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A multi-sector to multi-product analysis

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PERSPECTIVE

Putting the costs and benefits of carbon capture and storage into perspective: a multi-sector to multi-product analysis

Simon Roussanaly[1,*], **Truls Gundersen**[2] **and Andrea Ramirez**[3]

[1] SINTEF Energy Research, Trondheim, Norway
[2] Department of Energy and Process Engineering, NTNU, Trondheim, Norway
[3] Deparment of Chemical Engineering, Delft University of Technology, Delft, The Netherlands
[*] Author to whom any correspondence should be addressed.

E-mail: simon.roussanaly@sintef.no

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Abstract

Carbon dioxide capture, transport, and storage (CCS) is essential in achieving the net-zero target. Despite this increasing recognition, current CCS deployments are far behind targeted ambitions. A key reason is that CCS is often perceived as too expensive. While assessments of the costs of CCS have traditionally looked at impact at the plant level, the present study seeks to understand the costs and environmental benefits that will be passed to consumers via end-products and services. In particular, nine end-products/services (bridge construction, electricity from onshore wind power, electricity from offshore wind power, transport of a container via ship, a magazine, the production and transport of an avocado, a beer can, waste treatment via waste-to-energy, and long-distance air travel) connected to ten potential areas of application for CCS (cement production, iron and steel production, oil and gas production, natural gas processing, refining, ship propulsion engines, pulp and paper production, urea production, waste-to-energy, and direct air capture). The evaluations highlight that significant emission reductions (beyond 50%) could be achieved at marginal costs for end-users in six end-products/services: bridge construction, electricity from onshore wind power, electricity from offshore wind power, transport by ship, magazine, and waste treatment. Moderate emission reductions (between 11 and 37%) could be achieved in two cases at virtually no cost (increase below 1%): beer can and avocado production. Finally, only the case of using direct air capture to compensate for emissions from air travel was found to raise the cost for end-users significantly. Although more research is still needed in this area, this work broadens our understanding of the real cost and benefits of CCS and provides useful insights for decision-makers and society.

Abbreviations

bioCCS	bioenergy production with CCS
CCS	carbon capture and storage
CI	cost increase
DAC	direct air capture
ER	emissions reduction
IEA	International Energy Agency
IMO	International Maritime Organisation
IPCC	Intergovernmental Panel on Climate Change
IRA	inflation reduction act
LNG	liquefied natural gas
UNFCCC	United Nations Framework Convention on Climate Change

Nomenclature

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.
$Cost_{EndP,no\ CCS}$	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.
$GHG_{EndP,no\ CCS}$	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,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).
$Quantity_i$	Quantity of material *i* used to make the considered end-product/end-service (in, for example, t).

1. Introduction

The exponential rise of anthropogenic greenhouse gas emissions is now widely accepted to be the cause of global warming [1, 2]. Over the past few decades, governments under the aegis of the UNFCCC have been working towards limiting global warming and its dramatic consequences. These efforts resulted in several key international milestones (Kyoto Protocol, Copenhagen Accord, Paris Agreement) towards limiting global warming to well below 2 °C, and preferably 1.5 °C, compared to pre-industrial levels [3]. To achieve this target and the associated net-zero target, several technological approaches must be deployed, including renewable energy, nuclear energy, improvement in energy efficiency, CCS, switching to low-carbon fuels, etc.

Among these, carbon dioxide capture, transport and storage (CCS) has been consistently highlighted by the IPCC and the IEA as a key contributor to meeting the Paris Agreement [3, 4]. Although the past few years have shown a significant increase in the number of in-development projects, CCS, as well as nearly all emission reduction technologies[4], is still behind from where it should be to contribute to the climate targets [5]. The slow CCS deployment can partly be explained by three reasons. First, CCS is negatively perceived by some as it can prolong the use of fossil fuels and, therefore, slow down the transition. Second, until the recent IRA in the United States [6] and the EU Carbon Management Strategy in Europe [7], very limited policy and regulatory frameworks were in place to support the deployment of CCS. Last but not least, CCS has often been criticised for being too expensive.

Indeed, implementing CCS can significantly impact the economics of the plant where it would be implemented, leading to a significant increase in the cost of production. This CI, which, for example, can be as high as 50%–100% in the case of cement production [8, 9], has hindered industrial actors from investing in CCS due to the fear that their products would become economically non-viable, especially for products with limited or no greenhouse gas emission penalties. However, the products of industrial plants where CCS can be implemented (for example, cement, steel, ammonia) are rarely directly used by individuals. If the impact of CCS on products/services needed by individuals is to be better understood, a different approach to assess the costs and benefits of CCS is required. Over the past few years, several studies have sought to investigate the impact of industrial CCS implementation on products or services relevant to end-users. Rootzen and Johnsson were among the first authors evaluating the impact of carbon capture, transport, and storage (CCS) implementation on the cost of several end-products: CCS from cement production on the cost of a residential building [10], CCS from steel production on the cost of a car [11], etc. These studies concluded that CCS implementation results in a marginal CI. Building on this, Subraveti *et al* [12] sought to explore the combined impact of CCS implementation in cement and steel production on the cost and emissions associated with the construction of a bridge. The results showed that the CI was marginal (∼1%) while the ER was significant (∼51%), thus better highlighting the cost and benefit of CCS implementation in this case. Emanuelsson and Johnsson [13] used a similar approach as Subraveti *et al* [12] to understand the impact of CCS from multiple sectors on the cost and emissions of several products. While these types of studies have allowed a better understanding of the cost and benefit of CCS, they are time- and data-intensive

[4] Appart from solar photovoltaic, electric vehicles, efficiency improvement in building lighting.

as complete value chains, from primary material production to end-products or services, need to be modelled. This limits the applicability of the approach for supporting decision-making.

