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Role of Underground Carbon Storage to Assist Reaching Net Zero by 2050: Perspectives on Petroleum Reservoirs

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ABSTRACT

This article focuses on the critical role of sedimentary basins in underground carbon storage. Focusing on both depleted petroleum reservoirs, as well as sedimentary reservoirs in the field's petroleum stratigraphy (associated sedimentary reservoirs), it highlights the importance of complete CO₂ storage in saline aquifers associated with petroleum reservoirs.

This paper provides a novel approach to the understanding of underground carbon sequestration (UCS) by combining the examination of target reservoirs and regulation of activities in these reservoirs. By combining this consideration of physical characteristics with legal issues arising from the regulation of UCS, and their application to emerging Australian UCS projects, this novel evaluation of the progress in UCS provides a unique insight into Australian existing and planned UCS Projects.

The findings of the research indicate that depleted petroleum reservoirs are more suited to enhanced oil recovery techniques, while associated sandstone reservoirs (saline aquifers) of the same formation are more suited to UCS. The suitability of a reservoir should be considered in the regulation of UCS activities. The example of Australia presented in this paper demonstrates the difficulties in such regulation.

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1. Introduction

As the world transitions to an economy where net zero carbon emissions by 2050 (NZE2050) are required to limit global temperature increase to 1.5°C it is essential that nations utilise all the technological tools available to limit the release of greenhouse gases (GHG) into the atmosphere. The two most common GHG are methane and carbon dioxide (CO₂). Methane release from energy activities primarily arises from fugitive emissions from hydrocarbon activities (such as leaking wells and flaring of gas), agricultural activities, industry activities and waste [1]. Sources of CO₂ emissions include fossil fuel burning (approximately 93%), cement (5%), and other smaller sources (2%) [2], which is the focus of this paper. According to the US Environmental Protection Agency, CO₂ emissions from fossil fuel and industrial processes comprise 65% of GHG emissions, 11% from forestry and other land use, 16% from methane, 6% from nitrous oxide, and 2% from fluorinated gases [3]. Given the dominance of CO₂ emissions, it is hardly surprising that much activity is focused on CO₂ emissions removal from the atmosphere and its permanent storage.

Indeed, the International Energy Agency (IEA) notes that without a profound transformation in the way we produce and use energy, which can only be achieved with a broad suite of technologies, net zero carbon emissions by 2050 will be impossible to achieve [4]. The IEA views carbon capture, utilisation, and storage (CCUS) as a critical technology for the energy transition since it is the only group of technologies that contributes to both reducing emissions in key sectors directly and removing CO₂ to balance emissions in 'hard to abate' sectors such as concrete and mining [4].

In 2020, the IEA's examination of technology considered CCUS, noting that it 'will need to form a key pillar of efforts to put the world on a path to net zero emissions... [as] it is the only group of technologies that contributes both to reducing emissions in key sectors and to removing CO₂ to balance emissions that cannot be avoided' [5]. By 2023, in its *World Energy Outlook* [5], the IEA noted that the application of technology to reduce CO₂ emissions is advancing most rapidly in areas where technologies are already mature and cost competitive, especially in the electricity generation and ground transportation sectors [5]. Many technological advances have been occurring in both pre- and post-capture of CO₂, and include techniques such as liquid amine scrubbing, and adsorption technology using solid porous materials which are now comparable in performance to liquid amines [6].

The IEA is clear in its view that the energy transition and the attainment of NZE2050 will require investment and technological development in all sectors, including hard-to-abate industries. Thus, the IEA has called for policy initiatives that support innovation and early deployment of thus-far little-used technologies, including low-emissions hydrogen and CCUS technologies [5], noting that investment in these technologies is commencing from a low base, with only a handful of projects commercially viable [5]. For CCUS, these projects were initially confined primarily to Europe and North America, although increasingly applied to the Asia-Pacific region, and especially Australia.

According to the IEA's *Clean Energy Transitions Programme* report [7], the extent to which CCUS can contribute to reducing emissions for NZE2050 depends on technological development. In some hard-to-abate industries, such as the cement industry, CCUS will be necessary to deliver a 60% reduction in industry emissions. Yet, carbon capture in this industry is presently only at the demonstration stage [7]. Once captured, the CO₂ requires storage, hence the need for underground sequestration. Theoretically, the capacity for storing CO₂ in deep geological formations is vast, with the volume of storage available in petroleum and associated reservoirs greater than that required to achieve NZE2050 [7]. However, CO₂ sequestration hinges on technological development in carbon capture as well as the characteristics of suitable reservoirs for the storage of the captured carbon. It is ironic that perhaps the greatest limiting factor for the success of CCUS is not the development of technology for the capture of carbon, but rather the physical characteristics of the sedimentary reservoirs in which the CO₂ will be stored, and which no amount of technological development can alter.

