The Economics of CCS: Why have CCS technologies not had an international breakthrough?

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Abstract

Eleven years on since the United Nations' Intergovernmental Panel on Climate Change was awarded the Nobel Peace Prize in recognition of its efforts in combating climate change, fossil fuels remain the most dominant global energy source. As the total replacement of fossil fuel energy is not expected to take place immediately in the near future, the International Energy Agency has repeatedly declared carbon capture and sequestration (CCS) as a key technology for mitigating climate change. However, CCS lacks the scale required for substantial reduction in carbon dioxide emissions from fossil fuel power generation. Even though CCS is one of the key technologies for mitigating climate change, why has this technology not had an international breakthrough? To shed light on this question, this paper employs a simple model of energy generation, scrutinizes the economic drivers of CCS based on the analytical results, and discusses the possible obstacles that can prevent a widespread rollout of the technology. This is followed by a state-of-the-art in literature pertaining to the economics of CCS, and a discussion that points to a dichotomy between the economic theory and reality. The study concludes with some policy suggestions and directions for future research.

Keywords: *Carbon capture and storage; Renewable energy; Fossil fuels; Climate change; Environmental Policy; State-of-the-art*

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1 Introduction

The Earth's surface would be below the freezing point of water, and therefore, largely uninhabitable, if it was not for the greenhouse effect. It is a process by which the solar energy that reaches the Earth's surface is radiated back and partially absorbed by the atmosphere, making the atmosphere and hence the earth's surface warmer (IPCC, 2007; Freund, 2013). This effect comes from the so-called "greenhouse gases" (GHGs).[1]

Human activities have been changing the natural greenhouse. One of the consequences of changing the natural atmospheric greenhouse is that the Earth becomes warmer. It is now extremely likely that human influence has been the dominant cause of the observed warming since the mid-20th century. In other words, more than half of the observed increase in global average surface temperature from 1951 to 2010 was extremely likely caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together (IPCC, 2014).

Rising global temperatures that alter the Earth's climate has already started to take its toll. Consequences include global mean sea level rise, the retreat of glaciers, increased surface melting of the Greenland ice sheet, as well as higher incidences of heat waves, destructive storms, changes to rainfall patterns that lead to droughts and floods affecting food production, human disease and mortality (IPCC, 2007; Freund, 2013; IEA, 2013a). Unless the anthropogenic GHG emissions decrease substantially in the near future, concentrations of GHGs in the atmosphere will continue to rise and cause further warming, long-lasting changes in all components of the climate system, and severe, pervasive and irreversible impacts for people and ecosystems (IPCC, 2014).

Energy emissions account for the largest share of global anthropogenic GHG emissions. Within the energy sector, CO_2 dominates the total GHG emissions with its 90% share and represents almost 65% of the global anthropogenic GHG emissions (see Figure 1).[2]

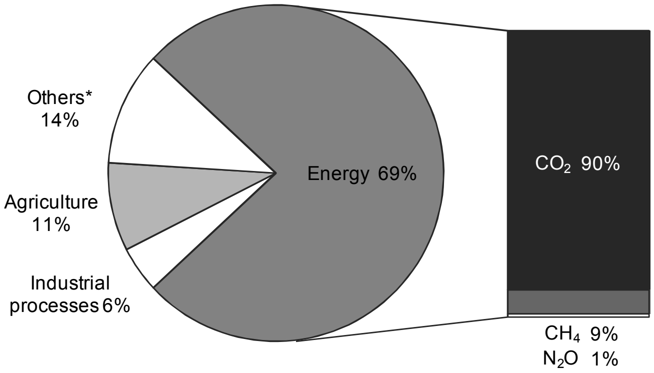

Figure 1: *Global anthropogenic GHG shares, 2010. Source: IEA (2014)*

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[1] Water vapor and CO_2 are the two major GHGs. Others are methane, nitrous oxide and ozone.

[2] Smaller shares correspond to agriculture, producing mainly CH_4 and N_2O from domestic livestock and rice cultivation, and to industrial processes not related to energy, producing mainly fluorinated gases and N_2O.

Despite the strong advances worldwide and growth in clean energy technologies, the share of fossil fuels within the world energy supply has been relatively the same over the past 40 years. These fuels still supply over 80% of all primary energy needs and will remain the dominant source of energy for the decades to come (IEA, 2013a).

Figure 2 shows the CO_2 emissions from fuel combustion since the Industrial Revolution. The emissions have risen exponentially during this time period.[3] The positive trend in CO_2 emissions and the dominant role that fossil fuels maintain will prove disastrous for future generations unless there will be significant reductions in energy-related CO_2 emissions. This could be achieved with a massive deployment of clean energy technologies, such as wind, sun and nuclear energy, and hydropower. Given that fossil fuels will continue to supply a major share of the energy needs, however, carbon capture and storage (CCS) appears to be the only technology that can substantially reduce CO_2 emissions (Amigues et al., 2016).[4]

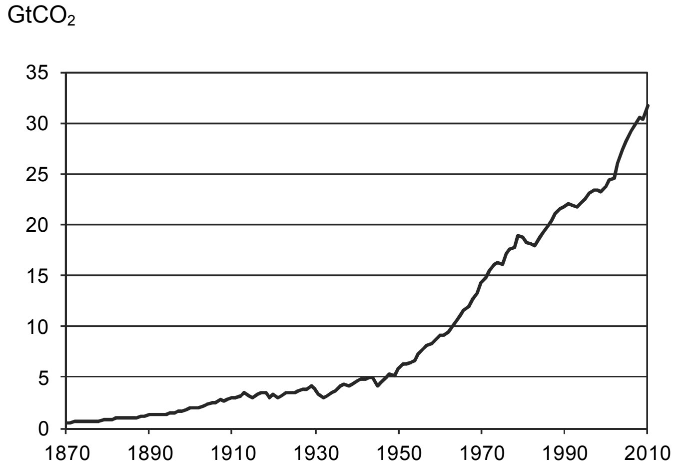

Figure 2: *Accumulated CO_2 emissions from fossil fuel combustion. ('Gt' stands for gigaton.) Source: IEA (2014)*

CCS is a technology that comprises the separation of CO_2 from industrial- and energy-related activities, and the transportation to storage locations, such as saline aquifers and depleted hydrocarbon fields, oil fields with the potential for enhanced oil recovery (EOR), and coal seams that cannot be mined with potential for enhanced coal-bed methane recovery (IEA, 2013a; Balat et al., 2009).[5] Its main goal is to prevent CO_2 emissions from entering the atmosphere. The technology can be used by large stationary point sources, such as fossil fuel-fired power plants and emission-intensive industrial facilities. The rates of carbon captured can be as high as 85–95%, in both the pre- and post-combustion systems.

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[3] In 2014, the concentration of CO_2 in the earth's atmosphere was 3095 gigatons (Gt) or 398 parts per million (ppm). Considering the 450 scenario, which is consistent with the goal of limiting the global temperature rise to 2°C by stabilizing the concentration of the atmospheric CO_2 to 450 ppm (IEA, 2013b, Annex B), one realizes that the atmospheric CO_2 is rapidly approaching this limit (Durmaz, 2015).

[4] Further efforts to increase energy efficiency in power and industrial production and more energy efficient consumption will also be required to reduce CO_2 emissions.

[5] EOR is a practice to increase the amount of crude oil that can be extracted from an oil field.

There are three methods for capturing CO_2. *Post-combustion* carbon capture removes carbon from coal-fired power generation or natural gas combined cycles after combustion. Here, CO_2 is separated from the flue gases (whose main constituent is nitrogen) using a liquid solvent. In *pre-combustion* carbon capture, fuel is pretreated and converted into a mix of CO_2 and hydrogen. The hydrogen is then separated from the carbon before being burned to produce electricity. In the *oxy-fuel combustion process*, the fuel is burned using oxygen rather than air. The result is a flue stream of CO_2 and water vapour. Because no nitrogen is present, CO_2 can be easily removed (Golombek et al., 2011; Metz et al., 2005).[6]

Several international and intergovernmental agencies, including International Energy Agency (IEA), Intergovernmental Panel on Climate Change (IPCC), U.S. Energy Information Administration (EIA), envision an important role for CCS and recommend its use in order to achieve the environmental goals. Yet, the progress in CCS is slow and far below than what is required to limit the global temperature rise to 2°C (IEA, 2013a).[7] Even though the CCS technology is a key technology in mitigating the CO_2 emissions, why have these technologies not had an international breakthrough, and will it come?

This paper tries to shed light on these questions by presenting a simple and yet still interesting model of energy generation. It is important to note that the economics of CCS literature has developed in several directions including partial *vs* general equilibrium models, theoretical dynamic models *vs* numerical solutions to empirically calibrated models, and models encompassing exogenous *vs* endogenous technical progress. The models that have been utilized can be rather complex, encompassing several details and reflecting the dynamic nature of the changing climate, technological change, and exhaustible resource extraction, to name a few. The simple model that this paper utilizes, nevertheless, allows considering several economic factors that affect the demand for CCS in a single paper and connect the results to the studies in the literature.

