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The Insurability of the CO2 Leakage Liability

Master's Thesis

Master's Degree Programme in Science, Technology & Policy
Climate Finance and Policy Group
Weather and Climate Risk Group
Swiss Federal Institute of Technology (ETH) Zurich

Supervision

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August 8, 2024

Eidgenössische Technische Hochschule Zürich
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Abstract

Geological storage of CO_2 has been employed as a climate mitigation technology for more than 25 years, and in the EU there has been a comprehensive regulatory regime in place since 2009. Despite this, there are as yet no documented examples of the CO_2 leakage liability being commercially insured in the EU. This raises the question of whether there are fundamental insurability barriers facing the CO_2 leakage liability that could be holding back the CO_2 storage method's growth. In addition, the planned integration of removals, some of which rely on geological storage, into the EU's climate policy regime poses the question of whether and how insurance could play a role in safeguarding carbon storage integrity. This thesis takes the insurability criteria of Berliner (1982) as a framework and undertakes a systematic comparison of the insurability of the CO_2 leakage liability with analogues from established insurance markets, namely upstream oil & gas insurance and pollution insurance. It is found that there are no fundamental barriers to insurability facing the CO_2 leakage liability, but with challenges emerging from the regulatory environment. In particular, the combination of the low frequency of loss occurrence with the EU ETS price (EUA) volatility presents a challenge to insurability. An industry-wide in-kind reinsurance pool that holds EUAs as reserves could mitigate this challenge. More broadly, insurance can contribute best to the policy goals of scaling up geological storage and integrating removals into EU climate policy when its risk-pricing function is supported.

Acknowledgements

This thesis is the product of nearly two years of conversations I had with a great variety of people across different fields: among others CCS policy, emerging risks, carbon removal, and of course (re)insurance, wherein I slowly understood that there was a large gap in understanding, most of all in myself, about how to think about insurance in the context of carbon storage and what it could be useful for. Moreover, I heard again and again about the challenges with the liability of geological storage in the EU: this piqued my interest as an relevant policy conundrum with any number of possible outcomes. I would like to express my heartfelt thanks to all the people I had these conversations with and who nudged me towards tackling this problem in my thesis. I no particular order, I would like to thank Paul Zakkour, Mischa Repmann, Eadbhard Pernot, Kenneth Oye, Peter Freudenstein, Hélène Schernberg, Mark Preston Aragonès, Sarah Hülsen, Wolf Heidug, Lu Meng, and Brooke Davies, and I would like to sincerely apologise to all those I have surely forgotten from this list.

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Contents

Chapter 1

Introduction

1.1 Context and research question

In 2015, the UNFCCC Conference of Parties (COP21), with representatives from nearly every country in the world, agreed to limit global warming to 1.5°C. Not to breach this temperature limit is a challenge: it implies a greatly restricted global carbon budget and a target to reach net-zero CO_2 emissions worldwide as early as 2050. Emissions reductions on this scale will first and foremost require accelerating the energy transition from fossil-fuelled to renewable energy systems, as well as deep sectoral emissions cuts in transport, buildings, agriculture and industry (Lee et al., 2023).

In this context, geological storage of CO_2 remains a crucial part of the portfolio of climate change mitigation actions in multiple sectors. Geological storage is the end-point of CO_2 captured in a wide range of different processes, commonly grouped under the term carbon capture and storage, or CCS. These processes range from CCS in energy generation, industrial applications such as decarbonising cement, aluminium and steel production, and direct removal of CO_2 from the atmosphere (so-called direct air carbon capture and storage, DACCS) among others.

For the purpose of this thesis, geological storage is taken to refer to the injection of CO_2 captured from the atmosphere or point sources in deep geological formations with the intention of storing it permanently. Because this thesis focuses on the insurability of leakage of stored CO_2 from geological formations, attention is given to those formation types with non-negligible leakage risk, i.e. depleted oil & gas reservoirs and saline aquifers. Geological storage with accelerated mineralisation, e.g. in basaltic (Carbfix in Iceland) or ultramafic (44.01 in Oman) formations are not considered, nor is injection of CO2 into geological formations without the intention of permanent storage, e.g. enhanced oil recovery.

Geological storage of CO_2 has been ongoing for more than 25 years. The Sleipner CCS project in the Norwegian North Sea was the first large-scale international demonstration of CCS and since 1996 has stored more than 20 million tonnes of CO_2 (Ma et al., 2022). Despite this long history, CCS has not played the role in climate change mitigation originally envisioned by its supporters. In Europe, as of 2024 only 5 geological storage sites are operational (Global CCS Institute, 2024). Despite the volume of technical knowledge generated about safely implementing geological storage, significant economic, institutional and regulatory barriers remain (Lau et al., 2021).

One challenge is handling the liabilities related to CO_2 leakage. When CO_2 is stored in geological formations such as disused oil & gas reservoirs and saline aquifers, permanent storage cannot be guaranteed beyond all doubts (Metz et al., 2005). Especially when site selection, CO_2 injection or well decommissioning are done poorly, the risk of CO_2 leakage and return to the atmosphere becomes important. This leakage risk can potentially remain for decades after injection has stopped and until the CO_2 becomes permanently stabilised. In the EU context, there is a comprehensive but largely untested liability regime in place around geological storage of CO_2 that consists of the ETS directive, the CCS directive, and the attendant guidance documents (Dixon et al., 2015).

However, there is a perception in the industry that difficulties handling liability are a reason that CCS has disappointed expectations over the past 15 years, with the climate liabilities (i.e., damage to the global environment) posing particular problems (Havercroft, 2019). In particular, the hesitancy of insurers to underwrite such liability has been noted, sparking fear that this novel risk is inherently uninsurable due to factors such as long timescales and lack of knowledge (Wilson et al., 2009).

As will be explored in greater depth in chapter 3, the EU's liability regime included a role for insurance from the beginning. That no insurance market for the CO_2 leakage liability from geological storage exists therefore poses a challenging question: **Are there fundamental insurability barriers facing the CO_2 leakage liability that have hindered the development of an insurance market for this risk, and therefore also the sector as a whole?** If so, did the EU make a mistake in designing its liability regime with a clear expectation that insurance could play a role that it fundamentally could not? This is the first of two policy challenges this thesis contributes to.

The second policy challenge is more future-looking. As of November 2023, net zero targets covered close to 90% of global emissions (Climate Action Tracker, 2023). Net-zero emissions means any remaining emissions are balanced by an equal number of permanent removals: this implies a dramatic scale-up of the amount of permanent carbon removal carried out (Lee et al., 2023). The EU has a target for climate neutrality by 2050, also implying a dramatic scale-up of removals within EU borders (EU Commission, 2024). In this context, geological storage can be expected to play an important role alongside permanent removals utilising other types of carbon sink, each with different risk profiles of leakage. In the EU, new liability mechanisms will have to be implemented in the process of integrating removals into the climate policy regime (Meyer-Ohlendorf, 2023). Understanding what role insurance can best play in an evolved EU climate liability regime is the second motivating policy challenge of this thesis.

1.2 Structure of the thesis

In order to answer the research question, the thesis draws on methods from the applied insurance economics literature, in particular that found in *The Geneva Papers on Risk and Insurance*[1]. The insurability criteria of Berliner (1982) have been applied numerous times in this research area to analyse the insurability of new risks, from the impacts of climate change (Charpentier, 2008), to pandemics (Braun et al., 2020), cyber risk (Biener et al., 2015), microinsurance markets (Biener and Eling, 2012) and more besides (see section 4.2).

In this case, the insurability criteria of Berliner (1982) are used as a framework in which to conduct a systematic comparison of the CO_2 leakage liability with real-world analogies from different insurance markets.

Chapter 2 Background: The leakage risk of CO_2 from geological storage gives the technical background to geological storage, the CO_2 leakage risk and the current state of monitoring practices. The important distinction between geological and well leakage pathways is introduced and explored. However, the technical risk is only half the story - to understand the CO_2 leakage liability as a whole the regulatory context must be understood.

Chapter 3 Research case: The climate liability regime for geological storage in the EU is a detailed analysis of the climate liability regime in the EU and describes the resultant shape of the CO_2 leakage liability. In addition, this chapter briefly discusses the current policy debate around the future of the EU

[1]The Geneva Papers on Risk and Insurance - Issues and Practice | palgrave

climate liability regime and how that relates to the CO_2 leakage liability in order to frame the later discussion.

Chapter 4 Insurability & methodology first gives theoretical background to the role of insurance in society, followed by a review of the literature that uses the insurability criteria of Berliner (1982), before a deeper explication of the method used in the analysis. The chapter ends by providing background to the individual insurability criteria, serving to explain the role they play and justify certain methodological choices taken in the thesis about how to use them.

Chapter 5 Analogies from other insurance markets provides background to the analogies used for comparison in the analysis. Additionally, there is a discussion of risk transfer in carbon credit markets and a broader discussion of the different structures used across the insurance industry to solve different risk transfer problems. These latter two sections form a basis for the discussion following the analysis.

Chapter 6 Analysis: the insurability of the CO_2 leakage liability contains the core systematic analysis, while chapter 7 Discussion & policy implications summarises the results of the analysis before discussing how the results answer the research questions posed in section 1.1. This involves a discussion both of what policy and market solutions there are to strengthen the insurability of the CO_2 leakage liability, and what further public policy goals insurance for the CO_2 leakage liability could contribute towards.

Chapter 2

Background: The leakage risk of CO_2 from geological storage

2.1 Introduction to geological storage

Reservoirs of CO_2 form naturally in the subsurface as part of the same process by which oil and gas reservoirs form, namely as organic matter is subject to decomposition, heat and pressure. Much CO_2 used in enhanced oil recovery is extracted from production wells from these reservoirs (Gozalpour et al., 2005), and some gas reservoirs contain high concentrations of CO_2 which must be removed after extraction (so-called sour gas; Burgers et al. (2011)). After extraction and separation, this CO_2 is usually vented into the atmosphere but in some jurisdictions, where these emissions are taxed, it is reinjected into the subsurface: this has been taking place at the Sleipner gas field since 1997 (Torp and Gale, 2004).

Subsurface reservoirs are (collections of) geological units, often of porous rocks such as sandstone, where there is sufficient space between sand grains to hold fluids, and sufficient connection between these pores for the fluid to flow (Dabiels et al., 2023). The fluid can be hydrocarbons such as oil or gas, or other fluids such as water or CO_2. For reservoirs to stably hold buoyant CO_2 over geological time, there is usually a structural trapping mechanism whereby the migration of the CO_2 to other geological units or the surface is prevented by the presence of impassable structural features, such as an impermeable caprock or fault system (Metz et al., 2005). Over time, additional trapping mechanisms become effective, as the capillary forces of the CO_2 in the pores hinder migration (residual trapping), the CO_2 dissolves into any fluid already present (solubility trapping), and eventually (usually after 1'000s-10'000s of years) the CO_2 mineralises, leaving the carbon permanently trapped (Fig.

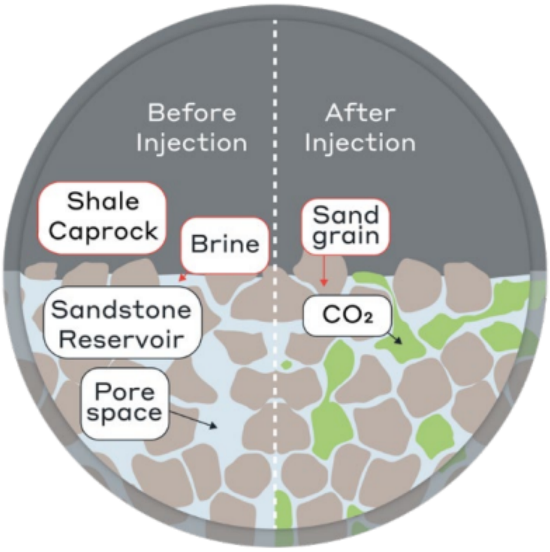

Figure 2.1: Diagram to illustrate how CO_2 is stored in a saline aquifer after injection. From Dabiels et al. (2023)

2.2).

Despite CO_2 being pressurised into supercritical phase (more dense than gaseous CO_2) before injection, it is still buoyant in the subsurface, meaning that storage operators must apply an overpressure in order to inject sufficient quantities of CO_2 (Metz et al., 2005). When CO_2 is injected for long-term storage, there are two main types of site that are used: depleted oil & gas reservoirs and saline aquifers (Dabiels et al., 2023). Depleted oil & gas reservoirs are those which are no longer productive for hydrocarbon extraction; the extraction of hydrocarbons leaves behind low pressure pore space, meaning a lower overpressure is required for storage operators to inject CO_2. This, combined with the presence of structural trapping features that resulted in the accumulation of hydrocarbons over geological time, and the experience and knowledge related to such reservoirs owing to their former use, makes them attractive candidates for CO_2 storage. Saline aquifers are subsurface reservoirs (e.g. sandstone formations with structural seals) containing brine i.e. non-potable water. Because there has been no extraction from saline aquifers, they are usually less well understood than depleted oil & gas reservoirs and injection of CO_2 will necessarily lead to an increase in pressure above its natural level (Dabiels et al., 2023).

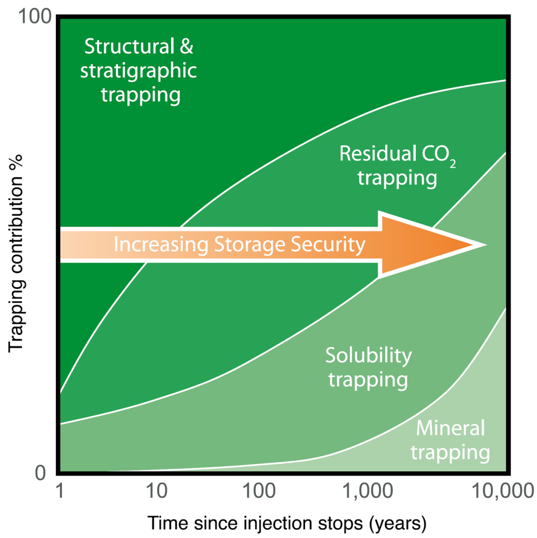

Figure 2.2: Schematic representation of the how the contribution of different trapping mechanisms evolves over time. From Metz et al. (2005)

2.2 Leakage of CO_2 from geological storage

If CO_2 is able to leave the storage reservoir, it might migrate directly to the surface and enter the atmosphere, or it might subsequently become trapped elsewhere in the subsurface, e.g. in a shallower reservoir. In some cases (e.g. how leakage is defined in the EU's CCS Directive) any event whereby CO_2 leaves the predefined storage area is defined as a leakage, while in other cases CO_2 is only defined as having "leaked" if it enters the atmosphere (European Parliament, 2009b). Nonetheless, in the EU climate liability regime, the climate liabilities (EUA surrender as described in in Chapter3, European Parliament (2009a)) only apply to CO_2 released into the atmosphere. Therefore, for the remainder of this thesis, leakage is defined as CO_2 previously injected into storage entering the atmosphere.

For CO_2 leakage to occur, there must be a leakage pathway. The leakage pathway might have existed since the commencement of injection, or it might come into existence after injection started, resulting from the injection process itself or a natural event. An existing leakage pathway can also be activated or worsened by these injection-linked or natural events. The remainder of this section analyses the most common leakage pathways and potential worsening events.

2.2.1 Well leakage pathways

Wells are man-made conduits for moving fluid between the surface and subsurface: CO_2 storage relies on injection wells for injecting CO_2 into the storage site and monitoring wells for measuring pressure and fluid properties at depth (whether the injected CO_2 or the surrounding brine). Also relevant are oil and gas exploration or extraction wells, which may have been formerly drilled in the storage site and subsequently abandoned (Dabiels et al., 2023).

In order to move fluids between the surface and sub-surface safely, wells rely on casings and cement that surround the conduit and valves to control pressure differences over the entire length (Dabiels et al., 2023). In addition, abandoned wells will have one or multiple cement plugs along the conduit to block fluid flow. The failure of any of these casings, surrounding cement, valves or plugs can breach the well integrity and increase the likelihood of CO_2 leakage. CO_2 leakage can occur through injection wells either from the injection stream or from already injected CO_2 in the storage reservoir. For monitoring and abandoned wells, leakage can occur from the already-injected CO_2.

Poorly constructed wells may have cracks or other flaws in the casing or cement, valves or other components that provide pathways for CO_2 migration out of the conduit during injection or vertically up the conduit (Zhang and Bachu, 2011). Poorly abandoned wells may also have imperfect plugs which allow for vertical migration of CO_2. Under certain conditions, or in the presence of impurities in the injected CO_2, the cement plug can degrade. Improperly abandoned wells present perhaps the most significant leakage pathway in otherwise secure storage sites (Benedictus et al., 2009).

2.2.2 Geological leakage pathways

Lateral migration

When CO_2 is injected into the storage formation, the CO_2 grows in lateral extent as it moves away from the point of high pressure, before moving upwards due to buoyancy. If the CO_2 is able to move laterally beyond the structural trapping of the caprock and find a route to the atmosphere, that is a potential leakage pathway (Gholami et al., 2021). The ability of the CO_2 to migrate laterally is limited by the residual CO_2 and solubility trapping mechanisms (fig. 2.2). The selection process for geological storage sites should avoid any sites where the caprock does not have sufficient lateral extent (Alcalde et al., 2021), Carpenter et al. (2011). Therefore, this leakage pathway is unlikely to be relevant in practice; more likely geological leakage pathways have to do with lack of integrity in the caprock itself.

Caprock diffusivity

The ability of CO_2 to diffuse through the caprock depends on the presence and size of interconnected pore space and the adherence of water to the rock grain surfaces (the so-called "wettability" of the rock: the better water adheres to the rock surface within pore spaces, the more resistance there is to CO_2 migration through the pore spaces; Gholami et al. (2021). Caprocks should be chosen based on their impermeability and certain common rock types such as shale are known to be highly impermeable. Permeable rock types should not be considered as caprocks, therefore this risk should not be relevant in practice.

