Essays on investment in Carbon Capture Technology: The Role of Markets, Competitors and Policy

Giorgio Cabrera

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for the examination which has led to the award of a degree.

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Abstract

In this thesis, three different economic models under an industrial organization approach are presented modelling different types of carbon capture technology adoption. The thesis aims to understand the incentives that drive a carbon capture technology decision making at a firm level and develop policy solutions to inform government and policymakers to increase carbon capture technology adoption.

The first model constructed considers a carbon capture and storage (CCS) technology adoption in different competitive environments. The focus is to explore how competition influences a firm's decision toward CCS technology.

The second model investigates the strategic interaction that firms experience in an industry where a firm adopts carbon capture and CO2 utilization (CCU). The model also evaluates the environmental impact of a CCU industry, as a major drawback of final goods produced by CO_2 utilization is the carbon emissions are released back into the atmosphere once consumed in the final goods market. In this chapter, a series of policy solutions are proposed to obtain an increase in the adoption of CCU whilst accomplishing a positive environmental impact.

The third model investigates the optimal CCS adoption decision time of a follower influenced by a learning-by-doing and spillover effect. A follower is a firm that adopts a second-generation CCS technology with a lower production cost caused by a learning effect from a pioneer. A pioneer is a firm that adopts a first-generation CCS technology with a high production cost, and it experiences a learning-by-doing effect. We discover, that if the adoption of CCS technology is sequential, a pioneer is always at an economic disadvantage by adopting first. The main contribution of this chapter recommends a policy solution that balances the adoption cost of a pioneer and a follower, achieving an increase in the diffusion of CCS technology.

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Contents

Chapter 1

Introduction

1.1 Introduction

The increasing use of fossil fuels – i.e., coal, oil, and gas – has steadily increased the emission of carbon dioxide (CO_2) in the earth's atmosphere since the mid-18th century, causing the worldwide phenomenon of global warming. Several studies show that future projections of the average global temperature rise above pre-industrial levels are predicted to reach almost 5.5-degrees Celsius in the long term, and almost 4-degrees Celsius by the end of this century (IEA, 2015b). Such trends could have significant impacts on the natural environment such as reduced crop yields, stressed water resources, changes in precipitation, and higher sea levels (WBG, 2014). The truth is, "*climate change is unequivocally happening*" (IPCC, 2014). Hence, on the 12^{th} of December 2015 at the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, a historical consensus known as the Paris Agreement was established. The main aim of the agreement is to keep the global temperature increase to well below 2 degrees Celsius above pre-industrial levels – the temperature threshold that should avert some of the most severe effects of climate change – and to pursue efforts to limit the increase to 1.5-degrees Celsius (IEA, 2015b; UNFCCC, 2015).

The rise of the Paris Agreement has prompted a surge in research looking for the most effective ways to defeat the warming of the planet. For example, a leading intergovernmental organisation informing about the potential strategies to combat climate change is the International Energy Agency (IEA). The IEA repeatedly publishes two influential reports: *The World Energy Outlook* and *Energy Technology Perspectives*. The two reports provide vital information about future predictions of global emission trends or the scenarios that the world might face ahead. Moreover, the two reports also discuss the different technologies that are going to contribute to achieving the 2-degrees scenario or 2DS (IEA, 2015a). The strategies raised by the IEA range from improved supply and distribution efficiency, fuel switching from coal to gas, nuclear power, renewable heat and power, and combined heat and power targeting the power industry. Amongst the mentioned technologies, the IEA also underlines a pivotal role for carbon capture and storage (CCS) to tackle climate change.

The mitigation strategy of interest in this research is CCS, a technology that achieves a profound reduction in carbon dioxide emissions by targeting large emitting sources such as power plants and industrial processes. The emission reduction potential of CCS adopted in a power generation can reduce emissions by eighty to ninety percent (Kocs, 2017). Similarly, this can be also achieved in multiple industries - i.e., cement, chemical and steel. More specifically, CCS technology is composed of three stages. The first stage of CCS is the capture of carbon dioxide (CO_2), where there are three main carbon capture processes: post-combustion, pre-combustion, and oxyfuel combustion. Post-combustion systems separate CO_2 from the flue gases produced by the combustion of a primary fuel (i.e., coal, natural gas, oil, or biomass) in the air. Oxy-fuel combustion uses oxygen instead of air for combustion, producing a flue gas that is mainly H_2O and CO_2 and which is readily captured. The pre-combustion system processes the primary fuel in a reactor to produce separate streams of CO_2 for storage and H_2, which is used as fuel (IPCC, 2005). The second stage of CCS technology is the transportation of the CO_2 gas which links the emitting source to the last stage, the injection of CO_2 into an underground facility for permanent storage.

Despite there being many different greenhouse gases emitted to the atmosphere – i.e., methane, nitrous oxide, fluorinated gases, etc – the most attention given is the release of carbon dioxide or CO_2 into the atmosphere. The reason for this is because CO_2 not only is the most abundant greenhouse gas emitted by human activity but also, it is the greenhouse gas that remains in the atmosphere longer than the other major heat-trapping gases emitted as a result of human activities. For example, after a pulse of CO_2 is emitted into the atmosphere, 40% will remain in the atmosphere for 100 years and 20% will reside for 1000 years, while the final 10% will take 10,000 years to turn over. Whereas gases like methane (CH_4) take about a decade to leave the atmosphere (before converting into CO_2) and about a century for nitrous oxide (N_2O).[1]

In economics, pollutants such as carbon dioxide, methane, nitrous oxides, or any other greenhouse gas emissions are called negative externalities. A negative externality is an economic activity that imposes a negative effect on an unrelated third party[2]. A concept that was first developed by economist Arthur Pigou in 1933. Pigou argued that a tax, equal to the marginal damage or marginal external cost, (later called a "Pigouvian tax") should be imposed to offset the impact of negative externalities to reduce their incidence to an efficient level (Pigou, 1933). With the introduction of these concepts by Pigou subsequent thinkers have then debated the efficacies of taxes to regulate negative externalities. Nowadays, many researchers have developed many negative externality models that are critical learning components in introductory microeconomic and environmental economics courses. In particular, many of these models understand the effects of negative externalities in different competitive environments. In particular, studies that are important for this thesis are for example studies by Mills and Smith (1996), Elberfeld (2003), Elberfeld and Nti (2004), Pal (2010) or Zhu and Weyant (2003) who all address the environmental pollution as a negative externality whilst there is decision on-going for environmental technology adoption. A usual outcome from these studies offers many nuances for policy design to achieve the most optimal social outcome.

A real-world example of policy design addressing the nuances of negative externalities of pollution, in particular addressing carbon dioxide emissions, was the adoption of the European emission trading system (EU-ETS) implemented in Europe[3] or the various carbon dioxide taxes adopted worldwide. The design of these policies is intended to redress economic injustices or imbalances created by the negative

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[1] Why Does CO2 Get More Attention than Other Gases? | Union of Concerned Scientists. https://www.ucsusa.org/resources/why-does-co2-get-more-attention-other-gases. Accessed 28 Mar. 2022.

[2] Volokh, Alexander. "Externalities." The Encyclopaedia of Libertarianism, SAGE; Cato Institute, 2008, pp. 162–63, https://books.google.com/books?id=yxNgXs3TkJYC.

[3] In Great Britain, the Carbon Price Floor (CPF) is currently capped at £18 per tonne of CO2 and the EU ETS sits at around £5 t/CO2– meaning power generators and heavy industry pay around £23 t/CO2 altogether. When initially formulated by the coalition government in 2010, it was intended the CPF would reach £30 per tonne by 2020 and £70 per tonne by 2030. However, the EU ETS has since fallen therefore the UK government chose to cap the carbon price support at £18 per tonne until 2020.

externalities. A successful story that has implemented a carbon dioxide tax and increased the use of CCS technology is the country of Norway. In 1991, Norway introduced a carbon tax, which is roughly equivalent to €60 per tonne of CO_2 emitted. The Norwegian carbon dioxide tax is exceedingly high price and has led Norway to be one of the leading countries for CCS technology who has implemented the world's first commercial CO2 storage project known as the Sleipner Project. Norway is seeking to more than triple its tax on carbon dioxide by 2030, increasing its charge for a ton of emitted CO2 equivalents from €60 to €200.[4] However, despite the success story in Norway, not all policy systems had led countries to achieve large emission reductions. For example, the EU-ETS adopted in Europe was at an average of €7 per tonne of CO_2 emitted in 2015-2018.[5] With these CO_2 prices, the EU-ETS does provide the large immediate emission reduction as promised. Overall, the truth is that with the current state of the economy and policy implementation, but also where CCS technology is at the moment, to reach the full mitigation potential of CCS technology requires stronger environmental policies. Hence, in this thesis, we understand the policies required to increase the adoption of CCS technology. Furthermore, another reason for focusing on CCS technology adoption is because certain industrial processes in the industrial sector have no other abatement options but to adopt CCS technology. Many industrial processes require very specific chemical or industrial methods which cannot be altered (Psarras et al., 2017). The adoption of CCS technology is of extreme importance for certain industries in the industrial sector to continue to be viable and bring economic benefits.

According to the IEA, CCS has the potential of contributing up to 14% of cumulative CO_2 emission reductions by 2050 to reach a 2DS world compared to the business-as-usual scenario or 6DS[6] (IEA, 2017). This is equivalent to 94 gigatons (Gt) of carbon dioxide captured in the period to 2050, with around 55% of this (52 Gt) in the power sector and 42 Gt in industrial applications and fuel transformation (WCA, 2017). The adoption of CCS technology not only provides an environmental improvement but is

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[4] "Norway Proposes €200 per Ton CO2 Tax by 2030." Bellona.Org, 10 Feb. 2021, https://bellona.org/news/ccs/2021-02-norway-proposes-e200-per-ton-co2-tax-by-2030.
[5] An emissions trading case study - IETA. (n.d.). Retrieved April 4, 2022, from https://www.ieta.org/resources/Resources/Case_Studies_Worlds_Carbon_Markets/euets_case_study_may2015.pdf
[6] Business-as-usual scenario where no mitigation strategies or efficiencies are adopted.

also widely recognised as a necessary part of the portfolio of measures required to meet climate change mitigation targets cost-effectively (Townsend, 2018). Recently, the Intergovernmental Panel on Climate Change (IPCC) has stated that global mitigation costs are 138% higher without CCS power plants. Furthermore, the Low Carbon Innovation Coordination Group (LCICG) has also estimated in the UK that fully integrating CCS technology into the nation's energy system can potentially reduce costs between 2010 and 2050 by £100–500 billion (Heuberger et al., 2016).

Other benefits of investing in CCS technology include reducing the decommissioning cost for the oil and gas sector. CCS technology can use existing infrastructure that would otherwise be decommissioned. A recent study conducted by the University of Edinburgh investigated the use of Beatrice oilfield, 15 miles off the northeast coast in the outer Moray Firth, for CO_2 storage purposes (Scafidi and Gilfillan, 2019). The study found that under a simulation of over 30 years, using the field and its infrastructure as a carbon capture and storage site would be around ten times cheaper than decommissioning, which is expected to cost more than £260m. Furthermore, CCS technology has other broader economic benefits such as creating more jobs in the construction, operation, and maintenance of the CCS facility and the plant at which it is applied. A typical CCS project is estimated to need 2,500 employees in the construction and 200-300 employees in the operation and maintenance of the facility. Finally, the development and deployment of new technologies like CCS can generate knowledge and stimulate innovation, which has long been identified as a major source of economic growth.

Despite the clear environmental and future economic potential of the adoption of CCS technology, "*the pace is well below the level required for CCS to make a substantial contribution to climate change mitigation*" (GCCSI, 2013). The current state of CCS technology only has roughly 31 million metric tons per year of anthropogenic carbon dioxide that is captured and injected into geological formations for permanent storage. While studies estimate that 200–1,000 Mt per year will be required by 2030 and 5,000–10,000 Mt per year by 2050 to reach the Paris Agreement (Edwards and Celia, 2018). The slow deployment of CCS technology is due to the many barriers that it faces such as its extremely high costs, technological uncertainties, immaturity of markets and incentives, the absence of political propellant, and also the fact it is a complex value-chain needing collective action from relevant parties (Bowen, 2011; Davies et al., 2013); Budinis et al. (2018); (Ye et al., 2019). Overall, CCS projects are complex system (Sara et al., 2015),and there are still significant uncertainties in technical, economic, political and financial and other aspects of CCS. The challenge is to assess how the current uncertainties could come to be reduced, managed, or adapted to, and how technological viability could come about through innovation processes (Markusson et al., 2012). Amongst all, the cost of CCS has been identified as the major barrier preventing the widespread of CCS technology. In other words, another barrier to CCS technology is that it is not a profitable strategy or decision for a firm to adopt technology as it will incur no revenue. Given this most studies in CCS literature have been focusing on estimating the actual costs of CCS, or in other words, investigating the economics of CCS. According to the Grantham Institute for Climate Change from LSE, the economics of CCS: "*refers to the barriers and drivers of the uptake of CCS which are related to capital and operating expenditure, the costs of financing construction and operation, and the effect of CCS on revenue streams*" (Hills and Fennell, 2014). The significant strand of literature addressing the economics of CCS is mainly investigated in four different aspects: cost analysis, project planning, investment, and operational decisions which are discussed in the next section.

1.2 Existing Literature on the Economics of CCS

The existing research on the economics of CCS deployment is analysed mainly through three different aspects: cost analysis, project planning, investment and operation.

The cost analysis of CCS technology is an important work to uncover improvements and cost reductions for CCS technology. The cost analysis of CCS is mainly investigated through a techno-economic assessment (TEA), which according to Arno W. Zimmermann et al. (2020b) is defined as: "*a methodology framework to analyse the technical and economic performance of a process, product or service and includes studies on the economic impact of research, development, demonstration, and deployment of technologies quantifying the cost of manufacturing and market opportunities".* Overall, CCS investigations through a TEA framework provide a good understanding of the cost components of CCS, the structure of the costs and the technological uncertainty connected to the estimation of these costs.

CCS studies under TEA can be distinguished into two groups: (a) the analysis of single CCS component structures – i.e., capture, transport, and storage; (b) the investigation of CCS as a fully integrated system. In the group of the individual components of CCS, the most studied individual CCS component is the carbon capture process. The reason for this is that the carbon capture process in the power industry represents the highest accumulated potential emission abatement. The cost estimate that researchers use to compare the different technologies available in the power industry is called the Levelized cost of electricity (LCOE). According to the Global CCS Institute: "*LCOE is the present value of costs per unit of electricity generated over the life of a particular plant. It may be interpreted as the price of output the plant must receive over its lifetime to break even, expressed in a way so as to be comparable to other plants that have different lifetimes and cost profiles"* (IEA, 2015a). Researchers focus on identifying the LCOE of the carbon capture process due to the lack of empirical data (currently, in the power sector there are only two full-scale CCS plants in operation – Petra Nova and Boundary Dam).

In a study conducted by the Global CCS Institute (2017) some of the key observations using the LCOE cost estimate were found:

- Natural gas combined cycle (NGCC) with CCS is the cheapest technology (in US$/MWh) in almost all the fourteen countries examined.
- The cheapest locations for NGCC with CCS (in US$/MWh) are large gas-producing nations such as Saudi Arabia, UAE, and Algeria. On the other hand, expensive locations are in South Korea and Germany due to higher imported gas prices.
- The cheapest locations for a coal-fired generation with CCS (in US$/MWh) are the United States, Canada, Mexico, and China. These results are due to factors such as:
    - the low coal price in Canada, which offsets relatively high labour and equipment costs.
    - significantly low labour costs in Mexico.

    - the relatively low cost of labour and equipment in China.
- The most expensive locations for a coal-fired generation with CCS (in US$/MWh) are Germany and Poland because of:
    - higher coal prices and equipment costs in Poland, which offset lower labour and materials costs.
    - high labour costs in Germany.
- Integrated gasification combined cycle (IGCC) with CCS (in US$/MWh) is the most expensive option in all countries.

In the assessment of CCS as a whole integrated process, the common indicator used is the cost of CO_2 avoided. The latter represents a cost measure that compares a plant with CCS to a baseline plant without CCS to quantify the average cost of avoiding a unit emission of CO_2 to the air (typically measured in dollars per tonne of CO_2or $/t$CO_2$) while still providing a unit of useful product (i.e., one MWh of electricity). In other terms, the CO_2 avoidance cost is equivalent to the price or tax on CO_2 emissions that would equalize the cost of electricity production for the plants with and without CCS. Therefore, it provides an economic benchmark of what it would take to make CCS more attractive in a particular case. In a study conducted by the Global CCS Institute (2017), the CO_2 avoidance cost was used to compare various sectors adopting CCS technology in different countries. Some of the key observations in the report were:

- Countries with lower labour costs (i.e., China, Mexico, Indonesia, and Poland) and low energy costs (i.e., Saudi Arabia) have the lowest cost of implementing CCS. For example, in the power sector, China has the lowest CO_2 avoidance cost of adoption of CCS in a pulverised coal (PC) supercritical power plant around approximately $60/t$CO_2$ and Saudi Arabia has the CO_2 avoidance cost of a natural gas combined cycle (NGCC) with CCS is around $80/t$CO_2$ which is also lowest for this type of power plant.
- Germany has the highest costs in each of the five industrial processes largely due to high labour costs – PC supercritical $121/t$CO_2$; IGCC $148/t$CO_2$; NGCC $138/t$CO_2$; Iron and steel $113/t$CO_2$; Cement $188/t$CO_2$.

- The lowest cost for CCS adoption is in natural gas processing, fertiliser, and bioethanol with a range of \$20 to \$27/tCO_2 avoided cost.
- CO_2 avoided costs in cement have a much larger range, from \$104 to \$194/tCO_2, while iron and steel costs vary from \$71 to \$119/tCO_2.

Besides the CO_2 avoidance cost, another available indicator in the literature is the cost of CO_2 captured. The cost of CO_2 captured has the same units as the cost of CO2 avoided, however, they have quite different meanings. The cost of CO_2 captured measure quantifies only the cost of capturing (producing) CO_2 as a chemical commodity sought by commercial markets. Hence, it is motivated by commercial considerations, and not climate change mitigation potential. Numerically, it also excludes any costs for transporting or storing the captured CO_2 product, whereas the cost of CO_2 avoided does not. Furthermore, because of the capture system energy requirement, more CO_2 is captured than avoided per net MWh of electricity generated (IPCC, 2005). Thus, the cost of CO_2 captured is always significantly less than the cost of CO_2 avoided. In some studies such as Zhai and Rubin (2013), the cost of CO_2 captured is the only cost measure prominently reported for a technology. In such cases it is more likely to be mistaken for the commonly reported CO_2 avoidance cost, therefore one should exercise care in using this cost metric to ensure proper context and understanding.

Overall, the cost estimates got through a TEA framework provide a good overview of the cost of CCS. These then provide useful data input for partial equilibrium and general equilibrium models. Partial equilibrium models are based on a bottom-up approach, which incorporates detailed information on the employed technologies such as capital costs for new plants, capacities of existing plants, efficiencies, operation and maintenance costs, prices of natural gas and coal, carbon prices resulting from the imposed CO_2-emissions constraints, etc. A partial equilibrium model aims to determine the financially cheapest way to achieve a given target based on the best available technologies and processes (Rivers and Jaccard, 2005). However, the outcomes from partial equilibrium models are restricted by the issue that the following models are not capable to incorporate feedback mechanisms between product and factor demand and supply. For instance, partial equilibrium models do not incorporate the impact of increasing electricity prices, induced by carbon penalties, on electricity demand. The type of model that is not restricted by these drawbacks is the general equilibrium model which uses a top-down approach. A general equilibrium model (also referred to as computable general equilibrium – CGE) are models that are a detailed representation of the economy with multiple sectors and often include higher resolution of energy technologies and regional detail. Rather than seeking optimal policies, they consider the impacts of specific policies on economic, social and environmental parameters. The richer representation of the economy comes at a cost in that the growth of the economy is harder to model and its structure more complex (Nikas et al., 2019).

Other aspects investigating the economics of CCS have been focused on project planning and investment and operational decision-making perspective. The research on CCS project planning aims to provide a reference for finding more economically feasible projects to be conducted on a priority basis to promote the development of CCS technology. The primary research method adopted in this field is cost curve models and optimisation techniques. The investigation of operational decisions also uses optimisation models, which seek to identify recommendations that optimise some objective function without violating resource constraints. Optimisation techniques can be classified into two distinct categories: deterministic and stochastic models. Under the deterministic technique, which embodies algorithms that rely heavily on linear algebra, the classical approaches include linear programming (LP), non-linear programming (NLP) and mixed-integer linear programming (MILP). A very well-known model in the CCS literature which falls under this category is the study by Middleton and Bielicki (2009). The authors developed a framework for spatially optimising CO_2 capture and sequestration infrastructure (named SimCCS) by generating candidate networks and then selecting the optimal topology using MILP. This framework allows managers to economically and geo-spatially optimise the CCS network project. The proposed model allows determining the network infrastructure of pipelines to be built and operated to capture, transport, and store a predetermined volume of CO_2 which was then used to solve a network design problem for a hypothetical CCS case in California, USA.

Stochastic optimisation models which include techniques such as fuzzy linear programming model, fuzzy integer programming model, linear interval programming, etc., have also been proposed to get more realistic results that consider various uncertainties associated with CCS deployment planning – see, for example, the study by Han and Lee (2012). Overall, the CCS studies that investigate the economics of CCS under a project planning perspective, the focus is to examine where and how much CO_2 is captured, transported, and stored; addressing the specifics of where and what size of pipelines are constructed; and how to match design sources and storage networks. Other studies in this field, using optimisation models in CCS infrastructure have also aimed to minimise the total system cost, where studies consider constraints such as the CO_2 flow, mass balance, CO_2 captured and stored capacity, and decision variable conditions.

The research on the economics of CCS under an investment and operational decision-making perspective not only enables investors to understand the investment value, investment opportunity, optimal operation strategy, etc. but can also provide a reference for policymakers (governments) to plan policies to promote CCS developments. Studies investigating the investment decision-making of CCS are predominantly studied under the research method of the real options approach (ROA). A real options approach is useful in capturing uncertainty and flexibility in investment decisions. ROA is applicable when three conditions are met: costs are at least partly irreversible (a sunk cost), there is uncertainty about future cash flows, and firms have the flexibility to delay investment or control the timing of investment. The central concept behind the real options theory is that decisions are often not a now or never but can be postponed. Waiting for more information has an (economic) value because if for example, the expected NPV of an (irreversible) investment opportunity increases, the investment can still be made. In contrast, if the NPV decreases, the company does not have to invest. The option to invest will only be exercised if the NPV of the investment is higher than the waiting value. Under these conditions, ROA outperforms the traditional net present value analysis, which ignores the opportunity cost of making a commitment now and thereby giving up the option to delay the investment and reduce risk. The theoretical foundations of ROA have been established by Dixit and Pindyck (1994) and Trigeorgis (1996). The objectives of studies in CCS using a real options approach are mostly studies identifying the optimal investment decision on power plant replacement or retrofitting with CCS by evaluating the economic feasibility (Abadie and Chamorro, 2008; Zhou et al., 2010). Each study differs in the solution technique and the type of uncertainty considered in the model which can include uncertainties such as electricity prices, carbon prices, technological change, climate policies, etc – see for instance Heydari et al. (2012), Zhang et al. (2014), and Wang and Du (2016).

1.3 Research Aim and Objectives

The purpose of the previous section was to provide a good understanding of the existing literature investigating the economics of CCS. In section 1.2, the economics of CCS was discussed in three different aspects: cost analysis, project planning and investment and operational decision-making. After a thorough discussion of the existing literature, what has been identified is that the CCS has been meticulously focused on aspects that are engineer focused and the examination of the economics of CCS is only an analysis of the cost of CCS technology in a cost accounting method. The reason many studies use a cost accounting approach to understand the economics of CCS is because there is a lack of empirical data, difficulty in choosing the baseline when comparing different CCS plants, a variety of currencies and currency base years in the reported literature, cost differences because of unavailability of transport and storage infrastructure and a variety of processes, operating conditions and capture processes (Budinis et al., 2018). However, a missing insight or an existing knowledge gap is a detailed economic assessment conducted for CCS at a firm level. Specifically, little is known about the added value of the microeconomic effects when CCS technology is adopted for individual sectors involved.

Therefore, in this thesis, an industrial organization (IO) approach has been adopted to investigate the economics of CCS to achieve a deeper economic understanding at a firm level when CCS technology is adopted. Industrial organization theory is an economic field based mainly on game-theoretical foundations and it is concerned with the structure of the market and how it is functioning (Tirole, 1988). More specifically, industrial organization theory is about, how a structure of a market influences the strategy and decision-making of a company (Ramsey, 2001). The purpose of selecting an industrial organization point of view in this thesis is that the following allows us to seek an increase in understanding of the methods by which industries operate, improve industries' contributions to economic welfare (Ramsey, 2001; Barthwal, 2010; Belleflamme & Peitz, 2010). This is something that is not addressed in the current CCS literature, comprehending how industries adopting CCS technology affect each other in a market. In particular, little is known about the value-added to using CCS for individual sectors and also there is a lack of understanding about the economic co-effects of CCS in general and in particular for individual economic sectors. In other words, we can investigate the impact that the strategic interaction of firms can accomplish on CCS adoption decisions (Audretsch et al., 2001).

Thus, in this thesis, three different economic models under an industrial organization approach are presented modelling different carbon capture technology adoption environments. Finally, in the 1970s with further development of industrial organization theory, another reason for choosing an industrial organization approach is that this research method allows us to identify policy interventions (Porter, 1981). As previously, mentioned the current policy designs adopted in the market – i.e., EU ETS – are not providing the right market conditions for firms to adopt a CCS technology. In this thesis, with the aid of industrial organization results, we also seek to find CCS-specific policy solutions to get the technology more deployed.

Overall, the overarching aim of the research is:

Research Aim*: "How do the strategic interactions of firms affect the incentives of CCS adoption decisions at a firm level, and what policy solutions can be provided to the key stakeholders to increase CCS technology deployment to reach the global climatic targets?"*

With the context established, the three essays presented in this research have the following research objectives:

Objective 1 – *To construct an economic model under an industrial organisation point of view of different CCS environments to assess the effects of the strategic interaction of firms in CCS adoption decisions.*

Objectives 2 – *To inform governments and policymakers of the policy solutions to reach the global environmental target by increasing CCS adoption.*

1.4 Contribution to Knowledge

The contributions obtained in this research are results from implementing an industrial organisation (IO) approach. Specifically, the contribution to the current knowledge in CCS literature is showing the role of strategic interaction of firms in three different CCS environments. Each economic model presented in this study considers different CCS environments and therefore each offers different microeconomic insights. We also contribute to the current knowledge by informing governments and policymakers by suggesting a series of policy solutions under the different CCS environments considered. Let us present the insights got for each economic model in the upcoming subsections.

1.4.1 *Chapter 2 – The Role of Competition in the Adoption of CCS Technology at a firm-level*

The first model constructed in this research investigates the effects of the strategic interaction of firms on CCS adoption decisions under different competitive market environments. In this chapter, two different market structures are considered examining the effects on CCS adoption decisions at a firm level. The first market structure investigated is a market that is a monopoly, and the second market structure is a duopoly producing homogeneous goods. In both market structures, a firm has the option to invest in CCS technology or choose to pay a carbon dioxide tax for any carbon emissions released into the atmosphere.

The main contribution of this chapter reveals the importance of the competitive environment that the firm operates in when dealing with a CCS adoption decision. In this chapter, we discover that if a market is a monopoly, there is only a singular direct effect gained by the firm. The direct effect is the reduction of the marginal cost of production for using CCS technology if the environmental regulations are strict such as a high carbon dioxide tax. However, if a market has competition such as a duopoly, an additional effect is gained by a firm that is not present in a monopoly market. The additional gained effect is called the strategic effect. The strategic effect is as follows. Assuming that there is a carbon dioxide tax that is extremely high, this assumption induces a firm to choose CCS technology as there is going to be a reduction in the marginal cost for the adopting firm. The adoption decision adversely affects the output of the rival firm and, thus, increases the adopting firm's profit. This effect is precisely the strategic effect on the firm's profit adopting CCS technology. Overall, under certain parametric conditions, what is learnt is that a firm in a duopoly market has a greater incentive toward CCS adoption decision because of two gained effects, a direct and strategic effect. We also discover that a duopoly market is better for increasing CCS technology because more carbon emissions can be mitigated as a competitive market has a higher total output compared to a market without competition – i.e., monopoly.

In this study, we identify two factors that are problematic for the deployment of CCS technology. Firstly, we readdress that a major impediment of CCS technology for its widespread adoption is its high upfront investment cost. Secondly, we also find that CCS technology is expensive to operate as is in its first-of-a-kind with only a few numbers of CCS projects worldwide. Thus, in this chapter, a series of policy solutions are proposed to increase the adoption of CCS technology – i.e., higher carbon tax, governmental subsidies, etc. We illustrate the effects of the policy solutions using a simple decision-making tool which we call the decision threshold curve or DTC. Overall, we solidify the case that CCS technology without stronger policy interventions will never reach its full potential to reach the Paris Agreement.

Finally, in this chapter, another contribution to the current literature is informing relevant stakeholders such as governments and policymakers of the competitive nature of the market that should be targeted to increase the widespread adoption of CCS technology. Specifically, we understand that if the carbon dioxide tax is assumed exceptionally low, the market structure giving the highest chance for the adoption of CCS technology is a monopoly. Conversely, if the carbon dioxide is assumed to be relatively high, we find the opposite result where under certain parametric conditions a duopoly market has a better chance of success for CCS technology adoption than a monopoly. The economic intuition behind this result is because of the effects on the marginal cost of production when the carbon dioxide tax is varied from low to high values.

The research questions driving Chapter 2 are:

- *What are the main factors that influence the decision making of a firm when it adopts a CCS technology?*
- *What policy solutions can we identify to inform governments and policymakers to increase the adoption of CCS technology?*
- *How are the incentives of a CCS adoption decision affected by competition?*
- *Which market structure promotes the highest chance of success for CCS deployment?*

1.4.2 *Chapter 3 – Carbon Capture and CO_2 Utilization – A Microeconomic Analysis*

The second model constructed in this research investigates the microeconomic interactions of an industry where a firm adopts a carbon capture and CO2 utilisation (CCU) process. The process of CO_2 utilisation is another option for a firm implementing carbon capture technology, where instead of transferring captured carbon emissions for only CO_2 storage, the other available option is to sell the captured gas to a separate industry that requires CO_2 gas to produce their final product.

The motivation for investigating a CCU adoption decision is because a major benefit of CCU over CCS technology is that for the former strategy, a revenue stream can be obtained for the adopting firm as the captured emissions from adopting the carbon capture technology are sold. Specifically, we want a better understanding of the effects generated at the firm level when a CCU strategy is adopted and understand the benefits of CCU over the usual CCS value chain.

In this chapter, the model presented has a market structure that is a non-vertically integrated market. The non-vertically integrated market is composed of an upstream and downstream sector. The upstream sector represents firms producing homogenous intermediary goods – in this case, CO_2 inputs – which are initially produced only by conventional methods that come from fossil fuel sources. The downstream sector is the industry that requires the CO_2 inputs necessary to produce their final good. To analyse the microeconomic effects of a firm adopting carbon capture and CO_2 utilisation this is captured by considering a firm entering the upstream sector. However, the entrant firm is unlike the rest of the firms in the upstream sector. The CO_2 input supplied by the entrant firm is obtained from having invested in a carbon capture technology where the captured CO_2 gas is a by-product of the production of the actual output by the firm.

In this study, there are three main objectives. First, the strategic interaction of firms when the entrant firm enters the CO_2 input market is investigated. Also, the study analyses the environmental impacts of the industry as one of the major drawbacks of final goods produced by CO_2 utilisation; the CO_2 content is eventually released back again into the atmosphere once consumed by final consumers. In this chapter, we discover that although CO_2 utilisation allows the entrant firm to recoup some of its investment in adopting a CCU technology, we find CCU is still an expensive investment for the entrant firm than not investing. Thus, the last objective of this study is the proposal of a series of policy solutions to achieve an increase in the adoption of carbon capture technology and CO_2 utilisation.

The findings of this chapter reveal several microeconomic results for all the stakeholders involved in the non-vertically integrated market. For example, when a firm enters the upstream market by adopting a carbon capture and CO_2 utilization process, the upstream market or the intermediary market of CO_2 inputs follows a quasi-competitive environment, meaning that the market-clearing price of CO_2 inputs falls as the number of firms increases in the market. Because of the latter assumption, we then also learn that the downstream sector is always going to get a positive effect on the market when CCU is adopted. This is because when a firm enters the upstream market this causes lowers the equilibrium price of the intermediary good which leads to lower marginal costs of production for downstream firms. Consequently, downstream firms' outputs are going to increase and therefore higher profits are obtained. On the other hand, the entrant firm who adopts a CCU technology, despite the strategy allows the firm to recoup some of its investment cost for adopting carbon capture and CO_2 utilization process, we find that under some exogenous parameters replicating the current economic situation of carbon capture technology will still not select to invest in a CCU technology. The reason for this is that the revenue generated from selling CO_2 gas to the downstream market does not outweigh the expensive adoption cost of CCU technology. Therefore, in this chapter, we propose a series of policy solutions to inform governments and policymakers to increase the chance of success of carbon capture and CO_2 utilisation adoption.

In addition to this study, we also identify policy solutions that are not only economically driven such that the entrant is going to adopt a carbon capture technology, but we also suggest policies that are focused on achieving a positive environmental outcome. The reason for this policy is because in some situations using numerical examples, we discover that the adoption of carbon capture with CO_2 utilisation can have cases where the adoption is worse off for the environment despite having adopted a carbon capture technology. Therefore, the suggested policy solutions in this chapter are to inform the government and policymakers to avoid CCU adoption which does not negatively impact the environment.

The research questions driving Chapter 3 are:

- *How is each stakeholder in a non-vertically integrated market structure affected when a firm enters the upstream sector by adopting the carbon capture and CO_2 utilization process?*
- *What is the optimal equilibrium strategy chosen by the entrant firm when it adopts a carbon capture and CO_2 utilization process?*
- *How is the environment impacted when a firm enters the upstream sector by adopting the carbon capture and CO_2 utilization process?*
- *What policy solutions should governments and policymakers implement to increase CCU adoption? And what policy solutions should governments and policymakers implement to increase CCU adoption whilst considering a positive environmental outcome?*

1.4.3 *Chapter 4 – The Effects of Learning-by-doing and Knowledge Spillover on the Adoption Timing Decision of CCS technology*

The last economic model presented in this thesis investigates the optimal adoption of a 'new generation' CCS technology by a firm influenced by the learning-by-doing effect and technological spillover. The new generation of CCS technology has a lower marginal cost caused by a prior adopter who has adopted an earlier CCS generation and provided the reduction cost by learning-for-others. The motivation behind this study is to have a better understanding of the effects affecting a firm's CCS adoption decision of the new CCS generation. Also, another motivation of this study is to solve what we call the waiting factor impeding CCS deployment. The waiting factor is that firms are choosing to delay CCS investment knowing that if another firm adopts first there are more potential savings by waiting for more advanced technology in the future. Thus, this chapter aims to overcome the waiting factor to increase CCS deployment and CCS diffusion.

The model presented for this study considers two firms. The two firms both have the option of adopting a first-generation CCS technology. If a firm adopts first, the firm is called a pioneer. The pioneer experiences a learning-by-doing effect causing its marginal production cost to decrease. The consequence of a learning-by-doing effect gained by the pioneer and the fact there is also a spillover effect taking place in the market generates the availability of a second-generation CCS technology for later adopters. The second-generation CCS technology is a more efficient technology at a lower cost and fast learning rate.

In this chapter, the optimal adoption time of a follower who adopts a more advanced CCS technology is evaluated. We discover several factors affecting the optimal adoption time. Thus, in this study, we examine each factor and assess its impact on the optimal time of a new generation of CCS technology. However, the main contribution of this chapter is a policy solution to inform governments and policymakers that if a scenario is obtained where there is an initial adopter (pioneer) and then later the other firm adopts (follower), we propose a policy that achieves a balance in cost of adoption between a pioneer and a follower. The policy aims to increase CCS technology deployment and solve the waiting factor. The waiting factor is that firms are choosing to delay CCS investment knowing that if another firm adopts first there are more potential savings by waiting for more advanced technology in the future. Therefore, the policy suggested in this chapter eliminates the waiting factor to increase CCS deployment and its diffusion.

The research questions driving Chapter 4 are:

- *What is the optimal adoption decision time of a follower for a CCS technology adoption influenced by a learning-by-doing and spillover effect?*
- *What factors affect the adoption decision time of the follower?*
- *What policy solution should governments and policymakers implement such that a pioneer and follower achieve equally balanced benefits in adopting different generations of CCS technology?*

1.5 Thesis Structure

The remaining structure of this thesis is as follows. In chapter 2, the first economic model is introduced which investigates the effects of the strategic interaction of firms on CCS adoption decisions under different competitive market environments. Chapter 3 presents the second economic model investigating the strategic interaction of firms when carbon capture and CO_2 utilization (CCU) are adopted. Here, the focus of this study is not only interested in an economic assessment of the industry but also seeks to examine the environmental impacts to avoid the shifting of the burden of carbon emissions when CCU is adopted. Chapter 4 presents the last economic model which examines the optimal CCS investment decision time when a learning-by-doing effect and technological spillover exist in a CCS market. Finally, Chapter 5 concludes the thesis by summarizing the findings of the research and delineating its contribution to knowledge, discussing the practical implications and limitations of the research, and proposing areas for future research.

Chapter 2

The Role of Competition in the Adoption of CCS Technology at a firm-level

2.1 Introduction

Carbon capture and storage (CCS) is a mitigation technology that prevents profound carbon dioxide emissions into the atmosphere. According to the International Energy Agency, CCS has the potential of contributing up to 14% of cumulative CO_2 emission reductions through 2050 to reach a 2-degree scenario or 2DS world compared to the business-as-usual scenario or 6DS[7]. However, the current state of CCS technology only has roughly 31 million metric tons (Mt) per year of anthropogenic carbon dioxide that is captured and injected into geological formations for permanent storage. To achieve the 2-degree scenario studies estimate that 200–1,000 million metric tons per year will be required by 2030 and 5,000–10,000 million metric tons per year by 2050 (Edwards and Celia, 2018).

The obstacles holding CCS technology deployment are due to several factors. For instance inconsistent and insufficient policy support, a lack of economic drivers, and the inherent large-scale and associated enormous cost of individual projects (Edwards and Celia, 2018). But the inadequacy of government support policies is probably crucial among them. For example, the governmental policy in the EU known as the European Emission Trading Scheme is designed to reduce CO_2 emissions by putting a price on emitting carbon emissions. However, so far it has not managed to pressure firms in making a greener technology decisions such as the adoption of CCS technology. Currently, a firm rather emits carbon emissions in the atmosphere as this is cheaper than adopting a green technology like CCS. While it is currently unclear whether CCS will indeed develop into a cost-competitive component of a future

[7] Business-as-usual scenario where no mitigation strategies or efficiencies are adopted.

emission reduction portfolio once relevant market failures are addressed, CCS will not become a viable abatement option without policy support. To secure the role of future deployment of CCS, a good understanding of the necessary policy solution to change the incentives of CCS adoption decision is needed now (Krahé et al., 2013).

In the current literature, many studies have focused on identifying policy options to promote CCS. For example, works by Groenenberg and de Coninck (2008), von Stechow et al. (2011), and Al-Juaied (2010), discuss the policy instruments for advancing the large-scale deployment of CCS for the European Union and the US electricity generation sector. In the environmental economics literature, which contains discussions of various types of market failures and public policy proposals, Grubb et al. (2014), IEA (2012) and Krahé et al. (2013) analyse these issues specifically in a CCS context. The crucial points contained in the environmental economics literature are: "*Innovative emerging clean technologies will not make it to deployment without appropriate policy incentives" (Yang et al., 2018)*. Also, "*The nature, scale and scope of policy incentives need to be calibrated to the specific needs of particular technologies. Policy incentives also need to change as technologies develop*" (Yang et al., 2018). In this chapter, the aim is also to contribute to the current CCS literature by recognizing the necessary policy interventions that governments and policymakers should implement to increase the adoption of CCS technology. Let us note that the purpose of this chapter is not to promote that CCS is definitely welfare-enhancing. In fact, we investigate the cases where it is welfare-enhancing and find policy solutions why there are not adopted in the market. Furthermore, in this chapter, it also contributes to the current CCS literature by understanding the effects of the strategic interaction of firms to the adoption decision for CCS technology. To achieve the following we implement an industrial organization (IO) approach, a subfield in microeconomics dominated by game-theoretic tools to context of CCS adoption. A main reason for this approach is because most existing literature studies of CCS technology diffusion are mainly from a macro and engineering perspective, providing little insight into the behavioural strategies of the stakeholders involved in the process of CCS adoption at a microeconomic level.

Therefore, the aim of the chapter is four-fold. First, we investigate the effects of the strategic interaction of firms on the adoption decision of CCS technology in two different market structures – monopoly and duopoly. Second, we identify the policy solutions that will favour the incentives toward a CCS adoption decision. Third, we investigate the effect of market competition on the incentives of the CCS adoption decision. Last, we examine which market structures achieve the highest chance of success in the widespread of CCS technology.

The questions driving this chapter are:

- *What are the main factors that influence the decision making of a firm when it adopts a CCS technology?*
- *What policy solutions can we identify to inform governments and policymakers to increase the adoption of CCS technology?*
- *How are the incentives of a CCS adoption decision affected by competition?*
- *Which market structure promotes the highest incentives to adopt CCS technology?*

In this chapter several insights are discovered:

- *Insights for firms* – By implementing an IO approach, a decision-making tool to detect the optimal CCS adoption decision of a firm with or without competition is presented. However, the core result of the study shows the importance of competition for the adoption of CCS technology. We learn that a market with competition (i.e., duopoly) has the advantage of achieving greater incentives to adopt CCS technology over a market without competition (i.e., monopoly). The reason for this is due to a strategic effect that is only present in a market with competition. The strategic effect is, if the adoption of CCS technology lowers a firm's marginal cost of production, thus making the firm more competitive in the market. Then, this adversely affects the output of the rival which then increases the CCS adopting firm's profit in question.
- *Insights for governments or policymakers* – In this chapter, a multitude of policy solutions are proposed to increase the adoption of CCS technology –

i.e., higher carbon taxes and subsidies. However, the other core result discovered in this chapter is the type of market structure that governments or policymakers should target to increase the widespread of CCS technology. Specifically, we discover that if the carbon dioxide tax is assumed extremely low, the market structure with the highest chance for the adoption of CCS technology is a monopoly. On the contrary, if the carbon dioxide tax is assumed to be relatively high, the opposite result is discovered. The economic reason behind this result is the changes in the carbon dioxide tax affecting the marginal cost of production of a firm. When the carbon dioxide tax is assumed high, this causes the marginal cost of production of CCS technology to become more efficient and a firm in a duopoly market is the superior market structure to increase CCS deployment because of the strategic effect that is only present in a market with competition. Therefore, what one learns here is that if the carbon dioxide tax is high, governments should target a market that has more competitive because we discover that firms have greater incentives in CCS technology adoption due to the strategic effect. Finally, we also discover if the carbon dioxide tax is high, a duopoly market should be the targeted market structure by governments and policymakers for achieving an increase in CCS technology adoption. The reason for this is because more carbon emission can be mitigated in a duopoly as the total industry output in a duopoly market under Cournot competition are higher than in a monopoly market.

The rest of this chapter proceeds as follows. In the next section, the relevant stream of literature to our study is reviewed. Subsequently, the first model of a monopoly market structure is introduced in section 2.3. Here, several factors affecting the decision-making for a CCS adoption decision are identified at the firm level. Also, in this section, the effects of policy solutions to increase the incentives for CCS technology are investigated. In section 2.4, the second economic model of a duopoly market competing under Cournot competition is introduced. In this section, the effects of market competition on the incentivisation of CCS technology are investigated. In section 2.5 the main findings of the study are presented by comparing the two market structures investigated. Finally, section 2.6 concludes the chapter by presenting a summary of the results and discusses future work recommendations.

2.2 Relevant Literature

In this section, the relevant literature for this study is reviewed. The relevant studies for this chapter are research topics in the field of industrial organization (IO) theory. Before discussing the relevant studies for this chapter, we discuss the reason we consider studies in the IO literature.

The reason for considering studies in the field of IO theory is because we have identified that most existing literature studies investigating the economics of CCS are mainly investigated through a macro and engineering perspective. The dominant research methodologies that analyse the economics of CCS use modelling techniques from optimization and mathematical modelling. The main drawback of the current research methods analysing the economics of CCS is that the existing type of models use heavily rigorous computations, and some other models have specific parameters within their models. Thus, the current models can become overly complicated to manage, and as well loses portability, especially when not all CCS projects are the same. The purposes of a model are to understand a certain phenomenon eliminating details that are not essential to the problem at hand (Jennings, 2015). Sometimes it is necessary to abstract from reality to recognize what the problem is. As Albert Einstein stated: “Everything should be made as simple as possible, but not simpler.” Einstein meant that there is no need to make things more complicated than they need to be, but at the same time, if they are too simple, they eventually do not make sense. In the current CCS literature, the research methodologies implemented do not investigate the economics of CCS at a firm level. Therefore, the opportunity that we have identified is to understand the economics of CCS at a firm level using economic theory. Specifically, we implement an industrial organization approach to the context of CCS adoption decisions. The following research method not only allows us to understand the same cost-benefit of CCS technology that is well investigated in the current literature but also allows us to explore the effects of strategic interaction of firms on CCS adoption decisions. The decision of using an industrial organization approach allows us to assess the economics of CCS with a simplified description of reality, designed to yield hypotheses about economic behaviour at a firm level. Also, on the same basis of why simplicity is crucial, one of the main principles in philosophy is

Occam's razor (or Ockham's razor). The principle states that if there exist two explanations for an occurrence, the simpler one is usually better.

The main contribution of this chapter in the current literature is that implementing an industrial organization approach to the context of the economics of CCS allows us to achieve a better understanding of the effects of the strategic interaction of firms when a firm chooses to adopt a CCS technology. Specifically, in this chapter, we investigate the effects of market competition on CCS technology adoption at a firm level. Therefore, the relevant studies for this chapter are research topics in the field of IO theory exploring the adoption of new technology, innovation, economics, and pollution control mechanisms under an industrial organization (IO) approach.

The IO literature on technology adoption of new technology has been investigated in various aspects. For example, several studies assess the optimal timing of the adoption of new technology under competition where the current literature often exhibits a pre-emptive result. In other terms, firms in a competitive industry pre-empt each other by investing early (Dasgupta and Stiglitz, 1980; Fudenberg and Tirole, 1985; Katz and Shapiro, 1986; Reinganum, 1985; Spence, 1986). The reason for this result is that firms seek to gain a better strategic advantage – i.e., enhancing market share and deterring potential entrants. However, a drawback of the pre-emptive literature, the following are not able to encapsulate the role of uncertainty, which may tend to smooth out the incentive to move early (Dixit and Pindyck, 1994).

The research method which allows analysing the effect of uncertainties during an investment is through the use of a real options approach (ROA) which was established by Dixit and Pindyck (1994) and Trigeorgis (1996). ROA is implemented when the opportunity to adopt new technology is equivalent to a call option with an exercise price equal to the investment outlay, and the underlying asset is the new technology (Zhu and Weyant, 2003). Typically, the real options literature stresses the option value to wait. For example, a delay in the adoption decision for CCS technology under ROA was displayed by Abadie and Chamorro (2008), who investigated the optimal investment decision on power plant replacement or retrofitting with CCS by evaluating the economic feasibility. The limitation of implementing a ROA is that it has been typically based on two specific assumptions: (a) the firm has monopoly power over an investment opportunity, and (b) the product market is perfectly competitive.

Since real-world markets are rarely perfectly competitive, another aspect in which new technology adoption has been investigated in the IO literature is analysing the effects of market structures in the adoption decision of green or clean technology. For example, Davis (2017) constructed a simple microeconomic model of a monopoly market that had an adoption choice between two technologies: a dirty technology with a high marginal cost and low fixed cost versus a clean technology with low marginal cost and high fixed cost. The main outcome of this paper discovered that a firm may choose to continue using dirty technology over a known, freely available, and socially superior green technology, even when the monopoly is fully internalizing the costs of environmental damage. The model constructed by Davis is an extension of work from Hennessy (1998) who gave first a brief exposition of possibly inefficient technology choices under monopoly. The reason for the extension was because Hennessey's framework was limited considering only technologies that change marginal costs and assuming no fixed costs. Moreover, Hennessey did not make the connection to green technology in the presence of pollution pricing, which is a public policy issue of significant importance. Another study investigating the adoption of new technology under a monopoly market structure is the study by Krass et al. (2013), who examine the role that environmental taxation can play in reducing environmental pollution and inducing the choice of greener technology by a profit-maximizing firm. This study is especially useful as it considers a firm adopting CCS technology. However, Krass et al. (2013) neglect the exploration of the role of imperfect competition in green technology adoption which will be the main exploration of this chapter.

A pioneering study understanding the effects of a more complex market structure involved with green or clean technological adoption is the study by Mills and Smith (1996). The model constructed by the authors considers a two-stage game with two identical firms. In the first stage, firms decide whether to adopt a (new) technology with low marginal cost or to continue using technology with high marginal cost and in the second stage, they compete a la Cournot. The main results of this study found that in some cases, the model generates an equilibrium where firms select different technologies (heterogeneous-firm), and in others, an equilibrium is obtained where the technologies are the same for both firms (homogeneous-firm). Mills and Smith also implemented a social welfare analysis and discover that if a heterogeneous-firm equilibrium exists, it is socially optimal and in comparison, a homogeneous-firm industry structure would not produce as great a total surplus. Several authors extended the work of Mills and Smith (1996). For example, Elberfeld (2003) extends the original Cournot duopoly setting to a Cournot oligopoly. Elberfeld shows that asymmetric technology choices can arise in an industry with more than two firms. However, the welfare result obtained by Mills and Smith (1996) does not hold beyond duopoly. Furthermore, Elberfeld and Nti (2004) explored the effects of uncertainty in the Cournot oligopoly model to analyse the effects on the adoption of new technology. On the other hand, Pal (2010) examined firms' choice of technology adoption in a differentiated duopoly considering both Cournot and Bertrand's competition. Another study investigating the effects of market structures in green or clean technological adoption in a more complex market is the study by Zhu and Weyant (2003). In this study, the main aim was to investigate the effects of asymmetric information on firms' decision to adopt the technology with a two-stage game-theoretical model. The authors discover that information asymmetry leads to different incentives and strategic behaviours in the technology adoption game. By relaxing the typical full-information assumption in the literature, Zhu and Weyant show how asymmetric information alters the adoption equilibrium.

The other strand of literature relevant to this study are also studies exploring the effects of pollution control on innovation. Pollution control is an economic incentive policy implemented by governments or policymakers that is designed to discourage CO_2 emissions into the atmosphere (Santibanez-Gonzalez, 2017). The reason many studies research innovation under pollution control is because firms do not intend to conduct green innovations and as previously mentioned environmental regulations are created by the government to encourage green innovations. Normally, environmental policies aim to correct external externalities. However, if environmental policies promote technological progress as a side effect, they can achieve more socially desirable outcomes. The conditions necessary to conduct green innovations have been analysed in environmental economics literature so far. Many existing studies have used the Bertrand and Cournot models to examine what kind of environmental regulations (e.g., direct controls, environmental tax, and marketable permits) lead to green innovations and have compared their effects on social welfare (Cao et al., 2016; D'Amato and Dijkstra, 2015; Fischer et al., 2003; Innes and Bial, 2002; Lambertini et al., 2017; Milliman and Prince, 1992; Montero, 2002a; Montero, 2002b; Perino and Requate, 2012; Requate, 1998). Finally, in the current literature is well understood that stronger environmental policies can stimulate the adoption of new technologies that reduce marginal emissions or save abatement costs (Perino and Requate, 2012; Porter and van der Linde, 1995; Requate, 2005).

To the best of our knowledge, the current CCS literature is lacking in a detailed microeconomic assessment to understand the effect of strategic interaction of firms on CCS adoption decisions. In this study, we seek to fill the research gap in CCS literature by investigating the effects that strategic interaction of firms brings to CCS adoption decisions by implementing an industrial organization approach. The first economic model we present in this chapter is based on the study conducted by Krass et al. (2013). We build an economic model that has a monopoly market structure so that firstly we can have a better understanding of the economic incentives that a firm achieves when adopting a CCS technology adoption with no market interaction. Consequently, we then extend the work by presenting a second model which has a market structure composed of two competing firms or duopoly based on the study by Mills and Smith (1996).[8] In the end, the main contribution to the current CCS literature is by highlighting the importance that the effects that the strategic interaction of the firm has on the adoption decision for CCS technology. Specifically, we explore the importance of the effects of considering different market structures on CCS adoption decisions. In other words, in this chapter, we investigate the role of competition in the CCS adoption decision to ultimately provide more useful information for governments and

[8] The rationality of selecting a duopoly market for assessment was because the focus of this chapter is to highlights the effects of when decisions made by firms are dependent on each other on CCS adoption decision. Another possibility for this chapter was to consider a perfectly competitive market, where firms are price takers meaning that they cannot control the market price of their product. The decision of not considering a perfectly competitive market is because the firms using CCS technology especially the power generation industry there are not enormous number of companies. For example, in the UK there are "Big 6" energy suppliers and therefore considering a duopoly which is a form of an extreme form of oligopoly is an appropriate decision to understand the impacts of imperfect competition on CCS adoption. Nevertheless, the complete understanding of a perfectly competitive market on CCS adoption decision can be considered for further future work.

policymakers who intend to increase the chance of success of CCS technology adoption.

