Supplementary Information for "*Putting the costs and benefits of Carbon Capture and Storage into perspective: A multi-sector to multi-product analysis*"

Simon Roussanaly[a,*], Truls Gundersen[b], Andrea Ramirez[c]
[a] SINTEF Energy Research, Trondheim, Norway
[b] Department of Energy and Process Engineering, NTNU, Trondheim, Norway
[c] Delft University of Technology, Delft, The Netherlands

* Corresponding author: simon.roussanaly@sintef.no

Abbreviations

bioCCS, bioenergy production with carbon capture and strorage; CAC, CO_2 avoidance cost; CCS, carbon, capture and storage; DAC, direct air capture; DACCS, direct air capture with CO_2 storage; LNG, liquefied natural gas; TEU, twenty-foot equivalent container unit.

Nomenclature

$Av\ CO_{2,bio}$	Quantity of biogenic CO_2 emissions avoided by CCS implementation from waste-to-energy plant (in kt/y)
$Av\ CO_{2,fossil}$	Quantity of fossil CO_2 emissions avoided by CCS implementation from waste-to-energy plant (in kt/y)
CAC_i	CO_2 avoidance cost associated with emissions reduction of material i via CCS (in €/tCO_2,avoided)
$Cost_{EndP,CCS}$	Cost of producing the considered end-product/end-service (in, for example, € per unit) when CCS is implemented.
$Cost_{EndP,\text{ no CCS}}$	Cost of producing the end-product/end-service (in, for example, € per unit) when CCS is not implemented. This is the reference cost of the end-product/end-service.
$GHG_{EndP,CCS}$	Greenhouse gas emissions associated with the considered end-product/end-service (in, for example, tCO_2,eq per unit) when CCS is implemented.
$GHG_{EndP,\text{no CCS}}$	Greenhouse gas emissions associated with the considered end-product/end-service (in, for example, tCO_2,eq per unit) when CCS is not implemented. This is the reference greenhouse gas intensity of the end-product/end-service.
$GHG_{i,CCS}$	Greenhouse gas emissions associated with the industrial plant producing material i when CCS is considered. These emissions are normalised per quantity of material (in, for example, tCO_2/t).
$GHG_{i,\text{no CCS}}$	Greenhouse gas emissions associated with the industrial plant producing material i when CCS is not considered. These emissions are normalised per quantity of material (in, for example, tCO_2/t).
i	Index of summation for the different materials used to make an end-product/end-service and whose production could be integrated with CCS (for example, cement and steel).
P_{NEG}	Price at which negative emissions are considered to be sold.
$P_{\text{product, CCS}}$	Price of producing the considered end-product/end-service (in, for example, € per unit) when CCS is implemented.
$P_{\text{product, no CCS}}$	Price of producing the end-product/end-service (in, for example, € per unit) when CCS is not implemented. This is the reference price of the end-product/end-service.
$Quantity_i$	Quantity of material i used to make the considered end-product/end-service (in, for example, t).
$\%_{pulp}$	Content of pulp in the coated paper
$\%_{recycling}$	Level of recycling in the magazine in-take
$\Delta_{WtE,CCS}$	Required increase in waste treatment fees to cover the cost of achieving CO_2 neutrality via CCS

1 Infrastructure cases

To illustrate the potential environmental benefit and cost impact of carbon, capture and storage (CCS) implementation in the cement and steel sector on infrastructures, a set of three case studies are examined: a bridge, an onshore wind farm, and an offshore wind farm.

While more details on each case are presented in Subsections 1.1 and 1.2, this section presents the common basis for the impact of CCS on the emissions of the cement and steel plants and the associated CO_2 avoidance cost (CAC). As in our earlier bridge study [1], the emissions of the cement production with and without CCS, as well as the associated CO_2 avoidance cost, are based on the evaluation of oxy-fuel based capture performed in the H2020 CEMCAP project [2], [3]. However, compared to our previously published study[1], [2], here it is considered that a deeper emission reduction of steel manufacturing could be achieved by integrating bioenergy production with CCS (bioCCS) in the iron and steel plant based on Tanzer et al. [4]. The cost of achieving this reduction in greenhouse gas emissions from steel production is here based on the study of Mandova et al. [5].

A summary of the associated assumptions is presented in Table 1.

Table 1: Assumed characteristics of the cement and steel productions with and without CCS.