Faults and fractures

Faults are planar discontinuities in the subsurface geology where there has been displacement between the two sides of the fault. On or close to the surface (in the "brittle zone") this displacement occurs through earthquakes, while deeper (in the "ductile zone") the displacement is more gradual and continuous. Fractures are discontinuities in the geology without displacement: networks of fractures can form in brittle rocks in response to tectonic deformation and provide a CO_2 leakage pathway (Gholami et al., 2021). Whether faults or fractures in the caprock act as a leakage pathway or an impermeable seal depends heavily on the caprock geology and depth, as well as the fault and fracture properties. Caprocks with a high proportion of clay or halite (rock salt) are self-sealing and impermeable while brittle rocks such as limestone may allow CO_2 migration above a threshold pressure.

2.2.3 Activating and worsening events

Pressure increase

The evolution of pressure over time in the storage reservoir upon commencement of injection varies throughout the volume of the reservoir. The pressure directly around the injection well peaks at the beginning of injection and typically stabilises at a high level for the remainder of the injection period (Vilarrasa et al., 2019). This is because the CO_2 has a low viscosity and should be able to move freely in a storage formation with high-enough porosity. The exception is when there are "injectivity" problems, i.e. the CO_2 is less mobile around the injection well than anticipated due to e.g. salt crystallisation triggered by the lower temperature of the injected CO_2 than the surroundings. This can lead to local spikes in pressure. In the rest of the storage formation, pressure typically increases with time as the CO_2 plume grows and the storage capacity of the formation is used up (Dabiels et al., 2023).

The likelihood of a leakage pathway activating and leading to an actual leakage of CO_2 from storage increases in every case with the pressure of CO_2 at the initiating side of the leakage pathway (Gholami et al., 2021). In the case of well leakage pathways, the likelihood of mechanical failure of plugs, casings or other barriers increases with pressure. Geological leakage pathways are similarly affected: lateral migration of the CO_2 plume and the rate of diffusion both increase with pressure. Additionally, increasing CO_2 pressure can induce seismicity and hence lead to activation or reactivation of new or existing faults and fractures, potentially inducing CO_2 leakage.

The sensitivity of leakage pathways to increase in pressure also depends critically on the past pressure evolution of the reservoir. When CO_2 is injected into depleted oil & gas reservoirs, the reservoir pressure is below its long-term stable level, hence increasing the pressure by injecting CO_2 is much less likely to activate leakage pathways, at least until the long-term stable (pre-extraction) pressure level is reached. This is different for saline aquifers where the reservoir pressure is already at its long-term stable level; any injection of CO_2 will increase the pressure beyond those experienced by the reservoir, meaning the behaviour of leakage pathways will be less certain. Also important is the fracturing pressure of the caprock: regulations typically require that operators ensure that the reservoir pressure is maintained at a level lower than the fracture pressure. A mitigating measure is to drill a second pressure-relief well to extract brine from the reservoir and dispose of it in another, hence maintaining the pressure level. This, however, comes with significant additional cost.

Induced and natural seismicity

There is always an existing stress field surrounding faults and fractures. There are multiple mechanisms by which injection CO_2 can alter this stress field or the properties of the faults and fractures to induce seismicity (Vilarrasa et al., 2019). Depending on the orientation of the faults and their surrounding stress field, increasing the hydrostatic pressure with CO_2 injection can bring the stress field of the fault to its activation threshold, or it can stabilise it. Additionally, because injection induces a pressure gradient in the reservoir (not merely hydrostatic pressure), new stress fields are imposed on existing ones. The lower temperature of injected CO_2 than the surroundings can lead to changes in the stress fields and mechanical properties in the surrounding rock. The mechanical properties of the rock might also change if there are chemical reactions between it an the CO_2

Induced seismicity is a general concern for CO_2 storage projects because of damage it can cause to property and opposition it can generate from affected communities (Vilarrasa et al., 2019). For leakage of CO_2 from storage, induced seismicity is potentially problematic because it can generate new or worsen existing leakage pathways. This could be due to the generation of new faults or fractures through which CO_2 leaks, increases in the permeability of existing faults (Gholami et al., 2021), or changes in the distribution of pressure throughout the reservoir which leads to activation of other leakage pathways.

These mechanisms by which induced seismicity can generate new or worsen existing CO_2 leakage pathways apply also to natural seismicity. Tectonic stress on the Earth's crust leads to natural stresses and tensions which release themselves in the form of earthquakes or other crustal deformation. In the case of natural seismicity, there would be concern mainly in areas with strong seismic activity. Endres et al. (1991) reports seismic activity weakening cement used in hydrocarbon extraction wells in California, and of earthquakes precipitating "movement along fault plans, allowing [methane] to migrate along these planes to the surface."

2.3 Monitoring for leakages

Monitoring, reporting & verification (MRV) are mandatory activities in the EU regulatory regime that seek to manage risks associated with geological storage sites, above all the risk of CO_2 leakage. MRV consists of taking relevant measurements (monitoring), verifying their integrity and reporting them to the regulator and potentially other interested parties, e.g. insurers. Monitoring is either shallow-focussed, being concerned with the surface or shallow sub-surface up to the depth of drinking water aquifers (a few hundred meters), or deep-focussed, aiming to understand the overall CO_2 plume and its surroundings, potentially kilometres in depth (Dabiels et al., 2023).

2.3.1 Deep-focussed monitoring

There are multiple deep-focussed monitoring methods, with seismic surveys being the best known. Seismic surveys are conducted by reflecting artificially-produced sound waves off of layers in the rock. The travel time of waves to surfaces and back to the receiver provides information about the structure and material properties of intervening rock layers. Sound waves travelling through rock saturated with CO_2 has a different velocity than rock saturated with brine, making seismic surveys ideal for monitoring the 3D shape of the CO_2 plume (Furre et al., 2017). At the Sleipner storage site, seismic surveys were conducted roughly every two years over a 20-year period to give a dynamic picture of the evolution and stabilisation of the CO_2 plume.

2.3.2 Shallow-focussed monitoring

Shallow-focussed monitoring differs significantly between onshore and offshore geological storage sites: both present challenges and opportunities for monitoring. Onshore sites are generally easier to access and traverse than offshore sites. However, there can often be greater heterogeneity in surface features, infrastructure and potential legal obstacles such as fragmented land ownership.

There are a wide variety of monitoring methods that can be applied for onshore geological storage sites. During the development of the monitoring plan for the Quest CCS project in Alberta, Canada, 56 different technologies were identified and assessed (Bourne et al., 2014).

Shallow-focussed offshore monitoring meanwhile presents a more challenging operating environment, although with the opportunity to "both 'see' and 'hear' emissions via bubble-streams" (Hannis et al., 2015) and detect changes in the seabed using sonar technology. Additionally, geochemical, geophysical and biological sampling can be conducted using autonomous marine vehicles (AUVs). The project *Energy Technologies Institute Measurement, Monitoring and Verification of* CO_2 *Storage* conducted between 2014 and 2018 used sonar and chemical sensors on an AUV was was able to detect small leaks of 10-50 litres per minute over a large area (Dean et al., 2020).

2.3.3 Summary

In general, while there is a wide variety of different monitoring techniques that could be employed and a long history of successful application of certain monitoring techniques (e.g. seismic surveys at the Sleipner storage site), there is only limited experience in putting these techniques together in a cost-effective way that maximises likelihood of detecting CO_2 leakages while minimising false positives. Storage site operators (who are charged with conducting the monitoring by the regulators) have an interest in minimising the cost of monitoring efforts, possibly at the expense of monitoring effectiveness. Compounding this, undetected leaks cannot be translated into liabilities for the operator: therefore, the regulator has a crucial role in ensuring the effectiveness of monitoring plans and their consistent application.

Chapter 3

Research case: The climate liability regime for geological storage in the EU

In 2005, the year the Kyoto Protocol first came into force, carbon capture and storage broke through into the consciousness of policymakers with the IPCC's 2005 Special Report on Carbon Capture and Storage (Metz et al., 2005). An analysis of regulations in place in 2005 part of this report found a lack of regulations worldwide that were tailored for geological storage. Within the EU, the legislative framework in 2007 put geological storage in an ambiguous position with regards to the treatment of CO_2 as a waste and whether it should be subject to existing landfill and water safety directives (Mace et al., 2007). In addition, aspects of the liability regime, particularly handling damage to the global climate, were missing outright. It is in this context that the EU Commission proposed the CCS Directive (European Parliament, 2009b) as well as amendments to, among others, the ETS Directive (European Parliament, 2009a) and the Environmental Liability Directive (European Parliament, 2004) to the European Parliament in 2007.

The ETS Directive and the Environmental Liability Directive together impose the liabilities for environmental damage associated with geological storage in the EU. That is, damage to the global environment and damage to the local environment respectively. In addition, there are third-party liabilities related to damage to health and property which are governed by the specific member state's laws, and liabilities (in the sense of legal obligations) related to operating and decommissioning of the site which are defined in the CCS Directive (Dixon et al., 2015).

The CCS Directive shapes the liability regime for geological storage in two important ways: first by defining the level of financial security the operator should have in place before beginning storage operations and second by giving guidance on when the storage site and associated liabilities can be transferred to the competent authority (CA, i.e. the local regulator). This on the one hand caps liability to the CA during the operator's tenure, eliminating risk from bankruptcy etc. and on the other hand caps liability to the operator over the long term, provided they act to ensure safe CO_2 storage. It does this by defining conditions for transfer and by laying out the requirements for operators to gain a storage permit from the CA.

The EU decided to include geological storage of CO_2 in the ETS in order to, firstly, properly incentivise CCS deployment and thereby capture the positive externalities of deploying CCS and, secondly, to address the global environmental damage of leakage of CO_2 from geological storage. This would mean that CO_2 emitters could on the one hand avoid paying fees under the ETS if their CO_2 was captured and stored, thereby creating a financial incentive for CCS. On the other hand, in the event of leakage of CO_2 from geological storage, the storage operator must surrender an equivalent amount of EUAs (EU Allowances) or face a fine of EUR 100/tonne in addition to the cost of the EUAs. The size of the CO_2 leakage liability therefore depends on the EUA price, which in turn depends on the overall functioning of the ETS. Therefore it is worthwhile now to look into that in detail.

3.1 The EU Emissions Trading Scheme: creating climate liabilities

The EU ETS is a climate liability regime insofar as it creates obligations for certain greenhouse gas (GHG)-emitting facilities, based on their GHG emissions. On an annual cycle, these facilities must purchase and retire EUAs (EU Allowances) sufficient to cover their emissions or face additional fines. The EU ETS is the main policy instrument for the EU to meet its emissions reduction targets, in 2023 covering 45% of the EU's total GHG emissions. These emissions are in the categories of power generation, industry, aviation and international maritime transport, and will expand to cover emissions from buildings, road transport and other sectors later in the 2020s. The expressed goal of the ETS is "to promote reduction of GHG emissions in a cost-effective and economically efficient manner" (European Parliament, 2009a).

The rationale behind the EU ETS is that through a trading scheme, the most economically efficient allocation of remaining emissions should be found. The ETS relies on the trading of EUAs which permit the emission each of 1 tonne of CO_2 equivalent (tCO_2e). The supply of EUAs is determined top-down by the EU's emissions reduction target of 55% reduction compared to 1990 levels by 2030, meaning the ETS emissions cap will decrease by 62% compared to 2005 levels by 2030. The primary way of allocating such allowances is through auctions (70% in 2020) which are held on a daily basis throughout the year. In addition, free allowances are allocated by member state governments, although these will be phased out by 2027. Allowances are also traded in secondary markets by licensed entities who do not own GHG-emitting facilities. Revenues from the EUA auctions are collected by member state governments and and both distributed to member states and form the EU innovation fund. In each case, the revenues are used to fund further climate mitigation measures and redistribute funds to the population in other forms.

The EUA price primarily emerges through the balance of supply and demand in the ETS. Supply is directly connected to the policy ambition of member states with respect to emissions reduction. It is the outcome of negotiations in the European Parliament over the EU's emission reduction targets. Demand, on the other hand, depends on the actual level of emissions covered by the ETS, which is an outcome of a complex of economic and technological factors, as well as the expectations of future demand developments by speculators in the market.

The main drivers of EUA price have been studied and modelled in detail (Lovcha et al., 2022). In the short term, the EUA price is driven by the actions of speculators. EUAs can be "banked" if unused i.e. transferred from one year to the next, meaning actors who expect the EUA price to increase can hold them and hope to generate arbitrage profits. Over the medium term, fossil fuel prices and economic activity are the most important drivers. The relative level of fossil fuel prices determines the extent to which facility operators switch between more and less carbon-intensive fuels. Economic activity influences the EUA price through the overall demand for carbon-intensive goods and services throughout the economy. Lovcha et al. (2022) found that the link between economic activity and EUA price has diminished over time, suggesting the EU is successfully decoupling economic activity from GHG emissions. Over the long term, policy drives the EUA price. Policies that incentivise low-carbon alternatives to electricity generation, transport, or activities in other covered sectors will decrease the demand for EUAs. In addition, there are market mechanisms that aim to dampen sharp increases in the EUA price, namely the Market Stability Reserve, which has a stock of EUAs it can release to the market when the rate of price increase is above a certain threshold.

Overall, long-term EUA price developments contain information about attempts to mitigate climate change: on the one hand, the political ambition to tackle it (which presumably will track with actual and expected damage) and on the other, the costs of fighting it (which means the costs of avoiding such damage). Its developments follow large-scale real-world processes. To this extent it is a climate liability, addressing the damage caused to the global environment by GHG emitters covered by it.

3.2 The CCS Directive: shaping the CO_2 leakage liability

Directives passed by the European Parliament mandate only the minimum requirements of the legislation member states should then pass in their national laws. Therefore, in addition, the EU Commission publishes guidance documents that are not legally binding but offer guidance to national lawmakers and civil servants on how to implement the directives. There are currently four guidance documents to the CCS directive. EU Commission (2011): guidance document 1 (GD1) - CO_2 Storage Life Cycle Risk Management Framework, GD2 - Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures, GD3 - Criteria for Transfer of Responsibility to the Competent Authority, GD4 - Financial Security and Financial Mechanism. GD1 and GD2 offer guidance on the technical details of how member states can manage permitting, monitoring, modelling and reporting. GD3 and GD4 are more important for shaping the liability regime, covering the transfer of liability to the Competent Authority (CA - the local regulator), and the financial security that should be in place for a permit to be issued. As of early 2024, the EU Commission is updating the guidance documents and has contracted certification and standards body DNV to lead the update process with stakeholders. The way the CCS directive and the corresponding Guidance Documents shaped the liability regime will now be examined.

3.2.1 Minimising the potential liability: permitting

Art. 4 (4) of the CCS directive (European Parliament, 2009b) states: "A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist." Art. 8 (1) further states that for a member state to grant a storage permit, all relevant requirements of the directive must be met. Therefore, the permitting process should already exclude potential storage sites where there is a significant risk of leakage. This is the first step in shaping the potential liability, as the member state is able to limit the risk by only issuing permits to sites with no significant geological or well leakage pathways.

3.2.2 Capping liability to operator: transfer to CA

Art. 18 of the CCS directive covers the transfer of responsibility to the CA. It states that CAs may approve the transfer of a closed geological storage site (i.e. a site where injection has stopped, the site sealed, and the injection facilities removed) once the CA is convinced that the CO_2 is completely and permanently contained. Despite a reference to a minimum period of 20 years, it is actually criteria-based, not time-based, since the CA is able to shorten the period from 20 years if they are convinced the CO_2 will be completely and permanently contained. In addition, the operator must fulfil all their financial responsibilities for the post-closure period (Financial Mechanism, Art. 20). The conditions for showing complete and permanent containment include conformity of CO_2 behaviour with models and absence of detectable leakage. GD3 suggests that a minimum time since the last detected leakage should have elapsed. This will depend on the member state, but 10 years is suggested. The consequence of this is that a leakage event close to the first possible date of transferring responsibility will push back that date, leading to additional expenditures in site monitoring and maintenance, and also to increased length of exposure to CO_2 leakage liability. Therefore, the financial risk exposure to operators from CO_2 leakage risk is greater than just that associated with the initial leakage.

3.2.3 Capping liability to the public: Financial security

The CCS Directive, Art. 19, establishes that operators shall have in place "financial security (FS) or any other equivalent" when they apply for a permit, in order to ensure that any obligations that arise can be met, particularly in the case that the operator is unable to meet them themselves e.g. bankruptcy or revocation of permit. This aims to protect the public from the situation where liabilities from geological storage are too great for the operator, leading them to declare bankruptcy, thereby transferring the burden of maintaining the site or correcting any leakages to the public. However, this article 19 provides hardly any further detail about what member states should accept as financial security and how they should calculate it.

	(Reasonably) certain in amount	**Uncertain in amount**
Certain likelihood of occurrence	Monitoring and reporting costs, site decommissioning costs	None
Uncertain likelihood of occurrence	Corrective measures (well closure in case of leakage)	Surrender of EUAs in case of leakage

Table 3.1: Overview of the difference liabilities covered by the FS, according to certainty of amount and occurrence

This is then taken up by GD4.

The FS exists primarily to be drawn from in the case that the operator is unable to meet its obligations. Once all the operator's obligations have been discharged, i.e. after transfer of the storage site to the CA, the FS no longer needs to be maintained e.g. any funds can be returned to the operator, or any insurance policies need not be renewed. GD4 lays out the types of financial instruments potentially suitable for FS; these range from capital provided by the operator and ring-fenced, e.g. in a trust fund, escrow, or given directly to the CA, to guarantees of capital provided by third parties e.g. bank guarantees, surety bonds and insurance.

The obligations to be covered by the FS include both those that are (reasonably) certain or uncertain in amount and those that are certain or uncertain in likelihood of occurrence. These are summarised in table 3.1. GD4 suggests that different sorts of obligations would be most efficiently met by different sorts of FS e.g. own capital for the fixed and certain obligations and insurance for the fortuitous obligations, particularly the EUA surrender obligation.

