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Public acceptance and the dynamic evolution of adopting carbon capture and storage¹

Kine Josefine Aurland-Bredesen², Tor Håkon Jackson Inderberg³ and Snorre Kverndokk⁴

Abstract

Public acceptance has influenced the evolution of carbon capture and storage (CCS) in Europe. To study the mechanisms behind this, we use evolutionary game theory where the governmental policy towards CCS, such as subsidies to the industry, is dependent on public acceptance. Public acceptance further depends on the perceived benefits and costs for individuals of CCS. We show that in this model, multiple equilibria may exist, and the starting point as well as the heterogeneity of firms will determine the equilibrium that will be reached over time. While the subsidy is tied to public acceptance, the government can affect development by correcting other imperfections in the market. Using such policy instruments, a new equilibrium may develop with a higher share of investments in CCS. The model also suggests an explanation of the different situations in many countries today with respect to CCS investments and investment plans.

Key words: Carbon capture and storage, evolutionary games, public acceptance, climate change.

JEL classification: C73, H23, Q35, Q38, Q54

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1. Introduction

Carbon capture and storage (CCS) can help mitigate emissions from hard-to-abate sectors, support production of blue hydrogen (hydrogen made from natural gas) and enable negative emissions through technologies like direct air capture (DACCS) and bioenergy with carbon capture (BECCS). CCS is expected to play a prominent role in reaching global and European climate targets (European Commission, 2024a; IPCC, 2023). However, there is a significant gap between the required scale and current efforts (Cavanagh & Lockwood, 2025)

While CCS can offer significant climate benefits, its deployment faces multiple barriers, including high cost, underdeveloped infrastructure, weak climate policy and a lack of public acceptance. Previous research has focused on e.g., the economic barriers to adoption (Durmaz, 2018), the coordination problem between the actors in the CCS value chain (Golombek et al., 2023), but also on public resistance to storage and fear of leakages (van der Zwaan & Gerlagh, 2016; Meissner et al, 2025)

Public acceptance, i.e., the degree of support in the general population (see, e.g., Wolsink (2018)), plays a key role in CCS adoption. One important determinant of public acceptance is social norms, which are shared standards of acceptable behavior. Studies show that these norms can have important impacts not only on social relations, but also on economic outcomes (see, e.g. Andvig and Moene (1990); Nyborg and Rege (2003)). Further, public reactions towards a technology can put a lot of pressure on governments and industry, slowing down or even stopping projects. In Europe for instance, multiple CCS projects have been cancelled citing lack of public acceptance as a key cause (Akerboom et al., 2021; Dütschke et al., 2015; Vögele et al., 2018).

Our study focuses on the role of public acceptance for CCS adoption. We do this by addressing two central questions. First, how public acceptance impacts the evolution of CCS adoption, and second, how various policy interventions shape this relationship.

Public acceptance for policies to mitigate climate change have been studied before. While there have been numerous studies of acceptance linked to renewable energy projects and policies, this research has developed different notions of acceptance, where ‘socio-political acceptance’ is most closely linked to our focus here on public acceptance (see e.g. Batel et al. 2013; Devine-Wright et al. 2017; Wolsink, 2018; Wüstenhagen et al., 2007). Within

economic and statistical methods, the field of acceptance is more limited, with some exceptions. Some important work has been done in particular for carbon taxes, see e.g., Carattini et al. (2017), Maestre-Andrés et al. (2019) Douenne and Fabre (2022) and Mildenerger et al. (2022), and wind turbines (Linnerud et al. 2022). There are some studies of acceptance of CCS (Zuch 2023; Pieri et al. 2023; Von Rothkirch & Ejderyan 2021; Federico d'Amore et al. 2020; Arning et al. 2019; Vögele 2018; Hansen et al. 2025; Fridal & Lehtveer, 2018; Lefstad et al. 2024). However, to the best of our knowledge, this is the first study to specifically use economic modelling to explore the impact of public acceptance on CCS adoption.

Using evolutionary game theory, we develop a dynamic model with two agents; individuals who decide whether to accept CCS based on their perceived benefit and cost of the technology, and firms, which decide whether to invest in CCS or not based on profitability.⁵ The individuals perceived benefits and costs of CCS are influenced by both average public acceptance and the share of firms that invest in CCS. We further assume that the government's willingness to use policy instruments to support CCS projects depends on public acceptance. Thus, political acceptance to support CCS projects is in the model dependent on public acceptance. For firms, profitability does not only depend on policy instruments and therefore, public acceptance, but also on potential cost reductions from for example, learning-by-doing, which in turn are shaped by the average share of firms investing. Thus, one contribution of our paper is to study the evolution of both social acceptance and investments in CCS simultaneously.

Meeting the EU's climate targets of reducing greenhouse gas emissions by at least 90% in 2040 and climate neutrality by 2050, requires a significant scale up of CCS. The EU Commission's assessment corresponding to the 2040 climate target, indicates that approximately 280 Mt CO₂ would need to be captured by 2040 and around 450 Mt CO₂ by 2050 (European Commission, 2024c). The importance of CCS in meeting EU climate targets is also supported by other decarbonization scenarios which consistently identify CCS as a crucial mitigation option especially for the electricity and industrial sectors (Dalla Longa et al., 2020; Hainsch et al., 2022; Herzog, 2011). To scale up capture, transport, storage and use of CO₂ in EU,

⁵ Another paper using evolutionary game theory to study CCS adoption is Zhao and Liu (2019). They model a game model between the government and power plants with a focus on China.

alongside launching the 2040 climate target, the European Commission also published its industrial carbon management strategy (European Commission, 2024b).

The scalability of CCS is also generally seen to require a ‘social license to operate’, which depends on sociopolitical factors that include public perceptions (Cox et al., 2020). Public acceptance plays an important role in the successful deployment of CCS, because it directly and indirectly influences firms’ decision to invest in CCS. First, public acceptance impacts the political feasibility of CCS policy (Karimi et al., 2016). Politicians want to attract voters, and policies without public support may be hard to implement (Eikeland et al., 2023; Inderberg et al., 2024). Thus, if technologies such as CCS gain public acceptance, the political feasibility of policy instruments to support the introduction of the technology may increase. Second, public acceptance may affect market demand. High public acceptance of CCS can boost market demand for products or services associated with CCS, such as low-carbon goods, encouraging firms to invest. On the other hand, low public acceptance can reduce this demand, discouraging firms from investing in CCS.

One main finding from our analytical analysis is that multiple equilibria may occur. What equilibrium the system ends in depends on the starting point, i.e., the initial public acceptance and the CCS investments and plans of firms, but also on the heterogeneity of firms with respect to costs. However, the government can implement policies that may change the equilibrium outcome, for instance by moving from an equilibrium with no or small investments in CCS to an equilibrium with more investments. The model also suggests an explanation of the different situation in several European countries as some countries have low public acceptance of CCS and low investments or investments plans, while in other countries, the situation is the opposite.

The paper is organized in the following way. In section 2 we give an overview of the literature on CCS and public acceptance in the EU and Norway. Then in section 3-5 we present the basic model and the solutions to the model. Public policies in the presence of imperfections are studied in section 6. Further, extensions of the model such as non-linearity, heterogenous firms and heterogenous individuals are given in section 7. We illustrate our results through a numerical example of the model based on EU data in section 8. while section 9 concludes.

2. CCS and public acceptance in the EU

CCS technologies first started to gain momentum in the early 2000s, primarily focusing on the capture of CO₂ from coal and gas power plants. Despite the initial momentum, large-scale deployment has been very limited. Across Europe, multiple CCS projects have been planned and subsequently cancelled, with public opposition often cited as one of the leading causes. While high cost, lack of political support and legal constraint also are important reasons, the latter two challenges also often stem from lack of public acceptance (Vögele et al., 2018). Notable examples of cancelled projects include the Barendrecht CCS project in the Netherlands, the Northern Netherlands CCS initiative, the ROAD project in the Netherlands and the Beeskow storage project in Germany (Akerboom et al., 2021; Brunsting et al., 2011; Dütschke et al., 2015; Kuijper, 2011; van Os et al., 2014). As of 2024, in Europe, only two large-scale CCS projects are operational, both of which are located in Norway. Namely, Sleipner launched in 1996, and Snøhvit launched in 2008, both of which store CO₂ from natural gas production (Global CCS Institute, 2024). In August 2025, a third project in Norway started to catch and store CO₂ offshore, namely a cement factory which is part of the Norwegian Government's Longship Program (see below).

After a period of stagnation, interest in CCS began to increase again around 2019–2020, with planned projects increasingly targeting industrial emissions in key countries such as Norway, the Netherlands, and the UK (Wettestad et al., 2024). In 2020, Norway launched the Longship project, a full-scale initiative demonstrating CO₂ capture from industrial sources, alongside transport and CO₂ storage (Ministry of Petroleum and Energy, 2020). Several other significant projects are now under construction in Europe, including two large-scale CCS projects in Denmark, one in Norway, and three in the Netherlands. The Netherlands have also started construction on the Porthos project for CO₂ transport and storage (Global CCS Institute, 2024). It has also been a notable political shift in other countries, such as the reconsideration of initial restrictions on CCS in Austria and Germany (Global CCS Institute, 2024). In sum, projections have even pointed to a situation with insufficient storage capacity, although this remains to be seen (Cavanaugh and Lockwood, 2025).

While public knowledge of CCS largely remains limited, it appears to be significant differences between countries. A recent survey found that 45–48% of respondents in the UK, Netherlands, and Germany had not heard of CCS, compared to 33% in Norway (Anders et al., 2024). Another study showed that 46–53% of respondents in Netherlands, Denmark, UK

and Germany did not know that CO₂ can be captured and stored, while the share was 25% in Norway (Merk et al., 2023).

There is gradually more research being done on the role of public acceptance as a barrier to deployment and what impacts public acceptance of CCS. Studies indicate that public acceptance depends on the perceived costs and benefits of the technology, awareness and knowledge of the technology, in addition to factors such as geography, culture, and trust.

Individuals have diverse opinions toward implementing novel technologies and associated infrastructure (Wettestad et al., 2024). At an individual level, the economic benefits of CCS can come from the potential to create local and national values, such as job protection and employment opportunities. The environmental benefits is due to the contribution of CCS to mitigate climate change, and information about climate change is shown to be a key driver for acceptance of CCS (Zuch & Ladenburg, 2023). Survey evidence shows that climate change beliefs are strongly linked to support for CCS (Anders et al., 2024), and that willingness to pay for CCS is higher among members of environmental organizations and among individuals who identify with or hold strong environmental values (Waring & Longo, 2025). Moreover, individuals who are more positive towards CCS, emphasize rapid emissions cuts, jobs, technology exports and green transition in the oil sector (Nordø et al., 2023).

If public awareness and knowledge of CCS are low, attitudes are left vulnerable to misinformation and preference instability (Cox et al., 2020; Demski et al., 2013; Whitmarsh et al., 2019). However, increased knowledge about the benefits of CCS can improve public acceptance (Cox et al., 2020). Survey evidence shows that support for CCS is higher among those with greater knowledge (Anders et al., 2024; Merk. et al., 2023) and willingness to pay for CCS is also higher among individuals familiar with the technology (Waring & Longo, 2025). As CCS continues to develop and gain visibility, further realization of CCS may increase general support rather than reduce it (Nordø et al., 2023), i.e., support for CCS increases with familiarity as the technology diffuses.

Attitudes toward CCS are also influenced by individuals' perceptions about the technology's role in addressing climate change. Some individuals may be ideologically resistant towards CCS because they view it as a 'techno-fix' rather than a true system transition (Nordø et al., 2023; Whitmarsh et al., 2019). For example, having concerns that CCS may be used to prolong the fossil energy era (Cox et al., 2020; Karimi et al., 2016; Merk et al., 2022; Nordø

et al., 2023). Nordø et al. (2023) find that respondents who are skeptical towards CCS, among other things, emphasize that technology could become a sleeping pillow that prevents necessary social change.

Additionally, public acceptance depends on the cost and risk of CO₂-leakage, which is often considered a safety issue (Arning et al., 2019; Cox et al., 2020; Pieri et al., 2023). The risk may be at the local level, including negative health impacts for the people living near CO₂-storage and transport infrastructure (Permentier et al., 2017), and at the global level, that is the risk it poses to climate mitigation efforts (Inderberg & Wettestad, 2015). While we are primarily interested in general public acceptance, Nordø et al. (2023) highlights that respondents who are skeptical towards CCS, emphasize the danger of leaks from storage. Studies also report a difference between the general support of CCS versus its local manifestation, and key to this difference is the perceived risk of leakage (Arning et al., 2019; Cox et al., 2020; Merk et al., 2022; Pieri et al., 2023). The perceived cost of leakage depends on location of the storage site, for example a recent study of acceptance in Norway and Germany finds larger accept for the storage of CO₂ offshore than onshore (Merk et al., 2022). The actual cost of leakage also depends on the storage site. Offshore storage is different than onshore storage as the ocean can buffer and disperse CO₂, and there are no human settlements close by or above. With regards to storage of CO₂, the public may also be concerned with the potential for increased seismic activity (Selma et al., 2014). There are mixed results regarding the impact of risk information on public attitudes toward CCS across the reviewed studies. Informing about existing CCS projects, tends to stimulate public acceptance while providing details on monitoring and safety procedures seems to reduce CCS acceptance (Zuch & Ladenburg, 2023). Importantly, however, previous studies indicate that more knowledge about CCS increases acceptance and decreases individuals' assumptions about CCS being inefficient and risky (Arning et al., 2019; Tokushige et al., 2007). Trust in developers and stakeholders is a critical factor influencing public response to CCS development, both at a community level and as a whole (Boomsma et al., 2020; Cox et al., 2020).