	Greenhouse gas emissions per ton of material (tCO_2/t)		CO_2 avoidance cost (€/tCO_2,avoided)
	Without CCS	With CCS[a]	
Cement production [3], [6]	0.626	0.072	53
Steel production	2.09 [7]	0.435 [5]	80 [5]

[a] These numbers include that greenhouse emissions taking place during CO_2 transport and storage represent 1.5% of the captured CO_2 corresponding to the middle of the 1-2% range corresponding to transport over 100 to 200 km via pipeline and storage in a saline aquifer [8]–[10][11].

1.1 Bridge case

The bridge case is based on our earlier study [1] on the construction of the Lake Pontchartrain Causeway located in Louisiana (USA). In this study, the greenhouse gas emissions associated with the bridge's construction were estimated to be 130 $ktCO_2$,eq, while the construction cost was estimated to be 379 M€ when CCS implementation is not considered.

Furthermore, the study estimated that 76 487 tonnes of cement and 24 209 tonnes of steel were required for the bridge construction.

Based on these elements, the bridge construction emissions and the costs, with CCS implementation on the cement and steel plants, can then be evaluated based on Equations 1 and 2.

$$GHG_{Bridge,CCS} = GHG_{Bridge,no\ CCS} - \sum_i Quantity_i \cdot \left(GHG_{i,no\ CCS} - GHG_{i,CCS}\right) \quad \text{Eq. 1}$$

$$Cost_{Bridge,CCS} = Cost_{Bridge,no\ CCS} + \sum_i Quantity_i \cdot \left(GHG_{i,no\ CCS} - GHG_{i,CCS}\right) \cdot CAC_i \quad \text{Eq. 2}$$

Where:

[1] Where CCS alone could reduce only 47 % of the emissions of steel manufacturing.

[2] Where CCS alone could only reduce the emissions from steel manufacturing by 47%.

- $GHG_{Bridge,CCS}$ are the greenhouse gas emissions associated with the bridge construction (in tCO_2,eq) when CCS is implemented in cement and steel productions.
- $GHG_{Bridge,no\ CCS}$ are the greenhouse gas emissions associated with the bridge construction (in tCO_2,eq) when CCS is not considered in cement and steel productions.
- $Cost_{Bridge,CCS}$ is the cost of building the bridge (in M€) when CCS is implemented in the cement and steel productions.
- $Cost_{Bridge,no\ CCS}$ is the cost of building the bridge (in M€) when CCS is not considered in the cement and steel productions.
- i is an index of summation for the different materials used to build the bridge and whose production could be integrated with CCS. Here, i comprise cement and steel.
- $Quantity_i$ is the quantity of material i used for the bridge construction (in t).
- $GHG_{i,no\ CCS}$ are the greenhouse gas emissions associated with the industrial plant producing material i when CCS is considered. These emissions are normalised per quantity of material (in, for example, tCO_2/t) as presented in Table 1.
- $GHG_{i,CCS}$ are the greenhouse gas emissions associated with the industrial plant producing material i when CCS is not considered. These emissions are normalised per quantity of material (in, for example, tCO_2/t) as presented in Table 1.
- CAC_i is the CO_2 avoidance cost associated with emissions reduction of material i via CCS (in €/tCO_2,avoided), as presented in Table 1.

A summary of the results is presented in Table 2.

Table 2: Summary of the greenhouse gas emissions and cost associated with the bridge's construction without and with CCS implementation in the cement and steel production plants.

	Without CCS	With CCS	*Variation (%)*
Greenhouse gas emissions ($ktCO_2$,eq)	130	41.6	*-68 %*
Construction cost (M€)	379	385	*1.6 %*

1.2 Onshore and offshore wind power cases

In this case study, the impact of CCS implementation in the cement and steel[3] sectors on the cost and emissions of the construction of an onshore wind turbine park and an offshore wind turbine park is evaluated based on the study from Bonou et al. [12]: 1) a 20-turbines onshore wind farm with a total power capacity of 46 MW (case G2 in the paper) 2) an 80-turbines offshore wind farm with a total power capacity of 320 MW (case G4 in the paper).

In their study, Bonou et al. assessed the greenhouse gas emissions associated with the construction of these wind farms to be 6 and 10.5 $kgCO_2$,eq/MWh for, respectively, for the onshore and offshore wind farms. Furthermore, they reported estimated electricity output per turbine, number of turbines in the farm, operational lifetime, and concrete and steel weights required for the construction of these wind farms, as illustrated in Table 3, which allows to estimate the quantity of cement and steel normalised per MWh of electricity produced,.