The present study builds upon these earlier works and seeks to further expand the understanding of the impact of CCS implementation on the cost and greenhouse gas footprint of different end-products (infrastructures, products, services, etc). In particular, ten potential areas of application for CCS and nine different end-products are considered, making this study the most comprehensive to date on the topic. In addition, to address the time and data-consuming approaches adopted in previous studies, a simplified approach for performing such evaluations is proposed.

The paper is organised as follows. Firstly, the selected CCS applications and end-product/service case studies considered are briefly introduced, followed by the simplified methodology adopted to evaluate the impact of CCS on the costs and greenhouse gas emissions for these case studies. Secondly, the case studies are further detailed together with the presentation of obtained results. Thirdly, we reflect upon the implications of the case study evaluations, as well as the drawbacks and opportunities of the simplified evaluation methodology adopted in this study. Finally, the overall conclusions of this study are drawn.

2. Case studies and adopted methodology

2.1. CCS applications and end-products/services considered

This study considers nine end-products/services[5]: bridge construction, electricity from onshore wind power, electricity from offshore wind power, transport of a container via ship, a paper magazine, the production and transport of an avocado, the production and transport of a beer can, waste treatment via waste-to-energy, and long-distance air travel. These end-products/services are linked to ten potential areas of application for CCS:[6] cement production, iron and steel production, oil and gas production, natural gas processing, refining, ship propulsion engines, pulp and paper production, urea production, waste-to-energy, and DAC. Together, these sectors are responsible for about 22%[7] of the global emissions. Figure 1 illustrates the main interconnections between the nine end-products/services and the ten potential areas of application for CCS. Each end-product/service is presented in more detail in section 3 (and the *supplementary information*), together with the particulars of the evaluation methodology and the detailed outcome of the CCS impact evaluations.

2.2. Methodology

In earlier studies, complete modelling of the materials-to-product value chain (i.e. from material extraction to end-products) was performed to obtain a complete picture of the costs and emissions of an end-product/service (without CCS) and the different contributions. The chain could then be modified to study the impact of CCS implementation on the end-product's costs and emissions. It is worth noting that the level of modelling detail for each element of the materials-to-product value chain is often heterogeneous in literature[8]. While this approach enables consistency in evaluating the costs and emissions of an end-product without and with CCS implementation, it is also a time-, resource-, and knowledge-intensive effort.

An alternative is to build on published life cycle assessments of a selected end-product. Such studies usually include the total greenhouse gas emissions associated with an end-product/service, a breakdown of the different components contributing to this footprint, and other key inputs required to understand the impact of CCS implementation on the cost and emissions of this end-product/service. While these studies rarely include cost aspects, the cost or price of an end-product (without CCS) can be obtained from, for example, literature, evaluations or market prices. Caution, however, should be taken with the system boundaries of the different studies so that the data is harmonised as much as possible.

[5] These end-products/services were selected based on the authors' reflection of relevant end-products/services for each of the considered CCS applications and, when possible, the opportunity to connect to more than one CCS application at the same time. It was then confirmed that, at least, a life cycle assessment study with sufficient levels of detail and transparency to conduct the evaluation was available in the open literature.

[6] All of these areas of application for CO_2 capture are assumed to be connected to CO_2 storage, except in the case of beer, where direct air capture is used to supply the required CO_2 intake thus corresponding to CO_2 utilisation.

[7] With the following individual contributions [26]: cement production (7%), iron and steel production (7%), oil and gas production (1.5%), natural gas processing (2.5%), refining (2%), pulp and paper production (1%), urea production (0.9%) [65]. No global contribution estimate was found for waste-to-energy.

[8] This can be based on advanced simulation or modelling, commercial data, literature data, guest estimates, etc.

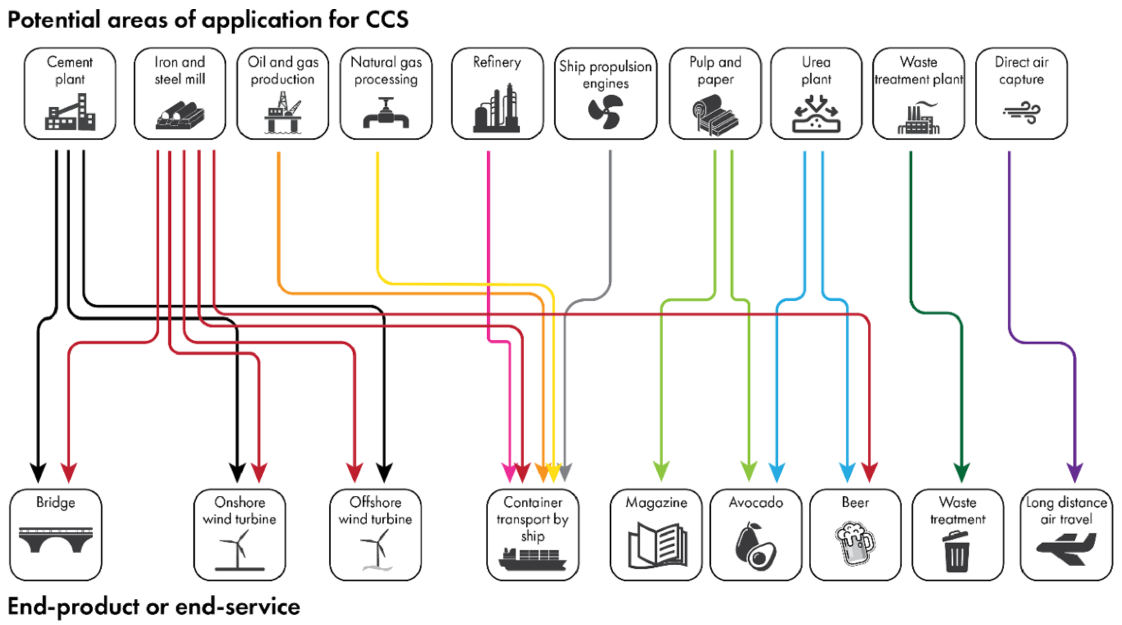

Figure 1. Interconnections between the considered end-products/services and the CCS applications considered in this study.