As is shown in this paper, as well as in the economics of CCS literature, the CCS technology is utilized as long as the environmental policy is in place, and the cost mark-up of CCS in fossil fuel energy production is sufficiently low. Technological change, exhaustibility, the available capacity of (underground) carbon reservoirs and the cost of clean energy are factors that induce the demand for CCS. While all components of integrated CCS systems exist and are in use today by the fossil fuel extraction and refining industries, CCS has not been applied at scale to a large and operational commercial fossil fuel power plant. For further and significant progress in CCS, two factors stand out. The first one concerns the carbon policy: a sufficiently high carbon price will allow for CCS. Nevertheless, the CCS technology has been facing 'first-of-its-kind risks' to costs, and lacks technological maturity, leading to numerous shutdowns and spiraling cost of capturing. The second factor that stands out is, therefore, the need for an improved CCS technology that will allow for a successful integration of three major component technologies –CO_2 capture,

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[6] There are also several industrial applications (e.g., iron, steel and cement production) involving process streams where CO_2 can be captured in large quantities. Considering that 25% of emissions are from manufacturing (IEA, 2013a), CCS technologies targeted at these industries can play an important role in combating climate change.

[7] The technology is still absent in a number of key industrial sectors, such as iron and steel, and cement.

transportation, and storage– into large-scale (commercial) projects. Because the aforementioned components of the technology are proven, well-tested and reliable, learning-by-doing (LbD) is expected to play a major role for the successful integration of these components.[8]

The next section presents the model, states the problem and discusses its solution. Section 3 scrutinizes the economic drivers of CCS based on the results that are obtained in Section 2. Section 4 presents a literature survey, which mainly builds on Section 3. Section 5 explores the obstacles that prevent a widespread rollout of the CCS technology, and point to the dichotomy between the relevant economics literature and real life. Section 6 concludes with some policy suggestions and directions for further research.

2 The model

To begin with, consider an economy where energy is produced from fossil fuels (e.g., coal), q_d. The economic and climatic systems are linked by anthropogenic CO_2 emissions, which are generated by burning fossil fuels. Without CCS, the CO_2 released into the atmosphere is equal to ξq_d, where ξ is the unitary polluting content the fossil fuel. The CCS activity allows for a reduction of the effective emissions by q_a. Thus, when the CO_2 is captured and stored, the net amount of emissions is $\xi q_d - q_a$. It is assumed that the capture rate cannot be higher than the effective amount of emissions: $q_a \leq \xi q_d$.

Because CO_2 emissions have environmental impacts that are damaging for the society, e.g., global warming, a damage function, $h(\xi q_d - q_a)$, which is positive, strictly increasing (decreasing) in CO_2 emissions (CCS), $h' > 0$, strictly convex, $h'' > 0$, and $h'(0) > 0$, is considered. The latter is strictly positive due to the previously accumulated CO_2 emissions in the atmosphere. To be concise, only the current effective emissions are considered.[9]

Consuming energy provides utility denoted by $u(q_d)$. The utility function is strictly increasing, $u' > 0$, strictly concave, $u'' < 0$, and satisfies the first Inada condition: $\lim_{x \to 0} u'(x) = +\infty$. It is assumed that $u(q_d)$ and $h(\xi q_d - q_a)$ are expressed in monetary terms. Thus, $u(q_d) - h(\xi q_d - q_a)$ can be viewed as the consumer's gross surplus.

The problem is the following:

$$\max_{\{q_d, q_a\}} u(q_d) - h(\xi q_d - q_a) - c_d q_d - c_a q_a$$
$$\text{subject to } q_a \leq \xi q_d \text{ and } q_a \geq 0,$$

where $c_d > 0$ and $c_a > 0$ are the constant unit costs of fossil fuel energy production and CCS, respectively.

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[8] LbD is simply productivity gains through production practice, minor innovations, and specialization.

[9] For more intricate analyses, the reader is referred to the papers that are presented in Section 4.

Solving the model

The first-order necessary condition for fossil fuel energy at a maximum is

$$u'(q_d^*) = c_d + \xi h'(\xi q_d^* - q_a^*). \tag{1}$$

The optimal decisions are denoted by placing "$*$" over them. In optimum, the marginal surplus from consuming energy should be equal to the sum of the marginal cost of energy generation, c_d, and the marginal environmental damage after CCS is accounted for.

The first-order condition with respect to q_a is

$$\begin{aligned} &\text{(2a)} \qquad h'(\xi q_d^*) \leq c_a && \text{if } q_a^* = 0, \\ &\text{(2b)} \qquad h'(\xi q_d^* - q_a^*) = c_a && \text{if } 0 < q_a^* < \xi q_d^*, \\ &\text{(2c)} \qquad h'(0) \geq c_a && \text{otherwise.} \end{aligned}$$

In light of Eqs. (2a)-(2c), I consider three cases.

Case 1: no CCS ($q_a = 0$)

From Eq. (2a), no CCS implies that $h'(\xi q_d^*) \leq c_a$, that is, the marginal cost of CCS is higher than the marginal damage from emissions at the optimal level of fossil fuel energy generation, q_d^*. When there is no CCS, Eq. (1) becomes $u'(q_d^*) = c_d + \xi h'(\xi q_d^*)$. Thus, at optimum, the marginal surplus from consuming q_d^* is equal to the sum of marginal cost of fossil fuel generation, c_d, and the marginal damage coming from emitting ξq_d^*; that is, $h'(\xi q_d^*)$. This is indeed the Pigovian tax. Let $\bar{\tau} \equiv h'(\xi q_d^*)$. Accordingly, whenever the unit cost of CCS is higher than $\bar{\tau}$, that is, $c_a > \bar{\tau}$, $q_a^* = 0$.

Case 2: partial CCS ($0 < q_a < \xi q_d$)

When $\bar{\tau} > c_a$ and it is optimal to partially capture emissions, that is, $0 < q_a < \xi q_d$, the marginal damage from the effective emissions, $\xi q_d - q_a$, will equal the marginal cost of CCS at any optimum:

$$h'(\xi q_d^* - q_a^*) = c_a. \tag{3}$$

Let $\tau \equiv h'(\xi q_d^* - q_a^*)$ denote the Pigovian tax on the effective emissions. When there is partial abatement, the Pigovian tax on the effective emissions and the marginal cost of abatement are equal.[10]

The former equality can be rewritten as

$$q_a^* = \xi q_d^* - h'^{-1}(c_a). \tag{4}$$

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[10] Unless it causes confusion, I use the terms CCS and abatement interchangeably.

Furthermore, using Eq. (3), Eq. (1) can be rearranged to yield the optimal level of the fossil fuel energy as a function of the marginal cost of energy generation and marginal cost of CCS:

$$q_d^* = u'^{-1}(c_d + \xi c_a). \tag{5}$$

By substituting the optimal level of fossil fuel energy in Eq. (5) for itself in Eq. (4), one can calculate the optimal level of CCS as

$$q_a^* = \xi u'^{-1}(c_d + \xi c_a) - h'^{-1}(c_a). \tag{6}$$

When there is partial CCS, it is straightforward to show that

$$\frac{\partial q_a^*}{\partial c_a} = \frac{\xi^2}{u''} - \frac{1}{h''} < 0. \tag{7}$$

Thus, for a lower unit cost of CCS, the demand for, and in turn, the level of CCS will become higher.[11] Furthermore,

$$\frac{\partial q_a}{\partial c_d} = \xi \frac{\partial q_d}{\partial c_d} = \frac{\xi}{u''} < 0. \tag{8}$$

Eq. (8) shows that a higher unit cost of fossil fuel energy, which will lead to a lower level energy generation and therefore emissions, will also lower the optimal level of CCS. Subsequently, CCS is an increasing function of the amount of the fossil fuel energy and vice versa:

$$\frac{\partial q_a}{\partial q_d} = \xi > 0. \tag{9}$$

Case 3: Full CCS ($q_a = \xi q_d$)

Lastly, consider the case when there is full CCS, that is, $q_a^* = \xi q_d^*$. The necessary condition for full CCS is $\underline{\tau} \equiv h'(0) \geq c_a$, that is, the marginal damage caused to the environment should be at least as large as the unit cost of CCS. In this case, the social marginal surplus is larger than the marginal cost of CCS, but the welfare program is technically constrained by the fact that CCS only applies to what is emitted, ξq_d^*.

The three cases allow me to graph the relationship between q_a and c_a in Figure 3:

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[11] Furthermore, $\frac{\partial^2 q_a}{\partial c_a^2} = -\xi^3 \frac{u'''}{u''^3} + \frac{h'''}{h''^3} > 0$.

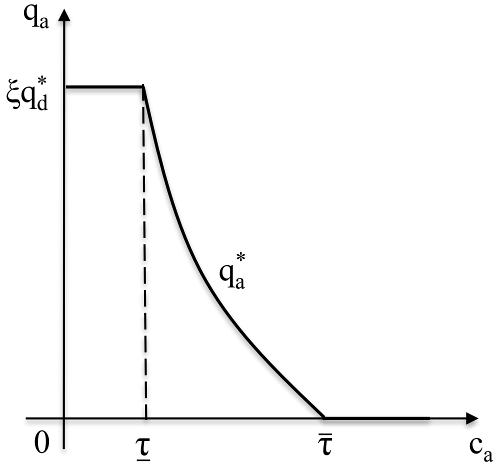

Figure 3: *The relationship between CCS and its cost*

Accordingly, when c_a is higher than $\bar{\tau}$, that is, the unit cost of CCS is sufficiently high, there will be no CCS. For a unit cost of CCS that is smaller than $\bar{\tau}$ but higher than $\underline{\tau}$, it is optimal to use CCS only partially. On the other hand, when c_a is sufficiently low, that is, lower than $\underline{\tau}$, it will be optimal to capture all the CO_2 emissions of the fossil fuel energy industry.

