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Carbon capture, utilisation and storage: Incentives, effects and policy

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ABSTRACT

We develop a model to explore the incentives, consequences, and policy implications related to utilising captured carbon. Our model incorporates the decision by a firm considering investing in carbon capture technology, as well as the market for CO_2. By including the latter, we investigate the effect the increase in supply of CO_2 (from captured sources) has on the equilibrium price, allowing us to accurately understand the revenue the investing firm will receive. More importantly, it also allows us to understand the implications for the behaviour of firms that use CO_2 as an input: the reduction in the price of CO_2 lowers their marginal cost of production, encouraging them to produce more. By accounting for this offsetting 'rebound' effect, we can accurately understand the environmental consequences of carbon capture and utilisation. We also explore the policy implications of our analysis.

1. Introduction

Large reductions in carbon dioxide (CO_2) emissions will be required to reach the Paris Agreement, a United Nations Framework Convention on Climate Change (UNFCCC) to combat global warming. Although not a panacea, carbon capture and storage (CCS) – where CO_2 is captured directly from anthropogenic sources (i.e., power or industrial process) and injected to geological sinks (Bachu and Adams, 2003) – can play a pivotal role in achieving this goal (IPCC, 2014). Globally at present, CCS facilities have the capacity to capture 40 Mt of CO_2 each year, which has more than doubled in the past ten years.[1] This is less than 0.1% of global emissions.

Large scale CCS projects are expensive and costs have varied across projects. The Petra Nova facility in Texas cost $1 billion for a retrofit that captures 1.6 million tonnes of CO_2 emissions annually from a coal fire unit, while a power plant in Kemper County Mississippi cost $7.5 billion and captures 3.3 million tonnes of CO_2 emissions annually.[2] The International Energy Agency (IEA) reports costs ranging from $15 to $120 per tonne of CO_2, depending on source.[3] A recent empirical study (Wang et al., 2021) of 263 CCS projects undertaken between 1995 and 2018 identified high project risk and poor expectations of financial returns as underlying causes of failure. Moreover, CCS technology is surrounded by inconsistent and insufficient policy support, a lack of economic drivers, technological uncertainties and a complex value-chain needing collective action from relevant parties (Bowen, 2011; Budinis, 2018; Davies et al., 2013; Edwards and Celia, 2018; Ye, 2019). The inherent large-scale and associated enormous cost of individual projects are crucial among the obstacles hindering the adoption of CCS.

Recently, an alternative related solution carbon capture and utilisation (CCU) has attracted much interest. CCU comprises a set of technologies that capture CO_2, temporarily store it, and use or convert it into value-added products (Kondratenko et al., 2013). Allowing for utilisation of captured CO_2 provides an additional economic incentive to adopt carbon capture technology, as it provides a revenue stream for offsetting investment costs and managing project risk (Zimmermann and Kant, 2017). Approximately, 230 Mt of CO_2 are used globally each year, primarily to produce fertilisers (around 125 Mt/year) and for enhanced oil recovery (around 70–80 Mt/year).[4] In addition, new uses continue to be developed such as fuels, chemicals and building materials.

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[1] https://www.iea.org/reports/about-ccus.
[2] https://www.eia.gov/todayinenergy/detail.php?id=33552.
[3] https://www.iea.org/commentaries/is-carbon-capture-too-expensive.
[4] https://www.iea.org/reports/putting-co2-to-use.

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Encouraging industries to sell their captured CO_2 to offset their costs could, however, result in a 'rebound' effect (Berkhout et al., 2000). A rebound effect occurs where an intervention to reduce harm to the environment (for example energy efficiency improvements) encourages a change in behaviour that has an indirect effect that partially offsets the direct improvement. In the case of CCU, the rebound effect emerges because the increase in the supply of CO_2 will lower its market price; this will consequently make CO_2 as an input cheaper for those firms that use it encouraging them to produce more with consequently higher emissions, thereby diminishing the benefits of the initial capture. In extreme cases, we may even experience a 'backfire' effect, also known as Jevons paradox, where we not only see a less than expected reduction of CO_2, but an increase of overall use (Chenavaz et al., 2021). It is essential that policymakers have adequate decision support to discriminate between critical conditions of fortune and calamity.

Our aim in this paper is to develop a model to support the identification of optimal policy intervention, anticipating the impact of incentivising carbon capture utilisation and storage (CCUS) on aggregate CO_2 production based on market conditions. We build a parsimonious model that explores the interaction between a large industrial firm that has the opportunity to invest in carbon capture technology, if it chooses to do so and then brings its captured CO_2 to market for utilisation, and the market for CO_2. The added value of our model is that it allows us to explore the incentives the adopting firm faces in considering whether or not to invest in carbon capture technology; the consequences if it does, accounting for the indirect effects in the CO_2 market; and appropriate forms of policy support to encourage carbon capture that considers the incentives of the key decision makers and the full consequences for the environment.

The remainder of the paper is structured as follows. In Section 2, we provide a summary of the literature with regard to relevant economic frameworks for analysis, market structures and rebound effects. Section 3 sets out the model, and Section 4 provides the preliminary analysis of the model. In Section 5 we consider the outcome following investment in carbon capture technology, and in Section 6 we compare this to the outcome under business-as-usual to understand the incentives for investment. We then turn in Section 7 to consider the environmental impact of CCU relative to both the business-as-usual case and the case in which no captured carbon is utilised but is instead stored. Section 8 explores a range of policy interventions to support the adoption of carbon capture technologies while allowing for utilisation, accounting for the depleted environmental benefits that stem from this relative to requiring any captured carbon to be stored.

2. Related literature

2.1. CCU Literature

The current literature investigating CCU technology is dominated by two research frameworks: techno-economic assessment (TEA) and life-cycle assessment (LCA). TEA allows a researcher to analyse the technical and economic performance of a process, product or service (Zimmermann, 2020). The reason for many CCU studies using a TEA framework is it supports the evaluation of the economic feasibility of a specific project, a forecast on the likelihood of the deployment of technology at a certain scale, or a comparison of the economic merit of different technological options that provide the same service. LCA considers the entire life cycle of products and processes, from extraction of raw materials via production and product use to recycling and final disposal of wastes (von der Assen, 2014). TEA generally aims to examine technological feasibility and economic profitability, while LCA in general aims to compare environmental impact reductions of technologies (Zimmermann et al., 2018).

For CCU, understanding the environmental impact of the technology is prominent due to the fact it is a mitigation technology diverting the use of fossil fuels. However, a major pitfall in CCU studies using an LCA method is that it overestimates the effect of the CO_2 reduction on the global warming impact due to the erroneous assumption that all products are stored permanently. For example, using CO_2 for fuel production, the final product only delays the carbon emissions rather than removing them over the long timescales needed for mitigating climate change. Similarly, the storage of some chemicals is also short-lived, depending on their use (Cuéllar-Franca and Azapagic, 2015). Therefore, a more accurate assessment of the environmental impact of CCU adoption is required.

2.2. Rebound and backfire effect

A major shortcoming of LCA is the failure to account for emission timing. Specifically, the timing of the capture of CO_2 and subsequent emissions are not accounted for, especially when products produced by CO_2 utilisation such as chemicals or fuels offer only a limited temporary storage of CO_2 from the atmosphere. Thus, a contribution of this paper is to understand the full consequences for the environmental impact of CCU, which may result in a rebound effect or backfire.

According to Zink and Geyer (2017), the rebound effect describes the phenomenon where increased efficiency makes consumption of some good (e.g., energy or transportation) relatively cheaper and, as a result, people consume more of it. This increased use decreases the environmental benefit of the efficiency increase, and can even lead to a 'backfire', where the increase in use is proportionally larger than the efficiency increase, leading to higher net impacts.

In the past two decades, many studies have considered the rebound effect. Greening et al. (2000) formulated a four-part typology of rebound, describing the nature and scope of the effect: (i) direct rebound the increase in consumer demand due to lower prices from increased efficiency; (ii) secondary effects the increases in demand of other goods attributed to consumers spending some energy savings elsewhere; (iii) economy wide effects which refer to larger, largely unpredictable effects that increased efficiency has on prices and demand of other goods; and (iv) transformational effects the potential of energy efficiency increases to change consumer preferences, societal institutions, technological advances, regulation, or other large-scale effects.

Initially, the rebound effect only considered the improvement on the production-side efficiency that decreased production costs and therefore prices. The notion has since been expanded to include efficiency improvements in the end-use consumer by Borenstein (2013), who provided a useful framework for energy efficiency rebound using the micro-economic concepts of price effect and substitution effect. The main finding of Borenstein's study was that as the consumer uses an upgraded product more, that expense necessarily reduces consumption of another good for which the additional income could have been used. This consumption shift is governed by the consumer's cross-price responses, indicating how willing the consumer is to substitute consumption of the upgraded good for the other goods (Zink and Geyer, 2017). On an economy-wide scale, these concepts can explain why, for instance, investments in efficient alternative energy do not fully displace fossil fuels (York, 2012).