[3] As for the bridge case, the implementation of CCS in the steel sector corresponds to the implementation of bioCCS.

The construction costs of such a wind farm, without CCS implementation in cement and steel productions, were estimated based on Stehly and Duffy [13]. A total capital cost of 23.12 and 97.62 €/MWh were reported for the onshore and offshore wind farms, respectively.

Table 3: Estimation of cement and steel quantities required for construction normalised per MWh of electricity produced.

	Onshore	Offshore
Electricity produced (MWh/turbine/y) [12]	11169	20528
Number of turbines in the farm (-) [12]	20	80
Lifetime (y) [12]	20	20
Infrastructure weight (kt) [12]	35.7	142
Concrete (% of infrastructure weight) [12]	72.8 %	4.7 %
Steel (% of infrastructure weight) [12]	22.3 %	78.4 %
Material requirement normalised to electricity produced (kg/MWh)	-	-
Cement[4]	0.82	0.03
Steel	1.782	3.390

Based on these elements, the construction emissions and costs of the wind farms, with CCS implementation in the cement and steel plants, can then be evaluated based on Equations 3 and 4.

$$GHG_{WF,CCS} = GHG_{WF,no\ CCS} - \sum_i Quantity_i \cdot \left(GHG_{i,no\ CCS} - GHG_{i,CCS}\right) \quad \text{Eq. 3}$$

$$Cost_{WF,CCS} = Cost_{WF,no\ CCS} + \sum_i Quantity_i \cdot \left(GHG_{i,no\ CCS} - GHG_{i,CCS}\right) \cdot CAC_i \quad \text{Eq. 4}$$

Where:

- $GHG_{WF,CCS}$ are the greenhouse gas emissions associated with construction of the wind farm per MWh of electricity produced (in $kgCO_2$,eq/MWh) when CCS is implemented in the cement and steel productions.
- $GHG_{WF,no\ CCS}$ are the greenhouse gas emissions associated with construction of the wind farm per MWh of electricity produced (in $kgCO_2$,eq/MWh) when CCS is not considered in the cement and steel productions.
- $Cost_{WF,CCS}$ is the cost of building a wind farm per MWh of electricity produced (in €/MWh) when CCS is implemented in the cement and steel productions.
- $Cost_{WF,no\ CCS}$ is the cost of building a wind farm per MWh of electricity produced (in €/MWh) when CCS is not considered in the cement and steel productions.
- $Quantity_i$ is the quantity of material i used for the construction of the wind farm per MWh of electricity produced (in t/MWh).

A summary of the results is presented in Table 4.

[4] It was estimated that a tonne of concrete requires 0.1417 tonne of cement to be produced [1].

Table 4: Summary of the greenhouse gas emissions and costs of building a wind farm without and with CCS implementation in the cement and steel production plants. The construction emissions and cost are normalised per MWh.

	Onshore wind farm			Offshore wind farm		
	Without CCS	With CCS	*Variation (%)*	Without CCS	With CCS	*Variation (%)*
Greenhouse gas emissions ($kgCO_2$,eq/MWh)	6.00	2.59	*-56.8 %*	10.90	5.28	*-51.6 %*
Cost (€/MWh)	23.12	23.38	*1.1 %*	97.62	98.07	*0.5 %*

2 Transport via ship

In this case, the impact of CCS implementation on ship propulsion, upstream fuel production[5], and steel production on the costs and emissions of transporting a Twenty-foot Equivalent container Unit (TEU) by a container ship, fueled by liquefied natural gas (LNG) from China to Germany is assessed based on Hua et al. [14].

Using the study of Hua et al. [14], which provides greenhouse gas emissions by type of greenhouse gas and generating activity, it is possible to calculate non-CO_2 and CO_2 greenhouse gas emissions by generating activity and normalised[6] per TEU, as shown in Table 5.

The greenhouse gas emissions associated with the transport of a TEU, when CCS is considered, can then be calculated considering the CO_2 emissions avoided by CCS for each sector: steel production [5], oil and gas production [15], natural gas sweetening [16], oil refinery [17], ship operations [18], and LNG well-to-pump. It is important to note that CCS from ship operations increase the fuel consumption by 25% and that corresponding greenhouse emissions must be included. It is worth noting that as the well-to-pump emissions of LNG comprise different sources of greenhouse gas emissions [19], a similar approach is used to estimate its emissions reduction (extraction and drying [15], sweetening [16], and transport of LNG [18]) as shown in Table 6.