3. The model

Public acceptance

Assume that the population is homogeneous. We relax this assumption in Section 7. Based on the studies cited above, public acceptance of CCS depends on the perceived benefits and

costs of the technology. An individual i decides whether to accept the technology based on the following payoff function,

$$U(y_i, x, y) = [(1 + y)\tau^*a - (1 - \delta x)((\tau^* + b)p + s)]y_i. \quad (1)$$

$U(y_i, x, y)$ is the individuals' payoff from accepting CCS. If $y_i = 1$, the individual accepts CCS, while if $y_i = 0$, the individual does not accept CCS. The individual will accept CCS if the term $(1 + y)\tau^*a - (1 - \delta x)((\tau^* + b)p + s)$ is positive and oppose CCS if the term is negative. The individual is indifferent to CCS if the term equals zero.

The perceived benefits of CCS, $((1 + y)\tau^*a)$, are a function of the average level of public acceptance (y) in the population, the social cost of carbon (τ^*) and a belief parameter (a). Greater acceptance of CCS in the population increases the likelihood that others will follow, creating a positive feedback loop. This reflects a bandwagon effect where individuals decisions are affected by the perceived popularity of CCS. As average public acceptance in the population increases, social norms shift, and the perceived benefits of accepting CCS also increase. The perceived social benefits also increase with τ^* , which reflects the objective benefit of CCS. It can be interpreted as the social cost of carbon, and thus a higher damage of climate change highlights the importance of capturing and storing CO₂. Alternatively, τ^* can be interpreted as the marginal abatement cost of a given climate target, and thus the more stringent the target is the higher τ^* will be. The parameter a can capture individuals' attitude towards both climate change and CCS technology. It reflects how concerned individuals are with climate change as a serious threat, as well as their general attitude towards technology by either scaling up or down the objective benefits of CCS represented by τ^*

The perceived costs of CCS $((1 - \delta x)((\tau^* + b)p + s))$ depend on the cost of leakage and the perceived risk of leakage, i.e., the combined perceived expected cost of leakage is $(\tau^* + b)p$. The parameter $p \in (0,1)$ is the perceived likelihood of leakage, and b reflects that the cost of leakage may be larger than the social cost of carbon due to local environmental and health costs. The perceived risk and cost of leakage can vary based on differences in individual risk preferences and geographical factors. In addition, individuals also recognize that a possible governmental subsidy for CCS has an opportunity cost for them since public funds allocated to subsidies could have been spent alternatively on, e.g., health care and education. The actual subsidy, s_y , given to firms depend on public acceptance, but individuals use a level s as a reference point, see below.

The perceived costs of CCS may change with the share of firms that invest or plan to invest in CCS (x). The parameter δ captures how individuals update their beliefs about the perceived cost of CCS depending on this share. A small δ implies, for instance, that individuals are less inclined to update their beliefs. If $\delta > 0$ then perceived costs reduce as more firms invest in CCS, for example because the population gains a better understanding of the actual risks of leakage. The opportunity cost is also decreasing when x increases. In line with findings from earlier studies described above, we interpret this as when individuals have little knowledge about CCS as few firms have invested, they may consider CCS to be expensive and inefficient. But when more firms invest, they change their attitude to CCS. If $\delta < 0$, perceived costs increase as more firms invest in CCS, which can reflect that individuals fear that larger volumes of CO₂ stored raises the likelihood of a severe leakage, increases in seismic activity as more and more CO₂ is stored, or that increases in investments in CCS place a heavier burden on public funds due to subsidies. Below, we assume that $\delta > 0$, but we also illustrate the case for $\delta < 0$.

Public acceptance determines the government's policy towards CCS, i.e., whether to introduce investment subsidies and the size of the subsidy. The governmental subsidy for CCS is a linearly increasing function of the average public acceptance in the population, i.e., sy , where s is the maximum subsidy the government is willing to offer, and the reference point for individuals when evaluating perceived cost of CCS.⁶

Investment decision

Assume that all firms are homogenous. In Section 7 below, we relax this assumption. Each firm must decide whether to invest in CCS or pay a carbon tax τ . The carbon tax can be larger, smaller or equal to τ^* . The cost of investing in CCS is c per ton of CO₂. If a firm chooses to invest in CCS, it may also receive a governmental subsidy as described earlier. As this subsidy depends on public acceptance, the subsidy it receives is sy , where y is the average acceptance in society. The cost of investing in CCS decreases as more firms adopt technology for two reasons. First, the cost per ton of CO₂ can fall as the CCS infrastructure expands, because of reduced transport costs due to shorter distances between storage sites, i.e., the indirect network effect (Golombek et al., 2023), and possible economies of scale in

⁶ An alternative interpretation of this mechanism is that public acceptance has a direct impact on the profitability of firms investing in CCS. For example, companies that invest in CCS can boost their reputation as environmentally responsible, which in turn may increase consumers' willingness to pay or increase demand, see the introduction above.

storage of CO₂, (Golombek et al., 2025). Second, there are also possible cost-reductions due to learning-by-doing. If a share x of the firms invests in CCS, the cost c is reduced by lx where l represent both the cost reducing effect of infrastructure expansion and learning.⁷ Finally, each firm emits e tons of CO₂ each year.

The pay-off for the firm's investment decisions is

$$\pi_j(x_j, x, y) = e(\tau - c + sy + lx)x_j \quad (2)$$

If $x_j = 1$, firm j invests in CSS, however, if $x_j = 0$ the firm does not invest in CCS. The firm invests if the term in the brackets on the right-hand side of the equation is positive and does not invest if it is negative. The firm is indifferent in investing in CCS if the term equals zero.

4. Nash equilibria

The model outlined above is a game between individuals and firms. Both agents benefit from a large degree of public acceptance (y) and in most cases, i.e., when $\delta > 0$, a large portion of firms investing in CCS technology (x). Thus, there are no conflicting interests,⁸ and the game thus constitutes a coordination game, where not all outcomes are equally good for the players. Note also that in this game, the government is a passive player, setting the subsidy based on the outcome of public acceptance. Below we generally assume $\delta > 0$, consistent with empirical evidence showing that familiarity with CCS and exposure to projects increase acceptance (Waring & Longo, 2025; Anders et al., 2024). For completeness, we also illustrate a scenario where $\delta < 0$, see Figure 3.

As shown in Appendix A.1, this game has a total of nine possible Nash equilibria due to different combinations of public acceptance and investment decisions. The Nash equilibria are outlined in Table 1 and illustrated in Figure 1.

⁷ We do not consider a falling learning rate over time in the basic model, but we do this in the extension of the model, see Chapter 7.

⁸ The exception is the subsidy rate, which is negative for the individuals, but this is set exogenously.

Table 1: Nash equilibria in the basic model

Firms' investments \ Public acceptance	No acceptance ($y = 0$)	Partial acceptance ($0 < y < 1$)	Full acceptance ($y = 1$)
No investments ($x = 0$)	$\omega < 1$ $\tau < c$	$y = \frac{1-\omega}{\omega}$ $\tau > c - sy$	$2\omega > 1$ $\tau < c - s$
Partial investments ($0 < x < 1$)	$\omega < (1 - \delta\bar{x})$ $x = \frac{c-\tau}{l}$	$y = \frac{l(1-\omega)+\delta(\tau-c)}{\omega l - \delta s}$ $x = \frac{\omega(c+s-\tau) - s}{\omega l - \delta s}$	$2\omega > (1 - \delta x)$ $x = \frac{c-\tau-s}{l}$
Full investments ($x = 1$)	$\omega < (1 - \delta)$ $\tau > c - l$	$y = \frac{1-\omega-\delta}{\omega}$ $\tau > c - sy - l$	$2\omega > (1 - \delta)$ $\tau > c - s - l$

where $\omega = \frac{\tau^* a}{(\tau^* + b)p + s}$ is the perceived benefit-cost ratio when both x and y are zero.

Proposition 1: Assume that $\frac{1}{2} < \omega < 1 - \delta$ and $s < c - \tau < l$. Under these conditions, the game has nine possible Nash equilibria. Four of these are "corner equilibria," where there is either full or no public acceptance combined with either full or no investments in CCS. The remaining five equilibria involve partial outcomes, where either a portion of the population accepts CCS, or a share of firms invest in the technology, or both occur.

Proof: See Table 1 and Appendix A.2.

The model yields nine possible Nash equilibria, arising from different combinations of public acceptance (x) and firm investment (y). In the no-acceptance/no-investment equilibrium, the perceived benefits for the population of CCS are too low relative to its cost, and the carbon price is insufficient to make investments profitable for the firms. On the other hand, in the equilibrium with full investments and acceptance, the perceived benefit-cost ratio is higher, and the carbon tax exceeds the costs of investing in CCS for the firms after accounting for the full subsidy and learning/infrastructure benefits.

The third corner equilibrium, full acceptance without investment ($x = 0, y = 1$), arises when the perceived benefits of CCS are substantially higher than its costs, but investment remains unprofitable due to insufficient government support. This requires the maximum governmental subsidy to be below a threshold $s < c - \tau$. In this scenario there is strong public support for CCS, but the technology is very costly, and the government is either unwilling or unable to provide sufficient incentives for adoption.

The fourth corner case, full investments in the absence of public acceptance ($x = 1, y = 0$), is theoretically possible when the positive learning and the indirect network effect is large enough to close the gap between the carbon tax and the cost of CCS.

In addition to these four corner equilibria, five internal equilibria are possible where partial public acceptance and/or partial investments occur. These equilibria arise when either individuals are indifferent towards CCS or firms are indifferent towards investing in CCS technology. Individuals are indifferent when

$$(1 + y)\tau^*a - (1 - \delta x)((\tau^* + b)p + s) = 0 \quad (3)$$

and firms are indifferent towards investing in CCS when

$$\tau - c + sy + lx = 0 \quad (4)$$

Solving equations (3) and (4) jointly yields an interior equilibrium where both partial public acceptance and partial investment occur, see Table 1. The equilibrium shares are given by

$$y = \frac{l(1 - \omega) + \delta(\tau - c)}{\omega l - \delta s} \quad (5)$$

$$x = \frac{\omega(c + s - \tau) - s}{\omega l - \delta s} \quad (6)$$

To sum up, the coordination game between individuals and firms may end up in many possible equilibria, where not all are equally good for the agents. The equilibria depend on several factors which are given initially, such as the parameters in both the payoff function and the profit function.

5. Evolutionary dynamics

To describe the evolution of the game, we use replicator dynamics, which is the standard way of describing dynamics in evolutionary game theory (Cressman & Tao, 2014). The evolution of average public acceptance is

$$\dot{y}(x, y) = y(U(1; x, y) - \bar{U}(x, y)), \quad (7)$$

where $U(1; x, y)$ is the payoff of an individual that accepts CCS, and $\bar{U}(x, y)$ is the average utility of all individuals. This implies that, $\dot{y}(x, y) > 0$ if $U(1; x, y) > \bar{U}(x, y)$. In other words, if the utility of the individual who accepts CCS is larger than the average utility of all individuals, then average public acceptance will increase. This is the replicator effect. Since, $\bar{U}(x, y) = yU(1; x, y) + (1 - y)U(0; x, y)$ the replicator dynamics can be written as

$$\dot{y}(x, y) = y(1 - y)[U(1; x, y) - U(0; x, y)]. \quad (8)$$

Combining equations (1) and (8), we derive

$$\dot{y}(x, y) = y(1 - y)[(1 + y)\tau^*a - ((1 - \delta x)(\tau^* + b)p + s)]. \quad (9)$$

Individuals learn by imitating the strategies that perform better than the average payoff, and when all individuals are identical it is the indifferent marginal individual that drives this dynamic.

Firms' investments in CCS follow similar dynamics,

$$\dot{x}(x, y) = x(\pi(1; x, y) - \bar{\pi}(x, y)). \quad (10)$$

Thus, $\dot{x}(x, y) > 0$ if $\pi(1; x, y) > \bar{\pi}(x, y)$. If the profit of the firm that invests in CCS is larger than the average profit in the industry, then there will be an increase in the share of firms that invest. Thus, the industry moves towards greater adoption of CCS if firms investing in CCS outperform the average. This reflects a learning process under uncertainty where firms are unsure about the profitability of investing in CCS and will consider investments based on observed profits. Equation (2) and (10) imply that

$$\dot{x}(x, y) = x(1 - x)e(\tau - c + sy + lx) \quad (11)$$

When all firms are identical, it is the indifferent marginal firm that drives this dynamic. Thus, if a firm at the margin starts investing in CCS, it signals that profitability has improved enough to make CCS profitable, prompting others to follow.