2.3. CCU business models

Carbon utilisation provides a potential business opportunity, which is attracting investment. The UK department for Business, Energy, and Industrial Strategy (BEIS) suggests that the potential for products where carbon utilisation could be applicable is worth over $5 trillion worldwide. BEIS have directly funded £5.6m of projects, such as with Tata Chemicals to construct a CCU facility in the UK as well as Research and Development projects with Econic Technologies, Carbon8 Systems, and CCm Technologies (BEI, 2020).

The economic value of captured CO_2 will motivate CCU through profit incentives if capture and transportation costs are covered. As such, the CO_2 value chain plays an important role, as this becomes more than just an emission reduction activity but a business activity. A feasible business model is required to realise market potential (Yao et al., 2018).

Governments have three potential policy instruments to provide more incentives for CCUS. These are carbon tax (Metcalf and Weisbach, 2009; Zhang et al., 2016), subsidies (Grimaud and Rouge, 2014) and creating emission-trading markets (Lin and Tan, 2021; Yao et al., 2018). Subject to these policies, business models for CCUS projects have focused on mechanisms of cooperation among multiple stakeholders, as realising this market potential relies on a complicated combination of technologies from industries. As such, different responsibility-sharing arrangements between stakeholders is the key characteristic that differentiates business models in CCUS. Yao et al. (2018) discusses the following four model types in the context of China.

- Vertical integration model: this model places a high degree of integration across the CCUS industry chain, where capture, transport, utilisation and storage are considered as a whole.
- Joint venture model: this model considers a joint venture that is established through a joint stock cooperative system, resulting in transaction costs that are higher than those of the vertical integration model.
- CCS operator model: this model considers a market-driven design for CO_2 trading. Liang (2009) (as cited by Yao et al., 2018) introduced this model, regarding it as the model with most potential, considering the economic incentives for selling CO_2 between stakeholders.
- CO_2 transporter model: this is a three-stakeholder model, introducing transportation and higher vertical specialisation.

As described in Section 2.4, we consider a vertically related market, similar to the CCS operator model. We explore the situation where CO_2 suppliers and consumers naturally form a competitive game, as each stakeholder has their own profit maximisation target, which has been recognised as an endogenous risk by Agarwal (2014).

2.4. Vertically-related markets

In this paper, we take an industrial organisation approach to modelling the incentives firms face when engaging in the market. The appropriate modelling strategy appeals to vertically-related markets, where an output an 'upstream' market is used as an input in the 'downstream' market. When it comes to modelling CCU decisions, there are two possible market structures to consider: vertically integrated, where the firm that captures the carbon upstream is the one that utilises it in the downstream market (for example in ammonia and urea production); and non-vertically integrated where the firm in the upstream market does not also engage in the downstream market. It is this latter type of model that we focus on, as there is far more scope for expansion of carbon capture facilities in these frameworks.

The first researcher who introduced the idea of the vertically related market was Spengler (1950). Spengler analysed the simplest possible case to capture the interlink between the downstream and upstream markets, assuming both to be monopolies. In this study, Spengler's main interest was fully invested in the effects of vertical collusive agreements between the upstream and downstream monopolist. Gabszewicz and Zanaj (2011) extended Spengler's model examining the effects of free entry when there is an interaction between upstream and downstream markets, considering more complex markets. Upstream firms non-cooperatively select the quantities of their output, but the output of the upstream firms serves also as input in the production of the final good in the downstream market. The link between the two markets follows from the fact that the downstream firm's unit cost is the price the upstream firms receive. This gives rise to two games. In the upstream game, input firms declare the amount of input that they supply; in the downstream game, downstream firms select the amount of input to use in the production of the output. Therefore, ultimately, they select the level of the final good to supply to the final consumers. The input price in equilibrium makes its demand and supply equal. The main finding in this paper was that free entry of firms in both markets does not always entail the usual convergence for the input price to adjust to its marginal cost; which only occurs in the downstream market.

In this study, we will seek to model the CCU industry using an industrial organisation approach where the markets are vertically related. Specifically, we borrow the concept as used by Gabszewicz and Zanaj (2011) where the price paid for a unit of input by downstream firms constitutes the unit receipt for upstream firms. However, a key difference in the models mentioned, and the model presented in this paper, is that in a CCU industry the firm entering the upstream sector does not solely produce the intermediate product necessary for the downstream market: there are 'conventional' firms that supply this input as well. Hence, the focus of this study is to understand the strategic interaction of firms when a firm enters the upstream market having adopted a CCU strategy.

Overall, in the current CCU literature, many studies do not fully account for the environmental impact of products produced by CO_2 utilisation after it has been sold into the end-user consumer market. Using the economic model that will be presented in this study, we study the actual environmental impact of CCU technology to inform government and policymakers of the real environmental potential of CCU technology. The aim of this research is to provide decision support to policymakers, accounting for incentives, behaviour, and the effects of that behaviour (in the form of rebound), so that policy impacts are better anticipated.

3. The model

Our aim in this paper is to understand the economic and environmental impact of a large firm that generates CO_2 emissions, capturing these emissions and subsequently sending them for utilisation in the market for CO_2. While allowing for utilisation of captured carbon will potentially provide an income stream, and therefore much needed additional incentive to install carbon capture technology, it is crucially important to understand the consequences of doing so. Our parsimonious model captures a scenario in which a by-product of a production process from a firm in one industry is used as an input (i.e., CO_2) into the production process of firms in a different industry, where there is a market already established for that input.

We capture this as a vertical relationship where the 'downstream' firms (labelled D) are those that use CO_2 as an input, and upstream there are 'conventional' firms (labelled C) that supply CO_2 from conventional sources, as well as the upstream firm of interest (labelled U) that is engaged in production for a separate market but that produces CO_2 emissions as a by-product of its production process.[5] We want to assess

[5] One example of such a vertical relationship is where the downstream industry is the fertiliser industry (that uses CO_2 as an input) and the upstream firm of interest is a gas-fired power plant. The conventional firms are those that traditionally supply the fertiliser industry with CO_2. Note, however, that our model is broadly applicable and is not specific to this example.

the incentives for, and subsequent consequences of, the upstream firm installing carbon capture technology to capture its CO_2 emissions and sending them for utilisation in the downstream CO_2 market, that will augment the supply from conventional firms.

Our model has several stages, as outlined below.

Stage 0: U decides whether or not to invest in installing carbon capture technology;
Stage 1: U decides on its level of production;
Stage 2: Conventional firms decide on their supply of CO_2 to the market, and U decides on the proportion of the captured carbon to send to the market with the remainder going to storage;
Stage 3: Downstream firms make their production decisions (which determine their demand for CO_2), and the CO_2 market clears.

In the downstream industry, there are m firms that each produce a homogeneous final good. For simplicity, we assume the demand for the final good is given by the linear inverse demand function $p(Q) = a - bQ$ where $Q = \sum_{i=1}^{m} q_i$ is the total supply of the good, q_i being the supply of firm i. Again for simplicity, we assume each firm in the downstream market is symmetric and has a (linear) cost function given by $C_D(q_i) = [\lambda + kr + \tau\xi_D]q_i$ where λ is the (non-CO_2) marginal cost of production, r is the price of CO_2 and k is the number of units of CO_2 required per unit of output, τ is the carbon tax and ξ_D is the carbon emissions per unit of output. We assume downstream firms do not have the opportunity to capture emissions and therefore pollute and have to pay an appropriate carbon tax. We assume that there are sufficiently many downstream firms that they can be reasonably assumed to treat both input and output prices as fixed and uninfluenced by their decisions. Under these assumptions, a typical downstream firm's profit function is given by

$$\pi_D(q_i) = pq_i - [\lambda + kr + \tau\xi_D]q_i. \qquad (1)$$

In the upstream market, there are two different types of suppliers for CO_2 as an input: conventional firms and our upstream firm of interest. The conventional firms, of which there are n in number, produce and supply CO_2 to the downstream firms from traditional sources. They are assumed to have a cost of production given by $C_C(y_i) = gy_i + \frac{h}{2}y_i^2$ where y_i represents the output of CO_2 and $g, h > 0$ are cost parameters. Again, we assume that these firms are sufficiently numerous that they treat the price of CO_2 as fixed and uninfluenced by their decisions. The convexity of the production cost of conventional firms ($C_C^{'} > 0$ and $C_C^{''} > 0$) implies that the cost incurred by those firms to produce CO_2 increases more than linearly with respect to CO_2 output, i.e., conventional firms experience decreasing returns to scale in the production of CO_2. In the industrial organisation literature, this is a standard assumption used to describe industries populated by numerous relatively small price-taking firms, which is consistent with our characterisation of the conventional CO_2 industry. A typical conventional firm's profit function is given by

$$\pi_C(y_i) = ry_i - \left[gy_i + \frac{h}{2}y_i^2\right]. \qquad (2)$$

The upstream firm of interest in turn supplies CO_2 to downstream firms by engaging in CCU. This firm is assumed to be a monopolist in its output market and faces the linear inverse demand given by $P(x) = A - Bx$, where x is its output and $A, B > 0$. The overall cost of production for the upstream firm is given by

$$C_U(x) = \Phi_I + \Psi + [\sigma + \xi_U[[1-\chi]\tau + \chi[\beta + [1-\omega]s - \omega\hat{r}(\omega x)]]]x. \qquad (3)$$

This cost has several components. It has a fixed cost of production, Ψ, as well as a constant marginal cost of production, σ. There is also a fixed cost associated with investing in carbon capture technology, Φ_I which takes the value $\Phi > 0$ if $I = 1$ (i.e., carbon capture technology is installed) and is zero if $I = 0$. If the firm installs a carbon capture device, then it will capture a fraction $\chi \in (0, 1]$ of emissions (this parameter represents the efficiency of carbon capture technology). There are ξ_U units of CO_2 emissions per unit of output, and each unit of captured emissions will incur a marginal cost of β. Of the captured emissions, the firm must decide on the fraction ω to send to the market for utilisation which will be sold for a price of r per unit.