2.3 A Monopoly Scenario

In this section, the first economic model is presented demonstrating a CCS adoption decision where the market structure considered is a monopoly. The section is subdivided into smaller subsections. In subsection 2.3.1 the model is described. Subsequently, the profit-maximization results are evaluated in subsection 2.3.2. In subsection 2.3.3 we present the decision threshold curve or DTC which is a simple decision-making model for the monopoly firm to decide whether to adopt CCS technology or not. Consequently, in subsection 2.3.4 the equilibrium outcomes are analysed. Policy levers to incentivise the adoption decision towards the CCS decision are discussed. In subsection 2.3.5. In section 2.3.6 the social welfare functions are evaluated for a monopoly scenario. Finally, section 2.3.7 concludes the analysis by summarizing the key findings for the monopoly model.

2.3.1 Monopoly Model Description

Let us consider a single firm in a market or a monopoly. Figure 1 below displays the schematic model decision for the monopoly firm that has the option to adopt a CCS technology or not.

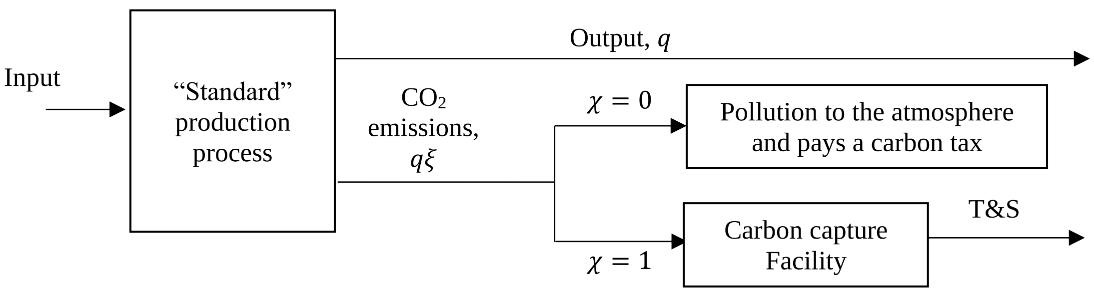


Figure 1 - Model Schematic

The "standard" production process of the monopoly firm, with a fixed cost equal to $\Psi > 0$, allows the firm to produce q units of output. The production of output q generates carbon dioxide (CO_2) as a by-product. Parameter ξ represents the carbon emissions per unit of product produced by the firm. Thus, the total amount of CO_2 produced by the monopoly firm is equal to $q\xi$.

In the model, CCS technology is considered an end-of-pipe technology, a technology that is not going to affect the "standard" production process of the firm and thus will not affect the final product produced by the firm. In the CCS literature, this type of technology is known as a CCS "retrofit" technology. The CCS investment decision of the firm is represented by χ, where $\chi \in \{0,1\}$. If $\chi = 0$, the monopoly firm has chosen not to invest in CCS technology and pollutes its carbon emission to the atmosphere. While $\chi = 1$, signifies the monopoly firm has chosen to invest in CCS technology, where for tractability reasons we assume that all the carbon dioxide emissions produced by the firm are going to be captured by the carbon capture technology.

The adoption of CCS technology impacts the cost of the firm both in the fixed and marginal costs. Parameter $\Phi(\chi)$ represents the fixed cost of adopting a CCS technology. This includes all the fixed cost components from capture, transport, and storage costs. Notice that $\Phi(\chi)$ depends on investment decision χ, where $\Phi(0) = 0$ and $\Phi(1) \equiv \Phi > 0$. The marginal cost of the monopoly firm for using a CCS technology is denoted by γ, where γ is a constant marginal cost (so there are no decreasing returns to scale in capturing carbon).

If the firm decides not to adopt the mitigation strategy – i.e., $\chi = 0$ – then the monopoly firm is going to pay a carbon dioxide tax t for every unit of emissions the firm releases into the atmosphere. The monopoly firm also has a standard marginal cost of production to produce output q denoted by σ, the marginal cost of production that does involve the emission unit cost and the unit cost of using the carbon capture technology. Overall, the total cost function[9] for the monopoly firm is equal to:

$$C_\chi(q) = \big(\Psi + \Phi(\chi)\big) + (\sigma + (1-\chi)t\xi + \chi\gamma)q \tag{1}$$

[9] The total cost function of the monopoly firm is a linear cost function. A theme in this thesis is considering simple functions not only for cost but also demand functions because as previously mentioned a research gap identified in the CCS literature is that the current studies understanding the economics of CCS have not assessed the effects of strategic interactions of firms. As George E.P. Box said: "All models are wrong, but some are useful." Therefore, in this thesis the aim is not to replicate immediately the real-life world characteristics but to initially understand and highlight the effects of market interactions on CCS adoption decision. Considering more complex functions – i.e., cost and demand – can be considered for further work.

The decision problem for the monopoly firm is as follows.

1. *Stage 0* – represents the investment decision χ of the monopoly firm, where $\chi \in \{0,1\}$.
2. *Stage 1* – In this stage, the optimal output of the monopoly firm is chosen. The output depends on the investment decision χ that is selected by the monopoly firm in the previous stage.

2.3.2 Profit-Maximization

The profit-maximization results of the monopoly firm are evaluated in this subsection. The demand function for the monopoly firm is given by

$$P(q) = a - bq \tag{2}$$

where $a, b > 0$.[10] The profit function of the monopoly firm is equal to

$$\pi_\chi(q) = P(q)q - C_\chi(q) \tag{3}$$

where $C_\chi(q)$ is equal to (1) and $P(q)$ is given by (2). Taking the first-order condition of the equation above and rearranging for q, the optimal quantity of the monopoly firm is obtained.

$$q^* = \frac{a - \sigma - (1-\chi)t\xi - \chi\gamma}{2b} \tag{4}$$

Notice that the higher the marginal costs such as the carbon dioxide tax t or the marginal cost of production σ, the lower quantity the firm will produce. Now, inserting the result above in equation (2), the equilibrium price is equal to

$$P^*(q^*) = \frac{a + \sigma + (1-\chi)t\xi + \chi\gamma}{2} \tag{5}$$

[10] The rationality for considering a linear demand function is due to because it is a standard practice in many IO research papers and also in many microeconomics books. In fact, author usually rarely justifies this assumption. However, because of its popular use in the literature we also considered it because recently Adam Bailey in 2021 has published a report called "In Defence of the Linear Demand Function". Adam Bailey justifies that the use of a linear demand showing that it is not an outrageous assumption through the means of utility theory – see article at: https://economicdroplets.com/2016/06/21/in-defence-of-the-linear-demand-function/

In equation (5), one can see that if the marginal costs increase then the equilibrium price will increase. Finally, the equilibrium profit of the monopoly firm can be obtained using equation (3) by inserting the results obtained in equations (4) and (5). This gives that the equilibrium profit of the monopoly firm is equal to

$$\pi_\chi^*(q^*) = \frac{(a - \sigma - (1 - \chi)t\xi - \chi\gamma)^2}{4b} - \big(\Psi + \Phi(\chi)\big) \tag{6}$$

2.3.3 The Decision Threshold Curve for a Monopoly

In this subsection, we investigate the conditions within our modelling framework for which the monopoly firm will adopt CCS, which requires the decision threshold curve or DTC.

DEFINITION 1 (***Decision threshold curve of a Monopoly***) – *The DTC demonstrates the locus of points of the marginal cost of using CCS technology* (γ) *and the fixed upfront cost of CCS* (Φ) *where the optimal profits of the monopoly firm are the same under a carbon dioxide tax and for adopting a CCS technology.*

The DTC is derived by setting the optimal profits equation for investing in CCS technology and not investing in CCS. In other words, $\pi_1^* = \pi_0^*$ using equation (6). Then, it is rearranged in terms of the marginal cost for using CCS technology or γ, which results in the following

$$\gamma = a - \sigma - \sqrt{(a - \sigma - t\xi)^2 + 4b\Phi} \tag{7}$$

Consequently, by considering the expression above as a function of Φ – the fixed cost of CCS technology – we obtain $\gamma(\Phi)$ which corresponds to the function of the decision threshold curve for the monopoly firm.

$$\gamma(\Phi) = a - \sigma - \sqrt{(a - \sigma - t\xi)^2 + 4b\Phi} \tag{8}$$

Equation (8) above delineates the combinations of Φ and γ where the monopoly firm is indifferent between investing in CCS technology or not. More specifically, the left-hand side of equation (8) represents the marginal benefit of adopting CCS technology, whereas the right-hand side is the marginal benefit of a carbon dioxide tax strategy. Equation (8) is useful when it is plotted. In Figure 2 an example of the function behaviour of the DTC and the decision-making conditions is presented.

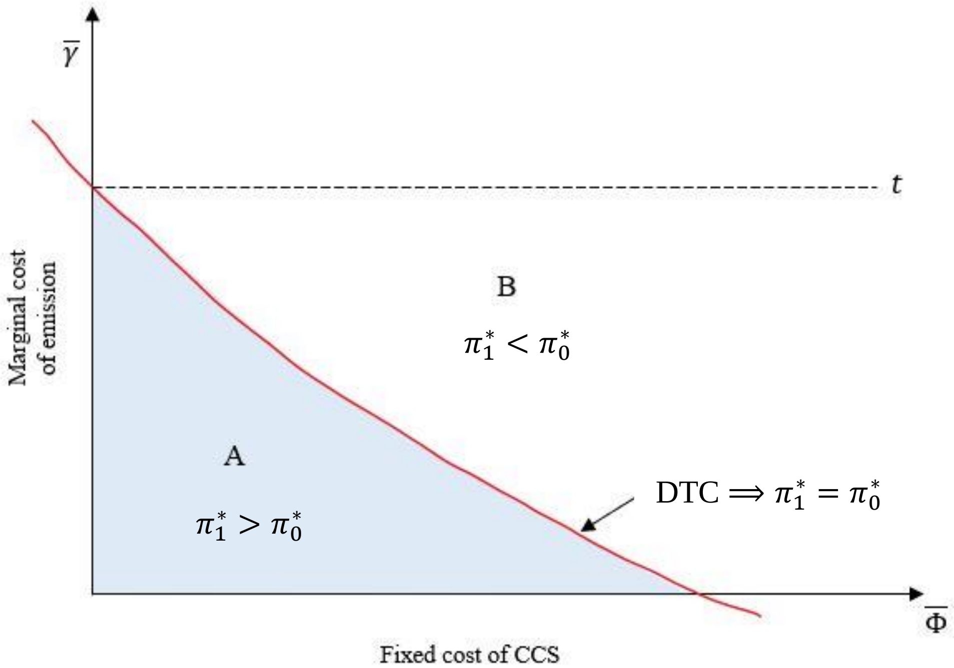


Figure 2–- The Decision Threshold Curve illustrated by the red line

In Figure 2, the DTC is represented by the red line which is a decreasing convex function of Φ. The DTC line generates two distinct regions: A and B. If an assumed coordinate (γ, Φ) is in region A or below the DTC line, this represents that the monopoly firm should adopt CCS technology because it is more profitable than choosing a carbon dioxide tax strategy – i.e., $\pi_1^* > \pi_0^*$. On the other hand, if the coordinate (γ, Φ) is in region B or above the DTC, the optimal strategy for the monopoly firm is a carbon dioxide tax strategy because the optimal profits are greater compared to adopting CCS technology – i.e., $\pi_1^* < \pi_0^*$. Overall, the DTC is a simple decision-making tool that allows the monopoly firm to identify whether it should adopt CCS technology or not.

2.3.4 Equilibrium Analysis

Having calculated the profit maximization results and presented the concept of the decision threshold curve of the monopoly, the question we seek to answer in this subsection is: "*What is the equilibrium decision of the monopoly for a CCS adoption*?"

In the current literature, it is well known that a major obstacle to CCS technology adoption is its high upfront investment cost. Hence, in our model $\Phi(1) \equiv \Phi > 0$ is extremely large when $\chi = 1$. Furthermore, CCS technology is known to have an expensive cost to operate. In the CCS literature, CCS technology is known for having a high energy penalty cost. In economic terms, the adoption of a CCS technology has a high marginal cost of production (or γ) compared to a carbon dioxide tax strategy. With the latter two identified factors, then we can determine that it is more profitable to not adopt a CCS technology for the monopoly firm. Precisely, using equation (6) if the monopoly firm invests in CCS technology – i.e., $\chi = 1$ – the profit function is equal to

$$\pi_1^*(q^*) = \frac{(a - \sigma - \gamma)^2}{4b} - (\Psi + \Phi) \tag{9}$$

On the other hand, if the monopoly firm decides not to invest in CCS technology – i.e., $\chi = 0$ – the profit function of the monopoly using equation (6) is equal to

$$\pi_0^*(q^*) = \frac{(a - \sigma - t\xi)^2}{4b} - \Psi \tag{10}$$

Knowing that there is a large fixed cost Φ and γ is greater than t, from the two equations above if all other parameters remain equal then $\pi_1^* > \pi_0^*$. Overall, what is learnt here is that using an industrial organization approach to replicate a firm's decision for CCS adoption has an equilibrium decision where a monopoly firm will not choose to invest in CCS technology or $\chi = 0$. In other words, a monopoly firm would rather choose to release its carbon emissions into the atmosphere than adopt a CCS technology.

What the equilibrium analysis shows is that there is a lack of incentives for a CCS adoption decision. Given the importance of CCS technology towards the Paris Agreement, the equilibrium analysis allows us to reaffirm that governments or policymakers should focus on achieving the correct market conditions for the technology to be adopted. Hence, in the next subsection, the objective is to provide solutions to the government and policymakers to achieve a CCS technology decision.

2.3.5 Policy Levers

In this subsection, a series of policy levers are presented to increase the incentives of the monopoly firm toward a CCS technology adoption.

2.3.5.1 Carbon Dioxide Tax

The first policy presented is an increase in the carbon dioxide tax. Let us consider t_1 and t_2, where $t_1 < t_2$.

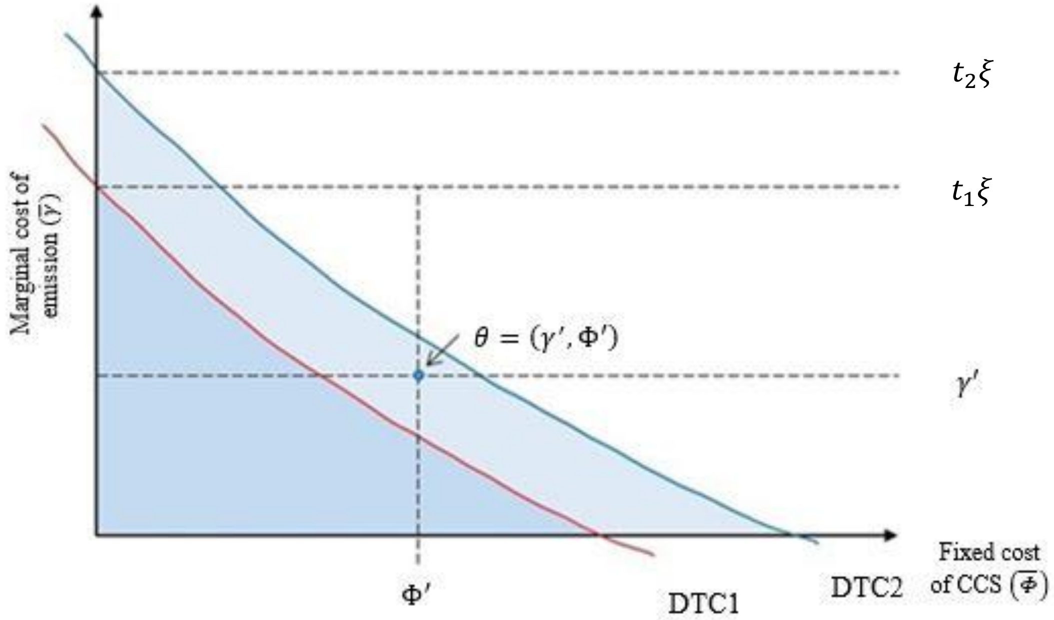


Figure 3 – The effects om DTC after an increase in the carbon dioxide tax from $t \rightarrow t'$, where $t < t'$.

In Figure 3, there are two decision threshold curves displayed denoted as DTC1 and DTC2. The initial starting curve is DTC1 where the carbon dioxide tax is at a preliminary value $t_1 > 0$. When the carbon dioxide tax is increased from $t_1 \rightarrow t_2$, the decision threshold curve shifts in the rightward direction. DTC2 represents the final position of the decision threshold curve with a carbon dioxide tax t_2. The effect of increasing the carbon dioxide tax increases the area beneath the decision threshold curve. This means that an increase in the carbon dioxide tax improves the chances of CCS adoption decision for the monopoly firm. Let us explain further the effect of the policy with a graphical explanation using Figure 3.

In Figure 3, one can notice that there is a coordinate θ, which is a combination of the marginal cost of using CCS technology and the fixed cost of CCS technology or $\theta = (\gamma', \Phi')$. When the carbon dioxide tax is equal to t_1, the initial position of coordinate θ is above DTC1. Thus, this means that the monopoly firm should choose a carbon dioxide tax strategy as it obtains a higher profit than investing in CCS technology. However, if the carbon dioxide tax is increased sufficiently, the position of coordinate

θ is relocated underneath the newly positioned decision threshold curve or DTC2. Hence, an increase in the carbon dioxide tax is a policy solution that can increase the incentives of a firm towards CCS adoption decision making the mitigation technology a more profitable strategy than not investing in CCS technology.

2.3.5.2 Fixed Cost Subsidy

The next policy lever introduced is a governmental subsidy targeting the high fixed cost of CCS technology. Let us illustrate the effect of this policy solution with another graphical explanation.

Assuming a firm with a marginal cost of emission for using CCS technology equal to $\gamma' > 0$ and a fixed cost for CCS technology equal to $\Phi' > 0$. The combination of the two assumed parameters gives a coordinate θ, where $\theta = (\gamma', \Phi')$. If the government intervenes by giving a firm a fixed cost subsidy for CCS technology, the policy solution does not affect the behaviour of the decision threshold curve. Instead, it affects the position of the coordinate θ. Specifically, it shifts the coordinate θ in a left horizontal direction as displayed in Figure 4.

In Figure 4, the initial assumed starting position of coordinate θ is located above the DTC. Thus, the monopoly firm should choose a carbon dioxide tax strategy as it is more profitable than investing in CCS technology. However, if a fixed cost subsidy – denoted by $FCsub$ – is given by the government and is sufficiently enough, the policy solution can alter coordinate θ to a final position θ' and one can easily notice that coordinate θ' is located underneath the DTC. Therefore, a fixed cost subsidy can change a monopoly firm's decision toward a CCS adoption decision.

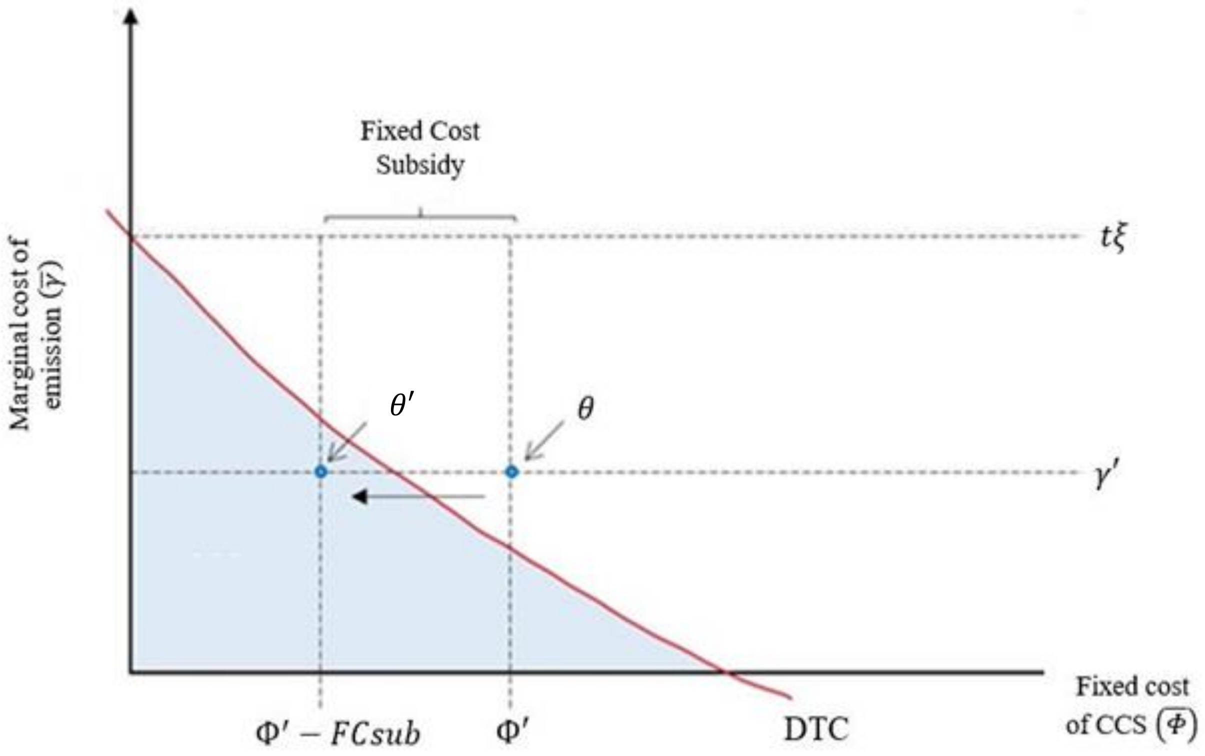


Figure 4 - The effect of a governmental subsidy using the DTC

2.3.5.3 CCS Process Subsidy

Another policy solution that the government can implement is to provide a firm with a production process subsidy for CCS technology.

A production process subsidy aims to decrease the marginal cost of production for using CCS technology. This policy solution affects the position of a coordinate θ in a vertically downward direction as shown in Figure 5. Let us illustrate the effect of the policy solution with another graphical explanation.

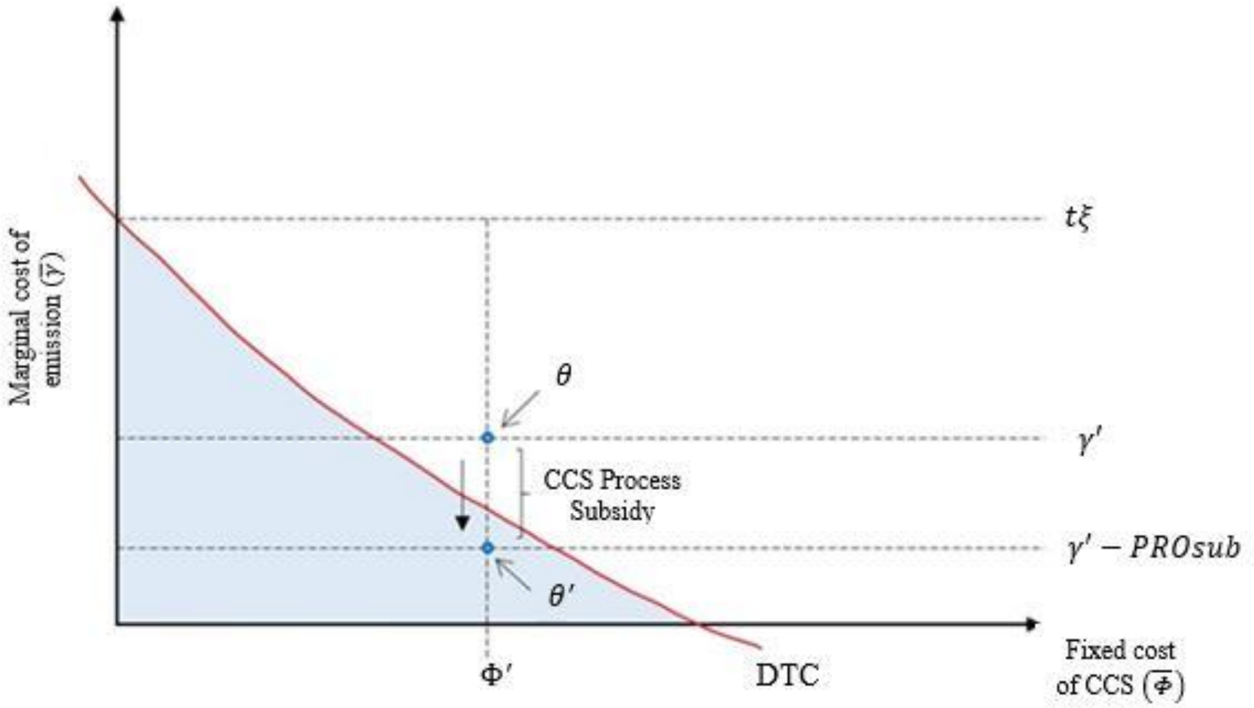


Figure 5 – The effect of a CCS production process subsidy using the DTC

In Figure 5, the initial starting position of an assumed coordinate θ is above the DTC. If a production process subsidy – denoted by $PROsub$ – is given by the government, the policy solution reduces the marginal cost of emission for using CCS technology γ' to $\gamma' - PROsub$. The policy intervention shifts the coordinate θ to a new position θ', where $\theta' = (\gamma' - PROsub, \Phi)$. If the process subsidy is large enough, then θ' can find itself underneath the DTC as displayed in Figure 5. This then signifies that the firm should choose a CCS technology adoption because it has a higher profit than not investing. Overall, a CCS process subsidy is a policy solution that can reduce the marginal cost of production of a firm to use CCS technology, which leads to higher optimal outputs and therefore higher optimal profit.

2.3.5.4 Demand

The final policy lever to increase the incentives for CCS adoption decision is a change in the market demand. In other terms, the government intervenes in the market by manipulating demand. The manipulation of demand is captured by a change in parameter b – the demand slope from the inverse linear demand or equation (2). A change in the demand slope b can be caused mainly by three main factors: (i) a change in the price level, (ii) a change in consumer's income level, or (iii) the availability of substitute products.

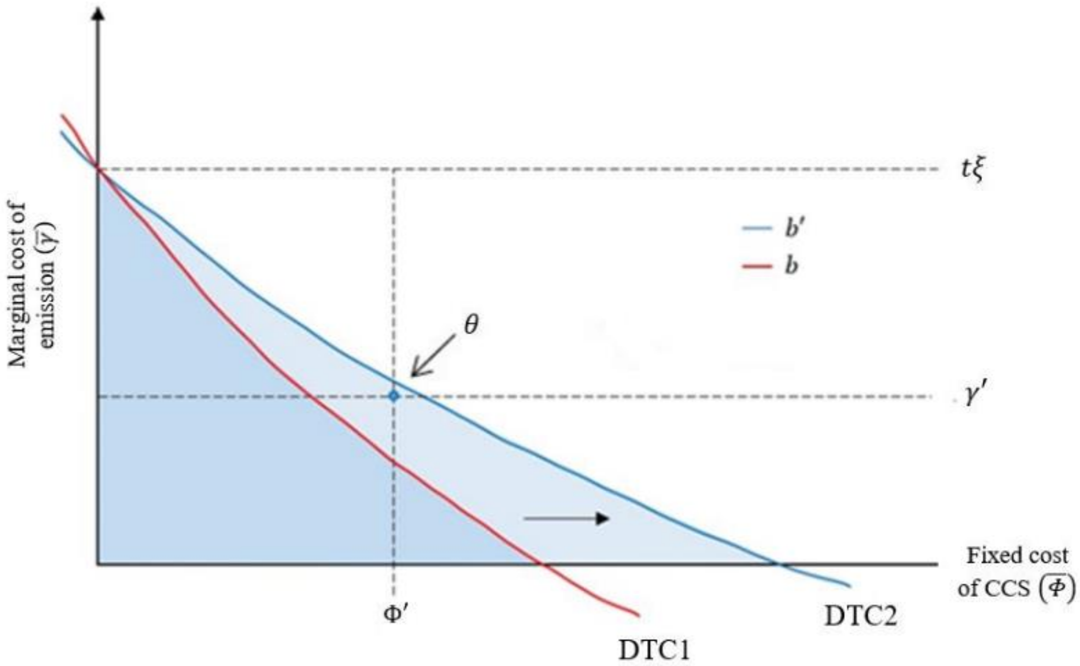


Figure 6 – The effects on the DTC after a change in the demand slope b → b′, where b′ < b

Our interest is only when the change in demand slope increases the area underneath the decision threshold curve. This is achieved by a decrease in parameter $b \to b'$, where $b > b'$. In Figure 6 an assumed coordinate θ, where $\theta = (\gamma', \Phi')$, it is initially located above DTC1 with a demand slope equal to b. However, if b is decreased by the government to b', the coordinate θ can be newly located underneath DTC2. Thus, it is more profitable to adopt CCS technology. A decrease in parameter b means that the elasticity of demand in the market has gone more elastic. A scenario for which this can happen is when the government implements consumer rebates to consumers that use the final product produced by the firm whilst adopting CCS technology. The consumer rebate can increase the brand loyalty of consumers towards the monopoly firm. Especially the fact not only they are producing a final product they need but at the same time, it is more environmentally friendly compared to a carbon dioxide tax strategy.

2.3.6 Social Welfare for a Monopoly Market

In this subsection, the social welfare function of a market in which there is a monopoly firm is presented. The purpose of evaluating social welfare is to learn which production choice – CCS investment or not – chosen by the monopoly firm generates the highest value for society. Evaluating the social welfare function, we can also determine if there should be any government intervention, where the optimal policy solutions can also be obtained.

The social welfare of a market in which there is a monopoly firm – denoted by W_χ – is given by:

$$W_\chi = \textit{Consumer Surplus} + \textit{Monopoly Profits} - \textit{Environmental Damage}$$

where χ is the investment decision of the monopoly firm with $\chi \in \{0,1\}$. The components are:

- The *Consumer Surplus* is equal to

$$CS_\chi = \frac{b\left(\frac{a-\sigma-(1-\chi)t\xi-\chi\gamma}{2b}\right)^2}{2} + (1-\chi)t\xi\left(\frac{a-\sigma-(1-\chi)t\xi-\chi\gamma}{2b}\right) \tag{11}$$

  The first part of the consumer surplus corresponds to the surplus generated by consumers buying the monopoly's final product – i.e., the area under the demand curve and above the market price. The second part of the expression relates to the surplus generated by the government imposing a carbon dioxide tax on the monopoly for emitting into the atmosphere. Thus, we assume that environmental tax revenues are redistributed back to consumers. Notice that when a monopoly firm adopts CCS technology (i.e., $\chi = 1$) no environmental tax revenues are gained by the government.
- The *Monopoly Profits* is equal to equation (6).
- The *Environmental Damage* is

$$\textit{Environmental Damage} = (1-\chi)hq^*\xi \tag{12}$$

where q^* is given by equation (4). The environmental damage is multiplied by a coefficient $h \geq 0$, the marginal social damage from the pollution which translates a firm's emission into monetary units. Coefficient h reflects the degree of environmental concern of the regulator and society. The higher the value of h the greater the environmental damage is perceived by society.

Specifically, the two social welfare functions depending on the investment decision χ chosen by the monopoly firm are:

- If the monopoly firm adopts CCS technology (or $\chi = 1$),

$$W_1 = \frac{3(a - \sigma - \gamma)^2}{8b} - \Phi \quad (13)$$

- If the monopoly decides not to invest in CCS technology (or $\chi = 0$),

$$W_0 = \frac{3(a - \sigma - t\xi)^2}{8b} + \frac{\xi(t - d)(a - \sigma - t\xi)}{2b} \quad (14)$$

2.3.6.1 Analysis of the Social Welfare Results

Having evaluated the social welfare function for a market that is a monopoly market, this leads us to three questions:

1. *Which investment decision chosen by the monopoly firm generates the highest benefit for society*?
2. *What is the optimal carbon dioxide tax that governments should implement?*
3. *What is the threshold damage coefficient h*?

To answer the first question, we illustrate a numerical example of the two social welfare functions – equations (13) and (14) – where the carbon dioxide tax t is considered the function variable. Let us note that only W_0 or equation (14) has the variable t in the expression. Therefore, W_1 will only be a constant value when graphically presented.

Suppose the market size of the monopoly market structure has $a = 120$ and a demand slope $b = 1$. The monopoly firm has a marginal cost of production not involving emission unit cost and unit cost of using CCS technology equal to $\sigma = 30$. The marginal cost of production per unit of product for utilizing CCS technology is $\gamma =$

30. The CO_2 emission intensity produced by a firm per unit of product is equal to $\xi = 1$ and the fixed cost of adopting CCS is $\Phi = 200$. Figure 7 illustrates the graphical result of the social welfare function of a market in which there is a monopoly firm considering different damage coefficients h.

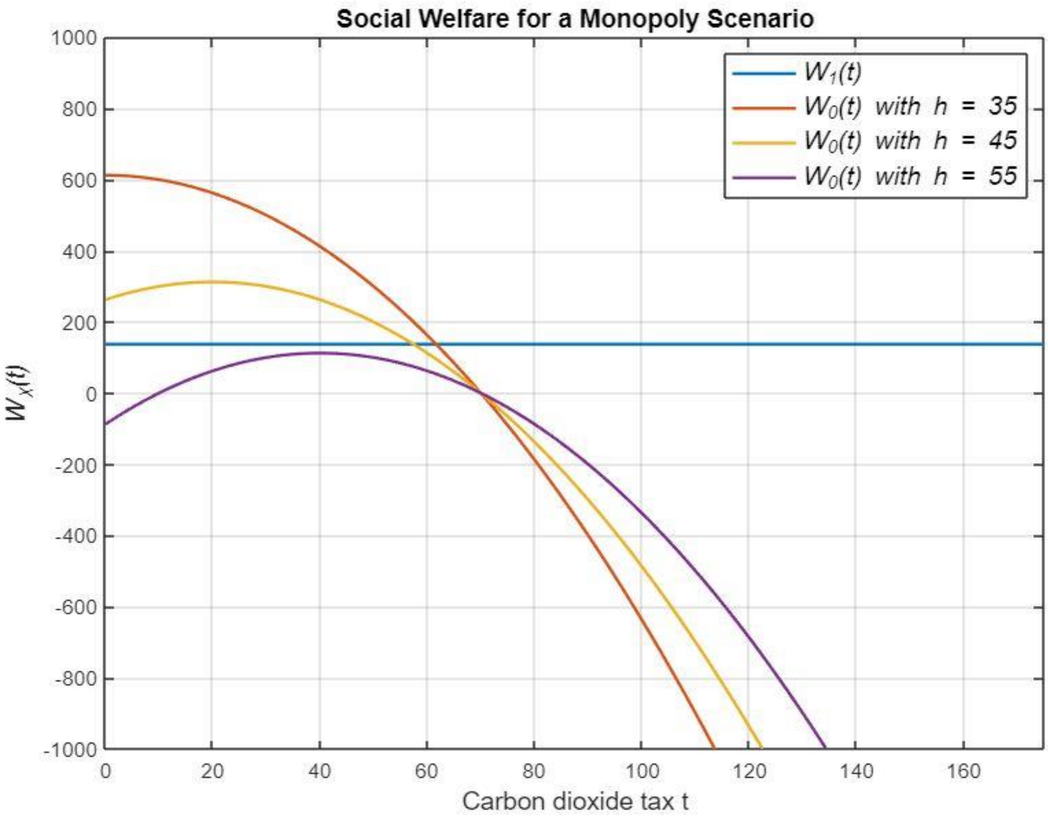


Figure 7 – The social welfare function for the monopoly firm as function of t with different coefficients h, where $h = \{35.45.55\}$

In Figure 7, the blue horizontal line corresponds to $W_1(t)$ or equation (13). The other quadratic curves – red, yellow, and purple – correspond to the social welfare function of $W_0(t)$ with different damage coefficients h. Specifically, with $h \in \{35, 45,55\}$.

To analyse which production strategy produces the highest benefit for society, this is assessed by evaluated by assessing which social welfare function $W_1(t)$ and $W_0(t)$ obtains the highest social welfare value. For example, when $h = 35$ one can easily notice that $W_0(t)$ has several points that are above $W_1(t)$ or the blue line. This then means it is more optimal for society to not have CCS technology adopted as there exist several points where $W_0(t)$ achieves $W_0(t) > W_1(t)$. On the other hand, when the damage coefficient h is high – i.e., $h = 55$ – we find that the social welfare function

$W_0(t)$ is completely below $W_1(t)$. This indicates that the adoption of CCS technology provides a higher benefit for society and therefore CCS technology adoption should be pursued. Overall, we find that as the damage coefficient h increases, the social welfare function $W_0(t)$ decreases. The reason for this is because a high coefficient of h signifies that society values more the environment. Therefore, if the damage coefficient h is high, society is better off with the presence of CCS technology as it can reduce carbon emissions to improve the environment.

Now, let us answer the second question. To find the optimal carbon dioxide tax, one should identify the production strategy which provides the highest social welfare result and then the optimal carbon dioxide tax is evaluated by finding the carbon dioxide tax that maximizes social welfare. However, this is dependent on the level of damage coefficient h.

For example, if society values the environmental damage coefficient $h = 35$. In Figure 7 we can see that there exist several points where it is more optimal for society to not have CCS technology adopted or $W_0(t) > W_1(t)$. Thus, if the damage coefficient achieves the condition that $W_0(t) > W_1(t)$, the optimal carbon dioxide tax – denoted by t^s – that the government should implement is equal to,

$$t^S = \frac{2h\xi - a + \sigma}{\xi} \tag{15}$$

Equation (15) above is obtained by taking the first-order derivative of $W_0(t)$ or equation (14) with respect to t and then solve for t.[11]

In contrast, if society values a high environmental damage coefficient – i.e., $h = 55$. In Figure 7 we can see that $W_1(t) > W_0(t)$ for any $t > 0$. As previously mentioned, $W_1(t)$ does not have a variable t. Therefore, the optimal carbon tax is evaluated by setting the equilibrium profit functions of the monopoly under a CCS adoption decision and carbon dioxide tax strategy equal to each other – i.e., $\pi_1^* = \pi_0^*$ using

[11] Note that the optimal tax t^s is not equal to the marginal damages h. This result is not unique which has been already explored by Nimubona, A.-D. and Sinclair-Desgagné, B. (2005), highlighting that optimal emission tax will depart from the marginal social cost of pollution due to forces such as polluters' and market structures market power.

equation (6). Then, rearranged for t. By doing so, the optimal carbon dioxide tax that the government should implement if the damage coefficient h is high is given by

$$t^* = \frac{a - \sigma - \sqrt{(a - \sigma - \gamma)^2 - 4b\Phi}}{\xi} \tag{16}$$

If the government selects a carbon dioxide tax t that is greater than t^*, the monopoly firm is going to obtain higher equilibrium profits than a carbon dioxide tax strategy. In other words, $\pi_1^* > \pi_0^*$.

Finally, we answer the last question in this subsection. What is the threshold damage coefficient h? To obtain this answer we substitute t with t^s in equation (14) to obtain $W_0(t^s)$. Then, we equate $W_0(t^s) = W_1(t)$ and solved for h. The threshold damage coefficient (denoted by h^*) is given by

$$h^* = \frac{a - \sigma - \sqrt{2\left(\frac{3(a - \sigma - \gamma)^2}{8b} - \Phi b\right)}}{\xi}$$

- If $h < h^*$ this obtains $W_1(t) < W_0(t)$. Thus, CCS technology is not an appropriate strategy benefitting society and therefore, the socially optimal tax should be equal to t^s – equation (15).
- If $h^* < h$ this obtains $W_1(t) > W_0(t)$. This means that CCS technology adoption is more socially optimal to society and the socially optimal tax should be equivalent to t^* – equation (16).

Overall, the results obtained in this subsection such as equations (15) and (16) can be used by governments to determine the optimal carbon dioxide tax to be set depending on the value of the damage coefficient h.

2.3.7 Summary of Findings

This subsection presented an economic model in which the market structure consisted of a monopoly firm that had the option to invest in CCS technology or not. We find that by analysing the profit-maximization results, the equilibrium decision of the monopoly firm is not to invest in CCS technology because of a lack of economic incentives toward a CCS adoption decision. Therefore, in this section, a series of policy solutions were proposed to increase the decision toward a CCS adoption. These were:

1. The government can increase the carbon dioxide tax.
2. The government can provide a fixed cost subsidy to reduce its expensive investment cost of CCS technology.
3. The government can provide a CCS process subsidy where it reduces a firm's marginal cost of using CCS technology.
4. The government can manipulate demand to change consumers' behaviour towards CCS technology.

Overall, CCS technology without stronger policy interventions will never reach its full potential contributing to the Paris Agreement. Furthermore, we also discovered that if society perceives a high degree of environmental concern, then the government and policymakers should pursue CCS technology.

2.4 A Duopoly Scenario

In this section, the second economic model is presented demonstrating the CCS adoption decision where the market structure considered is a duopoly market. The section is divided into smaller subsections. In subsection 2.4.1, the model is described. The profit-maximization results are evaluated in subsection 2.4.2. The decision threshold curve or DTC for a duopoly model is introduced in subsection 2.4.3. In section 2.4.4, the game is analysed. We conclude the section by investigating the social welfare function of a duopoly market in subsection 2.4.5.

2.4.1 Duopoly Model Description

Let us consider two firms producing homogeneous goods denoted by $i = \{1,2\}$. We assume that both firms are identical and have the same option to adopt a CCS technology or not. The main difference between the duopoly model and the monopoly model presented in section 2.3 is that not only there are more firms in the market but the decision-making of a firm in a duopoly market is now affected by the presence of the rival in the market.

The game of the duopoly market proceeds in two constituent stages as displayed in Figure 8.

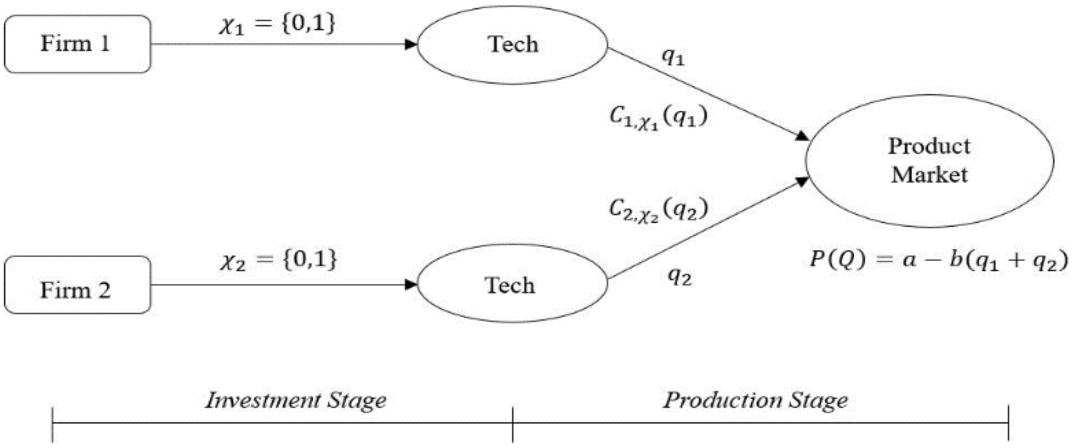


Figure 8 - The 2-stage game for the duopoly market

In the "*investment stage"* both firms simultaneously choose their investment CCS decision, where χ_1 signifies firm 1's investment choice with $\chi_1 \in \{0,1\}$ and χ_2 denotes signifies firm 2's investment choice with $\chi_2 \in \{0,1\}$. When a firm selects whether to adopt CCS or not, a firm i's cost function which is given by

$$C_{i,\chi_i}(q_i) = \big(\Psi + \Phi(\chi_i)\big) + (\sigma + (1 - \chi_i)t\xi + \chi_i\gamma)q_i, \quad \text{with } i = 1,2 \tag{17}$$

The parameters in the cost equation above have the same description as previously described for the monopoly firm in subsection 2.3.1. However, there is an added subscript i in equation (17) to differentiate between the two firms in the duopoly market.

In Figure 8, the next stage in the game is the "*production stage*". This is where the two firms compete in the same product market under Cournot competition.[12] The revenues are realized according to the results of a Cournot-Nash equilibrium where a firm's

[12] The reason for selecting a duopoly with Cournot competition it is because, for the context of CCS technology, the fundamental question that has to be asked is not really: "Do firms choose quantities? Or do firms choose prices?" As we know firms in the real-world firms will likely be choosing prices. Instead, the real question we have to ask: "Do firms have to commit upfront to their capacity or not?" If they do, then the analysis should be modelled with a Cournot analysis, and if they do not it should be under Bertrand's. In my research, we are dealing with industries in which they have large, fixed costs investments that are at least in the short to medium run and not changeable. Therefore, the capacity is somewhat fixed and modelling a la Cournot competition is the respectable candidate for the analysis (Kreps, D.M. and Scheinkman, J.A., 1983).

optimal outputs depend on the outcome of its own investment decision and the rival's decision. Overall, for the duopoly scenario there are 4 possible equilibrium outcomes, which are:

- Both firms investing in CCS technology.
- Firm 1 invests in CCS and firm 2 does not.
- Firm 2 invests in CCS and firm 1 does not.
- Both firms do not invest in CCS technology.

2.4.2 Profit-Maximization

In this subsection, the 2-stage game for the duopoly is solved using backward induction. First, we solve the sub-game perfect Nash equilibrium in the *production stage*, where firm i chooses its output to maximise its profits whilst taking into consideration its rival's decision. The profit function of a firm i is given by

$$\pi_{i,\chi_i}(q_i) = P(Q)q_i - C_{i,\chi}(q_i) \tag{18}$$

where $P(Q)$ is the demand function given by $P(Q) = a - bQ = a - b(q_1 + q_2)$[13]. In a duopoly market under Cournot competition, the standard Nash equilibrium output of a firm i is equal to

$$q_i^* = \frac{a - 2c_{i,\chi_i} + c_{j,\chi_j}}{3b}, \quad i,j = 1,2 \tag{19}$$

where, c_{i,χ_i} represents the marginal cost of production of firm i and c_{j,χ_j} is equal to the marginal cost of production of the rival firm.[14] To obtain the standard Nash equilibrium output above this was achieved by taking the first-order condition of equation (18) for each firm in the duopoly with respect to the firm's output and setting it equal to zero. Then, the expression is rearranged for the firm's output. By doing so, two expressions are obtained which correspond to the best response function of a firm in response to the rival's output decision. Plotting the two best response functions in the same graph, the intersection point is equal to equation (19) or the Cournot-Nash equilibrium. The

[13] For rationality of linear demand function see footnote 10.

[14] For a firm i the marginal cost of production function it is equal to $c_{i,\chi_i} = \frac{dC_{i,\chi_i}}{dq_i} = (\sigma + (1 - \chi_i)t\xi + \chi_i\gamma)$. Interchanging $i \rightarrow j$ one can obtained the marginal cost of production of the rival firm j.

Cournot-Nash equilibrium output is the output produced by a firm i where it maximises its profits whilst taking into consideration its rival's decision. In fact, in equation (19) the output of a firm is affected by its rival as the marginal cost of the rival is present in the equation.

Now, substituting equation (19) into $P(Q)$, we get that the optimal market price is

$$P^*(Q) = \frac{a - c_{i,\chi_i} - c_{j,\chi_j}}{3}, \qquad i,j = 1,2 \tag{20}$$

The optimal market price is affected by both of the firms' marginal costs of production. Finally, substituting equation (19) into equation (18), we get that the optimal profit function of a firm i is equal to

$$\pi^*_{i,\chi_i}(q_i) = \frac{\left(a - 2c_{i,\chi_i} + c_{j,\chi_j}\right)^2}{9b} - \left(\Psi + \Phi(\chi_i)\right), \qquad i,j = 1,2 \tag{21}$$

Overall, what is different from the monopoly scenario is the presence of the firm. Previously, the profit of a monopoly was only affected by its marginal cost of production. In a duopoly, a firm needs to consider its rival decision. For this reason, for the rest of this study, a new notation for the equilibrium profits of a firm i will be introduced. Let us consider instead of π^*_{i,χ_i}, we introduce $\pi^*_{i,\chi_i|\chi_j}$. An additional notation is added in the subscript "$|\ \chi_j$" which illustrates a conditional belief of "*what the rival firm has chosen for its investment decision*" from the investment stage. The reason for this is that the decision-making of a firm in a duopoly market is also going to be affected by the decision of its rival in the market. Therefore, the additional notation in the subscript monitors what the other firm has chosen.

2.4.3 The Decision Threshold Curve for a Duopoly Market

Before analysing the profit maximization results, we investigate the conditions for which a firm in the duopoly firm will adopt CCS using the concept of the decision threshold curve or DTC.

In subsection 1.3.4, the DTC for a monopoly market was introduced. For the duopoly case since firms are being strategic, an additional statement is necessary to define the

DTC of a firm in a duopoly market: "*whilst there is a fixed belief of the rival's investment decision for its carbon emission strategy*." Hence,

DEFINITION 2 (***Decision Threshold Curve of a firm in a Duopoly***) – *The decision threshold curve demonstrates the locus of points of the marginal cost of production using CCS technology* (γ) *and for a fixed upfront cost of CCS* (Φ), *where the optimal profits of a firm in a duopoly are the same under a carbon dioxide tax and for adopting a CCS technology, whilst there is a fixed belief of the rival's investment decision for carbon emission strategy.*

For the duopoly scenario, a firm obtains two decision threshold curves. Let us assume firm 1. The first DTC for firm 1, whilst it has a fixed belief that firm 2 is going to choose a carbon dioxide tax – denoted by $\gamma_{1,1|0}(\Phi_1)$ – is given by

$$\gamma_{1,1|0}(\Phi) = \frac{a-\sigma+t\xi}{2} - \frac{1}{2}\sqrt{(a-t\xi-\sigma)^2+9b\Phi} \tag{22}$$

The expression above is obtained setting $\pi^*_{1,1|0} = \pi^*_{1,0|0}$, rearranging for γ and then considering γ as a function of Φ, the fixed cost of CCS. In equation (22), the left-hand side of equation (22) represents the marginal benefit of adopting CCS technology for firm 1, whereas the right-hand side is the marginal benefit of a carbon dioxide tax strategy given firm 2 is going to choose a carbon dioxide tax.

The second DTC for firm 1 is denoted by $\gamma_{1,1|1}(\Phi)$ where there is a fixed belief that firm 2 is going to adopt a CCS technology is given by

$$\gamma_{1,1|1}(\Phi) = \frac{4t\xi(a-\sigma-t\xi)-9b\Phi}{4(a-\sigma-t\xi)} \tag{23}$$

Expression (23) is obtained setting $\pi^*_{1,1|1} = \pi^*_{1,0|1}$, rearranging for γ and considering γ as a function of Φ, the fixed cost of CCS. Similarly, the left-hand side of the equation (23) represents the marginal benefit of adopting CCS technology for firm 1, whereas the right-hand side is the marginal benefit of a carbon dioxide tax strategy given firm 2 is going to choose a carbon dioxide tax.

Plotting the two decision threshold curves in the same graph, an example behaviour of the DTC function for firm 1 is shown in Figure 9 below.

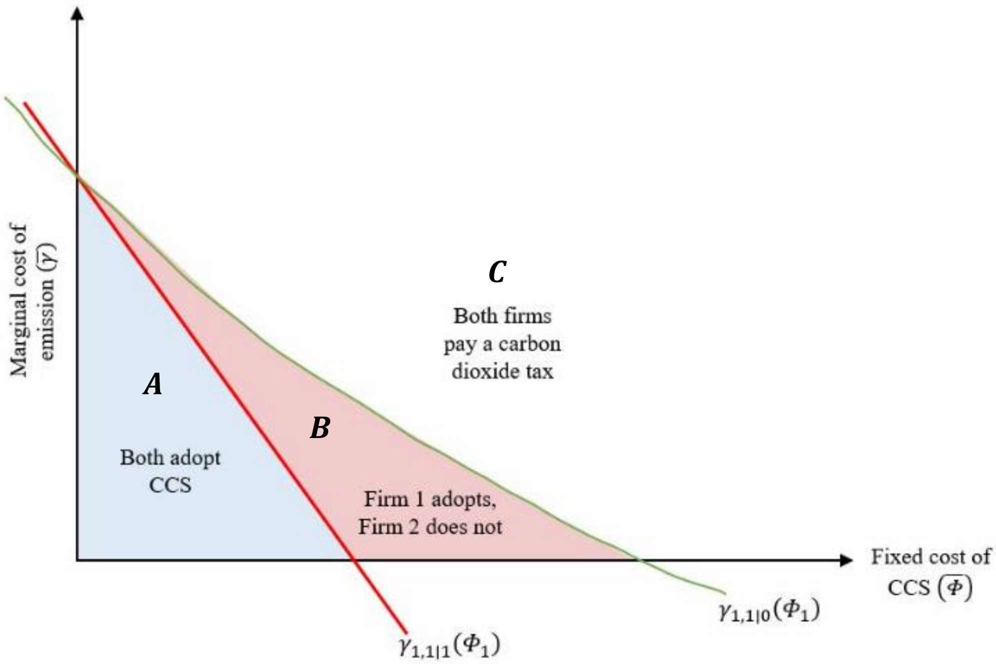


Figure 9 – The decision threshold curves for firm 1 competing in a duopoly market under Cournot competition.