Note that equation (3) defines the boundary separating $\dot{y} > 0$ from $\dot{y} < 0$, because for $y \in (0, 1)$, $\dot{y} > 0$ if $(1 + y)\tau^*a - ((1 - \delta x)(\tau^* + b)p + s) > 0$ and decreases if this term is negative. Similarly, equation (4) defines a boundary separating $\dot{x} > 0$ from $\dot{x} < 0$ because for $x \in (0, 1)$, $\dot{x} > 0$ if $\tau - c + sy + lx > 0$ and vice versa. Equations (3) and (4) can be rewritten as threshold functions of x ,

$$y^{Eq.3} = \frac{1 - \delta x - \omega}{\omega} \quad (12)$$

$$y^{Eq.4} = \frac{c - \tau - lx}{s} \quad (13)$$

By combining these functions we can classify the dynamics for different combinations of x and y . It follows from equation (11) that $\dot{x}(x, y) > 0$ whenever $\tau - c + sy + lx > 0$, which is equivalent to $y > \frac{c - \tau - lx}{s} = y^{Eq.4}$. Hence, the share of firms investing increases

when $y > y^{Eq.4}$ and decreases if $y < y^{Eq.4}$. From equation (12) it likewise follows that $\dot{y}(x, y) > 0$ for $y > y^{Eq.3}$ and $\dot{y}(x, y) < 0$ for $y < y^{Eq.3}$.

Based on this, the dynamics of the system can fully be characterized by whether average public acceptance y lies above, below or between the two thresholds. For example if $y > y^{Eq.3}$ and $y > y^{Eq.4}$, in other words $y > \max\{y^{Eq.3}, y^{Eq.4}\}$ then $\dot{x}(x, y) > 0$ and $\dot{y}(x, y) > 0$.

The full set of criteria are summarized in Table 2.

Table 2: Criteria for the evolutions of y and x

	$\dot{x}(x, y) > 0$	$\dot{x}(x, y) < 0$
$\dot{y}(x, y) > 0$	$y > \max\{y^{Eq.3}, y^{Eq.4}\}$	$y^{Eq.4} > y > y^{Eq.3}$
$\dot{y}(x, y) < 0$	$y^{Eq.3} > y > y^{Eq.4}$	$y < \min\{y^{Eq.3}, y^{Eq.4}\}$.

The criteria outlined in Table 2 hold for all combinations of equilibria and is independent of the existing number of equilibria. Below we will study some subsets where not all equilibria exist.

Figure 1 illustrates the dynamics when all the nine equilibria exist. In contrast, Figure 2 illustrates a case where two of the corner equilibria do not exist and the middle equilibrium is semi-stable. By semi-stable we mean that the equilibrium is stable for small deviations in some directions, but unstable for deviations in other directions. Thus, whether the system returns to the equilibrium or moves away, depends on the direction of the change. The equilibria are marked with a dot in the figures. The figures also show the evolution of y and x , and the stability of the equilibria.

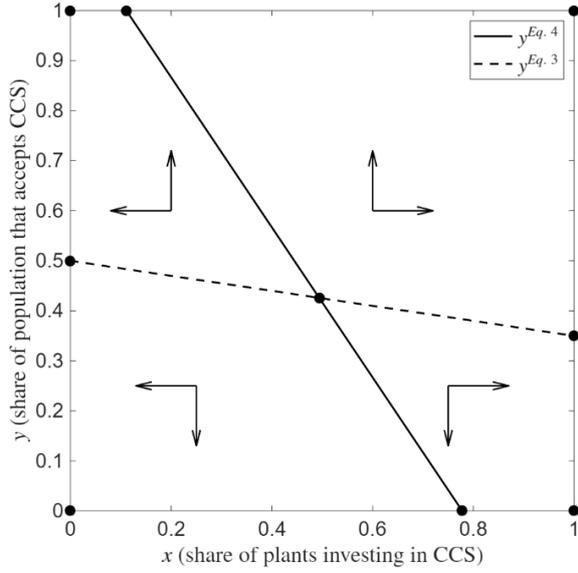


Figure 1: Evolutionary dynamics when all nine Nash equilibria exist, and the middle equilibrium is unstable.

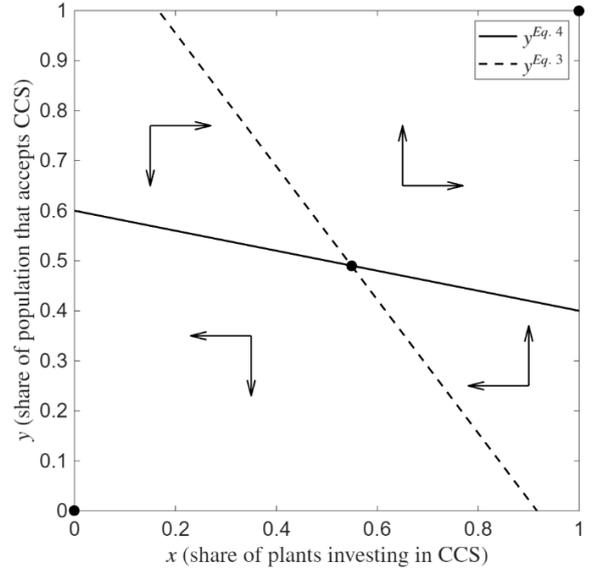


Figure 2: Evolutionary dynamics when only three Nash equilibria exist, and the middle equilibrium is semi stable.

Proposition 2: If $c - \frac{1-\omega}{\omega}s > \tau > c - l - \frac{1-\delta-\omega}{\omega}s$, the middle-equilibrium will be unstable, and all corner equilibria (if they exist) will be stable. If $c - l - \frac{1-\delta-\omega}{\omega}s > \tau > c - \frac{1-\omega}{\omega}s$, the middle-equilibrium will be semi-stable, and only the corner equilibria of no investments and no acceptance, full investments and full acceptance are stable. If neither condition holds, the middle equilibrium does not exist.

Proof: This follows from the criteria in Table 2 and from the fact that $y^{Eq.3}$ and $y^{Eq.4}$ are linear functions of x . If $y^{Eq.4} > y > y^{Eq.3}$, then $\dot{x}(x, y) < 0$ and $\dot{y}(x, y) > 0$. Thus if $y^{Eq.4} > y^{Eq.3}$ when $x = 0$, the middle-equilibrium will be unstable, and the corner equilibria of full-acceptance/no-investment equilibrium will be stable if it exists. We identify the criteria by solving $y^{Eq.4}(0) > y^{Eq.3}(0)$ for τ , which yields $c - \frac{1-\omega}{\omega}s > \tau$. Similarly, if $y^{Eq.4} < y^{Eq.3}$ when $x = 1$, then corner equilibria of no-acceptance/ full-investment equilibrium will be stable if it exists. Solving $y^{Eq.4}(1) < y^{Eq.3}(1)$ for τ yields $\tau > c - l - \frac{1-\delta-\omega}{\omega}s$. Combining the two inequalities yields the inequality in Proposition 2. QED

Proposition 2 outlines the sufficient criteria for identifying if the middle-equilibria is unstable or semi-stable. From the inequality $c - \frac{1-\omega}{\omega}s > \tau > c - l - \frac{1-\delta-\omega}{\omega}s$ we can deduce that it is necessary that $c - \frac{1-\omega}{\omega}s > c - l - \frac{1-\delta-\omega}{\omega}s$ which can be simplified to $\frac{l}{s} > \frac{\delta}{\omega}$. Thus, a

necessary but not sufficient criteria for middle-equilibrium to be unstable is $\frac{l}{s} > \frac{\delta}{\omega}$. Thus, the smaller the maximum subsidy is relative to the spillover benefit from learning and infrastructure expansion, the more likely it is that the middle-equilibrium is unstable. On the other side, the smaller the perceived benefit-cost ratio of CCS is, the more likely it is that the middle-equilibrium is stable.

We can also derive another proposition from Table 2.

Proposition 3: *The full-acceptance/full-investment and no-acceptance/no-investment equilibria are always stable if they exist.*

Proof: This follows from the criteria in Table 2. For the corner equilibrium of full-acceptance/full-investment equilibrium to exist both $1 > y^{Eq.3}$ and $1 > y^{Eq.4}$ because full acceptance requires $(1 + y)\tau^*a - (1 - \delta x)((\tau^* + b)p + s) > 0$ for all $x \in [0,1]$, which is the same as $y > y^{Eq.3}$ and with full acceptance $y = 1$. Same goes for $y^{Eq.4}$. Since $y = 1$ in this equilibrium, it follows that $y > \max\{y^{Eq.4}, y^{Eq.3}\}$ holds, therefore, $\dot{y} > 0$ and $\dot{x} > 0$.

Similar proof for no-acceptance/no-investment equilibrium. The only exception occurs if the partial equilibrium coincides exactly with one of the corner equilibria. In that case, stability is determined by the conditions for the partial equilibrium. QED

It may also be the case that the middle equilibrium does not exist because $y^{Eq.3}$ and $y^{Eq.4}$ do not cross. In this situation, the criteria outlined in Table 2 still apply.

In Figures 1-2, the boundaries separating the different regions are downwards sloping. The threshold equation for firms, $y^{Eq.4} = \frac{c-\tau-lx}{s}$, is always downward sloping since $l > 0$. Intuitively, due to spillover/infrastructure benefits, as more firms invest, a lower level of public acceptance (subsidy) is required for investment to be profitable. In section 7 below, we will look at an extension of the model where the boundary is upward sloping due to heterogenous firms. For homogenous firms, the threshold equation for individuals, $y^{Eq.3} = \frac{1-\delta\bar{x}-\omega}{\omega}$, is downwards sloping as long as $\delta > 0$. In this case, more adoption lowers the perceived cost of CCS. However, if $\delta < 0$ then $y^{Eq.3}$ will instead slope upwards. This is because perceived cost increases the more firms invest in CCS. However, the criteria outlined in Table 2 hold regardless of whether the threshold curves slope upwards and downwards. The case of $\delta < 0$ is illustrated in Figure 3.

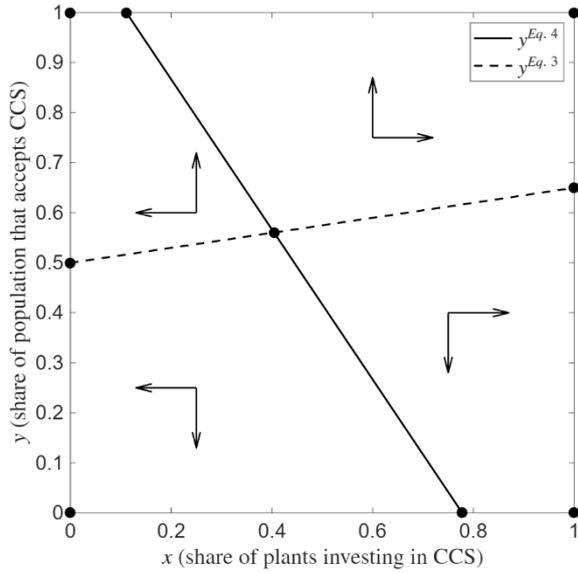


Figure 3: Evolutionary dynamics when $\delta < 0$.

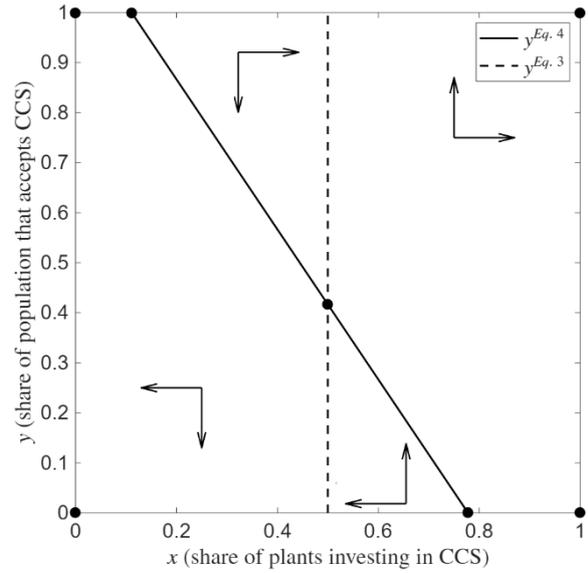


Figure 4: Evolutionary dynamics when there is no bandwagon effect.

Figure 4 illustrates a special case where greater acceptance of CCS in the population has no impact on other individuals' decisions. $y^{Eq.3}$ is then derived from solving $\tau^*a - (1 - \delta x)((\tau^* + b)p + s)$ for x , thus creating a boundary equation that is a straight line for a fixed value of x . The only partial acceptance Nash equilibrium that exist is then the middle equilibrium.

From the cases illustrated in Figures 1-4, we see that the starting point determines what Nash equilibrium we will reach. In most cases, a given level of public acceptance is important for not ending up in an equilibrium with no investments and no public acceptance as in the south-western regions of the figures. Thus, public acceptance above a threshold value determined by the threshold curves, is needed for the economy to move towards Nash equilibria with partial investments or full investments.