Since the upstream firm of interest is large, we consider that its supply of CO_2 to the market will be large relative to that of individual conventional suppliers. As such, we account for the fact that the upstream firm will influence the price of CO_2 as a result of its decision that alters its supply of CO_2 to the market. We denote this price relationship as $\hat{r}(\omega x)$ (defined formally below).

The remaining fraction of captured emissions, $1-\omega$, will go to storage at a cost of s per unit. For the fraction $1-\chi$ of emissions, which are not captured, the carbon tax will have to be paid. If a carbon capture device is not installed, then $\chi \equiv 0$ and the firm must pay the carbon tax for all emissions. Consequently, their profit function takes the form

$$\pi_U(x) = [A - Bx]x - [\Phi_I + \Psi + [\sigma + \xi_U[[1-\chi]\tau + \chi[\beta + [1-\omega]s - \omega\hat{r}(\omega x)]]]x] \qquad (4)$$

While the production cost incurred by conventional firms decreases in CO_2 output, the upstream firm has increasing returns to scale in the production of CO_2: the upstream firm will have a lower cost of producing and supplying CO_2 with a larger capture capacity.[6] Note that we are not considering the choice of capture capacity (χ) in our model (i.e., we assume that χ is fixed). However, for a given chosen capture capacity, it is straightforward to see from (3) that the cost incurred by the upstream firm to produce and supply CO_2 decreases with its CO_2 supply capacity: the variable cost of producing and supplying CO_2 decreases when the amount of captured CO_2 increases.

4. Preliminary analysis

Since we have a sequential model, we solve it backwards, starting from the final stage. The downstream firms at the final stage, who take all prices as given, will make their production decisions to maximise their profit defined in (1) by choosing output such that their marginal cost $\lambda + kr + \tau\xi_D$ is equal to the output price p. Since $p = a - bQ$, this allows us to deduce that the equilibrium aggregate output of the downstream firms will be given by

$$\hat{Q} = \frac{a - [\lambda + kr + \tau\xi_D]}{b}$$

and therefore the demand for CO_2 is given by

$$D(r) \equiv k\hat{Q} = \frac{k[a - [\lambda + kr + \tau\xi_D]]}{b}.$$

Notice that demand for CO_2 is decreasing in its price, r: intuitively, if the price of CO_2 goes down then downstream firms, seeing a reduction in their marginal cost, will increase production of their output and therefore demand for the input will increase.

We now want to consider the supply of CO_2. The conventional firms, who treat the price of CO_2 as fixed, will each seek to choose their supply y_i to maximise their profit defined in (2). In doing so, they will choose their supply to equate their marginal cost of production, given by, $g + hy_i$ to the price of CO_2, r. As such, the n firms in total will supply $\frac{n[r-g]}{h}$ units of CO_2 to the market. In addition, if the upstream firm invested in carbon capture technology, it will supply CO_2 to the market in the quantity $\chi\xi_U\omega x$, which depends on its output choice x and the proportion ω it sent to the market. We assume that from the perspective of the users of CO_2 it is a homogeneous good, so CO_2 from a captured source is perfectly substitutable for that from a conventional source. As such, the total supply of CO_2 is given by

[6] We thank an anonymous reviewer for suggesting this clarification.

$$S(r) \equiv \frac{n[r-g]}{h} + \chi\xi_U \omega x.$$

Equating this supply with the demand from the downstream firms allows us to understand what the market clearing price of CO_2 will be, which takes the form

$$\widehat{r}(\omega x) = \frac{kh[a-[\lambda+\tau\xi_D]]+bng}{nb+hk^2} - \frac{bh}{nb+hk^2}\chi\xi_U\omega x. \tag{5}$$

This price relationship depicts how the upstream firm's decisions, which significantly influence the supply of CO_2, influence the market clearing CO_2 price. Intuitively, the CO_2 price is decreasing in the supply of captured carbon to the market, given by $\chi\xi_U\omega x$, as this supply augments that from conventional sources.

For a given output choice x, the upstream firm has to decide on the proportion of the captured emissions ω to send to the CO_2 market for sale, with the remainder going to (costly) storage. In addressing this problem, U will seek to

$$\min_{\omega\in[0,1]} \chi\xi_U x[[1-\omega]s - \omega\widehat{r}(\omega x)].$$

As more CO_2 is sent by the upstream firm to market, the price reduces. Since the alternative to utilisation is costly storage, so long as the price remains above $-s$ U will send *all* of its captured emissions to market ($\omega = 1$) so long as there are no regulations preventing it from doing so. Were this not the case, U would optimally choose ω such that $\widehat{r}(\omega x) + \omega\frac{\mathrm{d}\widehat{r}(\omega x)}{\mathrm{d}\omega} = -s$: a proportion would be sent to the market for utilisation, with the remainder being sent to costly storage. As we develop the analysis in the sequel, and proceed with our simulation, we do not solve for the optimal ω but rather consider equilibrium objects as a function of ω, the reason being that we subsequently want to consider constraining ω as a policy lever.

5. Equilibrium with carbon capture and utilisation

The upstream firm, anticipating the effect of its production decision on the price of CO_2, will seek to optimally choose its output x to maximise its profit as depicted in (4). As such, the upstream firm's optimal output will satisfy

$$A - 2Bx = \sigma + \xi_U\left[[1-\chi]\tau + \chi\left[\beta + [1-\omega]s - \omega\left[\widehat{r}(\omega x) + x\frac{\mathrm{d}\widehat{r}(\omega x)}{\mathrm{d}x}\right]\right]\right]$$

where, from (5),

$$\frac{\mathrm{d}\widehat{r}(\omega x)}{\mathrm{d}x} = -\frac{bh\omega\chi\xi_U}{nb+hk^2}.$$

Solving this for the equilibrium supply gives

$$x^*(\omega) = \frac{A-\sigma-\xi_U\left[[1-\chi]\tau + \chi\left[\beta + [1-\omega]s - \omega\frac{kh[a-[\lambda+\tau\xi_D]]+bng}{nb+hk^2}\right]\right]}{2\left[B + \frac{bh\omega^2\chi^2\xi_U^2}{nb+hk^2}\right]}. \tag{6}$$

This is our main equilibrium object of interest, and using this we can now derive the equilibrium values of the prices, along with firms' profits. We write all equilibrium objects as depending on ω, because this will be a key parameter when discussing policy implications in the forthcoming sections. To simplify expressions, we henceforth restrict attention to the case where $\chi = 1$, that is, we assume that if a carbon capture device is installed it will capture all carbon emissions.[7]

Using (6) and the appropriate expressions above, we can deduce that the equilibrium price of the upstream firm of interest is given by

$$P^*(\omega) = \frac{2A\frac{bh\omega^2\xi_U^2}{nb+hk^2} + AB + \sigma B + \xi_U B\left(\beta + (1-\omega)s - \omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B + \frac{bh\omega^2\xi_U^2}{nb+hk^2}\right)}$$

The equilibrium price of CO_2 inputs is

$$r^*(\omega) = \frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2} - bh\xi_U\omega\frac{A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}$$

The equilibrium profit of the upstream firm of interest is given by

$$\pi_U^*(\omega) = \frac{\left(A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)\right)^2}{4\left(B+\frac{bh\omega^2\xi_U^2}{nb+hk^2}\right)} - \Phi_I - \Psi$$

Turning now to the conventional firms, their equilibrium supply of CO_2 is given by

$$y_i^*(\omega) = \frac{k(a-(\lambda+\tau\xi_D))-gk^2}{nb+hk^2} - b\xi_U\omega\frac{A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}$$

and their equilibrium profit is

$$\pi_C^*(\omega) = \frac{h}{2}\left(\frac{k(a-(\lambda+\tau\xi_D))-gk^2}{(nb+hk^2)} - b\xi_U\omega\frac{A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}\right)^2$$