The impact of CCS on the emissions and costs of a given end-product/end-service using the above information can be calculated[9] as shown in equations (1) and (2).

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

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

where:

- $GHG_{EndP,CCS}$ are the greenhouse gas emissions associated with the considered end-product/end-service (in, for example, tCO_2,eq per unit) when CCS is implemented.
- $GHG_{EndP,no\ CCS}$ are the 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.
- 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 (for example, cement and steel).
- $Quantity_i$ is the quantity of material i used to make the considered end-product/end-service (in, for example, t).
- GHG_i,no 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).
- $GHG_{i,CCS}$ 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). Note that the emissions associated with CO_2 transport and storage are also included.
- $Cost_{EndP,CCS}$ are the cost of producing the considered end-product/end-service (in, for example, € per unit) when CCS is implemented.
- $Cost_{EndP,no\ CCS}$ are the 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.
- CAC_i is the CO_2 avoidance cost associated with emissions reduction of material i via CCS (in €/tCO_2,avoided).

[9] It is worth noting that the ship transport case is evaluated differently, i.e. using percentate reduction in greenhouse gas emissions, as explained in the supplementary information.

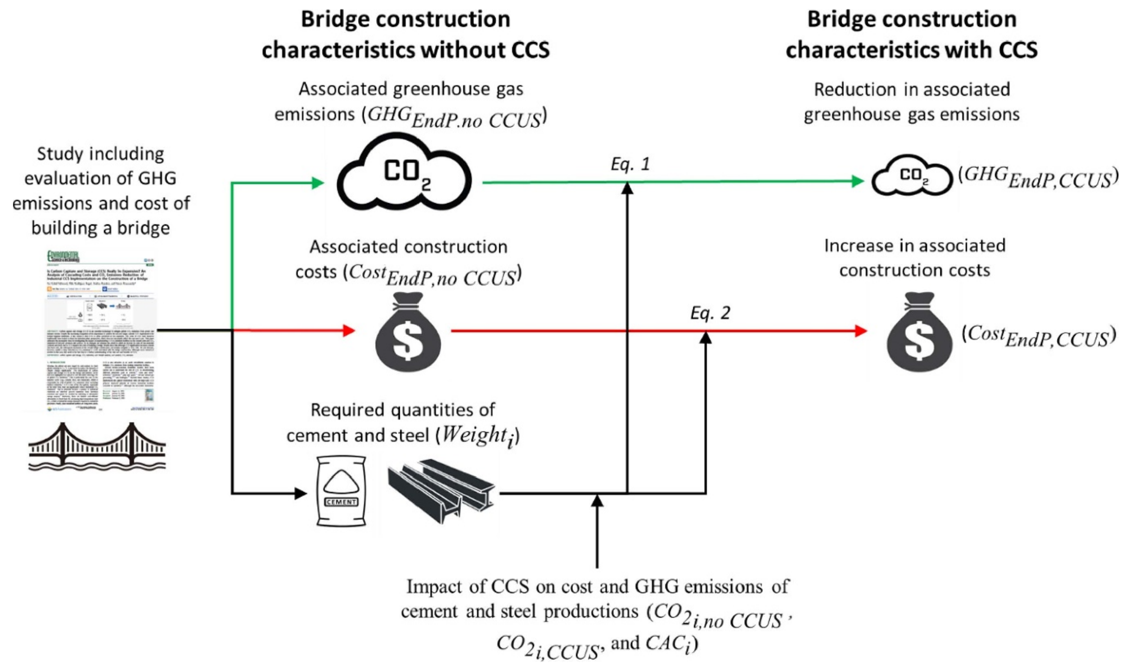

Figure 2. Illustration of the adopted methodology on the case of the impact of CCS implementation in the cement and steel sectors on the emission and cost of building a bridge.

While the details of evaluations performed for each end-product/end-service can be found in the supplementary information, appendix A illustrates the application of this simplified approach by reprising a case study by Emanuelsson and Johnsson [13] and figure 2 illustrates the flow of information and steps for the case. It is worth noting that figure 2 highlights the terms of equations (1) and (2) in parenthesis where relevant, the arrows indicate information flows.

The emissions and cost considered for each end-product without CCS ($GHG_{EndP,no\ CCS}$ and $Cost_{EndP,no\ CCS}$) and the characteristics considered for each potential area for CCS application, with and without CCS, (CO_{2i},no CCS, $CO_{2i,CCS}$ and CAC_i) are summarised in tables 2 and 3 (see appendix B). Note that to properly account for the GHG ER enabled by CCS implementation, calculated emission reductions also include the fossil CO_2 emissions associated with energy consumption along the whole CCS chain.