6. Governmental policies

We assume that the government is interested in achieving the best possible Nash equilibrium from a social point of view. Different market imperfections may hinder such an equilibrium. There are multiple sources of market imperfections in the model that the government may want to correct. First, there is a negative externality caused by CO₂ emissions from the firms if they do not invest in CCS technology. There may also be a market failure arising from

individuals' lack of information or cognitive bias, and there is a positive externality arising from the spillover benefit of firms' investments in t CCS technology.

Correcting these imperfections implies changing the parameters in the model. These changes affect outcomes in three different ways. First, they may influence the existence of different Nash equilibria. Second, they impact the equilibrium values in the Nash equilibria with partial investment and/or acceptance. Finally, they also alter the boundaries (threshold functions) of the regions' leading to the different equilibria by expanding or contracting the regions' that will give no adoption, partial adoption or full adoption of CCS.

In our model, the policy instruments the government can use are limited as it cannot freely set the subsidy rate. Thus, while the first best solution is not possible, the government still wants to correct imperfections to avoid undesirable outcomes. As noted above, it cannot pick a Nash equilibrium as they depend on the values in the payoff and profit functions given by (2) and (3). But policy shifts will likely lead to a new Nash equilibrium.

Below we will go through the effects of correcting the different imperfections through policy measures.

The climate externality

The government can correct the negative externality caused by CO₂ emissions by a Pigouvian tax, thus, setting the *carbon tax* equal to social cost of carbon, $\tau = \tau^*$. This ensures that the firms internalize the social cost of emissions.

The government can also use the carbon tax to compensate for the lack of other policy instruments. This will be a second-best taxation given that it cannot use the subsidy rate as a policy instrument, see e.g., Greaker and Midttømme (2016).

The carbon tax plays an important role in determining firms' investments in CCS because it acts as an economic threshold. If the carbon tax is too low ($\tau < c - s - l$), even high levels of public acceptance or large learning or network benefits may not provide sufficient incentives for firms to invest. Similarly, a sufficiently high carbon tax ($\tau > c$) makes investment in CCS universally optimal for all firms, regardless of public acceptance and learning/network effects.

Assume now that the carbon price was not implemented or that it was set below the social cost of carbon due to political constraints or uncertainty, i.e., $\tau < \tau^*$. The boundary equation

$y^{Eq.4} = \frac{c-\tau-lx}{s}$ illustrates that increasing the carbon tax shifts the boundary to the left, i.e. $\frac{\partial y}{\partial \tau} = -\frac{1}{s} < 0$, meaning that it shifts the boundary between $\dot{x}(x, y) < 0$ and $\dot{x}(x, y) > 0$ to the left. Thus, it expands the range of x and y values that lead to full adoption and full acceptance, given that the two curves cross (Figures 1 and 2), while shrinking the range that results in no adoption and no acceptance.

The size of these effects also depends on the boundary curve for the individuals, i.e., $y^{Eq.3} = \frac{1-\delta x}{\omega} - 1$, thus, it depends on the perceived benefit-cost ratio including public acceptance. If the perceived benefit-cost ratio, ω , is high, meaning that the slope of the threshold curve for individuals will not be very steep, the effect will be larger. If public acceptance is low, a tax increase may have little or no effect. The economy may remain in a no-investment, no-acceptance state even after the tax rise due to the dynamic effects. This leads us to study the correction of the second imperfection.

Lack of information or cognitive bias

There may be a market failure arising from lack of information or cognitive bias. Cognitive bias may cause deviations between subjective and objective values. Individuals may misperceive the probability of leakage and the additional cost of leakage, such that $p \neq p^*$ and $b \neq b^*$ where p^* and b^* are the true objective values. Behavioral economics suggests that individuals' overweight small probabilities such that $p > p^*$ (see, e.g., Tversky & Kahneman, 1992), and overestimate the cost of leakage if it happens, such that $b > b^*$ (see, e.g., (Finucane et al., 2000)), leading to an overestimation of the perceived cost of CCS. On the other hand, the perceived benefits of CCS are given by $a\tau^*$ where the parameter a captures individuals' attitudes towards both climate change and CCS technology. The value of a may be set too low if the attitude is based on wrong information about climate change or the CCS technology. Also, climate damages are abstract, distant, and uncertain, which can lead individuals to undervalue them and underestimate the benefits of CCS. To sum up, the overestimation of costs and underestimation of benefits mean that ω is lower than what is considered to be optimal from a social point of view, set at ω^* .

If $\omega < \omega^*$, the social planner can attempt to achieve $\omega = \omega^*$. An increase in ω can be implemented through for example, information campaigns on climate damage and the risk and costs CO₂ leakages, but also through measures that can reduce the risk of leakages.

To study the effect of these policy measures, consider the threshold curve for individuals, i.e., $y^{Eq.3} = \frac{1-\delta x}{\omega} - 1$. Increasing the perceived benefit-cost ratio ω shifts the threshold curve of the individuals to the left, lowers the interception for $x = 0$ as $\frac{\partial y}{\partial \omega} = -\frac{(1-\delta x)}{\omega^2}$, and flattens the slope of the curve. This expands the range of x and y values that lead to full investments in CCS and reduces the range for the no acceptance and no adoption of CCS equilibrium. In sum, raising the perceived benefits relative to the costs of CCS makes it easier for CCS adoption to take off.

To sum up, increasing the carbon tax or increasing the perceived benefit–cost ratio have similar effects as they shift $y^{Eq.3}$ and $y^{Eq.4}$ towards origo. This unambiguously increases the range of x and y values that lead to full adoption and full acceptance and decreases the range of x and y values that lead to no adoption and no acceptance. However, it also lowers the share of firms that invest in CCS in the middle equilibrium.

Learning by doing and indirect network effects

Firms investing in CCS do not internalize that their investment reduces costs for all firms through either indirect network effects or learning benefits. The marginal benefit of an increase in x is l . To internalize this externality the social planner should offer a subsidy $s_y = l$.

In our model, however, the actual subsidy is increasing in public acceptance and capped at s , i.e., the maximum subsidy. Thus, the government cannot implement the socially optimal subsidy. For example, in an equilibrium with $y = 0$ and $x > 0$ the subsidy is zero by construction, even though the spillover benefit is positive ($lx > 0$).

Overall, the government can shift the boundary curves for individuals and firms. The shifts to correct the market imperfections will expand the range where full acceptance and full investments will be reached in the long run. In a similar way, the range where we will end up with no acceptance and no investments will be smaller. However, what Nash equilibrium that evolves over time is dependent on the starting point, i.e., the public acceptance and investments before the government introduced the policy. If we start with low public acceptance and where only a minor share of the firms has invested in CCS, the possibility of ending up in a Nash equilibrium with positive investments in CCS will be low, even after correcting for market imperfections. This means that the government cannot pick an equilibrium. It can only increase the possibility of ending up with positive investments. Even

if it uses the carbon tax to compensate for the lack of subsidy as a policy instrument (second-best), the connection between the subsidy and public acceptance means that the government may not be able to reach the (second) best equilibrium.

7. Extensions

In this section, we describe three changes in the basic model. Non-linearity, heterogenous population and heterogenous firms.

Nonlinear learning and indirect network effects

In the basic model, all functional forms are linear. We relax this assumption for the learning and indirect network effects (lx) which typically exhibit diminish returns. Early adoption can generate substantial cost reductions through piloting and demonstration of technology, but as the industry matures, opportunities for further cost reductions decline, leading to slower gains from learning by doing over time. Because CO₂ storage involves large, fixed costs, unit costs decline when the total volume of CO₂ stored increases. However, the decrease in unit costs becomes smaller when the amount of stored CO₂ grows, which is directly correlated with the share of firms investing in CCS (x). Similarly, Golombek et al. (2023) show similar diminishing returns in terms of how number of terminals, and thus average transport distance and transportation cost respond to increased investment in CCS.

A more realistic formulation of the learning and indirect network effect as a function of share of firms investing, would be lx^γ where $\gamma \in (0,1)$. This also implies that profits become a concave function of the share of firms investing in CCS. The conditions for the four corner equilibria are the same as in the basic model since $lx^\gamma = lx$ when $x = 0$ or $x = 1$. The main difference is for the equilibrium with partial investment in CCS. The boundary curve is again found by solving for the indifference conditions where firms are indifferent between investing or not, which yields

$$y^{Eq.4^{nl}} = \frac{c - \tau - lx^\gamma}{s} \quad (14)$$

where $\gamma \in (0,1)$. Since $y^{Eq.4^{nl}} < y^{Eq.4}$ when $\gamma \in (0,1)$ and $x \in [0,1]$ it follows that the range of values that lead to full investments in CCS increases, while the range that leads to no investments decreases. The threshold curve for the firms is still downward sloping, but it shifts inwards. Thus, the extension of diminishing returns in the learning and indirect network

effects make the full investment equilibria more attainable. However, the share of firms that invest in the middle-equilibrium is reduced.

Heterogenous population

In the main model, individuals are assumed to be homogenous. However, people may differ in their attitude towards CCS. These differences can be due to regional or national factors such as climate damage or leakage risk, or individual differences such as attitude to the stringency of climate targets, risk preferences and the relative importance placed on the benefits of reducing emissions using CCS. Such heterogeneity is likely to influence both the perceived benefits and costs of CCS.

For simplicity we focus on heterogeneity in perceived benefits. To capture this, we introduce heterogeneity in the model by allowing individual attitudes represented by a_i , to differ. Specifically, we assume that individual i has an attitude parameter a_i towards CCS, which is uniformly distributed, and $a_i \in [\underline{a}, \bar{a}]$.

This changes the criteria for the four corners equilibria. Let $\bar{\omega} = \frac{\tau^* \bar{a}}{(\tau^* + b)^p}$ and $\underline{\omega} = \frac{\tau^* \underline{a}}{(\tau^* + b)^p}$.

Full public acceptance requires that the individual with least favorable attitude towards CCS (\underline{a}) accepts CCS. The criterion for full public acceptance is now $2\underline{\omega} > (1 - \delta\bar{x})$. Since $\omega > \underline{\omega}$, it is less likely that full public acceptance equilibria exist. On the other hand, no public acceptance requires that even the individual with the most favorable attitude (\bar{a}) rejects CCS, which is true for $\bar{\omega} < (1 - \delta\bar{x})$. Since $\bar{\omega} > \omega$, it is also less likely this the no public acceptance equilibria exists. In sum, with heterogeneity the corner outcomes become less likely and the interior outcome where only a share of the population accepts CCS becomes more relevant.

For evolutionary dynamics we apply the same principle as in the basic model, i.e., that the marginal individual serves as the learning benchmark. In the heterogenous case this is a simplification, and without the simplification, the Nash equilibria would not coincide with the steady states, see Appendix B.2. The boundary curve for public acceptance is now,

$$y^{Eq.3^{hp}} = \frac{\underline{\omega} \pm \sqrt{\Delta(x)}}{2(\bar{\omega} - \underline{\omega})} \quad (15)$$

where $\Delta(x) = \underline{\omega}^2 - 4(\bar{\omega} - \underline{\omega})((1 - \delta x) - (\bar{\omega}))$. $y^{Eq.3^{hp}}$ is non-linear, and its existence and direction depend on the parameter values. Thus, analytically the implications of extending to

heterogenous population is ambiguous. In the basic model $y^{Eq.3}$ is a decreasing function in x . Since $\Delta(x)$ is increasing in x , the first root, $y^{Eq.3_1^{hp}} = \frac{\omega - \sqrt{\Delta(x)}}{2(\bar{\omega} - \omega)}$, is also decreasing in x if an economically meaningful solution exists. The second root, $y^{Eq.3_2^{hp}} = \frac{\omega + \sqrt{\Delta(x)}}{2(\bar{\omega} - \omega)}$, is increasing in x . This may change the dynamics of the model since it changes the direction of the boundary curve. If heterogeneity leads to a shift in the boundary curve for individuals such that $y_1^{Eq.3^{hp}} < y^{Eq.3}$ it will either contract the regions' leading to no adoption and/or expand the region that leads to full adoption, but the effect on the partial equilibrium is still ambiguous.

Heterogenous firms

In the basic model, firms are assumed to be homogenous. In reality, the cost of investing in CCS varies between firms due to factors such as the distance to CO₂ storage sites, differences in technology and efficiency, and the scale of operations (Rubin et al., 2015). To reflect this variability, we follow Golombek et al. (2023) and assume that the cost of investing in CCS for firm i is c_i , which is uniformly distributed, and $c_i \in [\underline{c}, \bar{c}]$.

Similarly, as with heterogenous population, this changes the criteria for the four-corner equilibria. For all firms to invest, the firm with the highest cost (\bar{c}) of investing in CCS must find it profitable to invest. Therefore, all firms invest if $\tau > \bar{c} - sy - l$. Since $\bar{c} > c$ it is less likely that all firms invest when firms are heterogenous. For no firms to invest, the firm with the lowest cost of investing in CCS (\underline{c}) must find it unprofitable to invest, implying $\tau < \underline{c} - sy$. Since $\underline{c} < c$ it is less likely that no firms invest when firms are heterogenous. All four corner equilibria exist if $\bar{c} - l - s < \bar{c} - s < \tau < \underline{c} - s < \underline{c}$. Thus, $\bar{c} < \tau + s < \underline{c}$ and $\bar{c} - \underline{c} < l$ are necessary criteria for all Nash equilibria to exist. For all nine Nash equilibria to be possible when cost is heterogenous, the cost interval must be larger than the maximum cost reduction due to learning, $l > \bar{c} - \underline{c}$. If $l < \bar{c} - \underline{c}$, then the cost reductions are insufficient to overcome the gap between the cost of CCS and the carbon tax, as a result the equilibrium where there is full investments when there is no social acceptance will not exist.