Finally, for the downstream firms, their aggregate equilibrium supply of the final good to the market is

$$Q^*(\omega) = \frac{\frac{nb((a-\lambda-t\xi_D)-g)}{nb+hk^2} + kbh\xi_U\omega\frac{A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}}{b}$$

the equilibrium price of the final good is

$$p^*(\omega) = \frac{ahk^2+nb(\lambda+t\xi_D+g)}{nb+hk^2} - kbh\xi_U\omega\frac{A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}$$

and each firm's equilibrium profit is

$$\pi_D^*(\omega) = \left(\frac{g(1-k)}{nb+hk^2}\right)\left(\frac{nb((a-\lambda-t\xi_D)-g)}{nb+hk^2} + kbh\xi_U\omega\frac{A-\sigma-\xi_U\left(\beta+(1-\omega)s-\omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}\right)$$

6. The carbon capture decision

In the previous section, we analysed the equilibrium outcome in the scenario where the upstream firm of interest had invested in carbon capture technology. However, this is a matter of choice for the upstream firm. To evaluate this decision, the firm needs to compare its profits following investment, that we have just deduced, with its profits in a business-as-usual scenario where it just pays the carbon tax on its

[7] This, of course, is not consistent with the reality of capturing carbon, but means we can ignore any effect of the carbon tax on production decisions of a firm that has invested in carbon capture technology. Assuming firms that invested in carbon capture technology were exempt from the carbon tax on residual emissions would give qualitatively similar results.

emissions. We now consider this decision.

In the scenario where the upstream firm of interest does not install a carbon capture device (and therefore the CO_2 market is left unaffected) the equilibrium involves the following equilibrium objects:

- Equilibrium output of the upstream firm: $x^{\#} = \frac{A-\sigma-\tau\xi_U}{2B}$.
- Equilibrium price: $P^{\#} = \frac{A+\sigma+\tau\xi_U}{2}$.
- Upstream firm's equilibrium profit: $\pi_U^{\#} = \frac{(A-\sigma-\tau\xi_U)^2}{4B} - \Psi$.
- Equilibrium price of CO_2 inputs: $r^{\#} = \frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}$.
- Equilibrium supply of CO_2: $y_i^{\#} = \frac{k(a-(\lambda+\tau\xi_D))-gk^2}{nb+hk^2}$.
- Equilibrium profit of a conventional firm: $\pi_C^{\#} = \frac{h}{2}\left(\frac{k(a-(\lambda+\tau\xi_D))-gk^2}{nb+hk^2}\right)^2$
- Equilibrium supply of the final good: $Q^{\#} = \frac{n((a-\lambda-t\xi_D)-gk)}{nb+hk^2}$
- Equilibrium price of the final good: $p^{\#} = \frac{ahk^2+nb(\lambda+t\xi_D+gk)}{nb+hk^2}$
- Equilibrium profit of a downstream firm: $\pi_D^{\#} = \left(\frac{hk^2(a-\lambda-kr-\tau\xi_D)+nbk(g-r)}{nb+hk^2}\right)\left(\frac{a-\lambda-\tau\xi_D-gk}{nb+hk^2}\right)$.

When deciding whether to invest in carbon capture technology or not, the upstream firm of interest compares their profit in the equilibrium in which they have invested, with that in the equilibrium where they do not, and if the former is larger than the latter they choose to install the carbon capture technology. Thus, U will install carbon capture technology if and only if

$$\pi_U^*(\omega) > \pi_U^{\#}. \tag{7}$$

In Fig. 1 we plot the profit of the upstream firm of interest as a function of ω, the proportion of the captured carbon the firm sends to the market for utilisation. We simulate the model using a particular collection of parameters associated with our baseline scenario detailed in Appendix. In panel (a) the CO_2 tax is low (\$15/tCO_2), and as can be seen in that figure the firm always makes lower profit by investing in carbon capture regardless of the amount that it sends to the CO_2 market for utilisation. In contrast, in panel (b) the CO_2 tax is higher (\$50/tCO_2) making the business as usual scenario less attractive and as illustrated, so long as the firm sends more than 45% of its captured carbon to the market it is profit-enhancing to invest in carbon capture. Notice that U's profit following investment in carbon capture, $\pi_U^*(\omega)$, is monotonically increasing in ω, which is a general feature so long as the price of CO_2 remains above $-s$, the storage cost: as ω increases less captured carbon is sent for costly storage, and more is sent to the market for which revenue is received. As such, left to its own devices, the firm would always choose to send all captured carbon to the market for utilisation so long as it doesn't have too large an impact on the market price for CO_2.

As such, it is clear that allowing for utilisation of captured carbon creates an added incentive for firms to invest in carbon capture technology: under the parameter combinations depicted in Fig. 1(b) the firm would not invest if it could not utilise any captured carbon ($\omega = 0$), but would invest if it was allowed to utilise above a proportion $\widetilde{\omega}$ which is the level of ω that ensures equality of the two profit functions in (7), in this case around 0.45. As is apparent from a comparison of these two figures, the CO_2 tax also plays a key role in the firm's decision by making business as usual less attractive: a general feature is that the threshold level of ω above which firms would choose to invest in carbon capture is decreasing in τ.

7. Environmental impact of CCU

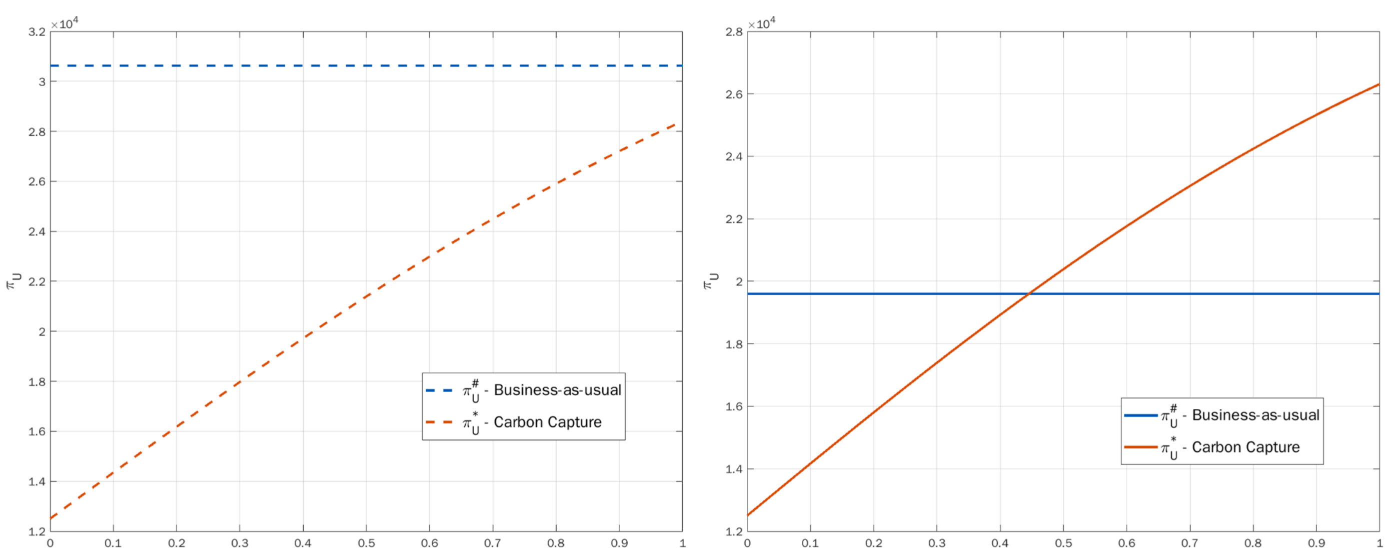
We now turn to consider the environmental impact of the upstream firm of interest investing in carbon capture technology, and subsequently sending the captured carbon to market for utilisation. The level of pollution in the model is given by the emissions of all firms – upstream, conventional CO_2 producers, and downstream – as well as the carbon that is embodied in the downstream product. Ultimately this will enter the atmosphere over time, but for simplicity we account for it as being instantaneously emitted. Since we assume conventional firms do not produce emissions in their production process, we can neglect them in our consideration of the environmental impact.