There are four parts to CCUS: the capturing of CO₂; the processing of the CO₂ for transport; the temporary storage (and usually transporting) of the captured CO₂ in readiness for permanent storage; the utilisation of CO₂ for other industrial processes; and the permanent storage of CO₂, usually through sequestering in underground

geological formations. Each of these steps is technically complex, and together require a suite of technologies so that CO₂ can be diverted from the environment (and thus adding to global CO₂ volumes) to permanent storage underground or utilised in other technologies. Existing activities in the capture and storage space (especially Sleipner, Snøhvit, the Longship Project, and Barrow Island) assess existing technologies for the capture and storage of CO₂, as well as inform the development of new technologies.

The capture of CO₂ relies on engineering technology to capture the gas at its source. Since 2020, CCUS research and utilisation have been steadily increasing, with many countries adding it to their NZE2050 toolkit [8], to the chagrin of many who see CCUS as continuing to encourage fossil fuel use [9]. In the early 2000s, unfavourable publicity surrounded carbon capture, especially as applied to coal and the concept of 'clean coal'. In the period 2009-2013, R&D on CCUS exceeded USD1 billion per annum as research focussed on 'clean coal' technology [10]. By 2014, when 'clean coal' was debunked, and there was a shifting emphasis on global carbon,¹ the IEA noted that 'CC[U]S is advancing slowly, due to high costs and lack of political and financial commitment [10]. By 2020, CCUS remained a low profile, but its advantages in NZE2050 were recognised [11]. In addition, the refining of existing technologies and development of new technologies for carbon dioxide capture, ranging from pre-combustion, post-combustion, oxy-fuel combustion, direct air capture, and other emerging technologies are increasingly providing a suite of techniques for various industrial and commercial applications. Similarly, the analysis of the target reservoir for sequestration, be it a depleted petroleum reservoir or associated sedimentary reservoir, is important as we shift increasingly toward large-scale underground sequestration. The development of other forms of marine carbon dioxide removal (mCDR), and the physical, legal, and economic implications of these activities [12], to require further investigation to enable environmentally, economically, and socially acceptable ocean carbon removal to progress.

The petroleum industry has a critical role to play in the successful commercialisation of UCS, due to geological, geomechanical, and geophysical knowledge of reservoirs, experience in drilling and well management, as well as the reservoir engineering capability, all technical skills crucial for successful UCS. The petroleum industry is currently the only industry sector with the experience, knowledge, and skilled personnel for all aspects of UCS, and therefore is critical for a successful global energy transition that integrates carbon capture and UCS as suggested by the IEA [10].

This paper focuses on the final stage in the CCUS process: the permanent storage of CO₂ in deep geological formations, which may include saline sedimentary aquifers or depleted petroleum reservoirs. This geological storage process is generally known as underground CO₂ sequestration (UCS). In considering UCS, it provides a timely outline of the process, including differentiation from enhanced oil recovery (although the two often go hand in hand). It then turns its focus to an examination of successful, long-term offshore projects in Norway. Finally, it considers the contemporary implementation of UCS in a new jurisdiction, focussing on both onshore and offshore Australia. In undertaking these examples, it is possible to examine the features of successful UCS projects and consider some of the challenging issues that have affected recent projects.

2. Geological Conditions for Commercial UCS

There have been numerous attempts to undertake CCUS activities, to demonstrate either the potential or actual utility of the technology. Although there have been numerous pilot and demonstration projects, historically many successful commercial projects have occurred offshore in petroleum-producing jurisdictions. Norway has been an early mover on the commercialisation of UCS, commencing in 1996, particularly when compared with the USA today where less than 0.4% of the total CO₂ is captured through CCS and sequestered at 15 facilities [13].

It is important to distinguish between commercial projects, and pilot/demonstration projects. Commercial CCUS facilities are defined by the *Global CCS Institute* as a facility where CO₂ is captured and transported for permanent storage as part of an ongoing commercial operation, the facilities have economic longevity similar to

¹Noting that in the following year, 2015, the Paris Agreement was adopted, and a global push commenced to drastically reduce the use of coal given its high CO₂ emissions.

the facility whose CO₂ they capture and must support a commercial return and meet a regulatory requirement while operating [14]. Conversely, a pilot and demonstration facility is one where CO₂ is captured for testing, developing, or demonstrating CCUS technologies or processes. In the pilot/test project the captured CO₂ may not be permanently stored, and it has a short lifespan compared to commercial facilities; and a commercial return is not expected from the facility.

This paper will primarily consider commercial facilities but consider pilot/demonstration facilities where appropriate. For a commercial UCS project to succeed, the critical factor is the identification and assessment of a suitable reservoir. Therefore, this section will address the requisite geological conditions for both enhanced oil recovery (EOR) and UCS, and reservoirs suitable for permanent underground storage of CO₂.