Using the CO_2 avoidance cost associated with these CO_2 emission reductions, it is then possible to evaluate the increase in transport cost, as presented in Table 5. This increase can then be compared to the fare of shipping such a container, estimated to be 6510 €[7] [20].

[5] This includes emissions associated with an offshore oil and gas production facility, the CO_2 co-extracted with the natural gas, and the emissions associated with refining of oil and gas products.

[6] As the emissions are provided in Hua et al. are provided for the whole lifetime, these can be normalised per TEU considering 25 years of operations, 10 one way travel per year, and 8600 TEU per trips [14].

[7] Corresponding to a fare of 7000 USD and a considered exchange rate of 0.93 €/USD.

Table 5: Summary of the greenhouse gas emissions and cost increase associated with ship transport without and with CCS implementation in steel production, oil and gas production, natural gas sweetening, oil refining, and ship propulsion. The emissions and cost are normalised per TEU.

	GHG emissions without CCS (tCO_2,eq/TEU) [14]			GHG emissions with CCS (tCO_2,eq/TEU)				Increase in transport cost	
	Non-CO_2	CO_2	Total	Non-CO_2	CO_2 emission avoided via CCS[a]	CO_2	Total	CAC (€/tCO_2)	Additional cost (€/TEU)
Steel production	0.000	0.036	0.036	0.000	79 % [5]	0.007	0.007	80 [5]	2.3
Shipbuilding	0.000	0.004	0.004	0.000	0 %	0.004	0.004	-	-
Oil production	0.000	0.005	0.006	0.001	80 % [15]	0.001	0.002	117 [15]	0.5
Very Large Crude Carrier	0.000	0.001	0.001	0.000	0 %	0.001	0.001	-	-
Oil refining	0.000	0.006	0.006	0.000	54 % [17]	0.004	0.004	155 [17]	0.4
Bunkering	0.000	0.000	0.000	0.000	0 %	0.000	0.000	-	-
Ship propulsion	0.033	0.796	0.829	0.041	58[b] % [18]	0.333	0.375	246 [18]	113.8
LNG well-to-pump	0.003	0.170	0.173	0.004	52 %	0.103	0.107	131	8.8
Sum	0.037	1.018	1.055	0.046	-	0.453	0.500	-	125.7

[a] As in earlier cases, tThese numbers include that greenhouse emissions taking place during CO_2 transport and storage represent 1.5% of the captured CO_2.
[b]Already includes the impact of the fuel consumption increase.

Table 6: Summary of the greenhouse gas emissions and CAC associated with the production and transport of LNG.

	Emission (tCO_2/MJ)			
	Without CCS [19]	Reduction via CCS	With CCS	CAC (€/tCO_2,avoided)
Oil and gas production	2.3	78 % [15]	0.50	117 [15]
Natural gas processing	5.9	89 % [16]	0.67	50 [16]
Natural gas liquefaction	5.5		5.50	-
Transport of LNG (ship propulsion)	6.8	52[b] % [18]	3.26	246 [18]
Total	20.5	-	9.93	-
Average	-	51.6 %	-	131

[a] As in earlier cases, these numbers include that greenhouse emissions taking place during CO_2 transport and storage represent 1.5% of the captured CO_2.
[b]Already includes the impact of the fuel consumption increase.

A summary of the results is presented in Table 7.

Table 7: Summary of the greenhouse gas emissions and fare for transporting a TEU without and with CCS implementation.

	Without CCS	With CCS	*Variation (%)*
Greenhouse gas emissions (tCO_2,eq)	1.055	0.500	*-52.6 %*
Shipping fare (€)	6510	6636	*1.9 %*

3 Magazine

This case study is based on the life cycle analysis of a National Geographic magazine performed by Boguski [21]. The author estimated that the greenhouse gas emissions associated with the

production and transport of the magazine were 0.82 $kgCO_2$,eq per magazine in the case considering a 5% recycled paper content. It is worth noting that the footprint excludes the biogenic CO_2 emissions emitted during the production process.
Based on an average magazine weight of 349 g per magazine [21], it is estimated that 265 g of new pulp will need to be produced by a pulp and paper plant using Equation 5.

$$\text{Quantity}_{\text{Pulp}} = \left(1\text{-}\%_{\text{recycling}}\right) \cdot \%_{\text{pulp}} \cdot \text{Weight}_{\text{Mag}} \qquad \text{Eq. 5}$$

Where:

- $\text{Quantity}_{\text{Pulp}}$ is the quantity of pulp required to make a magazine (g/magazine).
- $\text{Weight}_{\text{Mag}}$ is the weight of a magazine (g/magazine).
- $\%_{recycling}$ is the level of recycling in the magazine in-take, here 5% [21].
- $\%_{pulp}$ is the content of pulp in the coated paper, which is assumed to be 80% based on low coat weight paper [22].