In Figure 9 the green line is equivalent to $\gamma_{1,1|0}(\Phi)$ and the red line is equal to $\gamma_{1,1|1}(\Phi)$. Figure 9 illustrates the best response decision of firm 1 in response to the action that is chosen by firm 2, where there are three distinct regions: $\boldsymbol{A}$, $\boldsymbol{B}$ and $\boldsymbol{C}$.

If a coordinate finds itself below $\gamma_{1,1|1}(\Phi)$ or is in the region $\boldsymbol{A}$, this means that firm 1 is better off investing in CCS technology as it is more profitable than choosing a carbon dioxide tax strategy. Also, since $\gamma_{1,1|1}(\Phi)$ has the condition that a fixed belief that firm 2 is going to adopt a CCS technology we also achieve an equilibrium outcome where both firms are adopting a CCS technology.

If a coordinate finds itself above $\gamma_{1,1|1}(\Phi)$ but below $\gamma_{1,1|0}(\Phi)$ or it is inside region $\boldsymbol{B}$, this represents that firm 1 should invest in CCS technology as it is more profitable than a carbon dioxide tax strategy. In this case, the equilibrium outcome of the game produces heterogeneous adoption as there was a fixed belief that firm 2 is going to do a carbon dioxide tax.

Finally, if a coordinate finds itself above $\gamma_{1,1|0}(\Phi)$ or is in the region $\boldsymbol{C}$, firm 1 is better off not investing in CCS technology. This outcome obtains an equilibrium outcome in the game where both firms are choosing a carbon dioxide tax strategy as it is more profitable to do so.

Overall, the purpose of the DTC for the duopoly market illustrates a simple decision-making tool where a firm can identify its optimal strategy for adopting CCS technology or not, whilst there is a fixed belief on the rival's investment decision.

2.4.4 Equilibrium Analysis

In this subsection, we investigate the equilibrium outcome of the duopoly game by examining the profit functions of the firms in a duopoly obtained in subsection 1.4.2. As previously mentioned, in the duopoly game there are four possible equilibrium outcomes that the two firms can achieve from the two-stage game. This can also be represented by the pay-off matrix as displayed in Table 1.

		Firm 2	
		CCS	**TAX**
Firm 1	**CCS**	$\left(\pi^*_{1,1\|1}, \pi^*_{2,1\|1}\right)$	$\left(\pi^*_{1,1\|0}, \underline{\pi^*_{2,0\|1}}\right)$
	TAX	$\left(\underline{\pi^*_{1,0\|1}}, \pi^*_{2,1\|0}\right)$	$\left(\underline{\pi^*_{1,0\|0}}, \underline{\pi^*_{2,0\|0}}\right)$

Table 1–- Payoff Matrix for Stage 1

2.4.4.1 Equilibrium Outcome under Real-World

In Table 1 notice that the pay-off matrix has a Nash equilibrium equal to both firms choose not to invest in CCS technology or (TAX, TAX). The reason for obtaining this equilibrium outcome is due to the current economic state of CCS technology. As previously mentioned, CCS technology has an expensive investment cost to adopt. Thus, in the model, the fixed cost of CCS or Φ is extremely large. Furthermore, in some industries the marginal cost for using CCS or γ, it is more expensive than choosing a carbon dioxide tax strategy. With the latter two discussed factors, then neither firm in the duopoly market is going to have any incentives to adopt a CCS technology. Therefore, what we obtain is a dominant strategy where both firms are not investing in CCS technology or choosing a carbon dioxide tax strategy. However, this thesis aims to find solutions for increasing the incentives for CCS adoption decisions.

In the next subsection, we investigate the conditions such that firms will be choosing to adopt a CCS technology.

2.4.4.2 Equilibrium Outcome with CCS Adoption

In this subsection, we evaluate the necessary circumstances for obtaining a CCS adoption decision where firms are in a competitive market. We seek to find the answers to two questions:

1. *Assuming firm* 1*, what are the conditions such that firm* 1 *is going to invest in CCS technology whilst firm 1 has a fixed belief that firm* 2 *is not going to adopt CCS technology or* $\chi_2 = 0$*?*
2. *Assuming firm* 1*, what are the conditions such that firm* 1 *is going to invest in CCS technology whilst firm 1 has a fixed belief that firm* 2 *is going to adopt a CCS technology or* $\chi_2 = 1$*,?*

2.4.4.3 A fixed belief that firm 2 does not invest in CCS

Assuming firm 1, the first outcome investigated is what are the conditions such that firm 1 is going to invest in CCS technology whilst there is a fixed belief that firm 2 is not going to adopt CCS technology or $\chi_2 = 0$. Let us note that satisfying the previously mentioned inequality, is equivalent to obtaining an equilibrium outcome where the two firms are going to have heterogeneous equilibrium adoption. Specifically, firm 1 invests in CCS technology whilst firm 2 does not. In the duopoly game, there are two cases of a heterogenous Nash equilibrium as displayed in Table 2 below.

		Firm 2	
		CCS	**TAX**
Firm 1	**CCS**	$(\pi^*_{1,1\|1}, \pi^*_{2,1\|1})$	$(\underline{\pi^*_{1,1\|0}}, \underline{\pi^*_{2,0\|1}})$
	TAX	$(\underline{\pi^*_{1,0\|1}}, \underline{\pi^*_{2,1\|0}})$	$(\pi^*_{1,0\|0}, \pi^*_{2,0\|0})$

Table 2 – Normal form game where the Nash equilibrium is with firms choosing heterogeneous carbon emission strategies.

To obtain a heterogeneous equilibrium outcome – i.e., firm 1 adopts CCS and firm 2 does not – two conditions are required: $\pi^*_{1,1|0} > \pi^*_{1,0|0}$ and $\pi^*_{2,0|1} > \pi^*_{2,1|1}$.

Setting the full inequality of $\pi^*_{1,1|0} > \pi^*_{1,0|0}$ we get

$$\frac{\left(a-2(\sigma+\gamma)+(\sigma+t\xi)\right)^2}{9b}-\Phi>\frac{\left(a-2(\sigma+t\xi)+(\sigma+t\xi)\right)^2}{9b}.$$

Then, rearranging for γ, we get the first parametric condition

$$\gamma<\frac{a-\sigma+t\xi}{2}-\frac{1}{2}\sqrt{(a-\sigma-t\xi)^2+9b\Phi} \tag{24}$$

Also, setting the full inequality of $\pi^*_{2,0|1}>\pi^*_{2,1|1}$ we get

$$\frac{\left(a-2(\sigma+t\xi)+(\sigma+\gamma)\right)^2}{9b}>\frac{\left(a-2(\sigma+\gamma)+(\sigma+\gamma)\right)^2}{9b}-\Phi$$

Isolating for γ on one side, we get the second parametric condition

$$\gamma>\frac{4t\xi(a-\sigma-t\xi)-9b\Phi}{4(a-\sigma-t\xi)} \tag{25}$$

Overall, to achieve a heterogeneous equilibrium adoption such as firm 1 adopts CCS and firm 2 does a carbon dioxide tax strategy, firm 1 needs a marginal cost of CCS or γ satisfying the condition (24). Whereas firm 2 needs to satisfy the condition (25).

However, let us recall that in the model we assumed that the two firms are assumed to be identical. Thus, this leads us to the question: "*How is it possible to have an equilibrium with heterogeneous adoptions?"* The only option to obtain a heterogenous adoption is for governments to implement policy solutions as presented in section 1.3.5 that only affects the decision of a singular firm in the duopoly market. The corresponding policy solutions that allow this is through a fixed cost subsidy ($FCsub$) or a CCS process subsidy ($PROsub$).

For example, let us assume that the government intervenes by giving a fixed cost subsidy only to firm 1. The presence of a fixed cost subsidy affects the right-hand side of the equation (24),

$$\gamma<\frac{a-\sigma+t\xi}{2}-\frac{1}{2}\sqrt{(a-\sigma-t\xi)^2+9b(\Phi-FCsub)}$$

If $FCsub$ is sufficiently large enough, firm 1 can attain $\pi^*_{1,1|0}>\pi^*_{1,0|0}$. On the other hand, firm 2 has no choice but to choose a carbon dioxide tax strategy as it is the dominant strategy previously discussed in section 2.4.4.

If a CCS process subsidy is given by the government, the following affects the left-hand side of equation (24),

$$\gamma - PROsub < \frac{a-\sigma+t\xi}{2} - \frac{1}{2}\sqrt{(a-\sigma-t\xi)^2 + 9b\Phi}$$

Equally, if $PROsub$ is sufficiently large enough, firm 1 has the incentives to adopt a CCS technology as it provides higher profits than choosing not to invest in CCS.

Overall, the two policy solutions discussed in the subsection can achieve a heterogeneous equilibrium adoption. In the real world, a possibility of how this scenario can occur is where governments can increase the deployment of CCS technology with a competition selecting a firm with the best project for initiating the roll-out of CCS technology. For example, in the UK, Peterhead power station and the White Rose scheme in North Yorkshire were in the running to win the £1bn contract for carbon capture and storage technology[15]. Although the competition was cancelled in 2015, if the competition went forward there would have been a situation where the government aided a single firm in the adoption of CCS technology.

2.4.4.3.1 A fixed belief that firm 2 invests in CCS

Assuming again firm 1, the second outcome investigated is what are the conditions such that firm 1 is going to invest in CCS technology whilst there is a fixed belief that firm 2 is going to adopt CCS technology or $\chi_2 = 1$. The corresponding Nash equilibrium outcome for this case is when both firms select a CCS adoption strategy as illustrated in Table 3.

		Firm 2	
		CCS	**TAX**
Firm 1	**CCS**	$\left(\underline{\pi^*_{1,1\|1}}, \underline{\pi^*_{2,1\|1}}\right)$	$\left(\underline{\pi^*_{1,1\|0}}, \pi^*_{2,0\|1}\right)$
	TAX	$\left(\pi^*_{1,0\|1}, \underline{\pi^*_{2,1\|0}}\right)$	$\left(\pi^*_{1,0\|0}, \pi^*_{2,0\|0}\right)$

Table 3–- Normal form game where the Nash equilibrium is when both firms choose the adoption of CCS technology.

[15] "UK Government Spent £100m on Cancelled Carbon Capture Project." BBC News, 20 Jan. 2017. https://www.bbc.com/news/uk-scotland-scotland-business-38687835.

To obtain an equilibrium outcome where both firms are going to adopt a CCS technology, two conditions are required: $\pi^*_{1,1|1} > \pi^*_{1,0|1}$ and $\pi^*_{2,1|1} > \pi^*_{2,0|1}$.

The full inequality of $\pi^*_{1,1|1} > \pi^*_{1,0|1}$ is equal to

$$\frac{\big(a - 2(\sigma + \gamma) + (\sigma + \gamma)\big)^2}{9b} - \Phi > \frac{\big(a - 2(\sigma + t\xi) + (\sigma + \gamma)\big)^2}{9b}$$

Isolating for γ on one side, we obtain

$$\gamma < \frac{4t\xi(a - \sigma - t\xi) - 9b\Phi}{4(a - \sigma - t\xi)} \tag{26}$$

The full inequality $\pi^*_{2,1|1} > \pi^*_{2,0|1}$ and then rearranging for γ, is the same expression as the obtained result above or expression (26). The reason for this is because let us recall that the firms in the duopoly market are assumed to be identical.

Therefore, to obtain an equilibrium outcome where both firms adopt a CCS technology, firm 1 and firm 2 need to satisfy expression (26). If expression (26) is attained, this means that there is a dominant strategy where the two firms are going to adopt a CCS strategy. However, "*how can this equilibrium outcome be achieved?*" The simplest solution to achieve this is by implementing stricter environmental regulations. Increasing the carbon dioxide tax high enough such that the marginal cost of production doing CCS is lower than a carbon dioxide strategy or $t\xi > \gamma$. The government can easily adopt this which is the adoption of the first-best policy solution to increase the incentives of firms in the duopoly market to choose CCS adoption decisions. However, in certain cases, the first-best policy solution is not always achieved, and the next best options are second-best policies. For example, if the carbon dioxide tax has been changed by the government but it is still not sufficiently high enough to incentivise CCS technology then governments can additionally support the adoption of CCS technology by aiding the firms with further policies such as a fixed cost or production subsidies.

2.4.5 Social Welfare for a Duopoly Market

In this subsection, the social welfare of a market that is a duopoly is evaluated. The social welfare of a market that is a duopoly is given by:

$$W_{\chi_i,\chi_j} = \textit{Consumer Surplus} + \textit{Equilibrium Profits} - \textit{Environmental Damage}$$

where the first parameter in the subscript of W_{χ_i,χ_j} indicates firm i's investment decision χ_i, with $\chi_i \in \{0,1\}$. Next, is the firm j's investment decision χ_j, with $\chi_j \in \{0,1\}$.

The individual components in the social welfare W_{χ_i,χ_j} are:

- The *Consumer Surplus* of a market that is a duopoly is equal to

$$CS_{\chi_i,\chi_j} = \frac{2\big(a - \sigma - 2\big((1-\chi_i)t\xi + \chi_i\gamma\big) + \big(1-\chi_j\big)t\xi + \chi_j\gamma\big)^2}{9b} + t\xi\left((1-\chi_i)(q_i^*) + \big(1-\chi_j\big)\big(q_j^*\big)\right) \tag{27}$$

  where q_i^* and q_j^* is equal to equation (19) which depends on chosen the investment decision χ_i and χ_j by the firms.
- The *Equilibrium Profit* of a firm in a duopoly is equal to equation (21).
- The *Environmental Damage* of the duopoly market is equal to

$$\textit{Environmental Damage} = (1-\chi_i)hq_i^*\xi + \big(1-\chi_j\big)hq_j^*\xi \tag{28}$$

  The first component corresponds to the environmental damage created by firm i, where q_i is equal to equation (19) and multiplied by coefficient $h \geq 0$, the marginal social damage from the pollution translates firm i's emission into monetary units. The second component is equal to the environmental damage created by firm j, q_j is equal to equation (19) and multiplied by coefficient $h \geq 0$, the marginal social damage from pollution.

For a duopoly market, there are four social welfare functions. The first social welfare function corresponds to when both firms decide not to invest in CCS technology – i.e., $\chi_i = \chi_j = 0$ – it is equal to

$$W_{0,0} = \frac{2(t\xi + \sigma - a)\left(\left(h - \frac{t}{3}\right)\xi - \frac{2a}{3} + \frac{2\sigma}{3}\right)}{3b} \quad (29)$$

The second social welfare function when both firms invest in CCS technology – i.e., $\chi_i = \chi_j = 1$ – it is equal to

$$W_{1,1} = \frac{4(a - \sigma - \gamma)^2}{9b} - 2\Phi \quad (30)$$

The third social welfare function is when firm 1 chooses to invest in CCS but firm 2 does not – i.e., $\chi_i = 1$ and $\chi_j = 0$ – it is equal to

$$W_{1,0} = \frac{1}{18b}\left((12ht - t^2)\xi^2 + \xi\left(6\sigma\left(h + \frac{t}{3}\right) - a(6h + 2t) - \gamma(6h + 8t)\right) + 8a^2 - a(8\gamma + 16\sigma) - 18\Phi b + 11\gamma^2 + 8\sigma\gamma + 8\sigma^2\right) \quad (31)$$

The last social welfare function is the opposite investment decision of the above or $\chi_i = 1$ and $\chi_j = 0$. Since the firms in the duopoly market are assumed to be identical, then the final social welfare function is exactly given by equation (31). In other words, $W_{1,0} \equiv W_{0,1}$.

2.4.5.1 Analysis of the Social Welfare Results

To evaluate optimal outcomes for society in the duopoly market, the three social welfare equations (29), (30) and (31) are graphed where the carbon dioxide tax or t is the function variable.

Suppose the market size of the duopoly market structure is equal to $a = 120$ with a demand slope $b = 1$. The marginal cost of production not involving emission unit cost and unit cost of using CCS technology is equal to $\sigma = 30$. The marginal cost of production per unit of product for utilizing CCS technology is $\gamma = 30$. The CO_2 emission intensity produced by firm 1 per unit of product is equal to $\xi = 1$. The fixed of adopting CCS is equal to $\Phi = 200$ and the damage coefficient is $h = 35$. Using the parameters, the graphical behaviour of the three social welfare functions as a function of t is displayed in Figure 10 – see Appendix B for MATLAB code.

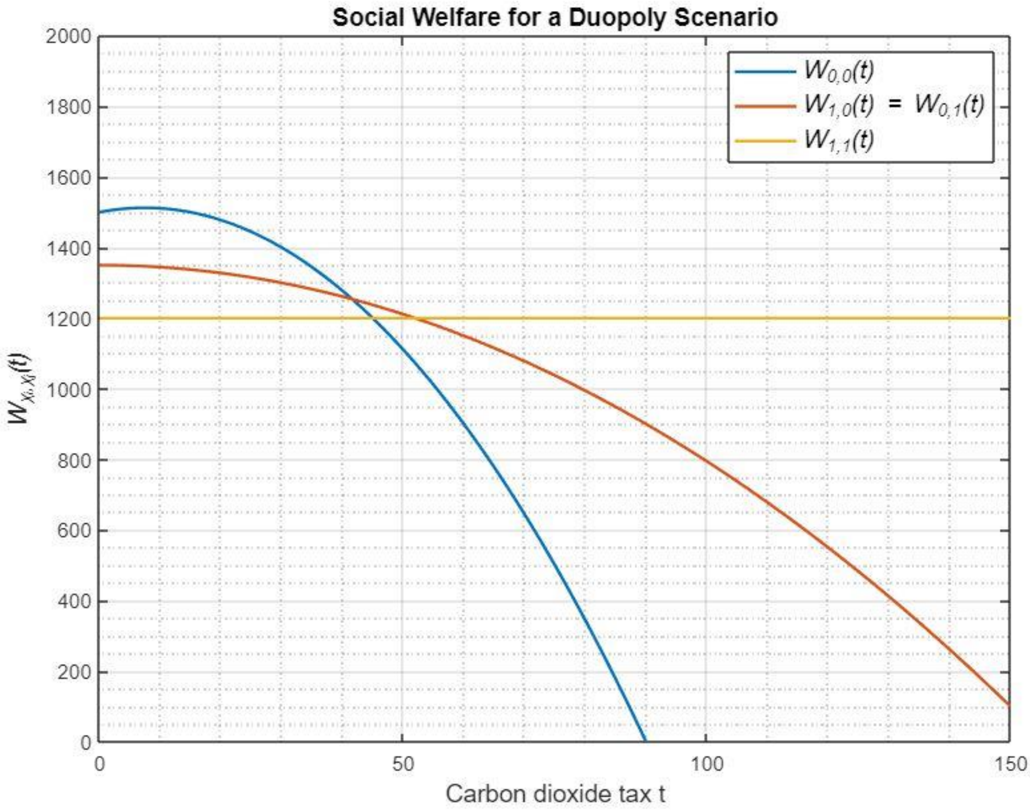


Figure 10 - Social welfare functions for the duopoly market with a damage coefficient $h = 35$

To investigate the graphical result obtained in Figure 10, we examine two assessments of the social welfare functions:

- $W_{0,0}(t)$ vs. $W_{1,0}(t)$ – blue line vs. red line
- $W_{0,1}(t)$ vs. $W_{1|1}(t)$ – red line vs. yellow line

2.4.5.1.1 $\boldsymbol{W_{0,0}(t)}$ vs. $\boldsymbol{W_{1,0}(t)}$

In Figure 10, when the damage coefficient is equal to $h = 35$, the highest social welfare result between $W_{0,0}(t)$ and $W_{1,0}(t)$ is given by $W_{0,0}(t)$. The reason for this is because the maximum of $W_{0,0}(t)$ is greater than the maximum of $W_{1,0}(t)$. In other words, or $\max W_{0,0}(t) >$ or $\max W_{1,0}(t)$. Therefore, society is better off without CCS technology in the market.

With $\max W_{0,0}(t) > \max W_{1,0}(t)$, the optimal social carbon dioxide tax the government should implement is evaluated by taking the first-order derivative of

$W_{0,0}(t)$ with respect to t, set equal to zero and rearranged for t. By doing so, the optimal social carbon tax that the government should is equal to

$$t_0^S = \frac{3h\xi - a + \sigma}{2\xi} \tag{32}$$

The subscript 0 in the expression above denotes the number of firms adopting CCS technology. For $t_0^S > 0$ the damage coefficient should be equal to $h > \frac{a-\sigma}{3\xi}$.

The maximum point of $W_{1,0}(t)$ is equal to

$$t_1^S = \frac{6h\xi - a - 4\gamma + \sigma}{\xi} \tag{33}$$

The expression above is obtained by taking the first-order derivative of $W_{1,0}(t)$ with respect to t and then rearranged for t. For $t_1^S > 0$, the damage coefficient should be equal to $h > \frac{a-\sigma+4\gamma}{6\xi}$.

To obtain the reverse condition – i.e., $\max W_{0,0}(t) < \max W_{1,0}(t)$ – the necessary condition for some damage coefficient h needs to be greater than h_1^*, we get

$$h_1^* = \frac{\gamma + \frac{\sqrt{6\Phi b}}{3}}{\xi}$$

The expression above is obtained by firstly substituting t with t_0^s in equation (29) to obtain $W_{0,0}(t_0^s)$. Secondly, we substitute t with t_1^s in equation (31) to obtain $W_{1,0}(t_1^s)$. Thirdly, equate $W_{0,0}(t_0^s) = W_{1,0}(t_1^s)$ and finally solve for h.

Overall, what we learn here is that if a damage coefficient h is below h_1^* then the government has no incentives to pursue further actions to increase the adoption of CCS technology. This is because both firms not adopting CCS in the duopoly market produces a higher benefit for society. On the other hand, if for some $h > h_1^*$ then the government should intervene to increase the incentives toward CCS adoption decision with policy solutions as previously discussed in subsection 1.3.5.

2.4.5.1.2 $W_{0,1}(t)$ vs. $W_{1,1}(t)$

In the numerical example shown in Figure 10, when the damage coefficient is valued at $h = 35$, the highest social welfare result between $W_{0,1}(t)$ and $W_{1,1}(t)$ is given by

$W_{0,1}(t)$. Let us recall that $W_{0,1}(t) \equiv W_{1,0}(t)$, due the fact the two firms in the duopoly market were assumed identical. Therefore, since $W_{0,1}(t) > W_{1,1}(t)$ the corresponding optimal carbon dioxide tax is equal to t_1^s or equation (33).

To achieve the reverse condition – i.e., $\max W_{0,1}(t) < \max W_{1,1}(t)$ – two conditions are needed to be fulfilled at the same time.

1. First, the damage coefficient h must be greater than h_2^*, where

$$h_2^* = \frac{3(a - \sigma + 3\gamma) - \sqrt{5(a - \sigma - \gamma)^2 - 72\Phi b}}{12\xi}, \tag{34}$$

   The expression above is obtained by substituting t with t_1^s in equation (29) to obtain $W_{1,0}(t_1^s)$. Then, we set $W_{1,0}(t_1^s)$ equal to $W_{1,1}(t)$ and rearrange for h.

2. Second, the fixed cost of adoption of CCS technology needs also to satisfy the condition below

$$\Phi^* < \frac{5(a - \sigma - \gamma)^2}{72b}$$

   The expression above is obtained by inputting firstly h_2^* into t_1^s or equation (33) obtaining $t_1^s(h_2^*)$. Then, we substitute t with $t_1^s(h_2^*)$ in equation $W_{1,0}(t)$. Finally, we set $W_{1,0}(t_1^s(h_2^*))$ equal to $W_{1,1}(t)$ and rearragned for Φ. If for some $\Phi > 0$, where $\Phi > \Phi^*$, then there are no solutions regardless of any environmental damage coefficient h such that the welfare of both firms adopting CCS is greater than a heterogeneous technological adoption.

Overall, if both two conditions are satisfied above, the optimal social carbon dioxide tax that should be implemented by the government is equal to

$$t_2^S = \frac{4\gamma(a - \sigma - \gamma) + 9\Phi b}{4\xi(a - \sigma - \gamma)} \tag{35}$$

The above is obtained by equating $\pi_{1,1|1}^* = \pi_{1,0|1}^*$ and then rearranged for variable t. Thus, if for some t, where $t > t_2^S$ then both firms are incentivised to adopt CCS technology as it is more profitable than not investing in CCS.

2.5 Comparison of Market Structures

This section aims to compare the two market structures investigated in this study to analyse the effects of competition on a firm's decision in adopting CCS technology. Two questions are answered in this section:

- *What is the key difference in the adoption decision of CCS technology between a monopoly market and a duopoly market?*
- *Which market form promotes the highest incentives to adopt CCS technology?*

2.5.1 Direct and Strategic Effect

The apparent difference between a monopoly and a duopoly is the number of firms that is present in the market. A duopoly market has two firms in the market, whereas a monopoly is only a single firm in its market. In other words, the difference between the two market structures is that a duopoly market has the presence of competition, whereas a monopoly does not experience any competition. In a competitive environment, a firm's decision making is not only affected by its own strategic choice but also by the strategy that will be chosen by its rival in the market. Thus, the presence of a rival in the market has an influence on the strategic choice of a firm when a market is competitive.

Another difference between a monopoly and a duopoly market structure involved in the technology adoption such as CCS technology, a duopoly market experiences two effects. The first effect is called a direct effect which is the reduction of a firm's unit cost of production using CCS if the adoption of CCS technology lowers a firm's marginal cost of production. Let us note that the direct effect is experienced both in a monopoly and duopoly market. However, if a market is a duopoly, a second effect that is exclusive to a competitive market is called the strategic effect. The strategic effect is, if the adoption of CCS technology lowers a firm's marginal cost of production, thus making the firm more competitive in the market. Then, this adversely affects the output of the rival which then increases the CCS adopting firm's profit in question. The latter description is the strategic effect. Thus, what one learns here is:

FINDING 1–- *When the adoption of CCS technology lowers a firm's marginal cost, a firm in a competitive market has a greater incentive to adopt CCS technology because of two gained benefits, a direct and strategic effect.*

2.5.2 Monopoly versus Duopoly

In this subsection, we respond to the research question: "*Which market form promotes the highest incentives to adopt CCS technology?"* To answer the research equation, we achieve this by comparing the decision threshold curve for the monopoly firm – equation (8)–- against the decision threshold curves for a firm in a duopoly market – equations (22) and (23).

2.5.2.1 Comparison 1 – "A low carbon dioxide tax"

Suppose the market size $a = 120$, with a demand slope $b = 1$, the standard production variable cost is $\sigma = 50$ and the CO_2 emission intensity produced by a firm per unit of product is equal to $\xi = 1$. Furthermore, let us consider the carbon dioxide tax set by the government is set equal to $t = 15$. The carbon dioxide tax assumed here is relatively low. The reason for this is to reflect what is currently happening now behind a CCS adoption decision. Let us recall that the current economic incentives such as the carbon dioxide tax are not high enough to incentivise firms to adopt a CCS technology.

Using the stated exogenous parameters, the graphical result of all the decision threshold curves in the same graph is displayed in Figure 11.

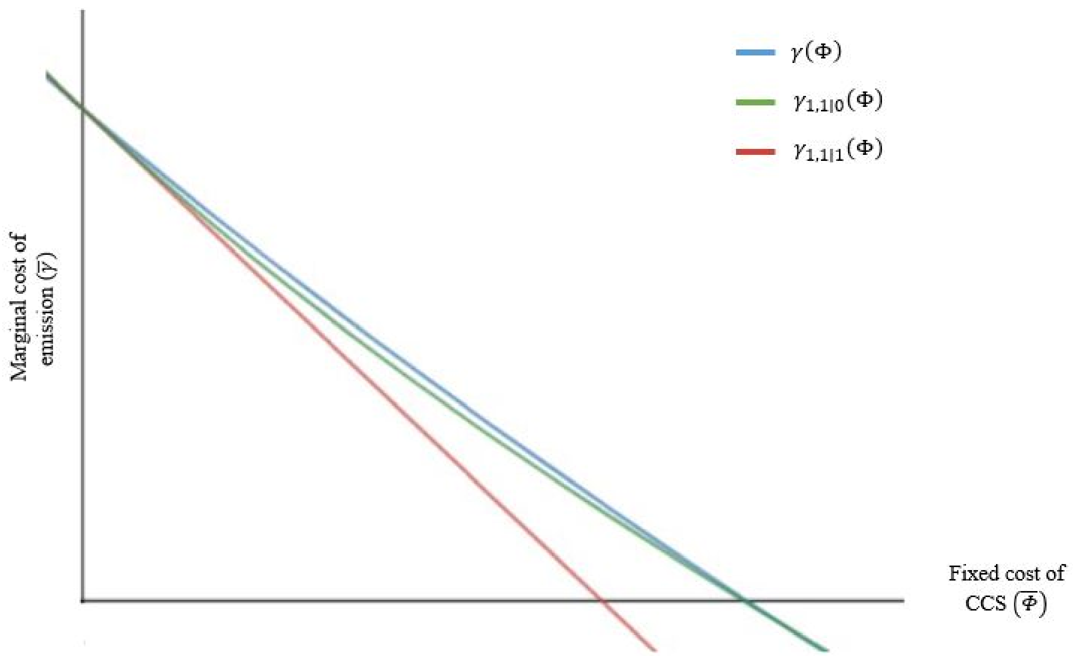


Figure 11 – Comparison 1. Plot of the decision threshold curves for a monopoly firm and for a firm 1 in a duopoly market, where $a = 120$, $b = 1$, $\sigma = 50$, $\xi = 1$ and $t = 15$

In Figure 11, when the carbon dioxide tax is exceptionally low the market structure that allows the highest success for CCS deployment is a monopoly market. The reason for this result is that a monopoly market generates the largest area under the decision threshold curve. One can notice that the decision threshold curve for a monopoly firm or $\gamma(\Phi)$ (or the blue line) is always strictly above the other two decision threshold curves for a firm in a duopoly market, $\gamma_{1,1|0}(\Phi)$ and $\gamma_{1,1|1}(\Phi)$ (the green and red line). Hence, what is learned here is:

FINDING 2 – *When the carbon dioxide tax is low, governments or policymakers should target a market industry that has no competition to increase the deployment of the CCS technology because it is less expensive to achieve CCS adoption decisions for a firm if policy solutions are implemented.*

For example, let us assume a coordinate $\theta = (\Phi', \gamma')$. The initial starting position of coordinate θ is located above all the decision threshold curves in Figure 11. If the government intervenes with a fixed cost or production process subsidy which only affects the position of coordinate θ, the first curve in which the coordinate θ is going to be underneath a decision threshold curve is the DTC of a monopoly market or $\gamma(\Phi)$.

Furthermore, even though coordinate θ relocates underneath the decision threshold curves $\gamma(\Phi)$ and $\gamma_{1,1|0}(\Phi)$ but not $\gamma_{1,1|1}(\Phi)$. Once again, we still realize that the market structure that the government should select to increase the deployment of CCS technology is a monopoly market. The reason for this outcome is due to the fact more CCS activity or the amount of carbon captured and mitigated to the atmosphere is larger under a monopoly market. In firms in a duopoly, the optimal outputs are not only affected by its own initial investment decision which then determines its production process cost but also the output decision of a firm is affected by the presence of the rival's activity in the market. Overall, the output produced by a firm under competition is going to be less compared to a monopoly market, which in return also means that if the government selects to help a firm in a competitive environment less carbon emission is then going to be mitigated.

2.5.2.2 Comparison 2 – “A high carbon dioxide tax”

In Comparison 2, we consider the same exogenous parameters selected for Comparison 1 apart from the carbon dioxide tax. In Comparison 2, the carbon dioxide tax t is assumed to be equal to $t = 30$. The plot of the decision threshold curves considering the stated parameters is displayed in Figure 12.

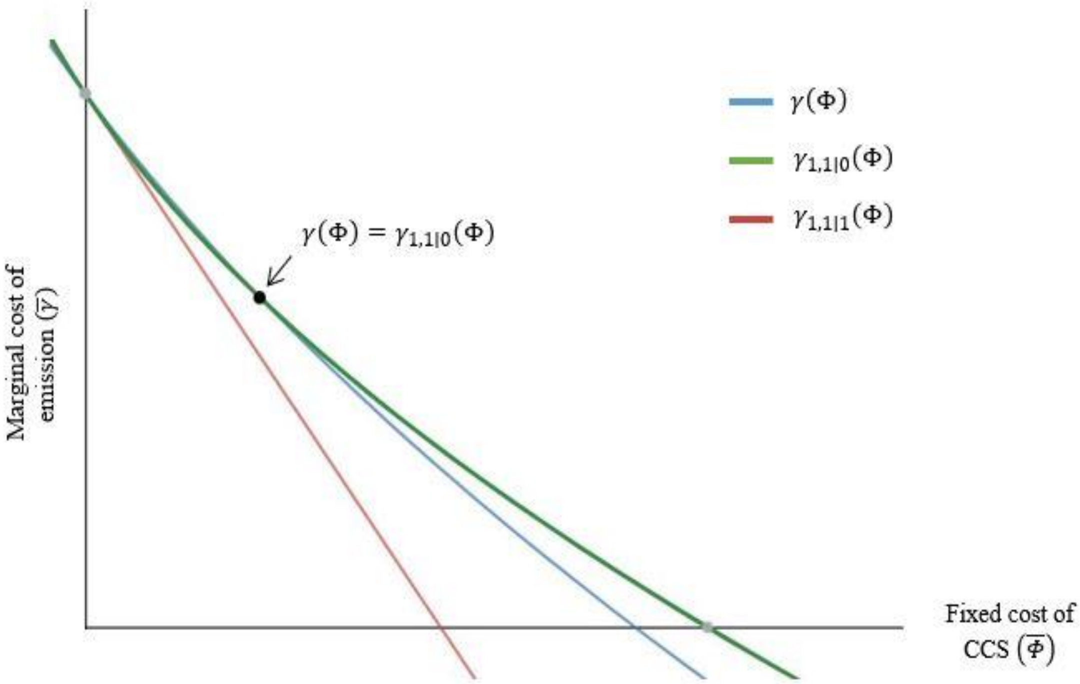


Figure 12 - Comparison 2. Plot of the decision threshold curves for a monopoly firm and firm 1 in a duopoly market, where $a = 100$, $b = 1$, $\sigma = 3$, $\xi = 1$ and $t = 40$

The main difference between the graphical result of Comparison 2 and Comparison 1, is that the DTC $\gamma_{1,1|0}(\Phi)$ it is not always underneath the monopoly firm’s decision threshold curve or $\gamma(\Phi)$. Therefore, what is discovered in this scenario is:

FINDING 3 – *When the carbon dioxide tax is high, governments or policymakers should target a market industry that is competitive to increase the deployment of the CCS technology.*

The finding above is only true if the marginal cost of emission for CCS technology has passed the intersection point between $\gamma(\Phi)$ and $\gamma_{1,1|0}(\Phi)$. The intersection between $\gamma(\Phi)$ and $\gamma_{1,1|0}(\Phi)$ equates the following coordinates for γ and Φ:

$$\left(\frac{8(\sigma + t\xi - a)^2}{49b}, a - \sigma - \frac{9\sqrt{(a - \sigma - t\xi)^2}}{7}\right) \quad (36)$$

Thus, in Comparison 2 if an assumed marginal cost of emission for CCS technology or parameter $\gamma'$is less than $130/7$ then a duopoly market scenario has a greater chance of adoption compared to a monopoly market structure.

The economic intuition behind FINDING 3 is due to the increase in the carbon dioxide tax which affects the marginal cost of production of a firm. When the carbon dioxide tax is assumed to be relatively high, the marginal cost of production of CCS technology becomes lower. However, a duopoly market becomes the superior market structure to increase CCS deployment because of the strategic effect. When the carbon dioxide tax is high, this induces a to choose a CCS technology which will allow the firm to reduce its marginal cost, which adversely affects the output of the rival firm and, thus, increases the adopting firm's profit. The latter description is the strategic effect. Finally, because of the strategic effect we also discover:

FINDING 4 – *When the carbon dioxide tax is high, a duopoly market is the preferred market structure for CCS technology adoption because more carbon emissions can be mitigated as the total industry output in a duopoly market under Cournot competition is higher than in a monopoly market.*

2.6 Conclusion

The adoption of carbon capture and storage technology is a pivotal mitigation technology to achieve the Paris Agreement. However, despite the well-known environmental and future economic potentials of the adoption of CCS technology, "*the pace is well below the level required for CCS to make a substantial contribution to climate change mitigation*" (GCCSI, 2013). The current existing literature studies of CCS technology diffusion are mainly from a macro and engineering perspective, providing little insight into the behavioural strategies of the stakeholders involved in the process of CCS adoption at a microeconomic level. Thus, in this chapter, we investigated the role of competition in the adoption of CCS technology achieved by implementing an industrial organization approach to the context of CCS technology adoption. We also identified a series of policy solutions to inform government and policymakers to increase the deployment of CCS technology.

Our analysis provides a series of policy solutions to increase a firm's incentives toward a CCS adoption decision. Specifically, the policies identified were:

1. The government can increase the carbon dioxide tax.
2. The government can provide a fixed cost subsidy to reduce its expensive investment cost of CCS technology.
3. The government can provide a CCS process subsidy where it reduces a firm's marginal cost of using CCS technology.
4. The government can manipulate demand to change consumers' behaviour towards CCS technology.

However, the main contribution discovered in this chapter reveals the importance of the nature of the competitive environment that a firm operates in when dealing with a CCS adoption decision. Under a monopoly market, a firm only gains a singular effect called the direct effect. The direct effect corresponds to the reduction of the monopoly firm's unit cost of production using CCS, if and only if there are stricter environmental regulations such as an increase in carbon dioxide tax t. However, a firm in a market with competition not only gains the direct effect, but a firm also has an additional effect that is only present in a market with competition. The additional gained effect is called the strategic effect. The strategic effect is if the adoption of CCS technology lowers the marginal cost of production of a firm, thus making a firm more competitive in the market. Then, this adversely affects the output of the rival which then increases the CCS adopting firm's profit in question. Therefore, what is learnt in this chapter is that in a duopoly market, whilst the unit cost of using CCS is lower than the unit cost of not investing in CCS, a firm in a market with competition has a better chance of successful CCS adoption because there are two gained effects, a direct and a strategic effect.

In this study, we also inform government and policymakers of which market structure promotes the highest incentives to adopt CCS technology. We find that when the carbon dioxide tax is assumed low, the market structure with the highest chance for CCS technology adoption is a monopoly. Conversely, when the carbon dioxide is assumed to be relatively high, we find a duopoly market has a better advantage for CCS technology adoption. The economic intuition behind this result is due to the changes in the carbon dioxide tax affecting the marginal cost of production of a firm. When the carbon dioxide tax is assumed high, this causes the marginal cost of production of CCS technology to become more efficient. However, when the carbon dioxide tax is high, a duopoly market is the superior market structure to increase CCS deployment because of the strategic effect that is only present in a market with competition. Therefore, what one learns here is that if the carbon dioxide tax is high governments should target a market that has more competitive because firms have greater incentives for CCS technology adoption due to the strategic effect. Furthermore, we also discover that if the carbon dioxide tax is high, a duopoly market should be the targeted market structure by governments and policymakers for achieving an increase in CCS technology adoption. The reason for this is because more carbon emission can be mitigated in a duopoly as the total industry output in a duopoly market under Cournot competition are higher than in a monopoly market.

Overall, the results obtained in this chapter provide important information to increase the widespread of CCS technology. However, one should note that there are some limitations to the study. In this chapter, the model was only focused on the simplified setting involving two players. Moreover, a strict assumption in the model was considering that when a firm adopts CCS technology, the firm was going to capture all its emissions. However, two options are available to a firm. First, what is the optimal operating capture decision that a firm should choose? Secondly, a firm can also choose a partial investment for its carbon capture facility. For example, if an investment is low then a firm is going to have a capture facility that is designated to capture only a set proportion of the total emissions produced by the firm. These are two interesting avenues for future works. Finally, in this chapter, the business model of a firm adopting a CCS technology is considered to "self-build and operate." The self-build model is one in which CCS operations are owned and operated by a single entity with an internal staff of engineers, geologists, and on-site field technicians and operators. However, the other two possible business models for CCS adoption technology, as addressed by Esposito et al. (2011) are through a joint venture model or a pay-at-the-gate model. A joint-venture model is a partnership where the host site utility/owner's engineer and external operators and consultants jointly execute CCS. A pay-at-the-gate model is externally contracting to a third-party owner/operator with a positive fee for sequestration and cash positive pricing such as CO_2-EOR. The latter two business models are interesting models for future research, where an interesting research question would be: "*Which business model creates the best chance of success for CCS technology?*"

2.7 Appendices Chapter 2

A – Monopoly Social Welfare MATLAB code

```
% Parameters
a=120;          % Y-intercept of inverse linear demand
b=1;            % Slope of inverse linear demand
sigma=50;       % Marginal cost of production not involving carbon capture
                    % and carbon emissions
gamma=40;       % Marginal cost of production for doing carbon capture
xi=1;           % Pollution intensity
Phi=200;        % Fixed cost of CCS technology

% Damage coefficients
h1=35;
h2=45;
h3=55;

t=0:1:400;      % Carbon dioxide tax variable

for i=1:size(t,2)

    % Social welfare investing in CCS
    W_1(i)=((3*(a-sigma-gamma)^2)/8*b)-Phi;

    % Social welfare not investing in CCS with h1=35
    W0_h1(i)=((3*(a-sigma-t(i)*xi)^2)/8*b)+((xi*(t(i)-h1)*(a-sigma-
                 t(i)*xi))/2*b);

    % Social welfare not investing in CCS with h2=45
    W0_h2(i)=((3*(a-sigma-t(i)*xi)^2)/8*b)+((xi*(t(i)-h2)*(a-sigma-
                 t(i)*xi))/2*b);

    % Social welfare not investing in CCS with h3=55
    W0_h3(i)=((3*(a-sigma-t(i)*xi)^2)/8*b)+((xi*(t(i)-h3)*(a-sigma-
                 t(i)*xi))/2*b);

end
```

B – Duopoly Social Welfare MATLAB code

```
%Parameters
a=120;              % Y-intercept of inverse linear demand
b=1;                % Slope of inverse linear demand
sigma=50;           % Marginal cost of production not involving carbon capture
                        % and carbon emissions
gamma=40;           % Marginal cost of production for doing carbon capture
xi=1;               % Pollution intensity
Phi=200;            % Fixed cost of CCS technology

h=35;               % Damage coefficient

t=0:1:400;          % Carbon dioxide tax variable

for i=1:size(t,2)

    % Social welfare both firms do not invest in CCS with h=35
    W_00(i)=2*(xi*t(i)-- a + sigma)*((h-- t(i)/3)*xi-- (2*a)/3 +
                 (2*sigma)/3)/(3*b);

    % Social welfare one firm invest in CCS and the other does not with h=35
    W_10(i)=((12*h*t(i)-- t(i)^2)*xi^2 + ((-6*h-- 2*t(i))*a + (-6*h -
                 8*t(i))*gamma + 6*(h + t(i)/3)*sigma)*xi + 8*a^2 + (-
                 8*gamma-- 16*sigma)*a-- 18*Phi*b + 11*gamma^2 +
                 8*sigma*gamma + 8*sigma^2)/(18*b);

    % Social welfare both firms invest in CCS with h=35
    W_11(i)=(4*(a-- sigma-- gamma)^2)/(9*b)-- 2*Phi;

end
```

Chapter 3

Carbon Capture and CO2 Utilization Adoption–- A Microeconomic Analysis

3.1 Introduction

Carbon capture and storage (CCS) is known to be a pivotal mitigation technology to tackle climate change. However, the mitigation technology is still faced with major obstacles such as its high cost and uncertainties associated with its technological development impeding its rapid diffusion to reach a full-commercial state. Recently, an alternative related solution – carbon capture and utilization (CCU) – has attracted a lot of interest from researchers. The reason for this is because the process of CO_2 utilization can use CO_2 *"directly or as a feedstock in industrial or chemical processes, to produce valuable carbon-containing products* (IPCC, 2005)", whilst at the same time contributing to climate change mitigation. A major benefit of CCU over CCS is that for the former strategy, a revenue stream can be obtained for the adopting firm as the captured emissions using the carbon capture technology are sold (Arno Zimmermann and Kant, 2017). Researchers investigating CCU are also interested and motivated by the procedure for several other reasons:

- CCU is identified as a potential gateway to closing the carbon cycle or creating a circular economy (Styring et al., 2014).
- CO_2 utilisation can have an important role in supporting the demonstration phase of CCS development, especially in the absence of strong carbon prices and in emerging economies (GCCSI, 2011).
- CO_2 utilisation also contributes to improving the exploitation of renewable energy (Arno Zimmermann and Kant, 2017). The process of CO_2 utilisation can help to stabilise electricity grids when there is a growing share of

fluctuating renewable energy (Mennicken et al., 2016). The excess energy can instead be used to produce hydrogen, an important ingredient reacted with CO_2 to obtain many CO_2-based products.

- Carbon capture with CO_2 utilisation is also beneficial due to the lack of geological storage potential for CCS in specific areas (Hendriks et al., 2013).
- Finally, CO_2 utilisation has a better perception of the public compared to CCS regarding the safety and viability of CO_2 storage in some jurisdictions (Hendriks et al., 2013).

The current literature investigating CCU technology is mainly dominated by two research methods. The first dominant research method investigating CCU is using a techno-economic assessment or TEA. TEA is a framework that allows a researcher to analyse the technical and economic performance of a process, product or service (Arno Zimmermann et al., 2020a). The aim of a TEA study includes 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. For example, a study using this method is by Zhang (2017), who analysed two options of carbon-dioxide-utilized gas-to methanol. The study then used economic evaluation indicators such as net present value (NPV), internal rate of return (IRR), and discounted payback period (DPBP) to assess the profitability of the two options. Another study using a TEA method is the study conducted by Dimitriou (2015). This paper was focused on the manufacture of transport hydrocarbon fuels from CO_2 waste, and it investigated whether the production of hydrocarbon fuels from different CCU process configurations is economically viable. The authors discovered that the production of liquid hydrocarbon fuels using the existing CCU technology is not economically feasible because of the low CO_2 separation and conversion efficiencies and the high energy requirements. Overall, the mentioned CCU studies using a TEA framework perform an analysis that investigates a specific process and adopts a cost modelling and sensitivity analysis to examine the feasibility of a project.

On the other hand, a vast majority of studies in CCU are focused on investigating the environmental impact of a CCU strategy. The reason for this is that not all products generated by CO_2 utilisation are infinitely 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). Thus, the second dominant research method in CCU literature is through a life-cycle assessment or LCA. An LCA is a study that 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 et al., 2014). In some studies, TEA is integrated with LCA results, as the decision making often is dependent on economic as well as ecological aspects of CCU technologies (Angunn et al., 2014; Man et al., 2014; Pérez-Fortes et al., 2016; Szima and Cormos, 2018).

Having discussed the two most dominant research methodologies in CCU literature, the research gap identified is that there has been not a proper evaluation of the microeconomic interactions that occur in a CCU industry. Thus, in this chapter, a better understanding of the effects of the strategic interaction of firms that involves a CCU industry is investigated. Moreover, in the current literature on CCU, many studies do not comprehend a deep understanding of the economic effects that are occurring in the intermediary market of CO_2 inputs when a CCU project is installed. Many times, it is assumed that the stream of CO_2 emissions is coming from an outside source at a steady market price. However, knowing that a market price for a product is determined by the law of supply and demand, if CCU is adopted the supply of CO_2 inputs should increase and therefore, the market price should decrease. These are the types of economic effects that are going to be analysed in this study.

Therefore, the purpose of this research is to understand the microeconomic effects or the strategic interaction of firms occurring in a CCU industry. Overall, the aim of this chapter is three-fold. First, we aim to address the lack of understanding of the effects of the strategic interaction of firms when a CCU strategy is adopted. The analysis is achieved by presenting a simple economic model under an industrial organization approach where we consider a market setting that is non-vertically integrated. The non-vertical integrated market consists of an upstream and downstream sector. The upstream market is the producer of CO_2 inputs that are required for the final good of the downstream sector. A CCU strategy occurs due to an entry of a firm in the upstream market – i.e., the intermediary CO_2 input market – where the entrant firm is the only firm producing CO_2 inputs by adopting a carbon capture technology with CO_2 utilization. We assess the microeconomic effects on each sector when the entrant firm adopts a CCU strategy. Second, we aim to identify necessary policy solutions to inform the government and policymakers to achieve an increase in the adoption of CCU technology. Last, an environmental impact assessment of CCU adoption is also examined. The motivation for this is to ensure that a carbon emission reduction is achieved as final CO_2-based products when consumed release carbon emissions back into the atmosphere. We address the issue by doing a comparative static of the model and investigating whether there are any instances of worse environmental impacts when CCU is adopted in an industry compared to an industry without. If a negative environmental outcome is obtained due to a CCU strategy, we then aim to discover further policies to inform policymakers or governments so that both a positive economic and environmental outcome are achieved.

In this study two main insights are obtained:

- *Insights for the firm* – Despite the adoption of CCU technology allowing a firm to recoup some of its cost invested in carbon capture technology, in this chapter we discover that stronger environmental regulations are still required for a firm that wants to invest in a CCU strategy. With the assumption that the intermediary market of CO_2 inputs is a market that is quasi-competitive, meaning that the price falls and the volume of trade increases, we then find that the downstream sector that necessitates the CO_2 inputs is always going to obtain a positive outcome (i.e., higher profits) when CCU is adopted.
- *Insights for policymakers or governments* – In this study, several policy solutions are identified to inform government and policymakers to achieve an increase in the adoption of carbon capture technology. However, besides the economic impacts generated by policy solutions identified, we also assess the consequence of the policy solutions to the environment. Thus, we also suggest policy interventions that generate both a positive outcome economically and environmentally when a CCU industry occurs.

The remainder of the chapter is organised as follows. In section 3.2 the relevant literature for this study is discussed. The model of study is presented in section 3.3. Then, using backward induction the model is solved in section 3.4. The environmental impact of a CCU industry and the social welfare are presented in sections 3.5 and section 3.6, respectively. Consequently, in section 3.7 a numerical result is introduced to analyse the model. Policy interventions are discussed in section 3.8 to inform the government and policymakers to increase the adoption of CCU technology. Finally, a summary of the findings and discussion of future works is given in section 3.9.

3.2 Relevant Literature

The relevant stream of literature for this study is findings in economic theory investigating non-vertically integrated markets. The reason for this is because in this chapter the market structure considered for the CCU industry is a non-vertically integrated market. In this study, the non-vertically integrated market is composed of two separated industries: an upstream and downstream sector. The two industries are interlinked due to the exchange of an intermediary good. Specifically, the upstream sector sells an intermediary good to the downstream sector that is necessary to produce the final product.

In the CCU process, a vertically integrated market or vertical integration is also a possible market structure that can occur. A vertically integrated market is the combination of one firm of two or more stages of production normally operated by separate firms. A specific example of a vertically integrated market doing a CO_2 utilization process is the ammonia-urea industry. The production of ammonia requires two inputs: hydrogen and nitrogen molecules. An ammonia facility can produce hydrogen molecules on-site, along with CO_2 molecule which is obtained as a by-product. The production of urea is obtained with ammonia which is then reacted with CO_2 recycled back obtained by the production of hydrogen. Overall, the ammonia-urea production is a special case where two things are achieved in a single action or "kill two birds with one stone." The reason for neglecting a market structure that is vertically integrated is because in a vertically integrated market the exchange interaction between the upstream and downstream sectors would not exist since the two sectors would be merged. The purpose of a market that is vertically integrated is that it reduces the amount of firm interaction and at the same time solves the problem of double marginalization. Double Marginalization is the phenomenon where different firms in the same industry that have their respective market powers but at different vertical levels in the supply chain (for example, upstream and downstream) apply their mark-ups in prices (Gabrielsen and Shaffer, 2018).

However, not all industries can produce CO_2 inputs on-site like the ammonia-urea industry. Therefore, in this study, a non-vertically integrated market structure is selected because it allows us to uncover the microeconomic interaction that occurs between an upstream and downstream sector. At the same time, we can investigate the effects of the CCU strategy where we consider the entry of a firm in the upstream sector that is the only CO_2 inputs producer using a carbon capture technology with CO_2 utilization. Furthermore, another reason for selecting a non-vertically integrated market structure is because there is a larger potential to implement support, policy and regulation that can affect the incentives or decision-making of firms compared to a vertically integrated market.

The first researcher who introduced the idea of the vertically related market was published in a seminal paper by 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 double marginalisation phenomenon and the effects of vertical collusive agreements between the upstream and downstream monopolists.

However, market structures can be more complex than just monopolies. The study previously mentioned by Spengler neglected the phenomenon of free entry in the two sectors. Hence, Gabszewicz and Zanaj (2011) proposed an extension of Spengler's model examining the effects of free entry when there is an interaction between upstream and downstream 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 appears as the unit revenue for the upstream firms: the price paid for a unit of input by downstream firms constitutes the unit receipt for upstream firms. 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 the free entry of firms in both markets does not always entail the usual convergence for the input price to adjust to its marginal cost. The usual convergence of the price to the corresponding marginal cost only occurs in the downstream market. In this chapter, the model we are about to present nearly has a similar market structure presented by Gabszewicz and Zanaj (2011). Therefore, the main finding by Gabszewicz and Zanaj (2011) is of extreme importance to be reminded of whether it also is present in a market structure with a firm adopting a CCU technology. 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 between the models mentioned and the model presented in this chapter, is that in a CCU industry the firm entering the upstream sector does not solely produce the intermediate product necessary for the downstream market. The CO_2 input supplied by the entrant firm is obtained as a by-product from the actual output produced by the entrant firm. However, by investing in a carbon capture technology the entrant firm gains an opportunity to enter the intermediary CO_2 input market. 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.