3. Case studies

The following sections further describe the case studies considered and the results of evaluating the impact of CCS implementation on the costs and emissions of the products. While further details on the performed evaluations and underlying assumptions can be found in the supplementary information, the following sections present the key results of each case. A summary of the results of the evaluations performed is also presented in appendix C (tables 4 and 5) for each end-product/end-service.

3.1. Infrastructure cases

Infrastructure often requires large quantities of cement and steel, which are associated with sector producing large amounts of greenhouse gas emissions. To illustrate the potential environmental benefit and cost impact of CCS implementation in the cement and steel sector on infrastructure [14–17], a set of three case studies are examined: a bridge, an onshore wind farm, and an offshore wind farm.

3.1.1. Bridge case

The bridge case is based on the same case as our earlier study [12], i.e. the construction of the Lake Pontchartrain Causeway located in Louisiana (USA). However, compared to the previously published research[10], here it is considered that a deeper emission reduction of steel manufacturing could be achieved by

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

integrating bioCCS in the iron and steel plant based on Tanzer *et al* [16]. Based on this revised assumption, implementing CCS in both the cement and steel sectors can result in an even deeper reduction of the emissions associated with the bridge construction. CCS implementation here results in an overall ER of 68% of the emissions associated with the bridge's construction (i.e. 17% higher than in our previous study). Regarding costs, CCS implementation results in a minor increase (2%) in the bridge construction cost. The ER and CI are linked rather equally to changes in the steel and cement sectors, while the increase in cost is mainly linked to the change in steel price as a consequence of CCS deployment (about two-thirds of the increase).

3.2. Onshore and offshore wind power cases

Wind power is set to become a key element of the global power system as the world moves towards net-zero power production. While wind power brings down running-fuel emissions to zero, non-negligible quantities of greenhouse gas emissions are associated with its manufacturing and installation (up to 45 g/kWh [18–20]), especially the cement and steel required for these infrastructures. The impact of CCS implementation in the cement and steel[11] sectors on the cost and emissions of building an onshore and an offshore wind park, located in Europe, is evaluated based on a study from Bonou *et al* [21], which considers: a 20-turbines onshore wind farm with a total power capacity of 46 MW, and an 80-turbines offshore wind farm with a total power capacity of 320 MW. As for the bridge case, significant ER is observed once CCS is deployed in the iron and cement sectors, as emissions from the onshore and offshore wind farms decrease by 57 and 52%, respectively. The cost of electricity production would increase by around 1% in both cases. CCS implementation in the steel sector plays the key role in these changes as it is responsible for around 85%–90% of the emissions decrease in both cases. This is due to the inherently large quantities of steel required for the construction of wind turbines (around 173 and 348 kt_{steel} per GW of installed wind power capacity for respectively onshore and offshore in the cases considered [21]).

3.3. Transport via ship

The shipping sector is an essential element of the global economy and is responsible for about 3% of global greenhouse gas emissions [22]. As the maritime traffic associated with most of these emissions is of transnational and intercontinental nature, adopting ambitious policies to reduce emissions for this sector has historically been challenging. However, the adoption of pathways towards a net-zero maritime sector by the IMO and, more recently, the European Union, has accelerated interest in developing and deploying emission reduction technologies in this sector. As a result, onboard carbon capture[12] from ship propulsion engines has gained strong industrial interest [23]. Based on Hua *et al* [24], the impact of CCS implementation on the costs and emissions of transporting a 20-foot container by a container ship, fuelled by LNG, from China (Yingkou) to Germany (Bremen) is assessed. CCS could reduce the emissions of this transport in five possible ways. First, CCS implementation in the steel sector could reduce the emissions associated with the steel used to build the ship. Secondly, CCS from ship propulsion engines could reduce emissions associated with fuel combustion on the ship. Finally, CCS can reduce the emissions of upstream fuel and consumable production (LNG well-to-tank) via CCS from offshore oil and gas production, CCS from natural gas processing, and CCS from refineries[13]. Implementing CCS in these five applications can enable an overall reduction in associated greenhouse gas emissions of 53%. Most of this reduction (45%) is due to the implementation of CC in the ship engines. The use of low carbon footprint steel to build the ship also plays a role (around 3%), while the implementation of CCS in other steps of the LNG well-to-tank supply (production, sweetening and transport of LNG) is responsible for the remaining 5%. As in earlier cases, CCS has only a minor impact on the cost of this service. The fare increase is estimated to be 2% of the fare for one-way transport of a 20-feet container (6510 € per container [25]). This increase is primarily due to CCS in the ship engines, which represents 85% of the increase.

3.4. A magazine

Pulp and paper mills are responsible for about 1% of global emissions [26]. Since a large share of these CO_2 emissions are of biogenic nature, CCS in this sector has gained increased interest due to the possibility of obtaining negative emissions. In order to understand the potential impact of CCS implementation in the pulp and paper sector, the case of producing and transporting[14] a paper magazine is considered based on the

[11] As for the bridge case, the implemention of CCS in the steel sector is examined here as the implementation of bioCCS in the sector.

[12] Note that onboard carbon capture has to be connected to CO_2 storage to effectively reduce CO_2 emissions from the maritime sector.

[13] Altough LNG is used as a fuel, oil-derived additives and lubricants are used during the ship operations, which are then affected by the deployment of CCS in refineries

[14] From the printer to relevant off-sites.

life cycle analysis study by Boguski [27]. The study is based on production in the US for US customers but also for export to relevant foreign countries. It is worth noting that the study considers that only 5% of the paper intake during the magazine production comes from recycling and that most magazines are landfilled after use. This reflects US-based practices but may be relevant for other locations such as Europe and Asia.