In their pulp and paper study [23], IEAGHG estimated that producing a tonne of air-dried pulp led to 2.704 tonnes of CO_2 emissions (biogenic and fossil). In their case "2A-6 REC+MFB+LK", the report evaluated that 90% of these emissions could be avoided by introducing CO_2 capture from the recovery boiler, the multi-fuel boiler and the limekiln of the pulp and paper mill. The study also estimated the CO_2 avoidance cost of these emissions, including CO_2 transport and storage, to be 63 €/tCO_2,avoided.
Considering these aspects, the greenhouse gas emissions footprint of the magazine once CCS is included in the pulp and paper mill can be calculated, as shown in Equation 6.

$$\text{GHG}_{\text{Mag,CCS}} = \text{GHG}_{\text{Mag, no CCS}} - \text{Weight}_{\text{Pulp}} \cdot \left(\text{GHG}_{\text{Pulp,no CCS}} - \text{GHG}_{\text{Pulp,CCS}}\right) \qquad \text{Eq. 6}$$

Where:

- $\text{GHG}_{\text{Mag, CCS}}$ are the greenhouse gas emissions associated with the magazine with CCS implemented in the pulp and paper production (gCO_2,eq per magazine).
- $\text{GHG}_{\text{Mag, no CCS}}$ are the greenhouse gas emissions associated with the magazine without CCS implemented in the pulp and paper production (gCO_2,eq per magazine).As mentioned earlier, it was estimated to be 0.82 $kgCO_2$,eq per magazine based on Boguski [21].
- $\text{GHG}_{\text{Pulp,no CCS}}$ are the greenhouse gas emissions associated with the pulp and paper plant without CCS. The greenhouse gas emission CO_2 emissions to air, biogenic and fossil, associated with the production of pulp (g of CO_2 per g of pulp), and considered to be 2.704 [23].
- $\text{GHG}_{\text{Pulp,CCS}}$ are tthe greenhouse gas emissions associated with the pulp and paper plant with CCS. These are considered to be 0.307 [23][8].

In addition, the required new magazine price to cover the cost of implementing CCS in the pulp and paper production is estimated as presented in Equation 7.

$$\text{P}_{\text{Mag, CCS}} = \text{P}_{\text{Mag, no CCS}} + \left(GHG_{Mag,no\ CCS} - GHG_{Mag,CCS}\right) \cdot \text{CAC}_{\text{Pulp}} \qquad \text{Eq. 7}$$

[8] As in earlier cases, this number includes that greenhouse emissions taking place during CO_2 transport and storage represent 1.5% of the captured CO_2.

Where:

- $P_{Mag, CCS}$ is the required new magazine price to cover the cost of implementing CCS in the pulp and paper production (€ per magazine).
- $P_{Mag, no\ CCS}$ is the regular price of the magazine as currently available at newsstands (5.5 €/magazine).
- CAC_{Pulp} is the cost of avoiding a tonne of CO_2 via CCS from the pulp and paper productions, set to 63 €/tCO_2,avoided [23].

A summary of the results is presented in Table 8.

Table 8: Summary of the greenhouse gas emissions and required price per magazine without and with CCS implementation in the pulp and paper mill.

	Without CCS	With CCS	*Variation (%)*
Greenhouse gas emissions (gCO_2,eq)	0.820	0.184	*-77.5 %*
Magazine price (€)	5.500	5.54	*0.7 %*

4 Avocado

In this case, the impact of CCS implementation in fertiliser production and pulp and paper mills on the cost and emissions of producing a kilogram of avocado is evaluated based on the study from d'Abbadie and Akbari [24]. The avocadoes are produced in Manjimup (Western Australia), packaged and transported to a local market in the Perth region (Caning Vale market). In their study, the production emissions and the packaging and transport emissions were estimated to be 0.319 and 0.167 kgCO_2,eq/$kg_{avocado}$, thus leading to a total footprint of 0.486 kgCO_2,eq/$kg_{avocado}$.

From communication with the authors of this study, we estimated the quantity of pulp required for packaging to be 0.0727 $kg_{pulp}/kg_{avocado}$ and the average urea in-take to be 0.0296 $kg_{urea}/kg_{avocado}$.