The CA determines the amount of FS that is appropriate for issuing a permit. In the case of the CO_2 leakage liability, the size of the liability depends on the EUA price. GD4 therefore suggests that the CA uses a current or reasonable short-term estimate of the EUA price to calculate the liability. Additionally, GD4 suggests using a "reasonable worst case", i.e. where the probabilitly that the size of a given leakage exceeds that amount is sufficiently low. Note this is not the same as the expected value (or risked cost) of the leakage, which would multiply the likelihood of a leakage occurring with its average (mean) size. Rather it means, given a leakage has occurred, what is a size that will only be exceeded in X% (e.g. 5%) of cases.

This is a particularly important point, as it means operators are obliged to fully cover their CO_2 leakage liability without taking the probability of occurrence into account. It is a prudent formulation from the regulator's perspective, as it protects the public from paying for CO_2 leakages in all cases but those where the size of the leakage is above a certain threshold. However, it creates a burdensome requirement for operators to make significant amounts of capital available with a low probability of usage. This is one of the key points potentially up for revision in the updated guidance documents.

The CA is required to regularly reassess the amount of FS required to reflect the potential liability. In the case of the CO_2 leakage liability, this means if the reasonable worst-case of leakage size (not occurrence likelihood) is reassessed, or if the EUA price changes, the CA should request an updated amount of FS. GD4 suggests reassessment of the FS every 3-5 years.

3.3 Clarifying the research question: Challenges of the CO_2 leakage liability in the EU

Operators who intend to inject CO_2 into geological storage in the EU must first seek a permit from the competent authority. This first step should ensure that geological storage should only commence in sites which are sufficiently well-understood and which do not have any potentially significant leakage pathways (geological or well). If these conditions are fulfilled, the storage site should resemble those studied in Dabiels et al. (2023), i.e. the expected worst case losses of CO_2 over the lifetime of the site would be approximately less than 0.1% of the total capacity. This expected worst-case loss is small; in itself, it should not present major barriers for operators to make the business case for storage. However, there are two difficulties that arise due to the particular form of the liability regime surrounding geological storage: the uncertain and uncapped nature of the liability due to linkage with the EU ETS and the requirement to post financial security for the reasonable worst-case leakage scenario, not the expected (or risked) worst case leakage over the lifetime.

The EU ETS linkage means that every tonne of CO_2 injected into storage negatively exposes the operator to EUA price developments for decades to come until the storage site is transferred to the CA. The EUA price is fundamentally uncapped, meaning the liability for storage is technically unlimited. This unlimited liability attached to geological storage in the EU has become spectre haunting the industry for the past 15 years, with some potential operators claiming that it is a critical issue that scares away investment into the whole CCS value chain (Havercroft, 2019). However, it is simplistic to talk about the EUA price as uncapped in practice. The price follows large-scale real-world economic and technological processes, within political bounds. The EUA price will respond to the interplay between the mitigation options available in the EU and the political will to implement new policies or further limit the remaining carbon budget. Moreover, there is political interest in keeping the EUA price within reasonable bounds, using measures such as the Market Stability Reserve. Therefore, liabilities connected to the EUA price, while uncertain, are not realistically unlimited. A prudent investor could assess how the business case fares in realistic EUA price development scenarios and therefore make an informed decision. Many business cases across a wide variety of sectors are exposed positively or negatively to developments in the EUA price over decades and nonetheless attract investment. This variability nonetheless becomes challenging from the perspective of insurers, as explored in section 6.3.1.

The requirement to post financial security presents a different problem. Because the amount of financial security does not take the probability of occurrence into account, it can be very large. In the case of the ROAD CCS project in the Netherlands, cancelled in 2017, the amount of FS calculated by the CA was more than EUR 60 million, compared to a total capital investment of EUR 30 million for the project (Rycroft and Wildenborg, 2020). The critical issue here is whether the capital posted can be used for other purposes while it is not needed for the project. This depends on the financial instrument used, but a key case to consider in this light is insurance.

The current role of insurance in the CO_2 leakage liability regime in the EU

The basic business case of insurance is that by making capital available for a large number of potential losses, the same capital can be used to provide security for these events, at least to the extent that their occurrence is independent. As the number of potential losses an insurance company covers grows, the amount of capital they must keep available approaches the expected value of the losses, i.e. the risked cost. This means that while, in the case of the CO_2 leakage liability, the operators are not able to take the probability of leakage occurrence into account when posting financial security, an insurance company is able to do so to the extent that they cover a sufficient number of other independent risks (not necessarily of the same type). Therefore, once there is a competitive market for suitable products to cover the

CO_2 leakage liability, the burden of covering the worst case scenario without taking probability of occurrence into account will disappear. Until that point, insurance companies will be competing with far less favourable forms of financial security which entail greater capital lock-up, meaning they can charge higher premia, which should encourage them to enter the space.

According to impact assessment documents compiled by the EU Commission for the CCS directive, the climate liability regime for geological storage in the EU was designed in conversation with insurance companies, and with insurance as a crucial part of the liability regime. The subsequent lack of insurance products developed therefore could speak to deeper problems with the insurability of geological storage. Alternatively, there could be another explanation such as lack of demand for insurance products due to the lack of a business case for geological storage overall. Answering these questions can indicate to policymakers whether the existing liability regime is fit-for-purpose, or whether it is too onerous for operators to the benefit of the public. The remainder of the thesis attempts to answer the question of whether there are fundamental insurability challenges facing the CO_2 leakage liability.

3.4 The future of the EU climate liability regime

3.4.1 Principles for relating emissions reductions, removals and geological storage

If one tonne of CO_2 is removed from the atmosphere and stored permanently, or at least with a duration longer than the lifetime of CO_2 in the atmosphere, the benefit to the climate should in principle be the same as preventing one tonne of CO_2 from entering the atmosphere. It is on this basis that the world has adopted net-zero emissions targets in order to halt temperature rise (Lee et al., 2023). This also means that in principle, if there is a leakage of CO_2 from geological storage, removing an equivalent amount of CO_2 and storing it permanently should remediate the damage to the climate.

This principle of equivalence between removals and emissions does not always hold; there are a number of reasons why reductions and removals should not be treated equivalently from a climate policy perspective. An important reason is that removals can have varying degrees of permanence or risk of reversal: especially where the expected duration of storage is lower than the atmospheric lifetime of CO_2, as is the case with many nature-based methods, removals have a lower benefit to the climate than reductions. In addition, there are challenges relating to ensuring high-enough quality of storage, locking in industrial development pathways that rely on removals and high uncertainty about the ability of removals to deliver climate benefits at scale (Meyer-Ohlendorf, 2023).

3.4.2 Options for integrating removals into EU climate policy

The currently in-force climate liability regime around geological storage in the EU is centered around point-source carbon capture and storage, i.e., preventing fossil CO_2 from entering the atmosphere and storing it in permanent storage. Penalties are then applied through the ETS for releasing carbon into the atmosphere. This regime does not recognise the climate benefits of removing CO_2 from the atmosphere and storing it, temporarily or permanently. In light of the EU's target to achieve climate neutrality by 2050, the EU Commission has recognised the need to support permanent carbon removal (EU Commission, 2024). As part of this, the EU Commission is required to submit a report by July 2026 to the Parliament and Council on the possibility of integrating removals into the ETS (Carbon Gap, 2024). This would substantially shape the CO_2 leakage liability, hence some options for this integration are explored here.

Direct integration of removals into the ETS

Direct integration would enable removal activities to issue additional EUAs. This could effectively cap the EUA price at the cost of removals, channelling financial support to removals while insulating the ETS from potential political opposition resulting from price spikes (Sultani et al., 2024). However, it relies strongly on the principle of equivalence between reductions and removals, with the drawbacks discussed above.

Mediated ETS integration through a Carbon Central Bank

A centralised institution, dubbed a "Carbon Central Bank" (CCB), could mediate the integration of removals into the ETS, aiming to gain some of the benefits of direct integration without the drawbacks (Rickels et al., 2022). The CCB would have a mandate to issue additional EUAs in order to manage supply in the ETS and prevent price spikes, while backing up that additional EUA supply by supporting high-quality removals with a range of support mechanisms, potentially including long-term offtake agreements, carbon contracts for difference (CCfDs), and auctions. This would allow a more targeted and effective support of the carbon removal industry with a tighter control on quality than an open market.

Removals Trading Scheme

A removals trading scheme would be disconnected from the ETS and would impose removals purchasing obligations on entities based on their attributes other than their current level of emissions, for example their historical emissions (Meyer-Ohlendorf, 2023). This model would have few implications for the CO_2 leakage liability.

Chapter 4

Insurability & methodology

4.1 Introduction to insurability

Insurance is a tool for transferring risk and wealth between actors. Actors exposed to a risk can attain cover in exchange for a premium. If the risk materialises and the actor suffers a loss, they receive an indemnity (payout) from the insurer. Insurance cannot directly mitigate the risk. Nor does insurance reduce the overall amount of loss for society; someone is always paying in the end. However, insurance can be an effective tool for transferring the impact of losses between actors. This can be beneficial for society in multiple ways, including but not limited to: protecting actors from fortuitous, unintentional losses, protecting actors from losses that are too big for them to absorb on their own (i.e. limiting the risk of ruin), improving predictability of the business environment for actors and improving overall social fairness.

If an actor exposed to a risk can attain cover for that risk from a professional risk carrier, it is insurable (Berliner, 1982). If they cannot, the risk *might* be uninsurable, or there might be other barriers to attaining coverage, such as if the relevant insurance market is undeveloped due to lack of demand. Distinguishing the situations where a risk is uninsurable because of fundamental characteristics of the risk, or because of other more transitory or assailable reasons is relevant to all parties potentially exposed to that risk. For new risks where the regulatory environment is still being designed by policymakers, it is especially important to understand what role the rest of society could expect insurance to play.

Insurability is a policy-relevant concept: the availability of insurance to cover certain risks can guide the direction of technological innovation, encourage societal fairness and promote sustainable development, and policymakers can directly influence the availability of insurance (Stahel, 2003). This has historically been done through mechanisms from insurance mandates (e.g. third-party car insurance and mandatory flood insurance), to insurance bans (e.g. the flood insurance ban in the Netherlands following the devastating 1953 floods: "only engineers can prevent catastrophic floods, not insurance".) In order for insurance to help fulfill societal aims, policymakers actively define and shape insurability through policy. Insurability is part of the "division of labour" (Giarini, 1995) between the private and public sector: risks that are too difficult for private actors and the private insurance industry (i.e., are uninsurable) must be mitigated or covered by the public sector. The question of insurability is therefore highly relevant for policymakers: it becomes a tool in their hands to help achieve society's aims.

4.2 Berliner's criteria of insurability

A highly productive framework for analysing insurability was established by Berliner (1982) (table 6.2). It consists of nine criteria organised into three overarching categories: if a risk breaches the conditions of one or more of the nine criteria, it is very likely that a professional risk carrier would not provide cover for that risk. Insurability is not an exact science; there are considerable subjective aspects that will influence whether a professional risk carrier would offer coverage. However, when we are dealing with risks that are not covered by professional risk carriers, potentially for reasons other than their fundamental uninsurability, it is a useful framework for running through the same "checklist" they might when considering to offer coverage. It has therefore been used fruitfully in the applied insurance literature for a number of decades for assessing emerging risks.

In a 2005 issue of insurance economics research publication sigma, global reinsurer Swiss Re expanded the number of criteria to eleven, introducing *risk/uncertainty* as one and *industry capacity* as another (Swiss Re, 2005). These expanded criteria were applied by Herweijer et al. (2009) to examine the threats and opportunities of climate change adaptation on the private insurance industry. Similarly, Charpentier (2008) examined the insurability of climate risks using six criteria derived from Berliner (1982) and proposed potential solutions to some of the challenges, e.g. reinsurance markets and alternative risk transfer to avoid insolvency problems. Biener and Eling (2012) applied Berliner's nine insurability criteria to microinsurance markets in developing countries to find problems related to the insurability of life, health and non-life microinsurance products. They then proposed traditional and innovative solutions to address the found insurability issues. Biener et al. (2015) used the same criteria to conduct an empirical analysis of the insurability of cyber risk. More recently, analysis of insurability using Berliner's criteria has been applied to pandemic risk (Braun et al., 2020) and the impact of digitalisation and telematics on insurance markets (Eling and Lehmann, 2018; Eling and Kraft, 2020).

In studies directly applying the criteria of Berliner (1982), the insurability criteria are examined one by one for the relevant risk in order to come to a judgement in each case about the insurability of the risk. The choice of criteria, particularly if any are combined or if new ones are added, varies between the studies: my choice of criteria is justified in section 4.4. Additionally, the form of the analysis varies between the studies, and different types of judgements are made in each case. Biener and Eling (2012) conducted a literature review to capture all relevant insurability issues and used the insurability criteria to group and identify these issues. The analysis therefore does not come to new conclusions about the data, but rather categorises and collates existing conclusions in the academic literature. Biener et al. (2015) relies on a mixture of literature review and own analysis of an existing cyber risk dataset to makes judgements in each case. The judgements take the form of statements about whether the criteria are satisfied in each case, which are backed up variously by evidence from the literature and the authors' own assessment. Eling and Kraft (2020) conduct a literature review and try to assess whether for each criterion, evidence from the literature suggests a change in insurability due to the impact of telematics compared to the previous or current state of affairs in insurance markets.

4.3 Methodology

The analysis of the insurability of the CO_2 leakage liability has to take a novel approach compared to those found in the literature for other risks due to the lack of direct data on the occurrence of this risk. In fact, there have been no documented leakages of CO_2 from geological storage on record. However, there do exist analogues in other industries that share certain characteristics with the CO_2 leakage liability and for which there are existing insurance coverages available.

The analysis systematically applies the insurability criteria with a two-step process for each criterion. Firstly, theoretical knowledge of the characteristics of the CO_2 leakage liability and its actual regulatory context are applied to identify potential insurability challenges. Secondly, analogies are chosen and the potential insurability challenges are compared with these analogies from other industries in order to come to a judgement about whether the insurability criteria are likely to be fulfilled.

The theoretical knowledge of the characteristics of the risk are drawn from chapter 2 while for the regulatory context the research case described in chapter 3 is applied. The analogies applied are described in detail and background is given in chapter 5. Each analogy may already be insurable (i.e., there is a well-established insurance market with products to cover the risk) or it may face insurability challenges of its own. Depending on whether the comparison deems the CO_2 leakage liability more or less insurable than the analogy, a judgement can be made about its overall insurability.

4.4 Background to the insurability criteria

4.4.1 1. Randomness of loss occurrence

Insurance works on the principle of the law of large numbers: the greater the number of independent risks in a portfolio, the closer the actual losses in the portfolio approach the expected losses of the portfolio. Through this, the portfolio is more predictable than any given risk in it and the insurer can charge a premium (equal to the expected losses plus various loadings) to hold the risk. Therefore, the independence of risks is crucial to their insurability. More precisely, risks in a portfolio should be uncorrelated in order that the law of large numbers applies.

There are two ways that risks in a portfolio can be correlated: either the probability of multiple portfolio risks occurring is increased by a non-portfolio event

Table 4.1: The insurability criteria of Berliner (1982)

		Insurability criteria	*Requirements*
Actuarial	1	Randomness of loss occurrence	Independence and predictability of loss exposures
	2	Maximum possible loss	Does not pose solvency challenges
	3	Average loss per event loss frequency	Premium sufficiently recovers loss
	4	Information asymmetry	Moral hazard and adverse selection not excessive
Market	5	Insurance premium	Affordable for the market
	6	Cover limits	Overall coverage acceptable to the market
Societal	7	Public policy	Consistent with societal values
	8	Legal restrictions	No legal restrictions on coverage

(common cause), or one risk occurring increases the probability of further risks in the portfolio occurring (contagion).

In the first case, it is relevant to the insurance company how predictable the non-portfolio event is, and how much of the portfolio can be affected. If the non-portfolio event is predictable (i.e., losses on a motor insurance portfolio can be expected to increase in the winter in snowy regions by a predictable amount), its effects on the portfolio losses can be incorporated in the premium: whether the higher premium is then affordable to the market is a different question. When the non-portfolio event is random, a typical approach in the insurance industry is to cede that part of the risk to a reinsurance company. For example, claims in a motor insurance portfolio will increase dramatically after a hail storm. If the insurer has "catastrophe excess-of-loss" reinsurance, their portfolio losses for a given event above a predefined deductible are indemnified by the reinsurer, meaning the insurer is protected from the effect of common-cause losses across their whole portfolio (Swiss Re, 2013).

The second case is known in the insurance industry as risk *contagion* or *accumulation*, and presents a serious challenge to insurability. When risks are very tightly dependent on one another, it might be advisable to treat them as single risks e.g. multiple buildings on the same site covered by a fire insurance policy. This effectively reduces the number of risks in the portfolio, reducing the effect of the law of large numbers. When there are unknown dependencies between risks, especially across large parts of the portfolio, contagion can cause existential challenges to the insurance industry. During the 2008 financial crisis, unknown levels of financial dependence between firms (counterparty risk) covered by credit risk insurance in the same portfolio (as well as the insurance companies' exposure to the same credit risk on their asset side through credit default swaps, CDS), brought some insurance companies close to insolvency (Baluch et al., 2011).

This framework with four different types of loss dependency: common cause correlation & loss contagion, and predictable vs. unpredictable, is used in the analysis to identify potential insurability challenges.

4.4.2 2. Maximum possible loss

The maximum possible loss criterion evaluates whether insuring a risk will present insolvency challenges to the insurer in case the loss occurs. This criterion is closely linked to 6. cover limits because if a very large risk is made insurable (from a maximum possible loss standpoint) by setting a lower overall cover limit, the risk might then become uninsurable from a cover limit point of view: if the coverage is low, the insurance product might be unattractive to potential customers.

4.4.3 3. Loss frequency and average loss per event

The criteria "loss frequency" and "average loss per event" are given as two separate criteria in Berliner (1982) but then analysed together in the same work. This is because the two are closely linked to the point of really being one criterion, for which there is one condition of insurability: that the actual losses in the portfolio and the premia collected converge quickly enough to have predictable expenses for the insurer.