In addition to understanding the economic result of the firms, other researchers have also analysed the effects on social welfare when there is free entry in a vertically related market. For example, the study by Ghosh and Morita (2007) considers a successive vertical model, in which downstream firms produce a final product using an intermediate product purchased from upstream firms. The authors demonstrate that free entry in an industry that produces a homogeneous product can lead to a socially insufficient, rather than excessive, number of firms when its vertical relationship to the other industry is explicitly considered. The following is particularly an interesting result especially the fact the insufficient entry result is in contrast with previous findings in the theoretical industrial organization literature. Mankiw and Whinston (1986) and Suzumura and Kiyono (1987) showed that in a market that produces homogeneous products, (i) if firms must incur fixed set-up costs upon entry, (ii) if the post-entry game is characterized by quasi-Cournot conjectures and (iii) if output per firm falls as the number of firms in the industry increases (a "business-stealing" effect), then the level of entry in a free-entry equilibrium is socially excessive (Perry, 1984). However, Ghosh and Morita (2007) main contribution were to demonstrate that insufficient entry can occur even in a homogeneous product market when firms' interactions with other firms in vertically related industries are considered.

The studies mentioned in this section illustrate that there are many directions of research for understanding non-vertically related markets. However, a key difference in this chapter is that our model investigates the environmental impact of the model which is not typically researched in non-vertically related markets. Specifically, in this chapter, we also seek to understand the environmental impacts that a CCU industry generates to inform relevant stakeholders.

Overall, the contributions obtained in this chapter to the current literature in CCS are two-fold. Firstly, we investigate the microeconomic effects that stakeholders achieve when carbon capture and CO_2 utilization are adopted. Also, we intend to provide informative policies for governments and policymakers when carbon capture and CO_2 utilisation exchange is present in the intermediary market. Furthermore, the policy interventions suggested in this study are not only economically driven but also aim at achieving positive environmental outcomes due to the fact final CO_2-based products when consumed are released back again into the atmosphere.

3.3 The Model

In this section, the model of the study is introduced. We consider a non-vertically integrated industry composed of two sectors: upstream and downstream. The two sectors are interlinked where the upstream market produces an intermediate product – i.e., CO_2 input – that is a necessary input to produce the final output of the downstream sector.

The upstream sector is composed of n firms, where CO_2 inputs are initially produced using only conventional methods that come from fossil fuel sources. We assume all firms in the upstream market are identical and competing in a perfectly competitive market.[16] A firm in the upstream sector is denoted by i, where $i \in \{1,2, \dots n\}$. The cost function of a firm i is given by $UC(y_i) = \tilde{a}y_i + 0.5\tilde{b}y_i^2$, where y_i is the output of an upstream firm i and $\tilde{a}, \tilde{b}$ are constants both of which are strictly positive. The cost function increases in the output level ($UC' > 0$) and there are decreasing returns to production ($UC'' > 0$).

The downstream market is composed of m identical firms. A firm in the downstream sector is denoted by j, where $j \in \{1,2, \dots m\}$. A downstream firm j has a linear cost function equal to $DC(q_j) = (\lambda_j + k_jR + t\xi_j)q_j$, where the output of a downstream firm is denoted by q_j; λ_j corresponds to downstream firm j's marginal cost of production that it does not involve costs related to the purchases of CO_2 inputs and the cost of emitting carbon dioxide into the atmosphere; k_j is the necessary amount of CO_2 inputs for a firm j to produce one unit of output; R indicates the market cleared price for CO_2 inputs which is determined by the demand of the downstream firms equal to the total amount of the intermediate product supplied by the upstream market; t is equivalent to carbon dioxide tax; and ξ_j denotes the carbon emission intensity per unit of the product of firm j produced from the production process. The downstream sector faces an inverse linear demand $P_D(Q) = a - bQ$, where Q is the aggregate output in the downstream sector or $Q \equiv \sum_{j=1}^{m} q_j$.

The focus of the model is the analysis of the entry of a firm into the upstream sector. The entrant firm is different from the rest of the upstream firms. The entrant firm can enter the intermediary CO_2 input market having adopted a carbon capture technology and sending its captured CO_2 for CO_2 utilisation. Let us note that the CO_2 input produced by the entrant firm is not its primary produced output. The entrant firm is a monopoly in its market, and it obtains the CO_2 input as a by-product from the

[16] The non-linearity of the cost function captures the idea that for each firm the cost of CO_2 extraction increases at an increasing rate, with the implication that each firm operates on a small scale, consistent with our assumption that there are numerous price-taking firms serving the market.

production process of its actual produced good, denoted by x. Overall, an important assumption considered here is that we assume "CO_2 is CO_2." In other words, sources of CO_2 inputs are perfect substitutes.[17] Thus, downstream firms do not have a preference in the production choice of CO_2 inputs.

The investment decision of the entrant firm for adopting a carbon capture technology is denoted by I, where $I \in \{0,1\}$. If $I = 0$ this signifies the entrant firm is not investing in a carbon capture technology. If $I = 1$ indicates the entrant firm has invested in a carbon capture technology. In the model, the carbon capture facility can capture all carbon emissions of the entrant firm if it chooses to do so. The decision of how much carbon emissions the entrant firm captures, or the capture rate, is denoted by χ, where $\chi \in (0,1]$. If $\chi = 1$, this signifies that the entrant firm has decided to capture all its carbon emissions. Whereas, if $\chi = 0$ indicates that no carbon emissions are captured. Another operating decision for the entrant firm is the amount of captured CO_2 to be sold for CO_2 utilisation, denoted by ω, where $\omega \in [0,1]$. If $\omega = 1$, this signifies the entrant firm is trading all its captured CO_2 in the CO_2 input market. Whereas, if $\omega = 0$ this indicates no CO_2 inputs are traded by the entrant firm. If there are proportions of carbon emissions that are not captured by the entrant firm, then a carbon dioxide tax (denoted by t) is needed to be paid for any emissions released into the atmosphere.

The adoption of carbon capture technology impacts the cost of the entrant firm both in the fixed and marginal costs. Parameter $\Phi(I)$ represents the fixed cost of the entrant firm for investing in the carbon capture technology, where $\Phi(I)$ depends on the investment decision I. Specifically, if $I = 0 \Rightarrow \Phi(0) = 0$ and if $I = 1 \Rightarrow \Phi(1) > 0$. Parameter Ψ is the fixed cost of the entrant firm for its standard production process.

If the monopoly firm adopts a carbon capture technology or $I = 1$, it impacts the firm's marginal cost through three possible additional unit cost parameters whose existence depends on the chosen operating decisions χ and ω. The three additional marginal costs are: (i) the entrant firm has an additional operating unit cost for using the carbon

[17] In a real-world context, the CO_2 that is considered in this model is the highest type of concentration of CO_2. Industries who operate under these conditions are for example enhanced oil recovery (EOR), urea yield boosting, renewable methanol, formic acid and more. One of the main reasons assuming that "CO_2 is CO_2" is because in the listed industries these are the highest potential of making a difference environmentally as they have the most demand for CO_2 inputs but also in the listed industries, they are not vertically integrated organizations.

capture facility denoted by β; (ii) the entrant firm can also have an additional marginal cost of production for when it channels its captured CO_2 for CO_2 storage, denoted by STO; (iii) Last, if entrant firm decides to send some of its captured CO_2 for CO_2 utilisation, instead of considering as an additional unit cost, in the model denoted by CDU represents the unit revenue that the entrant firm gains for selling its captured CO_2 for CO_2 utilisation.

Another marginal cost parameter for the entrant firm is parameter σ, this is a marginal cost that does not involve the emission unit cost and the unit cost of using the carbon capture technology. In the model, the entrant firm's marginal cost of production is assumed to be constant (so there are no decreasing returns to scale in capturing carbon). Overall, the total cost function for the entrant firm is given by:

$$EC_I(x^k) = \Phi_I + \Psi + [\sigma + (1-\chi)\tau\xi + \chi\xi(\beta + (1-\omega)STO - \omega CDU)]x^k \quad (37)$$

Equation (37) is a linear cost function, where the cost function of the entrant firm is dependent on the investment decision I[18]. Furthermore, if $I = 1$, then the cost function of the entrant firm also depends on the chosen operating decisions variable χ and ω, $\chi \in (0,1]$ and $\omega \in (0,1]$.

The stages of the model are as follows:

- *Stage 0* – is the investment decision I of the entrant firm, where $I \in \{0,1\}$.
- *Stage 1* – In this stage, the output of the entrant firm x is chosen. The output of the entrant firm is affected by its chosen investment decision I in the previous stage. If the investment decision of the entrant firm is to adopt a carbon capture technology – i.e., $I = 1$ – then the optimal output is also affected by the operating decisions χ and ω, where $\chi \in (0,1]$ and $\omega \in (0,1]$. Furthermore, if $I = 1$ and both $\chi > 0$ and $\omega > 0$, the CO_2 input market price will be affected by a new market-clearing price influencing upstream market revenues.

[18] In this chapter, the total cost function considered is a linear cost function. As previously mentioned, in this thesis some costs and demand functions are considered to be linear because a research gap identified in the CCS literature is a lack of understanding the economics of CCS using economic theory. In this thesis the aim is not to replicate immediately the real-life world characteristics but to highlight the effects of market interactions on CCS adoption decision.

- *Stage 2* – This stage involves a Cournot competition in the downstream sector in which profit-maximising downstream firms commit to the quantities of the final product, taking the input price of CO_2 inputs as given.

The schematic model for this study is displayed in Figure 13 below.

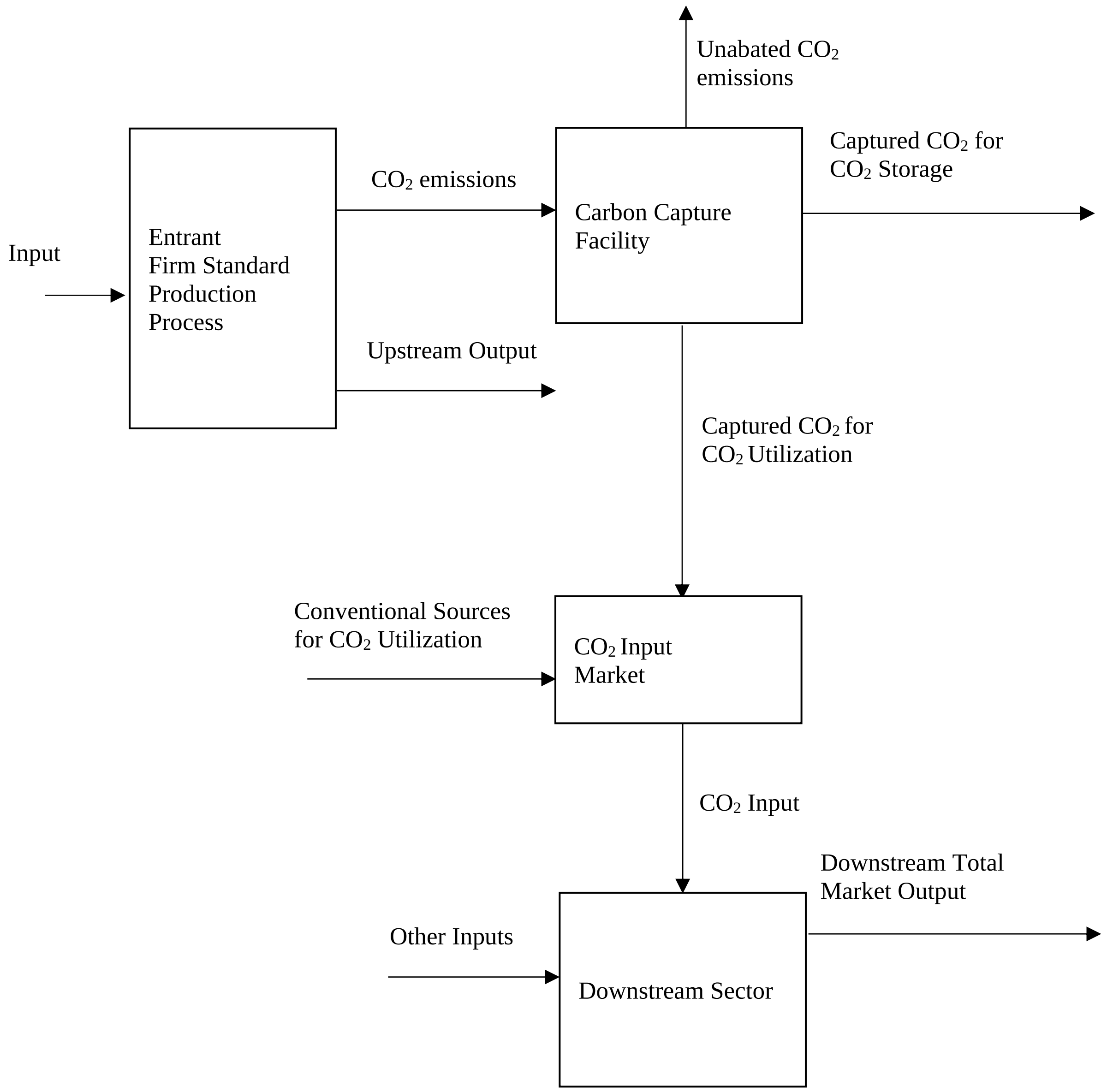


Figure 13 - Schematic model for a vertically non-integrated market where upstream and downstream sector can have a strategic interaction through CO_2 utilization.

3.4 Profit-Maximization

In this section, the game of the model is solved using backward induction. The section is subdivided into smaller subsections. In subsection 3.4.1 we first solve the sub-game Nash equilibrium in *Stage 2*. Subsequently, in subsection 3.4.2 we determine the CO_2 input market-clearing price R. Then, the profit-maximization results of the entrant firm are evaluated in subsection 3.4.3.

3.4.1 Downstream Sector

In *Stage 2* each downstream firm chooses its output to maximise its profits, taking other downstream firms' output and CO_2 input price, as given.[19] The profit function of a downstream firm j is equal to

$$\pi_j(q_j; Q_{-j}) = [a - b(q_j + Q_{-j})]q_j - (\lambda_j + k_j R + t\xi_j)q_j \tag{38}$$

where $Q_{-j} \equiv Q - q_j$, corresponding to the sum of the quantities produced by all downstream firms besides downstream firm j. Taking the first-order condition we get

$$\frac{d\pi_j(q_j; Q_{-j})}{dq_j} = -2bq_j + (a - bQ_{-j}) - (\lambda_j + k_j R + t\xi_j) = 0 \tag{39}$$

Rearranging for q_j, we obtain

$$q_j(Q_{-j}) = \frac{a - bQ_{-j} - (\lambda_j + k_j R + t\xi_j)}{2b} \tag{40}$$

The equation above corresponds to the reaction function of a firm j. Since all firms in the downstream sector are assumed to be symmetric, every downstream firm has the same reaction function and behaviour. Thus, $q_1 = q_2 = \cdots = q_m = q$ and $Q_{-j} \equiv (m-1)q$. Consequently, the expression above can be rewritten to

$$q = \frac{a - b(m-1)q \ - (\lambda_j + k_j R + t\xi_j)}{2b} \tag{41}$$

[19] The downstream firms have no oligopsony power over the upstream sector and take the input price as given. This is a standard modelling choice in the literature on successive vertical oligopolies – see Greenhut, M. and Ohta, H. (1979)', Salinger, M. (1988), Ishikawa, J. and Spencer, B.J. (1999) – and a natural simplifying assumption when the number of downstream firms, m, is sufficiently large relative to the equilibrium number of upstream firms.

Rearranging equation (41) for q, the equilibrium output of a firm j in the downstream sector can be obtained which is given by

$$\hat{q} = \left(\frac{1}{m+1}\right)\left(\frac{a - \left(\lambda_j + k_j R + t\xi_j\right)}{b}\right) \tag{42}$$

The total equilibrium output of the downstream sector is given by

$$\hat{Q} = \left(\frac{m}{m+1}\right)\left(\frac{a - \left(\lambda_j + k_j R + t\xi_j\right)}{b}\right) \tag{43}$$

The equilibrium price in the downstream market is equal to

$$\hat{P}_D\left(\hat{Q}\right) = a - b\hat{Q} = a\left(\frac{1}{m+1}\right) + \left(\frac{m}{m+1}\right)\left(\lambda_j + k_j R + t\xi_j\right) \tag{44}$$

Finally, the equilibrium profit of a firm in the downstream market is given by

$$\hat{\pi}_j = \hat{P}_D\left(\hat{Q}\right)\hat{q} - DC(\hat{q}) = \frac{\left(a - \left(\lambda_j + k_j R + t\xi_j\right)\right)^2}{b(m+1)^2} \tag{45}$$

In equation (45), we can observe that the equilibrium profits of a downstream firm decrease if the marginal cost components increase. Moreover, the equilibrium profits are negatively affected if the number of downstream firms in the market increases. A parameter that needs to be further evaluated in equation (45) is R – the market clearing price for CO_2 inputs. This will be determined in the next subsection.

3.4.2 Determining the CO_2 Input Market Clearing Price *R*

In this subsection, the market-clearing price R of CO_2 inputs is determined. To evaluate the market-clearing input price R, we need to define the CO_2 input supply curve and the CO_2 input demand curve and then set both equations equal.

The total equilibrium supply of CO_2 inputs – denoted by S – is given by

$$S = \hat{Y} + \chi\omega\xi x \tag{46}$$

where,

- $\hat{Y}$: represents the total supply of CO_2 inputs from conventional sources.

- $\chi\omega\xi x$: denotes the total amount of CO_2 inputs supplied by the entrant firm that has adopted a carbon capture technology ($I = 1$) and is choosing operating decisions where $\chi > 0$ and $\omega > 0$.

Equation (46), can be rewritten to

$$S = n\frac{(R - \tilde{a})}{\tilde{b}} + \chi\omega\xi x \tag{47}$$

where $\hat{Y}$ has been replaced by the expression equal to the aggregate equilibrium output of firms in the upstream sector using only conventional methods. The following is found by the optimisation problem of the price-taking conventional firms.[20]

The total demand for CO_2 inputs by the downstream sector is equal to $k_j\hat{Q}$, where k_j represents the necessary CO_2 inputs that a downstream firm requires to produce one unit of product and $\hat{Q}$ is equivalent to the aggregate equilibrium output of the downstream sector or equation (43).

Consequently, equating the CO_2 input supply curve equals the CO_2 inputs demand, or $S = k_j\hat{Q}$, we obtain

$$\frac{n(R - \tilde{a})}{\tilde{b}} + \chi\omega\xi x = k_j\left(\frac{m}{m+1}\right)\left(\frac{a - \left(\lambda_j + k_jR + t\xi_j\right)}{b}\right) \tag{48}$$

Rearranging the equation above for R, the market-clearing price of CO_2 inputs with or without the presence of the entrant firm in the CO_2 input market is given by

$$\hat{R}(x) = \frac{\tilde{b}mk_j\left(a - t\xi_j - \lambda_j\right) + b\tilde{a}n(m+1) - \chi\omega\xi x(m+1)b\tilde{b}}{bn(m+1) + \tilde{b}mk_j^2} \tag{49}$$

If the entrant firm does not invest in carbon capture technology (or $I = 0$), it follows that $\chi\omega\xi x = 0$. Thus, the market-clearing price for CO_2 inputs without the entrant firm – is denoted by $\hat{R}_0 \equiv \hat{R}(0)$ – is given by

[20] The profit function of a firm i producing CO_2 input under a conventional method is equal to $\pi_i(y_i) = Ry_i - \tilde{a}y_i - 0.5\tilde{b}y_i^2$. The first-order condition is $d\pi_i/\,dy_i = R - \tilde{a} - \tilde{b}y_i = 0$. Then, the equilibrium output is $\hat{y}_i = (R - \tilde{a})/\tilde{b}$. Since all the firms are assumed to be identical, the aggregate equilibrium output or total supply of CO_2 inputs is equal to $\hat{Y} = \sum_{i=1}^{n}\hat{y}_i = n\,\hat{y}_i$.

$$\hat{R}_0 = \frac{\tilde{b}mk_j(a - t\xi_j - \lambda_j) + b\tilde{a}n(m+1)}{bn(m+1) + \tilde{b}mk_j^2} \tag{50}$$

The presence of the entrant firm in the upstream sector reduces the market-clearing price of CO_2 inputs, as $\hat{R}_0 > \hat{R}(x)$. What we have here is the market phenomenon where the intermediary CO_2 input market is quasi-competitive: meaning that the market price of the intermediary product falls as a new entrant becomes active in the market. Therefore, with the assumption that the intermediary market is quasi-competitive, we expect this to be advantageous to the downstream market as it reduces the marginal cost of a downstream firm. In contrast, we predict that lower revenues should be generated by upstream firms because the price of CO_2 inputs is going down due to an increase in the number of firms in the upstream market.

3.4.3 Upstream Sector

In this subsection, we continue the back induction by calculating the profit-maximisation results for the entrant firm. Let us first consider the case where the entrant firm invests in carbon capture technology – i.e., $I = 1$.

Let us assume that the entrant firm is facing a linear demand function equal to $P_E(x) = A - Bx$, where $A, B > 0$. The total cost function of the monopoly firm choosing to invest in a carbon capture technology is given by

$$EC_1(x) = \Phi_1 + \Psi + [\sigma + (1-\chi)t\xi + \chi\xi(\beta + (1-\omega)STO - \omega CDU)]x$$

In the total cost function, CDU was previously defined as the unit revenue that the entrant firm gains for selling captured CO_2 for CO_2 utilisation. However, CDU can also be rewritten to

$$CDU = \hat{R}(x) - \eta \tag{51}$$

where,

- $\hat{R}(x)$: represents the market-clearing price that the entrant firm sells one unit of captured CO_2 for CO_2 utilisation, which is given by equation (49).
- η : represents the marginal cost of production that the entrant firm incurs for selling its captured CO_2 for CO_2 utilisation.

Therefore, the full cost equation for the entrant firm can be rewritten to

$$EC_1(x) = \Phi_1 + \Psi + \left[\sigma + (1-\chi)t\xi + \chi\xi\left(\beta + (1-\omega)STO - \omega\left\{\frac{\tilde{b}mk_j\left(a - t\xi_j - \lambda_j\right) + b\tilde{a}n(m+1) - \chi\omega\xi x(m+1)b\tilde{b}}{bn(m+1) + \tilde{b}mk_j^2} - \eta\right\}\right)\right]x \tag{52}$$

Taking the first-order condition of the profit function of the entrant firm when it invests in a carbon capture technology and then rearranging for the output x, we get the equilibrium output of the entrant firm which is given by

$$\hat{x} = \frac{1}{2B\left(bn(m+1) + \tilde{b}mk_j^2\right) + 2(\chi\omega\xi)^2(m+1)b\tilde{b}}\left[(A-\sigma)\left(bn(m+1) + \tilde{b}mk_j^2\right) + \xi\left(\left(\left(n\left((\tilde{a} + STO - \eta)\omega - STO + t - \beta\right)b + k_j\left(\left(a - \lambda_j - t\xi + (STO - \eta)k_j\right)\omega + k_j(t - \beta - STO)\right)\tilde{b}\right)m + n\left((\tilde{a} + STO - \eta)\omega - STO + t - \beta\right)b\right)\chi - t\left(bn(m+1) + \tilde{b}mk_j^2\right)\right)\right] \tag{53}$$

With the result obtained above, the equilibrium price of the entrant firm is given by

$$\hat{P}_E(\hat{x}) = A - \frac{B}{2B\left(bn(m+1) + \tilde{b}mk_j^2\right) + 2(\chi\omega\xi)^2(m+1)b\tilde{b}}\left[(A - \sigma)(bn(m+1) + \tilde{b}mk_j^2) + \xi\left(\left(\left(n\left((\tilde{a} + STO - \eta)\omega - STO + t - \beta\right)b + k_j\left(\left(a - \lambda_j - t\xi + (STO - \eta)k_j\right)\omega + k_j(t - \beta - STO)\right)\tilde{b}\right)m + n\left((\tilde{a} + STO - \eta)\omega - STO + t - \beta\right)b\right)\chi - t\left(bn(m+1) + \tilde{b}mk_j^2\right)\right)\right] \tag{54}$$

Furthermore, by substituting equation (53) into equation (49), the full expression of the market-clearing price of CO_2 inputs for when the entrant firm enters the upstream sector can be found as

$$\hat{R}(\hat{x}) = \frac{1}{2\left(n(m+1)b + \tilde{b}mk_j^2\right)\left(b(m+1)\left(Bn + \tilde{b}(\chi\omega\xi)^2\right) + B\tilde{b}mk_j^2\right)}$$
$$\times \left(2\tilde{a}Bb^2n^2(m+1)^2 - \tilde{b}\left(\left((m+1)^2 n\chi\omega\xi\left(A - \sigma + \xi(\chi(t - \beta - STO)\right.\right.\right.\right.$$
$$\left. - \chi(\eta - STO + \tilde{a})\omega - t)\right)b^2 + m(m+1)\left(t\tilde{b}\omega^2\chi^2\xi^3 - \omega\left(\chi\left((\eta - STO)\right.\right.\right. \quad (55)$$
$$\left. - \lambda_j + a\right)\omega + \left((\beta - t + STO)\chi + t\right)k_j\Big)\chi\tilde{b}\xi^2 + \left(\chi\tilde{b}k_j(A - \sigma)\omega\right.$$
$$\left.\left.\left. + 2tBn\right)\xi + 2Bn\left(\lambda_j - a - \tilde{a}k_j\right)\right)bk_j + 2B\tilde{b}m^2k_j^3\left(t\xi + \lambda_j - a\right)\right)\Big)\Big)$$

Finally, the equilibrium profit of the entrant firm if it invests in carbon capture technology and decides to channel some of its captured CO_2 for CO_2 utilisation it is given by

$$\hat{\pi}_E = \hat{P}_E(\hat{x})\hat{x} - EC_1(\hat{x}) \quad (56)$$

where $\hat{P}_E(\hat{x})$ is given by equation (54); $\hat{x}$ is equivalent to equation (53); and $EC_1(\hat{x})$ is equal to inputting equation (53) into the cost equation (52).

On the other hand, if the entrant firm decides not to invest in carbon capture technology – i.e., $I = 0$, thus $\chi = \omega = 0$ – the entrant firm is going to obtain the standard profit maximisation results of a monopoly market structure, which are displayed below.

- Equilibrium output: $\hat{x}_0 = \frac{A - \sigma - t\xi}{2B}$ (57)
- Equilibrium price: $\hat{P}_E(x_0) = \frac{A + \sigma + t\xi}{2}$ (58)
- Equilibrium profits: $\hat{\pi}_E(x_0) = \frac{(A - \sigma - t\xi)^2}{4B}$ (59)

Let also note that, if $I = 0$, the market-clearing price of CO_2 input is unaffected. Hence, the market-clearing price of CO_2 inputs is $\hat{R}_0$ given by equation (50).

3.5 Environmental Effects

In this subsection, we introduce an environmental impact assessment of our model. The reason for this is to understand whether the presence of the entrant firm in the upstream market produces a benefit or detriment to the environment. We investigate the environmental effects of CO_2 utilization because not all products produced by CO_2 utilisation prevent the release of anthropogenic gas into the atmosphere. The release of carbon emissions from final products produced by CO_2 utilization may vary from days to years or decades depending on when final consumers used the final product.

The environmental effect of the model is the summation of three elements: (i) the environmental impact of the monopoly firm for producing its final product; (ii) the environmental impact of the downstream sector caused by its production process, and (iii) the environmental effect when the final product of the downstream firms is consumed in the final goods market.

If the investment decision of the entrant firm is equal to $I = 1$, the environmental effect of the model is denoted by Z_1 and it is equal to

$$Z_1 = \hat{x}\xi - \chi(\hat{x}\xi) + \hat{Q}(\hat{R})k_j + \hat{Q}(\hat{R})\xi_j \qquad (60)$$

where,

- $\hat{x}\xi$: is the total amount of pollution produced by the entrant firm from its production process, where $\hat{x}$ is given by equation (53).
- $\chi(\hat{x}\xi)$: denotes the total amount of pollution mitigated for adopting a carbon capture technology, where $\chi = (0,1]$.
- $\hat{Q}(\hat{R})k_j$: is the total pollution generated by the downstream market, where $\hat{Q}(\hat{R})$ is given by equation (43) with $\hat{R}$ or equation (55).
- $\hat{Q}(\hat{R})\xi_j$: represents the pollution impact caused by final consumers.

On the other hand, if $I = 0$ the environmental effect of the model is denoted by Z_0 and is given by $Z_0 = \hat{x}_0\xi + \hat{Q}(\hat{R}_0)k_j + \hat{Q}(\hat{R}_0)\xi_j$, where $\hat{x}_0$ is equal to equation (57) and $\hat{Q}(\hat{R}_0)$ is given by equation (43) with $R \equiv \hat{R}_0$ or equation (50).

3.6 Social Welfare

In this subsection, the social welfare of the model is evaluated. The purpose of calculating social welfare is to understand the benefits that carbon capture and CO_2 utilization generate for society. Furthermore, it allows us to evaluate the optimal policy solutions that should be implemented by governments.

The social welfare function for the model is denoted by W_I, where $I \in \{0,1\}$, the investment decision of the entrant firm. The social welfare function is equal to the sum of the consumer surplus of the entrant firm's market, consumer surplus of the downstream sector, the equilibrium profits of the upstream firms, the equilibrium profits of the entrant firm, the equilibrium profits of the downstream market, minus the environmental damage from the pollution of the entire industry.

3.6.1 Entrant firm invests in carbon capture $(\boldsymbol{I = 1})$

The social welfare function when the entrant firm invests in a carbon capture technology – i.e., $I = 1$ – is equal to

$$W_1 = CS_E + CS_D + \hat{\pi}_E + m\hat{\pi}_j + n\hat{\pi}_i - hZ \tag{61}$$

The components are:

- CS_E : is the consumer surplus of the entrant firm's market having adopted a carbon capture technology that is equal to

$$CS_U^{\bar{k}} = \frac{B\hat{x}^2}{2} + (1-\chi)t\xi\hat{x}$$

  where $\hat{x}$ is given by equation (53). In the expression above, the first part corresponds to the surplus generated by consumers buying the entrant firm's final product – i.e., the area under the demand curve and above the market price. The second part of the expression relates to the surplus generated by the government imposing a carbon dioxide tax on the entrant firm for emitting into the atmosphere. We assume that the carbon tax is revenue neutral. In other words, every dollar generated with the carbon dioxide tax is returned to consumers in the form of personal and business tax measures.
- CS_D : is the consumer surplus of the downstream sector given by

$$CS_D^{\bar{k}} = \frac{b\left(\hat{Q}(\hat{R})\right)^2}{2} + t\xi_j m\hat{Q}(\hat{R})$$

where $\hat{Q}(\hat{R})$ is given by equation (43) with $\hat{R}$ or equation (55). The first part in the expression above corresponds to the area under the demand curve and above the market price for the downstream market. The second part of the expression relates to the surplus generated by the government imposing a carbon dioxide tax on the monopoly for emitting into the atmosphere. Once again, we assume that the carbon tax is revenue neutral.

- $\hat{\pi}_E$: is equal to the equilibrium profits of the entrant firm having adopted a carbon capture technology – equation (56).
- $m\hat{\pi}_j$: is equal to the total equilibrium profits of the downstream sector when the entrant firm enters the upstream sector, where the CO_2 input price $\hat{R}$ is given by equation (55).
- $n\hat{\pi}_i$: represents the total equilibrium profits of the upstream sector using only conventional methods to obtain CO_2 inputs. More specifically, $\hat{\pi}_i$ is equal to

$$\hat{\pi}_i = \hat{R}\hat{y}_i - UC(\hat{y}_i)$$

where,

  - $\hat{R}$ is given by equation (55).
  - $\hat{y}_i$ is equal to the equilibrium output of a firm i, which is equal to

$$\hat{y}_i = \frac{\hat{R} - \tilde{a}}{\tilde{b}}$$

    The expression above is obtained by taking the first-order condition of the profit function.
  - $UC(\hat{y}_i)$ is obtained by inputting the result $\hat{y}_i$ above into the production cost function of a firm i in the upstream sector,

$$UC(\hat{y}_i) = \tilde{a}\left(\frac{\hat{R} - \tilde{a}}{\tilde{b}}\right) + \tilde{b}\,\frac{\left(\frac{\hat{R} - \tilde{a}}{\tilde{b}}\right)^2}{2}$$

- hZ_1 : is the environmental impact when the entrant firm enters the upstream sector, where Z_1 is given by equation (60) multiplied by a coefficient h

representing the degree of environmental concern/ awareness of society. Higher h means that society perceives a more significant welfare loss because of emissions and is thus more interested in reducing the level of pollution.

3.6.2 Entrant firm does not invest in carbon capture $(I = 0)$

The social welfare of the model when the entrant firm does not invest in a carbon capture technology – i.e., $I = 0$ – is equal to

$$W_0 = CS_E + CS_D + \hat{\pi}_E + m\hat{\pi}_j + n\hat{\pi}_i - hZ_0 \tag{62}$$

The components are:

- CS_E : is the consumer surplus of the entrant firm's market

$$CS_E = \frac{B(\hat{x}_0)^2}{2} + t\xi\hat{x}_0$$

  where $\hat{x}_0$ is given by equation (57).

- CS_D : is the consumer surplus of the downstream sector

$$CS_D = \frac{b\left(\hat{Q}(\hat{R}_0)\right)^2}{2} + t\xi_j\hat{Q}(\hat{R}_0)$$

  where $\hat{Q}(\hat{R}_0)$ is given by equation (43) with $R \equiv \hat{R}_0$ or equation (50).

- $\hat{\pi}_E$: is the equilibrium profit of the entrant firm when it does not invest in a carbon capture technology given by equation (59).
- $m\hat{\pi}_j$: signifies the total equilibrium profits of the downstream sector equal to equation (45) where the input price is given by $\hat{R}_0$ equation (50).
- $n\hat{\pi}_i$: represents the total equilibrium profits of the upstream sector that produces CO_2 inputs only in a conventional method, where $\hat{\pi}_i$ is equal to

$$\hat{\pi}_i(\hat{y}_i) = \hat{R}_0\hat{y}_i - UC(\hat{y}_i)$$

  where

  - $\hat{R}_0$ is given by equation (50).
  - $\hat{y}_i$ is equal to the equilibrium output of a firm i which is equal to

$$\hat{y}_i = \frac{\hat{R}_0 - \tilde{a}}{\tilde{b}}$$

- $UC(\hat{y}_i)$ is obtained by inputting the result $\hat{y}_i$ above into the production cost function of a firm i in the upstream sector,

$$UC(\hat{y}_i) = \tilde{a}\left(\frac{\hat{R}_0 - \tilde{a}}{\tilde{b}}\right) + \tilde{b}\frac{\left(\frac{\hat{R}_0 - \tilde{a}}{\tilde{b}}\right)^2}{2}$$

- hZ_0 : is equivalent to environmental impact when the monopoly firm does not enter the upstream sector, where $Z_0 = \hat{x}_0\xi + \hat{Q}(\hat{R}_0)k_j + \hat{Q}(\hat{R}_0)\xi_j$, with $\hat{x}_0$ given by equation (57) and $\hat{Q}(\hat{R}_0)$ is given by equation (43) with $R \equiv \hat{R}_0$ or equation (50). Z_0 is multiplied by a coefficient h representing the degree of environmental concern/ awareness of society.

3.7 Analysis of Results and The Baseline Scenario

Having solved the model using backward induction in section 3.4, introduced the environmental effects in section 3.5 and evaluated the social welfare functions in section 3.6, in this subsection we present a numerical simulation using MATLAB to analyse the results of the model. The reason for presenting a numerical simulation instead of an equilibrium analysis is because a numerical simulation can quickly investigate the result of interest by assessing the graphical outcomes. Also, certain results obtained in the previous sections are intractable to be examined analytically.

The numerical simulation presented in this subsection is called the "*baseline scenario*." The baseline scenario presents a simulation result that should be representative reflecting the current situation that a firm is experiencing right now when choosing to adopt a carbon capture technology and CO_2 utilization.

Before presenting the results of the baseline scenario, Figure 14 displays the form of the upcoming graphical results. Most of the findings are three-dimensional illustrations. In the x and y-axis, these represent the two operating decisions χ and ω chosen by the entrant firm, where χ and ω are values incrementally increasing by $+0.1$

with both a maximum value equal to 1. The z-axis corresponds to the result of interest that is examined.

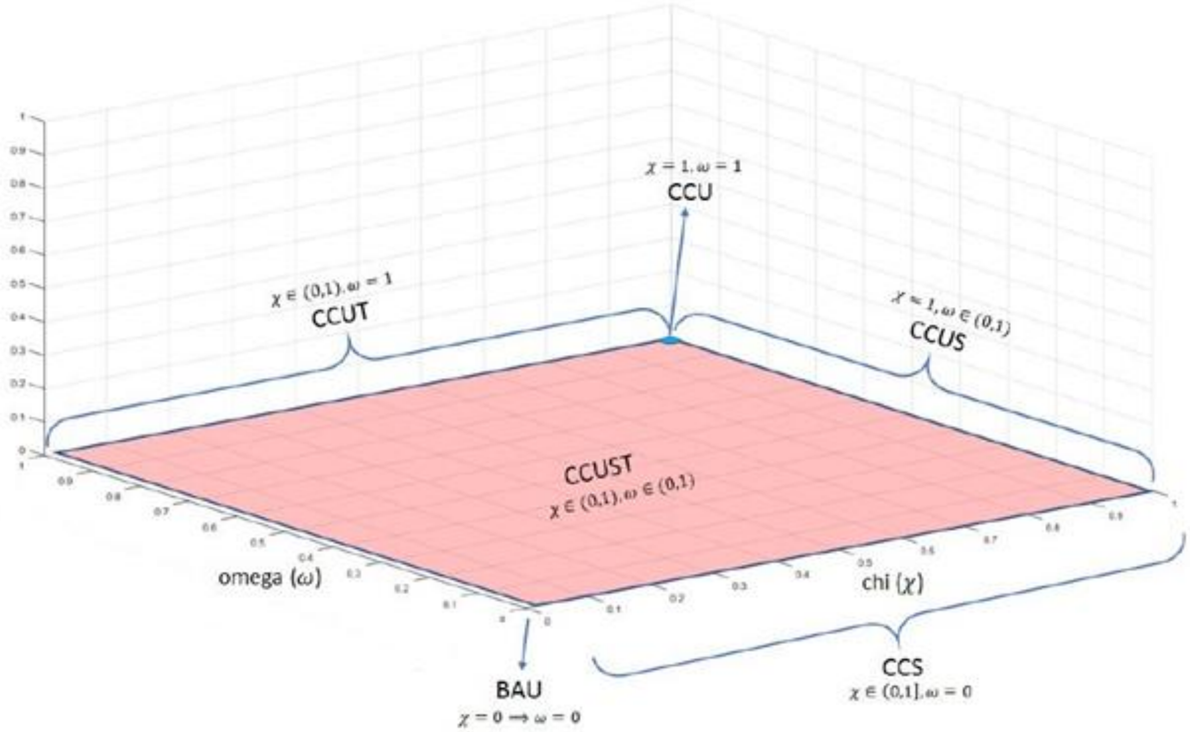


Figure 14 – An example of the upcoming graphical results. This figure also displays the production methods that the entrant firm can obtain for selecting an operating decisions χ and ω given the investment decision is equal to $I = 1$.

Figure 14 also illustrates the type of production method that the entrant firm can achieve when it chooses a particular operating decision χ and ω, given that it has chosen to adopt a carbon capture technology – i.e., $I = 1$. The production methods are summarised in Table 4 with the corresponding operation decisions of χ and ω.

Entrant Firm's Production Method	χ	ω
CCU	1	1
CCUT	(0,1)	1
CCUS	1	(0,1)
CCUST	(0,1)	(0,1)

Table 4 – Summary of all the possible production methods obtained by the entrant firm with the corresponding operating decision $\chi$and ω given that the entrant firm has invested in a carbon capture technology or $I = 1$.

- CCU: denotes that all the CO_2 emissions of the entrant firm are captured and then all of it is sold for CO_2 utilization in the intermediary CO_2 input market.

- CCUT: signifies only the entrant firm captures a proportion of CO2 emissions. The captured proportion is all sent for CO_2 utilization and for the rest of the uncaptured CO_2 emissions the entrant firm pays a carbon dioxide tax.
- CCUS: corresponds to when only a proportion of captured CO_2 of the entrant firm goes to CO_2 utilization and the rest is for CO_2 storage.
- CCUST: represents the production choice where the entrant firm sends a proportion for CO_2 utilization, another proportion for CO_2 storage and FOR the rest of the carbon emissions that are not captured the entrant firm needs to pay a carbon dioxide tax.

In the upcoming analysis of the results, the investigation is a comparison of the results between the production method obtained in Table 4 against the outcome when the entrant firm chooses a business-as-usual strategy or BAU – i.e., $I = 0$, thus it follows that $\chi = \omega = 0$.

The chosen parametric values for the baseline scenario are shown in Table 5. The coding for the numerical simulation is provided in the appendix.

Entrant Firm			
Parameter	Value	Description	Units
A	150	Y-intercept of inverse linear demand	$/unit
B	1	Slope of inverse linear demand	Integer
β	10	Marginal cost of production for doing carbon capture	$/t CAP/unit
σ	10	Marginal cost of production not involving carbon capture and carbon emissions	$/unit
t	25	Carbon dioxide tax	\$/tCO_2/unit
STO	10	Marginal cost of CO2 storage	$/t STO/unit
ξ_i	1	Pollution intensity of the entrant firm	tCO_2/unit
η	5	Marginal cost for doing CO2 utilization	$/t UTIL/unit
Φ	2000	Fixed cost of the carbon capture unit	Annualised fixed cost
Downstream Industry			
Parameter	Value	Description	Units
a	200	Y-intercept of inverse linear demand	$/unit
b	1	Slope of inverse linear demand	Integer
m	100	Number of downstream firms	Integer
λ	5	Marginal cost of production not involving carbon capture and carbon emissions	$/unit
ξ_j	1	Pollution intensity of a downstream firm	tCO_2/unit
k	1.5	Conversion factor of CO2 inputs into one unit of output	tCO_2/unit
Upstream Industry			
Parameter	Value	Description	Units
n	70	Number of upstream firms producing CO2 input under conventional method	Integer
$\tilde{a}$	5	Marginal cost parameter for conventional firm	$/unit
$\tilde{b}$	5	Marginal cost parameter for conventional firm	$/unit

Table 5–- Parametric values for the baseline scenario

The questions asked in this subsection are:

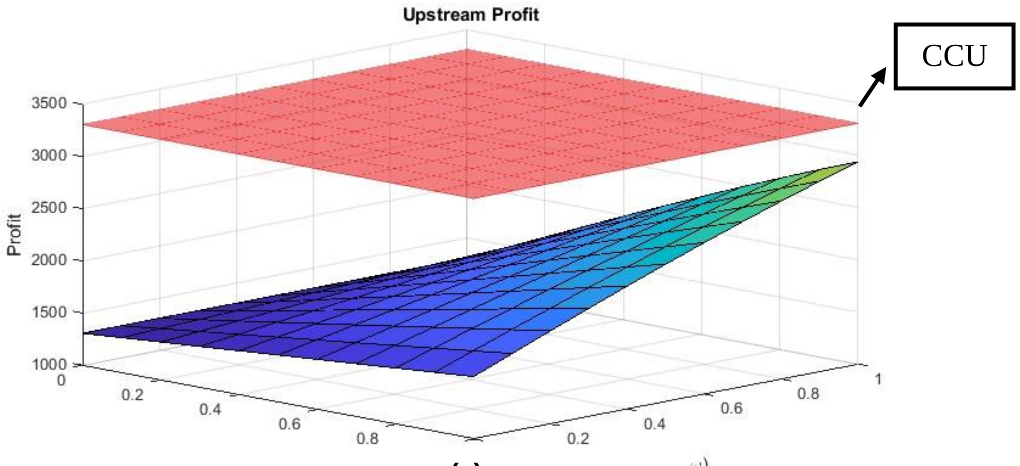
1. *If the entrant firm invests in carbon capture technology or* $I = 1$*, what are the entrant firm's best operating decisions* χ *and* ω*?*
2. *Is the adoption of carbon capture technology and* CO_2 *utilization by the entrant firm a better choice than not investing in carbon capture technology?*
3. *What are the effects caused by when the entrant firm enters the upstream market to the downstream market,* CO_2 *input intermediary market, and the environment?*

Let us first analyse the profit-maximization and environmental results obtained in sections 3.4 and 3.5 for the baseline scenario. Using MATLAB, three graphical plots are presented in Figure 15. For each plot in Figure 15, there are two planes.

- The red flat plane represents the outcome where the production choice of the entrant firm and downstream sector are both under a BAU scenario – i.e., the entrant firm decides not to adopt a carbon capture technology and therefore the entrant firm is paying a carbon dioxide tax for its released emissions.
- On the other hand, the multi-coloured plane illustrates the results of interest for the operating decision – χ and ω – chosen by the entrant firm after it has invested in a carbon capture technology – or $I = 1$.

Fig. 15(a) illustrates the equilibrium profit results of the entrant firm. The equilibrium profit of the entrant firm if decides to enter the upstream market, or the multicoloured plane, has a curvature where it is increasing as χ and ω are both approaching the maximum value of 1. The highest optimal profits gained by the entrant firm are achieved when the firm chooses a production method equal to CCU or $\chi = 1$ and $\omega = 1$. The reason for this is because the more the entrant firm sells its captured CO_2 for CO_2 utilization, this allows the entrant firm to recoup further its investment costs for adopting a carbon capture technology. However, in Fig. 15(a) one can see that the red flat plane, indicating the equilibrium profit of the entrant firm choosing a BAU strategy, is strictly above the multi-coloured plane. Hence, the entrant firm is better off under the baseline scenario than choosing to invest in carbon capture technology. The reason for this is that one of the major hurdles of carbon capture technology is that it

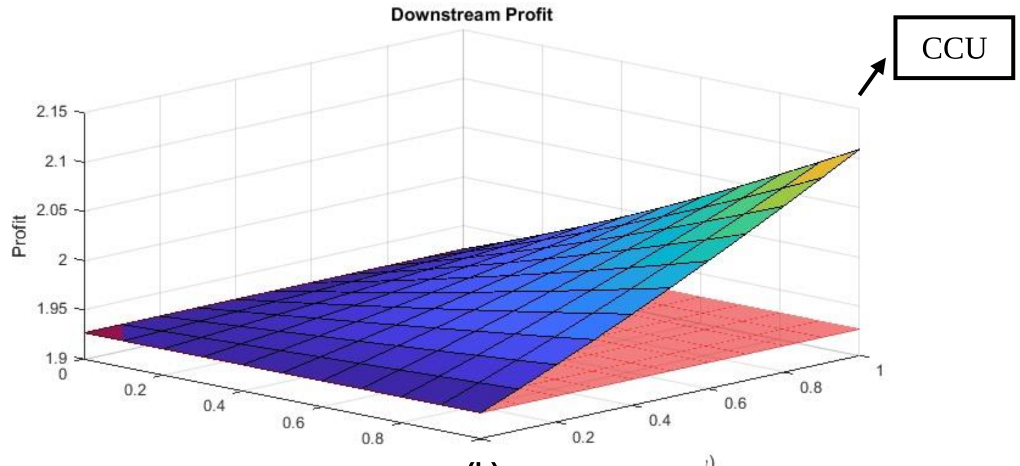
Entrant Monopoly Profit



(a)

(a)

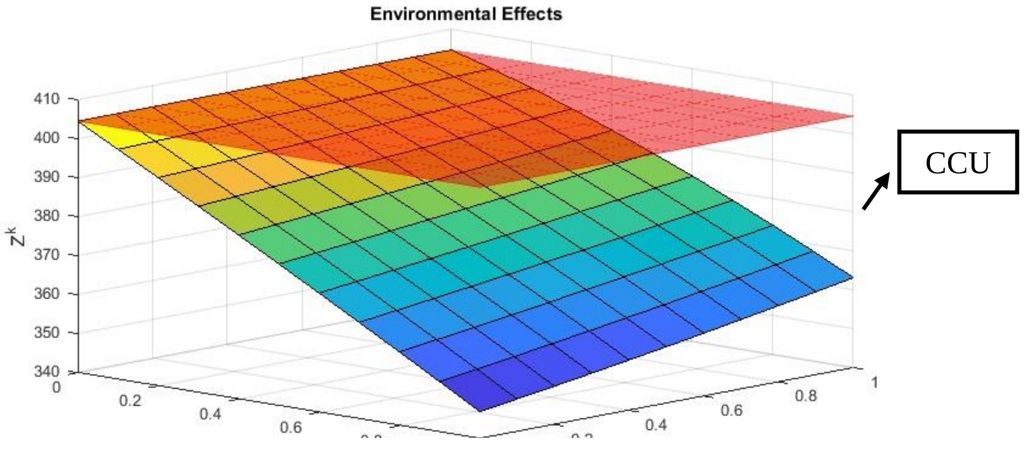
Downstream Firm Profit



(b)

(b)

Environmental Effects



(c)

(c)

Figure 15 – Graphical results of the baseline scenario - (a) Entrant firm's equilibrium profit, (b) Downstream firm's equilibrium profit, and (c) Environmental effects.

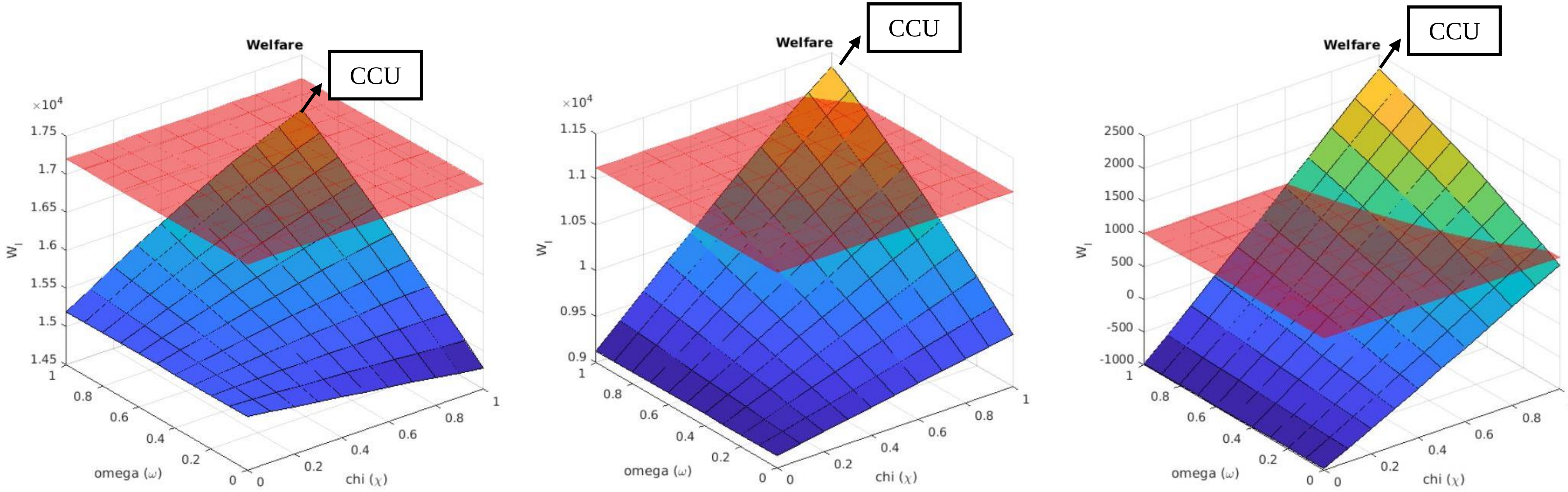
Note: 3-dimensional graph where χ is y-axis and ω is x-axis. CCU label in the graph points where ω and χ are both equal to 1.

has an expensive adoption and operation cost impeding the diffusion of the mitigation technology.

Fig. 15(b) shows the results of the equilibrium profit of a downstream firm. When the entrant firm is present in the upstream market, this has a positive effect on the downstream firm by increasing its equilibrium profit. In Fig. 15(b), this is proven by the fact the multi-coloured plane is strictly above the red flat plane. The highest optimal profits gained by the downstream firm are achieved when the entrant firm chooses a production method equal to CCU or $\chi = 1$ and $\omega = 1$. The reason for this outcome is because when the entrant firm sells all its captured gas in the CO_2 input market, this increases the supply of CO_2 inputs in the intermediary market. An increase in the total supply of CO_2 inputs causes a decrease in the market-clearing price of CO_2 inputs. The consequence of a lower market price for CO_2 inputs translates to lower marginal costs for the downstream firm. Overall, lower marginal costs for the downstream firm lead to higher outputs which then means higher equilibrium profits are gained.

Fig. 15(c) shows the results of the environmental effects with or without carbon capture technology. One can see that the red flat plane is always above the multi-coloured plane. This indicates that the environmental impact of a BAU scenario is worse compared to when a carbon capture technology is present in the model. Therefore, adopting a carbon capture technology with CO_2 utilization provides a positive outcome for the environment.