3 Economic drivers of CCS

The focus in this section is on the drivers of CCS which are crucial from an economic point of view and overlaps well with the analytical discussion thus far. Owing to the ongoing competition between fossil energy and carbon-free options, such as solar, wind and nuclear electric power, the impact of carbon-free options on CCS deployment will also be examined in this section (Section 3.4). The following figure presents these drivers as well as the factors that are crucial for their assessment.

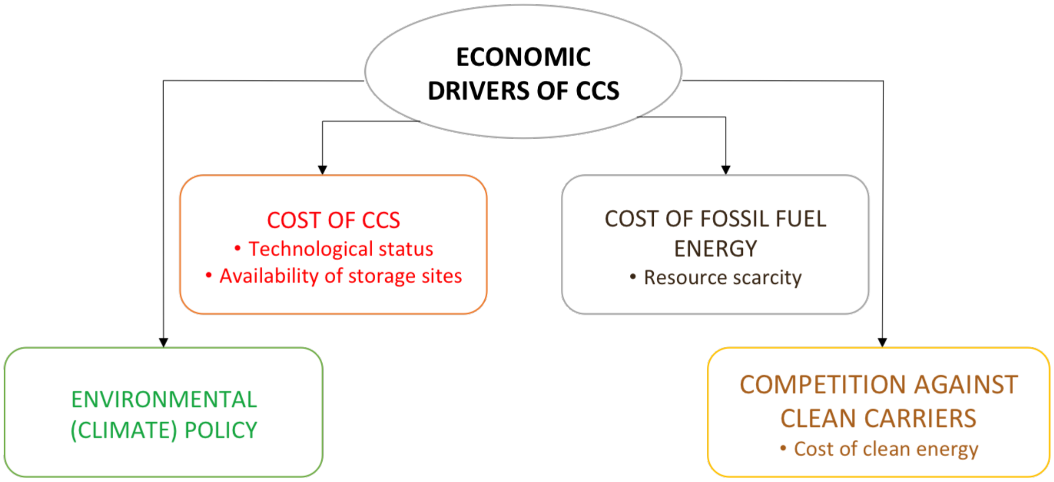

Figure 4: *Economic drivers of CCS*

3.1 Environmental (Climate) policy

In a market economy, energy generation and CCS decisions can be decentralized by means of a tax on the dirty energy production to correct for the negative environmental externality and lump-sum transfers to the representative consumer. Thus, an environmental policy that targets the CO_2 emissions via a carbon tax, τ, (or, alternatively, via pollution permits with price τ) is the main economic driver for the CCS technology. Unless there is a carbon tax, that is, $\underline{\tau} = \tau = \bar{\tau} = 0 < c_a$, there will be no demand for the CCS technology in a decentralized setting (see Case 1 on p. 6).

3.2 Cost of CCS

Another economic driver of the use of technology is its cost, c_a. As is seen in Figure 3, it will become optimal to use CCS only when the unit cost of CCS is sufficiently low, that is, when c_a is lower than $\bar{\tau}$. Otherwise, in a decentralized economy, and assuming away renewable energy (RE) momentarily, it will be more beneficial for the economy to emit CO_2 and pay the carbon price. When the marginal cost of CCS is lower than $\underline{\tau}$, the marginal benefit of CCS for the society is larger than the marginal cost of the pollution. Yet, as the welfare problem is constrained by the fact that abatement can only apply to contemporaneous emissions, the level of CCS will equal the level of emissions.

3.2.1 Technological change

Technological change implies that the same level of output (e.g., CCS) can be achieved with a lower level of cost. This naturally allows checking how CCS activity is affected by an increase in the level of CCS technology. Let A represent the current level of CCS technology, and $c_a(A)$ be the unit cost of CCS which is a twice continuously differentiable function with $c_a'(A) < 0$ and $c_a''(A) > 0$.

The optimal levels of q_d and q_a, in this case, are identical to the ones given by Eqs. (5) and (6). Doing a comparative static analysis, an improvement in the CCS technology has the following effects for an interior solution:

$$\frac{\partial q_a^*}{\partial A} = c_a'(A)\frac{\partial q_a^*}{\partial c_a} > 0 \text{ and}$$
$$\frac{\partial q_d^*}{\partial A} = \frac{\xi c_a'(A)}{u''} > 0,$$

where $\partial q_a^*/\partial c_a < 0$ (see Eq. 7). In addition, looking at the effect of a higher A on net emissions, one finds that net emissions go down with a more advanced CCS technology:

$$\frac{\partial\left(\xi q_d - q_a\right)}{\partial A} = \frac{c_a'(A)}{h''} < 0.$$

As the results indicate, a more advanced CCS technology, which lowers the unit cost of CCS, leads to a higher amount of CCS. Considering that it was not optimal to capture the emissions prior to the technological change, a lower unit cost of CCS can lead the way to partial and even full CCS. A more advanced CCS technology also leads to higher fossil fuel energy generation and, in turn, emissions. Although both q_d, and, therefore, emissions and q_a increase with the technical change in CCS, net emissions decrease.

When one formulates technological change such that an improvement in the CCS technology, ceteris paribus, would directly increase the level of CCS, that is, Aq_a, the outcome will be similar to the one where the technological change directly reduced the unit cost of CCS:[12]

$$\frac{\partial\left(Aq_a^*\right)}{\partial A} = -\frac{\partial q_a^*}{\partial c_a} > 0,$$

where

$$\frac{\partial q_a^*}{\partial c_a} = \frac{1}{A^2}\left(\frac{\xi^2}{u''} - \frac{1}{h''}\right) < 0.$$

Furthermore,

$$\frac{\partial q_d^*}{\partial A} = -\frac{\xi h'}{Au''} > 0.$$

When one looks at the impact of higher A on net emissions, however, net emissions go down

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[12] The two formulations for technical progress are frequently used in the relevant literature.

with a more advanced CCS technology:[13]

$$\frac{\partial\left(\xi q_d - A q_a\right)}{\partial A} = -\frac{h'}{A h''} < 0.$$

Figure 5 graphically summarizes the effect of an improvement in the CCS technology on CCS for the case where CCS activity is denoted by Aq_a. Let A', where $A' > A$, represent a more advanced CCS technology. Accordingly, for the same unit cost of CCS and given the Pigovian tax, a more advanced technology implies a higher level of CCS. Accordingly, if there was no CCS with the previous technology, it can become beneficial to capture CO_2 following the technological improvement. Moreover, owing to the technological change, full CCS can be achieved with a higher unit cost of CCS.

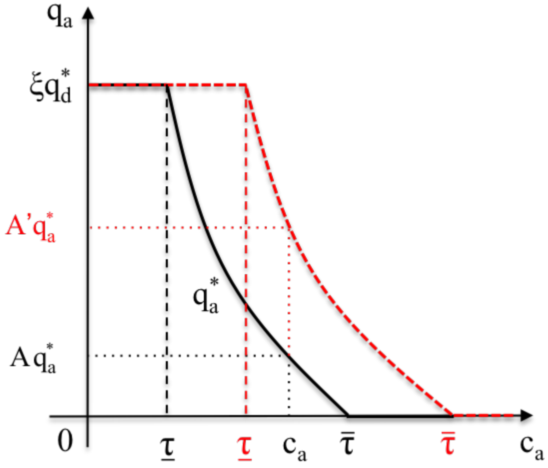

Figure 5: *The effect of an increase in CCS technology*

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[13] After a few calculations, one can show that the effect of a change in the CCS technology on the amount spent on CCS is uncertain:

$$\frac{\partial q_a^*}{\partial A} = \frac{h'}{A^2}\left(\epsilon_a - 1\right),$$

where

$$\epsilon_a \equiv \frac{\partial q_a / q_a}{\partial c_a / c_a},$$

is the price elasticity of CCS. Thus, the sign of $\partial q_a^* / \partial A$ depends on the following conditions:

$$\begin{array}{ll} \dfrac{\partial q_a^*}{\partial A} > 0 & \text{if} \quad \epsilon_a > 1 \\ \dfrac{\partial q_a^*}{\partial A} \leq 0 & \text{otherwise.} \end{array} \tag{10}$$

Accordingly, when the demand for CCS is price elastic, the demand for CCS and, in turn, the amount spent for CCS, upon an increase in the technology will increase and vice versa. This result follows from the fact that a quasi-linear utility function over energy consumption and a numéraire commodity (money or bundle of all other goods which are reduced to a single composite commodity, i.e., the numéraire) is considered. Thus, when the CCS technology improves, it is beneficial for the society to spend more resources on the numéraire commodity when the demand for CCS is inelastic and vice versa.

3.2.2 Limited carbon sinks

Although the simple model that this paper utilizes does not explicitly account for CO_2 storage activity in carbon sinks, it is well known that the limited availability of the geological carbon sinks leads to scarcity rents and, with it, increase in the unit cost of CCS. As demonstrated on p. 7, a higher unit cost of CCS will lead to a lower level of CCS.