There are two ways to achieve this (which is why the two criteria can be separated): either by having a high-enough frequency of losses per cover period, or a low average size of losses. With a high frequency of loss events per cover period, the actual losses per cover period will converge more quickly with the premium (charged once per cover period at a level exceeding the expected losses.) Meanwhile, with a low average loss per event, the same effect can be achieved.

Using the frequency *per cover period* means the loss frequency can be increased by extending the cover period. The loss frequency is therefore a parameter that can be adjusted and optimised for insurability. The average loss per event, on the other hand is fixed. Because there is actually only one condition of insurability underlying the two criteria, establishing insurability for one of the criteria is enough to make a judgement for both. Since loss frequency can be adjusted by way of the cover period, I focus only on analysing the loss frequency and then comparing it to the analogy.

4.4.4 4. Information asymmetry

Berliner (1982) analyses only moral hazard, while from Swiss Re (2005) and the literature that follows, moral hazard is grouped together with adverse selection under the criterion of information asymmetry. Both moral hazard and adverse selection result from decisions the (potential) insured can take on the basis of privileged information, which result in an insurance coverage that is more favourable to the insured and less favourable to the insurer than intended. When this occurs systematically across a market, it can hinder the insurability of risks. Adverse selection occurs when insureds have an informational advantage over the insurer before coverage commences, which leads to the insurer underrating the risk and charging a lower premium than appropriate. Moral hazard occurs when the insured has influence over the occurrence of the loss after coverage commences.

4.4.5 5. Insurance premium

The insurance premium criterion aims to assess whether the insurance premium for coverage will be too high for potential insurance buyers to accept. This is a "market" criterion, meaning whether it is fulfilled depends not on the underlying characteristics of the risk (as is the case with the above "actuarial" criteria) but rather on whether a balance of interests can be found in insurance markets between the buyers and sellers to enable the product to change hands. Because of this, its fulfillment depends crucially on the characteristics of the buyers and sellers: in particular each of their appetites for holding or taking risk. This makes it a particularly challenging criterion to assess, and more assumptions about the similarity of an eventual CO_2 leakage liability insurance market with analogous markets have to be made.

An insurance premium can be broken down into 3 main components: the pure risk premium, expense loadings and safety loadings. The pure risk premium should equal the expected loss of the insured risk over the period of cover. Therefore in the long run, or in aggregate, the pure risk premium should recoup any paid-out losses. If an insurer would charge only the pure risk premium, they can expect at best only to break even, and only then if the expenses are zero. In order to account for expenses, an expense loading is added to the pure risk premium to cover claims handling, administrative expenses etc. Any premium above the pure risk + expense loading will produce a profit in the long run, so long as the actual expected value of the risk is known. This extra profit-making component is the safety loading.

Following Berliner (1982), the safety loading can be further broken down into two types: the fluctuation safety loading and the uncertainty safety loading. The fluctuation safety loading should account for variance in the probability distribution of losses (in some senses, the "known unknowns".) This is directly calculable with various "premium calculation principles", although it requires knowledge of the underlying distribution and the utility function of the insurer (which reflects their risk appetite). One of the active research areas in actuarial science is finding such premium calculation principles that use the underlying loss distribution (Dickson, 2016).

The uncertainty safety principle accounts for the possibility of errors in either of the pure risk premium and the fluctuation safety loading (therefore the "unknown unknowns"). The uncertainty safety loading is challenging to estimate because the sources of uncertainty can be widely varying: from basic scientific or technical uncertainty, to uncertainty around the stability or predictability of regulatory regimes, to difficulties in measuring the heaviness of a probability distribution tail with only few observations. There is no rule that can translate these uncertainties into safety loadings: much relies on the experience of the underwriter and risk appetite of the insurance company.

4.4.6 6. Cover limits

The cover limits criteria is linked to all preceding criteria: when all overall coverage limits, deductibles, and exclusions put in place to make the risk insurable are summed up, is the resulting insurance product still attractive to the insurance market? It is in this sense that it is a market rather than an actuarial criteria: it aims to assess whether a balance between insurers and insurers buyers can be found in respect of the overall coverage.

Coverage limits here refers to the upper limit an insurer agrees to pay out under an insurance policy, and is therefore differentiated from the more general "cover limit". Deductibles are an amount that the policyholder agrees to pay upon an occurrence of loss, before the insurer pays anything. Exclusions are conditions of insurance coverage that exclude or restrict insurance coverage for certain events, locations, causes, etc. Adding exclusions to an insurance policy can remove or restrict coverage for the uninsurable or difficult-to-insure risks, leaving only insurable risks.

4.4.7 7. Public policy and 8. Legal restrictions

These final two criteria serve the important function of contextualising insurance coverage in the relevant society and legal system in order to identify potential barriers to insurability. Because of the similarility of these two criteria, I explain them together here.

Insurance markets may not exist for otherwise insurable risks for which there is demand if such insurance coverage clashes with public policy aims or legal requirements. Life and health insurance abound with examples where potential insurance coverage clashes with public morals, for example insurance against child mortality, taken out by the parents and resulting in a payout in case the child dies. This was common practice in the US until it was outlawed in the early decades of the twentieth century, following decades of campaigning (Zelizer, 1981). In the case of property and casualty insurance, a notable example is the outlawing of flood insurance in the

Netherlands mentioned in section 4.1.

Chapter 5

Analogies from other insurance markets

This chapter discusses in detail three analogies for CO2 leakage liability insurance that will be useful in the later analysis and discussion. The first analogy is insurance in the upstream energy sector: this is drawn from extensively in the analysis given there are significant commonalities between CO2 storage and upstream energy exploration and extraction. The specific commonalities that are relevant for each criterion are discussed in the analysis, but in general the similarities stem from the fact that both activities involve moving fluids between the surface and sub-surface geological formations. This means there is significant overlap in both the technical aspects of the risks involved and the surrounding liability regimes.

The second analogy is insurance for pollution risks: the relevance of this analogy is that the sector has faced insurability challenges also faced by CO2 storage, which have resulted in specific solutions being developed.

The third analogy is risk transfer in carbon credit markets. While not drawn on in the analysis, a deeper understanding of the challenges facing this sector is useful for the subsequent discussion and especially the proposal of policy solutions to insurability challenges. Similarly, the final section of this chapter is a more general discussion of the dimensions of policy and market solutions for tackling insurability that the preceding analogies in this chapter elucidate, which aids in the subsequent policy discussion.

5.1 Insurance in the upstream energy sector

Subsurface risks related to exploring for and extracting hydrocarbons from geological reservoirs are well understood in the oil & gas industry. Hydrocarbon exploration involves drilling wells through potentially poorly-understood geology into high-pressure reservoirs containing highly flammable and environmentally damaging oil and gas. When oil companies lose control of these wells, there can be significant costs for regaining control, cleaning up pollution and compensating affected parties. Insurance is available to cover oil companies for all these costs from the commercial insurance markets, through industry mutual insurers and captive insurers: this section examines how and why this insurance coverage works and these ways of organising the market as a basis for using it as an analogy for comparison in the later analysis. This section draws heavily from Sharp (2009) for its description of insurance in the upstream energy sector.

5.1.1 Control of Well Insurance

Control of well insurance is a standard insurance product available to drilling operators in the oil & gas industry. The most commonly-used standard policy wording available from commercial insurers is the 8/86 EED Policy Form. This is a standard policy wording developed by a consortium of upstream energy insurers in the London insurance market. Developing and using standard policy wordings in this way allows insurance buyers greater certainty about how their coverage will be applied and enables them to directly compare the same product across different insurers. Standard policy wordings like this one develop over time as the industry gains loss experience and they represent a compromise between the insurers and the insurance buyers on what coverage the buyers demand and what insurers feel they can offer, while providing terms certainty to both.

Control of well insurance is a currently existing product that could apply in large parts to CO_2 storage, in particular for insuring injection and other wells, although it would not cover the CO_2 leakage liability out of the box. Therefore, this section looks in detail into how it is structured and what it covers.

Peril covered

The peril that control of well insurance covers is loss of control of flows of fluids in the well (oil, gas, water, or drilling fluid) that cannot be stopped using standard equipment or mitigation measures. What this refers to in plain English is a blowout:

blowouts are caused by pressure imbalances between the drilling fluid and the reservoir. If the blowout leads to escape of hydrocarbons at the surface, the hydrocarbons can ignite, causing fires and damage to the drilling rig, or otherwise escape into the environment and damage ecosystems, natural resources or third parties.

Potential costs to the operator

In the event of a blowout, the operator will be exposed to various costs, particularly bringing the well back under control, repairing, replacement or redrilling costs and pollution clean-up and compensation costs. Bringing the well back under control might necessitate the drilling of an additional relief well in order to relieve pressure along the well bore or in the reservoir, which can incur significant additional costs.

What liabilities the operator is subject to following hydrocarbon pollution depends on the jurisdiction and liability regime around the incident. In most places, including the EU, UK, and USA, oil & gas exploration and extraction is deemed an inherently dangerous activity, therefore the operator is subject to strict liability, meaning they are liable for damage to third parties and the environment regardless of fault or criminal intent. In each of the above-mentioned jurisdictions, there are laws or voluntary agreements in place which simplify the apportioning of liability and compensation to victims in the event of oil pollution. In addition, polluters are required to implement remedial measures and clean up the pollution.

Coverage for costs under the policy

Control of well insurance is available to cover all the above-mentioned expenses to operators. The costs which are covered must be triggered by the occurrence of a loss of control event and coverage ends when the well is brought back into control. This applies also to the pollution coverage: only pollution which occurs as a consequence of a sudden & accidental event is covered (see 5.2.1 for a more in-depth discussion of gradual vs. sudden & accidental pollution insurance).

The coverage is available for wells over their entire life-cycle: while being drilled, while producing, and while plugged and abandoned. An operator will be able to purchase the insurance product to cover their global portfolio of wells, or may purchase it for a sub-section by location or type of well. Coverage can start from the earliest when the operator acquires an interest in the well or otherwise when ground is broken in drilling the well. Coverage ends when the operator's interest in the well ceases, at the expiry date of the policy or when the activity covered under the policy (e.g. well drilling, deepening or servicing) ceases.

Coverage is also subject to warranties in the policy that the operator is managing the risk according to common practice in the industry, and that the operator applies appropriate due diligence in the conduct of their operations and in preventing the losses insured.

Premium, Limits and Deductibles

The premium payable for the policy is determined according to standard ratings depending on the status of the insured well. Premiums are calculated according to the depth of the well, with different bands depending on well type (e.g. producing, abandoned etc.) and well location, and with premiums for offshore wells in remote areas with little experience being the highest. In addition, each policy will specify a limit and a deductible, depending on the operator's appetite for retaining risk.

5.1.2 The structure of the upstream energy insurance sector

Commercial insurers

The above profile of control of well insurance is for an insurance product offered on the commercial insurance market. Typically, commercial insurance business in the upstream energy sector is mediated by insurance brokers who represent the interest of the insurance buyer. Especially in the London market, co-insurance is common, with each risk being taken in lines (shares) by multiple insurers, the process and negotiations being organised by the broker. In other markets, there may be a "fronting" insurer who initially writes the risk and subsequently cedes it to one or multiple reinsurers.

The development of the upstream energy insurance sector is characterised by cycles, with periods of relatively few large losses leading to a steady depression of premiums and slackening of underwriting standards, driven by competition between insurers and low perception of risk. This comes to an end when large losses finally occur, particularly large North Atlantic windstorms. The occurrence of large losses in such an environment can cause commercial insurers to raise premiums or exit the market, either involuntarily if their claims push them to insolvency, or voluntarily if they perceive the risks as becoming uninsurable. This is known across the industry as the underwriting cycle.

A notable example of this dynamic occurred in 1969 following hurricane Camille. The retreat of the commercial insurers from the market following the losses from hurricane Camille spurred 15 oil companies to form in 1972 a mutual insurer backed by capital from the industry: Oil Insurance Limited, or OIL, which changed its name in 2022 to Everen.

Mutual insurers & Everen, formerly OIL

The logic of a mutual insurance company is that if there is a sufficient diversification of risk among its members in a certain industry, the industry can retain the risk and share it among its members. This has advantages in that the coverage can be tailored to the needs of its members and underwriting and investment profits are retained by the industry. The highly diversified geographical and operational scope of the oil industry, as well as the often highly particular risk types, means it is a prime candidate for mutualisation.

As of 2024, Everen has grown to 70 members and expanded membership eligibility to companies in the very broadly-defined "energy" sector, including mining, pharmaceuticals, biofuels, renewable energy and more. Coverage is by default on all of the insured's energy operations in order to achieve maximum risk diversification and minimum adverse selection of risks. Everen has a simple premium formula whereby members pay back the past five years of covered losses in their sector on a rolling basis, weighted only by the gross value of their assets. This means that Everen does not take on pricing risk (underwriting risk) in a traditional sense and makes no underwriting profit. Everen has specific control of well coverage, covering the same costs as the 8/86 EED wording available in the commercial markets, but with greater flexibility in terms of the definition of occurrence and the required warranties among others.

Captive Insurers

When companies have sufficient risk diversification within their own operations, they can benefit by self-insuring through a "captive" insurer, that is, a licensed insurance company wholly owned and controlled by its insureds. The high degree of risk diversification that major oil companies have in their own operations mean they can rely heavily on captives, not only for smaller risks but can sometimes completely forego reinsurance coverage, as is the case with BP's captive Jupiter (Yates, 2010).

Simple "self insurance" differs from insuring with a captive insurer because there is no licensed insurance company involved and the self insurer would instead hold the "reserves" on its own balance sheet.

5.2 Insurance solutions for pollution

Industrial and waste disposal facilities that handle dangerous substances pose a risk to the environment and human health. Over the course of the twentieth century, many jurisdictions responded to this risk by building liability regimes around the handling of dangerous substances that impose liabilities on responsible parties. Liabilities that polluting parties face in many liability regimes include first-party liabilities, such as responsibilities for pollution clean-up and facility repair, and third-party liabilities such as damage to property, and bodily injury. The Environmental Liability Directive (ELD) in the EU established strict liability for dangerous and potentially dangerous activities, including CO_2 storage.

Insurance products have been developed to indemnify parties for their liabilities related to pollution and these products could potentially cover the CO_2 leakage liability. However, the pollution insurance market faces severe challenges relating to the insurability of risks and insurance companies have faced and continue to face large losses on pollution insurance products, leading them to have restricted the availability of coverage over time. This section examines why and how these insurability challenges emerged.

5.2.1 The crisis in pollution insurance

The 1980 Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) in the US established strict liability for companies engaged with hazardous substances: both current and past owners, arrangers and transporters of hazardous waste can be identified as "Potentially Responsible Parties" and made liable for the cleanup and damages associated with the site. This broadened the scope of liability and lead to increased claims under existing pollution insurance policies that the insurers had not anticipated. In addition, several court decisions found policy wording to be more expansive than the insurers had anticipated, essentially nullifying pollution exclusions and widening the scope of what qualified as a "sudden and accidental" occurrence (Abraham, 1988).

This broadening of the liability regime led to an exodus of commercial insurers from the pollution insurance market. An October 1987 report of the United States Government Accountability Office to Congress (U.S. Government Accountability Office, 1987) found that very few companies involved in generating, handling or disposing hazardous waste had insurance coverage for pollution risk and only one insurance organisation was actively marketing pollution insurance. An important reason for this retraction of insurance coverage is examined in the next section.

Gradual vs. Sudden & Accidental pollution

This widening of the scope of pollution insurance policies exposed insurers to risks they had previously deemed uninsurable. In particular, gradual pollution is usually avoided by insurers because of significant uncertainties surrounding the related liabilities: there can be uncertainty about when the pollution started, how long it went on for, the intensity of pollution over that time, who caused the pollution and the effect of the pollution on human or environmental health (Berliner and Spuehler, 1989). This all leads to significant uncertainty in the size of eventual damages, which must be reflected in the insurance premium. An additional challenge is the potentially non-random nature of the occurrence: both scientific advances and changes in regulation can lead to damage being identified from gradual pollution, thereby triggering a claim. Such claims may be correlated across the portfolio, leading to unexpected risk contagion and straining the reserves of the insurer.

5.2.2 Pollution insurance products available today

The crisis in pollution insurance in the 1980s in the US was partly due to the inherent difficulties in insuring pollution, but it largely resulted from uncertainty in the liability regime surrounding pollution. With the stabilisation of the liability regimes, insurance products are again available to cover pollution damages, albeit under certain conditions.

Insurance for pollution linked to sudden & accidental pollution damage is available in standard products on the market: general third-party liability (GTPL) insurance will usually cover third-party damage e.g. bodily injury and property, while environmental impairment liability (EIL) insurance will extend this to clean-up costs and other statutory liabilities for sudden & accidental losses. EIL insurance can be extended to gradual pollution but only on a case-by-case basis and subject to site risk assessment by a specialised risk engineer.

Reinsurance pools

The availability of EIL insurance to cover gradual pollution has been helped in some countries by utilising co-reinsurance through the establishment of reinsurance pools. Assurpol in France is a reinsurance pool open to all insurance and reinsurance companies operating in the country that guarantees the availability of reinsurance to insurers offering gradual pollution insurance and additionally offers technical support, tools and claims support. This has the effect of easing the market entry for insurers for gradual pollution, thereby increasing the size of the risk pool and the extent of risk sharing. This overcomes some of the challenges related to gradual pollution insurance. The extent of collaboration across the industry that Assurpol represented is unusual and prompted the European Commission to expressly exempt it from anti-competition regulations (European Commission, 1993). Italy and Spain also have similar reinsurance pools.

Such reinsurance pools are used also to cover other risks or perils which are otherwise uninsurable, such as nuclear insurance. Nuclear insurance, meaning both property coverage for nuclear power plants, nuclear waste storage sites and other facilities, and liability coverage for damage caused by nuclear and radioactive contamination is deemed universally uninsurable due to the potential for catastrophic losses and risk accumulation across many lines of business (Andris et al., 2003). Nuclear exclusions are therefore standard parts of policies across the insurance industry. Nuclear facility operators are usually subject to a strict liability regime which channels all claims to the operator, who then must be insured. This is achieved through nuclear insurance pools, which all facilities operators in the country must participate in (via commercial, mutual or captive insurers) and provides limited insurance capacity for nuclear risks.