The next result investigated is social welfare using the results obtained in section 3.6. Using the stated parametric values in Table 5 and MATLAB, we obtain three graphical plots displayed in Figure 16. In Figure 16, for each of the graphs, the red flat plane corresponds to the social welfare result when firms choose a BAU strategy or carbon capture technology is not adopted. On the other hand, the multi-coloured plane is the social welfare result when carbon capture technology with CO_2 utilization is present in the model. There are three graphical plots displayed in Figure 16 because they consider different coefficients h on the social welfare function, where h is the degree of environmental concern or the awareness of society.



$h = 10$ $h = 25$ $h = 50$

Figure 16 - Social welfare result for the baseline scenario, where Fig.5(a) $h = 10$*; Fig. 5(b)* $h = 25$*; and Fig. 5(c)* $h = 50$.

Note: 3-dimensional graph where ω is y-axis and χ is x-axis. CCU label in the graph points where ω and χ are both equal to 1.

In Figure 16, when the damage coefficient is low – i.e., $h = 10$ – we find the highest result for social welfare result is when the entrant firm does not enter the upstream market. Simply because the fact the red flat plane or W_0 is strictly above the multi-coloured plane W_1 with $h = 10$. Therefore, this means society is better off when the entrant firm does not invest in carbon capture technology. However, when the damage coefficient h is high – i.e., $h = 25$ or 50 – we discover that if the entrant firm selects a CCU strategy or $\chi = 1$ and $\omega = 1$, the social welfare result for a CCU production outcome is greater than not investing or staying under a BAU strategy or $W_1 > W_0$. Therefore, what we discover is as the coefficient damage h increases the adoption of carbon capture technology becomes more important for society. Furthermore, we also find that the production choice equivalent to CCU provides the highest benefit for society if the damage coefficient h is sufficiently large.

Having shown the effects of the damage coefficient on the social welfare function, we then ask: *What is the threshold damage coefficient h such that the entrant firm should adopt a carbon capture technology*? To answer the question, we present Figure 17 below.

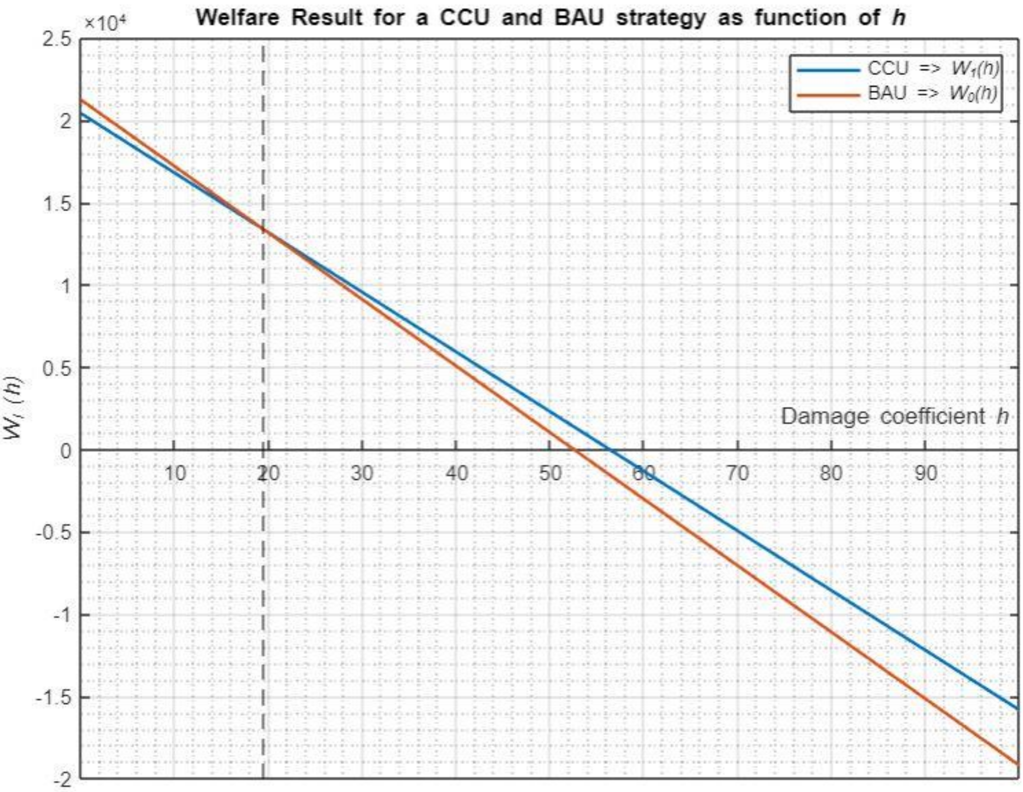


Figure 17 – Social welfare result for a CCU production method and BAU strategy as a function of h,the damage coefficient.

In Figure 17, the blue line represents the social welfare function as a function of the damage coefficient h where the entrant firm selects to adopt carbon technology and strictly chooses a CCU production method because it is the peak of every social welfare result as previously presented in Figure 16. Figure 17 also displays the social welfare when the entrant firm selects a BAU strategy also as a function of the damage coefficient h indicated by the red line. The threshold damage coefficient is denoted by h' and it is obtained by the intersection of the two lines in Figure 17. For the baseline scenario, we find $h' = 19.5351$. Therefore, if for some $h > 0$ where $h < h'$, the highest social welfare result for society is when carbon capture and CO_2 utilization are not present in the model. Conversely, if for some $h > 0$ where $h > h'$, we obtain the opposite condition or $W_1(h) > W_0(h)$.

3.7.1 Summary of Findings for the Baseline Scenario

In summary, the analysis of the baseline scenario has provided several findings to inform governments and policymakers of the firm's decision when CCU technology is adopted.

- When the entrant firm enters the upstream market, the intermediary market of CO_2 inputs follows a quasi-competitive environment, meaning that the market price of the intermediary product falls as a new entrant becomes active in the market. With this assumption, we discover that the downstream sector obtains higher equilibrium profits when the entrant firm enters the upstream market. The reason for this is that when the entrant firm enters the upstream market this triggers a decrease in the market-clearing price of the CO_2 inputs which translates to lower marginal costs of production for downstream firms. If marginal costs are lower, then leads to higher production which means that higher profits are obtained.
- When carbon capture technology is adopted by the entrant firm, any operating decision by the entrant firm provides a positive outcome for the environment compared to not investing in carbon capture technology.
- Furthermore, we have also discovered that if the value of the degree of environmental damage h is low, society is better off without the adoption of carbon capture technology. Conversely, if the value of the degree of

environmental damage h is high, society benefits from the presence of carbon capture technology.

- We also discover that if the entrant firm enters the upstream market, the firm is better off not investing in mitigation technology. The reason for this is because the equilibrium profits of the entrant firm are always strictly below compared to when the firm chooses to do a BAU strategy for any operating decision χ and ω. Therefore, the equilibrium decision outcome for the entrant firm under the baseline scenario will be not investing in carbon capture technology.

Ultimately, what is learnt in this subsection is that despite the adoption of CCU technology allowing a firm to recoup some of its cost invested in carbon capture technology, a firm would still not choose to adopt a carbon capture technology. Therefore, governments and policymakers should focus on developing better economic incentives for carbon capture technology especially knowing the fact, that carbon capture is a pivotal technology to meet the Paris accord. Thus, in the next subsection, a series of policy interventions are introduced such that the entrant firm has the incentives to adopt a carbon capture technology.

3.8 Policy Interventions

In this subsection, more graphical results are presented when policy interventions are implemented to the incentives toward a carbon capture technology investment decision.

3.8.1 Policy 1 – "An increase in the carbon dioxide tax t"

The first proposed policy solution is an increase in the carbon dioxide tax t, which we denote as Policy 1. The parametric values for Policy 1 are the same as considered for the baseline scenario – see Table 5– except for the carbon dioxide tax t which is doubled from a value of 25 to 50. Using MATLAB, the profit-maximization and environmental graphical results are displayed in Figure 18.

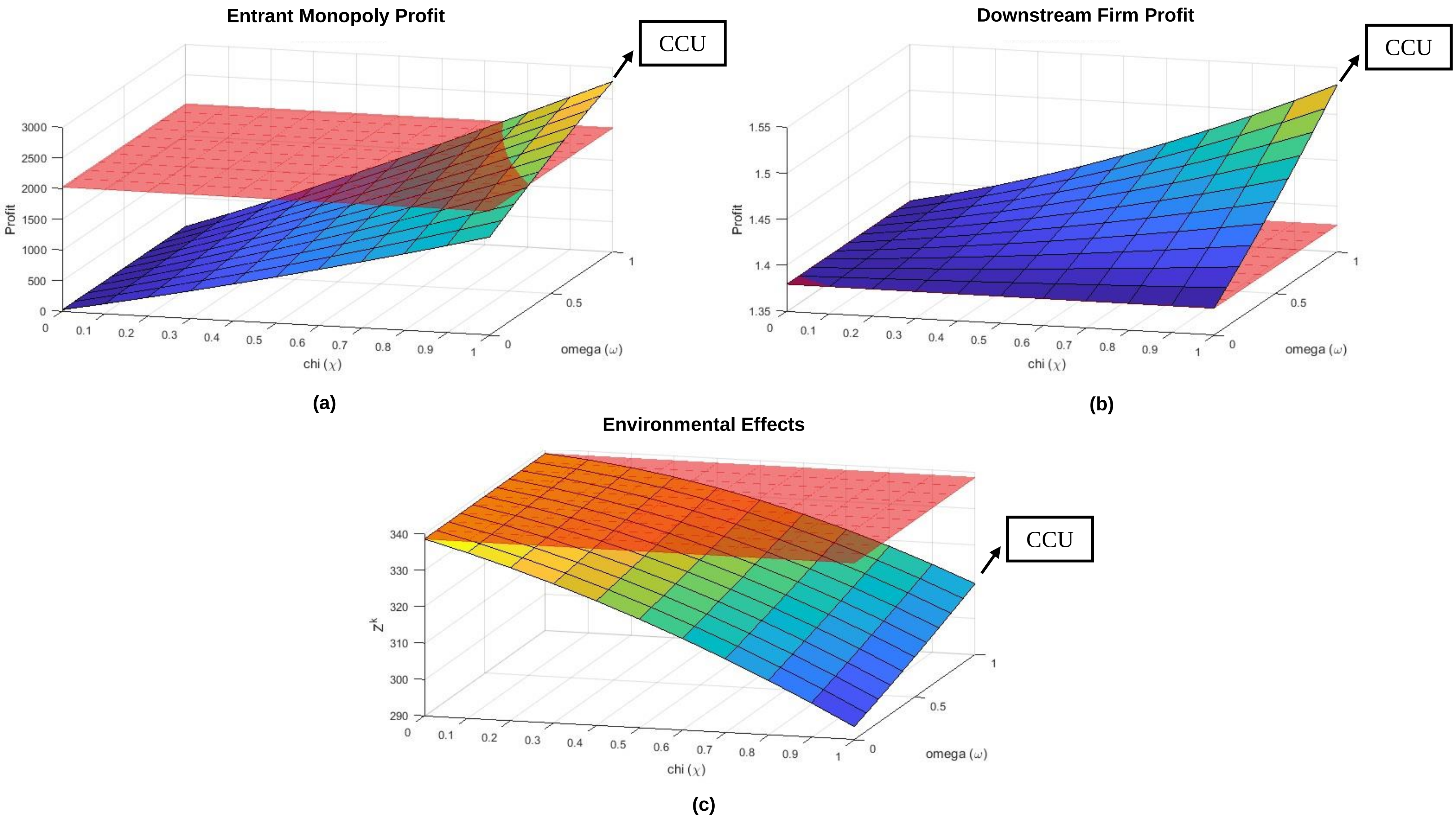


Figure 18 – Policy 1. An increase in the carbon dioxide tax t - (a) Entrant monopoly firm's equilibrium profit, (b) Downstream firm's equilibrium profit, and (c) Environmental effects.

Note: 3-dimensional graph where χ is y-axis and ω is x-axis. CCU label in the graph points where ω and χ are both equal to 1.

Fig. 18(a) illustrates the equilibrium profit of the entrant firm whilst considering Policy 1. An increase in the carbon dioxide tax t generates for the entrant firm where for some operating decisions χ and ω it is more profitable to adopt a carbon capture technology with CO_2 utilization than choosing a BAU strategy. In Fig. 18(a), this is illustrated by the multi-coloured plane found partially above the red flat plane. Overall, in Fig. 18(a) we obtain that the equilibrium decision by the entrant firm should be a production method equal to CCU or operating decisions where $\chi = 1$ and $\omega = 1$. This is because it is the production method that produces the highest optimal profits for the entrant firm.

Fig. 18(b) shows the effects of Policy 1 on a downstream firm's equilibrium profit. The effects of Policy 1 generate a positive effect on a downstream firm's equilibrium profits by increasing them. This is demonstrated by the multi-coloured plane being strictly above the red flat plane. However, with the implementation of Policy 1, a downstream firm's equilibrium profits are lower when $t = 50$ compared to the baseline scenario's result with $t = 25$. This is because the carbon dioxide tax is also a component in the marginal cost of production of a downstream firm.

Fig. 18(c) shows the environmental effects of the model under Policy 1. The graphical results have the multi-coloured plane completely underneath the red flat plane. Thus, this means that environmental the adoption of carbon capture technology and choosing any operating decision χ and ω it is better than a BAU decision.

In Figure 19, we present the graphical result of the social welfare function whilst considering Policy 1 with a damage coefficient equal to $h = 30$. An increase in the carbon dioxide tax shifts the social welfare results vertically downwards (indicated by the black arrows). The reason for this is because when the carbon dioxide tax is increased this affects both the entrant's and downstream firms' marginal cost of production by increasing them which then translates to less output produced. Since fewer outputs are produced by the entrant and downstream market then society is negatively affected. Furthermore, in Figure 19, because of Policy 1, the highest social welfare result is equal to when the entrant firm chooses a production method equal to a CCU strategy or $\chi = 1$ and $\omega = 1$. Thus, illustrating that the adoption of carbon capture technology with CO_2 utilization is good for society.

Overall, the main result obtained because of Policy 1 was a shift in the equilibrium decision by the entrant firm towards carbon capture technology adoption. Specifically, due to Policy 1, the entrant firm is going to choose a production method equal to a CCU strategy, or $\chi = 1$ and $\omega = 1$. This is because the entrant firm is gaining higher equilibrium profit compared to a BAU strategy – see Fig. 15(a). Therefore, an increase in carbon dioxide tax is a solution that can increase the incentives of a firm to adopt a carbon capture technology with CO_2 utilization making the entrant firm gain higher profits.

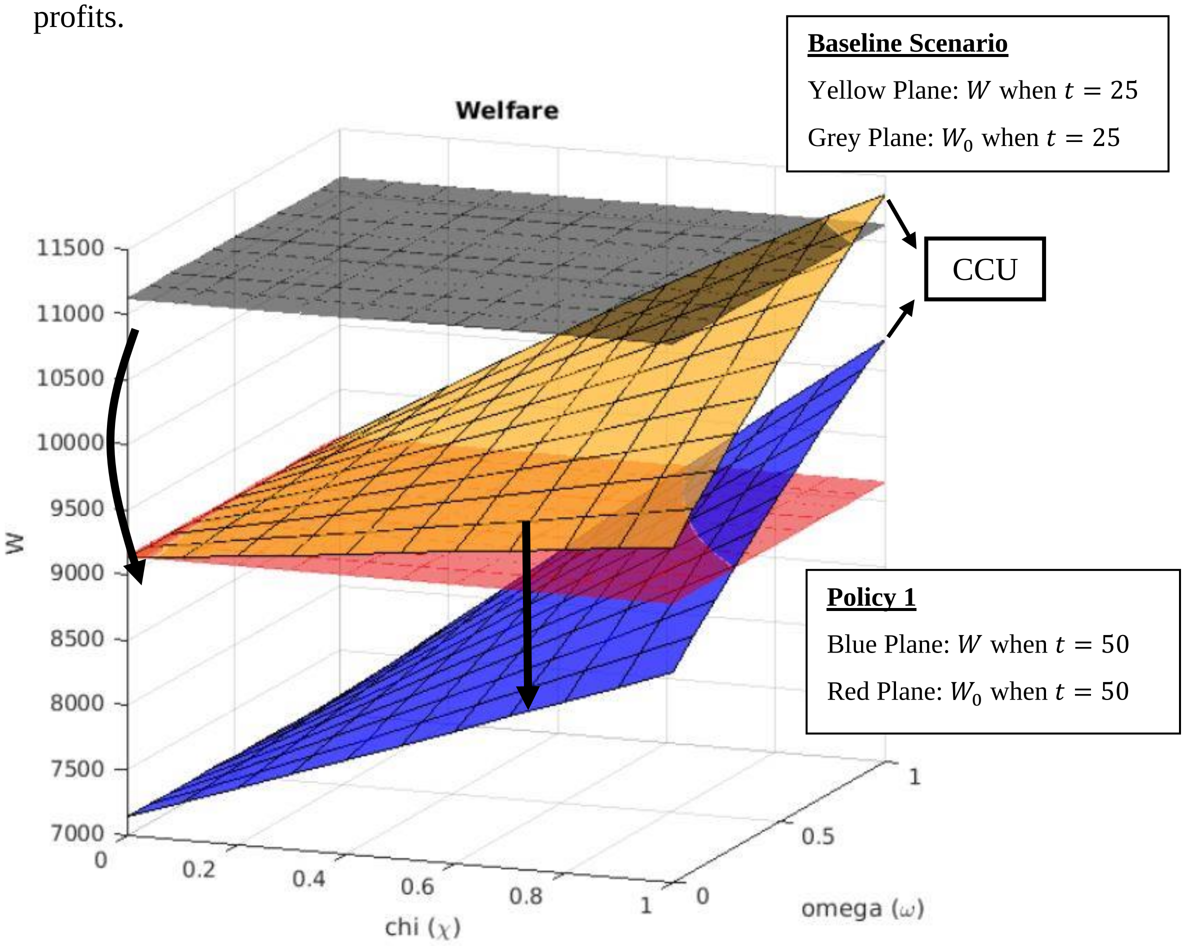


Figure 19 - Social welfare results of the baseline scenario and Policy 1 with $h = 10$.

Note: 3-dimensional graph where χ is y-axis and ω is x-axis. CCU label in the graph points where ω and χ are both equal to 1.

3.8.2 Policy 2 – "A Governmental Fixed Cost Subsidy"

The next policy solution is a governmental fixed cost subsidy (or denoted as Policy 2) to subsidise the adoption of carbon capture technology for the entrant firm. Let us assume that a governmental body is willing to subsidise the entrant firm's fixed cost related to carbon capture technology by up to 50%, denoted by $SUB \equiv 0.5\Phi_1$.

The parametric values used for Policy 2 are the same as the parameters presented for the baseline scenario – see Table 5. However, as shown in Table 6 below there is an additional parameter that has been added in the MATLAB code – highlighted in yellow – demonstrating the presence of the fixed cost subsidy.

Entrant Firm			
Parameter	Value	Description	Units
A	150	Y-intercept of inverse linear demand	$/unit
B	1	Slope of inverse linear demand	Integer
β	10	Marginal cost of production for doing carbon capture	$/t CAP/unit
σ	10	Marginal cost of production not involving carbon capture and carbon emissions	$/unit
t	25	Carbon dioxide tax	$/t CO_2/unit
STO	10	Marginal cost of CO2 storage	$/t STO/unit
ξ_i	1	Pollution intensity of the entrant firm	tCO_2/unit
η	5	Marginal cost for doing CO2 utilization	$/t UTIL/unit
Φ	2000	Fixed cost of the carbon capture unit	Annualised fixed cost
SUB	0.5*Φ	Governmental fixed cost subsidy	Annualised fixed cost subsidy
Φ_{NEW}	$\Phi - SUB$	New fixed cost of the carbon capture unit after subsidy	New annualised fixed cost

Table 6–- Parameters for when there is a governmental fixed cost subsidy

The implementation of Policy 2 only influences the profit maximization result of the entrant firm. Specifically, a fixed cost subsidy only affects the equilibrium profit of the entrant firm where the effect of the policy intervention is displayed in Figure 20.

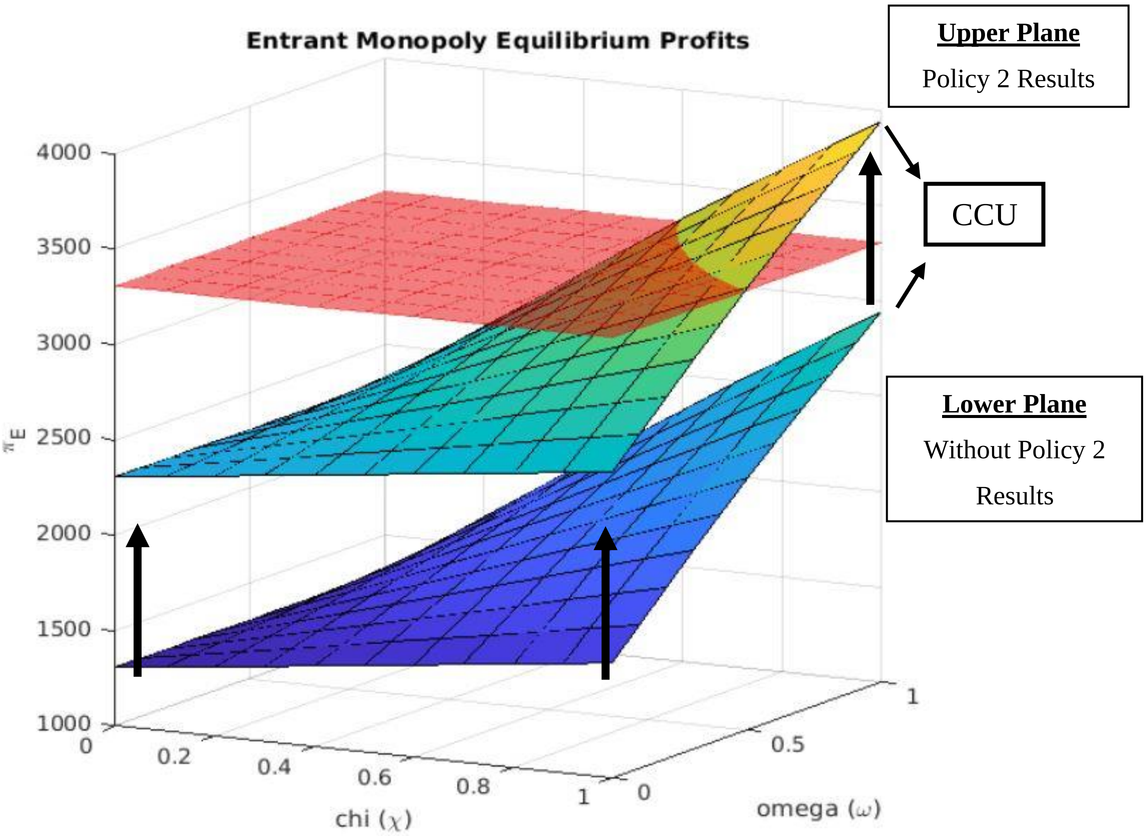


Figure 20 – The effect of a governmental fixed cost subsidy to the entrant firm's equilibrium profit.

Note: 3-dimensional graph where χ is y-axis and ω is x-axis. CCU label in the graph points where ω and

In Figure 20, the red flat plane illustrates the equilibrium profit of the entrant firm for not investing in carbon capture technology. The red flat remains unchanged if Policy 2 is implemented. In Figure 20 there are also two multi-coloured planes. The lower multi-coloured plane shows the equilibrium profits of the entrant firm without Policy 2. Whereas the upper multi-coloured plane displays the equilibrium profit of the entrant firm when Policy 2 is implemented. The effect of a fixed cost subsidy shifts the multi-coloured plane in a vertically upward direction. Due to Policy 2, in Figure 20 one can notice that there are solutions where some operating decisions χ and ω the equilibrium profit for the entrant firm are higher when the entrant firm invests in a carbon capture technology than a BAU strategy. With Policy 2 implemented, the equilibrium decision of the entrant firm is going to be an adoption of carbon capture technology ($I = 1$) where the entrant firm has a production method equal to a CCU strategy or $\chi = 1$ and $\omega = 1$. This is because a production method equal to a CCU strategy gives the highest profit for the entrant firm in Figure 20.

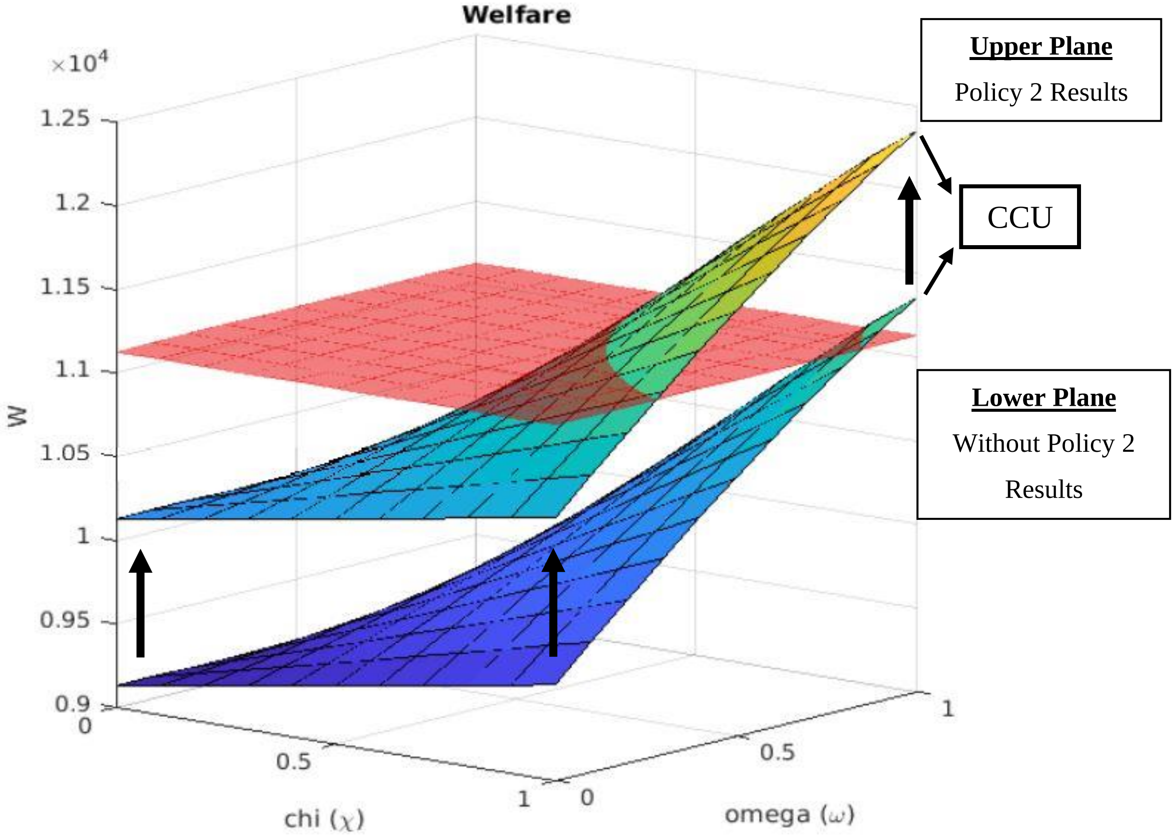


Figure 21 - Social welfare results of Policy 2 with $h = 25$ and the social welfare result without a fixed cost subsidy where $h = 25$.

Note: 3-dimensional graph where χ is y-axis and ω is x-axis. CCU label in the graph points where ω and χ are both equal to 1.

In Figure 21, the upper multi-coloured plane presents the social welfare result when Policy 2 is implemented where the damage coefficient is assumed to be equal to $h = 25$. In Figure 21, the social welfare result when there is no fixed cost subsidy is given by the lower multi-coloured plane. The red flat plane represents the social welfare result when firms are under a BAU strategy. What we discover is that the effect of a fixed cost subsidy increases the welfare of society, illustrated by the vertical arrows pointing in an upward vertical direction. However, note that even without the policy intervention of Policy 2, the lower multi-coloured plane indicates that the adoption of carbon capture technology by the entrant firm is good for society, as the lower multi-coloured has operating decisions that are above the red flat plane. Overall, the government should intervene to increase the adoption of carbon capture technology and a fixed cost subsidy can be a solution.

3.8.2.1 Policy 2.1 – "A Lump-Sum Tax on Downstream firms"

This subsection is a continuation of the analysis of Policy 2, where we answer the question: "*Where will the government get the money to fund the entrant's fixed cost subsidy?*"

A possible funding solution for the government is to impose a lump-sum tax in the downstream market to finance the investment cost of the carbon capture technology for the entrant firm. The reason for a lump-sum tax in the downstream market is because a consistent result obtained for a downstream firm is that it is always better off when the entrant firm enters the upstream market. For example, in the analysis of the baseline scenario, we discover that the equilibrium profits of a downstream firm are greater when carbon capture technology with CO_2 utilization is present in the model compared to a BAU decision by the entrant firm. The highest equilibrium profits gained by the downstream firm are when the operating decisions χ and ω chosen by the entrant firm are both equal to 1. Thus, if the entrant firm is going to adopt a carbon capture technology with a production method equal to CCU, "*what if taxing the positive effect generated in the downstream sector is sufficient to subsidise the entrant firm's carbon capture technology adoption for it to adopt the mitigation technology?*" Let us illustrate the policy by discussing a numerical example.

Using the stated parameters from the baseline scenario (see Table 5), if the entrant firm decides not to adopt a carbon capture technology, a downstream firm is going to obtain an equilibrium profit equal to $\hat{\pi}_j^{BAU} = 1.9267$. On the other hand, if the entrant firm invests in carbon capture technology and selects a CCU production method, a downstream firm obtains an equilibrium profit equal to $\hat{\pi}_j^{CCU} = 2.1039$. Taking the difference between $\hat{\pi}_j^{CCU}$ and $\hat{\pi}_j^{BAU}$, or $\hat{\pi}_j^{CCU} - \hat{\pi}_j^{BAU}$, this obtains us the positive effect generated to the equilibrium profits if the entrant firm invests in carbon capture technology. Multiplying the latter with the total number of downstream firms equal to

$m = 100$, the possible total lump-sum subsidy – denoted by LSS – that can be generated from the downstream market is equal to $LSS = 19.3558$, where $LSS = m\left(\hat{\pi}_j^{CCU} - \hat{\pi}_j^{BAU}\right)$.

The necessarily fixed cost subsidy to make the entrant firm indifferent in choosing to adopt a carbon capture technology or not is simply calculating the difference of equilibrium profit when the entrant firm chooses a production method equal to BAU and CCU or denoted as $\Delta\pi_E = \hat{\pi}_E^{BAU} - \hat{\pi}_E^{CCU}$. This is found to be equal to $\Delta\pi_E = 363.8503$. Comparing the result obtained for $\Delta\pi_E$ with the finding previously obtained of the lump-sum subsidy or LSS, we get $LSS < \Delta\pi_E$. Thus, the generated lump-sum subsidy is not enough to incentivise the entrant firm's carbon capture technology adoption with a production method equal to CCU. Policy 2.1 can cover only approximately 5% of the necessary subsidy such that the entrant firm can achieve at least the same equilibrium profits by adopting carbon capture with a production method equal to CCU and a business-as-usual strategy or $\hat{\pi}_E^{CCU} = \hat{\pi}_E^{BAU}$.

However, multiple policy solutions can be adopted at the same time. For example, let us consider a lump-sum tax in combination with an increase in carbon tax t. Considering the two policies, we further ask: *"What is the threshold carbon dioxide tax t if the production method of the entrant firm is equal to CCU to obtain the inequality $LSS > \Delta\pi_E$?"* To answer the question, we plot LSS and $\Delta\pi_E$ as a function t using the parameters stated in Table 6. Then, the intersection of the two functions will let us know the value of the threshold carbon dioxide tax t that can obtain the inequality $LSS > \Delta\pi_E$.

In Figure 22, the two functions $LSS(t)$ and $\Delta\pi_E(t)$ are shown. The blue line represents $LSS(t)$, the total lump-sum subsidy generated from the downstream market with the carbon dioxide tax t as the changing variable. Whereas the red line represents $\Delta\pi_E(t)$ displaying the function behaviour that shows the necessary fixed cost subsidy to make the entrant firm indifferent in choosing to adopt a carbon capture technology or not. In Figure 22, two vertical dashed lines are also illustrated – denoted by t^{lower} and t^{upper}. The left vertical dashed line or t^{lower}, this represents the carbon dioxide tax level where LSS and $\Delta\pi_E$ are both equal to each other. Using the parametric values as shown in Table 5 for the baseline scenario, we obtain $t^{lower} = 31.9727$. Therefore, if the government chooses a carbon dioxide tax t which is less than t^{lower} the lump-sum tax subsidy generated by the downstream market will not be enough to subsidise the entrant firm to do carbon capture technology. Whereas, if $t > t^{lower}$ then $LSS < \Delta\pi_E$. Thus, the lump-sum subsidy can prompt the entrant firm to do carbon capture with a production method equal to a CCU strategy. The vertical dashed line located on the right-hand side or t^{upper}, represents the carbon dioxide tax t where $\hat{\pi}_E^{CCU} = \hat{\pi}_E^{BAU}$. Using the parametric values stated in Table 5 we get $t^{upper} = 32.3612$. Note that this result is the same finding obtained for Policy 1 in subsection 1.8.1. Therefore, if a carbon dioxide tax t is greater than t^{upper} then there is no other necessary policy intervention required by the government to incentivise the entrant firm to do carbon capture technology with a production method equal to CCU. This is because the firm will be earning greater equilibrium profits than a BAU strategy. Overall, to consider the policy solution of a lump-sum tax subsidy, a carbon dioxide tax t should be within the range $t^{lower} < t < t^{upper}$ as displayed in Figure 22.

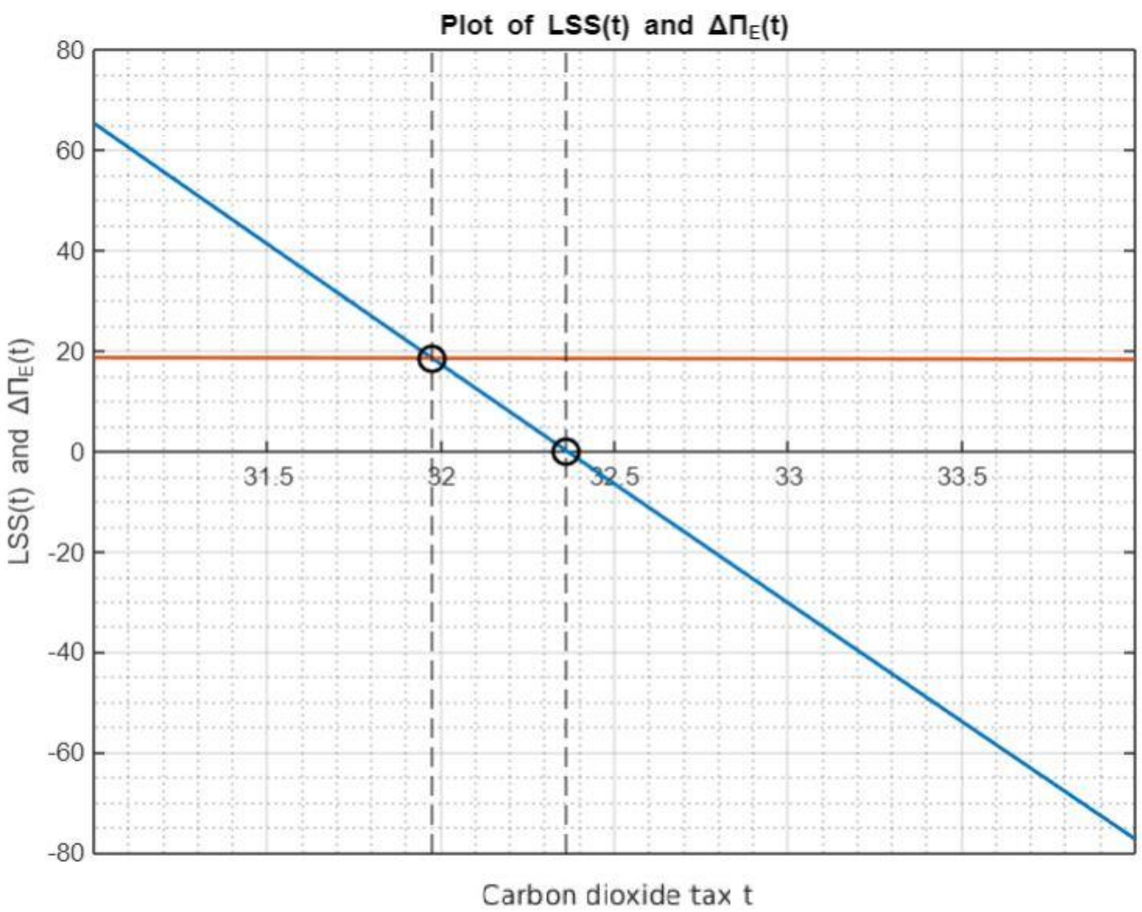


Figure 22 - Plot of LSS and $\Delta\pi_U$ as a function of t where it also displays the region for carbon dioxide t such that $LSS > \Delta\pi_U$.

3.8.3 Policy 3 – "An Environmental Regulation on Natural CO_2 Wells"

In this subsection, we propose a policy solution to restrict the extraction of CO_2 from natural wells to create CO_2 inputs for downstream firms, also called Policy 3.

The motivation of Policy 3 is the following. In section 1.3, the upstream market was presented to be a perfectly competitive market with identical firms. However, the description of the upstream market is a strong assumption as there are many different types of industries supplying CO_2 inputs. The main suppliers of CO_2 inputs are either produced from natural geological CO_2 reservoirs or industrial processes that generate CO_2 as a by-product (e.g., SMR, natural gas processing, ethanol production). Policy 3 targets the supply of CO_2 from natural wells. The use of CO_2 from natural wells is mainly used by the enhanced oil recovery or EOR industry – the process of increasing the amount of oil that can be recovered from an oil reservoir, usually by injecting a substance (i.e., CO_2) into an existing oil well. EOR is one of the largest consumers of CO_2, where most facilities are located in the USA. Approximately 80% of CO_2 used in EOR originates from natural wells because it is one of the cheapest methods to obtain CO_2 inputs. Also, in the USA there is about 6,500 km of CO_2 pipelines which have been operating for years for EOR operations. However, the replacement of natural CO_2 with man-made CO_2 in the EOR applications is a large potential. Hence, "*what if the government or policymakers implement an environmental regulation prohibiting the extraction of CO_2 from natural wells? How would the policy solution affect the adoption of carbon capture technology?*"

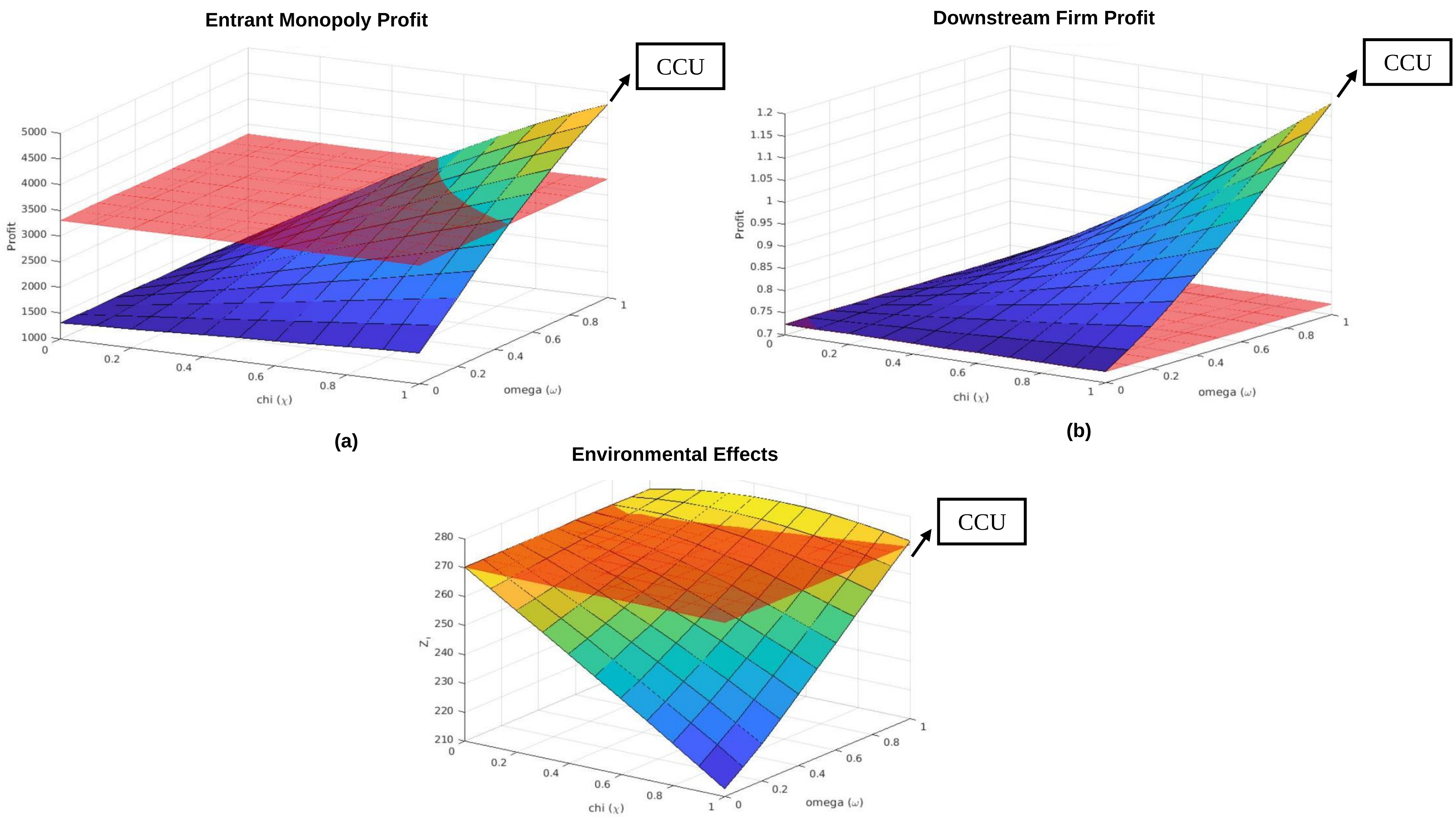
The effect of executing Policy 3 causes two parametric adjustments in the numerical example. Firstly, the number of firms in the upstream market using conventional sources or parameter n is considered to decrease. This is because the prohibition reduces the number of firms producing CO_2 inputs. Secondly, the cost production of a firm in the upstream market is going to increase, which captured by the parameter $\tilde{b}$. The reason for this is because the remaining firms in the upstream market after Policy 3 should experience a higher mark-up for selling CO_2 inputs as CO_2 inputs from natural wells is one of the cheapest options to obtain the intermediary product.

The parametric values considered for Policy 3 are shown in Table 7.

Entrant Firm			
Parameter	Value	Description	Units
A	150	Y-intercept of inverse linear demand	$/unit
B	1	Slope of inverse linear demand	Integer
β	10	Marginal cost of production for doing carbon capture	$/t CAP/unit
σ	10	Marginal cost of production not involving carbon capture and carbon emissions	$/unit
t	25	Carbon dioxide tax	$/t$CO_2$/unit
STO	10	Marginal cost of CO2 storage	$/t STO/unit
ξ_i	1	Pollution intensity of the entrant firm	tCO_2/unit
η	5	Marginal cost for doing CO2 utilization	$/t UTIL/unit
Φ	2000	Fixed cost of the carbon capture unit	Annualised fixed cost
Downstream Industry			
Parameter	Value	Description	Units
a	200	Y-intercept of inverse linear demand	$/unit
b	1	Slope of inverse linear demand	Integer
m	100	Number of downstream firms	Integer
λ	5	Marginal cost of production not involving carbon capture and carbon emissions	$/unit
ξ_j	1	Pollution intensity of a downstream firm	tCO2/unit
k	1.5	Conversion factor of CO2 inputs into one unit of output	tCO2/unit
Upstream Industry			
Parameter	Value	Description	Units
n	50	Number of upstream firms producing CO2 input under conventional method	Integer
$\tilde{a}$	5	Marginal cost parameter for conventional firm	$/unit
$\tilde{b}$	20	Marginal cost parameter for conventional firm	$/unit

Table 7–- Parameters for when there is an environmental regulation on natural CO_2 wells

Using MATLAB, the graphical result of the profit-maximization and environmental impact can be found in Figure 23.



(c)

Figure 23 - Results for Scenario 4 - (a) Entrant firm's equilibrium profit, (b) Downstream firm's equilibrium profit, (c) Environmental effects

Note: 3-dimensional graph where χ is y-axis and ω is x-axis. CCU label in the graph points where ω and χ are both equal to 1.

Fig. 23(a) displays the equilibrium profits of the entrant firm considering Policy 3. An environmental regulation on natural wells has a positive effect on the entrant firm. In Fig. 23(a) the multi-coloured plane can be found partially above the red flat plane, this indicates that for some operating decisions χ and ω chosen by the entrant firm it can achieve higher equilibrium profits when adopting a carbon capture technology with CO_2 utilization compared to a BAU strategy. This occurs because Policy 3 reduces the CO_2 supplies in the CO_2 input market. Consequently, this then would mean that the equilibrium price of CO_2 inputs is going to increase. Thus, the entrant firm is going to gain better margins when selling its captured CO_2 allowing the firm to achieve higher profits.

Fig. 23(b) displays the equilibrium profits of a downstream firm under Policy 3. The findings shown are the same as previously discussed for Policy 1 in Fig. 18(b) – see section 1.8.1.

Fig. 23(c) illustrates the environmental effects of Policy 3. One can notice that in Fig. 23(c) the multi-coloured plane can be found partially above the red flat plane. Thus, the environmental result shows that for some operating decisions χ and ω, the entrant firm can be worse off compared to a BAU strategy. This occurs because of the effects created by Policy 3 in the equilibrium price of CO_2 inputs. The first effect of Policy 3 is an increase in the market-clearing price for CO_2 inputs by eliminating the supply from the lowest cost of production of CO_2 inputs – i.e., natural CO_2 wells. Then, when an entrant firm adopts carbon capture technology and sends its captured emissions to the CO_2 input market, the market-clearing drastically decreases. Because of this effect, the downstream market is going to experience a larger decrease in its marginal costs leading to greater outputs. Ultimately, higher outputs equate to more pollution which causes the condition where some operating decisions χ and ω we are going to obtain $Z_1 > Z_0$.

Overall, by implementing Policy 3 the equilibrium outcome is a decision where the entrant firm is going to have a production method equal to a CCU strategy, or $\chi = 1$ and $\omega = 1$. However, "*should the government still adopt Policy 3 despite obtaining a negative environmental impact result?*" To answer the question, we further examine the environmental impact results obtained *after* Policy 3 is adopted (or post-policy) versus the results *before* implementing the policy solution (or pre-policy). Table 8 shows the environmental outcomes *before* and *after* Policy 3 is implemented.

	Z	
Production Method	**Post-Policy**	**Pre-Policy**
BAU	270.1963 (A1)	404.5104 (B1)
CCU	276.9886 (A2)	363.0082 (B2)

Table 8–- Environmental effect results before and after implementing Policy 3

So far, the assessment has been a comparison after the policy has been adopted or post-policy. In Table 8 these are the results obtained for (A1) and (A2). However, comparing the results of (A1) versus (B1), clearly (B1) is greater than (A1). Similarly, it is the same for (A2) and (B2), where (B2) > (A2). Therefore, what is clearly shown is the adoption of Policy 3 should be still a policy solution that governments could consider as it produces a positive environmental outcome in comparison to when the policy solution has not been adopted.

3.8.3.1 Policy 3.1 – "A Price Control on CO_2 Inputs"

The policy solution introduced in this subsection is the execution of a price floor in the CO_2 input market, called Policy 3.1. A price floor is the lowest legal price a commodity can be sold at and used by the government to prevent prices from being too low. The motivation behind this policy solution is because of the obtained environmental results in section 1.8.3 for Policy 3 – "an environmental regulation on natural CO_2 wells". A major finding of Policy 3 was the environmental effect of adopting carbon capture technology and choosing some operating decisions χ and ω, it can achieve a worse outcome than a BAU decision or $Z_1 > Z_0$. Therefore, the purpose of Policy 4 is to avoid obtaining the inequality $Z_1 > Z_0$.

We provide an example for illustration of the effect of Policy 3.1. Let the price floor of CO_2 inputs be denoted by the notation $\underline{R}$. To obtain the price floor $\underline{R}$, the environmental impact equations Z_1 and Z_0 as stated in section 1.5 are set equal and then rearranged for $\hat{R}$. By doing so the price floor for CO_2 inputs is equal to

$$\underline{R} = \frac{1}{\chi\omega b(m+1)(\chi-1)\xi^2 + 2Bm(\overline{y}+\overline{\xi})\overline{y}}\big[b(m+1)\xi^2\big((\eta - STO)\omega$$

$$+ STO - \tau + \beta\big)\chi^2 - b\big[\big((\eta - STO)\omega + STO - 2\tau + \beta\big)\xi \qquad (63)$$

$$+ A - \sigma\big](m+1)\xi\chi + 2Bm\overline{y}\hat{R}_0(\overline{y}+\overline{\xi})\big]$$

Using the parametric values stated for Policy 3 – see Table 7 – in MATLAB, the graphical result of the expression above is displayed in Figure 24.

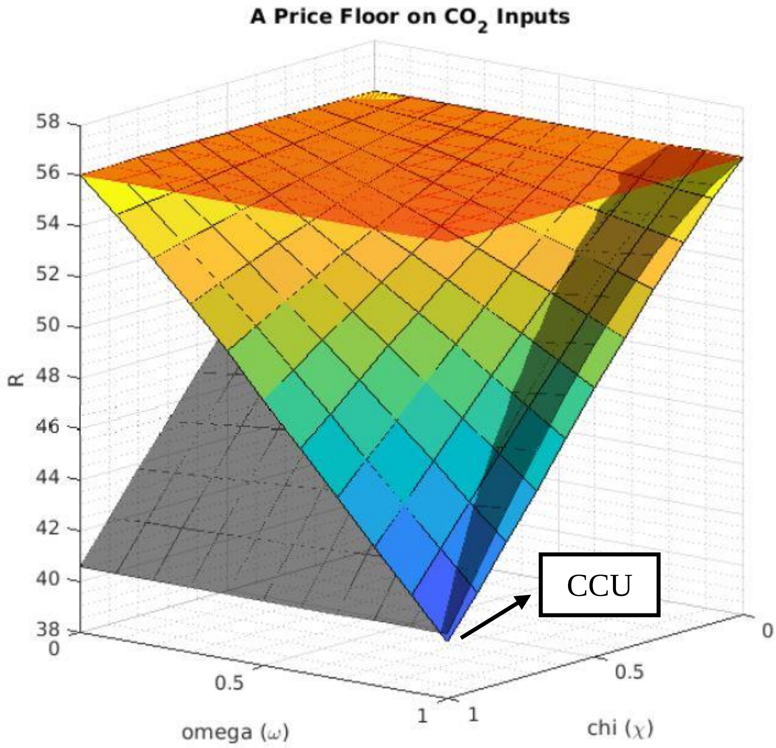


Figure 24–- The Price Floor on CO_2 inputs

Note: A 3-dimensional graph where ω is the y-axis and χ is the x-axis. CCU label in the graph points where ω and χ are both equal to 1.

In Figure 24 the three planes are:

- The red flat plane corresponds to the equilibrium price of CO_2 inputs without the presence of CO_2 inputs from the entrant firm.
- The multi-coloured plane corresponds to the effect on the equilibrium price of CO_2 inputs for any operating decision χ and ω chosen by the entrant firm after given that it has adopted a carbon capture technology.

- The grey plane illustrates the level of the price floor $\underline{R}$ to obtain $Z_1 = Z_0$ – i.e., the environmental outcome of adopting a carbon capture technology for any operating decision is equal to a business-as-usual strategy.

In Figure 24 one can see that the more captured CO_2 the entrant firm sends for CO_2 utilization, the lower the market-clearing price for CO_2 inputs is going to be. This illustrates that the CO_2 input market is quasi-competitive: meaning that the price falls and the volume of trade increases. However, the main result of Figure 24 is if the market price of CO_2 inputs is below the grey play or the price floor $\underline{R}$, then the model is going to achieve a negative outcome for the environment or $Z_1 > Z_0$. For example, since the equilibrium outcome of the game is where the entrant firm is going to choose to adopt a carbon capture technology with a production method equal to a CCU strategy because it corresponds to the highest equilibrium profit that the entrant firm achieves in this particular numerical example – see Fig. 23(a). The price floor that the government should set for the CO_2 inputs is equal to $\underline{R} = 40.5605$. If the government does not intervene and lets the equilibrium price of CO_2 inputs go below $\underline{R} = 40.5605$, then the environmental effect is going to better under a business-as-usual – i.e., for some $R < \underline{R}$ then $Z_1 > Z_0$. Whereas, if the government implements such that the equilibrium price of CO_2 inputs cannot go lower than $\underline{R}$ then the environmental outcome $Z_1 < Z_0$ is achieved.