In the scenario where U invests in carbon capture, all of its emissions are captured ($\chi = 1$ by assumption) and therefore the total emissions are those generated in the downstream industry, both from production and consumption. These are given by

$$Z^*(\omega) \equiv Q^*(\omega)(\xi_D + k).$$

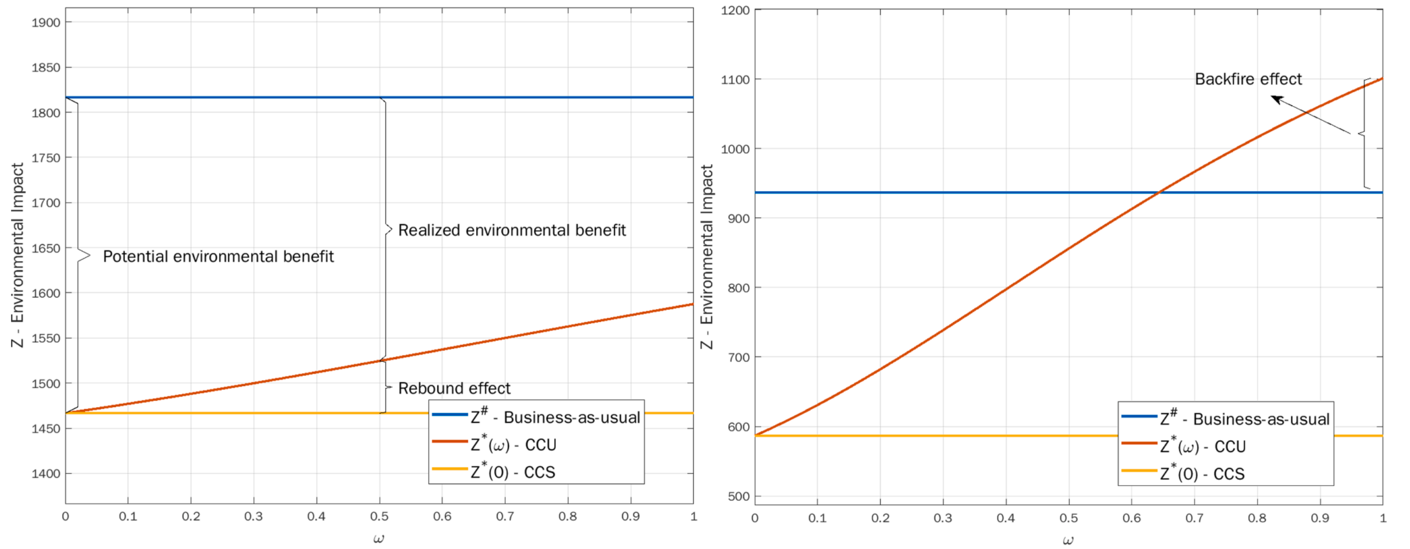
In the scenario where the upstream firm of interest does not capture carbon and instead pollutes and pays the CO_2 tax, the emissions are given by

$$Z^{\#} \equiv x^{\#}\xi_U + Q^{\#}(\xi_D + k).$$



(a) Low CO_2 tax **(b)** High CO_2 tax

Fig. 1. Equilibrium profit comparison: carbon capture vs. business as usual.



(a) Rebound **(b)** Potential 'backfire'

Fig. 2. The environmental impact of carbon capture and utilisation.

As such, the environmental benefit that is generated from the upstream firm of interest engaging in CCU is given by

$$Z^{\#} - Z^{*}(\omega) = x^{\#}\xi_U - (Q^{*}(\omega) - Q^{\#})(\xi_D + k).$$

The first term is the direct effect of capturing the carbon. Naively, one may think that this would be the environmental impact of the upstream firm of interest investing in carbon capture technology. However, simply removing the captured carbon from the atmosphere is not the full story. Since this is then sent to market for utilisation it increases the supply of CO_2 and therefore reduces its price. This makes CO_2 as an input less expensive for the downstream firms, lowering their marginal cost of production, and therefore incentivising them to produce more. Consequently, there is an offsetting 'rebound' effect that is captured by the second term in the above expression.

In Fig. 2 we plot the environmental impact as a function of ω in two different scenarios. Panel (a) depicts a typical scenario (based on the baseline parameters detailed in Appendix with a CO_2 tax of $15/t$CO_2$) where the full environmental benefit of capturing carbon is illustrated when $\omega = 0$ so all captured carbon is stored, but because the environmental impact (i.e., pollution) under carbon capture is increasing in the proportion of captured carbon that is utilised, the realised environmental benefit will be smaller the higher is ω, as a result of the rebound effect just cited.

In panel (b) an extreme situation is depicted in which there is actually a negative environmental impact from carbon capture when the proportion of captured carbon sent to the market is very high (this is again based on the baseline parameters but where $n = 10$ rather than 100, and the CO_2 tax is $25/t$CO_2$). While not representative, this extreme situation highlights the potential for 'backfire' of a seemingly environmentally friendly act. The difference between this setting and that in panel (a) is that here there are very few conventional firms supplying the CO_2 market. As such, when the upstream firm of interest captures carbon and sends the vast majority to market the supply increases dramatically, leading to a substantial reduction in the price of CO_2 and a large expansion in output in the downstream industry.

The identification of the rebound effect presents a trade-off between the incentives of the firm and the environmental impact of investing in carbon capture technology. As illustrated in Fig. 1, after investing in carbon capture technology, the firm wants to choose ω to be as large as possible to maximise profits. But as it increases, ω the rebound effect increases, as illustrated in Fig. 2, offsetting the environmental impact of capturing carbon in the first place.

The rebound effect materialises because the increased supply of CO_2 to the market lowers its price, thereby incentivising higher levels of production, and subsequent consumption, of the downstream good. This effect will be more significant in markets where the cost of CO_2 makes up a high proportion of the input cost of production (so changes in this cost will significantly alter optimal production decisions), and where the demand for the final good is elastic so that as the input price reduces the new equilibrium will result in a significantly higher quantity being sold.

In situations where the rebound effect is substantial, a policymaker could seek to set a limit on ω to cap the proportion of captured carbon the firm can send to market to limit the offsetting environmental consequences. While perhaps not conventional, the introduction of a cap on ω as a policy lever (combined with mandatory reporting on it) would give policymakers the ability to constrain the rebound effect. From an environmental perspective, the policymaker would like this to be as small as possible (i.e., zero). However, they are not acting without constraint, as the firm must find it profitable to invest in the first place. In the next section, we explore this policy trade-off.

8. Policy analysis

To enable us to carry out our policy analysis, let us first compute the social welfare levels under the two scenarios. The social welfare function takes the form

$$\begin{aligned} W \; = \; & \int_0^x (A - Bu)du - C_U(x, r) + nry_i - nC_C(y_i) + \int_0^Q (a - bu)du - C_D(Q) \\ & - v(Q(k + \xi_D)), \end{aligned}$$

which corresponds to the sum of the consumer surpluses for the final good in the upstream and downstream industry, the upstream firm's profit, the conventional CO_2 industry's profit, and the downstream industry profit, minus the monetary equivalent of the damage inflicted by CO_2 emissions, which is given by v per unit of emissions. Substitution of the equilibrium objects in the CCU scenario into this social welfare function yields the equilibrium social welfare level under that scenario (which is a complicated expression and so omitted).

The equilibrium social welfare in the baseline scenario of no carbon capture is given by