For evolutionary dynamics, we again apply the same principle as in the basic model, i.e., that the marginal firm serves as the learning benchmark. The threshold equation is derived from the firm that is indifferent towards CCS, see Appendix B.3, and is

$$y^{Eq.4^{hf}} = \frac{\underline{c} - \tau - x[l - (\bar{c} - \underline{c})]}{s} \quad (16)$$

In the basic model, the threshold curve of the firms slopes downwards because the more firms that invest, the larger the cost reduction, reducing the reliance on social acceptance and the need for subsidies. When costs are heterogeneous, the curve remains downward sloping as long as $l > \bar{c} - \underline{c}$. In isolation, heterogeneity implies that the marginal cost of additional CCS adoption increases with the share of firms investing, since low-cost firms adopt first. When $l > \bar{c} - \underline{c}$ these cost increases are offset by the learning and indirect network effects, and thus the curve is still downward sloping. However, if $\bar{c} - \underline{c} > l$, then the threshold curve is increasing in y because the cost increases are not offset by the learning and indirect network effects. This possible change in the slope is important because it can affect the dynamics in the game. Combined with the lower intercept of $y^{Eq.4^{hf}}$ relative to $y^{Eq.4}$, sufficiently large heterogeneity can alter the system's dynamics, shifting the middle equilibrium from unstable to semi-stable.

When combined with diminishing returns in learning and indirect network effects, the boundary equation becomes

$$y^{Eq.4^{hfnl}} = \frac{\tau - x(\bar{c} - \underline{c}) - \underline{c} + lx^\gamma}{s} \quad (17)$$

The criteria for the two corner equilibria with either full investment ($x = 1$) or no investments ($x = 0$) remain identical to the baseline model, and the same as before for $x \in (0,1)$ $y^{Eq.4^{hfnl}} < y^{Eq.4^{hf}}$. With heterogenous firms, the boundary curve for firms is upwards sloping if $l < \bar{c} - \underline{c}$. With diminishing returns and heterogenous firms, the boundary curve is an increasing function of x as long as $x > \left(\frac{\bar{c}-\underline{c}}{\gamma l}\right)^{\frac{1}{\gamma-1}}$. Thus, the diminishing returns may imply that the boundary curve for firms are decreasing for low x , but as learning effects weaken at higher x , the cost reduction becomes too small to offset the increasing marginal cost of CCS for the heterogenous firms. As a result, the boundary curve eventually becomes upward sloping.

8. Numerical illustrations

Because the existence of the Nash equilibria, the dynamics of the model and the impact of the extensions depend on the parameter values, we calibrate the model to current climate policy,

CCS costs and public attitudes in Europe. Table 3 reports on the parameter values used in the numerical illustrations. More details are provided in Appendix C.

Table 3: Parameter values for numerical illustrations

<i>Parameter</i>	<i>Description</i>	<i>Value</i>	<i>Unit</i>	<i>Source</i>
c	Unit cost of CCS (capture + transport + storage)	149.7	EUR2025/tCO ₂	Rubin et al (2015), ZEP (2011), Golombek et al.
\underline{c}	Minimum unit cost of CCS	82.1	EUR2025/tCO ₂	(2023), Atkins & Oslo Economics (2016; 2018),
\bar{c}	Maximum unit cost of CCS	217.3	EUR2025/tCO ₂	
l	Unit cost reduction of CCS from learning and indirect network effects	50	EUR2025/tCO ₂	ZEP (2011), Golombek et al. (2023); Gassnova SF (2020)
γ	Exponent for cost reduction function	0.5	-	
τ	EU ETS price	96	EUR2025/tCO ₂	BloombergNF (2024)
τ^*	Social cost of carbon	197	EUR2025/tCO ₂	Rennert et al. (2022)
s	Maximum government subsidy	242	EUR2025/tCO ₂	European Commission (2024)
a	Attitude parameter	0.67	-	Waring & Longo (2025)
\underline{a}	Minimum attitude parameter	0.54	-	For illustration purposes $\pm 20\%$ of a
\bar{a}	Maximum attitude parameter	0.80	-	
p	Perceived probability of leakage	0.0548	-	IEAGHG (2025), Tversky & Kahneman (1992)
b	Perceived local cost of leakage	58	EUR2025/tCO ₂	Lee & Choi (2018)

δ	Perception update parameter	0.32 (basic model) 0.12 (heterogeneous individuals)	-	Waring & Longo (2025)
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The baseline model

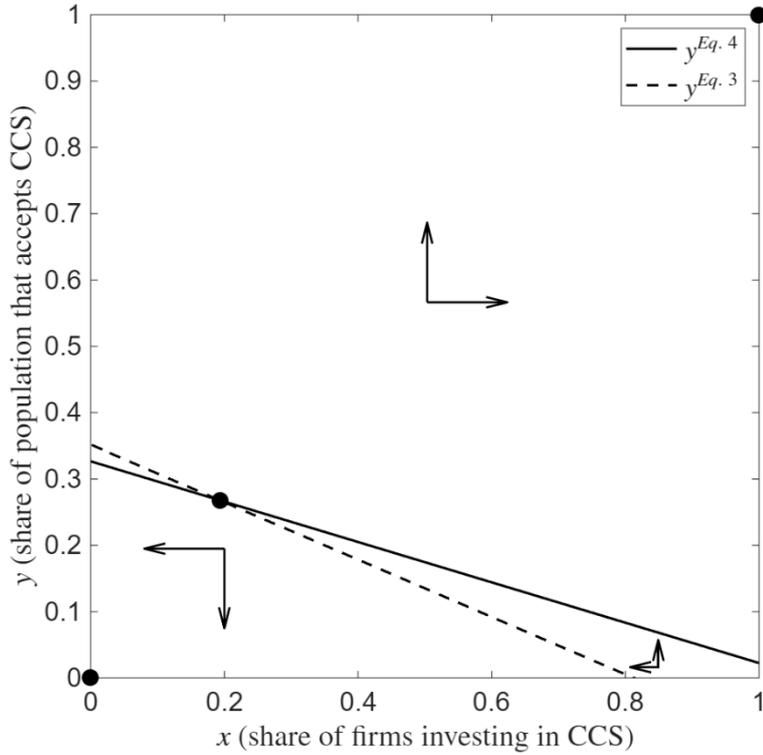


Figure 5: A numerical illustration of the baseline model

We start by illustrating the baseline model, see Figure 5. As seen, this figure shows similarities to Figure 2 discussed in Section 5 above, and therefore, three Nash equilibria exist. Two of them are corner equilibria, one with no acceptance and no investments, and one with full acceptance and full investments. In addition, there is a middle equilibrium with partial acceptance and partial investments.

The two corner equilibria exist because the learning effect is sufficiently large so that, if no one accepts, the perceived benefit-cost ratio is too low ($\omega < 1$), but with learning, the ratio is sufficiently high ($2\omega > (1 - \delta)$). The existence of both corner equilibria also depends on the carbon price alone not being sufficient to make CCS profitable ($\tau < c$), but CCS being profitable with the maximum subsidy and maximum learning effects. In other words, both corner equilibria exist because δ , s and l are sufficiently large.

In the middle Nash equilibrium, 27% ($y = 0.27$) of the population accepts CCS and 19% ($x = 0.19$) of firms invest or plan to invest in CCS. This equilibrium is semi-stable.

In the last five years there has been an increase in planned investment in CCS and a shift in attitudes towards CCS in multiple European countries, thus it is unlikely that Europe today is in a Nash equilibrium. It is therefore most useful to identify a possible starting point, and discuss which Nash equilibrium Europe might end up in. Despite an increase, planned deployment of CCS remains very limited. In the cement industry, planned capture capacity corresponds to about 0.02% of emissions (Clean Air Task Force, 2025; Global CCS Institute, 2024). In Northern Europe, the share of respondents that are positive or somewhat positive toward CCS, is in the range 40 to 60 percent (Merk et al. 2023; Anders et al., 2024). Due to direct exposure to demonstration projects and offshore storage locations, the share that accepts CCS in Northern Europe is expected to be higher than for the rest of Europe. Thus, while the acceptance rate in Northern Europe is likely to be above 27%, the acceptance rate for the rest of Europe can be below or above this percentage.

Overall, if public acceptance in Europe today is below 27% (starting point), then the baseline model suggests that the model will either converge to an equilibrium with partial acceptance and partial investment or one with no acceptance and no investments. In the last case, planned investments will be scrapped. This may be the likely outcome based on the low planned capture capacity in the cement industry. Among the available policy instruments, raising the carbon tax is in this case the most effective way to stimulate investments in CCS. Increasing the carbon tax expands both the region leading to the equilibrium with full public acceptance and full investments, and the middle equilibrium for current values of acceptance and investments. Increasing the perceived benefit-cost ratio has similar effects, but it does so for investments levels far above today's planned deployment. If public acceptance exceeds 27% (starting point), then there is no need for additional policy because with the current starting point the system will move toward a Nash equilibrium with full investments and acceptance.

Extensions of the model

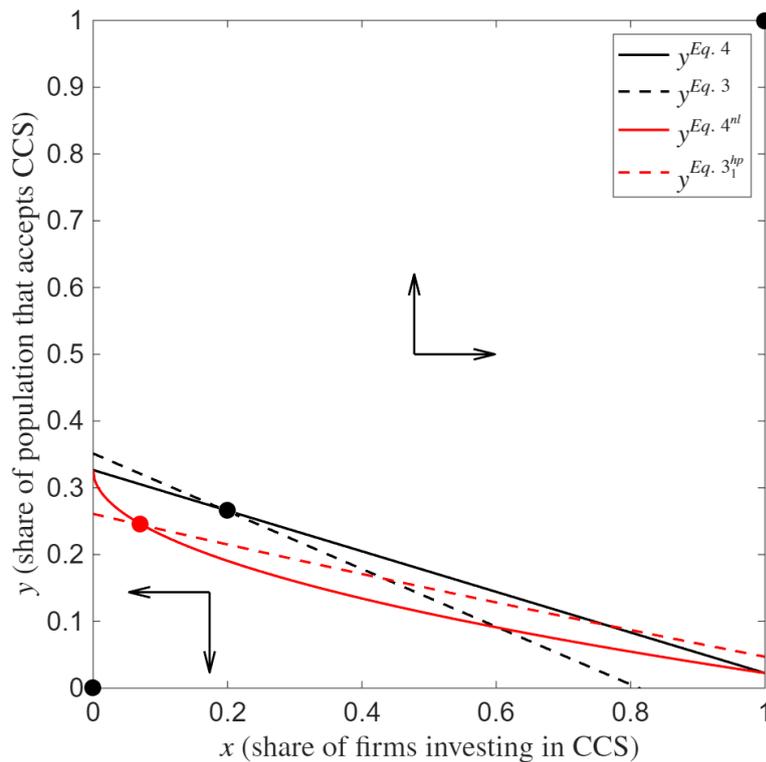


Figure 6: A numerical illustration of the model with diminishing returns and heterogeneous population

Introducing diminishing returns in learning and indirect network effects does not change the number of Nash equilibria, as the dynamics shown in Figure 6 are still similar to those in Figure 2. With non-linearity, the share of the population that accepts CCS in the middle Nash equilibrium decreases from 27% to 9%, while the share of firms investing or plans to invest increases from 19% to 60%. With diminishing returns, the cost reductions from early investments are larger than in the baseline model, making investment profitable at lower levels of public support, which explains an equilibrium with higher investments and lower public support. As the boundary curve for firms shifts downwards with non-linearities, the shift is in the similar direction as for a higher carbon tax apart from in the corners with zero or full investments. Thus, this shift increases the area leading to full investments and full acceptance, but it also extends the area leading to partial investments for a starting point with low investments.

A heterogeneous population does not change the number of Nash equilibria, as the dynamics in Figure 4 are still similar to those in Figure 2. Analytically, the shift in the boundary curve was ambiguous, see Section 7 above. In the numerical illustration, the boundary curve rotates

to the left, giving a significant increase in the region leading to the middle Nash equilibrium compared to the baseline model, for a low initial share of investments. The rotation leads to a significant increase in the share of firms investing in CCS, which now is 76% while the share of the population that accepts CCS is now 10%.

However, a further increase in heterogeneity may change the existence of the two corner equilibria, see the discussion in Section 7. If the most favorable individual's attitude (a) is 35% above the mean, the no acceptance and no investment equilibrium will not exist. On the other hand, if the least positive individual's attitude is 41% below the mean, then the equilibrium with full acceptance and full investment will not exist. There are very few empirical studies on the variation of attitudes towards CCS, but a study on the willingness-to-pay for CCS indicates low heterogeneity in preferences, at least in the UK (Waring & Longo, 2025) .