3.8.4 Comparison between Policy Interventions

In this section, policy interventions are compared. The comparison of the policies is examined by evaluating the change in the social welfare – denoted by $\Delta W(h)$ – when the policies are implemented, between the strategy of adopting a carbon capture technology versus business-as-usual result. Specifically, $\Delta W(h) = W_1(h) - W_0(h)$, where $W_1(h)$ corresponds to the social welfare result as a function of the damage coefficient h – equation (61) – and $W_0(h)$ is the social welfare when the monopoly firm decides not to enter the upstream sector also as a function of h – equation (62). Since all numerical examples obtained so far have a consistent result where the equilibrium decision of the entrant firm is going to adopt a carbon capture technology and choose a production method with a CCU strategy – i.e., $I = 1 \Rightarrow \chi = 1$ and $\omega =$

1 – we strictly consider only a CCU production method for the comparison of the policy interventions.

Figure 25 displays the graphical illustration of the change in social welfare result for each of the policy interventions as a function of the coefficient h and the production method chosen by the entrant firm in the model is equal to a CCU strategy.

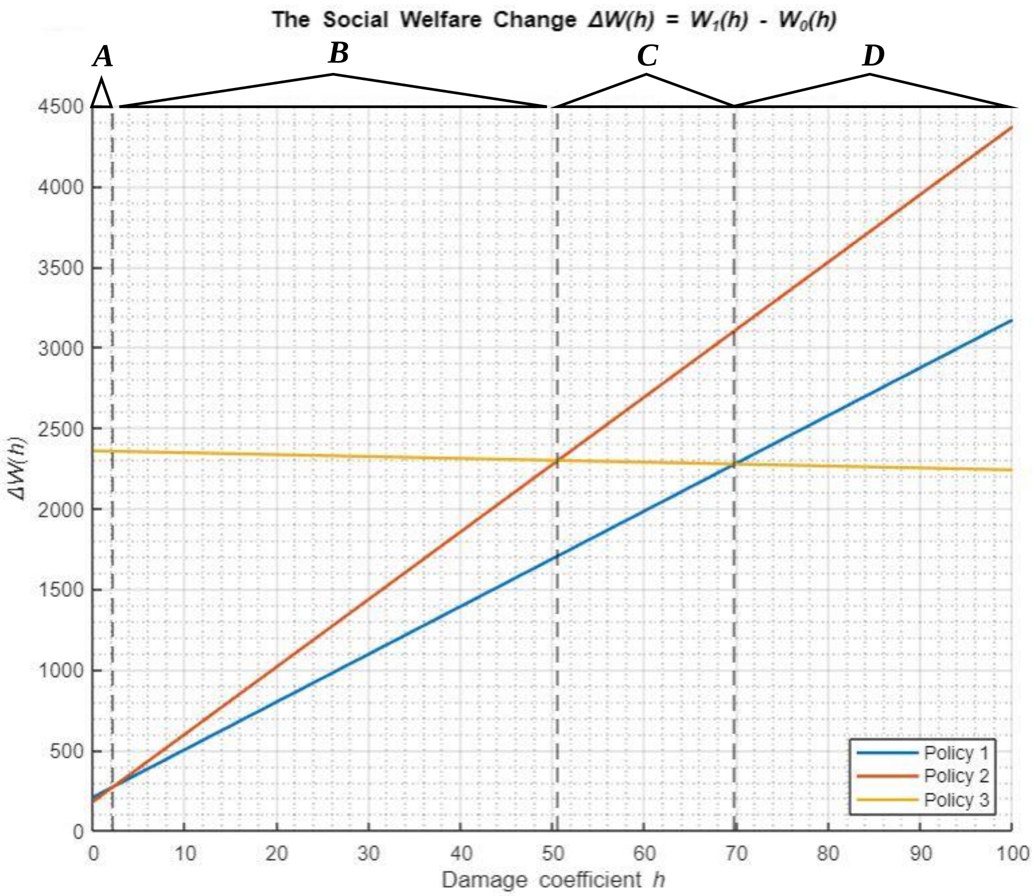


Figure 25 - The social welfare change $\Delta W(h)$ results for each policy intervention where the entrant firm chooses a CCU strategy.

The three lines in Figure 25 are:

- The blue line represents $\Delta W(h)$ when Policy 1 is considered.
- The red line represents $\Delta W(h)$ when Policy 2 is implemented.
- The yellow line indicates the result of $\Delta W(h)$ because of Policy 3.

In Figure 25 one can also notice that the graph is subdivided into four regions: $\boldsymbol{A}, \boldsymbol{B}, \boldsymbol{C}$ and $\boldsymbol{D}$. Let illustrate with an example of what the regions entail.

If the damage coefficient h is equal to 2, we are in region $\boldsymbol{A}$. Then, using the graphical results displayed above one can find that Policy 3 – “an environmental regulation on natural CO_2 wells” – obtains the highest difference between W_1 and W_0 or change in social welfare between all policy interventions. Thus, what this means is that Policy 3 generates the highest positive social welfare change among all policies when the damage coefficient $h = 2$. Implementing Policy 3 with a considered $h = 2$ will provide the highest benefit for society. The next policy generating the second-best change in social welfare corresponds to Policy 1, “an increase in carbon dioxide tax”. Last is Policy 2 – “a governmental fixed cost subsidy”. Overall, Figure 25 can be used to obtain which policy solution is a greater change in the social welfare for adopting the policy intervention depending on the level of the damage coefficient h. Thus, governments and policymakers can detect which policy solution should be prioritised depending on the level of the damage coefficient h to increase the adoption of CCS technology. Table 9 summarises the results of Figure 25 where we rank the policy interventions with the largest social welfare change on top depending on the level of damage coefficient h.

	Region $\boldsymbol{A}$	**Region $\boldsymbol{B}$**	**Region $\boldsymbol{C}$**	**Region $\boldsymbol{D}$**
Ranking of Policies	Policy 3	Policy 3	Policy 2	Policy 2
	Policy 1	Policy 2	Policy 3	Policy 1
	Policy 2	Policy 1	Policy 1	Policy 3

Table 9 – Summary of the ranking of the policies and the corresponding regions

For the numerical example if for some damage coefficient $h > 0$ corresponds to:

- $0 \leq h < 34.3310 \Rightarrow$ Region $\boldsymbol{A}$
- $34.3310 < h < 40.5403 \Rightarrow$ Region $\boldsymbol{B}$
- $40.5403 < h < 56.1557 \Rightarrow$ Region $\boldsymbol{C}$
- $56.1557 < h \Rightarrow$ Region $\boldsymbol{D}$

3.9 Conclusion

This chapter examined the microeconomic and environmental effects when a CCU strategy is adopted. In this chapter, an economic model under an industrial organization approach was presented where we considered a market structure that was a non-vertically integrated market composed of an upstream and downstream sector. The upstream sector represented firms producing an intermediary good, in this case, CO_2 inputs, which are only produced using conventional methods coming from fossil fuel sources. Whereas the downstream sector is the industry requiring the intermediary product or CO_2 inputs to produce their final good. The focus of the study was to explore the microeconomic effects caused by the entry of a firm into the upstream market. The entrant firm was different from the other firms in the upstream sector. The entrant firm is a single firm in its market that has the capability of entering the intermediary CO_2 input market with the adoption of carbon capture technology and CO_2 utilization (CCU). CO_2 utilisation is an alternative channel option where a firm sells the captured gas to an industry that requires CO_2 gas to produce its final product.

In this study, we uncover several microeconomics interactions with the stakeholders involved when CCU is adopted. First, when a firm enters the upstream market by adopting the carbon capture and CO_2 utilization process, a positive effect is always obtained for the downstream market as the entry of a firm in the upstream market lowers the equilibrium price of the intermediary good which leads to lower marginal costs of production for downstream firms. Consequently, downstream firms' outputs are going to increase and therefore higher profits are obtained. Overall, with an increase in the number of firms in the upstream market, there is an indirect strategic effect on the revenue of each downstream firm (i.e., higher total industry output) and a direct effect is generated on the intermediary good's cost (i.e., the lower marginal cost of production).

Furthermore, in this study, we also find that the entrant firm under some exogenous parameters replicating the current economic situation of carbon capture technology will still not select a CCU strategy, despite the strategy allowing the entrant firm to recoup some of its investment cost for adopting carbon capture and CO_2 utilization process. Thus, to revert this equilibrium decision, three policy solutions were discussed:

1. The government can increase the carbon dioxide tax.
2. The government can provide a fixed cost subsidy to reduce the expensive investment cost of CCS technology.
3. Governments can implement an environmental regulation restricting the extraction of CO_2 inputs from natural wells.

The policies suggested in this chapter are to inform governments and policymakers to increase the adoption of CCU adoption whilst also considering the environmental impact of adopting the mitigation strategy. The reason for this is because one of the main drawbacks of final goods produced by CO_2 utilisation; the CO_2 content is eventually released back again into the atmosphere once consumed by final consumers. Thus, we provide pivotal information on the economic and environmental outcomes when a CCU strategy is adopted so that governments are informed to not obtain a worse environmental outcome when adopting a CCU strategy.

The limitations of this chapter are due to some strict assumptions in the modelling process. If relaxed these could provide interesting avenues for future research. In particular, the assumption about the upstream market was assumed to be a perfectly competitive market with identical firms. Future work could, therefore, progress in considering a more realistic framework for the upstream sector. Moreover, the downstream was assumed to be a market with no bargaining power, where the price of CO_2 inputs to produce their final product was given. This assumption is not very satisfactory because it is difficult to justify that an economic agent behaves strategically in one market but not in another. A full treatment would require downstream firms to behave strategically simultaneously in the downstream and upstream markets. Hence, a promising future work idea is to explore the contract agreements between the two industries for the exchange of CO_2 inputs.

3.10 Appendices Chapter 3

A – Parameters–- MATLAB Example Script

```
% OPERATING DECISIONS

omega=0:0.1:1;
chi=0:0.1:X;

% ENTRANT FIRM
A=150;              % Y-intercept of inverse linear demand
B=1;                % Slope of inverse linear demand
beta=10;            % Marginal cost of production for doing carbon capture
sigma=10;           % Marginal cost of production not involving carbon capture
                            and carbon emissions
t=25;               % Carbon dioxide tax
STO=10;             % Marginal cost of CO2 storage
ei=1;               % Pollution intensity
eta=5;              % Marginal cost for doing CO2 utilization
Phi=2000;           % Fixed cost of the carbon capture unit

% DOWNSTREAM
a=200;              % Y-intercept of inverse linear demand
b=1;                % Slope of inverse linear demand
m=100;              % Number of downstream firms
lambda=5;            % Marginal cost of production not involving CO2 input and
carbon emissions
ej=1;               % Pollution intensity
k=1.5;              % Conversion factor of CO2 inputs into one unit of product

% UPSTREAM
n=70;               % Number of upstream firms producing CO2 input under
                            conventional method
tildea=5;           % Marginal cost parameters for conventional firm
tildeb=5;           % Marginal cost parameters for conventional firm


% DAMAGE FUNCTION
h=25;                % The marginal damage from pollution
```

B – Profit Maximization Results – MATLAB Example Script

```
I = 0:0.1:1;

for i = 1:size(I,2)
    for j = 1:size(I,2)

        % ENTRANT FIRM OPTIMAL OUTPUT
        x_hat(j,i)=(-chi(i)*ei^2*m*omega(j)*t*tildeb*k + (((-n*((eta-- STO -
                 tildea)*omega(j) + STO-- t + beta)*b-- k*tildeb*(((eta -
                 STO)*k + lambda-- a)*omega(j) + k*(-t + beta +
                 STO)))*chi(i)-- t*(tildeb*k^2 + b*n))*m-- n*(((eta-- STO -
                 tildea)*omega(j) + STO-- t + beta)*chi(i) + t)*b)*ei + (A -
                 sigma)*((tildeb*k^2 + b*n)*m +
                 b*n))/(2*omega(j)^2*tildeb*b*ei^2*(m + 1)*chi(i)^2 +
                 2*B*((tildeb*k^2 + b*n)*m + b*n));


        x_BAU(j,i)=(A-sigma-t*ei)/2*B;

        % CO2 INPUT EQUILIBRIUM PRICE
        R(j,i)=(-(m + 1)^2*n*(chi(i)*omega(j)*ei*((-chi(i)*(eta-- STO +
                 tildea)*omega(j) + (t-- beta-- STO)*chi(i)-- t)*ei + A--
                 sigma)*tildeb-- 2*tildea*B*n)*b^2-- m*(m +
                 1)*k*((t*omega(j)*chi(i)*ei^2 + (-chi(i)*((eta-- STO)*k -
                 lambda + a)*omega(j)-- ((-t + beta + STO)*chi(i) + t)*k)*ei
                 + k*(A-- sigma))*chi(i)*omega(j)*ei*tildeb + 2*B*n*(ei*t -
                 tildea*k + lambda-- a))*tildeb*b -
                 2*tildeb^2*B*m^2*k^3*(ei*t + lambda-- a))/(2*(n*(m + 1)*b +
                 m*tildeb*k^2)*((m + 1)*(chi(i)^2*ei^2*omega(j)^2*tildeb +
                 B*n)*b + B*m*tildeb*k^2));

        R_zero(j,i)=(tildeb*m*k*(-ej*t-- lambda + a) + tildea*b*n*(m +
                 1))/(n*(m + 1)*b + m*tildeb*k^2);

        % DOWNSTREAM OPTIMAL OUTPUT
        q_hat(j,i)=(-R(j,i)*k-- ej*t-- lambda + a)/((m + 1)*b);

        q_BAU(j,i)=(-R_zero(j,i)*k-- ej*t-- lambda + a)/((m + 1)*b);

        % ENTRANT FIRM EQUILIBRIUM PROFITS
        pi_UP(j,i)=(-B*x_hat(j,i) + A)*x_hat(j,i)-- Phi-- (sigma + (1-
                 chi(i))*t*ei + chi(i)*ei*(beta + (1-- omega(j))*STO -
                 omega(j)*(R(j,i)-- eta)))*x_hat(j,i);

        pi_UP_BAU(j,i)=(-ei*t + A-- sigma)^2/(4*B);

        % DOWNSTREAM EQUILIBRIUM PROFITS
        pi_DOWN(j,i)=(-ej*t-k*R(j,i)-lambda+a)^2/(b*(m+1)^2);

        pi_DOWN_BAU(j,i)=(-ej*t-k*R_zero(j,i)-lambda+a)^2/(b*(m+1)^2);

        % ENVIRONMENTAL EFFECTS
        Z(j,i)=x_hat(j,i)*ei-chi(i)*x_hat(j,i)*ei+m*q_hat(j,i)*(k+ej);

        Z_BAU(j,i)=x_BAU(j,i)*ei+m*q_BAU(j,i)*(k+ej);

    end
end
```

C – Social Welfare Results – MATLAB Example Script

```
for i = 1:size(I,2)
    for j = 1:size(I,2)

        % ENTRANT FIRM INVESTS IN CCU
        W(j,i)=n*(R(j,i)*(R(j,i)-- tildea)/tildeb-- tildea*(R(j,i) -
                 tildea)/tildeb-- (R(j,i)-- tildea)^2/(2* tildeb)) +
                 m*pi_DOWN(j,i)-- h*(x_hat(j,i)*ei-- x_hat(j,i)* ei*chi(i) +
                 m*q_hat(j,i)*(k + ej)) + b*m^2*(q_hat(j,i).^2)/2 +
                 t*ej*q_hat(j,i)*m + B*(x_hat(j,i).^2)/2 + (1-
                 chi(i))*t*ei*x_hat(j,i)+ pi_UP(j,i);

        % ENTRANT FIRM DOES NOT INVEST IN CCU
        W_BAU(j,i)=n*(R_zero(j,i)*(R_zero(j,i)-- tildea)/tildeb -
                 tildea*(R_zero(j,i)-- tildea)/tildeb-- (R_zero(j,i) -
                 tildea)^2/(2*tildeb)) + m*(-R_zero(j,i)*k-- ej*t-- lambda +
                 a)^2/(b*(m + 1)^2)-- h*(((-ei*t + A-- sigma)*ei)/(2*B) +
                 m*(-R_zero(j,i)*k-- ej*t-- lambda + a)*(k + ej)/((m +
                 1)*b)) + m^2*(-R_zero(j,i)*k-- ej*t-- lambda + a)^2/(2*b*(m
                 + 1)^2) + t*ej*m*(-R_zero(j,i)*k-- ej*t-- lambda + a)/((m +
                 1)*b) + (3*(-ei*t + A-- sigma)^2)/(8*B) + t*ei*(-ei*t + A -
                 sigma)/(2*B);

    end
end
```

Chapter 4

The Effects of Learning-by-doing and Knowledge Spillover on the Adoption Timing of CCS technology

4.1 Introduction

Carbon capture and storage (CCS) technology is still lacking in deployment. The reason for this is the mitigation technology has still several barriers preventing its transition to a full commercial state. For example, some of the hurdles impeding CCS deployment are the lack of policy incentives, regulatory framework, public acceptance, and technical-economic feasibility. However, the main hurdle is the cost viability of the technology. Hence, in the current literature, many studies have concentrated their attention on solving the issues using a technical-economic assessment (TEA). A TEA is a methodology framework that allows a researcher to analyse the technical and economic performance of a process, product or service and includes studies on the economic impact of research, development, demonstration, and deployment of technologies quantifying the cost of manufacturing and market opportunities (Arno W. Zimmermann et al., 2020b). In the CCS literature, TEA studies provide a detailed overview of the nature of the individual costs of the CCS components (i.e., the Levelized Cost of Electricity) or cost estimates as a full-chain system (i.e., cost of CO_2 capture or cost of CO_2 avoided).

A limitation of the current TEA studies in the literature is that they take only a static perspective on the cost of carbon capture systems. In other terms, technology performance and costs are assumed to remain constant. Thus, failing to investigate CCS economic feasibility for a long period, especially when the production cost of different carbon capture systems could be varying as a function of time, due to expansion of CCS technologies and upgrading of system efficiency.

In recognition of this limitation, in the current literature, some methods have been applied to simulate the possibility of cost reductions for carbon capture systems in the future. One way is through partial equilibrium models with the aid of a thorough analysis of possible technology upgrading. For example, studies using this method in the context of carbon capture systems can be found in the research by IEA (2004), NETL (2010), and Peeters et al. (2007). Partial equilibrium models are based on a bottom-up approach, which incorporates detailed information on the employed technologies such as capital costs for new plants, capacities of existing plants, efficiencies, operation and maintenance costs, prices of natural gas and coal, carbon prices resulting from the imposed CO_2-emissions constraints, etc. Overall, a partial equilibrium model aims to determine the cheapest way to achieve a given target based on the best available technologies and processes. The other approach is the application of a learning curve to explore the future cost trend of carbon capture systems. Learning curve theory can depict the cost slope of an energy technology that is caused by the continuous expansion of cumulative installed capacity. An academic study that has attempted the cost variation of carbon capture systems is for example the study conducted by Riahi et al. (2004), who applied learning curve theory to estimate the cost reduction potential for carbon capture and sequestration technologies. Furthermore, Edward S. Rubin et al. (2007b) and (2009) also took into consideration the learning effects of various CCS components. However, the authors assessed the learning effects in various CCS components by employing historical learning results from other processes that are similar to CCS technology to evaluate the future system cost.

The abovementioned studies provide a good understanding of the possible learning outcomes that a carbon capture system can experience. However, the current studies lack an understanding that the learning effects of using technology not only have a benefit for the adopting firm but also have an impact on other firms in the market with the presence of a technological spillover. For example, a real-world application of this situation has been reported by the International CCS Knowledge Centre established by BHP and SaskPower, the two companies that established the first industrial-scale CCS facility at a coal-fired power plant known as the Boundary Dam CCS project. In the report, the major findings discovered by the Knowledge Centre were the cost reduction in the possible retrofitting of carbon capture and storage technology to the Shand Power Station, a 300 MW coal-fired plant near Estevan, Saskatchewan, Canada. It is estimated that the cost of capturing carbon at Shand would be only one-third of what the Boundary Dam cost in the first place, a startling improvement for the 'next generation' of CCS technology. Specifically, per tonne, the cost of capture would be US$45/tonne, which importantly is under the US$50/tonne tax credit that the US government is now offering per tonne of captured carbon. The cost reduction is down to both operational efficiencies and capital cost improvements, with the power plant integration capital cost falling by 92% compared to Boundary Dam (ICCSKC, 2018). Overall, the Boundary Dam CCS Project has created an avenue for later organizations such as the Shand Power station where adoption of a CCS project has become more cost-effective due to a learning-by-doing effect and the presence of a technological spillover for future CCS adoptions.

Therefore, in this chapter, the contribution to the current knowledge is to explore the effects that learning-by-doing and technological spillover have on CCS adoption. In this study using an industrial organization approach, we consider the scenario of a firm that has adopted a first-generation CCS technology or is referred to as a pioneer and investigate when the other firm is going to optimally adopt a 'new generation' CCS technology which has a lower cost of operation due to learning-by-doing generated by the pioneer. The reason for analysing this scenario is because of the lack of CCS deployment not only due to its extremely high cost and the lack of policy incentives. However, another key factor is what we call the waiting factor. The reason for the lack of CCS technology deployment can also be because firms are choosing to delay CCS investment knowing that if another firm adopts it first there are more potential savings by waiting for more advanced technology in the future.

The findings obtained in this chapter contribute to the CCS literature that investigates CCS technology involved with learning effects. A primary difference between this study and the current literature is the chosen research methodology of an industrial organization approach. An industrial organization approach allowed us to evaluate the optimal adoption time of a follower who adopts a more advanced CCS technology given that another firm has previously adopted a first-generation CCS technology. Also, we were able to explore the factors that affect the optimal time of a new generation of CCS technology at a microeconomic level. However, the main contribution of this chapter is the suggestion of a policy solution to obtain a sequential scenario – i.e., an initial adopter (pioneer) and then later the other firm adopts (follower). As in the analysis of the game, we discover that no firm wants to invest in CCS technology now because of expensive cost but also due to the waiting factor that if another firm adopts it first there are more potential savings by delaying investment waiting for more advanced technology in the future. Therefore, the policy suggested is to obtain the scenario of a pioneer and follower where this is achieved by a transfer of payment between the firms because a firm that adopts technology 1 or pioneer, the benefits that the pioneer creates for others do not go back to the firm itself. Overall, the policy aims to achieve early CCS adoption and an increase in the diffusion of the mitigation strategy.

The guiding research questions addressed in this chapter are:

- *What is the optimal adoption decision time of a follower for a CCS technology adoption influenced by a learning-by-doing and spillover effect?*
- *What factors affect the adoption decision time of the follower?*
- *What policy solution should governments and policymakers implement such that a pioneer and follower achieve equally balanced benefits in adopting different generations of CCS technology?*

Overall, in this chapter, two insights are revealed:

- *Insight for firms* – In this chapter, the first insight is that we evaluate the optimal adoption time of a firm that is a follower. Then we also discover the factors that affect the optimal decision time of a follower given that a firm has previously adopted a first-generation CCS technology. Specifically, the optimal adoption time of a follower is affected by four main factors: (i) the marginal cost of production that a firm obtains by choosing to stay under a business-as-usual strategy, or in other words, choosing not to adopt a CCS technology; (ii) the lowest possible marginal cost of production that the follower achieves adopting a second-generation CCS technology from its own learning-by-doing; (iii) the learning capability that the follower achieves for adopting a second-generation CCS technology, and; (iv) the initial assumed marginal cost of production that the pioneer achieves for adopting a first-generation CCS technology. For each of these factors mentioned, all impact the optimal adoption time of the follower in different ways, which are explained in more detail later in the study.

- *Insight for governments or policymakers* – The main result obtained in this chapter is the construction of a policy solution that solves the issue where the is no disadvantage for a firm becoming a pioneer. The purpose of the policy suggested is to balance the benefits produced by the pioneer which are not directly experienced by the adopting firm. The policy aims to achieve early CCS adoption and an increase in the diffusion of the mitigation strategy.

The remainder of this chapter proceeds as follows. In section 4.2 we discuss the concept of technological learning and learning-by-doing. Then, in section 4.3 a review of the relevant literature for this study is presented. The model of the study is introduced in section 4.4 which is followed by the evaluation of the payoff functions in section 4.5. The optimal adoption time for a sequential adoption scenario is evaluated in section 4.6. This is then proceeded by a numerical example in section 4.7. In section 0, the game is analysed. The main contribution of this chapter is presented in section 4.9 describing a policy solution to balance the benefits produced by the pioneer which are not redirected to the adopting firm. Finally, a summary of the findings and future works are discussed in the final section 4.10.

4.2 Technological Learning and Learning-by-doing

The concept of "technological learning" first emerged by Wright (1936), who introduced a quantitative model describing time and cost savings in the rapidly growing aircraft manufacturing industry. Wright captured the phenomenon with an equation representing what he called a "progress curve" equal to $Y = ax^b$, where Y is the estimated average direct man-hours per unit for x units; a is the direct man-hours needed to manufacture the first unit; and b ($b < 0$) is a parametric constant. Wright demonstrated that the labour input, Y, dropped by 20% for every doubling of cumulative output, x - an 80% "progress ratio," where the exponent b was -0.32.

Later on, Arrow (1962) introduced the concept of "learning-by-doing". Arrow constructed a model of endogenous growth and related it to product manufacturing which initiated many empirical studies to characterize learning phenomena in a wide range of sectors. Today, the most common definition of a learning curve is the single-factor learning model which relates the general cost and cumulative output in a log-linear relationship. The single factor learning model is expressed as follows:

$$C = C_0 x^{-\alpha} \quad (64)$$

$$LR = 1 - 2^{-\alpha} \quad (65)$$

Equation (64) represents an empirical formula where C is the specific costs of a technology per unit – i.e., electricity (h/MW), C_0 is the initial investment cost at zero learning, x represents the cumulative production through a period and α is the learning elasticity. The learning elasticity α can then be converted into a learning rate (LR) using equation (65), which expresses the constant percentage of cost decline for every doubling of capacity.[21]

[21] Micek, Tomas. Carbon Capture and Storage (CCS) in 2100 : Price Estimate for ’ Technological Learning. 2010, https://www.semanticscholar.org/paper/Carbon-Capture-and-Storage-(-CCS-)-in-2100-%3A-Price-Micek/68b645d096f13d808a007016acad4e07cf016857.

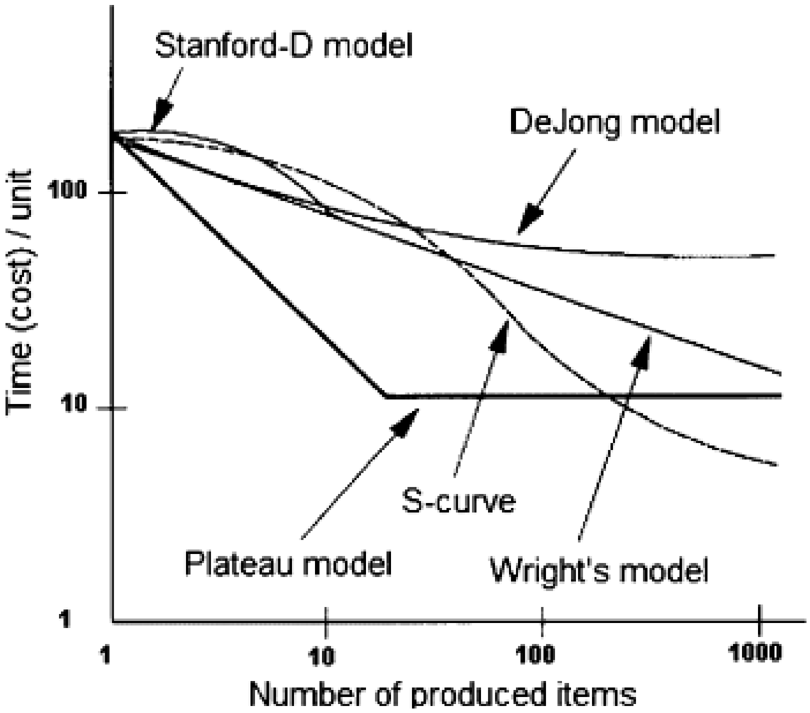


Figure 26 - Profiles from different learning curves on a logarithmic scale (Badiru, 1992)

Over the past few years, other studies have also suggested alternative models for the shape of an experience curve - see Figure 26. However, let us further discuss the inverted S-shaped or S-curve model. The S-curve was introduced by Carr (1946), who found that the learning curve for aeroplane production was best represented with an initial concavity showing slow initial improvements then followed by a more rapid rate of improvement and finally an eventual levelling off. In other words, at the top of the curve, initially, there is a slow build-up period before the worker/ organization can be fully proficient in accomplishing the task. Then, there is a gradual improvement in production time/ cost due to the repetition of the process. The trailing off effect is referred to as the slope of diminishing returns. Badiru et al. (1993) describe the slope of diminishing returns with the following scenario:

"[C]onsider when a worker begins learning a new task. The individual is slow initially at the tail end of the S-Curve, but the rate of learning increases as time goes on, with additional repetitions. This helps the worker to climb the steep slope segment of the S-Curve very rapidly. At the top of the slope, the worker is classified as being proficient with the learned task. From then on, even if the worker puts much effort into

improving upon the task, the resultant learning will not be proportional to the effort expended."

The typical equation for an S-shaped learning curve is given by

$$C_x = C_0[M + (1 - M)(x + B)^{-b}] \tag{66}$$

where C_x is the cumulative average cost after producing x units; C_0 is the cost to produce the first unit; M represents the incompressibility factor which informs the fraction of the task executed by the machines with $M \in [0,1]$. If M is equal to zero implies a fully manual operation and a value of one a completely machine dominated operation; x is a cumulative unit number; B corresponds to the number of units or prior experience; and b represents the slope of the learning curve, which describes the workers' learning rate and $b \in (0,1)$. High values of b - i.e., close to 1 - denotes a high learning rate and fast adaptation to task execution. Recently, Pan (2006) and (2007) suggested a new logistic curve approach to simulate technical change where the curve is defined as a general logistic curve (Richard's logistic curve) modified with a growth rate of investment in R&D as a variable driving the curve.

The model presented in this chapter will also consider the learning effect with an inverted S-shaped curve for the cost reduction of CCS technology. In CCS literature this is not the first time that has been considered. An S-shaped curved model has been investigated by Edward Rubin et al. (2007a), who utilised cost data of other technologies similar to the process of CCS – i.e. flue gas desulfurization (FGD) systems for sulphur dioxide (SO2) control and selective catalytic reduction (SCR) systems for nitrogen oxides (NOx) control – to predict the future cost reduction trend of CCS technology. Rubin explains that the reason for this trend for CCS where there is an initial low learning rate results in large part from the rapid deployment of the "first-generation" technology in response to new environmental regulatory requirements, with little time for learning. This is then followed by improvements in succeeding generations of the technology based on factors including continued R&D and experience with existing installations, also documented by Taylor et al. for FGD systems (Taylor et al., 2003) and by Yeh et al. for SCR systems (Yeh et al., 2006). Since the S-shaped curve represents a more realistic decrease in cost due to learning effects and also the fact it has been previously adopted in CCS literature we will also use it in our model.

However, the S-shape learning curve considered in this chapter is inspired by Pan (2006) and (2007) which is obtained by the properties of the survival function where the survival function is the probability that a subject will survive past time t. The reason for selecting a survival function was because using the typical S-shaped function curve, to obtain the plot a logarithmic transformation is required. In Figure 26, notice that the x-axis representing the number of produced items has a logarithmic scale. Due to this meaning that it will involve more complex calculations, this was one of the main reasons for choosing a survival function instead so that the results obtained can be more tractable. Overall, the survival function is defined as

$$S_{i,1}(t) = P(T > t) = 1 - F_{i,1}(t),$$

where $F_{i,1}(t)$ represents a cumulative distribution function. In this study the survival function is not used for its usual intention – i.e., calculating the probability. Instead, it is considered for its properties, a function monotonically decreasing depending on time t, where $t \in [0, \infty)$. A typical survival function at time $t = 0$ begins at a value of 1, or $S_{i,1}(0) = 1$, and as t tends to infinity it converges to zero or $\lim_{t \to \infty} S_{i,1}(t) = 0$.

4.3 Relevant Literature

The relevant literature for this study is studied in the field of industrial organization (IO) that explore topics of the adoption of new technology and investment under uncertainty such as technological learning or learning-by-doing (LBD) effects. Furthermore, this study also draws literature from game-theoretic real options models.

The IO studies that explore the adoption of new technologies are explored in many different aspects. For example, many studies assess the optimal timing of the adoption of a new technology (Fudenberg and Tirole, 1985; Götz, 1999; Götz, 2000; Hendricks, 1992; Hoppe and Lehmann-Grube, 2001; Reinganum, 1981b; Reinganum, 1981a; Reinganum, 1983a; Reinganum, 1983b; Ruiz-Aliseda and Ruiz-Aliseda, 2007). The mentioned literature has considered similar market structures, typically characterized by homogenous products and competition in quantities. The two main outcomes of this literature are pre-commitment and pre-emption. Pre-commitment was firstly shown by Reinganum (1981b), where new technology is diffused over time assuming that firms can pre-commit to specific adoption dates. On other hand, pre-emption was discovered by Fudenberg and Tirole (1985), where the authors show that firms can observe and react instantaneously to their rivals' adoptions, demonstrating that firms' profits are equalized in equilibrium since each firm adopts pre-emptively to prevent, or delay, adoption by its opponent (pre-emption).

In the context of CCS, the optimal adoption time to adopt CCS technology has been investigated with the addition of uncertainties. For example, Walsh et al. (2014) used a real options approach to investigating the optimal investment decision in carbon capture and storage technology (CCS) under carbon price being determined and stochastic. The finding of this study shows that carbon price volatility increases the critical investment threshold, and that adoption of this technology is not optimal at current prices. On the other, Wang and Qie (2018) analysed also the optimal investment timing in carbon capture and storage (CCS) however from the perspective of the supply chain. The aim of this study investigated the optimal investment threshold for CCS investment whilst considering a dual-echelon supply chain consisting of a power producer and a CCS operator. The finding of this paper showed that CCS investment requires a much higher threshold under the dual-echelon supply chain than singular supply chain industry. Also, similar to Walsh et al. (2014) result Wang and Qie (2018) find a positive relationship between the carbon price volatility and the threshold of CCS investment. However, the studies mentioned only consider a singular type or generation of CCS technology adoption neglecting the possibility of an available more efficient technology in the future.

The other relevant literature for this study is game-theoretical real options models. This is because some game-theoretical real options models have a similar context to our model and therefore the results are useful for our model to understand the findings we get in this chapter. For example, relevant work is a study by Huisman and Kort (2004). The model by Huisman and Kort considers a model with two firms that have the option of two technologies: technology 1 and technology 2. Technology 1 already exists at time zero and can be adopted at any time at a given one-time cost. Whereas technology

2 becomes available for adoption at some unknown time in the future. Technology 2 is superior to technology 1 but firms cannot adopt it if they have adopted technology 1 before technology 2 arrives. Overall, in this study, Huisman Kort discovers that the addition of technology 2 in the model delays investment and when the probability of arrival of technology is high, the authors discover that the game turns from a pre-emption game into a war of attrition, which is a game where the second mover gets the highest payoff. Last, in the study, they also discover that revenue uncertainty induces the adoption of the more modern technology 2. This study is relevant to our study as it has a similar context game. However, a major difference between the model presented in this chapter and the one by Huisman and Kort is that the existence of technology 2 is given by a learning-by-doing effect of a firm having adopted technology 1. The arrival of technology 2 in the study by Huisman and Kort follows a Poisson process such that at every point in time the probability that new technology arrives is the same.

The studies discussed in this section are relevant for the identified research gap which is the lack of understanding in the CCS literature of are impacts of learning effects produced in a competitive market. In other words, now there are no studies in the CCS literature that investigates the benefit that an adopting firm has on other firms in the market because of learning-by-doing and technological spillover. Currently, most CCS studies have a good understanding of how the cost reduction of CCS technology over time is reduced due to a learning effect. Therefore, in this chapter using an industrial organization approach we are going to present a model that has a similar context to the game from Huisman and Kort (2004). However, our study is unique because in our model the cost reduction of CCS technology from learning effects uses the functional properties of the survival function to achieve an S-shaped learning curve. The aim is to investigate the optimal CCS adoption decision time of a follower influenced by a learning-by-doing and spillover effect. Also, if necessary, a policy solution will be constructed such that CCS technology achieves early adoption and an increase in the diffusion of the mitigation technology.

4.4 Model Description

In this section, the model of the study is presented. Inspired by Huisman and Kort's (2004) model, we describe a game between two firms that have the option to adopt two different generations of CCS technology. The CCS technology adoption decision is influenced by the presence of a learning-by-doing and technological spillover effect in the market.

The game between the two firms is as follows. In this model, we assume two firms that are identical, risk-neutral, and cost-minimizing firms. A firm is denoted by i, where $i \in \{1,2\}$. At the beginning of the game, the two firms have an initial option to adopt a first-generation CCS technology which comes with a high initial marginal cost (also denoted as technology 1) or choose not to adopt the mitigation technology (also referred to as technology 0).

If a firm i selects technology 0, this is equivalent to where firm i remains with a business-as-usual or BAU production process by paying a carbon dioxide tax for every emission it releases to the atmosphere. On the other hand, if a singular firm i adopts technology 1 or is denoted as the pioneer, the firm will experience a learning-by-doing effect allowing the adopting firm to reduce its marginal cost over time. The learning-by-doing achieved by the pioneer also benefits other firms in the market, generating the existence of a second-generation CCS technology or technology 2, a more efficient technology with a lower initial marginal cost. The availability of technology 2 for other firms in the market is due to the presence of a technological spillover effect. A firm i who adopts technology 2 is denoted as a follower. If a firm becomes a follower, it ceases the learning effects of the pioneer and it experiences its personal learning-by-doing allowing it to reduce its marginal cost of production. In the model, we assume that firms can only invest once in a CCS technology and therefore a firm locks in into a technological choice. The investment cost of technology 1 and 2 are assumed to be equal.[22]

[22] This assumption is strict especially as previously mentioned the capital cost for example for Shand facility has been projected to be 67% lower than the Boundary Dam facility on a dollar per tonne of CO_2 basis. The reason for the assumption this is because the Shand CCS project is owned by the same company who built Boundary Dam CCS project. Thus, the cost reduction results obtained by BHP and SaskPower for Shand Project is certainly going to be adopted a at a lower cost by sharing full knowledge. However, the fixed cost of adopting CCS cannot be also said to be true for unaffiliated

Overall, the game between the two firms has four possible technological scenarios:

i. Both firms adopt technology 1 (Immediate adoption).
ii. Two cases of one firm adopting technology 1 and the other adopting technology 2 (Sequential adoption).
iii. Two firms choose technology 0 (Never adopt).

4.5 The Payoffs

The payoffs of the game are determined in this section. The structure of this section is subdivided into three subsections. The first subsection describes how the payoff functions are obtained using the marginal cost of production of a firm i. Also, the payoff functions of the scenario of a pioneer and follower or a sequential adoption of CCS technologies are evaluated. The second subsection evaluates the payoffs where two firms adopt a first-generation CCS technology or technology 1. The last subsection establishes the payoffs function for the case where both firms do not adopt any CCS mitigation technology, or both choose technology 0.

4.5.1 Sequential Adoption

To obtain the payoff functions for each of the scenarios, the following is determined by describing the marginal cost of production of the firms as the investment cost for technology 1 and 2 are equal. The marginal cost of production of a firm i for any possible technological choices in the game has a different cost path behaviour over time. Before introducing these, an important assumption is firstly presented.

ASSUMPTION 1 - *The marginal cost of production of a firm i is assumed to be proportional to time for all possible technological choices in the game.*

The assumption above means that if a firm i selects technology 1, the firm is going to produce the same quantity in each period despite there being a reduction in the

organizations. Even though there is evidence that the fixed of CCS technology is in a decline due a learning-by-doing effect, the knowledge gained by BHP and SaskPower can also be sold at a premium (higher) cost for future adopters. Hence, the assumption that fixed cost of technology 1 and 2 are assumed to be same is the most rationale decision as the fixed cost of CCS can either go up and down when a firm wants to adopt a CCS technology.

marginal cost of production due to the learning-by-doing effect. Similarly, these are also assumed for the other technological options. The reason for ASSUMPTION 1 is for tractability reasons in the model. However, this is also an appropriate assumption to consider where it can be true due to the demand of the output. For example, a power plant of 500MW means that can only produce up to 500MW. However, if there is a surge in demand, then the power plant cannot produce any further output due to a constraint in capacity. Therefore, another way of viewing ASSUMPTION 1 is that demand is always high expecting full capacity from a firm therefore despite any changes in inputs the output is always at full capacity.

With ASSUMPTION 1, to obtain the payoff function where firms achieve a sequential adoption, two types of the marginal cost of production are going to be introduced. The first type of marginal cost is called the cumulative marginal cost of production of a firm i.

DEFINITION 1 (***Cumulative Marginal Cost of Production or CMC***) - *The CMC of a firm i represents the total marginal cost of production that the firm obtains from the beginning of its life or $t = 0$ up to the end of the firm's lifetime $T_i > 0$.*

The CMC is denoted by $\tilde{c}_{i,j}(T_i)$, where i defines the firm and j illustrates the technology selected. Therefore, a pioneer or a firm i who adopts a first-generation CCS technology or technology 1 obtains a CMC equal to

$$\tilde{c}_{i,1}(T_i) = \int_0^{T_i} \Big((H_{i,1} - L_{i,1}) S_{i,1}(z) + L_{i,1} \Big) \, dz \qquad (67)$$

The cost path behaviour of equation (67) follows an inverted S-shaped curve to replicate the learning-by-doing effect allowing the firm to reduce its marginal cost of production. The cost reduction is achieved by the function $S_{i,1}(t)$, which is assumed to be a survival function.[23] In this study the survival function is not used for its usual intention – i.e., calculating the probability. Instead, it is considered for its properties which is a function monotonically decreasing depending on time t, where $t \in [0, \infty)$. A typical survival function at time $t = 0$ begins at a value of 1, or $S_{i,1}(0) = 1$, and as

[23] The survival function is the probability that a subject will survive past time t, defined as $S_{i,1}(t) = P(T > t) = 1 - F_{i,1}(t)$ where $F_{i,1}(t)$ represents a cumulative distribution function.

t tends to infinity it converges to zero or $\lim_{t\to\infty} S_{i,1}(t) = 0$. Thus, the cost path behaviour of equation (67) has an initial starting value equal to $H_{i,1}$. This then slowly decreases as time t increases. The CMC of the pioneer rapidly decreases and decreases slowly again, converging towards the lowest possible marginal cost of production that the firm i can obtain due to the learning-by-doing effect which is equal to $L_{i,1}$. An inverted S-shaped curve is an appropriate assumption of the cost path behaviour of the marginal cost of production because new technologies are hard to learn at the start. Then, as time goes by, with the firm using the technology repeatedly, the firm becomes more efficient gaining itself a lower marginal cost of production.

The CMC of a follower or a firm i who adopts a second-generation CCS technology or technology 2, given that the rival firm has previously adopted technology 1, is equal to

$$\tilde{c}_{i,2}(T_i) = c_{i,0}(t) + \int_0^{T_i - t} \left(\left(H_{i,2} - L_{i,2}\right) S_{i,2}(z) + L_{i,2} \right) dz \qquad (68)$$

In the equation above, the CMC of a follower has two components representing the cumulative marginal cost of production. The first component corresponds to the firm not adopting CCS technology or delaying its investment decision. Specifically, the follower is obeying a carbon dioxide tax up to time t, where $c_{i,0}$ is assumed a constant marginal cost of production over time for using technology 0. On the other hand, the second component corresponds to the cumulative marginal cost of production when the follower has adopted a technology 2. Like technology 1, technology 2 also has a cost path behaviour with an inverted S-shaped curve where $H_{i,2}$ is the initial marginal cost of production obtained by a follower for adopting technology 2. The firm then experiences a reduction in the marginal cost of production due to a learning-by-doing effect converging towards its lowest possible marginal cost of production equal to $L_{i,2}$. The integral in the second component has been readjusted from a lower limit equal to 0 and the upper limit to $T - t$. The reason for this is to achieve an easier evaluation of the integral later in the study.

The second type of marginal cost of production to obtain the payoff functions is called the excess cumulative marginal cost of production or ECMC – denoted by $\overline{c}_{i,j}(T_i)$.

DEFINITION 2 (***Excessive Cumulative Marginal Cost or ECMC***) – *The ECMC of a firm i is a normalization of the CMC obtained by subtracting the CMC equation minus the lowest possible marginal cost that the firm achieves due to a learning-by-doing effect throughout its lifetime or $L_{i,j}(T_i)$ for adopting a jth-generation CCS technology, where $j \in (1,2)$.*

To understand DEFINITION 2 more thoroughly the ECMC obtained by a follower or a firm i who adopts technology 2 is displayed in Figure 27. The ECMC of the follower is equal to the purple area in Figure 27 or region $C + D$. The ECMC describes a region where the area underneath $L_{i,2}$ is removed or region $E + F$. If we were to consider all regions together or region $C + D + E + F$ the following is, then equal to the CMC of the follower.

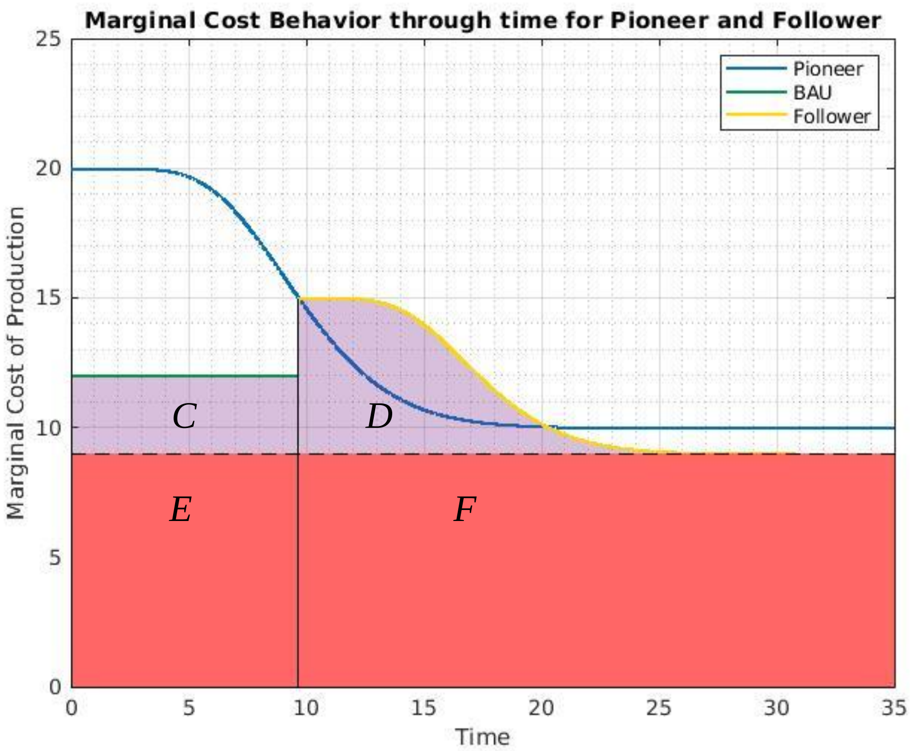


Figure 27 – The excess cumulative marginal cost for a follower is C + D.

The ECMC of a firm i who delays its investment and adopts technology 2 given that a firm has previously adopted technology 1 is equal to

$$\overline{c}_{i,2}(T_i) = \left(c_{i,0} - L_{i,2}\right)t + \int_0^{T_i - t} \left(\left(H_{i,2} - L_{i,2}\right)S_{i,2}(z)\right) \, dz \qquad (69)$$

Whereas the ECMC of a pioneer is given by

$$\overline{c}_{i,1}(T_i) = \left(H_{i,1} - L_{i,1}\right)\int_0^{T_i} S_{i,1}(z)\, dz \qquad (70)$$

The two expressions above can be further simplified by considering a special property of the survival function. Specifically, if the integral of the survival function is defined from 0 to infinity, then the integral is equal to the mean of the associated probability distribution considered – denoted by $\mu_{i,2}$. Hence, assuming $T_i \to \infty$ a follower obtains a simplification of the ECMC which is equal to

$$\overline{c}_{i,2}(T_i) = \left(c_{i,0} - L_{i,2}\right)t + \left(H_{i,2} - L_{i,2}\right)\mu_{i,2} \qquad (71)$$

On the other hand, the pioneer obtains a simplification of the ECMC equal to

$$\overline{c}_{i,1}(T_i) = \left(H_{i,1} - L_{i,1}\right)\mu_{i,1} \qquad (72)$$

Another assumption considered in the model is:

ASSUMPTION 2 – *Given that a firm has adopted technology 1 when technology 2 is adopted by a follower, the marginal cost of production of technology 2 is the same as the marginal cost of production of technology 1 at that time. In other words, at the adoption time t^* of the follower we have $c_{i,2}(0) = H_{i,2} = c_{i,1}(t^*)$.*

The assumption above signifies that the follower adopting technology 2 has purchased a CCS technology where the "eco-industry" selling CCS technology is a perfectly competitive market, as the market price of CCS technology is equal to the marginal cost of production at the time of adoption. ASSUMPTION 2 is a strong assumption given that CCS technology is not fully commercial. The reasoning behind ASSUMPTION 2 is that the marginal cost of production of the follower must be at least equal to the marginal cost of production that the pioneer has gained through time during the adoption time of the follower. If the cost of technology 2 is lower than technology 1 this does not make sense, otherwise, technology 2 will be immediately adopted by the follower. On the other hand, if the cost of technology 2 is assumed to be above technology 1, this can be a scenario, especially where the eco-industry wants to make some profits. However, ASSUMPTION 2 allows us to focus on deriving the optimal adoption of CCS technology between a sequential adoption between two firms. The relaxation of ASSUMPTION 2 should be considered as a follow-up study to examine the bargaining power that the eco-industry generates, which is not the focus of this study. Thus, taking into consideration ASSUMPTION 2, equation (71) can be rewritten to

$$\overline{c}_{i,2}(T_i) = \left(c_{i,0} - L_{i,2}\right)t + \left(c_{i,1}(t\,) - L_{i,2}\right)\mu_{i,2} \tag{73}$$

With this last assumption equation (73) corresponds to the payoff function for the follower.

4.5.2 Immediate Adoption

When both firms decide to adopt a first-generation CCS technology or technology the corresponding payoff function for a firm i is given by equation (72), where $i = \{1,2\}$.

4.5.3 Never Adopt

The payoff function if both firms decide not to adopt CCS technology is given by

$$\overline{c}_{i,0}(T_i) = \left(c_{i,0} - L_{i,2}\right)T_i \tag{74}$$

where $i = \{1,2\}$.

4.5.4 Summary

In summary, the payoff functions that will be used primarily for the investigation of this study are:

- If the scenario is a sequential adoption, a pioneer has a payoff function given by equation (72) and a follower has a payoff function equal to (73).
- If both firms immediately adopt, the payoff function for both firms is given by equation (72).
- If both firms choose to never adopt, the payoff function for both firms is given by equation (74).

4.6 Finding Optimal Adoption Time of a Follower under a Sequential Adoption

In this section, the optimal adoption of a follower using the payoff functions evaluated in the previous section is calculated. The reason for analysing this is because a sequential adoption scenario is the only scenario where CCS technological adoption is under the presence of a learning-by-doing effect and technological spillover in the market. Thus, this scenario will allow us to understand the impacts that learning-by-doing-effect and technological spillover have on a follower's CCS adoption decision.

The payoff function of a follower is given by equation (73), which is an objective function for a cost minimization problem. The reason it is a cost minimization problem is that we want to achieve the minimum excess cumulative marginal cost that the follower should achieve to adopt technology 2. To evaluate the optimal adoption time (denoted by t^*), the objective function equation (73) needs to be differentiated with respect to t, set it equal to zero and then solve for t.