3.3 Cost of fossil fuel energy generation

The cost of generating fossil fuel energy, which may be linked to the abundance of the fossil resource, also affects the demand for CCS. The analysis in the previous section shows that a higher c_d will lead to lower level of fossil fuel energy, CO_2 emissions as well as CCS (cf. Eq. (8), see the dashed-red line in Figure 6). On the contrary, cheaper fossil fuels will lead to a higher level of fossil fuel energy and CCS activity.

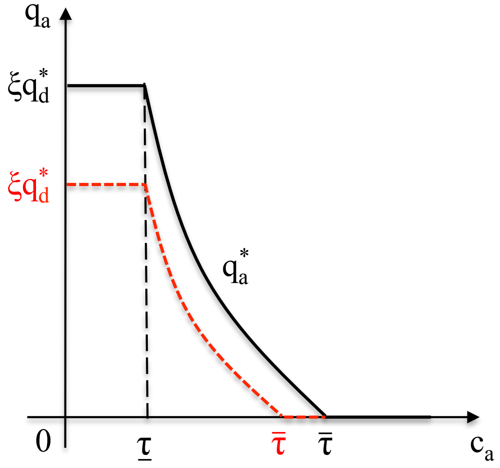

Figure 6: *The effect of an increase in the cost of fossil fuel energy generation*

3.3.1 Exhaustibility

Although the ongoing technical progress and discoveries of new fossil fuel reserves have shifted concerns away from sustainability of growth alongside resource scarcity to climate change and environmental degradation (Heutel and Fischer, 2013; Tsur and Zemel, 2011; Krautkraemer, 2005), fossil fuel resources are limited in nature. It is, therefore, important to consider exhaustibility, and with it, the resource scarcity rent of these limited resources. In this case, the unit cost of clean coal must also include the scarcity (or mining) rent. As has been shown, a higher cost of the fossil fuel resource leads to a lower level of fossil fuel energy and emissions. Subsequently, there will be a lower level of CCS.

3.4 Competition against clean energy carriers

The fourth main economic driver affecting the deployment of CCS is the competition between fossil energy complemented with CCS and carbon-free options, such as solar, wind and nuclear electric power. Assuming a constant-elasticity-of-substitution (CES) formulation for energy production, the problem becomes the following

$$\max_{\{q_d, q_c, q_a\}} u\left[(q_d^{\rho} + q_c^{\rho})^{\frac{1}{\rho}}\right] - h(\xi q_d - q_a) - c_d q_d - c_c q_c - c_a q_a$$
$$\text{subject to } \; q_a \leq \xi q_d, q_d \geq 0, q_c \geq 0, q_a \geq 0,$$

where q_c is energy generation from carbon-free options, $c_c > 0$ is the unit cost of clean energy and ρ is the substitution parameter.[14] The elasticity of substitution between the carbon-free options and fossil fuel energy with CCS can be calculated as $\epsilon = 1/(1-\rho)$. Papageorgiou et al. (2016) estimate the elasticity of substitution between clean and dirty energy to be between 1.7 and 2.8 for the electricity sector and between 1.4 and 3.2 for the non-energy sector. Moreover, Popp (2006) considers elasticities of substitution that range from 1.6 to 8.7. Accordingly, this study considers primarily the cases where clean and dirty carriers are substitutes. Thus, $\epsilon \in (1, \infty)$, or equivalently, $\rho \in (0, 1)$.

The necessary conditions for dirty and clean energy, and CCS at a maximum is

$$\begin{aligned} & u'(q^*)\left(\frac{q^*}{q_d^*}\right)^{1-\rho} = c_d + \xi h'(\xi q_d^* - q_a^*) - \mu, \\ & u'(q^*)\left(\frac{q^*}{q_d^*}\right)^{1-\rho} = c_c, \\ & h'(\xi q_d^* - q_a^*) - \mu = c_a - \nu_a, \end{aligned} \tag{11}$$

where

$$q \equiv \left({q_d}^{\rho} + {q_c}^{\rho}\right)^{\frac{1}{\rho}},$$

and μ and ν are the multipliers associated with the CCS constraints $q_a \leq \xi q_d$ and $q_a \geq 0$, respectively.

The optimal values for the clean and dirty carriers can be calculated as

$$\begin{aligned} & q_d^* = u'^{-1}\left[\left(1 + \kappa^{-\frac{\rho}{1-\rho}}\right)^{-\frac{1-\rho}{\rho}} c_c\right]\left(1 + \kappa^{\frac{\rho}{1-\rho}}\right)^{-\frac{1}{\rho}} \qquad \text{and} \\ & q_c^* = u'^{-1}\left[\left(1 + \kappa^{-\frac{\rho}{1-\rho}}\right)^{-\frac{1-\rho}{\rho}} c_c\right]\left(\kappa^{-\frac{\rho}{1-\rho}} + 1\right)^{-\frac{1}{\rho}} \end{aligned} \tag{12}$$

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[14] CES production function is frequently used in the relevant literature.

where

$$\kappa \equiv \frac{c_d + \xi(h' - \mu)}{c_c} \tag{13}$$

As $\rho < 1$, the share of both clean and dirty energy carriers in the total energy mix are strictly positive.

Taking a look at the effect of the cost of the clean energy on the demand for fossil fuels, and with it the CCS, one can calculate the following:

$$\frac{\partial q_d^*}{\partial c_c} = m(\epsilon - \sigma) \tag{14}$$

where

$$m = \frac{q_d q_c}{u' q^{1-\rho}} > 0 \quad \text{and} \quad \sigma = -\frac{u'}{u'' q}. \tag{15}$$

For $\epsilon > \sigma$, a higher price of clean energy leads to a higher demand for fossil fuel energy. This follows from the fact that a quasi-linear utility function over energy consumption and a numéraire commodity is considered. Accordingly, when the unit price of clean energy increases, the sign of the change in dirty energy depends on the difference between the elasticity of substitution between the dirty and clean carriers, ϵ, and the rate of substitution between energy generation and single composite commodity, σ. If $\epsilon > \sigma$, it is beneficial for the society to use more fossil fuels in the energy mix. If $\epsilon < \sigma$, however, it is optimal to decrease energy generation and spend more on the numéraire commodity.[15]

Considering that there is partial CCS, that is, $0 < q_a^* < \xi q_d^*$, one can demonstrate that

$$\frac{\partial q_a^*}{\partial c_c} = \xi \frac{\partial q_d^*}{\partial c_c},$$

and, thus,

$$\frac{\partial q_a^*}{\partial c_c} = \xi m(\epsilon - \sigma).$$

Similarly, an increase in the cost of clean energy increases the demand for CCS when the elasticity of substitution between the energy carriers is bigger than the rate of substitution between energy and the numéraire commodity.

As a result, when the price of the clean energy increases, the demand for the dirty carriers and with it CCS will increase only if both carriers are sufficiently substitutable. Otherwise, to avoid an increasing energy bill, it will be optimal to consume more of the numéraire commodity, which is money or bundle of all other goods that are reduced to a single composite commodity. Conversely, if the price of clean energy goes down, the demand for dirty energy will decrease when, again, the degree of substitutability between the two inputs of energy is sufficiently high. Otherwise, the demand for the dirty carriers

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[15] One can calculate that $\partial q_c / \partial c_c < 0$.

	Both energy carriers are sufficiently substitutable: $\boldsymbol{\epsilon > \sigma}$	**Both energy carriers are not sufficiently substitutable:** $\boldsymbol{\epsilon < \sigma}$
Unit price of clean energy ↗	Demand for fossil fuel energy with CCS ↗ Demand for clean carriers ↘	Demand for all energy carriers ↘ Spending on the numeraire commodity* ↗
Unit price of clean energy ↘	Demand for fossil fuel energy with CCS ↘ Demand for clean carriers ↗	Demand for all energy carriers ↗ Spending on the numeraire commodity ↘

*Numéraire commodity is an economic term that represents money or bundle of all other goods that are reduced to a single composite commodity, that is, the numéraire.

Table 1: *Competition against clean energy carriers: demand for fossil fuel energy with CCS*

will increase as the numéraire will be demanded less. The discussion and results thus far are presented in Table 1.

To the best of my knowledge, I am not aware of this discussion in the (relevant) studies that are confined to a partial equilibrium framework. This is because, such studies frequently employ the CES formulation when ρ (ϵ) is equal to 1 (infinity), and therefore, assume that the dirty and clean carriers are perfect substitutes (see Chakravorty et al. (2006) and the literature which builds on this study). This limiting case is considered in the following.

When $\rho = 1$, the production function is represented by the following linear form:

$$q = q_d + q_c. \tag{16}$$

At optimum, when the unit cost of generating RE is sufficiently high, that is, $c_c > c_d + \xi\tau$, it will not be optimal to generate energy from renewable sources. This can be calculated by taking the left-sided limit of Eq. (12). The problem will then be identical to the one in Section 3. Fossil fuel energy, accordingly, will be complemented with CCS when the unit cost of using the CCS is sufficiently low ($\tau \geq c_a$). If the unit cost of clean energy generation is such that $c_d + \xi c_a < c_c < c_d + \xi\tau$, the renewable sources will still not be employed while all the CO_2 emissions will be captured.

