increase its output without any additional fuel.

<u>Reference</u>:

Output = 50

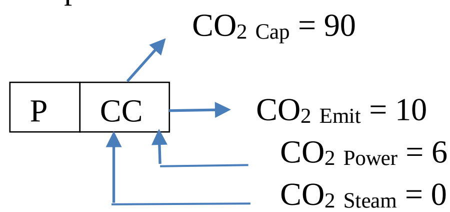


$CO_{2\ Ref} = 100$

Yearly Cost = $10,000

<u>CCS Case</u>:

Output = 65



Yearly Cost = $18,000

A) CO_2 Avoided = $CO_{2\ Ref} – CO_{2\ Emit} – CO_{2\ Power} – CO_{2\ Mitigate\ Derate}$ = 100 – 10 – 6 – (50-65)/50 X 100 = 114 t/yr

B) CO_2 Avoided = $CO_{2\ Cap} – CO_{2\ Power} – CO_{2\ Mitigate\ Derate}$ = 90 – 6 – (50-65)/50 X 100 = 114 t/yr

1) Avoided Cost = (18,000 – 10,000 + (50-65)/50 X 10,000)/ 114 = $43.8/t

2) Avoided Cost = (18,000/65 – 10,000/50) / [100/50 – (10+6)/65] = $43.8/t

Notice that the final term in the numerator in equation 1 adds back additional capacity which does not have to be built. Therefore the cost of this capacity is avoided.

It has been suggested that the values for the larger case could simply be factored down by the increase in the output to yield the correct avoided cost.
Therefore the values for the CCS case become:
Output = 65 X 50/65 = 50
$CO_{2\ Cap}$ = 90 X 50/65 = 69.23
$CO_{2\ Emit}$ = 10 X 50/65 = 7.69
$CO_{2\ Power}$ = 6 X 50/65 = 4.61
Yearly cost = 18,000 X 50/65 =13,846.1

3) Avoided Cost = (13,846.1/50 – 10,000/50) / [100/50 – (7.69+4.61)/50] = $43.8/t
   This approach can be used. However, it makes the values used hard to compare back to the original values.

3. Avoidance Rate Calculation:

Avoidance Rate = ($CO_{2\ ref}$/Energy $_{ref}$ – $CO_{2\ CCS}$ / Energy $_{CCS}$) / $CO_{2\ ref}$/Energy $_{ref}$

This is rearranged to give us:

$CO_{2\ ref}$/Energy $_{ref}$ X Avoidance Rate = $CO_{2\ ref}$/ Energy $_{ref}$ – $CO_{2\ CCS}$ / Energy $_{CCS}$

OR

$CO_{2\ ref}$ X Avoidance Rate = $CO_{2\ ref}$ – $CO_{2\ CCS}$ X Energy $_{ref}$ / Energy $_{CCS}$ = CO_2 Avoided

OR

Avoidance Rate = CO_2 Avoided / $CO_{2\ ref}$

This formula tells us of the CO_2 in the reference case how much is avoided. That last part of this formula ($CO_{2\ CCS}$ X Energy $_{ref}$ / Energy $_{CCS}$) is meant to deal with the impact of derating the power plant. This term is the only one which differs from the equation for the capture rate and says that we can't take credit for CO_2 which must now be produced to replace the lost capacity somewhere else in society.

There are two ways to handle power plant derates. One is to go with the original design and allow the output to decrease with CCS. The other is to increase the size of the power plant to give the same output as the original design of the plant but with CCS. If we do this we can think of this larger plant as still being derated as before but the reference emissions become those for this new larger plant. That is the CO2 emissions from the fuel be the reference emissions. The Energy $_{ref}$ is generally Energy $_{CCS}$ X 1/ (1 - % Derate).

Reference Assumptions:

Energy $_{Ref}$ = 4,000,000 MWh/yr

CO_2 Intensity $_{Ref}$ = .80 t/MWh

$CO_{2\ Ref}$ = 4.0X .8 = 3.2 Mt/yr

Amine Capture Assumptions:

Energy $_{CCS}$ = 3,000,000 MWh/yr

CO_2 Intensity $_{CCS}$ = .16 t/MWh

$CO_{2\ CCS}$ = 3 X .16 = .48 Mt/yr

CO_2 Avoided = (3.2 - .48) / 3.0 X 4.0 = 2.56 Mt/yr

Avoidance Rate = 2.56 / 3.2 = 80% OR (.80 - .16) / .8 = 80%