Taking the two changes together, the main implication of diminishing returns and a heterogeneous population is an expansion of the region leading to full acceptance and investment, for a starting point with small investments and investment plans but medium public acceptance. In the context of Europe, this makes both convergence to an equilibrium with full investments in CCS and convergence to an equilibrium with partial investment in CCS more plausible. In the latter equilibrium, the share of the population that accepts is 24% but share of firms investing is only 7%, see Figure 6.

The last extension introduces heterogeneity among firms. Figure 7 shows how this interacts with the other extensions, i.e., it includes all the extensions.

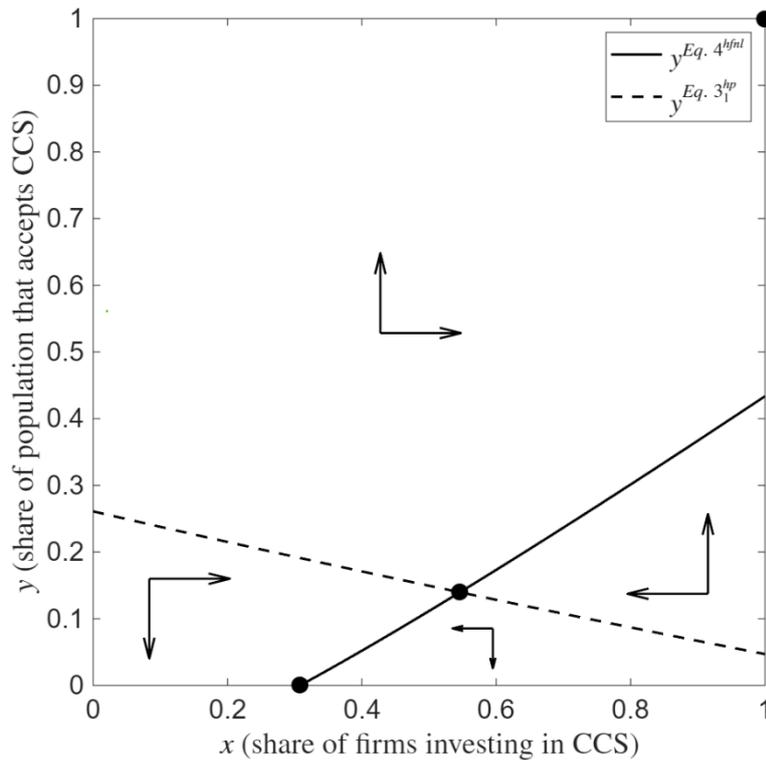


Figure 7: A numerical illustration of the model with all extensions

As seen from Figure 7, including heterogenous firms changes the boundary conditions for firms from a decreasing function in the share of firms investing to an increasing function, as $\bar{c} - \underline{c} > l$, see the discussion in Section 7.

There are still three Nash equilibria. No investments and no acceptance is not a Nash equilibrium anymore because $\underline{c} > \tau$. Instead, no acceptance and partial investment ($x = 0.30$) is a Nash equilibrium. This is the share of firms that will invest even if they do not receive a subsidy from the government. Even if 30% of the firms invest in CCS, the individual with the most favorable attitude towards CCS would not accept CCS because $\bar{\omega} < 1 - \delta x$ (see Section 7).

Assuming public acceptance in Europe lies in the range 15-25%, and the share of firms that either have made an investment or are planning to do so are in the range 1-10%, public acceptance will fall and share of firms increase until we reach the middle Nash equilibrium where 55% of firms invest. For similar levels of investment, but lower levels of social acceptance, it is more likely that public acceptance will fall, and the share of firms increase until it reaches the Nash equilibrium where only 30% of firms invest. The only way to avoid this is to use policy measures to increase social acceptance of CCS, i.e. move the boundary curve for individuals $y^{Eq.3}$ downwards. This can be done with policy instruments that

increase the perceived benefit-cost ratio of individuals, see Section 6. If we consider Figure 7 as the most realistic illustration of the model, we will end up with large investments in CCS without any corrections for externalities. However, this result significantly depends on the inclusion of coal- and gas power plants in the numerical example.

In the numerical example the carbon price is 96 EUR per ton CO₂, and the lowest cost of CCS in the illustration is 82 EUR per ton CO₂. However, the cost of 82 EUR per ton CO₂ corresponds to CCS on coal and gas power plants. The lowest cost for process emissions in industry in our data is 138 EUR per ton CO₂, which is above the carbon price. As illustrated in Figure 8, if we do not include coal and gas power plants, the equilibrium with no acceptance and no investment does exist. Moreover, with current planned investment levels in CCS and levels of public acceptance below 20% the system will push towards the Nash equilibrium with no investments in CCS if there are no additional policy interventions.

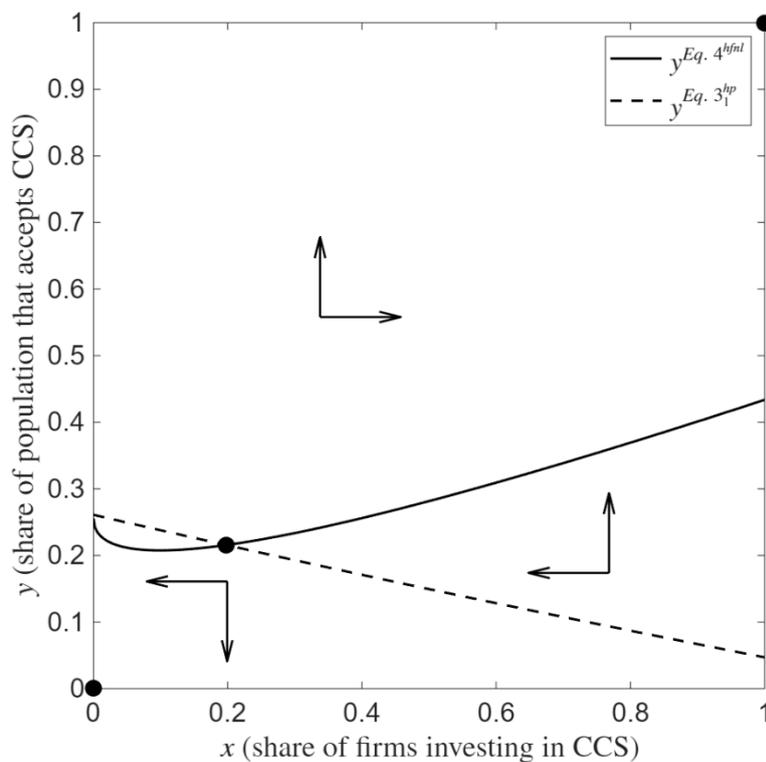


Figure 8: A numerical illustration of the model with all extensions without including gas and power plants

9. Conclusion

In this paper we have introduced a model for the evolution of adapting CCS technologies, where the governmental policy towards CCS is dependent on public acceptance. This can be justified by the concerns of the governmental parties to be reelected. We use an evolutionary game theory model to study the evolution of public acceptance and the investments in CCS, where public acceptance is dependent on the costs and benefits of accepting CCS, and the subsidy to firms depends on public acceptance. We show that there may exist several multiple equilibria in this model, where the number of equilibria depends on the different parameters in the model such as attitude to climate change and new technologies, the seriousness of the climate change problem, perceptions on risk and costs of leakage from carbon storage, as well as the carbon tax and the costs of investing in CCS.

The government can influence the development of CCS investments by correcting market imperfections due to the negative climate externality and individual's lack of information or cognitive bias. However, it cannot directly correct for the positive externalities arising from learning by doing or possible indirect network effects. as the subsidy is tied to public acceptance. Thus, it is not able to implement a first-best social optimum. What Nash equilibrium that will evolve over time depends on the starting point, i.e., what the public acceptance and investments were before the government introduced policies. This means that the government cannot pick an equilibrium. It can only increase the likelihood of ending up with positive investments by correcting for imperfections.

Our model is relevant to understanding the development of CCS investments in Europe. Public acceptance has played an important role in the governmental policy to support CCS in Europe, and several CCS projects have been cancelled due to lack of public acceptance. In the numerical illustration, we show that if we start with low public acceptance and where only a minor share of the firms has plans to invest in CCS, the possibility of ending up in a Nash equilibrium with large investments in CCS, is significant if the firms' costs of investing in CCS are heterogenous, even without correcting for market imperfections. In our example, this hinges on the inclusion of coal- and gas power plants, because these sectors are early movers that accelerate deployment of CCS when firms are heterogenous. Thus, it may be of great importance for the development of CCS in Europe to include low-cost options, even if this means investments in CCS in power plants that use fossil fuels. However, this is a dilemma, as earlier phases of CCS saw resistance in some countries, because of widespread

perceptions that they were aiming to save coal power, thereby not contributing to actual energy transition.

It is reasonable to believe that costs of investments in CCS are more homogenous for a country than for a region such as Europe, as not all countries have the low-option opportunities or industries with the most expensive investment options. We can use the cases of Germany and Norway to illustrate the importance of the starting point, within the model of homogenous firms. The public acceptance for CCS in Germany has been low, and politicians have therefore, not implemented policies to support CCS. One of the reasons for low public acceptance has been fear of leakage and the possible damages that may occur from storing CO₂ onshore. As illustrated in our model, this means that Germany is in the lower left corner in Figures 1 and 2. However, politicians have taken steps to change the situation.⁹ The target of climate neutrality by 2045 has reopened the debate of CCS as a mitigation strategy, especially for hard-to-abate industries. In our model, a focus on the target means a possible shift in the attitude to climate change and CCS technology, which may increase public acceptance and reduce the area in the graphs leading to no acceptance and investments. In addition to this, the government has adopted a draft to a law that would allow underground storage and enable large scale transport through pipelines, also utilizing storage locations abroad and offshore. Interpreting this in terms of our model would mean that the government weakens the linkage between subsidies and public acceptance, on the other hand this may also reduce the perceived costs of public acceptance by transporting CO₂ for offshore storage, as this reduces the damage from possible leakages compared to storing onshore.

In Norway, the situation has been different. Storing CO₂ onshore has never been an option, and the public acceptance for CCS has been high. In addition to this, two large-scale CCS projects became operational already in 1996 and 2008, as the petroleum industry decided to store CO₂ from natural gas production offshore, instead of emitting the CO₂ into the atmosphere and paying the carbon tax. The long experience in storage without any leakage may also have had an impact on public acceptance. In our model, this means that the initial starting point was very different from the one in Germany, and it would probably be above the threshold curve that would lead to no investments and acceptance. Thus, Norway will either end up in a situation with partial or full investments in CCS illustrated by Figures 1 and

⁹ <https://www.cleanenergywire.org/news/government-cabinet-paves-way-carbon-capture-and-storage-germany>

2. This is also supported by the recent Longship project that stores CO₂ from a cement factory, as well as the plans for using CCS in waste incineration.

These findings support empirical work that shows general links between public acceptance, CCS policies, and developments. However, this academic body of literature is still underdeveloped, and further refinement of the more precise interactions is highly warranted. This could include the conditions under which acceptance is likely to grow or wane, and under what concrete conditions this translates to supportive public policies and not, and what other factors may interact with this.

The model results and examples are relevant for more general points as well. As the results indicate the close interrelation between CCS, public acceptance and investments, companies may consider threshold effects of their project development on public acceptance and more favorable public policies, to CCS. Moreover, while governmental actions cannot entirely eradicate different starting points, for example linked to earlier controversies or differences related to offshore-onshore storage, public policies can contribute by increasing the likelihood of ending up with positive investments, through instruments correcting for market imperfections. Such policies may be crucial in terms of reaching climate goals, given the prominent role CCS has in net-zero scenarios for the EU and beyond.

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Appendix

Appendix A.1

Existence of Nash equilibria

Individuals decide whether or not to accept the technology based on the payoff function $U(y_i, x, y) = [(1 + y)\tau^*a - (1 - \delta x)(\tau^* + b)p]y_i$. If $y_i = 1$, the individual accepts CCS, while if $y_i = 0$, the individual does not accept CCS. Let $\omega = \frac{\tau^*a}{(\tau^* + b)p}$. If all individuals accept CCS, then $y_i = 1$ for all i . This occurs when $2\tau^*a > (1 - \delta x)(\tau^* + b)p$ or $2\omega > (1 - \delta x)$. If no individuals accept CCS, $y_i = 0$ for all i . This occurs when $\tau^*a < (1 - \delta x)(\tau^* + b)p$ or $\omega < (1 - \delta x)$. There could also be an interior equilibrium where some individuals accept CCS, leading to partial public acceptance, i.e., $0 < y < 1$. This occurs when $(1 + y)\tau^*a - (1 - \delta x)(\tau^* + b)p = 0$, $\bar{y} = (1 - \delta x)\frac{1}{\omega} - 1$. Along this line, if $y = (1 - \delta x)\frac{1}{\omega} - 1$ the individual is indifferent between accepting and rejecting CCS.