On the other hand, when the cost of generating energy from renewable sources is sufficiently low, it will be optimal to use only the clean energy source (or both the clean energy source and fossil fuels). In particular, if $c_c < c_d + \xi\tau \leq c_d + \xi c_a$ or if $c_c < c_d + \xi c_a \leq c_d + \xi\tau$, energy energy will only be generated from the clean sources. Thus, $q_c^* > 0$ and $q_d^* = 0$. As no energy will be generated from fossil fuels, there will be no CCS: $q_a^* = 0$. If, however, $c_c = c_d + \xi\tau$, both the renewable sources and fossil fuels will be used to generate energy. Yet, if the Pigovian tax on the CO_2 emissions is lower than the unit cost of CCS ($\tau < c_a$), fossil fuel energy will not be complemented with CCS. On the contrary, if $c_c = c_d + \xi c_a \leq c_d + \xi\tau$, all technologies will be employed. Alongside RE, there will be partial CCS if $c_a = \tau$, or all flow of emissions will be captured if $c_a < \tau$. Table 2 presents a summary of these results:

	$\tau < c_a$	$\tau \geq c_a$
$c_c > c_d + \xi\tau$	Fossil fuel energy only	Fossil fuel energy with CCS
$c_c > c_d + \xi c_a$	Fossil fuel energy only	Fossil fuel energy with CCS
$c_c < c_d + \xi\tau$	Clean carriers only	$c_d + \xi c_a < c_c$: Fossil fuel energy with CCS $c_c < c_d + \xi c_a$: Clean carriers only
$c_c < c_d + \xi c_a$	$c_d + \xi\tau < c_c$: Fossil fuel energy only $c_c < c_d + \xi\tau$: Clean carriers only	Clean carriers only
$c_c = c_d + \xi\tau$	Both dirty and clean carriers carriers carriers	$c_c = c_d + \xi c_a$: Both dirty carriers (with CCS) and clean carriers $c_d + \xi c_a < c_c$: Fossil fuel energy with CCS
$c_c = c_d + \xi c_a$	Fossil fuel energy only	Both dirty carriers (with CCS) and clean carriers

Table 2: *Summary of the results when energy carriers are perfectly substitutable ($\rho = 1$)*

As the final analysis and Table 2 demonstrate, the demand for CCS is not only influenced by the environmental policy, its cost and the cost of fossil fuel energy generation, but also the cost of generating the alternative clean energy. CCS will not be demanded if the cost of generating fossil fuel energy that is complemented with CCS is more expensive on the margin. However, if doing CCS is sufficiently cheap, it will be optimal to complement fossil fuel energy with it. In this case, there will be no RE generation.

4 In theory, CCS technologies have a global breakthrough

The literature on the economics of CCS has shown a dramatic progress in the recent years. Taking a long-term and, therefore, dynamic perspective, but mainly evolving around the aforementioned economic drivers, this literature has developed in several directions employing partial *vs* general equilibrium models, theoretical models *vs* numerical solutions to empirically calibrated models, models encompassing exogenous *vs* endogenous technical progress, and models that analyze fossil fuel extraction and demand for clean technologies under optimal (first-best) and under incomplete (second-best) climate policies. This literature mainly addresses the optimal use of the capture technology at point sources and, thereby, abstracts from geo-engineering where carbon is captured from the atmosphere.[16]

Before delving into the recent literature on the economics of CCS, Table 3 summarizes the key findings in the literature and presents the modeling frameworks utilized, technological

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[16] As an exception, the reader is referred to Amigues et al. (2014).

specificities and types of the climate policies considered, and climate damage specifications adopted. Because of limited space, the table is brief. For other studies as well as more detailed presentations and discussions, a closer inspection of this section is necessary.

4.1 Partial equilibrium models

Ayong Le Kama et al. (2013) study the optimal carbon capture and storage policy (in a deterministic world). The authors consider a one good (i.e., fossil fuel energy) economy where the final good is obtained from the extraction of a finite resource. Consumption of the fossil fuel energy generates CO_2 emissions and environmental damage. The study first investigates the social planner problem. Considering a CRRA utility function, a linear damage function, a CCS cost function that is quadratic, and limited carbon storage capacity (i.e., the CO_2 storage is limited by the physical capacity), CCS achieves its peak right from the start, and gradually declines toward 0.[17] The authors verify that the optimal amount of fossil fuel energy is an increasing and convex function of CCS (cf. Eq. (9) in the previous section). In a decentralized setting, the study then computes the extraction and CCS rates associated with the optimal environmental policy (i.e., first-best carbon tax), interest rate and fossil fuel price.

Ayong Le Kama et al. employs a damage function such that the damage due to CO_2 emissions adversely affects the social welfare.[18] Quite a few other studies have also followed this mainstream approach; e.g., Van Der Ploeg and Withagen, 1991; Hoel and Kverndokk, 1996; Van der Ploeg and Withagen, 2012; Acemoglu et al., 2012; Ayong Le Kama et al., 2013; Durmaz and Schroyen, 2013; Moreaux and Withagen, 2015. Instead of using a damage function, Chakravorty et al. (2006, 2008); Lafforgue et al. (2008); Amigues and Moreaux (2013); Amigues et al. (2014); Gerlagh et al. (2014); Kollenbach (2015) and Amigues et al. (2016) set a threshold on the accumulated pollution stock. This critical threshold is often referred to as ‘ceiling’ or ‘carbon cap,’ beyond which a catastrophe takes place (Moreaux and Withagen, 2015). The damages, accordingly, are negligible as long as the CO_2 in Earth’s atmosphere remain below the carbon cap but cataclysmic when the ceiling is exceeded.

Following the route pioneered by Chakravorty et al. (2006), Lafforgue et al. (2008) consider an economy where energy can be supplied by an exhaustible and dirty non-renewable, and an abundant clean renewable resource. The two energy sources are perfect substitutes and all marginal costs are assumed constant, with the marginal cost of solar energy assumed to exceed that of fossil fuel energy (with CCS). Captured CO_2 can be stored in various reservoirs ranked by strictly increasing order of costs. Different than in Ayong Le Kama et al. (2013) where there is a damage function of emissions, accumulation of pollution is constrained by a carbon cap.

The results indicate that it is only optimal to have CCS at the ceiling phase during which the use of the CCS allows for the relaxation of the carbon cap constraint on the fossil fuel use.

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[17] The authors provide the condition guaranteeing that the carbon reservoir will be filled in time.

[18] The appealing features of employing a damage function can be found in Moreaux and Withagen (2015).

	Modeling		Technology		Climate Policy		Damage Specification		
	Partial Eq.	General Eq.	Tech. Change	No Tech. Change	Optimal climate policy	Incomplete Climate Policy	Damage Function	Carbon Cap (Ceiling)	Findings
Ayong Le Kama et al. (2013)	✓			✓	✓		✓		•Study on optimal CCS policy •CCS achieves its peak right from the start of the implementation of the climate policy •Fossil fuel energy is an increasing and convex function of CCS
Lafforgue et al. (2008)	✓			✓	✓			✓	•CCS only optimal at the ceiling phase •Due to exhaustibility and scarcity rents, fossil fuels replaced by renewables eventually
Goulder and Mathai (2000)	✓		✓ (R&D, LbD)		✓		✓	✓	•Technological change in CCS lowers the time profile of optimal carbon tax •R&D efforts postpone some abatement activity to the future •The impact of LbD on the timing of abatement is ambiguous
Amigues et al. (2016)	✓		✓ (LbD)		✓			✓	•Study on optimal timing of CCS • High cost of solar implies it may not be used prior to the exhaustion of coal •CCS introduced at the ceiling •LbD leads to non-monotonous energy price and CCS dynamics during the ceiling phase •Eventually, economy enters the solar power phase accompanied with constant energy price
Gerlagh and van der Zwaan (2006)		✓	✓ (LbD)		✓			✓	•Use of carbon tax revenue as a subsidy for non-fossil energy use produces the least costly policy mix •Subsidization of RE use is the most expensive policy •Nearly half of new fossil fuel capacity complemented with CCS from 2050 onward
Grimaud et al. (2011)		✓	✓ (R&D)		✓	✓	✓	✓	•Optimal outcome calls for continuous increase in R&D favoring development of RE •When carbon cap is stringent, CCS R&D spending increases dramatically •This is because CCS is the cheapest mid-term mitigation alternative
Grimaud and Rouge (2014)		✓	✓ (R&D)		✓	✓	✓		•Greatest effort in CCS should be made today •Resource extraction rises with CCS •While an increase in second-best (SB) carbon tax delays resource extraction/emissions, an increase in CCS subsidy achieves the opposite •An increase in SB tax fosters economic growth in the long run, but CCS subsidies lead to the opposite outcome
Hoel and Jensen (2012)	✓			✓	✓	✓			•When emissions are optimally taxed, a lower cost of RE reduces carbon tax and energy prices but fossil fuel extraction and early emissions increase (green paradox) •A drop in non-energy cost of CCS lowers emissions tax •If policymakers can only commit to a future climate policy, a decrease in non-energy cost of CCS also lowers energy price and early emissions
Kalkuhl et al. (2015)		✓	✓ (LbD)		✓	✓		✓	•When carbon tax is less than optimal, the study considers a CCS policy that limits emissions by only subsidizing the CCS sector •CCS policy leads to more extraction, higher extraction costs and scarcity rents •Larger scarcity rents cause high RE deployment than under an optimal carbon price •CCS activity increases until 2050 after which RE begins to replace fossil fuels

LbD and R&D stand for learning-by-doing and research and development, respectively, and denote the source of technical progress. Climate policy is incomplete when optimal policies cannot be implemented. Several studies a damage function to mimic the adverse effects coming from CO_2 emissions. Other studies set a threshold (carbon cap/ceiling) on atmospheric CO_2 beyond which a catastrophe occurs.