The first-order derivative of equation (73) with respect to t is equal to

$$\frac{d\bar{c}_{i,2}}{dt} = c_{i,0} - L_{i,2} + \frac{dc_{i,1}(t)}{dt}\mu_{i,2} = 0 \tag{75}$$

where,

$$\begin{aligned} \frac{dc_{i,1}(t)}{dt} &= \left(H_{i,1} - L_{i,1}\right)\frac{dS_{i,1}(t)}{dt} \\ &= \left(H_{i,1} - L_{i,1}\right)\frac{d}{dt}\left(1 - F_{i,1}(t)\right) \\ &= -\left(H_{i,1} - L_{i,1}\right)f_{i,1}(t) \end{aligned} \tag{76}$$

In equation (76), $f_{i,1}(t)$ corresponds to a probability density function (pdf). This is obtained from the derivative of the cumulative distribution function $F_{i,1}(t)$, where $F_{i,1}(t) = 1 - S_{i,1}(t)$, due to the definition of the survival function. Let us recall, that the survival function is not used for its usual intention – i.e., calculating the probability. Instead, it is considered to obtain the inverted S-shaped curve for the marginal cost of production as time t increases. Hence, the pdf $f_{i,1}(t)$ in equation (76) is just a function of t that has the function form of the equation of a pdf. Inserting equation (76) to equation (73), we get

$$\frac{d\bar{c}_{i,2}}{dt} = c_{i,0} - L_{i,2} - \left[\left(H_{i,1} - L_{i,1}\right) f_{i,1}(t)\right]\mu_{i,2} = 0$$

or,

$$\left(H_{i,1} - L_{i,1}\right) f_{i,1}(t)\mu_{i,2} = c_{i,0} - L_{i,2} \tag{77}$$

So far in the model, no specific parametric function has been considered for the survival function $S_{i,j}(t)$. The reason for this is to allow the model to be as generalised as possible for other researchers to best fit the behaviour of the marginal cost of production affected by a learning-by-doing effect. Some of the main distribution functions of the survival function are the exponential, Weibull and Gompertz-Makeham distributions. However, for this study, the 2-parameter gamma distribution is selected. This is because it is the most versatile equation which some interesting special cases such as obtaining the Weibull and exponential. The pdf distribution of the 2-parameter gamma distribution is equal to

$$f(t; k, \theta) = \frac{(1/\theta^k)\ t^{k-1}\ e^{-(t/\theta)}}{\Gamma(k)} \tag{78}$$

In the equation above, $\Gamma(k)$ is equal to the gamma function[24] and for any positive integer $k \geq 1$, $\Gamma(k) = (k-1)!$. The parameter k is a shape parameter that translates to the learning rate of the firm. When k is large, the learning capability of the firm is slow. In other words, the marginal cost of production takes a long time to converge to the lowest possible marginal cost of production. On the other hand, parameter θ is a scaling parameter that is simply considered equal to $\theta = 1$.

The pdf presented in equation (78) can be substituted into equation (77). By doing so, we get

$$\left(H_{i,1} - L_{i,1}\right) \underbrace{\left(\frac{\left(1/\theta_{i,1}^{k_{i,1}}\right)\ t^{k_{i,1}-1}\ e^{-(t/\theta_{i,1})}}{\Gamma\left(k_{i,1}\right)}\right)}_{f_{i,1}(t; k_{i,1}, \theta_{i,1})} \mu_{i,2} = c_{i,0} - L_{i,2} \tag{79}$$

---

[24]Gamma function, generalization of the factorial function to nonintegral values, introduced by the Swiss mathematician Leonhard Euler in the 18th century.

Notice that in the 2-parameter gamma pdf a subscript (i, j) has been added to obtain $f_{i,j}(t; k_{i,j}, \theta_{i,j})$. This is because the pioneer and follower are going to have different learning capabilities. Finally, the mean of the survival function which considers a 2-parameter gamma distribution is equal to $\mu_{i,j} = k_{i,j}\theta_{i,j}$. Thus, the equation (79) can be also rewritten to

$$\left(H_{i,1} - L_{i,1}\right)\left(\frac{\left(1/\theta_{i,1}^{k_{i,1}}\right)\ t^{k_{i,1}-1}\ e^{-\left(t/\theta_{i,1}\right)}}{\Gamma\left(k_{i,1}\right)}\right)k_{i,2}\theta_{i,2} = c_{i,0} - L_{i,2} \tag{80}$$

From the equation above, the solution for the optimal adoption time of the follower can be solved. We do so by isolating variable t onto one side in equation (80), where we get

$$t^{k_{i,1}-1}\ e^{-t} = \frac{\Gamma\left(k_{i,1}\right)\left(c_{i,0} - L_{i,2}\right)}{k_{i,2}\left(H_{i,1} - L_{i,1}\right)} \tag{81}$$

The left-hand side of equation (81) has the form of ze^{z}. The solution for a function of this form is given by the Lambert W function – denoted $W(z)$. The Lambert W function is used to solve equations in which the unknown quantity occurs both in the base and in the exponent or both inside and outside of a logarithm. Therefore, the solution for the optimal adoption time for the follower to adopt a technology 2 using the Lambert W function is equal to[25]

$$t^{*} = -\left(k_{i,1} - 1\right)W_0\left(-\frac{e^{\left(\frac{\ln\left(\frac{\Gamma\left(k_{i,1}\right)\left(c_{i,0}-L_{i,2}\right)}{k_{i,2}\left(H_{i,1}-L_{i,1}\right)}\right)}{k_{i,1}-1}\right)}}{k_{i,1} - 1}\right) \tag{82}$$

and,

[25] See in Appendix for full algebraic calculation of how the two results are obtained.

$$t^* = -(k_{i,1} - 1)W_{-1}\left(-\frac{e^{\left(\frac{\ln\left(\frac{\Gamma(k_{i,1})(c_{i,0}-L_{i,2})}{k_{i,2}(H_{i,1}-L_{i,1})}\right)}{k_{i,1}-1}\right)}}{k_{i,1} - 1}\right) \tag{83}$$

For the optimal adoption time for the follower using a Lambert W function, we discover two solutions if all the parameters assumed in the model are all real integers. The solution W_0 is the larger solution and W_{-1} is the smaller solution.

This then leads us to the question: "*Which adoption time is the correct one*?" This will be discussed in the next section where we present a numerical example to illustrate the analytical results.

4.7 A Numerical Example

In this section, a numerical example is presented to examine the findings. Some of the parametric conditions considered for the numerical example are:

- The learning capability of the pioneer is slower than the learning capability of the follower. In other words, $k_{i,1} > k_{i,2}$. The reason for this assumption is that the second-generation CCS technology is more efficient technology than the first-generation CCS technology. Hence, technology 2 has a faster learning rate allowing the firm to achieve fast a lower marginal cost compared to the pioneer adopting technology 1.
- The lowest possible marginal cost of the follower is going to be lower than the lowest possible marginal cost of the pioneer – i.e., $L_{i,2} < L_{i,1}$. The two CCS technologies are of different generations. Once again, the second-generation CCS technology is more efficient, thus it has greater potential to reach a lower marginal cost of production than technology 1.
- Parameter $c_{i,0}(t)$ is going to be assumed in the range between $H_{i,1}$ and $L_{i,1}$. The reason for this is because if $c_{i,0} < L_{i,1}$ then no firm will ever adopt a first-generation CCS technology. Conversely, if $c_{i,0} > H_{i,1}$ then there would no economic problems for the deployment of CCS technology. In other words, all

firms would just immediately adopt CCS because it is cheaper than choosing a business-as-usual strategy.

- As previously mentioned, we are going to assume that the scale parameter $\theta_{i,j}$ in the pdf distribution is equal to 1 – i.e., $\theta_{i,1} = \theta_{i,2} = 1$.

The parameters chosen for the numerical example following the parametric conditions are displayed below.

PIONEER	FOLLOWER	BAU
$k_{i,1} = 10$	$k_{i,2} = 8$	$c_{i,0} = 12$
$H_{i,1} = 20$	$L_{i,2} = 9$	
$L_{i,1} = 10$	$\theta_{i,2} = 1$	
$\theta_{i,1} = 1$		

Table 10 - Parametric values for pioneer and follower scenario

Using the obtained results for the optimal adoption time of the follower – equation (82) and (83) – and the parametric values stated in Table 10, we get:

- Equation (82) → $t^* = 5.0422$
- Equation (83) → $t^* = 14.6281$

To identify which optimal adoption time is correct we used MATLAB to obtain graphical results and assessed the graphical findings. Figure 28 displays the graphical result of the numerical example.

The graph on the top left or Fig. 28A is the plot of equation (80). The illustration of this graph is another method to identify the optimal adoption time for the follower of when it should adopt a second-generation CCS technology. The optimal adoption time corresponds to the intersection points of the two curves in the graph. One can notice that there are also two possible solutions for the optimal adoption time for the follower.

To identify which one of the two solutions is the correct optimal adoption time, we use the plot of equation (73) displayed in Fig. 28B. Equation (73) was previously stated as equal to the objective function for the cost minimization problem of the model. Therefore, to identify the correct optimal adoption time we identify which optimal adoption time t^* provides a minimum point in equation (73). In the numerical example one can notice that the second optimal adoption time when $t^* = 14.6281$ provides the minimum value in Fig. 28B. The red dashed line in Fig. 28B is the plot of $\overline{c}_{i,2}\ (0)$ to make sure that at $t = 0$ there is no incentive for the follower to adopt immediately technology 2. For t^* to be a correct solution the ECMC function must have a minimum that is strictly below the red dashed line. Otherwise, if this is not met then the model suggests that the follower should adopt immediately technology 2. This cannot also be true because the adoption of technology 2 at time $t = 0$ cannot exist as no learning has been achieved by the pioneer to create the existence of the lower marginal cost of production of technology 2. Overall, the correct solution for the optimal adoption time of the follower in the numerical example is given by the second solution or equation (83).

The other two remaining plots Fig. 28C and Fig. 28D display the behaviour of the marginal cost of production of the pioneer and the follower with the two different possible adoption times for the follower. However, the only graph that we consider is Fig. 28D, which is equivalent to when the follower adopts at $t^* = 14.6281$. In Fig. 28D the follower does not immediately adopt technology 2, the firm instead is choosing to delay the investment for technology 2 after the marginal cost of production functions $c_{i,0}(t)$ (green line) and $c_{i,1}(t)$ (blue line) cross each other. Thus, an important property discovered is:

FINDING 1 - *The follower lets the pioneer do a little bit of learning for him rather than himself highlighting one of the advantages of adopting later. The follower can delay its investment decision optimally.*

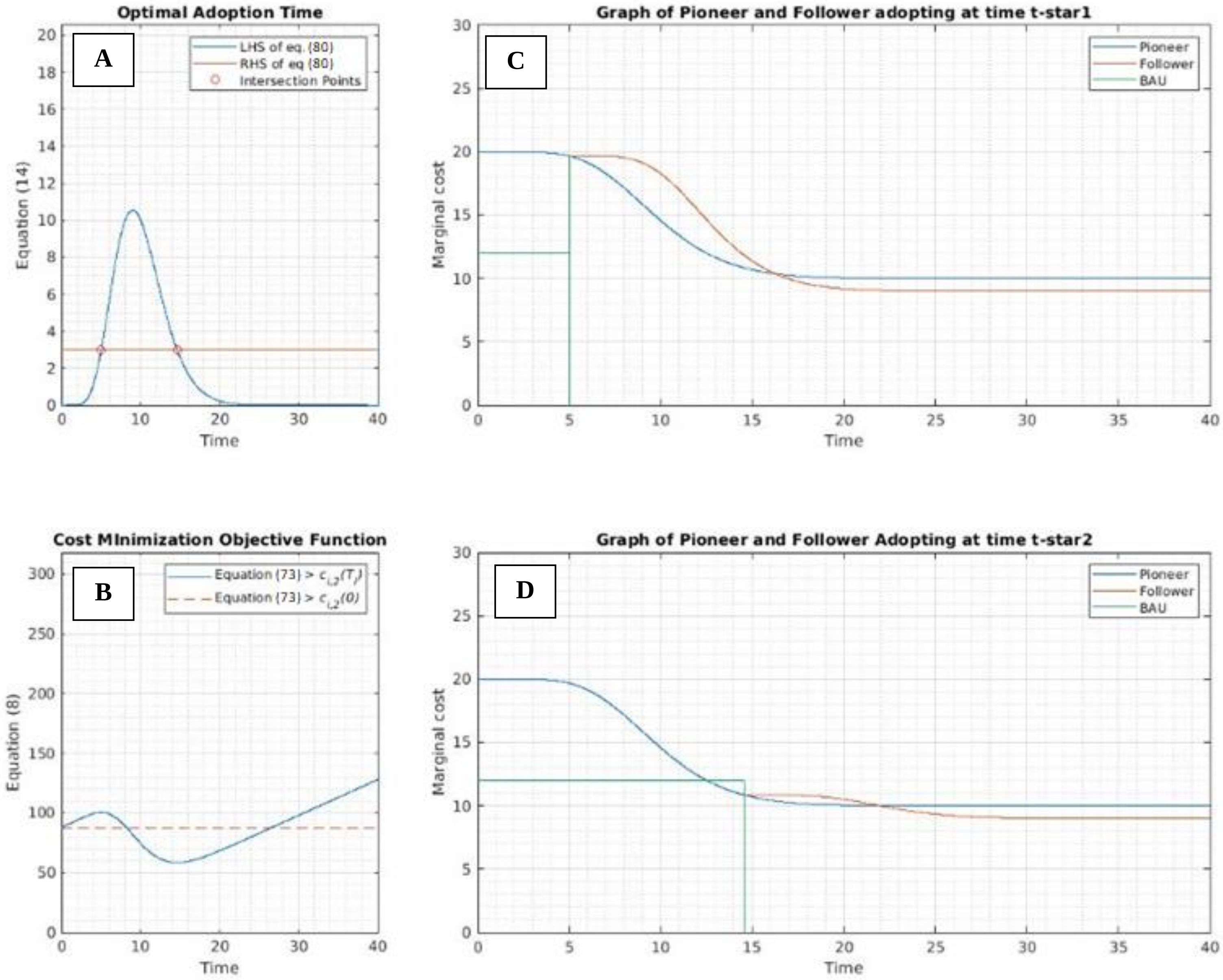


Figure 28 - Simulation result using the parametric values stated in Table 2.

4.7.1 Numerical Example Analysis and Key Parameters

In this subsection, the numerical example is investigated further by examining how the parameters affect the optimal adoption time t^* of the follower given that a pioneer has previously adopted a technology 1.

The parameters investigated for the analysis are:

- $c_{i,0}$: is the constant value per unit of time of the marginal cost of production of firm i for choosing not to adopt a CCS technology or technology 0.
- $L_{i,2}$: represents the lowest possible marginal cost of production of firm i adopting a second-generation CCS technology obtained by a learning-by-doing effect on its own.
- $k_{i,2}$: denotes the learning rate of a firm i for having adopted a second-generation CCS technology or technology 2.
- $H_{i,1}$: represents the initial marginal cost of production of a firm i having adopted a first-generation CCS technology or technology 1.

The reason $L_{i,1}$ and $k_{i,1}$ are not part of the list above, it is because firstly changing $L_{i,1}$ it provides the same results when we consider a change in the value of the parameter $H_{i,1}$. For example, if $H_{i,1}$ is increased (or decreased) this means that the difference between $H_{i,1}$ and $L_{i,1}$ has increased (or decreased). Similarly, parameter $k_{i,1}$ it is not investigated because by assessing a change in parameter $k_{i,2}$ the analysis should provide the same result. Therefore, $k_{i,1}$ is fixed. Nevertheless, an important condition satisfied in the comparative static is $k_{i,2} < k_{i,1}$, implying that technology 2 has a faster learning capability than technology 1.

The key learnings from the analysis are:

- When the marginal cost of production of a firm i without a CCS technology or $c_{i,0}$ increases (decreases) the optimal adoption time t^* of the follower decreases (increases).
- When the lowest possible marginal cost of production of the follower adopting a second-generation CCS technology or $L_{i,2}$ increases (decreases) the optimal adoption time t^* of the follower increases (decreases).

- When the learning capability of the follower for having adopted a second-generation CCS technology or $k_{i,2}$ increases (decreases) the optimal adoption time t^* of the follower increases (decreases).
- When the initial marginal cost of production of the pioneer or $H_{i,1}$ increases (decreases) the optimal adoption time t^* of the follower increases (decreases).

For continuity, the same parametric values stated in Table 10 are considered for the numerical analysis.

4.7.1.1 Parameter $c_{i,0}$

The first parameter examined is $c_{i,0}$, the marginal cost of production of firm i without a CCS technology. Parameter $c_{i,0}$ is strictly in between parameters $H_{i,1}$ and $L_{i,1}$. To assess the effects of $c_{i,0}$ we consider an increase in the parameter $c_{i,0}$ to a slight adjustment from $12 \rightarrow 14$ and compare the two outcomes. The graphical results using MATLAB are displayed in Figure 29.

Fig. 29A displays the plot of equation (80) as a function of t. This plot allows to identify the optimal adoption time of the follower where can be evaluated by looking at where the two curves intersect. Fig. 29B is the plot of equation (73) which allows us to find the real solution for the adoption time of the follower by identifying the curve with the lowest minimum point. The yellow line in Fig. 29B represents the results for the follower when $c_{i,0} = 14$, whereas the purple line is when the parameter $c_{i,0} = 12$. An increase in parameter $c_{i,0}$ has the effect where the follower is going to adopt earlier the second-generation CCS technology. This is illustrated in Fig. 29C which shows the marginal cost behaviour of the pioneer and the follower. This finding is consistent with the real world as one of the main policy solutions to get CCS technology more deployed is to have stricter environmental policies – i.e., higher carbon taxes.

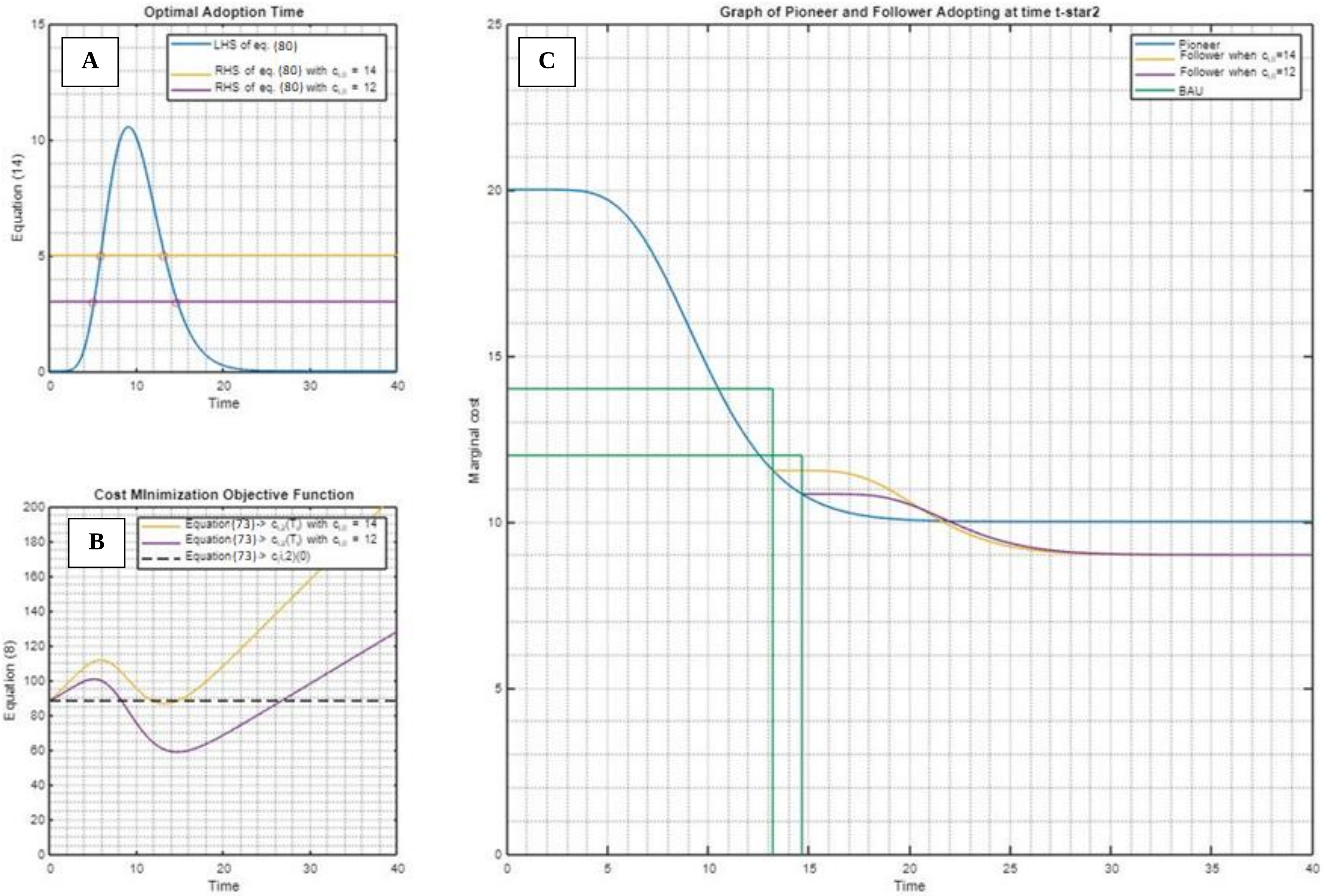


Figure 29 – The analysis of parameter $c_{i,0}$ with a numerical example

Figure 30 shows us the effects of parameter $c_{i,0}$ in the optimal adoption time of the follower adopting technology 2. This is obtained by plotting the equation (83) where $c_{i,0}$ is the changing variable or $t^*(c_{i,0})$.

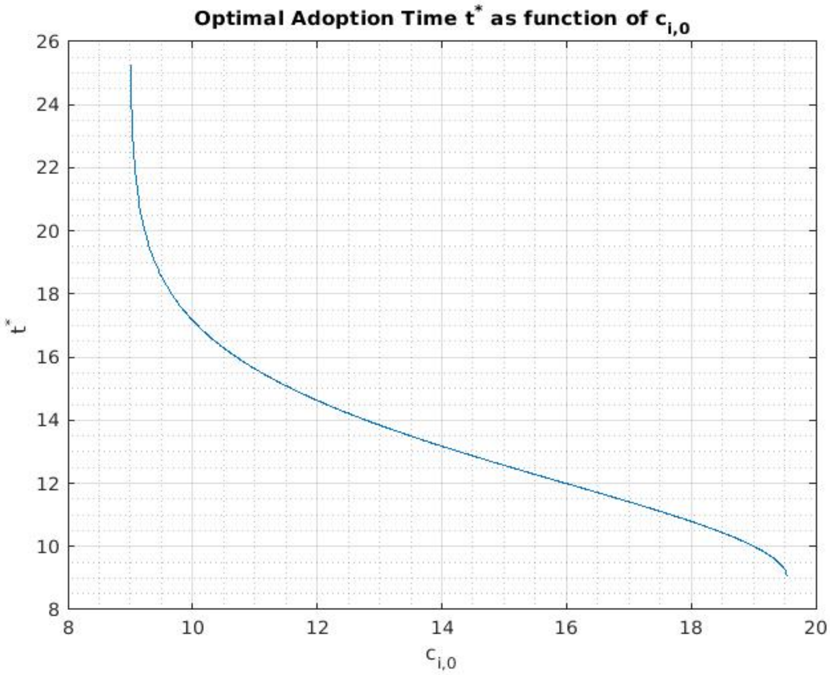


Figure 30 - Optimal adoption time t^* as function of $c_{i,0}$

The reason why we have only increased $c_{i,0}$ to a value equal to 14 is because as one can notice in the graph of the ECMC of the follower or Figure 29B, the minimum point of the function has almost surpassed the black dashed line, illustrating the ECMC of the follower equivalent to the time $t = 0$ or $\overline{c}_{i,2}(0)$. Thus, if a numerical example has the ECMC function that is all strictly above the black dashed line this means that the follower should adopt immediately at time $t = 0$ because any other adoption time will be more expensive. Overall, to have a working model, equation (73) needs to produce a minimum point that is below $\overline{c}_{i,2}(0)$, the result when a follower immediately adopts the technology. Therefore, this means that there exists an acceptable region for $c_{i,0}$ which we will now evaluate.

The lower interval of $c_{i,0}$ it is immediately given by the selection of $L_{i,1}$, the lowest possible marginal cost of production of a pioneer adopting technology 1. The reason it is equal to $L_{i,1}$ is because if $c_{i,0} < L_{i,1}$ then no firm will be ever technology 1. n the other hand, we obtained the upper interval of $c_{i,0}$ using MATLAB where the upper interval is given by the graphical result displayed in Figure 31 on the next page.

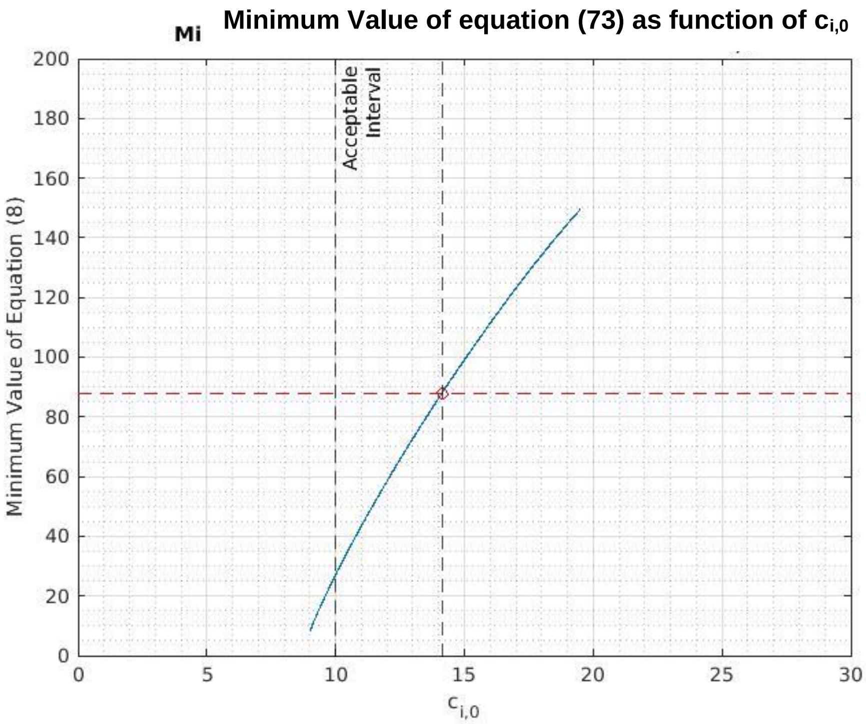


Figure 31 - Minimum value of equation (73) as function of $c_{i,0}$

In Figure 31 the red dashed line is equal to equation (73) equated at time $t = 0$, or

$$\overline{c}_{i,2}(0) = \left((H_{i,1} - L_{i,1})S_{i,1}(0) + L_{i,1} - L_{i,2}\right)\mu_{i,2} = (H_{i,1} - L_{i,2})\mu_{i,2} \tag{84}$$

Using the parametric values in Table 10, we get $\overline{c}_{i,2}(0) = 88$. The blue line represents equation (73) evaluated at the optimal time t^* with $c_{i,0}$ as the changing variable. Specifically, this corresponds to the equation displayed below.

$$\begin{aligned}\overline{c}_{i,2}(c_{i,0}) &= (c_{i,0} - L_{i,2})t^*(c_{i,0}) \\ &\quad + \left((H_{i,1} - L_{i,1})S_{i,1}\left(t^*(c_{i,0})\right) + L_{i,1} - L_{i,2}\right)\mu_{i,2}\end{aligned} \tag{85}$$

In the equation above $t^*(c_{i,0})$ corresponds to equation (83) where $c_{i,0}$ is the changing variable which is equal to the graphical result previously presented in Figure 30. The upper interval is found by the intersection between equations (84) and (85). For this numerical example, we obtain that $c_{i,0}$ should be within $10 < c_{i,0} < 14.134$, illustrated by the vertical black dashed lines. Any parameters of $c_{i,0}$ that is outside this range we will not produce a logical result.

4.7.1.2 Parameter $L_{i,2}$

The next parameter assessed is $L_{i,2}$, the lowest possible marginal cost of production of the follower adopting a second-generation CCS technology. Here, like the assessment of parameter $c_{i,0}$, we investigate how the optimal adoption time t^* of the follower is affected by changes in parameter $L_{i,2}$. Also, we evaluate the acceptable region for $L_{i,2}$.

The graph presented below displays the behaviour of the function of t^* with $L_{i,2}$ as the changing variable using the parametric values stated in Table 10.

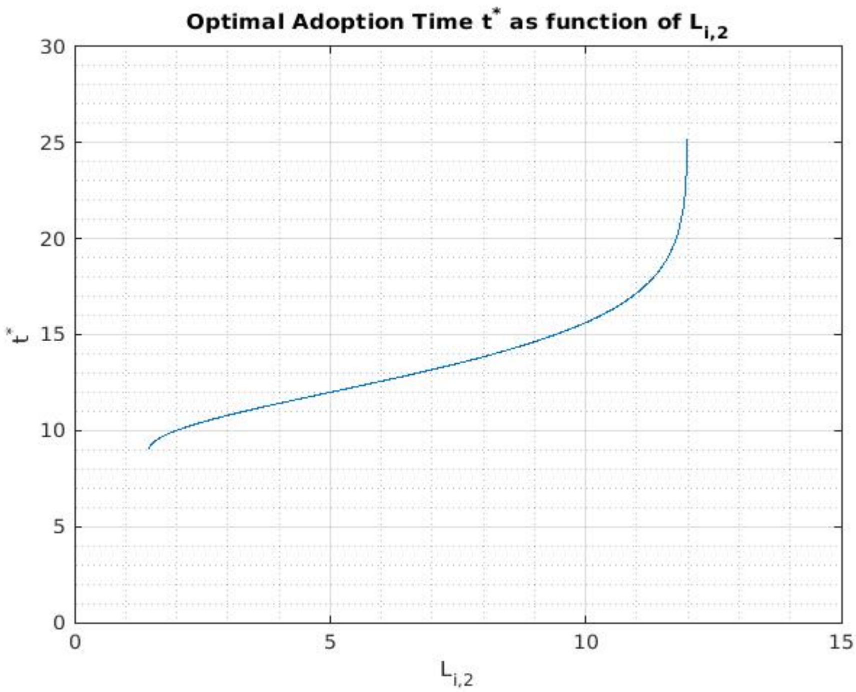


Figure 32 - Optimal adoption time t^* as function of $L_{i,2}$

The results show that the optimal adoption time t^* of the follower as $L_{i,2}$ increases then the follower is going to adopt technology 2 later. The reason for this is that with $L_{i,2}$ increasing this means that technology 2 is less efficient where then the follower is going to decide to delay the investment and let the pioneer do the learning for him for a longer time. Whereas, if $L_{i,2}$ is lower it is obtained that the follower is going to adopt earlier technology 2. Overall, if the follower knows that technology 2 is going to have a better marginal cost of production overall, the follower is better off adopting the technology earlier and learning by itself to gain a better marginal cost of production faster than letting the pioneer do so for him. investment.

Figure 33 below is the graphical result to identify the acceptable region for $L_{i,2}$. The upper interval is given by $L_{i,1}$, which is equal to 10. This is because one of the stated assumptions was that $L_{i,2}$ can never be greater than $L_{i,1}$. If assumed otherwise the second-generation CCS technology is never more efficient than the first-generation CCS technology. The lower interval is instead evaluated by the intersection point between the red line and the blue line.

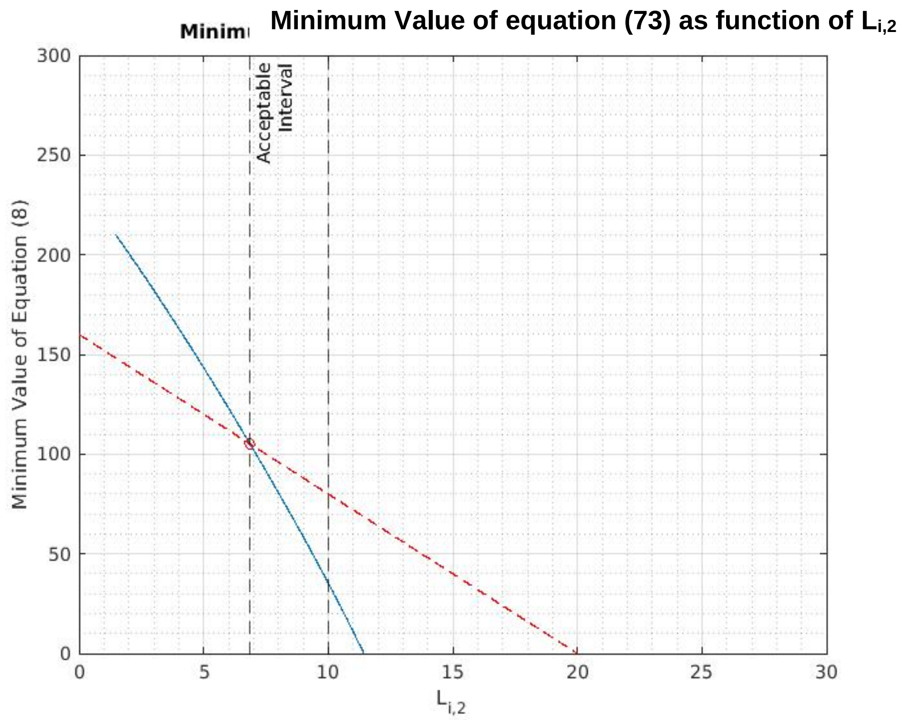


Figure 33 - Minimum value of equation (73) as function of $L_{i,2}$

The red line is equal to equation (73) evaluated at time $t = 0$ with $L_{i,2}$ as the changing variable or $\overline{c}_{i,2}(L_{i,2}; t = 0)$, which is equal to

$$\overline{c}_{i,2}(L_{i,2}; t = 0) = (H_{i,1} - L_{i,2})\mu_{i,2} \tag{86}$$

On the other hand, the blue line represents equation (73) evaluated at the optimal time t^* where $L_{i,2}$ is the changing variable, or

$$\overline{c}_{i,2}(L_{i,2}) = (c_{i,0} - L_{i,2})t^*(L_{i,2}) + \Big((H_{i,1} - L_{i,1})S_{i,1}\big(t^*(L_{i,2})\big) + L_{i,1} - L_{i,2}\Big)\mu_{i,2} \quad (87)$$

The intersection of these two curves gives us the lower interval such that the optimal adoption time of the follower has a minimum point that is below $\overline{c}_{i,2}(0)$. For the numerical example, we find a lower interval to be equal to 6.866. Thus, the acceptable region for $L_{i,2}$ should be in between $6.866 < L_{i,2} < 10$.

4.7.1.3 Parameter $k_{i,2}$

Parameter $k_{i,2}$ is an exogenous parameter that indicates the learning capability of the follower for having adopted a second-generation CCS technology. A high value for the parameter $k_{i,2}$ means that technology 2 has a slow learning rate.

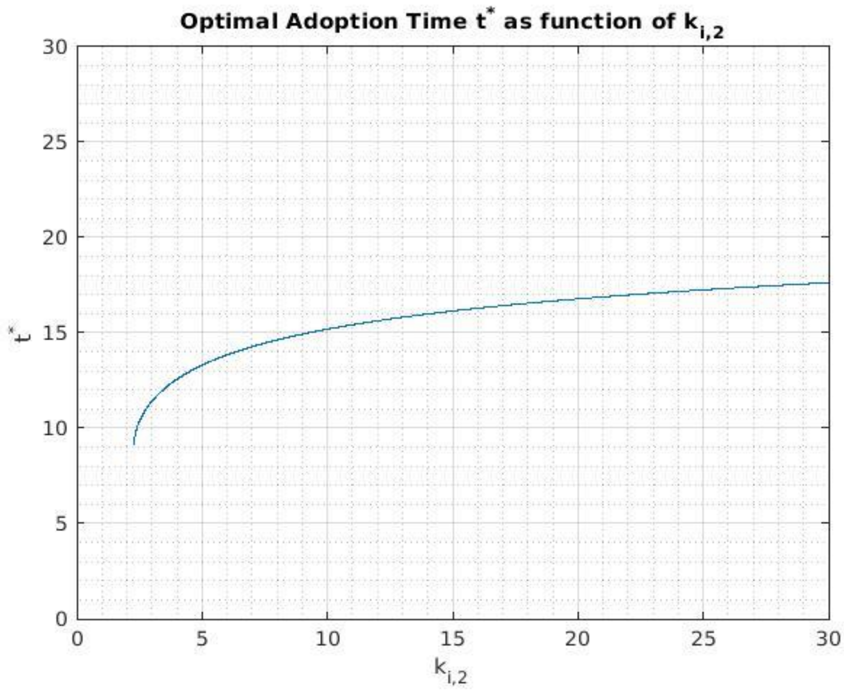


Figure 34 - Optimal adoption time t^* as function of $k_{i,2}$

Figure 34 illustrates how the optimal adoption time t^* is influenced by a change in the follower's learning capability or $k_{i,2}$. As $k_{i,2}$ increases the optimal adoption time of the follower is also increasing. Specifically, when the value of $k_{i,2}$ increases (i.e., learning rate is low) the follower chooses to wait longer to adopt a second-generation CCS technology. The follower is better off delaying the investment decision and letting the pioneer do the learning for him before it adopts technology 2.

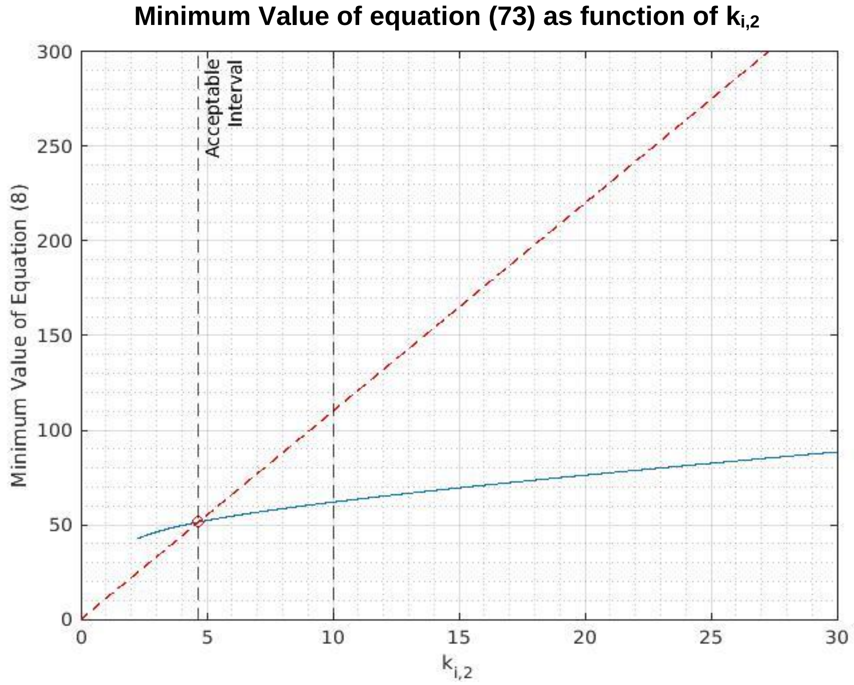


Figure 35 - Minimum value of equation (73) as function of $k_{i,2}$

The acceptable region for parameter $k_{i,2}$ for the chosen parameters should be within $4.6747 < k_{i,2} < 10$. The lower interval is obtained by setting up the expression below.

$$\overline{c}_{i,2}(k_{i,2}) = (c_{i,0} - L_{i,2})t^*(k_{i,2}) + \Big((H_{i,1} - L_{i,1})S_{i,1}\big(t^*(k_{i,2})\big) + L_{i,1} - L_{i,2}\Big)\mu_{i,2} \tag{88}$$

equal to $\overline{c}_{i,2}(k_{i,2}; t = 0)$, which is equal to

$$\overline{c}_{i,2}(k_{i,2}; t = 0) = (H_{i,1} - L_{i,2})k_{i,2}\theta_{i,2} \tag{89}$$

where $\mu_{i,2} \equiv k_{i,2}\theta_{i,2}$. The upper limit of the acceptable region is directly given by knowing that $k_{i,1}$ is equal to 10, as it assumed that $k_{i,1} > k_{i,2}$. If this is not satisfied, this then means that technology 2 would not be more efficient than technology 1.

4.7.1.4 Parameter $H_{i,1}$

The final parameter investigated is the parameter $H_{i,1}$, the initial marginal cost of production of the pioneer. Figure 36 below illustrates the effects of $H_{i,1}$ to the optimal adoption time of the follower or the plot of equation (83) as a function of $H_{i,1}$ using the parametric values stated in Table 10.

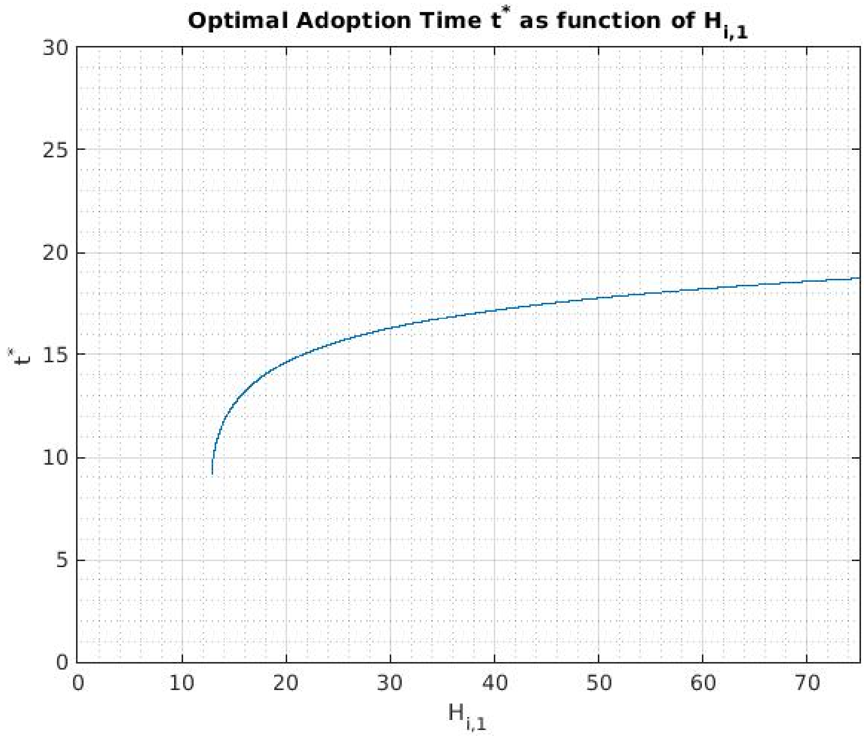


Figure 36 - Optimal adoption time t^* as function of $H_{i,1}$

In Figure 36, as the parameter $H_{i,1}$ increases the optimal adoption time of the follower is also increasing. Thus, if the difference between $H_{i,1}$ and $L_{i,1}$ for the pioneer increases, in other words, if the difference in the marginal cost of production from a learning-by-doing effect is large, this is going to influence the optimal adoption time of followers by delaying its decision longer. The reason for this is because the follower is better off waiting to adopt and letting the pioneer's learning bring the marginal cost of production down compared to adopting the technology earlier and doing the learning by itself. The follower's learning capability for this numerical example is slow, hence it prefers to wait to adopt the second-generation CCS technology.

Parameter $H_{i,1}$ is the only parameter by doing the comparative static where there is not a closed interval acceptable region compared to the other parameters analysed in the previous subsection. As one can see in Figure 37 so long parameter $H_{i,1}$ is greater than 15.8434, we satisfy the condition $\bar{c}_{i,2}(H_{i,1}) < \bar{c}_{i,2}(0)$.

Let us recall that if the reverse is obtained where $\bar{c}_{i,2}(H_{i,1}) > \bar{c}_{i,2}(0)$, this means that the follower should adopt a time $t = 0$. However, this condition cannot be true because the existence of technology depends on technology where it needs first some learning achieved by the pioneer for technology 2 to be developed. Therefore, $\overline{c}_{i,2}(H_{i,1}) < \overline{c}_{i,2}(0)$ is a strict condition for the modelling process.

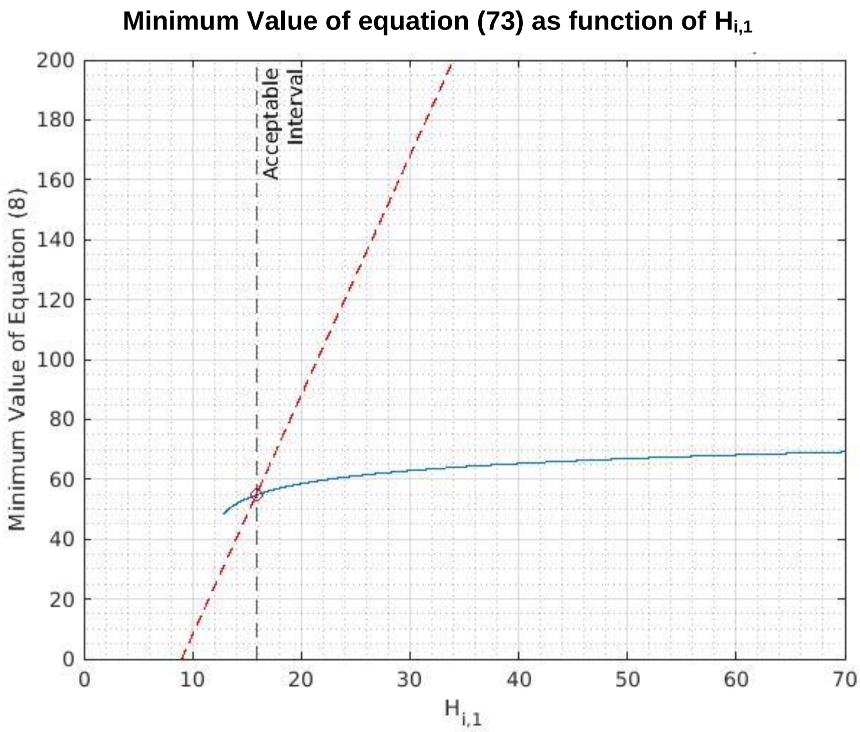


Figure 37 - Minimum value of equation (73) as function of $H_{i,1}$

4.7.1.5 Summary

In summary, several findings are discovered for the numerical example analysis of the parameters:

- When the marginal cost of production of a firm i without a CCS technology or $c_{i,0}$ increases (decreases) the optimal adoption time t^* of the follower decreases (increases).
- When the lowest possible marginal cost of production of the follower adopting a second-generation CCS technology or $L_{i,2}$ increases (decreases) the optimal adoption time t^* of the follower increases (decreases).
- When the learning capability of the follower for having adopted a second-generation CCS technology or $k_{i,2}$ increases (decreases) the optimal adoption time t^* of the follower increases (decreases).

- When the initial marginal cost of production of the pioneer or $H_{i,1}$ increases (decreases) the optimal adoption time t^* of the follower increases (decreases).

The following results are crucial so that government and policymakers can identify what is necessary to increase the deployment of CCS technology. For example, the effects of changing parameter $c_{i,0}$ it is found as many other researchers have identified that stricter environmental policy solutions should be implemented to increase CCS technology adoption.

4.8 Analysis of the Game

In this section, we are going to analyse the game by assessing the payoff functions. In the model description, it was previously stated that the game has four possible technological outcomes. This can be formed into a normal form as previously presented in Table 11.

		FIRM 2	
		Adopt Now (1st gen.)	**Delay (2nd gen.)/ Never**
FIRM 1	**Adopt Now (1st gen.)**	$\left(\overline{c}_{i,1}(T_i), \overline{c}_{i,1}(T_i)\right)$	$\left(\overline{c}_{i,1}(T_i), \underline{\overline{c}_{i,2}(T_i)}\right)$
	Delay (2nd gen)/ Never	$\left(\underline{\overline{c}_{i,2}(T_i)}, \overline{c}_{i,1}(T_i)\right)$	$\left(\underline{\overline{c}_{i,0}(T_i)}, \underline{\overline{c}_{i,0}(T_i)}\right)$

Table 11 - The normal form game of the model

The payoffs of a firm were identified in section 4.5 which were equal to:

- If a firm i adopts technology 0, the payoff is given by equation (74).
- If a firm i adopts technology 1, the payoff is given by equation (72).
- If a firm i adopts technology 2, the payoff is given by equation (73).

The current market situation of CCS technology is that a well-known major obstacle of the technology is its high upfront investment cost but also CCS technology is known to have an expensive cost to operate. Given this information, this translates that the payoff $\overline{c}_{i,1}(T_i)$ and $\overline{c}_{i,2}(T_i)$ in Table 11 are both greater than and $\overline{c}_{i,0}(T_i)$. Overall, this obtains that the Nash equilibrium will be equal to both firms choosing a production method equal to technology 0 or business-as-usual (BAU).

What is learnt here is that the current market incentives for firms to adopt CCS technology are lacking. Firms would rather choose to release their carbon emission into the atmosphere and pay a carbon dioxide tax. Thus, a major focus that governments and policymakers should focus on is creating market conditions such that firms can adopt the technology.

Besides the market conditions, another possible reason for the Nash equilibrium above is that both firms are choosing never to adopt because of the presence of a learning-by-doing and technological spillover effects. Specifically, there exists a waiting factor which is that the two firms could be choosing to delay CCS investment knowing that if a rival adopts first a first-generation CCS technology, then the firm can later gain a better production cost in the future. Therefore, governments and policymakers should also be aware of the strategic adoption of CCS technology in the market.

The preferred scenario that governments and policymakers should consider more important is a sequential adoption among the two firms – i.e., a firm adopts technology 1 and subsequently, the other firm adopts technology 2. The reason for this is because it is the only scenario where learning benefits will exist in the market which then is going to be spilt for other firms and more CCS knowledge can be created. For example, if both firms were to adopt immediately technology 1 then there will be no learning benefits for others and CCS technology will not achieve the stage of diffusion. Therefore, in the next subsection, the focus is to investigate the necessary conditions to obtain an outcome where there is a sequential adoption between the two firms.

4.9 The Policy Transfer

In this section, we present a policy solution such that a sequential adoption scenario can be obtained in the game. The reason for this again is because it is the only scenario where we can analyse the effects of learning-by-doing and technological spillover on CCS adoption decisions. The policy suggested in this section is balancing the cost of adoption of different generational CCS technologies through a transfer of payment between the firms. This is because for a firm that adopts technology 1 or pioneer, the benefits that the pioneer creates for others do not go back to the firm itself.

To achieve a balanced cost of adoption between a pioneer and follower we introduce a transfer payment G. Specifically, a transfer payment will be made by the follower to the pioneer. To evaluate the transfer payment G, the ECMC of the pioneer and follower are recalled, which were given by equation (72) and equation (73) respectively. The goal is to reach the condition such that equation (72) and equation (73) are the same. This signifies that both firms have the same ECMC for adopting sequentially a first-generation CCS technology and then a second-generation CCS technology.

Before displaying a numerical example for the policy solution to work an important condition is necessary. This is the pioneer's ECMC for adopting technology 1 or equation (72) needs to be at least equal to or less than the ECMC when it chooses to do a business-as-usual strategy or equation (74). Otherwise, if $\overline{c}_{i,0} \leq \overline{c}_{i,1}$ then the pioneer would not adopt technology 1 because it is going to be more expensive than just paying a carbon dioxide tax for its entire lifetime. Setting the inequality $\overline{c}_{i,0} \leq \overline{c}_{i,1}$ and then rearranging for $\overline{c}_{i,0}$ we get that condition below needs to be satisfied.

$$\overline{c}_{i,0} \geq \frac{(H_{i,1} - L_{i,1})\mu_{i,1}}{T_{i,1}} + L_{i,1} \tag{90}$$

Let us introduce how the transfer payment G is evaluated through a numerical example. The parameters of the numerical example are displayed in Table 12.

PIONEER	**FOLLOWER**	**BAU**
$k_{i,1} = 10$	$k_{i,2} = 8$	$c_{i,0} = 12$
$H_{i,1} = 20$	$L_{i,2} = 9$	
$L_{i,1} = 10$	$\theta_{i,2} = 1$	
$\theta_{i,1} = 1$	$T_i = 30$	
$T_i = 30$		

Table 12 - Parametric values for the Policy Transfer numerical example

Using the parameters above, the ECMC for the pioneer – equation (72) - with a sufficiently large T_i is equal to

$$\overline{c}_{i,1} = (H_{i,1} - L_{i,1}) \underbrace{\int_0^{T_i} S_{i,1}(z)\, dz}_{\mu_{i,1} = k_{i,1}\theta_{i,1}} = (20 - 10) * 10 * 1 = 100$$

On the other hand, the ECMC of the follower with an optimal adoption time $t^* = 14.6281$ using equation (73), it is equal to

$$\overline{c}_{i,2} = \left(c_{i,0} - L_{i,2}\right)t^* + \left(c_{i,1}(t^*) - L_{i,2}\right)\underbrace{\int_0^{T_i - t^*} S_{i,2}(z)\, dz}_{\mu_{i,2}}$$

$$= (12 - 9) * 14.6281 + (10.8284 - 9) * 8 * 1 = 58.5115$$

The transfer payment G is calculated by taking the difference between $\overline{c}_{i,1}$ and $\overline{c}_{i,2}$, or $G = \overline{c}_{i,1} - \overline{c}_{i,2}$. The reason for this is because the pioneer incurs a greater cost of adoption for adopting technology 1. However, the benefit of adopting technology 1 is that the pioneer can reduce its marginal cost over time due to a learning-by-doing effect. At the same time, the pioneer is also creating an indirect benefit for other firms in the market where it is for learning-for-others and with the presence of technological spillover in the market this benefits future adopters of a newer and more efficient CCS technology. Overall, in the previous calculations, we have $\overline{c}_{i,1} > \overline{c}_{i,2}$. Hence, the only way to make the benefits equal for each firm is to have a transfer payment where the follower is going to pay the pioneer such that the pioneer recoups some or all its cost from adopting first. Hence, the transfer G is equal to

$$G = \overline{c}_{i,1} - \overline{c}_{i,2}(t^*) = 100 - 58.5115 = 41.4885$$

What does the transfer G mean? Transfer G is the amount of payoff that the government should be taxing the follower off to equalize the cost of different generation CCS adoption of the pioneer and the follower. A policy design to obtain transfer G is for example to implement a production tax – i.e., per year – once the follower has adopted the second-generation CCS technology. For example, the amount of transfer $G = 41.4946$ can be quickly recouped within $t = 4.6105$ if the tax is immediately implemented – this is obtained by dividing G by parameter $L_{i,2}$. However, realistically this is not likely going to happen as the follower needs to be earning profits. Therefore, the government and the follower should negotiate on how to obtain the transfer of payment G which is out of the scope of this research. Once the amount transfer G is recouped for the pioneer, then the production tax should stop, and no more transfer payments are necessary anymore to balance the benefits between the two firms. From there on out whatever the follower earns is going to be solely his.