The characteristics of the pulp and paper mill, that would produce the pulp used to make the cardboard boxes in which avocadoes are placed, with and without CCS, are based on the same IEAGHG study [23] as in Section 3. Similarly, the characteristics of the urea production plant are based on the IEAGHG study on the corresponding industry [25]. The CO_2 emissions associated with the urea production plant without and with[8] are equal to 0.265 and 0.064 tCO_2/t_{urea}, while the corresponding CO_2 avoidance cost is 87.4 €/tCO_2,avoided.

Based on the above elements, the greenhouse gas emissions associated with the avocado's production, packaging and transport can be estimated using Equation 8.

$$GHG_{Avocado,CCS} = GHG_{Avocado,no\ CCS} - \sum_i Quantity_i \cdot \left(GHG_{i,no\ CCS} - GHG_{i,CCS}\right) \qquad \text{Eq. 8}$$

Where

- $GHG_{Avocado,CCS}$ are the greenhouse gas emissions associated with the production, packaging, and transport of a kilogramme of avocado (kgCO_2,eq/kg) when CCS is implemented in pulp and paper and urea productions.
- $GHG_{Avocado,no\ CCS}$ are the greenhouse gas emissions associated with the production, packaging, and transport of a kilogramme of avocado (kgCO_2,eq/kg) when CCS is not implemented in pulp and paper and urea productions.

- i is a index of summation for the different materials used to make an end-product/end-service and whose production could be integrated with CCS (here, pulp and paper and urea).
- Quantity_i is the quantity of material i used to produce, package, and transport a kilogramme of avocado (in kg/kg).
- $GHG_{i,no\ CCS}$ are the greenhouse gas emissions (in, for example, tCO_2/t)associated with the industrial plant producing material i when CCS is not considered.
- $GHG_{i,CCS}$ are the greenhouse gas emissions (in, for example, tCO_2/t) associated with the industrial plant producing material i when CCS is considered.

Based on the above elements and the market price of avocado of 3.34[9] €/kg, the avocado price required to cover the cost associated with CCS implementation is calculated based on Equation 9.

$$P_{Avocado,CCS} = P_{Avocado,no\ CCS} + \sum_i \text{Quantity}_i \cdot \left(GHG_{i,no\ CCS} - GHG_{i,CCS}\right) \cdot CAC_i \qquad \text{Eq. 9}$$

Where

- $P_{Avocado,\ CCS}$ is the avocado price required to cover the cost of implementing CCS in the pulp and paper and urea productions (€/kg).
- $P_{Avocado,no\ CCS}$ is the avocado price when CCS in the pulp and paper and urea productions is not considered (€/kg).
- CAC_i is the CO_2 avoidance cost associated with emissions reduction of material i via CCS (in €/tCO_2,avoided).

A summary of the results is presented in Table 9.

Table 9: Summary of the greenhouse gas emissions and required price per kilogramme of avocado without and with CCS implementation in pulp and paper, and urea productions.

	Without CCS	With CCS	*Variation (%)*
Greenhouse gas emissions (kgCO_2,eq/kg)	0.486	0.306	*-37.1*
Avocado price (€/kg)	3.34	3.35	*0.3%*

5 Beer production

After water and tea, beer is the most consumed beverage globally. The production of beer relies on several greenhouse gas-intensive industrial activities. For example, steel is required to manufacture the cans containing the beer and, similarly, urea is one of the fertilisers commonly used to grow the barley required to produce beer. Based on the study from Amienyo and Azapagic [28], the impact of CCS from steel and urea productions is investigated on the cost and emissions of beer production (in steel cans) in the United Kingdom. Based on their study, the greenhouse gas emissions of the production and transport of a 0.44 liter beer can was estimated to 224 gCO_2,eq when considering a steel can.