5.3 Risk transfer in carbon credit markets

If a carbon credit is issued on the basis of a carbon reduction or avoidance project, that carbon is stored and subsequently re-enters the atmosphere (a "reversal event") then the value underlying the carbon credit is compromised. The various carbon standards that issue credits in the voluntary carbon market (here taking Verra, Gold Standard, Puro and ACR as examples) have in place liability mechanisms that translate the loss in underlying value of the credit into a liability for the original issuer of the credits. In particular, the carbon standards each mandate the cancellation/retirement/surrender of a number of credits equivalent to the reversal event amount: Gold Standard and Puro implement an order of preference whereby credits issued by the project are preferentially surrendered, whereas Verra and ACR allow other project credits to be used, but with some requirements around type or use. For Puro, the liability then rests simply with original credit issuer (Puro.earth, 2024): they are free to handle this liability as they wish and it is plausible that these credit issuers would purchase insurance for such losses.

5.3.1 Buffer Pools

Verra, Gold Standard and ACR each have buffer pools in place. Buffer pools are pools of credits managed by the carbon standards that credit issuers must pay a certain number of credits into. When a reversal event occurs and credits must be surrendered, the buffer pool is drawn on to provide these credits.

The pay-in percentage to the buffer pool varies between Carbon Standards: Gold Standard operates a flat 20% buffer pool contribution, while Verra and ACR have risk-adjusted buffer pool contributions, with formulas depending on characteristics of the project, with most projects falling in the 10-20% range. Typically there is a distinction made between unintentional and intentional reversal events; the following discussion focuses on the unintentional reversal events, as these are insurance-relevant.

Verra operates the simplest buffer pool structure: in the event of a reversal, all credits in the pool from all projects may be used to compensate the reversal (Verra, 2024). This is analogous to an unlimited insurance coverage where the credit issuer retains none of the risk: credit issuers are fully indemnified for reversal events.

ACR operates a similar mechanism, but for any reversal event that exceeds the credit issuer's total buffer pool contribution, an additional "deductible" of 10% of the reversal event amount is payable by the issuer into the buffer pool (ACR, 2024). In insurance terms, this is mandatory self-insurance but with an unlimited cover that applies in excess of the self-insured amount, with a modest risk retention in the form of the "deductible".

In the case of Gold Standard, only the credit issuer's own buffer pool contribution can be drawn from to compensate the reversal event: beyond that further credits, firstly issued by the credit issuer and subsequently purchased from the other projects must be used to compensate the reversal event (Gold Standard, 2019). This is equivalent to mandatory self-insurance without any further coverage provided by the buffer pool.

An innovative feature of carbon credit buffer pools is that the risk sharing is carried out entirely in the "currency" of carbon credits: the buffer pool contribution shares are essentially premiums paid in carbon credits, the reserves are held in carbon credits and the payouts in the event of loss are also in carbon credits. This model of in-kind insurance is also conceivable for a commercial insurance model.

A challenge that buffer pools face is inadequate risk pricing: since the pay-in amount is set either at a flat rate or according to set rules which are the outcome of negotiation between involved parties, it is not a price that actually reflects the risk in the pool and necessarily keeps it adequately capitalised. Badgley et al. (2022) argue that California's offset market has a severely undercapitalised buffer pool as a result of this.

5.3.2 In-kind carbon insurance

Commercial insurers could also hold reserves of carbon credits and make payouts from carbon credit losses in carbon credits. A challenge here is regulation: regulators are likely to be extremely cautious about commercial insurers holding reserves in carbon credits due to general immaturity of the carbon credit markets, which manifests in challenges with liquidity and accurate pricing. CarbonPool is a Swiss-based start-up in the carbon credit insurance space that, as of mid-2024, is seeking approval from the Swiss Regulator FINMA to be able to do this.

5.4 Dimensions of risk sharing

The preceding discussion has covered existing insurance or risk-transfer solutions for risks that share some characteristics with the leakage of CO_2 from storage; this has elucidated some dimensions that a potential insurance solution for the CO_2 leakage liability could take, as well as providing a real-world basis for comparison in terms of insurability. This section spells out these dimensions.

5.4.1 Dimension 1: Extent of risk sharing

Insurance solutions rely on a principle of risk sharing to make the burden of covering risks easier. A limited form of this risk sharing is within the same organisation: this can be achieved with a captive insurer. This allows the form of coverage to be tailored to the specific needs of the organisation, removes moral hazard concerns and allows insurance profits to be retained in the organisation. This is a sophisticated form of self-insurance, the general principle of which is for a risk holder to build their own reserves to act as a buffer in case they experience a loss, helping to partially mitigate the risk of ruin/bankruptcy.

A greater extent of risk sharing can be achieved through sharing the risk with the rest of the industry, and the greatest still is through sharing the risk with the commercial insurance sector. The greater extent of risk sharing allows less capital

Table 5.1: Overview of the dimensions of risk sharing with examples mapped

		Extent of risk sharing		
		Insurance sector	**Own industry**	**Risk retention**
Organisation of risk sharing	**Commercial**	Commercial control of well EIL insurance In-kind carbon insurance Reinsurance	EIL reinsurance pools	Captive insurer
	Mutual	N/A	Everen/OIL Mutual	N/A
	Regulatory	Mandatory nuclear insurance	Other buffer pools (in kind)	Gold Standard buffer pool (in kind)

to cover the same risk, hence allows risk holders to access cheaper risk capital, but comes at the expense of foregoing insurance profits and making greater compromises with the rest of the industry and with insurers about which risks are covered. Reinsurance (not specifically reinsurance pools) allows risk sharing on a commercial basis with the whole commercial insurance sector.

5.4.2 Dimension 2: Organisation of risk sharing

In each case, there are multiple options available for how to achieve this greater extent of risk sharing. For risk sharing in the same industry there is the most diversity in organisation: risks can be shared through a mutual insurance structure, commercially through reinsurance pools or via a regulatory authority.

A mutual insurance structure relies on there being enough insureds with similar coverage needs and a diversified enough risk profile to enable risk sharing. If this is the case, members can benefit from tailored coverage and predictable availability of coverage, while retaining profits. However, the alignment of interests among insureds necessary to organise a mutual insurer means it is usually only insureds in the same industry that form mutual insurers.

Where there is a common risk among members who have otherwise very different coverage needs, reinsurance pools may be a better solution. In the case of gradual pollution, there is a difficult-to-insure risk shared by insureds across a wide variety of industries. In this case, commercial insurers have organised themselves on behalf of their insureds into a reinsurance pool in order to offer coverage they are otherwise unable to.

A challenge with both mutual insurers and reinsurance pools is non-participation of some insureds limiting the extent of risk sharing. In the oil & gas industry, the the largest players do not take part in the mutual insurers but rather self insure through captives: they have no interest in "subsidising" the risks of the smaller players with their already-diversified risk profiles. The size of the industry means there is still suitable risk diversification among the smaller industry players, but this is an exceptional case. Non-participation in the voluntary carbon market is mitigated by having mandatory risk sharing for all participants through the buffer pool mechanism. This is a case of risk sharing mandated by a regulatory authority.

5.4.3 Dimension 3: Risk sharing in money vs. risk sharing in kind

Risk sharing in kind is useful for eliminating the variability in the monetary value of the unit of loss, i.e. the risk that the price of the unit of loss increases is mitigated. The risk transfer solutions tailored to the voluntary carbon market, buffer pools and in-kind insurance, work on the principle that the the unit of loss, carbon credits, are fungible, i.e. a carbon credit lost can be replaced by another. In practice, this principle is disputed: carbon credit value is perceived as highly variable and often older vintages of credits as less valuable, which is also reflected in the range of market prices. This contributes to the weakness of buffer pools as a risk management tool.

The downside of in-kind risk sharing is that risk sharing is limited with any risks that do not take the same unit of loss: risk sharing with these requires factoring back in the risk of changes in the price of the unit of loss. There therefore needs to be a sufficient number of risks sharing the same unit to achieve enough diversification.

An advantage of risk sharing in kind is that the "reserves" can be maintained not just by collecting a premium, but also by engaging in activities that generate the unit of loss. For example, if the unit of loss is stored carbon, a loss of carbon that generates an insurance claim could be indemnified by storing additional tonnes of carbon to cover the loss. This then has the effect of maintaining the size of the carbon pool, rather than just making the claimant financially whole, meaning the climate benefit is more immediately maintained.

Chapter 6

Analysis: the insurability of the CO_2 leakage liability

As discussed in section 4.3, the analysis here goes through the eight insurability criteria following a set structure. First, there is the identification of the insurability challenge: here the CO2 leakage liability is analysed according to the criterion as described in section 4.4 in order to identify the largest challenges for the fulfillment of that criterion. Then, if a challenge is identified, an analogy is selected to compare it to and the comparison is carried out. Finally, an evaluation is given based on the outcome of the comparison; i.e., is the challenge identified greater or less than an analogous challenge from another industry. A summary of the analysis and results is given in table 6.2 to assist with orientation.

6.1 1. Randomness of loss occurrence

6.1.1 Identification of insurability challenge

Losses from CO_2 leakage can in each case be attributed to individual leakage pathways: one storage site will have multiple leakage pathways, each of which may lead to a loss. Attaching this level of granularity to losses will help the analysis, as it will allow establishing where the threshold of insurability lies across the range of leakage pathways, giving insight into which leakage pathways may be excluded from insurance coverage. However, it is only advantageous to the extent to which the losses are actually independent. This section of the analysis will identify where insurability challenges lie related to the independence of loss occurrences. The categories of loss independence developed in section 4.4.1 are used.

Table 6.1: Summary of the analysis and results

Criterion	**Challenges identified for CO2 storage**	**Analogy used for comparison**	**Evaluation**
1. Randomness of loss occurrence	Earthquakes	Upstream oil & gas: Control of well insurance.	Similar challenge already tackled in analogy. Criterion fulfilled.
2. Maximum possible loss	Macondo/Deepwater Horizon-style CO2 blowout.	Upstream oil & gas: Large well blowouts.	Challenge much smaller-scale than in analogy. Criterion fulfilled.
3. Loss frequency	Low frequency of CO2 leakage events.	Upstream oil & gas: Frequency of well blowouts.	Similar challenge to analogy, but solution there (increasing coverage length) does not translate to CO2 storage because of EU ETS linkage. Criterion not fulfilled.
4. Information asymmetry	Adverse selection: Information sharing during permitting. Moral hazard: induced seismicity & MRV.	Upstream oil & gas: Fracking & control of well insurance. Pollution insurance.	Similar challenges already tackled in analogies. Criterion fulfilled.
5. Insurance premium	High premium safety loading for all pathways due to heavy-tailed distribution and uncertainty. Especially high for geological leakage pathways and gradual seepages.	Upstream oil & gas: well blowouts. Pollution insurance: gradual seepages.	Criterion fulfilled for sudden & accidental well leakages. Chance of not being fulfilled for geological leakage pathways and gradual seepages.
6. Cover limits	Possible exclusion of earthquakes, geological leakage pathways and gradual seepages deemed not a challenge.	No comparison needed.	No challenge; criterion fulfilled.
7. Public policy	No realistic barriers from public policy.	No comparison needed.	No challenge; criterion fulfilled.
8. Legal restrictions	No realistic barriers from legal restrictions.	No comparison needed.	No challenge; criterion fulfilled.

Common-cause correlation from a predictable event

As CO_2 is injected into the storage reservoir, pressure increases throughout the reservoir in a predictable manner. For every leakage pathway, the risk of activation increases as the pressure of CO_2 at the initiating side of the pathway increases (see section 2.2.3). Therefore, every leakage pathway will follow a correlated but predictable risk profile over the lifetime of the site: starting from zero at the start of injection and increasing as the reservoir pressure increases, before stabilising when injection stops. Because this profile is predictable, the insurer can charge a higher premium per leakage pathway and plan to hold higher reserves at the times when the risk is greater. This effectively normalises the changes in the risk profile and the risks can be treated as independent. The common-cause correlation from pressure increase therefore does not present a barrier to insurability.

Common-cause correlation from an unpredictable event

It is in principle plausible that an earthquake could act as a random event that causes multiple leakage pathways to activate or worsen (see section 2.2.3). Seismicity in general (both natural and induced) therefore presents a potential insurability challenge as a common-cause correlation from an unpredictable event to be further assessed.

Loss contagion: predictable dependencies

A predictable dependency of one loss on another in the case of leakage of CO_2 from storage means one leakage pathway activating leading to an increase in the likelihood of another leakage pathway activating in a way that can be predicted ahead of time. It does not mean one leakage event leading to the reassessment of the likelihood of another leakage pathway activating, e.g. if one well casing failure leads to a reassessment of the failure rate of other similarly constructed wells. The difficulties of accurately quantifying leakage risk is dealt with in section 6.5. Predictable dependencies between pathways may occur if there is a geometric intersection of the pathways e.g. a fault cutting a well bore. CO_2 migrating along the fault may enter the well bore and cause a leakage in two places at the surface. To the extent to which the dependency is predictable, it can either be mitigated in the planning process by not choosing the site, or treated as a single risk.

In addition to dependencies of CO_2 leakage liabilities on one another, there will also be a predictable dependency of CO_2 leakage liabilities on other losses covered by insurance, such as regaining well control, well redrilling and replacing equipment in the case of a major CO_2 well blowout. Since these correlations are predictable, they do not pose a challenge to insurability from a risk independence point of view.

Risk contagion: unpredictable dependencies

Unpredictable dependencies between leakage pathways may occur when there is significant uncertainty around the leakage pathways in question. There would have to be unknown geometric intersections between leakage pathways, such as faults or fracture systems with greater lateral extensions than thought intersecting wells or other geological leakage pathways. Sites with greater geological complexity (e.g. geological formations with long histories of tectonic deformation), sites with greater geological uncertainty (i.e. when there has been insufficient geological surveying), and sites with long histories of hydrocarbon exploration where there are potential undiscovered abandoned wells are all more likely to have unpredictable dependencies. However, although unpredictable dependencies, if they exist, might lead to correlated losses across a small handful of pathways, the literature does not suggest other mechanisms that could lead to more systemic risk contagion. Unpredictable dependencies are therefore not a challenge to insurability

6.1.2 Comparison with analogy

Selection of the analogy

Earthquakes are a peril addressed in many insurance policies, mostly by way of exclusion. This is typically because earthquakes can cause many simultaneous losses within a geographical area and hence represent an unacceptable source of risk accumulation. Geological storage projects, particularly offshore ones, have a different exposure to earthquake risk than most onshore property: projects are likely to be more sparsely distributed, which may in turn reduce the potential for risk accumulation. To check whether there is a chance that earthquakes are not excluded for CO_2 leakage liability policies, a comparison is made with other offshore energy installations, in particular offshore oil drilling wells which are covered by control of well policies.

Earthquake exclusions for offshore energy installations

The 8/86 EED Control of Well insurance policy discussed in section 5.1.1 contains an earthquake exclusion by default: that would mean that damage caused by earthquakes or from events triggered by earthquakes would be excluded from coverage. However, according to Sharp (2009), this exclusion does not apply to areas of the world that are not active fault zones, and it is standard practice to delete this exclusion from insurance policies even in areas where there is seismic risk, and instead to add an earthquake risk loading to the premium.

6.1.3 Evaluation

Loss from CO_2 leakage, even losses in the same storage site, are mostly independent from one another, or at least predictably dependent. This is because each leakage pathway will have its own conditions for triggering which do not depend on other leakage pathways. There is a predictable correlation from the pressure increase in the reservoir as it fills up with CO_2, but this should not provide an insurability challenge since it is predictable.

In most property insurance markets, earthquakes are a challenge to insurability because of the possibility of highly correlated widespread losses: this insurability challenge is usually tackled by introducing an earthquake exclusion. The consequence of this exclusion is that earthquake damage often is a burden that the government and the public has to take directly. However, the comparison with offshore control of well insurance shows that correlated losses from earthquakes are less of a concern to insurers in the offshore upstream energy sector. Therefore, it likely does not present a challenge to insurability for the CO_2 leakage liability. In sum, the randomness of loss occurrence criterion is fulfilled and does not present any challenges to insurability.

6.2 2. Maximum possible loss

6.2.1 Identification of insurability challenge

Geological leakage pathways

Geological leakage pathways with the potential to leak significant amounts of CO_2 should be identified by the operator and the sites removed from consideration during the permitting process (see section 3.2.1). Large geological faults could have leakage rates exceeding those of large well blowouts, but are also easily identifiable before injection starts (Dabiels et al., 2023). In the case of depleted oil & gas reservoir storage sites, the former presence of hydrocarbons for geological time indicates that the formation lacks significant leakage pathways. Therefore in a properly permitted storage site, geological leakage pathways should not be the main source of risk, but rather well leakage pathways.

Well leakage pathways

The size of any given CO_2 leakage event will follow a probability distribution. According to the analysis in Dabiels et al. (2023), only well leakage pathways have a realistic possibility of leakages over 50 tonnes/day (the smallest "moderate" leakage size). Only these larger leakage events can pose an insurability challenge with regards to the maximum possible loss, therefore only well leakages are considered for the rest of this analysis. Due to the lack of a loss history for CO_2 leakages, calculating the probability distribution of well leakages can only be done by taking the probabilities of analogous events in other industries. The analysis in Dabiels et al. (2023) used in the loss frequency section (sec. 6.3.1 uses hydrocarbon extraction well leakage probabilities taken from literature review, which I use in this section to estimate a probability distribution for well leakages.