CCS implementation can enable significant negative emissions. These negative emissions would allow compensating for 78% of the fossil emissions associated with the overall emissions of the magazine, including delivery. Furthermore, while this reduction in emissions is significant, it comes at a marginal cost (less than 1%, corresponding to a 5 c€ increase per magazine).

3.5. Avocado

The agricultural sector is responsible for about 10% of the global greenhouse emissions and is also tied to greenhouse gas emissions associated with other sectors (fertiliser, packaging, transportation, etc). Based on a study by d'Abbadie and Akbari [28], the impact of CCS implementation in fertiliser production (more precisely, in urea production) and pulp and paper mills (for the packaging) on the cost and emissions of producing a kilogram of avocado is evaluated. The avocadoes are produced in Manjimup (Western Australia), packaged and transported to a local market in the Perth region (Caning Vale market)[15].

Compared to previous cases, a more modest emission reduction (37%) is observed as most of the greenhouse gas emissions are linked to other aspects of avocado production and transport, such as water irrigation, emissions during fertiliser use, transportation, etc. This reduction in emissions also comes at virtually no cost to the consumer, as the local market avocado price would not change (the change is below 1%). Interestingly, CCS from pulp and paper mills is by far the main contributor (around 95% in both cases), which can be explained by the significant amount of pulp and paper products involved in packaging (around 75 grammes per kilogramme of avocado, which with CCS from pulp and paper production result in around 175 grammes of biogenic and fossil CO_2 emissions to the air being avoided per kilogramme of avocado).

3.6. Beer can

After water and tea, beer is the most consumed beverage globally [29, 30]. 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 a study from Amienyo and Azapagic [31], the impact of CCS from steel and urea productions is investigated on the cost and emissions of beer production (in steel cans[16]) in the United Kingdom.

CCS implementation from steel and urea productions has virtually no impact on the required beer can price (less than 1%). However, they also result in a limited reduction in the emissions associated with the beer can (11%). The main reason for this decrease is, by far, the implementation of CCS from steel, which accounts for 95% of the reduction. Meanwhile, CCS implementation from urea production only leads to a marginal reduction in CO_2 emissions (less than 1%). Although these emission reductions are limited, the fact that they take place at virtually no cost could still make CCS a relevant complementary measure for the decarbonisation of this end-product.

3.7. Waste treatment

Over the past decades, the treatment of municipal solid waste via waste-to-energy has emerged as a more environmentally friendly approach to waste management than landfilling [32, 33]. However, this alternative still results in significant levels of CO_2 emission [34]. The potential of CCS from this sector has gained interest, as it can reduce fossil emissions from waste treatment and enable negative emissions through the capture and sequestration of biogenic CO_2 [35]. The potential for negative emissions is significant, considering that approximately 60% of the CO_2 produced by waste-to-energy in Europe is of biogenic nature [35]. The impact of CCS implementation on a generic Norwegian-based 40 MW waste-to-energy plant is thus investigated based on Roussanaly *et al* [36]. This plant typically treats 70 t/h of solid municipal waste and, without CCS, it produces 502 ktCO_2/y of which 65% is of biogenic nature.

In this case, the implementation of CCS not only leads to net-zero waste treatment but also enables negative emissions via the capture and permanent removal of the biogenic emissions from the plant. As the end-services of the waste-to-energy plant with CCS achieve and go beyond net-neutrality, the negative

[15] It is worth noting that the production and transport of the avocadoes remain local in this case. If the avocados were transported between countries or continents, the avocado transport would likely result in higher greenhouse gas emissions.

[16] While aluminium is today's predominantly used material for drink cans, steel cans still represent 25% of the drink can production (as is the case with, for example, the production of Sapporo Premium beer) [66]. Due to the limited openly available detailed techno-economic analyses of CCS from aluminium production, the case of steel-based beer cans was selected.

emissions beyond the net-neutrality could be sold to offset some of the cost CCS implementation. If these negative emissions could be sold at a price of around 290[17] €/t, the waste treatment fee would need to increase by 22.4 €/t_{waste} to cover the remaining costs of CCS. Such an increase would raise waste treatment fees by around 10%. For an average household, achieving net-zero emissions waste management would thus cost 18 €/y, if the generated negative emissions can be sold at the assumed price.

3.8. Long-distance air travel

Despite its currently high cost, DAC is gaining attention from private and public actors as a way of delivering negative emissions (when combined with storage) that can be used to compensate for hard-to-abate greenhouse gas sources and supply sustainable carbon for the different use such as the production of chemicals and food [37, 38]. The present subsection aims to understand the cost and greenhouse gas impact of using DAC to compensate for the emissions of long-distance air travel.

Indeed, greenhouse gas emissions from long-distance passenger travel by plane are notoriously difficult to reduce [39]. The purchase of carbon offsets has commonly been offered by airline companies to customers to compensate for their flight's greenhouse gas emissions. However, over the past few years, many of these schemes have been heavily criticised for their insufficient, and even lack of, environmental benefits [40, 41]. Due to its high-quality offset status, DAC and storage has been highlighted by several large airlines and aircraft constructors as a more effective way of compensating for travel emissions. To understand the implication of such a strategy, the impact of fully compensating 930 $kgCO_2$,eq associated[18] with a round trip between New York (USA) and Paris (France) [42] via negative emissions from DAC is assessed. Assuming a net removal cost of DAC of 585 €/tCO_2 [43], fully compensating for the travel emissions would increase the travel cost by 80%. This corresponds to an increase of 550 € for an assumed ticket price of 665 € [44][19]. If the radiative forcing effect of emissions at higher altitudes[20] is also compensated, the travel cost would more than double (a factor of around ∼2.3). In either case, these drastic price increases can limit the affordability of such an emission compensation approach.