Firms decide whether to invest in CCS based on the profit function $\pi_j(x_j, x, y) = e(\tau - c + sy + lx)x_j$. If $x_j = 1$, firm j invests in CSS, however, while if $x_j = 0$ the firm does not invest in CCS. If all firms invest in CCS, $x_i = 1$ for all i . This occurs when $\tau - c + sy + l > 0$ or $\tau > c - sy - l$. If no plants invest in CCS, $x_i = 0$ for all i . This occurs when $\tau - c + sy < 0$ or $\tau < c - sy$. There could also be an interior equilibrium where some firms invest in CCS and others do not, leading to partial investments in CCS, $0 < x < 1$. This occurs when $\tau - c + sy + lx = 0$, i.e., $x = \frac{c - \tau - sy}{l}$. Along this line the firms are indifferent between investing in CCS and not investing in CCS. The share of plants that invest and the share of the population that accepts CCS when there is partial acceptance and partial investment, are identified by solving the set of equations $(1 + y)\tau^*a - (1 - \delta x)(\tau^* + b)p = 0$ and $\tau - c + sy + lx = 0$, i.e., $x = \frac{\omega(c + s - \tau) - s}{\omega l - \delta s}$ and $y = \frac{l(1 - \omega) + \delta(\tau - c)}{\omega l - \delta s}$. All the criteria above are summarized in Table 1.

Appendix A.2

Proof of Proposition 1

The boundary curves for firms and individuals are linear boundaries that separate accept from not accept and invest from not invest, thus it is sufficient to check the four corner equilibria to

determine whether all nine Nash equilibria exist. For individuals, for the four corner Nash equilibria to exist, we need $\frac{1}{2} < \omega < 1$ and $\frac{1-\delta}{2} < \omega < 1 - \delta$. Since $1 - \delta < 1$ and $\frac{1-\delta}{2} < \frac{1}{2}$, this implies $\frac{1-\delta}{2} < \frac{1}{2} < \omega < 1 - \delta < 1$. Thus, the criteria is $\frac{1}{2} < \omega < 1 - \delta$. For firms, the four corner Nash equilibria exist if $c - l < \tau < c$ and $c - l - s < \tau < c - s$. Since $c - l - s < c - l$ and $c - s < c$, $c - l - s < c - l < \tau < c - s < c$, which imply $s < c - \tau < l$. Thus, $\frac{1}{2} < \omega < 1 - \delta$ and $s < c - \tau < l$ are sufficient for all nine equilibria to exist. Note that this implies that $\delta < \frac{1}{2}$ and $s < l$ are necessary (but not sufficient) criteria the nine equilibria to exist.

Appendix B.1

Non-linear learning and indirect network effects

The learning and indirect network effect as a function of the share of firms investing, is lx^γ where $\gamma \in (0,1)$. Firms now decide whether to invest in CCS based on the profit function $\pi_j(x_j, x, y) = e(\tau - c + sy + lx^\gamma)x_j$. The criteria for no, partial and full public acceptance, is the same as in Appendix A.1. Since $lx^\gamma = lx$ when $x = 0$ and $x = 1$, the criteria for the equilibrium with no and full investments is also the same as before. The change is in the equilibria where there is partial investment in CCS. Solving $\tau - c + sy + lx^\gamma = 0$ for x , yields $x^{Eq.4^{nl}} = \left(\frac{c-\tau-sy}{l}\right)^{\frac{1}{\gamma}}$, and solving for y yields $y^{Eq.4^{nl}} = \frac{c-\tau-lx^\gamma}{s}$. The share of plants that invest and the share of the population that accepts CCS when there is partial acceptance and partial investment, can be found by solving the set of equation $y^{Eq.3}$ and $y^{Eq.4^{nl}}$. Firms' investments in CCS follow the same dynamic as before given in Eq. 10, but now $\dot{x}(x, y) = x(1 - \bar{x})e(\tau - c + sy + lx^\gamma)$. Thus, $y^{Eq.4^{nl}} = \frac{c-\tau-lx^\gamma}{s}$ is also the new boundary curve for firms.

Appendix B.2

Nash equilibria with heterogeneous individuals

Individual i has an attitude parameter a_i towards CCS, which is uniformly distributed and $a_i \in [\underline{a}, \bar{a}]$. Individual i decides whether or not to accept the technology based on the payoff function $U(y_i, x, y) = [(1 + y)\tau^*a - (1 - \delta x)(\tau^* + b)p]y_i$. If $y_i = 1$, the individual accepts CCS, while if $y_i = 0$, the individual does not accept CCS. The criteria for no, partial and full

investments is the same as in Appendix A.1. Let $\bar{\omega} = \frac{\tau^* \bar{a}}{(\tau^* + b)p}$ and $\underline{\omega} = \frac{\tau^* \underline{a}}{(\tau^* + b)p}$. Full public acceptance requires that the individual with the least favorable attitude towards CCS (\underline{a}) accepts CCS. This occurs when $2\tau^* \underline{a} - (1 - \delta x)(\tau^* + b)p > 0$ or $2\underline{\omega} > (1 - \delta x)$. On the other hand, no public acceptance requires that the individual with the most favorable attitude (\bar{a}) rejects CCS. This occurs if $\bar{\omega} < (1 - \delta x)$. For full public acceptance and no public acceptance to exist as equilibria regardless of share that invest in CCS, $\frac{(1 - \delta \bar{x})}{2} < \underline{\omega} < \bar{\omega} < (1 - \delta \bar{x})$ and since $\frac{1}{2} < \underline{\omega} < \omega < \bar{\omega} < 1 - \delta$, it is overall less likely for corner Nash equilibria to exist with heterogeneous population.

If individual i is indifferent towards accepting CCS, then the share of the population that accepts CCS is given by $y = 1 - \frac{a_i - \underline{a}}{\bar{a} - \underline{a}}$. For individual i to be indifferent towards CCS, it also must hold that $(1 + y)\tau^* a_i - (1 - \delta x)((\tau^* + b)p + s) = 0$. Using the equation for the share of individuals accepting CCS, we find $(1 + y)\tau^* \left((1 - y)(\bar{a} - \underline{a}) + \underline{a} \right) - (1 - \delta \bar{x})((\tau^* + b)p + s) = 0$. Solving the equation yields $y^{Eq.3^{hp}}$, the share of the population that accepts CCS when there is partial acceptance,

$$y^{Eq.3^{hp}} = \frac{-\bar{\omega} \pm \sqrt{\bar{\omega}^2 - 4(\bar{\omega} - \underline{\omega})[\underline{\omega} - (1 - \delta \bar{x})]}}{2(\bar{\omega} - \underline{\omega})}.$$

To identify the criteria for the existence of all nine possible Nash equilibria, combine $2\underline{\omega} > (1 - \delta \bar{x})$ with $\bar{\omega} < (1 - \delta \bar{x})$, and the criteria for firms from the baseline model. This yields $\frac{1}{2} < \underline{\omega} < \bar{\omega} < 1 - \delta$ and $s < c - \tau < l$. Thus, if $\frac{1}{2} < \underline{\omega} < \bar{\omega} < 1 - \delta$ and $s < c - \tau < l$, then the game has nine possible Nash equilibria.

Let $\Delta(x) = \underline{\omega}^2 - 4(\bar{\omega} - \underline{\omega})((1 - \delta x) - (\bar{\omega}))$. For real solutions to exist, $\Delta(x) \geq 0$. A sufficient but not necessary condition for this is $(1 - \delta x) \leq \bar{\omega}$, i.e., the no public acceptance Nash equilibrium does not exist. However, real solutions may exist even if $(1 - \delta x) \geq \bar{\omega}$, as long as $\underline{\omega}^2 \geq 4(\bar{\omega} - \underline{\omega})((1 - \delta x) - (\bar{\omega}))$. Thus, any variable that increases $\Delta(x)$ also increases the likelihood of a real solution existing. For a solution to be economically meaningful it must satisfy $y^{Eq.3^{hp}} \in [0, 1]$. For the second root $y^{Eq.3_2^{hp}} = \frac{\omega + \sqrt{\Delta(x)}}{2(\bar{\omega} - \underline{\omega})} > 0$ always holds true, but $y^{Eq.3_2^{hp}} = \frac{\omega + \sqrt{\Delta(x)}}{2(\bar{\omega} - \underline{\omega})} \leq 1$ requires $\Delta(x) \leq (2\bar{\omega} - 3\underline{\omega})^2$. For the first root,

$y^{Eq.3_1^{hp}} = \frac{\omega - \sqrt{\Delta(x)}}{2(\bar{\omega} - \omega)} \geq 0$ require $s\omega^2 \geq \Delta(x)$, and $\frac{\omega - \sqrt{\Delta(x)}}{2(\bar{\omega} - \omega)} \geq 1$ requires $\Delta(x) \leq$

$(3\omega - 2\bar{\omega})^2$. $y^{Eq.3_1^{hp}} = \frac{\omega + \sqrt{\Delta(x)}}{2(\bar{\omega} - \omega)}$ is an increasing function of x , while $y^{Eq.3_2^{hp}} = \frac{\omega - \sqrt{\Delta(x)}}{2(\bar{\omega} - \omega)}$

decreases with x . In the basic model $y^{Eq.3} = \frac{1 - \delta x - \omega}{\omega}$ is a decreasing function in x . In the case of heterogenous population, the direction of change depends on whether $\Delta(x)$ is larger or smaller than $(3\omega - 2\bar{\omega})^2$, making it an empirical question. Thus, analytically the implications of extending to heterogenous population is ambiguous and depends on the different parameter values.

Evolutionary dynamics

In the basic model, the replicator dynamic means that public acceptance increases when the payoff of accepting CCS is larger than the average payoff of all individuals. Because everyone is identical it is the indifferent individual that drives the dynamics (see Eq. 9). The combination of the replicator dynamic and homogeneity also ensures that the dynamic steady state coincides with the Nash equilibrium. To maintain this consistency in the heterogenous extension, we adopt the same principle of the indifferent individual driving the dynamic and introduce a cutoff attitude a_i . Because the payoff of accepting CCS is increasing in the attitude parameter, individuals with attitudes above a_i will accept CCS, and those with attitudes below do not. We approximate the evolutionary dynamics using the cut-off as the individual with this attitude drives public acceptance. Under this approximation the replicator dynamics become $\dot{y}(x, y) = y(1 - y)(U(1; x, y|a_i))$, making $y^{Eq.3^{hp}}$ the boundary curve for individuals. Our simplification is similar to other standard simplifications used in threshold models and pairwise comparison dynamics (see, e.g., Sandholm 2010) where evolution is approximated by the payoff of the marginal individual (cutoff) rather than the average population. In the basic model, individuals learn by imitating strategies that perform better than the average payoff. In the heterogeneous case, this logic is adapted, and the cutoff attitude now serves as the learning benchmark. Intuitively, this also makes sense when attitudes vary widely, because when the population is heterogenous with possibly widespread beliefs, population average may be a poor guide for learning. Thus, simplification also reflects a more incremental and realistic approach here.

Appendix B.3

Nash equilibria with heterogeneous firms

The cost of investing in CCS for the firm i is c_i where $c_i \in [\underline{c}, \bar{c}]$ and uniformly distributed, and the profit for firm i is given by $\pi_i(x_i, x) = e(\tau - c_i + sy + lx)x_i$. The criteria for no, partial and full acceptance is the same as in Appendix A.1. For all firms to invest, the firm with the highest cost of investing in CCS must find it profitable to invest. Therefore, all firms invest if $\tau > \bar{c} - sy - l$. Similarly, for no firms to invest the firm with the lowest cost of investing in CCS must find it unprofitable to invest. Therefore, no firms invest if $\tau < \underline{c} - sy$.

There also exist three equilibria where a share of firms invests in CCS. Since cost are uniformly distributed, we know that for any given c_i , that the share of firms that invest for this cost is given by $x = \frac{c_i - \underline{c}}{\bar{c} - \underline{c}}$, thus $c_i = x(\bar{c} - \underline{c}) + \underline{c}$. Firm i is therefore indifferent towards investing in CCS if $\tau - x(\bar{c} - \underline{c}) - \underline{c} + sy + lx = 0$. Solving for x yields $x^{Eq.4^{hf}} = \frac{\tau - \underline{c} + sy}{\bar{c} - \underline{c} - l}$,

i.e., the share of firms investing in CCS in a partial equilibrium. Solved for y it yields

$y^{Eq.4^{hf}} = \frac{\underline{c} - \tau - x[l - (\bar{c} - \underline{c})]}{s}$. The share of firms that invest and the share of the population that accepts CCS when there is partial acceptance and partial investment can be found by solving the set of equations $y^{Eq.4^{hf}}$ and $y^{Eq.3}$.

For firms, for the four corner Nash equilibria to exist $\bar{c} - l - s < \bar{c} - s < \tau < \underline{c} - s < \underline{c}$ must hold. This implies $\bar{c} < \tau + s < \underline{c}$ and $\bar{c} - \underline{c} < l$. Thus, if $\frac{1}{2} < \omega < 1 - \delta$, $\bar{c} < \tau + s < \underline{c}$ and $\bar{c} - \underline{c} < l$ the game has nine possible Nash equilibria.