I took the database of leakage estimates collected from literature review from Dabiels et al. (2023). Where there was no specific leakage rate linked to probability, I used the overall range of leakage rates for the category, i.e. 1-50 tCO_2/day for minor leakages. Where a range of leakage rates was given for a probability estimate, I took the midpoint. Where Dabiels et al. (2023) supplied alternative or corrected probabilities in the comments, I used those. I took the duration of the leakage for the specific leakage rate and probability where it was supplied, otherwise I used the generic durations supplied by Dabiels et al. (2023): 120 days for minor leakages and 180 days for moderate and major leakages. To get to total mass of CO_2 leaked,

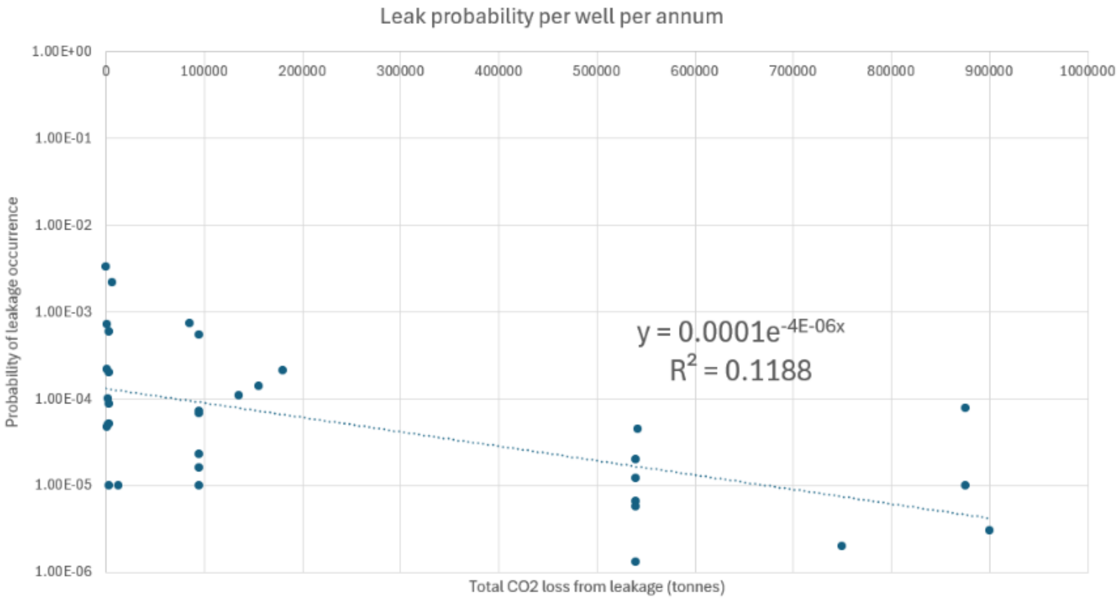

Figure 6.1: Estimates of the probability of occurrence of CO2 leakages of various sizes taken from the literature review conducted in Dabiels et al. (2023). The data processing is described in section 6.2.1.

I assume that the given leakage rate applies for the whole duration: this is very conservative, since in many cases the supplied leakage rate is only the maximum.

Although the probability of very largest events is low at between 10E-4 (1-in-10'000) and 10E-5 (1-in-1'000'000) per year, the possibility nonetheless presents a challenge to insurability. Expressed in another way, the curve fit to the events in fig.. 6.1 is exponential, which is a heavy-tailed probability distribution. Insuring risks with heavy-tailed loss distributions is challenging because the uncertainty in the size of the tail is high due to the lack of experience with such large losses, while also being highly impactful on the expected size of the risk. This is therefore a potential challenge to the insurability of the CO_2 leakage liability.

Maximum possible loss

In the EU, the climate liability is the EUA surrender and the financial loss will be the total loss of CO_2 in tonnes multiplied by the cost of EUAs. Assuming the operator does not have any already-purchased EUAs on their books, the cost of the EUAs will depend on the EUA price on the market at the time the leak is identified and reported. The EUA price is variable: in 2023 it peaked at EUR 105 in February and sank to EUR 70 in December. Conservatively taking an EUA price of EUR 100 for the estimate of approximately 1'000'000 tCO_2 referenced above gives a maximum possible loss of EUR 100 million.

6.2.2 Comparison with analogy

Selection of the analogy

Offshore upstream energy shares many characteristics with geological storage of CO_2 and many offshore geological storage sites will be developed by companies in the offshore upstream energy sector. Large dedicated offshore geological storage projects will involve offshore platforms and drilling operations, just like hydrocarbon extraction projects. Of the 23 geological storage projects announced in Europe as of August 2023, 20 had at least part ownership by entities involved in upstream exploration & production of oil & gas Global CCS Institute (2024). Therefore, upstream energy is taken as a good analogue in terms of the insurance coverage available in that sector.

Loss distribution of hydrocarbon well blowout events: heavy-tailedness

Losses from well blowout events, whether CO_2 or hydrocarbon, have multiple components, including both property losses and liability losses. Property losses are those related to containing the blowout event and repairing or replacing equipment. The explosive nature of hydrocarbons makes well blowouts more dangerous and costly in terms of property losses than CO_2 blowouts. Liability losses include those related to damage from pollution, which also differs significantly between CO_2 and hydrocarbon well blowouts: for CO_2, the main pollution liability, especially offshore, will be the CO_2 leakage liability. For hydrocarbon well blowouts, oil pollution can cause much further-reaching damages to the local environment on top of mandatory cleanup requirements. In the case of the Deepwater Horizon/Macondo blowout and resulting oil spill, the property losses were USD 798 million adjusted to 2023 USD (Marsh Energy Practice, 2024), while the total costs as recorded on BP's income statement were nearly USD 63 billion, with total costs estimated at nearly USD 145 billion (Gyo Lee et al., 2018).

The existence of such a loss event with a liability loss component almost 20 times bigger than the property loss component suggests that the loss distribution for hydrocarbon well blowout events is even heavier-tailed than for CO_2 blowout events. This presents a serious insurability challenge for the industry.

BP had no insurance coverage from the commercial market or through mutuals like Everen. Even its captive, Jupiter, only had a policy limit of USD 700m in 2010, when the Deepwater Horizon/Macondo event occurred: most of the loss had to be recognised simply as a loss on its income statement (Yates, 2010). For a smaller company that relied on the commercial or mutual insurance markets, the situation would have been worse. The largest single limit of coverage available in the upstream energy insurance market is the USD 450 million available from Everen (Sharp, 2009); this covers property (physical damage and control of well) and third-party pollution liability.

In summary, the insurability challenge stemming from the heavy-tail of the hydrocarbon blowout loss distribution is not solved, but rather losses above a certain threshold are simply excluded from coverage and remain uninsured.

6.2.3 Evaluation

In the case of hydrocarbon well blowouts, the possibility of very large losses (e.g. the size of Deepwater Horizon/Macondo) does not hinder the insurability of smaller events within the coverage limits discussed. The CO_2 leakage liability is smaller and less heavy-tailed than the liability component of hydrocarbon well blowout losses. The estimate of EUR 100 million for the maximum possible loss is well within the largest coverage limits for control of well and third-party pollution liability insurance available in the upstream energy insurance market. For it to be challenging, the associated property losses would have to be in the range of the largest property losses in the hydrocarbon industry, which is highly unlikely for non-explosive CO_2. Therefore, the maximum possible loss criterion is satisfied and does not present a barrier to insurability for the CO_2 leakage liability.

6.3 3. Loss frequency

6.3.1 Identification of insurability challenge

What follows is an estimate of the number of losses per year that could be expected if all the currently announced geological storage projects in Europe (covered by EU ETS and UK ETS) become operational. The Clean Air Task Force CCUS database lists 23 geological storage projects that had been announced as of August 2023 in Europe (Global CCS Institute, 2024). Thereof, 10 are depleted oil & gas reservoirs and 13 are saline aquifers.

The analysis in table A.1 and table A.2 shows that if all these projects are "typical" projects with the characteristics described in Dabiels et al. (2023), the frequency of leakages greater than a seepage (i.e., more than 1 tonne/day) and therefore with the possibility of leading to a claim across all projects is 0.30 per year, or roughly 1 claim every 3.3 years. Though this can be taken as only a rough first-order estimation, it demonstrates how infrequent even small claims are likely to be. When only moderate and major leakages are considered, the probability drops by an order of magnitude to roughly 1 in 38 years. This low frequency of loss events on its own is a potential insurability challenge (see section 4.4.3).

6.3.2 Comparison with analogy

Selection of the analogy

The loss frequency estimates derived above (section 6.3.1) ultimately share characteristics with hydrocarbon well blowout frequencies due to the latter being the primary data source for making the estimates. Therefore this is again taken as an analogy for comparing the insurance coverage

Loss frequency of hydrocarbon well blowout events

There have been relatively few recorded well blowout events: in the SINTEF Offshore Blowout Database there are 711 events recorded since 1955 (Holand, 2017). In UK & Norwegian waters there has been on average 1.05 loss of well control events per 10'000 well years in service, and 2.70 in US Gulf of Mexico waters; this is comparable to the upper end of estimates for the occurrence of the largest CO_2 leakage events.

The challenge to insurability from the low loss frequency in this case is responded to by increasing the length of coverage time: control of well insurance coverage is offered by default for the whole life-cycle of the well (see section 5.1.1). Increasing the coverage period in this way increases the effectiveness of the law of large numbers on the portfolio: fewer insurance policies will have to be written for the long-term expected loss to converge on the collected risk premiums. The low loss frequency of hydrocarbon well blowouts therefore does not present a challenge to their insurability.

6.3.3 Evaluation

The insurability of hydrocarbon blowout events indicates that the low loss frequency as such should not present a challenge to the insurability of the CO_2 leakage liability. However, a key difference is in the possibility of offering longer insurance coverage periods. In the case of the CO_2 leakage liability in the EU, the variable and uncapped price of EUAs means that longer-term coverages add another risk: an increase in the price of EUAs between the initiation of coverage and any eventual leakage event.

If the insurer has agreed to indemnify the insured regardless of the EUA price up to a cover limit, they might find much more of the limit used, i.e. a much bigger payout is due for a given leakage size, than they initially expected. Conversely, if the insured has agreed to be compensated at an EUA price that is fixed or has an upper limit, they might find their coverage for a given leakage event is less than they expected. In the first case, the insurer would likely add a significant premium loading to account for EUA price variability, and in the second case the insured may purchase a higher limit of coverage at a higher premium than they otherwise would. In both cases, the insurance coverage for a given CO_2 leakage becomes more expensive, possibly prohibitively so. In addition, the risk of EUA price increase would be one correlated unpredictably across the portfolio, meaning it fails the first criterion "randomness of loss occurrence". All this means coverage is most likely to be restricted to a yearly basis in order to eliminate the risk of EUA price increase.

This challenge with increasing the length of coverage means the low loss frequency remains as a potential insurability challenge in the absence of policy or market solutions.

6.4 4. Information asymmetry

6.4.1 Identification of the insurability challenge

Adverse selection

Adverse selection could occur in the case of the CO_2 leakage if there is information collected during the site selection and permitting process that is not shared with the insurer. Here, the interests of the insurer align with that of the regulator, both of whom want care to be taken in the permitting process that excessive risks are not taken, either intentionally or inadvertently. Therefore, it is hoped that in a functional regulatory environment, the regulator will require that all potentially material information is shared. This is currently the case in the EU regulatory environment. Moreover, since this type of insurance will be more bespoke than insurance markets that suffer from adverse selection (e.g. health insurance), insurers will be able to ask for all material information for review before they offer coverage. For these reasons, it is not thought that adverse selection pre-coverage will be an insurability challenge.

Moral hazard

In the case of the CO_2 leakage liability, there are three ways the insured could influence the occurrence of a loss: influencing the physical occurrence of a leakage, influencing the magnitude of loss of a leakage once it occurs and finally in the detection and reporting of a leakage.

If a storage operator induces seismicity due to the injection process which then causes a leakage, this would be an example of the insured influencing the physical occurrence of a leakage. Induced seismicity is therefore a potential insurability challenge.

Likewise, leakage occurrence can be more directly influenced by the insured through the care taken during the injection process: for example, by improperly controlling the reservoir pressure and exceeding safe bounds, or not maintaining injection equipment properly. The magnitude of the loss can be influenced by the insured by how rapidly they respond in mitigating a leakage once it is detected. Stopping a large well leakage may require drilling relief wells to intercept the flow, which is a very expensive and time-consuming process, and one the insured may put off if they do not also have insurance coverage for it. Influencing leakage occurrence through direct means and responding to a leakage once it has occurred are both termed leakage mitigation. Leakage mitigation is therefore a potential insurability challenge.

Fines from regulators due to breaching regulations are a unique type of loss because if the breach is not detected, there is no occurrence of loss for the responsible party. Given the responsible party is often the most well-equipped to detect a breach in the regulations, this gives rise to a moral hazard in running the monitoring regime. The incentives for running an insufficient monitoring system or engaging in fraud or cover-ups in such a situation are high. This is also the case in monitoring for CO_2 leakages, where in the EU the storage operator is tasked by the regulator in setting up an MRV plan (see section 2.3. There is a wide range of potential MRV plans, from the highly effective but expensive, to the ineffective but inexpensive. There is a real possibility that the storage operator changes the implementation of their MRV plan in response to taking out insurance, leading to a change in the occurrence (detection) of loss events. Therefore, there is a potential insurability challenge from leakage detection.

6.4.2 Comparison with analogy

Selection of the analogy

In the case of induced seismicity and leakage mitigation, control of well insurance in the oil & gas industry is taken as an analogy. Fracking operations, in particular deep saltwater disposal, have been linked to induced seismicity (Keranen and Weingarten, 2018). Meanwhile, well leakage mitigation is analogous to hydrocarbon well blowout mitigation and is actively dealt with in control of well policies.

The issues with CO_2 leakage detection are similar to those faced for pollution insurance more broadly, particularly when the pollution coverage is for regulatory fines from damage to the environment and there is no other interested third party who would carry out monitoring.

Moral hazard: induced seismicity

Control of well insurance coverage is offered for fracking operations. Fracking involves injecting saline water mixed with sand and other chemicals into natural gas-containing formations in order to fracture the rock and extract the gas. The saline water is then recirculated and must be disposed of. One disposal method is injecting the saline water into deep saltwater disposal wells. Saltwater disposal wells in particular are on the limit of insurability. One cited problem area is the earthquake induction risk from saltwater disposal wells (Alliance GRP, 2017). These have been taken out of control of well insurance bundles in some markets (CRC Group, 2021). However, it is not clear that the earthquake risk in particular is why saltwater disposal wells are having difficulty finding coverage - a more commonly cited issue is their susceptibility to lightning strikes (CRC Group, 2021). In general, where induced seismicity is mentioned as a problem area for insurers it is in the general third-party liability provisions, due to the risk of induced earthquakes causing damage to third party property (Weireter et al., 2014). No references could be found of the risk of induced seismicity causing loss of well control events, which are the relevant events for the CO_2 leakage liability.

As discussed in section 6.1, while the earthquake exclusion is standard in control of well policies, it is also common practice to delete this exclusion. In light of the new and unfamiliar earthquake risks from induced seismicity, insurers may opt to keep the standard earthquake exclusion in place, which would also exclude events caused by induced seismicity.

Induced seismicity-triggered losses may become more insurable if sufficient risk mitigation measures are in place to control their occurrence. "Traffic light" systems, whereby certain indicators of induced seismicity lead to halting of injection, have been successfully implemented in some drilling sites (Gholami et al., 2021). Insurers could specify in the policy that such measures are implemented in order for events to be covered (Weireter et al., 2014).

In sum, the moral hazard from induced seismicity seems to present a small barrier to insurability, but one that can be overcome with sufficient exclusions or risk mitigation measures.

Moral hazard: leakage mitigation

Well blowout mitigation is a familiar aspect of control of well insurance. Standard policy wordings such as the 8/86 EED policy form contain warranties that the insured carries out the drilling activity with appropriate care and according to common industry practice (see section 5.1.1 and Sharp (2009). Additionally, control of well insurance includes coverage for blowout mitigation costs such as drilling relief wells, meaning the insured should have no incentive to delay mitigating activities. Given these issues are broadly similar to CO_2 leakage through well pathways, there is no reason to think the same warranties and coverage can not be also implemented for CO_2 leakage liability insurance. Therefore, the moral hazard from leakage mitigation should not present any barrier to insurability.

Moral hazard: leakage detection

When regulators require regulated entities to monitor their own compliance, they introduce an incentive to reduce the effectiveness of the monitoring regime: this has been demonstrated to occur in the case of pollution monitoring (Mu et al., 2021). It is plausible that if the regulated entity has pollution insurance, this effect should be eliminated, leading to an overall more effective pollution monitoring regime. However, there does not seem to be any research on whether this effect is real. To the extent it is, the availability of insurance would be a public good as it would increase the effectiveness of monitoring regimes for pollution. However, it is a potential insurability barrier to the extent that the if the detection of pollution events increases when insurance is purchased, resulting in the premium charged being too low. This effect could be mitigated if the baseline level of monitoring is sufficiently high, as mandated through regulations or by insurers as a condition of coverage. This dynamic should be especially pronounced for the CO_2 leakage liability, due to the difficulty associated with MRV and the relatively high cost of an effective MRV plan. In sum, there is an insurability barrier only if the existing MRV regulations are weak.

6.4.3 Evaluation

In general, insurability challenges from information asymmetry, whether adverse selection or moral hazard, depend to a large extent on how robust the the regulations are around permitting and MRV. To the extent that the regulations require enough comprehensive understanding of the risk during the permitting process, sufficient sharing of information between parties and effective MRV, any insurability challenges from information asymmetry can be well mitigated.

6.5 5. Insurance premium

In the case of the CO_2 leakage liability, only the pure risk premium is directly estimable through the expected loss of covered events. The expense loading is assumed irrelevant, given that the coverage is likely to be included in an existing insurance product like control of well coverage and will only add minimal expenses on top of those already incurred by the insurer. The identification of insurability challenges therefore starts with the pure risk premium and then moves to the safety loadings.

6.5.1 Identification of the insurability challenge

Pure risk premium

The pure risk premium should be equivalent to the expected loss of the covered risk. In the insurance industry, normal practice to is calculate this from past loss data. In the case of the CO_2 leakage liability, the absence of past losses means it must be estimated through other means.