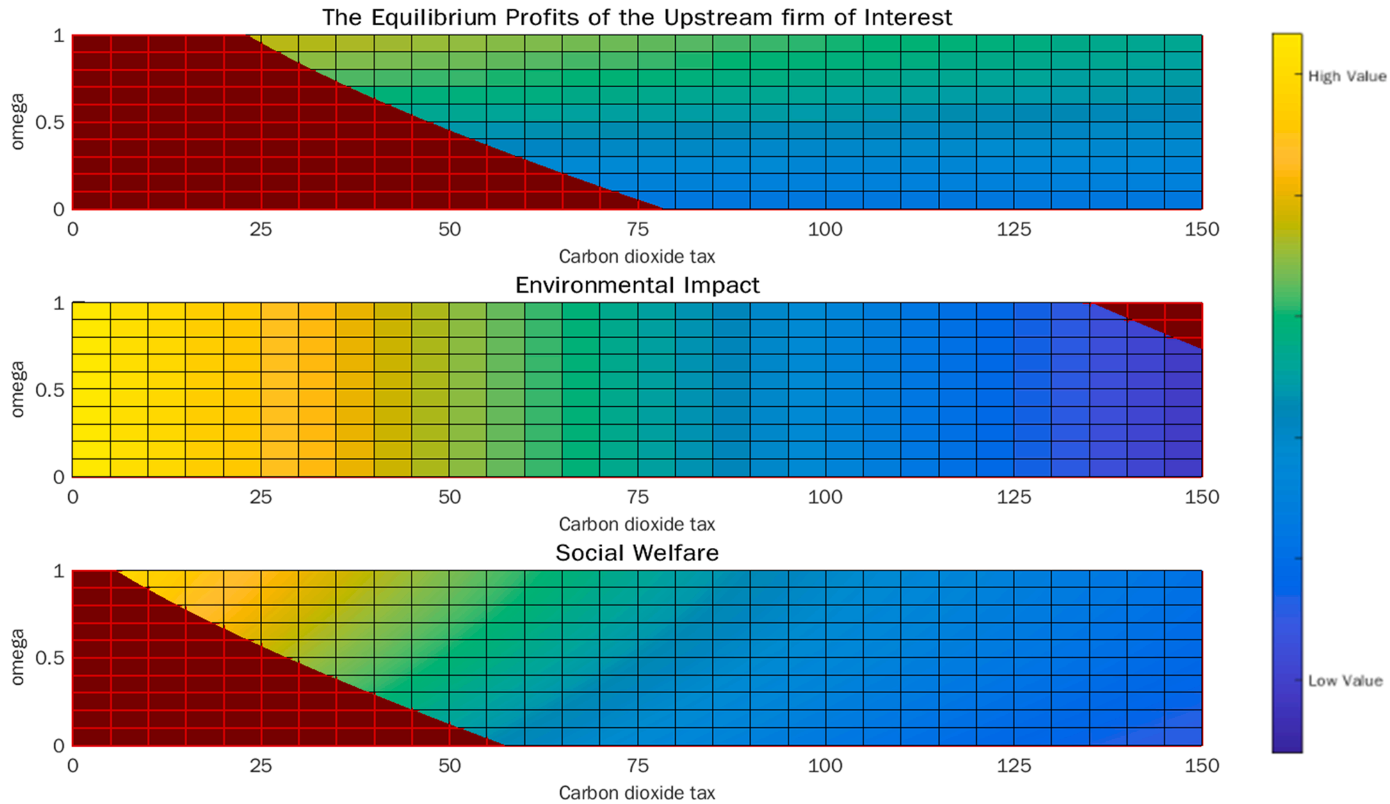


Fig. 3. Baseline Scenario. Parameters displayed in Appendix. Fig. 3 shows the relationship between carbon tax policy (τ) and proportion of CO_2 sent to market decision (ω) with profits, environmental impact and social welfare. Regions: (i) Red if a parameter is in this region it signifies no carbon capture (CC) technology should be adopted (ii) Multicolour represents that a carbon capture technology is a better strategy, where yellow has the high value and blue is a low value see colour-bar legend on the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$W^{\#} = \frac{3}{8B}(A-\sigma-\tau\xi_U)^2 - \Psi + n\left(\frac{1}{2}(a-\lambda-\tau\xi_D-gk) - v(k+\xi_D)\right)\left(\frac{a-\lambda-\tau\xi_D-gk}{nb+hk^2}\right).$$

For CCU to be a viable solution from the perspective of the investing firm, the environment, and a policymaker requires that the trilogy of the upstream firm's profit, social welfare and environmental quality be greater in the CCU scenario than the baseline scenario without carbon capture. The graphs in Fig. 3 (based on the baseline scenario parameters in Appendix) illustrate in the (τ,ω) space how the upstream firm's profit (top panel), the quality of the environment (middle panel), and social welfare (lower panel) compare under the two scenarios for a set of reasonable parameters of the model. The pairs of (τ, ω) lying in the red coloured area correspond to cases where the upstream firm's profit/quality of the environment/social welfare are higher under the baseline scenario than under the CCU scenario. In contrast, in the blue-green-yellow zones, the CCU scenario induces a more beneficial outcome in terms of the three measures.[8]

As discussed above, the profitability of CCU for the upstream firm of interest is increasing in ω. In other terms, allowing for utilisation makes it easier to incentivise carbon capture. A comparison of the profit under CCU with profit in the baseline scenario depends, *inter alia*, on the carbon tax, which influences profits in the latter. As can be seen in the top panel of Fig. 3, for $\tau \leq 23$ not investing in CCU is always best for the upstream firm of interest. For $23 < \tau < 78$ investing in CCU only gives higher profits if the firm is allowed to send a proportion of its captured emissions to market that exceeds a particular threshold, which is lower the higher τ is. If $\tau \geq 78$ profit under business as usual is so low that the upstream firm of interest will invest in carbon capture regardless of the proportion of captured emissions it is allowed to send to market, even if the extreme case of CCS ($\omega = 0$) is imposed.

Furthermore, there is a trade-off between incentivising carbon capture through utilisation and improving the quality of the environment (as we discussed in the previous section); utilisation encourages carbon capture, but reduces the environmental benefits associated with storage and may even exacerbate the pollution problem. While the middle graph in Fig. 3 suggests that CCU is favourable to the environment for most of the pairs of τ and ω, the environmental benefits from carbon capture decrease when ω increases (consistent with the idea of the rebound effect; this is not entirely obvious from the heatmap but can be confirmed from additional plots similar to Fig. 2). This plot illustrated that in the extreme case where τ is very high, CCU might even lead to an environmentally worse outcome when ω is sufficiently high, with the quality of the environment falling below the quality achieved under the baseline scenario without CC (consistent with the idea of backfire discussed previously).

As the bottom graph in Fig. 3 shows, social welfare follows the same trend as the profit of the upstream firm. Unsurprisingly, however, the interests of society and the upstream firm do not always align. When CCU is profitable for the upstream firm, it is always social welfare improving, but the reverse is not true. For example, in the extreme case of CCS with $\omega = 0$, τ must be equal or greater than 58 for CC to be welfare improving compared to the baseline case. Further, with some (τ, ω) pairs maximising social welfare calls for CCUS to be undertaken, but nevertheless the upstream firm of interest does not face the incentive to invest they prefer business as usual. The pairs of τ and ω for which the interests of the upstream firm and society don't align call for government intervention. From any point in the (τ, ω) space with conflicting

[8] These are heatmap plots, where for CCU regions the lighter the colour the more beneficial the outcome measure is.

interests, the government could achieve social-welfare enhancing outcomes by increasing appropriately τ and/or ω. Interestingly, however, increasing both τ and ω (for e.g., when $\tau = 150$, the maximum carbon tax level that guarantees positive outputs, and $\omega = 1$) could backfire, as noted above, with CCU giving rise to more CO_2 emissions than the baseline scenario. Putting more weight on the environmental impact (i.e., increasing v) would change this analysis and cause a policymaker to favour mitigating emissions through constraining ω if they have the choice.

Using the results from our simulations, we can identify other policy handles available, which the government can use to maximise the environmental and social benefits of CCU. First, the government can introduce an environmental regulation that restricts the number of conventional firms, n, that compete with the upstream firm in the CO_2 market. The main objective of this policy is to encourage the use of man-made CO_2 as a substitute for natural CO_2. Fig. 4 below (based on the parameters in the baseline scenario detailed in Appendix but where $n = 30$) shows how Fig. 3 changes when n is reduced from 100 to 30 as a result of this policy. From the top and bottom graphs in Fig. 4, it is clear that the pairs of (τ,ω) for which CCU is profitable for both the upstream firm and society increase. Even when $\tau = 0$, CCU can be profitable for the upstream firm provided that ω is high enough (e.g., when $\omega = 1$). For each level of τ, the ω threshold from which CCU is profitable is reduced when n is reduced, and the same trend is observed for social welfare. However, the reverse is true for the quality of the environment, as the middle graph in Fig. 4 shows. When n is reduced, the pairs of (τ,ω) for which CCU is favourable to the environment decrease.

Second, the government might favour the upstream firm by imposing a tax on natural CO_2 produced by conventional firms, with the objective of increasing their marginal cost parameter, h. Fig. 5 shows how Fig. 3 changes when h is increased from 5 to 25 (all the other parameters are the same as in the baseline scenario). The number of pairs of (τ,ω) for which CCU is profitable for both the upstream firm and society increases even more when h is increased compared to the previous case when n is reduced. At the same time, the number of pairs of (τ,ω) for which CCU is favourable to the environment decreases even more.

The result that the area in the $(\omega,\ \tau)$ space for which CCU is favourable to the environment decreases suggests that both the rebound and backfire effects of CCU are exacerbated by each of the above policy interventions. Intuitively, since both these policy interventions favour the upstream firm compared to the conventional firms, the ensuing control of the supply of CO_2 by the upstream firm would give rise to a greater sensitivity of the output level of the downstream industry to ω, the proportion of captured CO_2 sent to the CO_2 market. In this context, the government may instead decide to introduce a less discriminatory policy, which taxes each unit of CO_2 used as an input in the downstream market whether it is supplied by the upstream firm or a conventional firm. By taxing CO_2 in a non-discriminatory manner, the government may succeed to offset the rebound effect from CCU by essentially adding a tax that offsets the reduction in price brought about by the increased supply of CO_2 from capturing carbon. A better understanding of factors at play to determine the optimal level of this input tax requires detailed modelling, which is beyond the scope of this paper. However, from the main results of our model, we can establish that the optimal input tax depends on ω and is related to the difference between $r^{\#}$ and $r^{*}(\omega)$:

$$r^{\#} - r^{*}(\omega) = bh\xi_U\omega\frac{A - \sigma - \xi_U\left(\beta + (1-\omega)s - \omega\frac{kh(a-(\lambda+\tau\xi_D))+bng}{nb+hk^2}\right)}{2\left(B\left(nb+hk^2\right)+bh\omega^2\xi_U^2\right)}.$$