If we combine it with the non-linear learning and indirect network effects the indifference equation is $\tau - x(\bar{c} - \underline{c}) - \underline{c} + sy + lx^\gamma = 0$. Thus $y^{Eq.4^{hfnl}} = \frac{\underline{c} - \tau - lx^\gamma + x(\bar{c} - \underline{c})}{s}$. Note that

$$\frac{\partial y^{Eq.4^{hfnl}}}{\partial x} = \frac{(\bar{c} - \underline{c}) - \gamma lx^{\gamma-1}}{s} \cdot \frac{\partial y^{Eq.4^{hfnl}}}{\partial x} > 0 \text{ if } \left(\frac{\bar{c} - \underline{c}}{\gamma l}\right)^{\frac{1}{\gamma-1}} < x. \text{ Thus, } y^{Eq.4^{hfnl}} \text{ is a decreasing}$$

function of x if $\left(\frac{\bar{c} - \underline{c}}{\gamma l}\right)^{\frac{1}{\gamma-1}} < x$.

Evolutionary dynamics

We use the same simplification for heterogenous firms as for heterogenous individuals. Thus, we approximate the evolutionary dynamics by using the marginal (cutoff) firm, assuming that learning happens at the margin when firms are heterogenous. Note that this is also the case

when firms are homogenous because when all firms are identical it is the indifferent firms that drive the dynamics. This implies that firms do not evaluate the full distribution of payoffs but rather infer market conditions from signals, where the most informative signal comes from firms at the margin. When firms observe that those near the cutoff begin investing in CCS, they interpret this as a sign that profitability has improved enough to make CCS viable. This reflects a realistic learning process under uncertainty; firms update beliefs incrementally based on marginal changes rather than extreme cases or population averages.

Appendix C

The parameter values used in the simulation are summarized in Table 3.

Unit cost of CCS

The total unit cost of CCS per ton CO₂ includes the cost of capture, transport and storage. Capture costs depend on sector and technology. Rubin et al (2015) report cost ranging from 36.4 to 79.3 EUR2025 per ton of CO₂ for coal and gas power plants. Assuming a lifetime of 25 years and taking all costs into account, the annualized cost for CCS in ammonia, cement and waste management is estimated to range from 92.3 to 171.6 EUR2025 per ton CO₂ (Atkins and Oslo Economics, 2016, 2018; Golombek et al., 2023). For transport, we apply a unit cost of $t = 0.0143$ per ton CO₂ per kilometer (Rubin et al, 2015) and a transport distance of 1334.5 km, corresponding to a situation with one terminal around the North Sea in Golombek et al. (2023), which reflects today's structure where Northern Lights is the only operative terminal receiving CO₂. The resulting transportation cost per ton of CO₂ is 19.1 EUR2025. For storage, we assume a cost of 23.4 EUR2025 per ton CO₂, which corresponds to the upper end of the range reported in ZEP (2011). Combining all the cost components, the total cost of CCS per ton of CO₂ is in the range 82.1 EUR2025 (\underline{c}) to 217.3 EUR2025 (\bar{c}) per ton CO₂. The unit cost in the baseline model is the midpoint 149.7 EUR2025/tCO₂

Possible cost savings lx^γ

The possible cost savings because of more firm's adoption CCS in the non-linear model is given as lx^γ . There are three main sources of potential cost savings in CCS. Namely, learning-by-doing, economies of scale in storage and shorter transport distances as infrastructure expands when more firms invest in CCS. In the Longship project, (Gassnova SF 2020) applied learning curves for post-combustion flue gas desulphurization system, which historically displayed average learning rates of 12% for capital costs and 22% for

operation and maintenance costs. With the capture cost outlined above, a learning rate of 12% implies that the capture cost could fall from 36.4 to 18.0 EUR2025 per ton CO₂ for firms at the low end, and from 171.6 to 84.7 EUR2025 for the high end. For storage, ZEP (2011) reports costs per ton of CO₂ for different sizes of the storage facility. The cost per ton of CO₂ is 22.7 EUR2025 for a facility with 40 MtCO₂ capacity, 13.5 EUR2025 for 66 MtCO₂ and 5.7 EUR2025 for 200 MtCO₂. Scaling up from a small to a large storage facility, assuming full capacity utilization, reduces storage costs by as much as 17 EUR2025 per ton CO₂. For transport, Golombek et al. (2023) derive the relationship $n = \sqrt{\frac{txES}{a}}$, where n is number of terminals, x is share of firms investing in CCS, S is the circumference of a circle, and E is total emissions. Using the formula and the estimates for E and S in Golombek et al. (2023),¹⁰ we can calculate the number of terminals, and thus the average transport distance, as a function of the share of plants investing in CCS. Moving from zero to full adoption of CCS could reduce transport costs by 16.2 EUR2025 per to CO₂. Combining these elements provides an indication of plausible magnitudes for the parameter l and the exponent γ . The total potential cost reduction at the low-end of the cost interval (\underline{c}) amounts to approximately 50 EUR2025 per ton CO₂, which we take as our estimate for l as we do not want the cost to be negative. The exponent is set at 0.5.

Carbon tax τ

In the first half of 2025, the average EU ETS price was 72.5 EUR2025 per ton of CO₂ (Energi og Klima, 2025). BloombergNEF (2024) projects nominal EU ETS prices of 80 GBP in 2025, 150 GBP in 2030 and 194 GBP in 2035 (per tCO₂), corresponding to approximately 96 EUR2025 in 2025, 154 EUR2025 in 2030, 173 EUR2025 per tCO₂ in 2035 under an assumed nominal growth rate of 3 percent per year. For our analysis, we assume an EU ETS price of 96 EUR2025 per tCO₂ in line with this.

Maximum government subsidy s

The government's maximum willingness to pay for a subsidy can be interpreted as the maximum willingness to pay to achieve a given climate target. If the government wants to implement a cost-efficient climate policy, then this also coincides with the marginal cost of achieving the climate target. In the impact assessment report accompanying the communication *Securing our future – Europe's 2040 climate target and path to climate*

¹⁰ This formula corresponds to the market outcome with regulated storage.

neutrality by 2050, which outlines the EU’s strategy for reaching climate neutrality, the (European Commission, 2024c) evaluates a range of scenarios that all achieve climate neutrality by 2050 but differ in their 2040 emission levels. In each case, the carbon value is reported as the marginal abatement cost per ton of CO₂, ranging from 160 to 290 EUR₂₀₂₃. Interpreting these carbon values as the government’s maximum willingness to pay for abatement, it provides a benchmark for the maximum subsidy level. The lowest carbon value is 164.4 EUR₂₀₂₅ in 2040, and the highest is 297.9 EUR₂₀₂₅ in 2040. They do not provide carbon values for 2030, so we take the maximum subsidy to be 164.4 EUR₂₀₂₅ per ton CO₂.

*Social cost of carbon τ^**

There are many estimates of the social cost of carbon, and there is great uncertainty around the estimates. See for example Tol (2023) for a recent meta-analysis of how estimates have evolved over time. We use estimates from Rennert et al. (2022) which incorporate the latest scientific and economic research. The preferred mean estimates in Rennert et al (2022) is \$185 per ton of CO₂, which when converted into EUR₂₀₁₅, is 197 EUR₂₀₂₅ per ton CO₂.

Attitude parameter

Estimating the attitude parameter is challenging because there are very few studies that provide quantifications that are suitable. To approximate a , we assume that the payoff of the individual corresponds with their willingness to pay for CCS, thus $(1 + \gamma)\tau^*a - (1 - \delta x)((\tau^* + b)p + s) = WTP_{CCS}$. Mean WTP for CCS in the UK is 109.8 EUR₂₀₂₅. According to a survey in Anders et al (2024), 43% of the respondents strongly supports or somewhat supports CCS. Using the UK ETS price in 2024 as a proxy for the subsidy (74.6 EUR₂₀₂₅ per ton CO₂) and setting $x = 0$, we get $(1.43)\tau^*a - ((\tau^* + b)p + 74.6) = 109.8$. Inserting values for τ^* , b and p and solving for a yields $a = 0.67$.

Warring & Longo (2025) explore how environmental attitudes influence WTP for CCS. In the study, mean WTP is 95.5£, with a 95% confidence interval of 85.3 to 105.8£ suggesting a range of a that may be $\pm 10\%$. However, they also study how WTP for CCS is influenced by environmental beliefs. For example, individuals with strong environmental attitudes were willing to pay 5-18% more for CCS than mean WTP, while those who did not have a strong attitude were willing to pay 3-20% less. For illustration purposes, heterogeneity is here assumed to be slightly higher at $\pm 20\%$ of a .

Perceived risk of leakage p

CO₂ leakage could occur during capture, temporary storage, transportation, injection, or permanent storage. The likelihood of leakage depends on geological, technical, and regulatory factors, as well as the time horizon and the monitoring systems in place. IEAGHG (2025) examines scenarios where CO₂ might leak from geological storage and identifies levels of leakage that can be considered tolerable for CCS to deliver a net climate benefit - that is, when the amount of CO₂ permanently stored outweighs any leakage. They conclude that if leakage rates were to exceed 0.0001–0.001 per year, stored CO₂ would, over time, re-enter the atmosphere at a scale comparable to avoided emissions. Because large-scale CO₂ storage is still relatively new, there is very little data on actual leakage rates. We therefore instead assume that no government would authorize a storage site with estimated leakage rates above this level and set the objective risk of leakage at the average, namely $p^* = 0.00055$. From behavioral economics, it is well established that individuals do not weigh probabilities as expected utility theory suggests. More specifically, they tend to overweight small probabilities such as $p^* = 0.00055$. To capture this, we transform the risk using the probability weighting function of Tversky & Kahneman (1992), i.e.,

$$p = \frac{p^{*\theta}}{(p^{*\theta} + (1-p^*)^\theta)^{\frac{1}{\theta}}}.$$

For losses, they estimate $\theta = 0.69$. Substituting our value of p^* , the perceived probability of leakage becomes $p = 0.0548$.

Perceived cost of leakage ($\tau^ + b$)*

We distinguish between the global cost and perceived local cost of CO₂ leakage. At the global level, leakage contributes to climate damage, which we value at τ^* per ton of CO₂. At the local level concentrated leakage can have an impact on human health, animals, groundwater and ecosystems. When it comes to the local cost of CO₂ storage, the public may also be concerned about the potential for induced seismicity as well as potential for CO₂ leaks. Offshore storage is different than onshore storage as the ocean can buffer and disperse CO₂, and there are no human settlements close by or above. We were unable to find any studies estimating the actual cost of CO₂ leakage or what individuals may perceive the cost to be. Lee & Choi (2018) estimate the willingness to pay (WTP) to avoid CO₂ leakage for a CCS project in South Korea. Respondents were asked how much they would pay per year to fund a monitoring system for an offshore CCS project in the Ullung Basin. The reported annual mean WTP was 2,645.9 KRW (USD 2.4). Assuming an average lifespan of 30 years and a

discount rate of 2 percent, the lifetime WTP for the monitoring system corresponds to about 58 EUR2025 per household. We use this as an estimate for the perceived cost of leakage in our model (b).

In our framework, costs and benefits are implicitly measured per ton of CO₂, but in Lee & Choi (2018), WTP is for the overall monitoring system. They give no information on the amount of CO₂ captured in the project, but the Ulleung Basin is also the site of a CCS demonstration project at the Donghae Gas Field, which aims to scale up to 1.2 Mt per year (0.4 Mt in the demonstration phase). Spread over these volumes, the implied WTP per ton of CO₂ over a lifetime is close to zero. On the other hand, the perceived cost of leakage may be shaped by recent events or media coverage. One example is the CO₂ pipeline rupture in Satartia (US) in 2020 that released 31,405 barrels of CO₂ (equal to about 5,063 tons) causing the entire town to be evacuated and sending 45 people to the hospital. The company was fined USD 2.4 million for obstructing federal inspectors (InsideClimate News, 2025). This corresponds to roughly 504 EUR2025 per ton of CO₂ leaked.

Learning parameter δ

We model how the perceived cost of CCS evolves as the share of plants investing increases through the expression $(1 - \delta x)((\tau^* + b)p + s)$. Empirical evidence indicates that positive public attitudes toward CCS increase with knowledge. In a comparative study across UK, Canada, Norway, Germany and Netherlands, the support for CCS increased from 23 percent among those who had never heard of the technology to 73 percent among those who reported they knew a great deal about it (Anders et al., 2024). Although it is difficult to translate these findings directly into our parameter δ , the results suggest that more knowledge of CCS increases the likelihood of public acceptance, implying that at least $\delta > 0$. Similarly, among those who stated they know a great deal about CCS, 27 percent did not support CCS. Thus, even as x approach one, it is reasonable to assume that $1 - \delta x > 0$. Otherwise, the perceived cost of CCS would be zero if all firms invest in CCS. Hence, $\delta \in (0,1)$.

In Waring & Longo (2025), familiarity with CCS increased WTP with 11.6%. Beliefs about effectiveness of CCS, which also can come from learning, increased WTP from 80.2 £ among those who thought it was ineffective, to 105.98 £ among those who thought it was effective, which corresponds to an increase of 32%. Assuming this directly corresponds to a decrease in the perceived cost due to learning then $\delta \in (0.12,0.32)$. We use $\delta = 0.32$ in the basic model

and $\delta = 0.12$ for heterogenous individuals as beliefs about effectiveness also can be captured through heterogeneity.