Table 3: *Summary of the key findings in the literature*

During this phase, the geological reservoirs are never filled up simultaneously and are used by the order of their unitary costs, the one with the lowest unitary cost to be used first. This phase is then followed by another ceiling phase with no CCS. Due to the finiteness of fossil fuels, the scarcity rent grows at the discount rate while the fossil fuel energy consumption continues to decrease. This eventually leads to a subsequent phase where pollution gets lower than the natural regeneration rate. This pure Hotelling path where the cost of generating fossil fuel energy resumes to rise eventually comes to an ultimate end when the unitary cost of RE becomes lower.

4.1.1 Technological Change

An early contribution to this literature is by Goulder and Mathai (2000) who develop a partial equilibrium model to investigate the optimal trajectories of abatement activity and carbon taxes under endogenous technical change. Both analytically and through numerical simulations, the study shows that endogenous technical progress in augmenting the CCS activity (what they call "induced technical change" or the possibility of reducing the cost of abatement through devoting resources to research and development–R&D) lowers the time profile of optimal carbon taxes. Furthermore, R&D efforts shift some abatement activity from the present to the future.

Amigues et al. (2016) is mainly concerned with the optimal timing of CCS use relative to other clean energy sources when a carbon cap is present, and there are potential cost reductions coming from capacity increments, that is, coming from LbD. The study also scrutinizes the effects of LbD in CCS technology on the social cost of carbon and energy price dynamics. Amigues et al. consider two types of fossil fuel energy generation technologies. The first one is the conventional type that leads to releases of CO_2 into the atmosphere. The second option involves CCS and, thus, does not lead to CO_2 emissions. While the previous technique is referred to as 'dirty' coal, the latter is called 'clean' coal. Producing the clean coal is more expensive. This is because, in addition to the extraction cost of coal, the clean coal production involves the cost of CCS. The unit cost of CCS is assumed to depend on the amount of historically cleaned fossil fuel energy. Accordingly, a larger level of clean coal production, which leads to learning effects, results in a lower unit cost of CCS.[19] Moreover, coal is scarce, and therefore, the use of both the clean and dirty coals leads to scarcity effects. The third source of energy is renewable solar energy. All three types of energy are perfect substitutes (cf. Eq. 16). To focus on the relative competitiveness between clean coal and solar energy, the authors restrict the analysis to cases where clean coal is exploited along the optimal path.

The results indicate that both clean coal and solar energy are never exploited simultaneously, and prior to the ceiling phase. During the ceiling phase, the level of dirty coal is determined by the rate of natural decay of the pollution stock. This ensures that the ceiling constraint is not violated. During a ceiling phase where dirty coal is used alongside with clean coal, energy price and use of clean coal can exhibit non-monotonous dynamics.

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[19] Compare this to the formulation of the unit cost of CCS in Section 3.2.1.

When the cost of solar power is sufficiently high, solar energy is never produced prior to the exhaustion of coal. Hence, the timing and amount of clean coal only depends on the marginal cost of the dirty coal, which is composed of the marginal cost of extraction, scarcity rent and social cost of pollution. Accordingly, CCS is introduced at the beginning of the ceiling phase when the unit cost of clean coal is smaller than the energy price that would arise when only dirty coal is used during a ceiling phase. In the absence of LbD, the full marginal cost of clean coal and, in turn, energy price rises while clean coal production decreases. The rise in the energy price arises from the finiteness of fossil fuels which creates a Hotelling price effect.[20] Since dirty fossil fuel is an input into clean fossil fuel production, the scarcity effect leads to a lower use of the clean coal. If the potential of learning is high, however, energy price (clean coal production) decreases (increases) before having to increase (decrease) again. In this case, LbD effect initially leads to a reduction of full marginal cost of clean coal until eventually being dominated by the Hotelling effect.[21] The economy optimally stops producing clean coal prior to the end of the ceiling phase, and resumes using dirty coal until all coal is exhausted. Ultimately, the economy enters a permanent phase where only solar power is generated, and thus, energy price is constant.

The authors also investigate the case where the cost of solar power can be low enough to allow for solar power at a ceiling phase. When the marginal cost of solar power is smaller than the full marginal cost of clean coal, there is no clean coal production once the economy attains the ceiling phase. The continuous decline in the unit cost of clean coal before its use, nevertheless, allows for a subsequent phase of CCS only to be replaced by a phase of solar energy later on. This phase, during which both dirty coal and solar energy are simultaneously exploited, ends when the fossil resource is exhausted and is followed by a phase where only solar energy is generated. On the other hand, unless the unit cost of solar power is lower than the full marginal cost of clean coal, clean coal is used once the cumulative emissions reach the carbon cap. As the Hotelling effect eventually dominates the learning effect, clean coal loses its competitiveness when its full marginal cost becomes higher than the marginal cost of solar energy.

4.2 General equilibrium models

This part of the literature mainly encompasses models that explicitly account for technological change. Therefore, in the following, the survey will focus on studies that encompass technological change.

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[20] A Hotelling price effect means that the marginal social value of fossil fuels grows at the discount rate as long as the resource is not exhausted.

[21] Full marginal cost of clean coal production includes marginal cost of extraction, scarcity rent, cost of CCS and learning rent.

4.2.1 Technological Change

Gerlagh and van der Zwaan (2006) use a top-down computable general equilibrium model with an environment module to which they append a CCS sector. Technical progress in this sector stems from LbD. Assuming a marginal cost of abatement of $45 per tonne CO_2 avoided, they compute the carbon emission trajectories for 30 five-year periods (2000–2150) under five stabilization targets (ranging from 450 to 550 ppm–particles per million) and five policy scenarios in addition to a business-as-usual scenario. Their results reveal that irrespective of the stabilization target, subsidization of RE use is the most expensive policy, while a carbon emission tax in which revenue is recycled as a subsidy for non-fossil energy use represents the least costly policy mix. A carbon tax also dominates a policy that charges fossil fuel use since such a policy incentivizes the use of CCS activity. While CCS activity is low to begin with, about 30–50% of new fossil fuel capacity from 2050 onwards is complemented with CCS equipment.

Grimaud et al. (2011) extend the Goulder and Mathai (2000) framework to a general equilibrium setting, and develop an endogenous growth model in which energy services can be produced from polluting non-renewable fuels and renewable sources of energy. CO_2 can be captured by the use of the CCS technology. R&D investments can be directed at increasing the efficiency of energy use in final good production, the efficiency of RE, or the efficiency of CCS. Because fossil fuel energy is polluting, and technological change is subject to various market failures, the authors introduce two kinds of economic policy instruments: an environmental tax on CO_2 emissions; and research subsidies on R&D activities. The study then derives the levels of the carbon tax and R&D subsidies, implementing the first-best optimum.[22] The first-best outcome calls for a continuous increase in R&D budgets, favoring the development of the clean backstop technologies. When a stringent carbon cap is introduced, the share of CCS R&D spending in the total R&D budget increases dramatically. This is because CCS constitutes the cheapest mid-term mitigation alternative. The more stringent the carbon target, the higher becomes the amount the resources allocated to CCS R&D.

In Grimaud and Rouge (2014), endogenous growth is restricted to the final goods industry. Final output makes use of intermediate goods (embodying technology), labor, and the extracted amounts of a non-renewable energy resource. The use of energy in production causes emissions that can be captured and stored using labor. With a constant and inelastic labor supply, the main trade-off in their model is between output production and abatement. The authors characterize the socially optimal trajectories with and without access to CCS. It is shown that the amount of labor devoted to CCS activity is a constant proportion of resource use, and in turn, emissions. Because resource extraction diminishes over time, the CCS activity also decreases. This indicates that the greatest effort in CCS should be made today. The use of the CCS technology alters the socially optimal trajectories. In particular, CCS causes the pace of resource extraction to increase because CCS relaxes the

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[22] In the paper, a (multiplicative) net-of-damage function links final consumption and, in turn, welfare, to the climatic conditions. The motivation for the use of research subsidies is that investors can only capture a fraction of R&D returns in the economy.

environmental constraint. Although CO_2 emissions decrease in the long run, the short-run emissions are higher. This outcome is due to the fact emissions are partially compensated by CCS. Moreover, the availability of the CCS technology reduces the socially optimal output growth, since, the resources (labor) that would be employed for doing R&D, and contribute to the accumulated level of knowledge in the economy, is employed for resource extraction, which rises with CCS.[23] Lastly, as there are three basic market failures in this economy coming from the environmentally damaging emissions, public good character of knowledge, and monopolistic structure of the intermediate sector, the first-best economic policy can be implemented by levying a tax on emissions, subsidizing to the use of intermediate goods, and subsiding R&D.