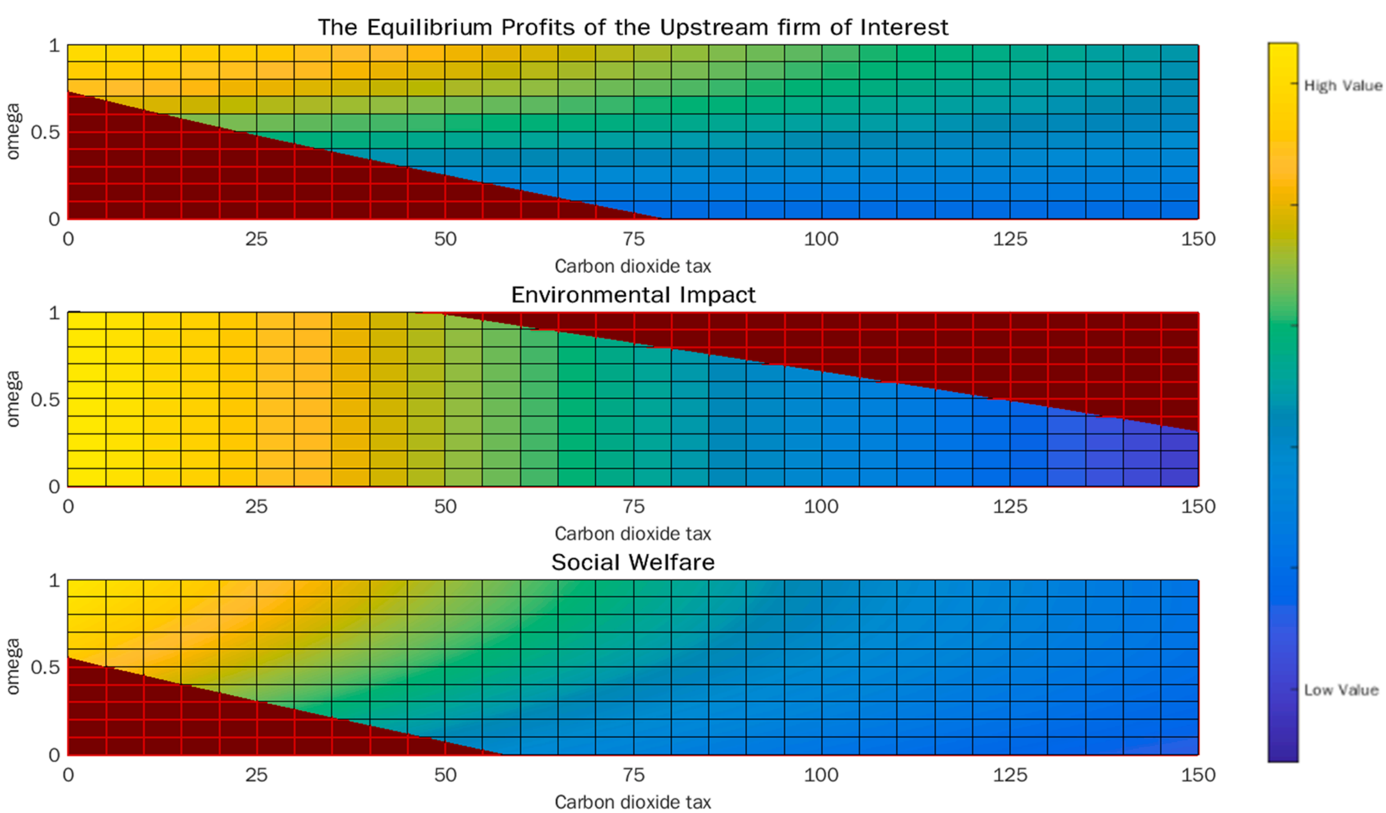


Fig. 4. An environmental regulation on the upstream market: a reduction in the number of conventional firms, from $n = 30$ to 100 (other parameters same as baseline scenario). Fig. 4 shows the relationship between carbon tax policy (τ) and proportion of CO_2 sent to market decision (ω) with profits, environmental impact and social welfare. Regions: (i) Red if a parameter is in this region it signifies no carbon capture (CC) technology should be adopted (ii) Multicolour represents that a carbon capture technology is a better strategy, where yellow has the high value and blue is a low value see colour-bar legend on the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

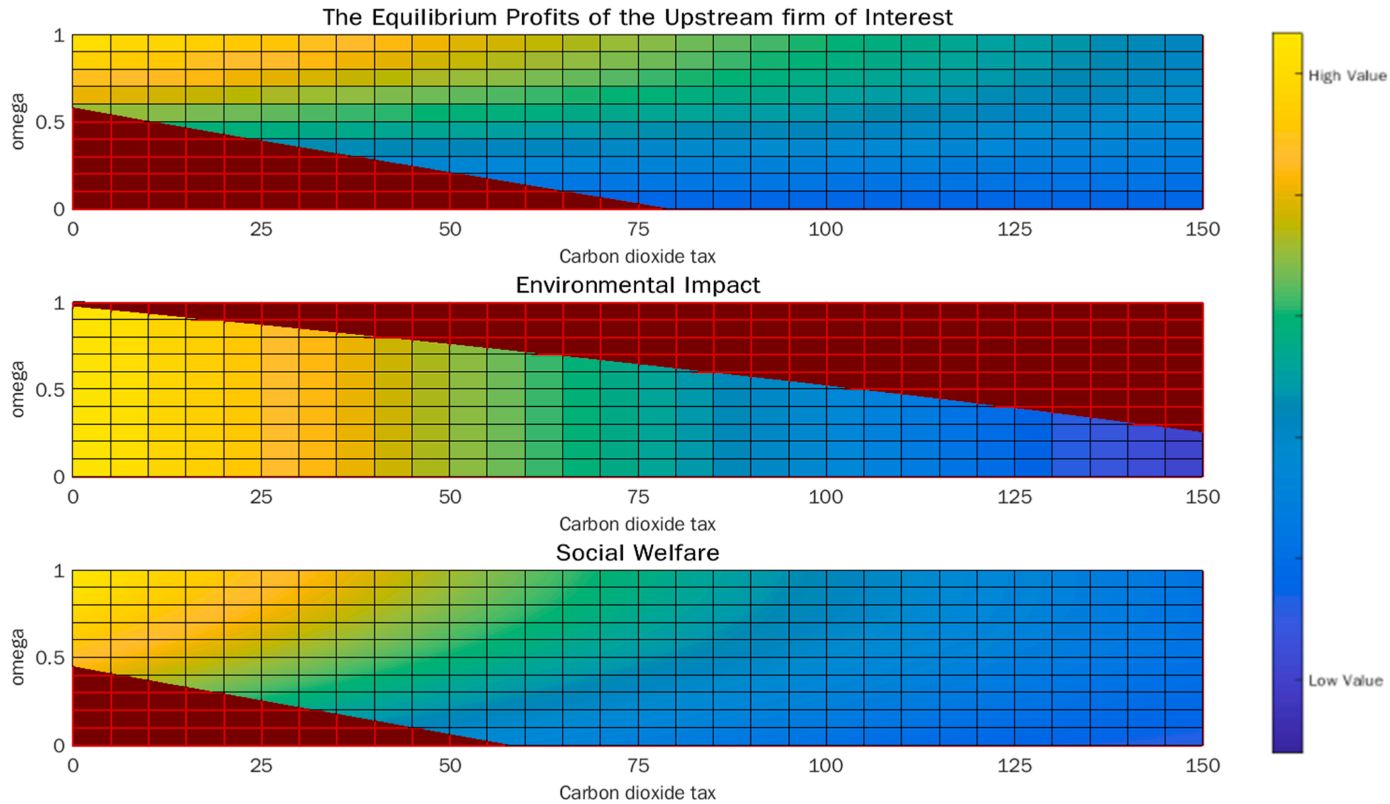


Fig. 5. A tax on CO_2 inputs in the upstream market. An increase in the marginal cost of the upstream firms, from $h = 5$ to 25 (other parameters same as baseline scenario). Fig. 5 shows the relationship between carbon tax policy (τ) and proportion of CO_2 sent to market decision (ω) with profits, environmental impact and social welfare. Regions: (i) Red if a parameter is in this region it signifies no carbon capture (CC) technology should be adopted (ii) Multicolour represents that a carbon capture technology is a better strategy, where yellow has the high value and blue is a low value see colour-bar legend on the right. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

9. Conclusions

Carbon capture is a crucial technology for achieving substantial greenhouse gas reductions. Allowing for utilisation of the captured carbon provides firms with additional incentives to invest in carbon capture technology. The purpose of this paper is to investigate the environmental consequences of carbon capture utilisation by accounting for the direct as well as indirect effects that stem from a change in behaviour for firms that use CO_2 as an input. To achieve this goal, we develop a parsimonious model where there are two different types of suppliers in the market for CO_2: many relatively small price-taking firms that produce CO_2 from conventional sources, and a large industrial firm that engages in the capture of CO_2 emissions generated as a by-product of this firm. We analyse the vertical relationships that arise between these upstream CO_2 suppliers and downstream firms that use CO_2 as an input. We characterise the optimal decisions of the different firms that interact in our model, and discuss the environmental and welfare impacts of carbon capture and utilisation (CCU). We compare the equilibrium outcomes when the upstream firm invests in CCU and the business-as-usual scenario, whereby the firm does not engage in CCU and just pays the carbon tax on its CO_2 emissions.