4. Discussion

While CCS has often been criticised as being a too costly measure with limited environmental benefits, the outcomes from the nine case studies (displayed in figure 3) provide a different picture. Out of the nine end-products/services considered, seven can achieve a reduction of their associated greenhouse gas emissions beyond 50% through CCS implementation in different sectors. Furthermore, ER levels beyond 65% can be achieved in four of the case studies. The cases in which CCS only enable moderate ER are the avocado and beer cases (37 and 11%, respectively), as most of their associated greenhouse gas emissions are linked to activities other than the ones where CCS can be used to reduce emissions.

With regards to cost, even when CCS can enable deep ER, its impact on the cost of end-products/services is often marginal. Indeed, CCS implementation in the considered sectors results in CIs below 2% in seven of the nine end-products/services cases. To place this into perspective, a 2% CI is smaller than the yearly global inflation of the last ten years (before COVID and the Russia-Ukraine conflict), which averaged to 2.7% [45]. Furthermore, while CCS implementation in waste-to-energy plants leads to a significant increase in waste treatment cost (10%), this increase has a limited impact on end-users in absolute terms (around 18 € per year for a household in the case considered). The main exception to this trend is the use of DAC with CO_2 storage to compensate for the emissions of a long-haul flight. This difference is due to the high net removal cost of DAC and the high carbon intensity of this service. Thus, apart from the long-haul flight case, CCS implementation in the different sectors enables significant deep ER at marginal CI for all the considered end-product/service cases.

As suggested previously [12], the CI associated with ER via CCS could, in most cases, be covered by a minor price increase for the consumer of these end-products/services. While this was also postulated in our previous study [12], willingness to contribute to significant ER at marginal cost has been indicated by recent

[17] The number has been indicated by waste-to-energy plant actors. It is worth noting that this negative emission price is significantly lower than the negative emissions production cost of direct air capture in, at least, the near-term [43].

[18] This number excludes the radiative forcing of higher altitude emissions.

[19] Based on an estimated travel price obtained on the 13th of December from the Delta.com website for a travel from the 4th to the 11th of March 2024.

[20] CO_2 emissions at high altitudes results in a radiative forcing, and this global warming potential, higher than low altitudes [67, 68].

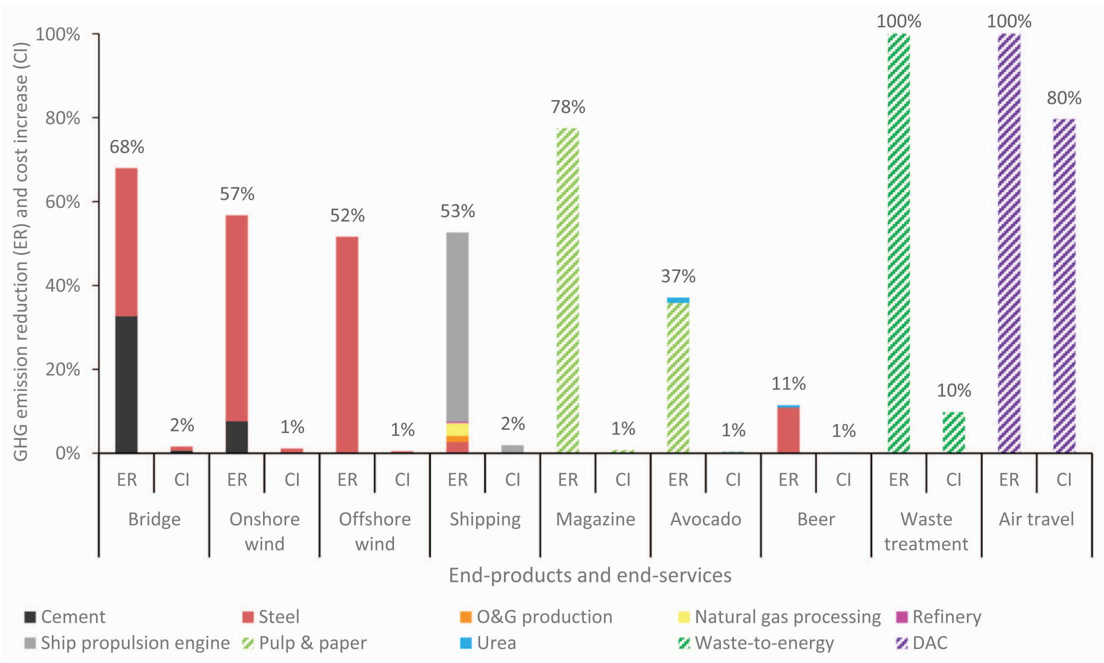

Figure 3. Summary of the impact of CCS implementation on the greenhouse gas emissions reduction (ER) and cost increase (CI) of the considered end-products. Contributions of applications where CCS lead to a net removal at the plant level (pulp and paper, waste-to-energy, and direct air capture) are displayed as dashed bars.

international surveys. For instance, Andre *et al* [46] show via a global survey of 130 000 people across 125 countries, the willingness of 69% of the worldwide population to contribute 1% of their income to reducing global emissions.