The creation of the policy is to obtain a sequential scenario between the two firms. This is because as previously discussed in section 0 which is displayed in Table 11, the two firms have a dominant strategy of not adopting CCS technology or choosing technology. The reason for this again is that currently, CCS technology is too expensive to invest in. Also, we have identified that firms are delaying the decision because there is the potential to have a better and more efficient CCS technology in the future if a firm has adopted it first. Before the policy solution suggested in this section, the normal-form game of the model is illustrated in Table 11. However, when the policy transfer G is implemented the normal-form game displayed in Table 13 is going to be obtained.

		FIRM 1	
		Adopt Now (1st gen.)	**Delay (2nd gen.)/ Never**
FIRM 2	**Adopt Now (1st gen.)**	$\left(\bar{c}_{2,1}, \bar{c}_{1,1}\right)$	$\left(\underline{\bar{c}_{2,1} + G}, \underline{\bar{c}_{1,2} - G}\right)$
	Delay (2nd gen)/ Never	$\left(\underline{\bar{c}_{2,2} - G}, \underline{\bar{c}_{1,1} + G}\right)$	$\left(\bar{c}_{2,0}, \bar{c}_{1,0}\right)$

Table 13 - Normal-form game post the Policy Transfer solution

The Nash equilibrium of the game corresponds to either firm 1 being the pioneer and firm 2 being a follower or vice-versa. The roles of who should go first then eventually do not matter as the firms equally have the same cost of CCS adoption with the transfer of payment G. Overall, this policy aims to achieve early CCS adoption and an increase in the diffusion of the mitigation strategy when the CCS adoption decision is influenced by learning-by-doing and technological spillover.

4.10 Conclusion

This chapter aimed to investigate the optimal CCS investment decision time of a follower who adopts a second-generation CCS technology. A second-generation CCS technology is a more efficient technology that comes at a lower cost and a faster learning rate decreasing the marginal cost of production of the technology. The existence of the second-generation CCS technology is due to the consequence of the learning-by-doing effect gained by a prior adopter. Also known as the pioneer who has adopted a first-generation CCS technology where it comes with a high operating cost. The reason for analysing this scenario is that CCS technology is lacking in deployment due to its extremely high cost and the lack of policy incentives. Furthermore, given that there also exists the potential of better technology in the future, there exists a waiting factor that can also hinder the deployment of CCS technology where firms are more willing to delay CCS investment, knowing that there could be a more advanced technology in the future to save some costs.

Thus, in this study, the optimal adoption decision of a follower adopting a second-generation CCS technology was evaluated whilst influenced by a learning-by-doing effect. The main variation of this chapter in the current literature is the approach of considering a different methodology in describing the learning cost curve for a firm. Inspired by Pan (2006)[26], an inverted S-shaped curve for the cost reduction of CCS technology was assumed achieved by using the properties of the survival function. Also, we identified the factors that affect the optimal decision time of a follower adopting a second-generation CCS technology. The factors identified were:

1. $c_{i,0}$ – The marginal cost of production of a firm i without a CCS technology.
2. $L_{i,2}$ - The lowest possible marginal cost of production achieved by the follower for adopting a second-generation CCS technology due to its own a learning-by-doing
3. $k_{i,2}$ - The learning rate of the follower for having adopted a second-generation CCS technology
4. $H_{i,1}$ - The initial marginal cost of production of the pioneer for adopting a first-generation CCS technology.

However, the main result obtained in this chapter is the construction of a policy solution such that the benefits generated by a pioneer spilt to the follower are returned to the pioneer. This is because for a firm that adopts technology 1 or pioneer, the benefits that the pioneer creates for others do not go back to the firm itself. Overall, the policy presented in this chapter aims to achieve early CCS adoption and an increase

[26] Technological change in energy systems: Learning curves, logistic curves, and input–output coefficients

in the diffusion of the mitigation strategy when the CCS adoption decision is influenced by learning-by-doing and technological spillover.

This study has several avenues for potential future works. In the model, we can relax the assumption of the fixed cost of CCS technology for the first generation and second generation to be the same. Despite evidence showing that the fixed of CCS technology is in a decline due to a learning-by-doing effect. The reason for assuming the fixed cost of technology 1 and technology 2 to be the same is because the fixed cost of CCS can either go up or down, as it depends on the industry that discovers the new CCS technology where they might sell the technology at a premium (higher) cost for future adopters. Thus, future works should explore different fixed costs for the separate generations of CCS technology. Furthermore, another strong assumption in the model was the assumption that the adoption of technology 2 is a CCS technology purchased where the "eco-industry" selling CCS technology is a perfectly competitive market. Specifically, the market price of technology 2 is equal to the marginal cost of production at the time of adoption. However, with CCS technology not fully commercially a better understanding of CCS providers should be understood. Overall, the two strong assumptions mentioned bring in the concept of the eco-industry which provides an interesting topic for future research. For example, some future research questions are: *what are the effects of an eco-industry in the adoption time of CCS technology? Does the eco-industry selling CCS technology have any bargaining power or not, and if so, what are the impacts on the adoption of CCS technology?* Other interesting avenues of research include analysing more than two firms in the game and investigating a more dynamic game with endogenous roles by the firms.

4.11 Appendices Chapter 4

A – MATLAB Example Script

```
% Parameters
t=0:0.01:100;                % Variable time t

% Pioneer
k1=10;                       % Learning rate
theta1=1;                    % Scale parameter
H1=20;                       % Initial marginal cost of production
L1=10;                       % Lowest possible marginal cost of production
                                % due to the learning-by-doing effect
S=1-gammainc(t/theta1,k1);   % Survival Function S(t) for Pioneer

for i=1:size(t,2)
    c1(i)=(H1-L1)*S(i)+L1;   % Marginal Cost Behaviour Pioneer
end

% Follower
k2=8;                        % Learning rate
theta2=1;                    % Scale parameter
L2=9;                        % Lowest possible marginal cost of production
                                % due to the learning-by-doing effect

% Business-as-usual (BAU)
c0=12;                       % Marginal cost of production of a firm not
                                % investing in CCS technology

% EQUATION 14 - MARGINAL BENEFIT (MB) = MARGINAL COST (MC)
for i=1:size(t,2)

    MB=(H1-L1)*(((t.^(k1-
         1)).*exp(t/theta1))./(theta1.^(k1)*gamma(k1)))*k2*theta2;

    MC(i)=c0-L2;

end

% EQUATION (8) - COST MINIMIZATION OBJECTIVE FUNCTION
for i=1:size(t,2)

   EMC(i)=(c0-L2)*t(i)+(c1(i)-L2)*(k2*theta2);

   EMC_zero(i)=EMC(1);

end

% FINDING THE OPTIMAL TIME t FOR FOLLOWER
y1=MB;
y2=MC;
x1=t;
x2=t;

P=InterX([t;MB],[t;MC]);

% disp('------------------------------------------------------------------')
% disp('The optimal adoption time for the follower are:')

t_star1=round(P(1,1),2);
t_star2=round(P(1,2),2);
```

```
% FINDING H2 THE INITIAL MARGINAL COST OF PRODUCTION OF FOLLOWER
p1=find(t==t_star1);
p2=find(t==t_star2);

% disp('------------------------------------------------------------------')
% disp('The corresponding H2 value for the two optimal adoption times are:')

H2_t_star1=round(c1(p1),2);
H2_t_star2=round(c1(p2),2);

% EVALUATING FOLLOWER SURVIVAL FUCNTION
tt1=t_star1:0.01:100+t_star1;
tt2=t_star2:0.01:100+t_star2;


for i=1:size(t,2)
    c2_t_star1=(H2_t_star1-L2)*(1-gammainc(t/theta2,k2))+L2;
    c2_t_star2=(H2_t_star2-L2)*(1-gammainc(t/theta2,k2))+L2;
end


ttt1=0:0.01:t_star1;
ttt2=0:0.01:t_star2;

for i=1:size(ttt1,2)
    BAUtt1(i)=c0;
end

for i=1:size(ttt2,2)
    BAUtt2(i)=c0;
end

% FINAL PLOT - E.G. FIGURE 3 in Subsection 1.5.3

HFig=figure();
% set(HFig,'Position', get(0, 'Screensize'));
subplot(2,3,1)
plot(t,MB,P(1,:),P(2,:),'ro')
title('Optimal Adoption Time')
ylabel('Equation (15)')
xlabel('Time')
hold on
plot(t,MC)
grid
grid minor
xlim([0 40])
ylim([0 max(MB)+10])
hold off

subplot(2,3,4)
plot(t,EMC)
title('Excess Cumulative Marginal Cost')
ylabel('Equation (8)')
xlabel('Time')
ylim([0 max(EMC)+10])
xlim([0 40])
grid
grid minor
hold on
plot(t,EMC_zero,'--')
hold off
```

```
for i=1
H11=zeros(1,1);
if H2_t_star1 < c0
H11(i)=c0;
elseif H2_t_star1 > c0
H11(i)=H2_t_star1;
end
end

subplot(2,3,[2 3])
plot(t,c1)
title('Graph of Pioneer and Follower adopting at time t-star1')
xlabel('Time')
ylabel('Marginal cost')
xlim([0 40])
ylim([0,H1+10])
grid
grid minor
hold on
plot(tt1,c2_t_star1)
hold on
plot(ttt1,BAUtt1,'color',[0 0.6 0.3])
hold on
line([t_star1 t_star1], [0 H11],'color',[0 0.6 0.3])
hold off

for i=1
H22=zeros(1,1);
if H2_t_star2 < c0
H22(i)=c0;
elseif H2_t_star2 > c0
H22(i)=H2_t_star2;
end
end

subplot(2,3,[5 6])
plot(t,c1)
title('Graph of Pioneer and Follower Adopting at time t-star2')
xlabel('Time')
ylabel('Marginal cost')
xlim([0 40])
ylim([0,H1+10])
grid
grid minor
hold on
plot(tt2,c2_t_star2)
hold on
plot(ttt2,BAUtt2,'color',[0 0.6 0.3])
hold on
line([t_star2 t_star2], [0 H22],'color',[0 0.6 0.3])
hold off
```

B – Further analysis of the Sequential Adoption Scenario

In this section, the sequential adoption scenario is further investigated. We assess the effects of adding a discount rate to the cost minimization problem. We also examine the impact of considering a finite lifetime T_i in the calculation of the optimal adoption time of the follower.

B.1 – The Effects of including a Discount Rate r

To analyse whether a firm should invest or not in a project, a typical appraisal is to calculate the net present value of the project. Hence, in this subsection, we consider the addition of a discount rate in the cost minimization objective function or equation (73). Let r be the discount rate, where $r > 0$. The net present value (NPV) of equation (73) – denoted by $NPV\overline{c}_{i,2}$ – is equal to

$$NPV\overline{c}_{i,2} = \left(c_{i,0} - L_{i,2}\right)\int_0^t e^{-ry}\,dy + e^{-rt}\left(c_{i,1}(t) - L_{i,2}\right)\int_0^\infty e^{-rz}\,S_{i,2}(z)\,dz$$

Solving the first integral in the expression above, we get

$$\begin{aligned} NPV\overline{c}_{i,2} &= \left(c_{i,0} - L_{i,2}\right)\left(\frac{1 - e^{-rt}}{r}\right) \\ &\quad + e^{-rt}\left(c_{i,1}(t) - L_{i,2}\right)\int_0^\infty e^{-rz}\,S_{i,2}(z)\,dz \end{aligned} \tag{91}$$

To solve the second integral, the Laplace transform of a function $f(y)$ needs to be introduced, which is defined as

$$L(r) = \int_0^\infty e^{-ry} f(y)\,dy \tag{92}$$

Also, a function $M(r)$ is considered which is equal to

$$M(r) = \int_0^\infty e^{-ry}\int_y^\infty f(x)\,dx\;dy$$

The definition of the survival function is $S(y) = 1 - F(y) = \int_y^\infty f(x)\,dx$. Thus, we can rewrite $M(r)$ into

$$M(r) = \int_0^\infty e^{-ry} S(y) dy \tag{93}$$

Notice that equation (93) has the form that is needed to be solved for the integral present in equation (91). To solve equation (93), we use integration by parts,

$$\begin{aligned} M(r) &= \left[-\frac{e^{-ry}}{r}S(y)\right]_0^\infty + \int_0^\infty \frac{e^{-ry}}{r}\frac{dS(y)}{dy}\,dy \\ &= \frac{1}{r} + \int_0^\infty \frac{e^{-ry}}{r}\frac{d}{dy}\big(1-F(y)\big)\,dy \\ &= \frac{1}{r} - \frac{1}{r}\underbrace{\int_0^\infty e^{-ry}\,f(y)\,dy}_{L(r)} \\ &= \frac{1-L(r)}{r} \end{aligned} \tag{94}$$

Overall, equation (94) provides the solution to the integral that has a similar form to equation (93). Hence, inputting equation (94) into equation (93), where it is also added the subscripts $(i,2)$ for $M(r)$ to obtain $M_{i,2}(r)$, the NPV of the ECMC of a follower is given by

$$NPV\overline{c}_{i,2} = \left(c_{i,0} - L_{i,2}\right)\left(\frac{1-e^{-rt}}{r}\right) + e^{-rt}\left(c_{i,1}(t) - L_{i,2}\right)M_{i,2}(r) \tag{95}$$

where,

$$M_{i,2}(r) = \int_0^\infty e^{-rz}\,S_{i,2}(z)\,dz = \frac{1-L_{i,2}(r)}{r} \tag{96}$$

with $L_{i,2}(r)$ equal to the definition of the Laplace transform as previously illustrated in equation (92).

The next step is to solve equation (95) to find the optimal adoption time t^* of the follower. However, so far, no distribution function has been assumed for the survival function. For consistency, like subsection 1.4.2, we consider again a survival function that follows a 2-parameter gamma distribution. By considering so, this allows rewriting equation (95) to

$$NPV\overline{c}_{i,2} = (c_{i,0} - L_{i,2})\left(\frac{1-e^{-rt}}{r}\right) + e^{-rt}(c_{i,1}(t) - L_{i,2})\underbrace{\left(\frac{1-\left(\frac{1/\theta_{i,2}}{1/\theta_{i,2}+r}\right)^{k_{i,2}}}{r}\right)}_{M_{i,2}(r)} \tag{97}$$

In equation (97) above, $M_{i,2}(r)$ is obtained by finding the Laplace transform of the 2-parameter gamma distribution. Achieved by solving the Laplace transform definition or equation (92) that has a probability density function equal to the 2-parameter gamma distribution as previously stated in equation (78). To find the optimal adoption time of the follower we take the first derivative of equation (97)

$$\begin{aligned}\frac{dNPV\overline{c}_{i,2}}{dt} &= (c_{i,0} - L_{i,2})e^{-rt} - M_{i,2}(r)(c_{i,1}(t) - L_{i,2})re^{-rt} + M_{i,2}(r)e^{-rt}\left(\frac{dc_{i,1}(t)}{dt}\right) = 0 \\ &= e^{-rt}\Big[(c_{i,0} - L_{i,2}) - rM_{i,2}(r)\left((H_{i,1} - L_{i,1})S_{i,1}(t) + L_{i,1} - L_{i,2}\right) - M_{i,2}(r)(H_{i,1} - L_{i,1})f_{i,1}(t)\Big] = 0\end{aligned} \tag{98}$$

Unfortunately, the derivative of $NPV\overline{c}_{i,2}$ with respect to t it cannot be rearranged for the variable t. Instead, the other methodology is to consider the two expressions above as functions of t. Then, by plotting the two functions on the same plot using MATLAB, wherever the curves intersect, will obtain the result of the optimal adoption time t^*.

Dividing equation (98) by e^{-rt} and then rearranging for $f_{i,1}(t)$, we get

$$f_{i,1}(t) = \frac{(c_{i,0} - L_{i,2}) - rM_{i,2}(r)\left((H_{i,1} - L_{i,1})S_{i,1}(t) + L_{i,1} - L_{i,2}\right)}{M_{i,2}(r)(H_{i,1} - L_{i,1})} \tag{99}$$

On the left-hand side, $f_{i,1}(t)$ is equivalent to the function of the probability density function of the 2-parameter gamma distribution, as previously illustrated in equation (78). Substituting equation (78) into the above, we obtain

$$\frac{\left(\theta_{i,1}^{k_{i,1}}\right)\ t^{k_{i,1}-1}\ e^{-\left(\frac{t}{\theta_{i,1}}\right)}}{\Gamma\left(k_{i,1}\right)} = \frac{\left(c_{i,0} - L_{i,2}\right) - rM_{i,2}(r)\left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)}{M_{i,2}(r)\left(H_{i,1} - L_{i,1}\right)} \tag{100}$$

Overall, equation (100) is the equation that will allow us to identify the optimal adoption time t^* of the follower. With no other means to solve analytically the optimal adoption time of the follower, we illustrate through a numerical example the analytical results.

For the numerical example in this subsection, the same set of assumptions as stated in section 1.4.3 is considered. Table 14 below displays the parametric values plus the additional new parameter r – the discount rate – which is equal to $r = 0.06$.

PIONEER	**FOLLOWER**	**BAU**	**DISCOUNT RATE**
$k_{i,1} = 10$	$k_{i,2} = 8$	$c_{i,0} = 12$	$r = 0.06$
$H_{i,1} = 20$	$L_{i,2} = 9$		
$L_{i,1} = 10$	$\theta_{i,2} = 1$		
$\theta_{i,1} = 1$			

Table 14 – Parametric values with a discount rate r

Using MATLAB, the plot of equation (100) with the set of parametric values illustrated in Table 14, a graphical result is obtained in Figure 38.

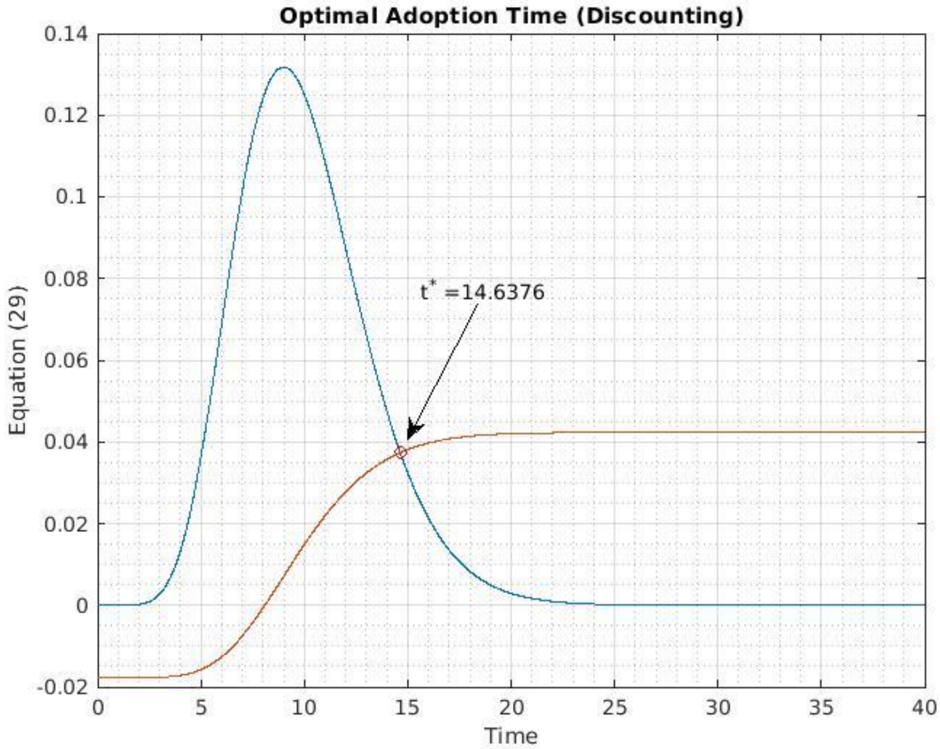


Figure 38 - Optimal adoption time of the follower with a discount rate r=0.06.

In Figure 38, the intersection of the two curves gives us the solution for the optimal adoption time for the follower to adopt a second-generation CCS technology where the optimal adoption time $t^* = 14.6376$. Comparing this result to the optimal adoption time of the follower with no discounting (where the result was $t^* = 14.6281$), the follower adopts earlier when $r = 0$. However, the difference between the two numerical examples is extremely small.

From this analysis two questions are further asked:

- Is the adoption of the follower always earlier when discounting is not considered in the cost minimization problem?
- How does parameter r affect the optimal decision time of the follower?

To answer the two questions, we required equation (100) which allowed us to calculate the optimal adoption of the follower with a discount rate. Then, we take the derivative of equation (100) with respect to r so that we can examine the effect of r in the optimal adoption time t^* for the follower.

The derivative of equation (100) with respect to r is equal to

$$\frac{dt^*}{dr} = \frac{\left(c_{i,0} - L_{i,2}\right)\left(\frac{dM_{i,2}(r)}{dr}\right) + \left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)\left(M_{i,2}(r)\right)^2}{\left(M_{i,2}(r)\right)^2\left(H_{i,1} - L_{i,1}\right)} \quad (101)$$

where $M_{i,2}(r)$ is equal to equation (96). The result obtained in equation (101) is too complex to understand how the discount rate r affects the optimal adoption time of the follower. Hence, equation (101) is instead plotted with r treated as the changing variable by using MATLAB and considering the parameters presented in Table 14. The graphical results obtained using MATLAB are displayed in Figure 39 where we first consider r at maximum value of 1.

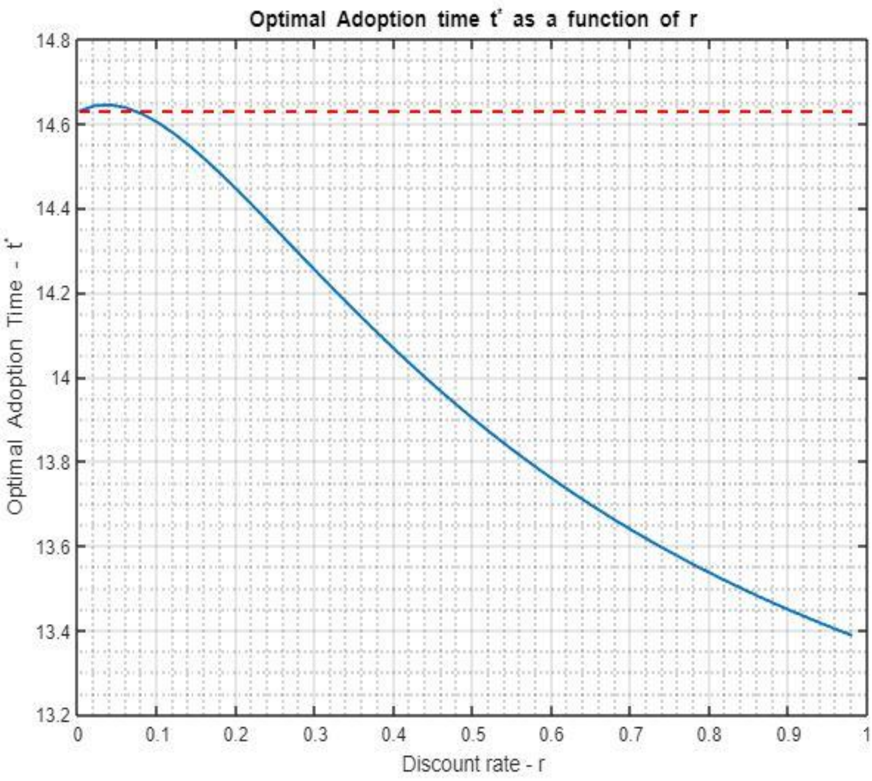


Figure 39 - Optimal adoption time t^*as function of r

In Figure 39, the red line dashed line represents the optimal adoption time of the follower when $r = 0$. In subsection 1.4.2, this was found to be equal $t^* = 14.6281$. The blue line is equivalent to the plot of equation (100) as a function of r.

When $r \to 0$, the optimal adoption time of the follower converges towards the optimal adoption time of the follower when the model does not consider discounting. On the other hand, when r converges towards 1 the optimal adoption time of the follower firstly increases and then decreases below the red dashed line. Thus, as r progressively get larger the follower decides to adopt the technology 2 earlier. In Figure 39 the discount rate r only shows a maximum value of $r = 1$. Hence, in Figure 40 is a continuation of Figure 39 where $r > 1$.

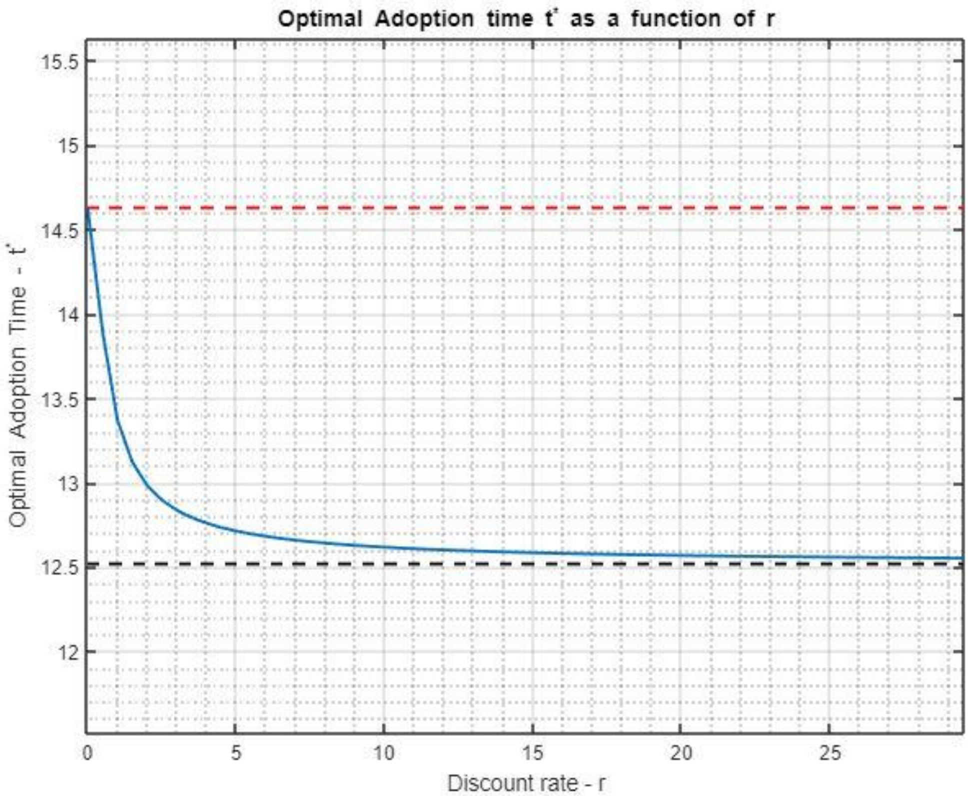


Figure 40 - Optimal adoption time t^* as function of r where $r > 1$

A higher discount rate implies that the follower does not care about the future but only about the present. In Figure 40 when the discount rate r is extremely high, the follower's optimal adoption time decreases. We find that as r increases the adoption time of the follower is heading towards the black dashed line in Figure 40 which is equivalent to the crossing point between $c_{i,1}(t)$ and $c_{i,0}(t)$. Respectively, these are the marginal cost of production adopting technology 1 and the marginal cost of production not adopting CCS technology at all. Thus, the follower's optimal adoption time gets closer to the marginal cost of production of the pioneer under a first-generation CCS technology and business-as-usual as the discount rate r increases.

B2 - The Effects of considering a Finite Lifetime T_i

The other component considered in the cost minimization problem is a finite lifetime T_i. So far, in all the calculations in the previous section the lifetime of a firm T_i was assumed to be going to infinity. The reason for assuming $T_i \to \infty$ was for achieving a simplification in the integral of the survival function which is equal to the mean of the distribution function considered. However, what if the lifetime of a firm T_i affects the optimal adoption time of CCS technology? Thus, in this section, we investigate the effects of positive finite integer for T_i to the optimal adoption time of the follower given a pioneer has previously adopted. In the upcoming calculations, we also consider the presence of a discount rate $r > 0$.

To analyse the effects of a finite lifetime T_i, we recall equation (69) which is equal to ECMC of the follower before the simplification that the integral of the survival function is from 0 to infinity is equal to the mean. Taking the net present value of equation (69) – denoted by $\overline{NPV}\overline{c}_{i,2}$ – is equal to

$$\overline{NPV}\overline{c}_{i,2} = \left(c_{i,0} - L_{i,2}\right)\int_0^t e^{-ry}\, dy + e^{-rt}\left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)\int_0^{T_i} e^{-rz} S_{i,2}\, dz$$

By solving the first integral we get

$$\overline{NPV}\overline{c}_{i,2} = \left(c_{i,0} - L_{i,2}\right)\left(\frac{1 - e^{-rt}}{r}\right) + e^{-rt}\left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)\int_0^{T_i} e^{-rz} S_{i,2}\, dz \tag{102}$$

The second integral $\int_0^{T_i} e^{-ry} S_{i,2}\, dy$ in the expression above is solved using integration by parts. By doing so, we obtain

$$\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz = \left[-\frac{S_{i,2}(z)e^{-rz}}{r}\right]_0^{T_i} - \int_0^{T_i}\left(-\frac{e^{-rz}}{r}\right)\left(\frac{dS_{i,2}(z)}{dz}\right) dz$$

$$= \left(\frac{1}{r} - \frac{S_{i,2}(T_i)e^{-rT_i}}{r}\right) + \frac{1}{r}\int_0^{T_i} e^{-rz}\frac{d}{dz}\left(1 - F_{i,2}(z)\right) dz$$

$$= \left(\frac{1}{r} - \frac{S_{i,2}(T_i)e^{-rT_i}}{r}\right) + \frac{1}{r}\int_0^{T_i} e^{-rz}\frac{d}{dz}\left(-F_{i,2}(z)\right)\,dz$$

$$= \left(\frac{1}{r} - \frac{S_{i,2}(T_i)e^{-rT_i}}{r}\right) - \frac{1}{r}\int_0^{T_i} e^{-rz} f_{i,2}(z)\,dz$$

We assume again that the survival function follows a 2-parameter gamma distribution, where $f_{i,2}$ in the expression above is substituted by equation (78) – the function of the probability density function of the 2-parameter gamma distribution. Thus, the expression above can be rewritten to

$$\int_0^{T_i} e^{-rz} S_{i,2}(z)\,dz = \left(\frac{1}{r} - \frac{S_{i,2}(T_i)e^{-rT_i}}{r}\right) - \frac{1}{r\,\Gamma(k_{i,2})}\int_0^{T_i} z^{\alpha_{i,2}-1}e^{-(1+r)z}dz \tag{103}$$

From equation (103), the integral $\int_0^{T_i} z^{k_{i,2}-1}e^{-(1+r)z}\,dz$ gives a solution equal to

$$\int_0^{T_i} z^{\alpha_{i,2}-1}e^{-(1+r)z}dz = \left(\frac{T_i^{k_{i,2}}}{\left(T_i(1+r)\right)^{k_{i,2}}}\right)\gamma_{i,2}\left(k_{i,2}, T_i(1+r)\right) \tag{104}$$

where $\gamma_{i,2}\left(k_{i,2}, T_i(1+r)\right)$ is the lower incomplete gamma function. Substituting equation (104) into equation (103) we obtain

$$\int_0^{T_i} e^{-rz} S_{i,2}(z)\,dz = \frac{1}{r} - \frac{S_{i,2}(T_i)e^{-rT_i}}{r} - \frac{\gamma_{i,2}\left(k_{i,2}, T_i(1+r)\right)}{r\,\Gamma(k_{i,2})}\left(\frac{T_i^{k_{i,2}}}{\left(T_i(1+r)\right)^{k_{i,2}}}\right) \tag{105}$$

Finally, equation (105) is substituted in equation (102) to obtain the full expression of the NPV of a follower adopting technology 2 whilst considering a finite lifetime T_i and a discount rate r.

$$\overline{NPV}\overline{c}_{i,2} = (c_{i,0} - L_{i,2})\left(\frac{1 - e^{-rt}}{r}\right) + e^{-rt}\left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)\left(\frac{1}{r} - \frac{S_{i,2}(T_i)e^{-rT_i}}{r} - \frac{\gamma_{i,2}\left(k_{i,2}, T_i(1+r)\right)}{r\,\Gamma(k_{i,2})}\left(\frac{T_i^{k_{i,2}}}{\left(T_i(1+r)\right)^{k_{i,2}}}\right)\right) \quad (106)$$

The expression above is the objective function that will obtain the optimal adoption time of the follower. However, before doing so, the solution of the integral $\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz$ in equation (105), has no variable t in the expression. Thus, for simplicity reasons in the upcoming calculations $\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz$ is considered rather than its full equation as stated in equation (105). By considering so, the derivative of equation (106) is

$$\frac{d\overline{NPV}\overline{c}_{i,2}}{dt} = (c_{i,0} - L_{i,2})e^{-rt} - re^{-rt}\left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz - e^{-rt}\left(H_{i,1} - L_{i,1}\right)f_{i,1}(t)\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz = 0 \quad (107)$$

Rearranging equation (107) for $f_{i,1}(t)$ we get

$$f_{i,1}(t) = \frac{(c_{i,0} - L_{i,2})e^{-rt} - re^{-rt}\left(\left(H_{i,1} - L_{i,1}\right)S_{i,1}(t) + L_{i,1} - L_{i,2}\right)\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz}{e^{-rt}\left(H_{i,1} - L_{i,1}\right)\int_0^{T_i} e^{-rz} S_{i,2}(z)\, dz} \quad (108)$$

where $f_{i,1}(t)$ is equal to equation (78) – the probability density function of a 2-parameter gamma distribution. Like section 1.4.5.1, the result obtained in equation (108) cannot be further simplified to be rearranged for the variable t. The other method to find the optimal time t^* is to treat both sides as functions of t. Then, by plotting the two functions on the same plot, wherever the curves intersect will obtain the result of the optimal time t^* of the follower. Hence, with no other means to solve analytically the optimal adoption time of the follower we illustrate through a numerical example the analytical results.

The parameters considered for the numerical examples are shown below in Table 15, where there is also the added parameter $T_i = 30$, because it is a typical lifetime of a power plant.

PIONEER	FOLLOWER	BAU	DISCOUNT RATE
$k_{i,1} = 10$	$k_{i,2} = 8$	$c_{i,0} = 12$	$r = 0.06$
$H_{i,1} = 20$	$L_{i,2} = 9$		
$L_{i,1} = 10$	$\theta_{i,2} = 1$		
$\theta_{i,1} = 1$	$T_i = 30$		

Table 15 – Parametric Values with a finite lifetime

Using MATLAB, the plot of equation (108) considering the parameters above is displayed in Figure 41.

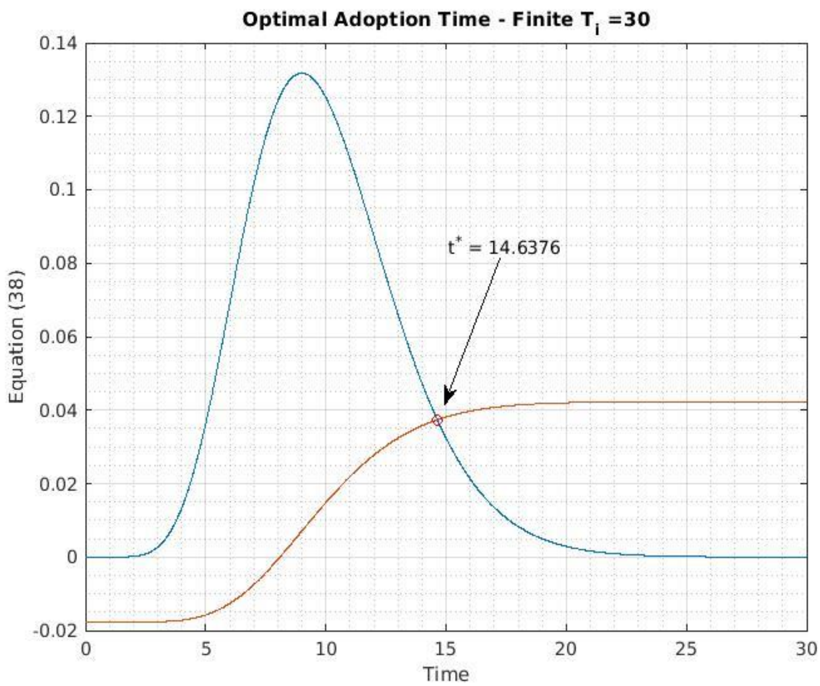


Figure 41 - Optimal adoption time - Finite time $T_i = 30$

In Figure 41 there only exists one solution for the optimal adoption time of the follower which is equal to $t^* = 14.6376$. Interestingly, comparing the following result with the result obtained when considering that the lifetime of the follower was assumed to go to infinity, the same optimal adoption time is obtained. Therefore, the lifetime of a firm T_i might not be an important factor that influences the adoption decision of a firm. However, to prove the claim the optimal adoption time of the follower needs further examination. Specifically, by taking the derivative of equation (108) with respect to T_i and see how the lifetime affects the optimal adoption time of the follower.

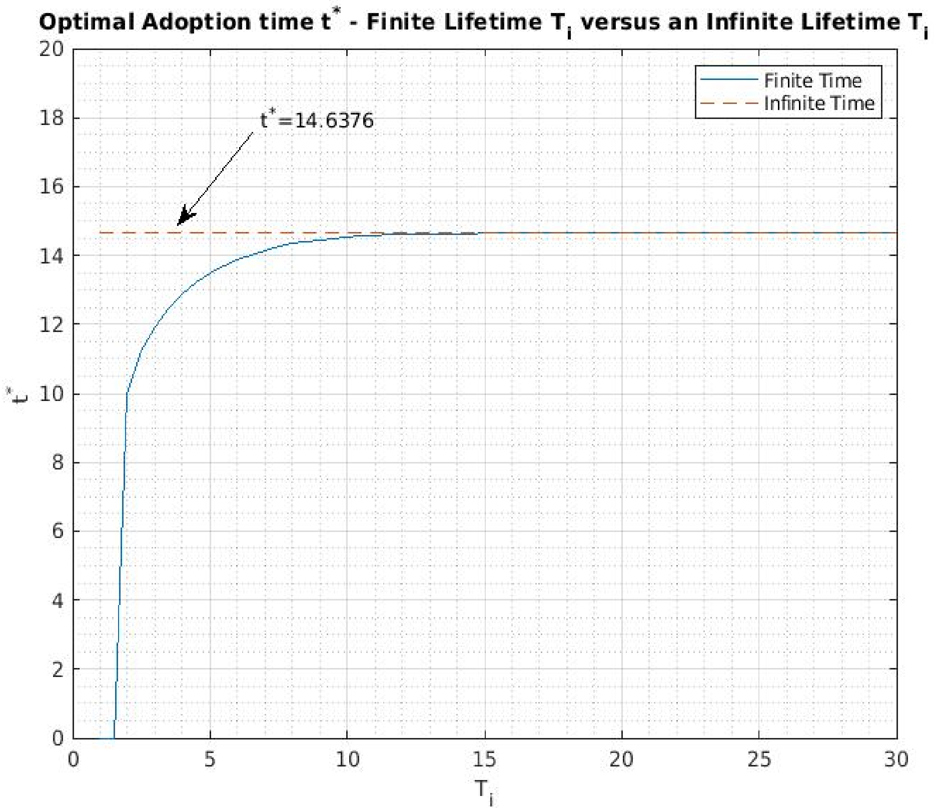


Figure 42 - Optimal adoption time t^* as function of T_i

The graph presented in Figure 42 displays the behaviour of equation (108) where T_i is the changing variable. The blue curve in Figure 42 represents the optimal adoption time of the follower whilst considering a specific lifetime Ti. The red dashed line shows us the result of the optimal adoption time t^* when T_i is assumed to go to infinity. When T_i is a finite integer and it is large, the blue curve is converging towards the same value as the red dashed. Therefore, a large positive T_i does not affect the adoption time of a follower. On the other hand, when T_i is less than 15, the optimal adoption decision of the follower is affected by a reduction in the value of t^*. In other words, the follower adopts the technology 2 earlier. The reason for this to happen is because the follower is better off adopting earlier where it would achieve the lower possible marginal cost of production $L_{i,2}$ faster by learning by itself to reduce its own marginal cost of production.

Overall, we discover that the lifetime of a firm can affect the optimal adoption time of the follower if and only if the firm has only a small lifetime. Otherwise, if the lifetime is sufficiently large the optimal adoption time of the follower is the same result when the lifetime is assumed to go to infinity.

Chapter 5

Conclusion

5.1 Summary of Research

On the 12th of December 2015, at the United Nations Framework Convention on Climate Change (UNFCCC) in Paris, a historical consensus known as the Paris Agreement was established. The agreed aim of the treaty is to try to keep the global temperature increase to well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the increase to 1.5 degrees Celsius (IEA, 2015b; UNFCCC, 2015). These are the temperature thresholds that should avert some of the most severe effects of climate change. One of the mitigation technologies that is recognized to contribute to the Paris Agreement's goal is the adoption of carbon capture and storage (CCS) technology. CCS technology is mitigation technology that targets major industrial or energy-related point sources, such as coal-fired power plants, where CO_2 emissions are captured, compressed, then transported to the sequestration site and permanently trapped deep in the targeted reservoirs (Wu et al., 2016).

According to the IEA, CCS has the potential of contributing up to 14% of cumulative CO_2 emission reductions through 2050 to reach a 2DS world compared to the business-as-usual scenario or 6DS[27] (IEA, 2017). This is equivalent to 94 gigatons (Gt) of carbon dioxide captured in the period to 2050, with around 55% of this (52 Gt) in the power sector and 42 Gt in industrial applications and fuel transformation (WCA, 2017). However, despite the environmental potential of CCS, the mitigation technology is lacking in deployments worldwide due to many obstacles – i.e., the extremely high costs, technological uncertainties, immaturity of markets and incentives, the absence of political propellant, and also the fact it is a complex value-chain needing collective action from relevant parties (Bowen, 2011; Davies et al.,

[27] Business-as-usual scenario where no mitigation strategies or efficiencies are adopted.

2013; Ye et al., 2019). Thus, a vast amount of CCS research has been devoted to solving the uncertainties of CCS which are analysed in four different aspects: cost analysis, project planning, investment, and operation. The latter research methods have been thoroughly focused on an engineering perspective where CCS technology has been investigated only on a cost accounting appraisal. The knowledge gap identified in the current literature is that there has been little detailed assessment in understanding the microeconomic interactions on CCS adoption. In other words, little is known about the impacts of strategic interaction of firms on CCS adoption decisions at a firm level.

Therefore, in this thesis, an industrial organization (IO) approach was implemented to investigate at a firm level when CCS technology is adopted. The reason for selecting an industrial organization point of view was because it allowed us to seek an increase in understanding of the methods by which industries operate and improve industries' contributions to economic welfare. Also, it allowed us to comprehend how industries adopting CCS technology affect each other in a market that has not been fully addressed in the literature. Thus, in this thesis, three different economic models under an industrial organization approach are presented modelling different carbon capture technology adoption. Finally, another purpose for choosing an industrial organization approach is that this research method allows us to identify policy interventions to increase the deployment of CCS technology. The research aim of this thesis was to understand:

"How do the strategic interactions of firms affect the incentives of CCS adoption decisions at a firm-level, and what policy solutions can be provided to the key stakeholders to increase CCS technology deployment to reach the global climatic targets?"

For each of the models presented in this thesis, the research objectives were:

- *To construct an economic model under an industrial organisation point of view of different CCS environments to assess the effects of the strategic interaction of firms in CCS adoption decisions.*
- *To inform governments and policymakers of the policy solutions to reach the global environmental target by increasing CCS adoption.*

5.2 Contribution to Knowledge

In this thesis, as all economic models presented considered a different CCS environment, each model offered different microeconomic insights or contributions to knowledge.

5.2.1 Chapter 2

In Chapter 2, what one learns are the effects that the strategic interaction of firms has on a firm when choosing to invest in CCS technology. Specifically, we find that a key difference between a monopoly and a duopoly when involved in a CCS adoption decision is that in a monopoly market there exists a singular and direct effect gained by the monopoly firm. The direct effect is the reduction of the monopoly firm's unit cost of production using CCS, if and only if there are stricter environmental regulations such as an increase in carbon dioxide tax. However, if a market is a duopoly, a second effect that is exclusive to a competitive market is called the strategic effect. The strategic effect is, if the adoption of CCS technology lowers a firm's marginal cost of production, thus making the firm more competitive in the market. Then, this adversely affects the output of the rival which then increases the CCS adopting firm's profit in question. The latter description is the strategic effect. Therefore, in a duopoly market if the conditions for the unit cost of using CCS are lower than the unit cost of not investing in CCS, a firm in a market with competition has a better advantage gaining two benefits, a direct and a strategic effect.

Also, another major contribution in this paper was comparing a monopoly market versus a duopoly market with the option of adopting CCS technology, for which then we were able to inform governments and policymakers of the type of market structure – with or without competition – that gives the best option for a firm to adopt CCS technology.

5.2.2 Chapter 3

Overall, what one learns in this chapter is an understanding of the microeconomic effects that occurs when a carbon capture with CO_2 utilisation is adopted by a firm. However, in this chapter, the main contribution to the current knowledge was suggesting a series of policy solutions that achieve both positive economic and environmental results when a firm invests in CCU technology. The policies suggested in this chapter are to inform governments and policymakers to increase the adoption of CCU adoption whilst also some policies oversee the environmental impact of adopting the mitigation strategy. The reason for this is because one of the main drawbacks of final goods produced by CO_2 utilisation; the CO_2 content is eventually released back again into the atmosphere once consumed by final consumers. Thus, in this chapter, we provide pivotal information on the economic and environmental outcomes when a CCU strategy is adopted so that governments do not obtain a worse environmental outcome.

5.2.3 Chapter 4

In Chapter 4, the optimal adoption decision of a follower adopting a second-generation CCS technology was evaluated whilst influenced by a learning-by-doing effect. The reason for analysing a scenario involving a pioneer and a follower is because of the lack of CCS deployment not only due to its extremely high cost and the lack of policy incentives. Also, another key factor identified is what we call the waiting factor. Another reason for the lack of CCS technology deployment can also be because firms are choosing to delay CCS investment knowing that if another firm adopts it first there are more potential savings by waiting for more advanced technology in the future.

The main variation of this chapter in the current literature is the approach of considering a different methodology in describing the learning cost curve for a firm. Inspired by Pan (2006)[28], an inverted S-shaped curve for the cost reduction of CCS technology was assumed achieved by using the properties of the survival function. Overall, in this chapter, a cost minimization problem was formed and solved which obtained us the optimal adoption time of the follower given that a pioneer has adopted previously a technology 1, where the follower minimizes its adoption cost for implementing technology 2.

Overall, with the current state of CCS technology, it is found that no firm wants to be a firm adopting first-generation CCS technology or a pioneer. Therefore, the major contribution of this chapter was a policy solution such that a firm that becomes a pioneer is not always at an economic disadvantage when it adopts a first-generation

[28] Technological change in energy systems: Learning curves, logistic curves, and input–output coefficients

CCS technology. The goal of the suggested policy solution was to balance the benefits between the pioneer and the follower, incentivising early adoption, and achieving an increase in the diffusion of CCS technology.

5.3 Limitations

In this section, we discuss some of the limitations of the thesis.

First, all of the economic models in this thesis need to be verified and validated so that there is confidence in the model results. To achieve this one can adopt four different main verification and validation of a model which are: (i) docking – model-to-model comparison, (ii) historical data validation – using historical data to build the model and the remaining data then used to determine if the model behaves as the system does, (iii) sensitivity analysis/ parameter variability – the change of input values and the internal parameters of a model to determine the effect upon the model and its output or (iv) prediction validation - comparing the model's prediction with actual system behaviour (Kennedy et al., 2005). Overall, using one of the methods listed should allow us to build stronger confidence in the model presented in this thesis.

Second, the model presented in this thesis has been only applied to CCS technology. However, the models presented in this thesis can have the possibility to be applied to other sectors such as oil and gas or renewable sector – i.e., wind and solar – which have a similar supply chain. With small adjustments to the economic models presented in this thesis, other sectors can also benefit from the key contributions highlighted in this thesis.

Third, a limitation in this study was considering only a carbon capture facility with full carbon capture capacity. However, another option of investment for a firm is the adoption of a partial carbon capture technology. A partial carbon capture technology is dependent on the level of investment by a firm for its carbon capture facility. For example, if an investment is low then a firm is going to have a capture facility that is designated to capture only a set proportion of the total emissions produced by the firm. Overall, a future work recommendation here would be to explore the strategic interaction of firms in such a scenario. Examples of research questions would be: *How* *does the level of investment in carbon capture technology affect the incentives for CCS technology? Is there any advantage of investing in a smaller carbon capture facility?*

Finally, a limitation for all chapters was only considering a carbon dioxide tax as the opposite strategy to the adoption of CCS technology. However, for each of the chapters, a further study can be considered involving a more stochastic result such as considering a cap-and-trade system such as the European trading system or EU-ETS. In a cap-and-trade mechanism, the government puts a firm limit, or cap, on the overall level of carbon pollution from industry and reduces that cap year after year to reach a set pollution target. As the cap decreases each year, it cuts industries' total greenhouse gas emissions to the limit set by regulation, and then forces polluters that exceed their emissions quota to buy unused quota from other companies. Thus, a future study could be understanding the difference provided in the strategic interaction of firms between carbon dioxide tax and cap-and-trade systems on CCS technology adoption.

5.4 Future Research

In this section, a discussion of possible future research investigations is discussed.

In Chapter 2, an interesting extension to the study is the assessment of the effects of competition on CCS adoption decisions where the industries are not related. For example, a future research idea is to explore the strategic interaction of firms where a CCS adoption decision happens even though firms are producing heterogeneous products. This type of firm interaction is possible, and it is known in the CCS literature as CCS cluster networks or CCS clustering. According to the Global CCS Institute, CCS clustering is firms that can share CCS infrastructure and knowledge and achieve an advantage in a reduction in costs compared with each facility attempting to individually reduce their carbon emissions (GCCSI, 2016). If this study were pursued, the potentially relevant literature for the study could be research in the field of cooperative game theory, as multiple parties participate in a CCS clustering process. Thus, a research question for future research is: "*Which industry/firm is going to pay and at what proportion for the adoption of a shared carbon capture and storage facility?*"

Moreover, an additional further study in Chapter 2 is that in this chapter the business model of a firm adopting a CCS technology considered is a “self-build and operate”. The self-build model is one in which CCS operations are owned and operated by the utility with an internal staff of engineers, geologists, and on-site field technicians and operators. However, the other two possible business models for CCS adoption technology, as addressed by Esposito et al. (2011) are through a joint venture model or a pay-at-the-gate model. A joint-venture model is a partnership where the host site utility/owner’s engineer and external operators and consultants jointly execute CCS. A pay-at-the-gate model is externally contracting to a third-party owner/operator with a positive fee for sequestration and cash positive pricing such as CO_2-EOR. The latter two business models are interesting models for future works – i.e., *which business models create the best scenario for CCS adoption? Also, how is risk shared among the players and who is liable for what?*

In Chapter 3, a strong assumption in the model was the upstream market was assumed to be a perfectly competitive market with identical firms. Future work could, therefore, progress in considering a more realistic framework for the upstream sector. Furthermore, the downstream sector was assumed to be a market with no bargaining power, where the price of CO_2 inputs to produce their final product was given. This assumption is not very satisfactory because it is difficult to justify that an economic agent behaves strategically in one market but not in another. A full treatment would require downstream firms to behave strategically simultaneously in the downstream and upstream markets. Hence, a future work idea is to explore contract agreements between the two industries for the exchange of CO_2 inputs.

In Chapter 4 we assumed the fixed cost of CCS technology for the first-generation and second-generation are the same. However, this assumption can be relaxed to understand to effects of having varied fixed costs of technology in the adoption time of CCS technology. Especially, when there is evidence that the fixed cost of CCS technology is in a decline due to a learning-by-doing effect. The reason for assuming the fixed cost of technology 1 and technology 2 to be the same was because the fixed cost of CCS can either go up or down, as it depends on the industry that discovers the new CCS technology where they might sell the technology at a premium (higher) cost for future adopters. Thus, future works should explore different fixed costs for the separate generations of CCS technology.

Another strong assumption in Chapter 4 was that the marginal cost of production of technology 2 is the same as the marginal cost of production of technology 1 at the adoption time. In other words, in the model, the adoption of technology 2 by the follower purchased the CCS technology where the “eco-industry” selling CCS technology is a perfectly competitive market. This is because the market price of CCS technology is equal to the marginal cost of production at the time of adoption. However, with CCS technology not fully commercial a better understanding of CCS providers should be understood. Overall, the two strong assumptions mentioned bring in the concept of the eco-industry which provides an interesting topic for future research. For example, some future research questions are: *what are the effects of an eco-industry in the adoption time of CCS technology? Do they have any bargaining power or not, and if so, what are the impacts on CCS adoption decisions?* Finally, Chapter 4 only investigated the decision making of the follower. Therefore, future work for Chapter 4 would be to explore a more dynamic game between two firms analysing endogenous roles influenced by learning-by-doing and technological spillover effects.

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