Calculations from Dabiels et al. (2023) put 27 "risked" tonnes per well per year, i.e. an expected loss of 27 tonnes of CO_2 per well per year (see table A.3 and A.4). Calculating the risked tonnes per well per year from the literature review in Dabiels et al. (2023) gives a range between 0 and 68 for different leakage sizes. These are wells with a maximum injection rate of around 1'000'000 tCO_2 per year, hence the expected value is very low in comparison. This would correspond to an extremely low pure risk premium, less than 0.003% of the revenue per well per year. The size of the pure risk premium itself therefore does not present a challenge to insurability.

For geological leakage pathways, the risked tonnes per year estimated using the Dabiels et al. (2023) analysis is even lower. For the whole site, there are only 11 risked tonnes per year. The estimates used were adjusted specifically for the UK continental shelf, which has a particularly low geological risk because of the good state of knowledge about the underlying geology and the low level of seismic activity, so higher estimates might be appropriate in other areas of the world. Nonetheless, it is extremely low.

Safety loading

The fluctuation safety loading on a strongly heavy-tailed loss distribution will necessarily be high. It is difficult to say how high, since it depends on the size of the insurer's reserves, the spread of their risk and generally their risk appetite. This is therefore a potential insurability challenge.

The uncertainty safety loading will likewise also be high, especially given the complete lack of a real loss history. While in the case of well leakage pathways there are analogues from the oil & gas industry, for geological leakage pathways the uncertainty is considerably higher.

This is compounded by the difficulty of detecting and measuring the size of geological leakage. MRV practices (see section 2.3) might change due to advances in the science and technology of monitoring, but also in response to changes in regulations or industry norms. Changes in MRV practices can directly lead to a change in the frequency of loss detection and the adjustment of loss sizes, both of which would entail a change in the expected losses from leakage. This level of uncertainty would have to be reflected in the uncertainty safety loading and presents a potential insurability challenge.

6.5.2 Comparison with analogy

Selection of the analogy

As discussed above, well blowouts are similarly low frequency, high-impact events, which present similar pricing challenges to the CO_2 leakage liability, but are nonetheless insured by the commercial insurance market. Pricing of control of well insurance is therefore taken as a analogy for comparison to assess the insurability challenge of the fluctuation safety loading for well leakage pathways.

For geological leakage pathways, a comparison is made with pollution insurance: pollution has similarly struggled with changes in the base frequency and size of losses resulting from changes to the surrounding regulatory regime.

Control of well insurance pricing

According to Carr (2014), offshore energy losses are rare enough that even the biggest energy companies will not have enough of their own losses to build a credible pricing model. Instead, pricing risk will rely on assembling loss data from across the industry and comparing to exposure data, i.e. the denominator of the loss rate.

As discussed above in section 6.2.2, the loss distribution of well blowout liability should be very heavy-tailed, due to the existence of very large liability losses like the Macondo/Deepwater Horizon blowout. Despite this, third-party liability coverage coverage "often costs a fraction of the main [property coverage] programme (Carr, 2014). In other words, the heaviness of the loss distribution tail does not lead to an excessively large safety loading. This is one point of evidence that the insurance premium is not likely to present an insurability challenge.

Mutual insurer Everen only charges a premium that recollects paid-out losses. Therefore the premium contains no safety loading and reflects only the actual losses over the previous 5 years. Everen offers control of well insurance, including liability coverage, as part of its standard energy offering. This reflects the fact that, within the coverage limits it sets, the heavy tail of well blowout losses is still relatively small compared to the size of insured risks across the industry, meaning a high fluctuation safety loading is not needed to protect the company from insolvency. Additionally, commercial insurers, who unlike Everen have to price risks in conventional manner, are able to remain competitive with Everen for their control of well coverage. Their ability to do so reflects the lack of insurability challenge presented by the heavy-tailed nature of control of well losses.

Pollution insurance

As explored in section 5.2.1, pollution insurance faced a crisis in the 1980s when the broadening of the liability regime compounded with the challenges inherent in insuring pollution, resulting in commercial insurers exiting the insurance pollution market. After the regulatory regime settled, insurers cautiously re-entered the market in the 1990's and 2000's, and today environmental impairment liability (EIL) insurance or pollution insurance is widely available in the market, albeit only for sudden and accidental events.

Geological leakages of CO_2 from storage face similar challenges to pollution in terms of their insurability. Changes in MRV practices or requirements could lead to a material change in the expected value of losses, meaning a high safety loading would be required. In addition, many geological leakages would be gradual, as opposed to sudden and accidental. Leakages may be discovered only a long time after they initiate and it may be very challenging to adjust the amount of leakage to the atmosphere of such a gradual leakage. These same challenges faced by pollution insurance make gradual events, and events highly sensitive to regulatory changes, uninsurable.

6.5.3 Evaluation

For well leakage pathways, where there is sufficient data to make an estimate of the pure risk premium, and where there is an insurable analogue in the oil & gas industry, there does not seem to be an insurability challenge from high insurance premiums. This is due to the very low expected value of the losses, and the relatively low size of the maximum possible loss compared to insured risks in the rest of the industry, meaning a large safety loading is not necessary. Therefore for well leakage pathways, there is not an insurability challenge from high insurance premiums.

In the case of geological leakage pathways, while evidence does suggest that the size of losses is likely to be lower than for well leakage pathways, the lack of experience means a larger uncertainty safety premium will likely be necessary. In addition, there are properties both of the regulatory regime around geological storage, particularly MRV requirements, and inherent characteristics of the risk which are shared with uninsurable pollution risks. These compound to mean that there is a chance the insurance premium criterion is not fulfilled for geological leakages from storage.

6.6 6. Cover limits

6.6.1 Identification of the insurability challenge

The overall coverage offered for the CO_2 leakage liability is likely to be in line with cover limits in the upstream energy insurance market: as explored in section 6.2.2, the largest cover limit in the upstream energy insurance market for control of well insurance is the USD 450 million offered by mutual insurer Everen. This leaves ample coverage for the maximum possible loss calculated in section 6.2.2. The overall coverage limit therefore does not impact the insurability of the CO_2 leakage liability.

For smaller events, the coverage will be limited by a deductible or risk retention. The level of the deductible should be negotiated between insurer and insured such that the insured's risk of ruin is mitigated and the insurer's costs for handling many small claims are not excessive. There is no reason to expect that the size of the deductible will be too high for storage operators to handle. The level of the deductible therefore does not provide a challenge to insurability.

In terms of exclusions, the preceding discussion has revealed that there will potentially be exclusions for leakages caused by earthquakes, especially induced seismicity, and seepages, i.e. leakages that are not sudden and accidental. The main mechanism through which induced seismicity would be thought to cause leakages is through triggering new fractures or reactivating existing faults. These are only two leakage pathways among many other potential leakage pathways which have trigger conditions unrelated to seismicity, such as improper sealing of wells, well blowout events during injection etc. Induced seismicity is not expected to be a major cause for leakages in most cases (Dabiels et al., 2023). Therefore, an exclusion of coverage for leakages triggered by induced seismicity is unlikely to materially restrict the overall level of coverage offered.

Seepages could be an important, even dominant pathway for loss of CO_2 containment over the lifetime of a storage site. The analysis in Dabiels et al. (2023) for a model 125 $MtCO_2$ capacity confined saline aquifer calculates a risked estimate of the total amount of CO_2 leaked over the 125 year lifetime of the storage site from seepages to be ca. 59'000 tCO_2, which is 54% of the the total risked estimate of CO_2 leakage from the site (see table 6.3). If seepages are not covered by insurance, this means a majority of the CO_2 leakage in this case would be uninsurable. However, a seepage, once identified, will represent a small yearly cost to the storage operator that will only be a small fraction of the total storage revenue. Seepages

Table 6.3: The proportion of risked CO2 tonnes from different leakage types for a "typical" confined saline aquifer. Values from Dabiels et al. (2023).

	Well leakage	**Geological**	**Sum**
Seepage	45,625 42%	13,848 13%	**59,473** 54%
Sudden & accidental	34,219 31%	16,126 15%	**50,345** 46%
Sum	79,844 **73%**	29,974 **27%**	**109,818** **100%**

should therefore not represent any risk of ruin for the storage operator, meaning their uninsurability will not present a barrier to the overall attractiveness of CO_2 leakage insurance for sudden and accidental events. In practical terms, the exclusion of seepages will likely occur by through the policy deductible, where the deductible level will be set in order to exclude them from coverage. The exclusion of coverage for seepages will not present any insurability challenge for the CO_2 leakage liability.

An exclusion for geological leakage pathways could potentially be more problematic. The same calculation as above, but only for sudden & accidental leakages from geological leakage pathways yields 16'126 tCO_2, 15% of the total risked tonnes over the lifetime of the site. However, despite being sudden & accidental, these are only minor leakages with maximum leakage rates of up to approx. 27 tCO_2/day. These minor leakages are less likely to pose a risk of ruin to the storage operator and their exclusion is therefore unlikely to restrict the cover limits to an extent to pose an insurability challenge.

This section has identified no challenges to the insurability of the CO_2 leakage liability from the cover limits criterion. Therefore, no analogy comparison is carried out and this criterion is deemed fulfilled.

6.7 7. Public Policy

6.7.1 Identification of the insurability challenge

This criterion would identify whether offering insurance for the CO_2 leakage liability would be contrary to any public policy aims. The question of whether offering insurance would encourage storage operators to take more risky behaviour themselves is tackled in section 6.4 under the analysis of moral hazard. The overall concordance of insurance coverage with public policy aims is suggested by the efforts of the EU to create a market for insurance products through the CCS Directive, as discussed in chapter 3. The specific ways that the public good elements of an insurance market for the CO_2 leakage liability could be strengthened are explored in chapter 7. It is concluded that the public policy criterion does not present any insurability challenges for the CO_2 leakage liability and therefore no analogy comparison is carried out.

6.8 8. Legal Restrictions

6.8.1 Identification of the insurability challenge

Given the overall concordance of insurance coverage for the CO_2 leakage liability with public policy aims discussed in section 6.7 and the explicit inclusion of insurance products as valid instruments for financial security in the CCS Directive guidance documents, there should not be any barriers to insurability presented by legal restrictions. This criterion is therefore deemed fulfilled and no analogy comparison is carried out.

Chapter 7

Discussion & policy implications

7.1 First policy challenge: does the CO_2 leakage liability face fundamental insurability barriers?

The actuarial characteristics of the CO_2 leakage risk do not pose a fundamental insurability challenge; by this, I mean the basic characteristics of the technical risk such as size and probability distribution have real-world analogues for which mature and functional insurance markets exist. There is therefore no reason to think that the CO_2 leakage liability is fundamentally uninsurable. In the context of the EU, there is no reason to think that policymakers were basically mistaken when designing insurance into the liability regime in the CCS directive. However, there are challenges unique to the CO_2 leakage liability which result from the specific regulatory context. In particular, the linkage of the CO_2 leakage liability to the EUA price exacerbates the challenge from the low loss frequency, because it rules out easy solutions that would deal with the latter challenge. The linkage of the CO_2 leakage liability to the EU ETS *per se* is not the challenge: many other investment decisions are exposed to long-term developments in the EUA price. The volatility (and subsequent risk of ruin) exacerbated by the linkage is the challenge. How this challenge can nonetheless be overcome is examined in the next section. In addition to the EUA price linkage, MRV regulations are a sensitive issue: if they are too weak, this can lead to moral hazard and challenges setting the insurance premium at the right level.

7.2 Policy and market innovations for strengthening the insurability of the CO_2 leakage liability

In-kind risk transfer as a mechanism to increase coverage length

The barrier to long-term insurance coverage stemming from EUA price variability could be tackled with in-kind risk transfer: like the buffer pool discussed in section 5.3.1 and the in-kind insurance discussed in section 5.3.2, a risk transfer mechanism that holds EUAs as reserves and pays out in them following a loss would eliminate the risk of EUA price increases decreasing the extent of coverage. A remaining challenge would be building up a sufficient reserve of EUAs to cover the largest possible events: given their low frequency, the risk premium (reflecting the expected value of the loss) would be likely be low, meaning it would take a long time to build up the reserves from premiums alone, and likely an initial capitalisation would be necessary. This is normal practice when setting up a mutual insurer, as happened when OIL (now Everen) was set up (see section 5.1.2).

A barrier to conventional in-kind insurance is regulations governing what insurance companies can use to maintain their reserves. EUAs are regulated as securities under the EU Markets in Financial Instruments Directives. Depending on the jurisdiction, insurance companies may be able to hold EUAs as reserves, as well as pay out in EUAs. In addition, It would be challenging to begin with to have a diversified-enough portfolio, given the relatively few number of assets. This is an area where state support at the beginning can crucially strengthen insurability.

Increasing the loss frequency with mandatory risk sharing

A potential challenge that may exacerbate the low loss frequency challenge is if many storage operators do not choose to share their risk with the commercial insurance market or with the industry through a mutual structure. The fewer losses there are in the portfolio, the less balanced it is. Storage operators owned by large oil & gas companies with their own captive insurers will likely rely on them instead of sharing the risk with smaller players in the industry, resulting in a more restricted and less balanced insurance portfolio. In the worst case, this could result in insurance not being available for storage operators without access to large captive insurers, hindering the develop of a diverse and competitive market for CO_2 storage. A potential solution for this is enforcing mandatory risk sharing in the industry.

Buffer pools are a model that incorporate both an in-kind and a mandatory risk sharing aspect. A potential host of such a buffer pool could be the Carbon Central Bank discussed in section 3.4.2: it could capitalise the pool with EUAs issued on the basis of procured removals. An outstanding challenge would be accurate risk pricing to ensure that the pool remains capitalised at a sufficient level, as is currently a challenge with existing buffer pools (section 5.3.1). When there is a centrally-managed mandatory buffer pool, there can lack the commercial incentives and competition to encourage accurate risk pricing, which can lead to adverse selection and undercapitalisation of the risk pool.

Increasing the scope of coverage with reinsurance pools

The challenges with insuring geological leakage pathways and seepages are analogous to those faced by the pollution insurance market discussed in section 5.2. There, extending coverage to otherwise uninsurable risks could be achieved by the creation of reinsurance pools which guaranteed the availability of reinsurance capacity to direct insurers. In the case of pollution insurance, the reinsurance pools are granted support from the government in the form of waivers for anti-competition regulations, but support can be more extensive, including direct financial support for capitalising the pool or providing "backstop" capacity.

Reinsurance pools can be for voluntary insurance, as is the case for pollution insurance, or mandatory, as is the case with the nuclear reinsurance pool: nuclear installations have mandatory insurance requirements which are then provided by commercial or mutual insurers (ensuring there is some competition in the market and more adequate risk pricing) whose capacity for insuring such risks is increased by the option to take part in the nuclear reinsurance pool. The existence of the reinsurance pool only partly diminishes the benefit of mandatory insurance, since all insurers have the option to participate in the pool and thus benefit from a more diverse insurance portfolio with more losses, even if not every insurer (e.g. captives) decides to participate.

7.2.1 Policy proposal for strengthening the insurability of the CO_2 leakage liability: EUA reinsurance pool

A reinsurance pool for CO_2 leakage liability insurance that holds EUAs as risk capital combines the benefits of the above-mentioned policy and market innovations to increase the insurability of the CO_2 leakage liability. The pool could benefit from state support, to the extent necessary, in a number of ways, including waiver of anti-competition laws, initial support in capitalising the pool while the number of risks is low, and guaranteed capacity. The pool could also be a venue for knowledge sharing and exchange on improving and aligning on MRV practices and loss adjustment, in order to further boost the insurability of geological leakage pathways and seepages.

7.3 Strengthening the public good contribution of CO_2 leakage liability insurance

So far, the discussion has been focussed on what policy and market innovations could make the CO_2 leakage liability more insurable. This is based on the proposition that the existence of a market for CO_2 leakage liability insurance is a public good, as it will allow the development of an effective and competitive CO_2 storage infrastructure that will help the public reach its climate targets. However, there are policy goals that an insurance market for the CO_2 leakage liability could support that go beyond its mere existence. This section examines those public policy goals and how CO_2 leakage liability insurance could support them.

7.3.1 Protecting the public over the long term

A CO_2 storage site may retain a risk of leakage for decades after CO_2 injection ceases. The question of who should hold the cost of the liability over that time is a question of how to split the risks and rewards of carbon storage between the storage operator and the public. This question has been settled in the EU with the CCS Directive, which gives the competent authority (CA) the mandate to make a judgement after approximately 20 years about whether the risks have suitably diminished to transfer the liability to the public.

Within this constellation, insurance can play the role of covering risks that could ruin the original holder, in exchange for a fee. If the actor ultimately responsible for the risk does not face the possibility of ruin, there is no reason for them to buy insurance: over the long run, they will pay more for the risk than if they had held it themselves. Therefore, it will not make sense for the public sector/the government to purchase insurance unless they have a very high cost of capital and cannot themselves cover the worst-case leakage scenarios. In the context of the EU, this situation should not arise.

If the assessment of the underlying risk increases, e.g. if additional leakage pathways are found during injection, that is a separate risk to the basic risk of leakage. I will refer to it here as the risk of basis change. Very long-term insurance coverage (i.e. multi-decade coverage) means transferring more of this risk of basis change to the insurer; this is problematic for a number of reasons. Firstly, that means the insurer will charge a much higher premium to cover this risk of basis change, with a very large uncertainty loading. Secondly, if an operator has this coverage, they might continue to inject CO_2 into a very risky reservoir where the expected value of the losses is higher than the revenues from CO_2 storage[1] (although a well-designed regulatory regime could also prevent this). This is therefore an uneconomical project and it would be more prudent if injection were to cease. The risk premium is an important price signal that allows operators to properly respond to a changing risk situation. Thirdly, this introduces a strong element of moral hazard that inadequate sites are selected with limited due diligence performed. Therefore, very long-term insurance coverage is not a public good and could lead to perverse outcomes.

The disadvantages from very long-term coverage explained here will be weighed against the benefits of increasing the cover period in order to increase the loss frequency and the insurability. This is a calculation that will be done be the insurer when they have the freedom to determine the optimal cover period. The point of this section is to argue that it should not be a policy aim to increase the cover length to the maximum possible for the sake of protecting the public over the long term.