5. Limitations and opportunities of the adopted evaluation approach

An important element that enables the evaluation of multiple end-products/services in the present study is the simplified approach adopted to estimate the impact of CCS implementation on the cost and greenhouse gas emissions of these different end-products/services. While this approach is less resource- and time-effective than the detailed approach adopted in previous literature on the topic [10–13], it also comes with some limitations and potential drawbacks. Firstly, the case study selection is limited to cases that have been published in literature with sufficient levels of detail and quality. Secondly, geographic specificity, authors'assumptions, and lack of transparency in the selected underlying studies introduce uncertainties in the outcome of these evaluations. While these uncertainties are hard to quantify, it is the authors' opinion that they are likely to remain acceptable when the approach is used to explore the rough impact of CCS implementation on emissions and cost of end-products/services, rather than estimating an exact impact.

Finally, illustrating the feasibility of this approach over nine end-products/services opens the door to more studies of this type, as well as to meta-type of studies considering, for example, hundreds of end-products/services. However, the latter is likely to require strong support from life cycle assessment practitioners to gather relevant cases and the corresponding necessary information.

6. Conclusion and way forward

The present study seeks to understand the impact of CCS implementation in different sectors on costs and environmental benefits passed to consumers via end-products/services. In particular, nine end-products/services connected to ten potential areas of application for CCS (cement production, iron and steel production, oil and gas production, natural gas processing, refining, ship propulsion engines, pulp and paper production, urea production, waste-to-energy, and direct air capture) are investigated.

The evaluations highlight that deep emission reductions (beyond 50%) could be achieved at marginal CIs (1–2%) in six of the case studies: bridge construction, electricity from onshore wind power, electricity from offshore wind power, transport by ship, magazine, and waste treatment. Moderate ERs (between 11 and 37%) could be achieved at virtually no cost (increase below 1%) for two other end-products: beer can and avocado production. Finally, only the case of using DAC to compensate for emissions from air travel was found to significantly raise the cost to end-users.

As a result, in most cases, the additional costs associated with these significant emission reductions via CCS could be covered by a fare increase acceptable for said end-users. However, support will be required to mitigate the higher costs and risks of early CCS movers.

Finally, while this work deeply broadens our understanding of the real cost and benefits of CCS for end-users and society, it would be interesting to expand this type of analysis in the future by combining multiple types of emission measures to understand the impact of achieving net-zero end-products and end-services.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Simon Roussanaly: conceptualisation, investigation, methodology, writing—original draft, writing—review and editing.

Truls Gundersen and Andrea Ramirez: writing—review and editing.

Appendix A. Illustration of the proposed simplified methodology

In order to illustrate and compare the results of the proposed simplified approach with an independently conducted evaluation based on the detailed approach, we reprise one of the case study from Emanuelsson and Johnsson [13]: 'cement to high-speed railway'. This case investigates the impact of CCS implementation in cement production on the costs and emissions of building a new high-speed railway in Sweden.

While the required data to reproduce and compare the evaluation via the simplified approach was not presented in the paper, it was obtained via personal communication with the authors:

- The total cradle-to-gate life-cycle emissions of the railway without CCS on the cement production are 6 444 kt$CO_{2,eq}$;
- The total cradle-to-gate life-cycle emissions of the railway with CCS on the cement production are 4 183 kt$CO_{2,eq}$;
- The construction costs of the railway without CCS on the cement production amounts to 28.3 M€;

- The construction costs of the railway with CCS on the cement production amounts to 28.7 M€;
- The railway construction requires 3 485 kt of cement.

Considering the characteristics of cement production presented in table 3 and the above data, the emissions and cost of the railway construction considering CCS from cement were reevaluated using equations 1 and 2. The results are presented in table 1.

The results highlight a good match between the level of emissions reduction between the detailed approach (35%) and the simplified approach (30%), with the difference being explained by differences between studies in assumed greenhouse gas emissions of cement production with and without CCS. In terms of cost increase, the detailed approach led to a higher cost increase than the simplified approach (1.2 vs 0.4%), although both are still in the range of 1%. This difference in results is here due to differences in assumed CO_2 avoidance between studies. In particular, Emmanuelsson and Johnsson assume a higher CO_2 avoidance cost (151 vs 63 €/t) to reflect the higher cost of early CCS implementation.

In conclusion, the detailed and simplified approaches lead to a reasonable match provided that similar CO_2 avoidance cost are considered.

Table 1. Results of the evaluation for the high-speed railway case using the detailed and simplified approach.

		With CCS		Variation	
	Without CCS	Detailed approach	Simplified approach	Detailed approach	Simplified approach
Emissions of railway construction (kt)	6 444	4 183	4 515	−35%	−30%
Cost of railway construction (M€)	28.3	28.7	28.4	1.2%	0.4%

Appendix B. Summary of the characteristics of end-products/end-services without CCS and characteristics of potential areas for CCS application

Table 2. Greenhouse gas emissions and cost considered for each end-product without CCS.

	CO_2eq emissions	Production Cost/Price
Bridge	130 ktCO_2,eq [12]	379 M€ [12]
Onshore wind	6.00 kgCO_2,eq/MWh [21]	23.12 €/MWh [47]
Offshore wind	10.90 kgCO_2,eq/MWh [21]	97.62 €/MWh [47]
Shipping	1.055 tCO_2,eq/TEU/way [24]	6510 €/TEU/way [25]
Magazine	0.82 gCO_2,eq/magazine [27]	5.5 €/magazine
Avocado	0.486 kgCO_2,eq/$kg_{avocado}$ [28]	3.34 €/$kg_{avocado}$ [48]
Beer	224 gCO_2,eq/can [31]	1.25 £/can [49]
Waste treatment	265 kgCO_2/household/y [36, 50, 51]	186 €/household/y [52]
Air travel	930 kgCO_2,eq/passenger [42]	684 €/passenger [44]

Table 3. Characteristics considered for each potential area for CCS application, with and without CCS.