The emissions reduction enabled by CCS from steel and urea production are estimated based on the material in-take of the beer-making process. In their study, Amienyo and Azapagic estimated that 11.7 g of new steel per can of beer (a steel beer can contains 30.8 g of steel, of

[9] This is based on an avocado price of 5.5 AUD/kg [37] and an exchange rate of 1.6455 AUD/€.

which 62% was recycled). They also estimated that 32.1 g of barley is necessary to produce a beer can. Assuming that 1 kg of urea is required to produce around 5 kg of barley [35], producing a beer can was estimated to result in a urea consumption of 6.4 grammes per can of beer during the cultivation of barley.
Based on the above elements, the greenhouse gas emissions associated with the beer production, packaging and transport with CCS can be estimated using Equation 11.

$$\mathrm{GHG_{Beer,CCS}} = \mathrm{GHG_{Beer,no\ CCS}} - \textstyle\sum_i \mathrm{Quantity_i} \cdot \left(\mathrm{GHG_{i,no\ CCS}} - \mathrm{GHG_{i,CCS}}\right) \qquad \text{Eq. 11}$$

Where

- $\mathrm{GHG_{Beer,CCS}}$ are the greenhouse gas emissions associated with the production, packaging, and transport of a beer can (gCO_2,eq/can) when CCS is implemented in urea and steel productions.
- $\mathrm{GHG_{Beer,no\ CCS}}$ are the greenhouse gas emissions associated with the production, packaging, and transport of a beer can (gCO_2,eq/can) when no CCS is implemented in urea and steel productions.
- i is an index of summation for the different materials used to make an end-product/end-service and whose production could be integrated with CCS (here, steel and urea).
- $\mathrm{Quantity_i}$ is the quantity of material i used to produce, package, and transport per can of beer (in g/can).
- $\mathrm{GHG_{i,no\ CCS}}$ are the greenhouse gas emissions associated with the industrial plant producing material i when CCS is not considered (in tCO_2/t).
- $\mathrm{GHG_{i,CCS}}$ are the greenhouse gas emissions associated with the industrial plant producing material i when CCS is considered (in tCO_2/t).

Based on an estimated price of 1.25 £ for a 0.44l beer can [36], the required price to cover the additional cost associated with the emission reduction can be calculated as shown in Equation 12.

$$\mathrm{P_{Beer,CCS}} = \mathrm{P_{Beer,no\ CCS}} + \textstyle\sum_i \mathrm{Quantity_i} \cdot \left(\mathrm{GHG_{i,no\ CCS}} - \mathrm{GHG_{i,CCS}}\right) \cdot \mathrm{CAC_i} \qquad \text{Eq. 12}$$

Where:

- $\mathrm{P_{Beer,CCS}}$ is the price of beer can (£/can) required to cover the cost associated with CCS urea and steel productions.
- $\mathrm{P_{Beer,no\ CCS}}$ is the price of a beer can (£/can) when no CCS is implemented in urea and steel productions.

A summary of the results is presented in Table 10.

Table 10: Summary of the greenhouse gas emissions and price of a beer can with CCS from steel and urea production.

	Fossil-based CO_2 supply	DAC-based CO_2 supply	*Variation (%)*
Greenhouse gas emissions (gCO_2,eq)	224	186	*-17.2 %*
Price (£)	1.25	1.26	*0.6 %*

6 Waste treatment

In this case, the impact of CCS implementation on a generic 40 MW waste-to-energy plant is investigated based on Roussanaly et al. [26]. Without CCS, this plant typically treats 70 t/h of solid municipal waste and results in 502 ktCO_2/y of which 65% is of biogenic nature.

Implementing CCS on this waste-to-energy plant would allow to capture 451 kt/y of CO_2, which 65% would be of biogenic nature thus enabling negative emissions. Here, it was assumed that while part of these negative emissions are kept by the waste-to-energy plant to ensure the waste treatment is fully carbon neutral, the remaining part would be sold on voluntary carbon markets or to private actors. Thus, implementing CCS on such a plant was evaluated by Roussanaly et al. to fully reduce the 175 kt/y of fossil CO_2 from the waste-to-energy plant to achieve fossil CO_2 neutrality, as well as to enable 276 kt/y of negative emissions at the plant level· It is assumed that negative emissions beyond fossil CO_2 neutrality would be sold on voluntary carbon markets or to private actors.

The study also computed a CO_2 avoidance cost of 202 €/t of biogenic and fossil CO_2. Assuming that these negative emissions would be sold at a price of 290[10] €/t, the waste treatment fee would need to increase by 18.3 €/t_{waste} to cover the remaining costs of CCS using equation 10.

$$\Delta_{\text{WtE,CCS}} = \frac{CAC_{WtE} \cdot (Av\ CO_{2,fossil} + A\ \ CO_{2,bio}) - P_{NEG} \cdot Av\ CO_{2,bio}}{Annual\ amount\ of\ waste\ treated} \qquad \text{Eq. 10}$$

Where:

- $\Delta_{\text{WtE,CCS}}$ is the required increase in waste treatment fees to cover the cost of achieving CO_2 neutrality via CCS.
- CAC_{WtE} is the cost of avoiding a tonne of fossil and biogenic CO_2 via CCS from the waste-to-energy plant, set to 202 €/tCO_2,avoided [26].
- $Av\ CO_{2,fossil}$ and $Av\ CO_{2,bio}$ are the quantities of fossil and biogenic CO_2 emissions avoided by CCS implementation. These are 175 and 276 kt/y, respectively [26].
- P_{NEG} is the price at which negative emissions could be sold by the waste-to-energy plant, here assumed to be 290 €/t.
- $Annual\ amount\ of\ waste\ treated$ is the annual amount of waste treated by the waste-to-energy plant, estimated to 521 kt/y based on a utilisation rate of 85% [26].

This emissions reduction and cost increase are here put in the context of an average household in Bergen (Norway) based on the location adopted in Roussanaly et al. [26]. A typical household in this city contains 2.12 persons on average, each producing on average 387 kg of waste per year [27], [28], thus resulting in a total amount of waste produced per household of 820 kg per year. Based on a waste treatment fee of 186[11] €/household/y without CCS in 2023 [29], the waste treatment fee would need to increase to 205 €/household/y to cover the cost of enabling zero fossil emission treatment of waste.
A summary of the results is presented in Table 11.

[10] Assuming that the waste-to-energy plant could manage to get paid half the negative emissions price of direct air capture [30].

[11] This corresponds to a waste treatment fee of 2126 NOK/househould/y and using an exchange rate of 11.4 NOK/€.

Table 11: Summary of the fossil CO_2 emissions from waste treatment and waste treatment fee for a household without and with CCS implementation in the waste-to-energy plant.

	Without CCS	With CCS	*Variation (%)*
Fossil CO_2 emissions ($kgCO_2$/household/y)	265	0	*-100 %*
Waste treatment cost (€/household/y)	186	205	*10.1 %*

7 Long-distance air travel

In this case, the aim is to use negative emissions enabled by direct air capture with CO_2 storage (DACCS) to compensate for the emissions of a round trip flight between New York (United States) and Paris (France).

The greenhouse gas emissions associated with this travel, in economy class, were estimated to 930 $kgCO_2$,eq using the online flight carbon footprint calculator of CarbonFootprint.com [31]. This value used as base case does not include the higher radiative forcing effect due to most of these emissions occurring at higher altitudes. A sensitivity analysis in which this radiative forcing is included is also discussed in the manuscript. In this scenario, the equivalent CO_2 emissions of the travel were estimated to 1570 $kgCO_2$,eq [31]. In both scenarios, it is assumed that negative emissions from DACCS are used to fully compensate for the greenhouse gas emissions associated with the travel.

An important element of evaluating these cases is the net removal cost considered for direct air capture. Indeed, a wide range of net removal costs have been published by different actors involved in research and development of direct air capture. The net removal cost of direct air capture assumed in the case studies evaluation is 577[12] €/$tCO_{2,removed}$. This cost corresponds to the one of the sorbent and solvent-based direct air capture once it has reached the cumulative deployment capacity of 1 Mt/y, according to Sievert et al. [30]. It is worth noting that this number is including a CO_2 transport and storage cost of 21 €/$tCO_{2,removed}$.

The basic travel price without DACCS compensation was obtained from the Delta website [32], on the 13th of December 2023, for an economy class travel from the 4th to the 11th of March 2024. This fare was estimated to 665 € for the round-trip travel. The required increase in the travel fare to cover the cost of fully compensating for the travel emissions is calculated by multiplying the equivalent CO_2 emissions by the DACCS cost presented in Section **Error! Reference source not found.**.

A summary of the results is presented in Table 12.

Table 12: Summary of the greenhouse gas emissions and travel fare of a round-trip flight between New York (United States) and Paris (France) without and with DACCS compensation. The evaluations are also presented for the scenarios in which the higher radiative forcing effect is excluded or included.

	Without higher radiate forcing effect			With higher radiate forcing effect		
	Without DACCS compensation	With DACCS compensation	*Variation (%)*	Without DACCS compensation	With DACCS compensation	*Variation (%)*
Greenhouse gas emissions ($kgCO_2$,eq)	930	0	*-100 %*	1570	0	*-100 %*
Tavel fare (€)	684	1228	*78 %*	684	1603	*134 %*

[12] This corresponds to a cost of net removal cost of 620 $/t assuming an exchange rate of 0.93 €/USD.

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