What insurance can do is enable storage operators to hold risks that otherwise pose a possibility of ruin e.g. bankruptcy. Protecting storage operators from bankruptcy enables them to continue to meet their obligations and hold the cost of the liability for longer than they otherwise would, meaning a better deal for the public in the long run. Insurance coverage need not be long-term to protect operators from bankruptcy: it only must continue to be available, even if the risk basis changes. Therefore, supporting the availability of insurance, also for difficult-to-insure risks, is the best way to protect the public over the long term.

7.3.2 Enabling the risk-pricing function of the insurance industry

As already suggested above, insurance premia can act as useful price signals for actors responding to different risks. Enabling the insurance industry to serve this risk-pricing function can allow it to serve many more public policy goals.

[1] An everyday insurance analogy: if you have a 20-year insurance policy on your car, you might be tempted to keep driving after the brakes have stopped working. If the policy instead renews every year, at some point the premiums will be unpayable and you will stop driving the car.

One such goals is the integration of diverse carbon removal methods into climate policy regimes. Different removal methods that rely on different storage types, e.g. mineralisation, geological storage, storage in biomass etc., have different risks of leakage. One way to make these different removal methods comparable is to attach a storage replacement obligation. In the case of geological storage, this storage replacement obligation is similar to the CO_2 leakage liability, but with the size of the liability being linked to the cost of recapture and storage of CO_2. To the extent that this obligation is insurable, the insurance premium would give information about the expected replacement cost plus loadings for fluctuations and uncertainty. Pricing this risk via insurance effectively internalises the reversal risk, enabling comparability between removal methods with diverse storage at the point of purchase.

As discussed in section 3.4.2, the EU Commission is exploring different options for integrating removals into the ETS. All three integration proposals discussed here rely on some level of comparability between removal methods in order to enable efficient functioning of a removals market. The proposals for direct ETS integration and integration mediated by a central body such as a CCB further rely on equivalence between reductions and removals. This further step of equivalence between reductions and removals is also enabled by insurability if there is a mandate to post financial security attached to every tonne of CO_2 removed. Exactly who has this obligation, whether the holder of the removal certificate at any given time, or the original storage operator, is another question. As discussed in section 3.3, insurance is likely to be the most capital-efficient form of financial security in most cases. A financial security mandate on removals could ensure that all removals are maintained over the 1000-year lifetime of atmospheric CO_2. If insurance is used, the insurance premium would get integrated into the price, meaning the risk of reversal from low-probability, high impact leakages is efficiently priced in. The danger then is that insurance becomes unavailable for a removal method or project: other less capital-efficient forms of financial security would need to be used, which would be based on the organisation's cost of capital and may also be challenging to find. For this reason, strengthening the insurability of the storage becomes an important policy measure to support the goal of integration of removals into climate policy regimes.

7.4 Second policy challenge: what role can CO_2 leakage liability insurance play in an evolved EU climate liability regime?

In general, CO_2 leakage liability insurance, not just for geological storage, but for other carbon storage methods too, can play a limited but invaluable role in the liability regime. In particular, this role is to price risk in a capital-efficient way and then hold that risk for parties unable or unwilling to hold it themselves. This means whatever the risk is, it can be handled in an efficient way without leading to more costs than necessary to the public. For example, if an exceptionally large CO_2 leakage bankrupts the liable party, insurance coverage means the liability will not have to be taken up by the public. Moreover, as the assessment of the risk profile of a storage site changes, it can be reflected in changing insurance premiums, meaning economically-motivated actors will respond immediately and not only if/when the risk materialises. What insurance cannot do is relieve actors of the costs of risks they have taken: in a well-functioning insurance market and in the long run, the costs of risks will always remain with the initial risk holders, whether that is the storage operator or the public who eventually takes over the liability. Therefore, insurance cannot solve the long-term liability issue of geological storage: the fact that CO_2 leakage may remain a risk for decades is a challenge society has to directly face up to.

7.5 Applicability of findings to other geographies

The result that there are no fundamental barriers to the insurability of the CO_2 leakage liability relates primarily to the technical aspects of the risk, which in principle does not vary between geographies. Therefore, the main finding should be applicable to other geographies, although they each will all have their own potential challenges stemming from the regulatory regimes in place.

7.5.1 The US liability regime for geological storage

In the US, there is no comprehensive climate liability regime in place that penalises emissions, owing to the failure of the US Congress to pass the American Clean Energy and Security Act in 2009. In its stead, the Inflation Reduction Act, passed in 2022, increased the value of the 45Q tax credit to a level sufficient to economically incentivise geological storage of CO_2. The 45Q tax credit can be claimed by taxpayers (i.e. entities capturing CO_2) per metric tonne of carbon oxide (in almost all cases CO_2, but potentially also CO) sequestered in secure geological storage instead of released to the atmosphere, with higher amounts available for direct-air captured CO_2 and projects fulfilling certain labour conditions. In the event of a CO_2 leakage, the IRA, who pays out the credit initially, is entitled to "recapture" the credit value by adding it to the original taxpayer's next tax return. This then essentially acts as a the CO_2 leakage liability, which could potentially be insured by the taxpayer.

While almost all potential insurability challenges translate from the EU context to the US, an exception is the low loss frequency. This is because rather than being attached to an unknown future ETS price, the size of the liability is always known based on the value of the claimed 45Q credits. The IRA carries out recapture on a "first-in, last-out" basis, meaning if there is a leakage, the value of the last-claimed credits is lost. The value of 45Q increases on a predefined schedule after 2026, meaning that the size of the future liability can be estimated. This should make it more straightforward for insurers to offer longer-term coverage and thus mitigate some of the challenge from the low loss frequency.

7.6 Critical reflection

7.6.1 Assessment of the insurability criteria framework and method employed

Insurability as a concept is one that depends highly on the surrounding market and regulatory context, both of which can change rapidly. Despite this, Berliner (1982) has made a strong effort to give the concept of insurability a degree of objectivity by developing a comprehensive framework for systematically making the checks that any underwriter would have to before considering to offer insurance for a new type of risk. This effort has been recognised by the insurance economics literature, as no other insurability framework has been so consistently applied and tested in assessing the insurability of new risks. This thesis has benefited greatly from these efforts to make the question of insurability robust and objective. In this thesis, it offered a systematic way to approach a pressing, policy-relevant challenge for which there has not yet been an answer.

Any finding about the insurability of a certain risk will eventually be tested by reality, in whether an insurance market for this risk really emerges. The eventual "test" will be a process in which many larger exogenous forces come into play, such as demand for the insurance product, regulations which change the shape of the liability landscape and overall economic activity. Therefore, the insurability criteria are primarily a heuristic tool for approximating the thought process of actors who have to respond to their own circumstances and engage in negotiations in order to achieve a complex commercial goal. It will therefore be difficult to tell, even with time, whether the analysis was truly robust.

Further, the analysis using the framework is likely not highly reproducible due to the number of qualitative judgements that must be made based on theoretical arguments. Partly this is the result of the framework not providing prescriptive methods for making the assessments of insurability criteria, meaning that novel arguments have to be found for each new risk and for every criterion. This is a consequence of the real-world complexity of the topic. Also, In the particular case of the CO_2 leakage liability, there is a lack of direct empirical evidence to ground a robust analysis. This same fact, however, directly leads to the urgency of the question. In other words, assessing the insurability of the risk before major CO_2 leakages actually occur is especially valuable.

Despite these challenges, the particular method employed in the analysis - that of systematic comparisons - was highly successful in allowing a strong conclusion to be drawn despite a lack of direct empirical evidence. Moreover, the comparisons with existing industries was invaluable in leading directly to potential solutions to the insurability challenges identified. In sum, what the method of comparisons was able to do was contextualise a seemingly unfamiliar risk in a well-established industry and show that many of the seemingly most challenging aspects of the risk have long been tackled elsewhere. This reframing of the discussion around the CO_2 leakage liability is the most important novel contribution of the thesis.

7.6.2 Outlook

As mentioned above, the eventual "test" of the thesis will come in reality. In fact, that is already starting to occur: while this thesis was being written, two insurance brokers announced insurance products to give comprehensive coverage to carbon capture and storage projects, both including the CO_2 leakage liability as a part of that (AON, 2024; Howden, 2024). This is not yet a sure indicator of the insurability of the CO_2 leakage liability: this announcement of a product by brokers does not mean that any direct insurers have yet engaged with them and decided to offer insurance capacity to geological storage projects for the CO_2 leakage liability. Moreover, two "first-of-a-kind" products is not yet indicative of a mature and functioning market. However, it is nonetheless an encouraging indication that well-established insurance industry players see this as a promising future market.

If the insurability of the CO_2 leakage liability is demonstrated with real examples in the near future then there will not be any need for further theoretical research into insurability: that question will have been answered. However, what will remain a pressing research question coming out of this thesis is the appropriate role for insurance to play in a larger climate policy regime. In particular, the question about the role of carbon insurance in a reformed EU ETS will remain pertinent through 2026 when the EU Commission will release its report on EU ETS reform and beyond. This therefore remains a promising area of research and one which could benefit from more quantitative and modelling results that this thesis did not deliver.

Chapter 8

Conclusion

This thesis aimed to answer the question of whether the CO_2 leakage liability from geological storage is insurable. This was motivated by the distinct lack of an emergence of such an insurance market in the EU since the relevant regulations have been in place over the past 15 years (in particular the CCS directive, passed in 2008). In addition, it sought to contribute to the existing policy debate about the future of the EU climate liability regime, particularly the integration of removals into a market structure (whether the EU ETS or a new removals trading scheme, RTS) and the appropriate role for insurance in such a structure.

This question was answered by seeking to identifying fundamental insurability barriers that would prevent commercial insurance underwriters offering insurance coverage to geological storage sites at acceptable rates and terms. This was done with a largely theoretical analysis, using the insurability criteria of Berliner (1982) with systematic comparisons to existing insurance markets that share characteristics with the CO_2 leakage liability.

The method used overcame the scarcity of actual loss data by using theoretical arguments backed by systematic comparison with established industries. thereby innovating on the existing literature that uses the criteria of Berliner (1982). The results, while relying on a largely qualitative analysis, nonetheless successfully gave an indication of where the main insurability challenges lie.

The eight criteria analysed were randomness of loss occurrence, maximum possible loss, loss frequency, information asymmetry, insurance premium, cover limits, public policy and legal restrictions. The first five criteria all identified potential insurability challenges, which prompted a comparison with existing insurance markets. A comparison with upstream energy insurance, in particular control of well insurance cover (which primarily insures hydrocarbon extraction well blowouts), and with pollution insurance, in particular environmental impairment liability insurance, was used in these five cases. In four of the five cases it was found that circumstances similar or more challenging from an insurability perspective are already tackled by these existing insurance markets, leading to the conclusion that there are no fundamental insurability challenges facing the CO_2 leakage liability in these respects.

Two notable such cases are information asymmetry and insurance premium: information asymmetry has potential moral hazard and adverse selection challenges that relate to how robust the MRV regulations in place are. Lack of robust MRV regulations will hinder insurability if there is too much scope in how operators detect leakages, meaning they can effectively increase the frequency of loss occurrence after attaining insurance coverage by increasing the stringency of monitoring. Additionally, adverse selection may occur if there are insufficient regulations around information sharing in the permitting phase. For the insurance premium criterion, there may be higher insurance premia for covering seepages (gradual leakages) and leakages through geological pathways owing to higher basic uncertainty about their likelihood of occurrence. However, in case these leakage types are excluded from coverage, their smaller size and less sudden characteristics than well leakages means it is unlikely to decrease the overall attractiveness of insurance coverage.

For one of the criteria, loss frequency, a challenge was identified with characteristics unique to the CO_2 leakage liability. The very low frequency of occurrence of CO_2 leakage events is not without precedent: hydrocarbon well blowouts are also very low frequency events, but this is tackled partly by insuring them for their whole lifetimes. This effectively increases the loss frequency per cover period, meaning the premium charged comes closer to recovering losses in case of an occurrence. In the case of CO_2 leakage events, this tactic is ruled out by the linkage of the leakage liability with the EU ETS through the EUA surrender obligation: the EUA price volatility over the long term is an additional risk that means either a greatly inflated premium, a stricter coverage cap (i.e. a cap on EUA price in the insurance policy, leaving the insured exposed to this risk) or annually renewing coverage with premia tracking the EUA price. The last example is the most realistic (and is in line with many types of property insurance), but leaves the low loss frequency challenge unresolved.

In light of the challenges identified above, especially the low loss frequency challenge, the thesis proposed the following solution for strengthening the insurability of the CO_2 leakage liability: A reinsurance pool that holds EUAs as risk capital that would eliminate the risk of EUA price increases over the coverage period while broadening the extent of risk sharing and offering guaranteed reinsurance capacity also for the more challenging leakage risks, such as seepages and geological leakage pathways. Governments could support with an initial capitalisation (paid back over time as premiums come in) and a waiver of anti-competition laws (as was given for e.g. pollution reinsurance pools). Such a reinsurance pool could also act as a venue for knowledge sharing and exchange on improving and aligning on MRV practices and loss adjustment.

In contributing to the existing policy debate on the appropriate role of insurance in the future EU climate liability regime, the thesis made two points.

Firstly, long-term insurance coverage should not be sought as an end in itself, or as a mechanism to offload the costs (expected value) of risks knowingly taken by actors best positioned to mitigate those risks, i.e. storage operators or the competent authority. Only when longer-term coverage increases the insurability of the risk should it be encouraged. This is because, in a well-functioning insurance market and in the long run, insurance always costs more than the expected value of holding the risk: if it does not, the insurer will make a loss and soon exit the market. The proper role of insurance is to reduce volatility for those actors it poses a risk of ruin to. Meanwhile, encouraging long-term coverages introduces new dimensions of moral hazard and reduces the effectiveness of the insurance premium as a price signal on the underlying risk.

Secondly, this role of insurance in giving price signals about the level of underlying risk by pricing risk in a capital-efficient way can be well utilised in the future EU climate liability regime. By efficiently pricing the risk of storage reversal, insurance can make carbon storage methods more directly comparable and allow an upfront pricing-in of reversal risk at the initial decision point. The commercial pressures on insurance companies should lead to a conservative approach in pricing reversal risk, therefore favouring more permanent carbon storage and thus better protecting the climate.

Appendix A

Tables

	Expected occurrence frequency per feature			
	Seep	**Minor**	**Moderate**	**Major**
Leak rate (tonnes/day)	1	1 to 50	50 - 1000	1000
Active well	1 in 10 yrs	1 in 1,000 yrs	1 in 10,000 yrs	1 in 100,000 yrs
Monitoring well	1 in 10 yrs	1 in 1,000 yrs	1 in 10,000 yrs	1 in 100,000 yrs
Brine-producing well	1 in 10 yrs	1 in 1,000 yrs	1 in 10,000 yrs	1 in 100,000 yrs
Legacy well	1 in 10 yrs	1 in 1,000 yrs	1 in 10,000 yrs	1 in 100,000 yrs
Block-bounding fault zone	0	1 in 10,000 yrs	0	0
Map scale fault	1 in 1,000 yrs	1 in 3,650 yrs	0	0
Fault re-activation	1 in 1,000 yrs	1 in 1,912 yrs	0	0
New fracture initiation	1 in 1,000 yrs	1 in 1,912 yrs	0	0

Table A.1: Expected occurrence frequency of leakages of different sizes from leakage pathways, used to calculate the overall loss frequency of leakage events. Values taken from Dabiels et al. (2023).

	Number of features per "typical" site		Total probability of occurrence of minor, moderate or major leakage per site		Total probability of occurrence of moderate or major leakage per site	
	Depleted Reservoir	**Saline Aquifer**	**Depleted Reservoir**	**Saline Aquifer**	**Depleted Reservoir**	**Saline Aquifer**
Active well	5	5	1 in 180 yrs	1 in 180 yrs	1 in 1,818 yrs	1 in 1,818 yrs
Monitoring well	1	1	1 in 901 yrs	1 in 901 yrs	1 in 9,091 yrs	1 in 9,091 yrs
Brine-producing well	0	2	0	1 in 450 yrs	0	1 in 4,545 yrs
Legacy well	5	2	1 in 180 yrs	1 in 450 yrs	1 in 1,818 yrs	1 in 4,545 yrs
Block-bounding fault zone	1	0	1 in 10,000 yrs	0	0	0
Map scale fault	4	0	1 in 912 yrs	0	0	0
Fault re-activation	1	1	1 in 1,912 yrs	1 in 1,912 yrs	0	0
New fracture initiation	1	1	1 in 1,912 yrs	1 in 1,912 yrs	0	0
Expected occurrence freq. per site			1 in 69 yrs	1 in 82 yrs	1 in 826 yrs	1 in 909 yrs
Number of sites			10	13	10	13
Combined				23		23
Total expected occurrence freq./year			**1 in 7 yrs**	**1 in 6 yrs**	**1 in 83 yrs**	**1 in 70 yrs**
Combined				**1 in 3 yrs**		**1 in 38 yrs**

Table A.2: Calculation of the loss frequency of CO2 leakages for all CO2 storage sites planned in Europe as of mid-2024, using values and parameters for a "typical" storage site from Dabiels et al. (2023).

Active well	Max	Probability per	Max Total loss	Max risked tonnes per year
Minor	1.00E-03	per well per annum	9125	9
Moderate	1.00E-04	per well per annum	121667	12
Major	1.00E-05	per well per annum	608333	6
Total				**27**

Table A.3: Risked tonnes for different types of well leakage pathway, values from Dabiels et al. (2023)

Table A.4: Risked tonnes for different types of geological leakage pathway, values from Dabiels et al. (2023)

Geological feature	Max	Probability per	Max Total loss	Max risked tonnes per year
Block-bounding fault zone	1E-04	per site per 100 years	25000	0.03
Map scale fault	3E-04	per site per 100 years	100000	0.3
Fault re-activation	5E-04	per site per 100 years	1000000	5
New fracture initiation	5E-04	per site per 100 years	1000000	5
Total				11

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