4.3 Incomplete climate policies

The contributions above assume that a first-best climate policy can take place. Nevertheless, in reality, such a comprehensive policy has yet to be attained. Examples include the recent withdrawal of United States from the Paris Agreement, a non-binding Copenhagen accord which merely recognized the scientific case for keeping temperature rises to no more than 2°C, to name a few. Furthermore, policies that are intended to reduce fossil fuel use, and flatten the time profile of carbon emissions, would lead to a paradox when they induce a steeper extraction profile. Hans-Werner Sinn identifies this phenomenon as ‘green paradox,’ argues that such a paradox occurs when demand-reducing policies become more stringent over time (Sinn, 2008). Furthermore, policies that stimulate the development of low carbon energy technologies can lead to a similar outcome since fossil fuel producers may anticipate a future reduction in demand, and therefore, increase their current production. Such adverse outcomes call for second-best solutions (Grimaud et al., 2011). Subsequently, another line of research has emerged, analyzing the fossil fuel extraction decisions and the demand for clean technologies under incomplete climate policies.

While the green paradox discussion is rigorously facilitated by studies, such as Gerlagh (2011) and Van der Ploeg and Withagen (2012), Hoel and Jensen (2012) particularly focus on the market outcomes of reductions in the cost of CCS and RE technologies under imperfect climate policies. The authors employ a simple two-period model. In the first period, CCS and RE energy are not available, and energy can only be generated by burning fossil fuels, leading to CO_2 emissions and climatic damages. In the second period, fossil fuel energy can be complemented with CCS, and RE can perfectly be substituted for the conventional fossil fuel energy. When emissions are optimally taxed in both periods, the results indicate that a lower cost of RE lowers the carbon tax, and the consumers benefit from lower energy prices in both periods. Nevertheless, the level of fossil fuel extraction increase and early emissions rise.[24] While a change in the non-energy cost of CCS has no effect on the energy price and the level of early emissions, it lowers the tax. If policymakers can only commit to a future climate policy, the effects of a cost reduction in RE stay the same. When the non-energy cost

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[23] Such an outcome can also be observed in growth models with renewable resources (Smulders and Gradus, 1996; Durmaz and Schroyen, 2013).

[24] The same outcomes hold when the energy penalty of CCS decreases.

of CCS decreases, however, the authors show that the energy price, tax, and early emissions decrease. Further results indicate that the early extraction of fossil fuels in time may make a technological improvement in CCS and, thus, a reduction in the cost of CCS, more desirable than a cost reduction in RE.

When the carbon tax cannot be imposed at its Pigovian level, Grimaud and Rouge (2014) consider second-best policies, such as a second-best tax on net emissions, a subsidy to CCS, and a subsidy to labor employed in the CCS industry.[25] The study investigates how changes in these policies (e.g., imposing a second-best carbon tax when there is none, or increasing the second-best carbon tax while keeping it below its first-best alternative) affect the time profile of the resource use as well as the CCS, carbon emissions, R&D and output trajectories. Results indicate that an increase in the second-best carbon tax leads to an additional effort in CCS by diverting more labor away from the R&D industry. Furthermore, the resource price gets higher but increases at a slower pace in time, thereby postponing resource extraction. While an increase in the carbon tax delays resource extraction, increases in the two subsidies accelerate it. Although the increase in the carbon tax decreases short-term carbon emissions, the rise in two subsidies can increase them, yielding a green paradox. Unlike the subsidies, the increase in the tax has a negative impact on the total output and consumption in the short run. Lastly, an increase in the tax generally fosters growth whereas an increase in the two subsidies reduce it. However, when the weight of the CCS sector in the economy is high, these impacts can be reversed.

Extending the model in Kalkuhl et al. (2012a) by an additional fossil energy industry that captures CO_2 emissions, and by a CO_2 transport and storage industry, Kalkuhl et al. (2015) study the welfare implications of various second-best policy instruments. When the carbon tax is fixed at a rate lower than the socially optimal level, the study considers three second-best policies so that the carbon budget is satisfied with the least costs. The second-best policies are a CCS policy that limits emissions by only subsidizing the CCS (fossil fuel) sector; an RE policy that subsidizes RE; a hybrid policy that subsidize both RE and CCS. While the dynamics in welfare losses are similar, the three second-best policies lead to significantly different levels of mitigation costs. The results indicate that the mitigation cost becomes highest for the CCS policy. This is followed by RE policy, and simultaneous RE and CCS policies. As to the impacts on the cumulative emissions, the numerical results indicate that the CCS policy leads to a significantly high amount of extraction for low levels of the carbon tax. While the RE policy leads to the lowest amount of cumulative emissions, the RE and CCS policy lead to cumulative emissions that are in between the former two. In line with intuition, when the carbon tax is constrained further, the CCS policy leads to more extraction and therefore, higher extraction costs and scarcity rents.[26] Interestingly, pure CCS policies can lead to high RE deployment than the level under an optimal carbon price. This is because as CCS subsidies increase fossil resource prices, the relative price of RE in comparison with fossil fuel energy decreases.

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[25] Kalkuhl et al. (2012b) show that under highly stylized conditions, such as large storage capacities and no leakage from CO_2 storage sites, a subsidy to CCS can be an effective alternative to carbon pricing.

[26] For sufficiently low levels of the carbon tax, fossil resource rents can get higher than in the business-as-usual economy for the CCS policy.

As to the time paths of the policies, the CCS subsidies exhibit an inverted U-shape behavior. Accordingly, following a rise for several decades, subsidies decline and even take on negative values in the long run. RE becomes competitive due to the scarcity of the fossil resource, and negative subsidies. On the other hand, RE policy leads to RE subsidies that are roughly constant per energy generation. Moreover, the second-best policies that subsidize energy generation activities lead to substantially lower energy prices by 2050. However, although initially lower, pure CCS policy leads to higher energy prices in the very long run because fossil resources become more expensive due to the accelerated exploitation. The CCS activity increases strongly until 2050, after which RE commences to replace fossil fuels. Additionally, CCS policies induce a flatter emission reduction path, implying lower emissions initially and, therefore, less drastic reductions later on. On the other hand, RE policies lead to higher emission levels in the first period and strong declines subsequently. Lastly, CCS policies, while leading to a reduction in short-term consumption, has a smaller impact on the consumption in the midterm.

In addition to characterizing the first-best optimum, Grimaud et al. (2011) characterizes second-best trajectories for a carbon tax and three R&D subsidies when only one instrument is available. When there are no research subsidies, the carbon tax is shown to follow an increasing trend unless there is a global climate stabilization target. In this scenario, there is a minimal level of CCS and no expenditure on CCS R&D. Furthermore, when two stabilization of CO_2 concentration at 550 and 450ppm are considered, and that, both the carbon tax and R&D subsidies can be used, there is a massive development of CCS and a considerable amount of resource allocation for CCS R&D. In fact, investments in CCS R&D in short– and mid-term become more relevant with stringent stabilization targets. Under these scenarios, carbon tax follows an inverted U-shaped trajectory. While the carbon tax mainly curbs emissions, subsidies incentivize R&D activities.

5 A dichotomy presented: theory and reality

In light of the analyses in Sections 2 and 3, and the literature survey in Section 4, it is evident that we have a rather good understanding of the economics CCS. In particular, when constraints are well defined, a sound discussion as to the bridging role of CCS in the coming decades can be facilitated. It can, nevertheless, be argued that some studies come to very strong conclusions (e.g., there is no CCS until a ceiling phase, or there is RE generation only at or after a ceiling phase when we continually witness record growth rates for various types of renewable energies) that seem rather impractical and to be dependent on modeling assumptions.[27] We, nonetheless, also need to keep in mind that some of these works take a normative approach, and assume that a first-best climate policy can take place. As is discussed, such optimal decisions necessitate comprehensive climate policies which have yet to be made and agreed upon, making it impossible to test those optimal outcomes.

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[27] Amigues et al. (2016) provide an exception in this regard. Considering the case where the marginal cost of solar power is smaller than the full marginal cost of clean coal, it is demonstrated that RE is generated at a ceiling phase. The continuous decline in the unit cost of clean coal owing to LbD allows for a subsequent phase of CCS only to be replaced by a phase of solar energy later on. See p. 20 for further discussion.

The challenges in making comprehensive policies led to a subsequent line of research that analyze fossil fuel extraction decisions and demand for carbon-free technologies under incomplete climate policies (e.g., a carbon tax that is fixed at a lower rate than the socially optimal, and subsidies which are allocated to CCS as well as renewable sources to achieve a carbon cap target). Considering the prescribed circumstances, such studies can be of significant use for policy making when complemented with calibration and numerical simulations.

That being said, even if the optimal combination of second-best policy instruments can successfully be determined, the ongoing failures encountered when integrating the component CCS technologies into large-scale commercial CCS projects can make it impossible to implement these best practices in reality. As was explained earlier in Section 1, CCS has three major components: (CO_2) capture, transportation (of CO_2 in a liquid-like state) and storage. While all these components are in commercial use today by the fossil fuel extraction and refining industries, the biggest challenge thus far has been the integration of component technologies into large-scale commercial CCS projects. Except for the Boundary Dam project in Saskatchewan, Canada, the world's first large-scale application of CCS at a power plant, CCS has not been applied at scale to a large and operational commercial fossil fuel power plant.

Nonetheless, the SaskPower's Boundary Dam CCS project has been plagued with numerous shutdowns that cost \$1 million (C\$1.2 million, where C\$ stands for Canadian dollar) in penalties (Langenegger, 2016). According to the Report of the Office of the Canadian Parliamentary Budget Officer (see p. 40, PBO, 2016), the cost for the Boundary Dam CCS project has come in at \$754 million (C\$917 million –15% higher than originally budgeted). Putting together estimates of revenues and expenditures, the project is expected to generate a loss of \$0.82 billion (C\$1 billion).