We find that the equilibrium profit of the upstream firm under CCU increases with respect to the stringency of the tax and the fraction of captured emissions sent to the CO_2 market for utilisation. With regard to the quality of the environment, we identify a rebound effect that emerges as a result of CCU. We show that if the upstream firm engages in CCU, then (1) there is an initial direct positive effect on the quality of the environment stemming from the amount of CO_2 emissions captured by the upstream firm, but (2) there is also an offsetting negative effect that arises from the increase in the emissions of CO_2 released into the environment by downstream firms. More specifically, the captured carbon increases the supply of CO_2, which thus lowers the equilibrium price for CO_2. By lowering the marginal cost of downstream firms that use CO_2 as an input, CCU consequently increases the production of those firms, with the natural implication of an offsetting increase in carbon emissions. We show that the size of this offsetting rebound effect increases with respect to the proportion of captured CO_2 emissions sent to the market for utilisation. In extreme circumstances where the rebound effect is very large, we find that CCU could backfire and worsen the quality of the environment.

Our analysis concludes with a discussion on the design of policies to incentivise the adoption of CCU. Our results suggest that simply incentivising the adoption of CCU, for example through the implementation of more stringent carbon taxes, might not necessarily benefit the environment. In addition, the regulator should account for the indirect environmental effects from CCU. The regulator should seek to implement environmental policies that simultaneously provide incentives to polluting firms to adopt CCU and tackle the displacement of the environmental problem from the upstream market to the downstream market.

Declaration of Competing 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.

Appendix

Table 1
Baseline scenario parameters used in MATLAB with description, symbol, value and units.

Upstream Firm of Interest	Symbol	Value	Unit
Y-intercept of inverse linear demand	A	400	\$/unit
Slope of inverse linear demand	B	1	integer
Marginal cost of production for doing carbon capture	β	20	\$/tCO_2 captured/unit
Marginal cost of production (not involving carbon capture)	σ	20	\$/unit
Marginal cost of CO_2 storage	s	20	\$/tCO_2 stored/unit
Carbon tax	τ	15	\$/tCO_2
Pollution intensity	ξ_U	2	tCO_2/unit
Fixed cost of the carbon capture unit	Φ_I	10000	Annualised fixed cost
Other fixed costs (not involving carbon capture unit)	Ψ	0	Annualised fixed cost
Downstream Industry	***Symbol***	***Value***	***Unit***
Y-intercept of inverse linear demand	a	500	\$/unit
Slope of inverse linear demand	b	1	integer
Marginal cost of production	λ	20	\$/unit
Carbon tax	τ	15	\$/tCO_2
Pollution intensity	ξ_D	2	tCO_2/unit
Conversion factor of CO_2 inputs into one unit of product	k	2	tCO_2/unit
Conventional CO_2 Input Firms	***Symbol***	***Value***	***Unit***
Marginal cost parameter	g	5	\$/unit
Marginal cost parameter	h	5	\$/unit
Number of conventional CO_2 input firms	n	100	integer
Other	***Symbol***	***Value***	***Unit***
Marginal damage coefficient	ν	10	integer

References

BEI, 2020. Department for business, energy & industrial energy. Carbon Capture, Usage, and Storage A Governmental Response on potential business models for Carbon Capture, Usage, and Storage.

Agarwal, A., 2014. Risk sharing inCO_2 delivery contracts for the CCS-EOR value chain. MIT Center for Energy and Environmental Policy Research, Massachusetts, USA.

von der Assen, N., et al., 2014. Life cycle assessment ofCO_2 capture and utilization: a tutorial review. Chem. Soc. Rev. 43 (23), 7982–7994.

Bachu, S., Adams, J.J., 2003. Sequestration ofCO_2 in geological media in response to climate change: Capacity of deep saline aquifers to sequesterCO_2 in solution. Energy Convers. Manage. 44, 3151–3175. https://doi.org/10.1016/S0196-8904(03)00101-8.

Berkhout, P.H.G., Muskens, J.C., Velthuijsen, J.W., 2000. Defining the rebound effect. Energy Policy 28 (6-7), 425–432.

Borenstein, S., 2013. A microeconomic framework for evaluating energy efficiency rebound and some implications (No. 19044). NBER Working Paper Series. National Bureau of Economic Research, Cambridge, MA, USA.

Bowen, F., 2011. Carbon capture and storage as a corporate technology strategy challenge. Energy Policy 39, 2256–2264.

Budinis, S., et al., 2018. An assessment of CCS costs, barriers and potential. Energy Strategy Rev. 22, 61–81.

Chenavaz, R., Dimitrov, S., Figge, F., 2021. When does eco-efficiency rebound or backfire? An analytical model. Eur. J. Oper. Res. 290 (2), 687–700.

Cuéllar-Franca, R.M., Azapagic, A., 2015. Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts. Journal ofCO_2 Utilization 9, 82–102.

Davies, L., Uchitel, K., Ruple, J., 2013. Understanding barriers to commercial-scale carbon capture and sequestration in the united states: an empirical assessment. Energy Policy 59, 745–761.

Edwards, R.W.J., Celia, M.A., 2018. Infrastructure to enable deployment of carbon capture, utilization, and storage in the united states. Proc. Natl. Acad. Sci. 115 (38), E8815–E8824.

Gabszewicz, J.J., Zanaj, S., 2011. Free entry in successive oligopolies. Int. J. Econ. Theory 7 (2), 179–188.

Greening, L.A., Greene, D.L., Difiglio, C., 2000. Energy efficiency and consumption-the rebound effect-a survey. Energy Policy 28 (67), 389–401.

Grimaud, A., Rouge, L., 2014. Carbon sequestration, economic policies and growth. Resour. Energy Econ. 36 (2), 307–331.

IPCC, 2014. Intergovernmental panel on climate change climate change 2014 synthesis report summary for policymakers.

Kondratenko, E., Mul, G., Baltrusaitis, J., Larrazábal, G., Pérez-Ramírez, J., 2013. Status and perspectives ofCO_2 conversion into fuels and chemicals by catalytic, photocatalytic and electrocatalytic processes. Energy Environ. Sci. 6, 3112–3135. https://doi.org/10.1039/C3EE41272E.

Liang, D., 2009. Simulation of china's CCS operation model based on electricity market. China Soft Sci. (2), 151–163.(in Chinese)

Lin, B., Tan, Z., 2021. How much impact will low oil price and carbon trading mechanism have on the value of carbon capture utilization and storage (CCUS) project? Analysis based on real option method. J. Clean. Prod. 298, 126768.

Metcalf, G.E., Weisbach, D., 2009. The design of a carbon tax. Harv. Environ. Law Rev. 33, 499.

Spengler, J.J., 1950. Vertical integration and antitrust policy. J. Political Econ. 58.

Wang, N., Akimoto, K., Nemet, G., 2021. What went wrong? learning from three decades of carbon capture, utilization and sequestration (CCUS) pilot and demonstration projects. Energy Policy 158, 112546. https://doi.org/10.1016/j.enpol.2021.112546.

Yao, X., Zhong, P., Zhang, X., Zhu, L., 2018. Business model design for the carbon capture utilization and storage (CCUS) project in china. Energy Policy 121, 519–533.

Ye, B., et al., 2019. Technical and economic analysis of amine-based carbon capture and sequestration at coal-fired power plants. J. Clean. Prod. 222, 476–487.

York, R., 2012. Do alternative energy sources displace fossil fuels? Nat. Clim. Change 2 (6), 441–443.

Zhang, K., Wang, Q., Liang, Q.M., Chen, H., 2016. A bibliometric analysis of research on carbon tax from 1989 to 2014. Renew. Sustain. Energy Rev. 58, 297–310.

Zimmermann, A., et al., 2020. Techno-economic assessment guidelines forCO_2 utilization. Front. Energy Res. 8 (5), 23.

Zimmermann, A., Kant, M., 2017.CO_2 utilisation today report 2017.

Zimmermann, A., Müller, L., Marxen, A., Armstrong, K., Buchner, G. A., Wunderlich, J., Kätelhön, A., Bachmann, M., Sternberg, A., Michailos, S., Naims, H., Styring, P., Schomäcker, R., Bardow, A., 2018. Techno-economic assessment & life-cycle assessment guidelines forCO_2 utilization. 10.3998/2027.42/145436.

Zink, T., Geyer, R., 2017. Circular economy rebound. J. Ind. Ecol. 21 https://doi.org/10.1111/jiec.12545.