	Greenhouse gas emissions of the industrial facility (tCO_2/relevant unit)			
	Without CCS	With CCS[a]	CO_2 emissions reduction (%)	CO_2 avoidance cost (€/tCO_2,avoided)
Cement production [8, 15]	0.626 t/t_{cement}	0.072 t/t_{cement}	88.5	63
Steel production	2.09 t/t_{steel} [53]	0.435 t/t_{steel} [17]	79.2	80 [17]
Oil and gas production[a] [54]	—	—	78	117
Natural gas processing[a] [55]	—	—	90	50
Refining[b] [56]	—	—	54.3	155.5
Ship propulsion engines[b] [57]	—	—	58.1	246
Pulp and paper production[c] [58]	2.704 t/t_{adt}	0.307 t/t_{adt}	88.5	63
Urea production [59]	0.2654 t/t_{urea}	0.0643 t/t_{urea}	75.8	87.4
Waste-to-energy[d] [36]	0.962 t/t_{waste}	0.096 t/t_{waste}	88.5	202
Direct air capture	—	−0.961 t/t [60][b]	—	577 [43]

[a] Note that to properly account for the GHG emissions reduction enabled by CCS implementation, calculated emission reductions also include the non-fossil CO_2 emissions associated with energy consumption along the whole CCS chain. For the capture part and conditioning steps, this is already accounted for in the CO_2 avoidance rate calculated in the techno-economic study used as a basis. However, in addition, it is here assumed that GHG associated with CO_2 transport and storage represent 1.5% of the captured CO_2, equivalent to the average of the 1%–2% range corresponding to transporting CO_2 over 100–200 km via pipeline and storing it in a saline aquifer [61–64].

[b] The CO_2 emissions reduction enabled by CCS in this sector is measured by an avoidance rate of the activity associated CO_2 emissions.

[c] The CO_2 emissions number reported includes both biogenic and fossil CO_2 emissions.

[d] Corresponds to the quantity of CO_2 net removed per amount of CO_2 removed of the air assuming that heat and power requirements are supplied by renewable energy (see supplementary information for more detail).

Appendix C. Summary of the results of the evaluation performed for each end-product/end-service

Table 4. Summary of the greenhouse gas emissions and cost of each end-product/service with and without CCS.

		Without CCS	With CCS	Variation
Bridge	GHG emissions ($ktCO_2$,eq)	130	41.6	−68.0%
	Cost (M€)	379	385	1.7%
Onshore wind	GHG emissions ($kgCO_2$,eq/MWh)	6.00	2.59	−56.8%
	Cost (€/MWh)	23.12	23.38	1.1%
Offshore wind	GHG emissions ($kgCO_2$,eq/MWh)	10.90	5.28	−51.6%
	Cost (€/MWh)	97.62	98.07	0.5%
Shipping	GHG emissions (tCO_2,eq/TEU/way)	1.055	0.500	−52.6%
	Cost (€/TEU/way)	6510	6636	1.9%
Magazine	GHG emissions (gCO_2,eq/magazine)	0.82	0.184	−77.5%
	Cost (€/magazine)	5.5	5.54	0.7%
Avocado	GHG emissions ($kgCO_2$,eq/kgavocado)	0.486	0.306	−37.1%
	Cost (€/kgavocado)	3.34	3.35	0.3%
Beer	GHG emissions (gCO_2,eq/can)	224	186	−17.2%
	Cost (£/can)	1.250	1.258	0.6%
Waste treatment	GHG emissions ($kgCO_2$/household/y)	265	0[a]	−100%
	Cost (€/household/y)	186	205	10.1%
Air travel	GHG emissions ($kgCO_2$,eq/travel)	930	0	−100.0%
	Cost (€/travel)	684	1228	79.6%

[a] CCS implementation from a waste-to-energy plant achieve and go beyond net-neutrality, however negative emissions beyond the net-neutrality are here assumed to be sold to external actors to offset some of the cost CCS implementation.

Table 5. Summary of the role of CCS from each application to the GHG emissions reduction (ER) and the cost increase (CI) for the considered end-products/end-services. An empty cell means that CCS from the potential area of application was not considered and/or relevant in the evaluation of the end-product/end-service.

		Potential areas of application for CCS										Total
		Cement	Steel	O&G production	Natural gas processing	Refinery	Ship	Pulp & paper	Urea	Waste-to-energy	DAC	
Bridge	ER	32.7%	35.3%									68.0%
	CI	0.7%	1.0%									1.7%
Onshore wind	ER	7.6%	49.1%									56.8%
	CI	0.1%	1.0%									1.1%
Offshore wind	ER	0.1%	51.5%									51.6%
	CI	0.0%	0.5%									0.5%
Shipping	ER		3.4%	1.6%	3.7%	0.3%	46.2%					55.1%
	CI		0.0%	0.0%	0.0%	0.0%	1.8%					2.0%
Magazine	ER							77.5%				77.5%
	CI							0.7%				0.7%
Avocado	ER							35.9%	1.2%			37.1%
	CI							0.3%	0.0%			0.3%
Beer	ER		10.9%						0.6%			11.5%
	CI		0.2%						0.0%			0.2%
Waste treatment	ER									100%		100%
	CI									9.8%		9.8%
Air travel	ER										100%	100%
	CI										79.6%	79.6%

ORCID iDs

Simon Roussanaly https://orcid.org/0000-0002-4757-2829
Truls Gundersen https://orcid.org/0000-0003-2553-5725
Andrea Ramirez https://orcid.org/0000-0003-4715-9548

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