Furthermore, the Kemper Project, a lignite plant which will allow for the production of clean energy through the use of integrated gasification combined cycle and carbon capture technologies, has been struggling with delays, most recently, related to the ash removal system (URS Corporation, 2017). As the Report points out, any extension of the in-service date adds around \$30 million a month to the total cost of the project.

Additionally, Norway, the country that once had the ambition to lead the world in carbon capture, dropped its plan to capture CO_2 at a large scale from an oil refinery and gas power plant at Mongstad, following several delays and mounting costs (Van Noorden, 2013). Considering also the fact that at least 10 European power plants postponed its plans to implement CCS in 2015 (Neslen, 2015), it is evident that there are considerable risks associated with costs. As a result, the CCS technology has been facing 'first-of-its-kind risks' to costs and lacks the satisfactory degree of technological maturity.

The ongoing competition between fossil energy complemented with CCS and carbon-free options, such as nuclear, solar, wind, and the ongoing decline in prices for renewable energy technologies, can be seen as another obstacle for CCS. Wind and solar (possibly coupled with storage technologies to tackle intermittency issues) allow power generation without GHG emissions. With an estimated 161 gigawatts (GW), RE generating capacity witnessed its largest annual increase in 2016 and contributed nearly 62% to the net additions to the global energy generating capacity (REN21, 2017).

The limited availability of fossil fuel resources as well as geological carbon sinks are also considered as other setbacks because of scarcity rents, which would cause increases in the unit of CCS.

In overcoming barriers to attaining the scale required for substantial reduction in CO_2 emissions from fossil fuel power, two factors stand out. The first one concerns the carbon policy. As it is already apparent from the discussions in Sections 3 and 4, carbon policy is imperative for CCS. Unless CO_2 emissions are taxed, a coal-fired power plant will have no incentives for using CCS. It will simply release CO_2 into the atmosphere. The same applies if the emission tax is lower than the cost of CCS. It is estimated tax of \$47 (C\$57) per ton CO_2 will be sufficient to undertake CCS, considering that

- \$754 million cost of the CCS component of the project in the Boundary Dam complex will be amortized over 30 years;
- operating cost of the CCS component will be \$8.2 (C\$10) per MWh;
- inflation-adjusted cost of capital will be 3%; and
- net power generation capacity will be 115 MWh (PBO, 2016).

The second factor that stands out is an improved CCS technology that would allow for a successful integration of the three major CCS components at a lower cost. To improve the CCS technology, an important component is LbD. In fact, LbD can reduce costs by approximately \$164 million (C\$200 million) of SaskPower's ongoing CCS activities in the Boundary Dam CCS project. In this case, a \$38.6 (C\$47) per ton CO_2 carbon tax will allow the power company to undertake a CCS project (PBO, 2016). Subsequently, early introduction of CCS, which would allow for significant gains through advancing production practices, can allow for substantial decreases in the cost of the mitigation efforts through LbD.

As to the competition between the energy carriers, the high cost of nuclear energy compared to the costs of fossil fuels render an unlikely threat to the use of CCS. Note also that the public acceptance of nuclear energy has been on decline following the Fukushima Daiichi nuclear disaster. Furthermore, despite the strong advances worldwide and growth in RE technologies, fossil fuels still supply around 80% of all primary energy needs. As total replacement of fossil fuel burning is not expected to take place in the near future, it is unlikely that RE can replace fossil fuel energy –with CCS– in the short run.

Regarding the exhaustibility of fossil fuels, the technically recoverable amounts of gas and coal are, indeed, much higher than the proved reserves.[28] As an example, the U.S. Energy

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[28] According to BP (2016), global proved oil reserves, 1697.6 thousand million barrels in 2015, are sufficient to meet 51 years of production. Roughly, the same holds for natural gas (186.9 trillion cubic meters, which can meet 53 years of current production). For coal, the global reserves-to-production ratio is much higher. With 891531 million tons, world proved coal reserves are sufficient to meet 114 years of global production.

Information Administration (EIA, 2013) estimates that the technically recoverable amount of gas is 579 trillion cubic meters, three times the globally proved oil reserves.[29] Moreover, the ongoing technical progress and discoveries of new fossil fuel reserves have shifted concerns away from the sustainability of growth alongside resource scarcity to climate change and environmental degradation (Heutel and Fischer, 2013; Gerlagh, 2011; Tsur and Zemel, 2011; Krautkraemer, 2005). Therefore, exhaustibility concerns do seem to play a smaller role than before.

Lastly, in the recent years, there has been significant progress in understanding the size and distribution of technically accessible carbon sinks. IPCC (2005) indicates that the amount of CO_2 that is kept in appropriately selected and managed geological reservoirs is very likely to be above 99% over 1000 years. This indicates that the risks associated with geological storage can successfully be addressed through careful storage site selection and by monitoring CO_2. The availability of specific storage sites that can accept CO_2 at large scales can be deemed low because of insufficient level of efforts to identify specific storage sites. Nevertheless, the incentives of the power industry to carry out further exploration works, leading to discoveries of new suitable storage sites, will likely increase once CCS deployment speeds up.

Table 4 summarizes the discussion on the obstacles to CCS deployment in scale.

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[29] Of the recoverable amount, 32% is shale gas.

	Obstacles to CCS Breakthrough
Two factors stand out	**Lack of comprehensive climate (carbon) policies** Challenges in making comprehensive carbon policies call for second-best solutions (incomplete climate policies). Requires optimal second-best policy instruments (i.e., optimal second-best combination of carbon taxes and subsidies) to be determined
	Technological immaturity First-of-its-kind risks to costs. CCS lacks the technological maturity. Integration of component technologies into large-scale commercial CCS projects is a big challenge. To improve the CCS technology, an important component is LbD
Other factors	**Competition - Clean Energy Carriers** RE generating capacity witnessed significant expansion. However, total replacement of fossil fuels (FFs) not expected in the near future. As of today, FFs supply around 80% of the global energy needs. Nuclear energy on decline since the Fukushima Daiichi nuclear disaster
	Exhaustibility Technically recoverable amount of gas and coal much larger than proved reserves. Thus, exhaustibility plays a smaller role than before
	Risks Associated with (Geological) Storage Significant progress in understanding the capacities and distribution of accessible storage sites. Incentives for further exploration and discoveries of new storage sites will increase with CCS deployment

Table 4: *Obstacles to widespread rollout of CCS technology*

6 Conclusion

The literature on the economics of CCS has shown a dramatic progress in the recent years. This progress has led to a better understanding of the factors that affect the demand for the technology, and the impact that the use of CCS can have on carbon policy, and timing of the use of alternative sources, such as renewables. The peculiarity at this point, however, is that, contrary to our enhanced understanding of the economics of CCS, there are still difficulties with integrating component technologies into large-scale commercial CCS projects. CCS's lack of scale, which is necessary for substantial reduction in CO_2 emissions, contradicts the important role of CCS envisioned by several international and intergovernmental agencies. Even though the CCS technology is key to achieve substantial reductions in global CO_2 emissions, why have these technologies not had an international breakthrough, and will it come?

I tried to shed light on these questions by presenting a simple model of energy generation. The simplicity of the modeling allowed me to consider several economic factors that affect the demand for CCS, and connect the results to various studies in the literature. The majority of the results in the literature suggest optimal policies that lead to large-scale deployment of CCS. The fact that this is barely the case in reality allows me to point at two issues: a need for an improved technology, which would allow for a successful integration of the major components of CCS at a lower cost; and a credible carbon policy, which would boost investor confidence when undertaking CCS projects. Addressing these two issues effectively will be crucial in building a global CCS industry that can successfully complement fossil fuel energy in the coming decades.

A few comments are in order about the literature on the economics of CCS. The difficulties in attaining comprehensive policies, which would allow for first-best allocations, led to a subsequent line of research that analyzes fossil fuel extraction decisions and demand for carbon-free technologies under incomplete climate policies. This has been a crucial step forward for the economics of CCS literature. Yet, the technical difficulties in integrating CCS' three major components, which led to spiraling cost of capturing, is setting a significant barrier to CCS deployment. Accordingly, a new line of research that explicitly considers CCS cost uncertainty can deliver valuable contributions to this literature.

One other important component that can be considered when incorporating CCS within economic models is the economic use of captured CO_2. Considering that the captured CO_2 can be sold for EOR, as is the case with the Boundary Dam project in Saskatchewan, which sells CO_2 to an integrated oil company for \$20.5 per tonne, an emission tax of \$26.5 per ton CO_2 would be sufficient to undertake a CCS project (PBO, 2016). (An emissions tax of \$47 per ton CO_2 is sufficient to achieve the same outcome in the absence of EOR.) As a result, investigating the consequences of similar uses of captured CO_2 can generate added value for the literature pertaining to the economics of CCS.[30]

It is true that there is a lack of well-defined regulations concerning short- and long-term responsibilities for storage, concerns about the operational safety and long-term integrity of CO_2 storage as well as transport risks, etc., which must be resolved for the large-scale future deployment of CCS. However, as the focus of the current study is on the economics of CCS, such issues can be better addressed in another study.

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[30] One other possible use is turning CO_2 into fuel, such as ethanol.

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