3. CO₂ and Enhanced Oil Recovery (EOR)

Historically, CO₂ has been utilised to enhance the recovery of oil and gas from conventional reservoirs. When a reservoir is first producing, the hydrocarbon is produced at the wellhead from the pressure of the reservoir. As reservoir pressure decreases, other methods are required to extract the oil and gas from the reservoir. Secondary methods of oil recovery usually include water flooding of the reservoir, often with the incorporation of suitable chemicals, to move the hydrocarbon through the pore spaces [15]. With 65% or more of the oil often remaining within the reservoir, tertiary methods of recovery, such as EOR, are utilised to increase reservoir production. This process involves the injection of dense CO₂ into poorly producing petroleum reservoirs, thereby altering the properties of immobile hydrocarbons and allowing them to be recovered. CO₂ EOR has the potential to produce an additional 5 to 15% of hydrocarbons and extend the field life by 10 to 20 years [15, 16]. It is this injection of CO₂ into reservoirs that fuels the debate that CO₂ UCS merely promotes the recovery of fossil fuels.

Like other EOR processes, the efficacy of the CO₂ EOR process is primarily a function of the interaction between the CO₂ and the hydrocarbon itself, determined by the miscibility properties of the oil.² The miscibility of CO₂ and oil depends on the state of the CO₂ when injected. At the appropriate supercritical pressure and temperature, CO₂ is miscible with oil, combining completely to enable further recovery of oil [15]. Successful CO₂ EOR therefore occurs when the CO₂ combines with the oil, assisting the oil in moving through the rock pore spaces, thereby enabling greater in-situ recovery of petroleum [15].

EOR through CO₂ injection first occurred in 1972 in the Permian Basin in West Texas [15]. At present, this method is utilised in 56 oil fields in the Permian Basin in West Texas, collectively producing about 200,000 barrels of oil per day and accounting for 85% of CO₂ EOR production in the US [15]. CO₂ EOR is also extensively utilised in the US eastern New Mexico Permian Basin [16]. US experience demonstrates that where the technical criteria for achieving miscibility are present, there is sufficient unrecovered oil after primary and secondary oil production, affordable access to CO₂ is available, sufficient technical knowledge of CO₂ EOR technologies exist, and government incentives promote the implementation of CO₂ EOR, then EOR through CO₂ sequestration is achievable [16].

According to a study of the 54 largest petroleum-producing basins in the world, which together account for 95% of the world's estimated ultimately recoverable oil, CO₂ storage capacity can be significantly increased if CO₂ is utilised for EOR [17]. Approximately half of the CO₂ required for global CO₂ EOR, around 65Gt, can be met by anthropogenic CO₂ sources within distances comparable to existing and planned pipelines transporting CO₂ to EOR projects (up to 800km) [18], supporting the production of up to 225 billion barrels of oil [16]. Thus, the injection of CO₂ into existing hydrocarbon fields near the end of their life will have the dual effect of both producing the last of the recoverable oil, as well as potentially sequestering up to 65Gt of CO₂ from the atmosphere.

² Miscibility is when multiple liquids mix, becoming a completely homogenous liquid. For example, water and vinegar are completely miscible. In contrast, water and oil are immiscible since they do not combine at any proportion. See Institute for 21st Century Energy, *CO₂ Enhanced Oil Recovery* (Report, 2013), 4.

3.1. Selection of a Suitable Reservoir

The storage of CO₂ in suitable sedimentary reservoirs can be achieved in four ways: as a mobile substance within a structural trap (eg a petroleum reservoir with an impermeable cap rock to prevent the upward flow of CO₂); as an aqueous species dissolved in brine (such as supercritical CO₂ (sCO₂) in a saline aquifer); as a precipitated mineral; and through capillary entrapment as a residual phase [18]. It is the first two methods of storage that are the focus of this analysis.

Sedimentary basins are crucial for the success of CO₂ injection projects, since they contain high porosity and high permeability sandstone layers, with low permeability and low porosity cap rocks which limit the upward transfer of CO₂ [17]. Two types of reservoirs are suitable for deep underground storage of CO₂. Both are deep sedimentary basins usually associated with petroleum fields. The first is the depleted or near depleted petroleum reservoir itself, which often has already been subject to EOR techniques, including CO₂ EOR. The second is saline aquifers in petroleum-bearing formations. Identifying the type of reservoir that the CO₂ will be injected into (depleted petroleum reservoir or saline aquifer) is critical since the reservoir type will determine the form of the injected CO₂ – whether gas injection (also often associated with EOR activities and/or depleted petroleum reservoirs), or sCO₂, a fluid state of CO₂ held at or above its critical temperature and pressure, and which is chemically stable and non-flammable [19]. This fluid state of CO₂ is usually injected into saline aquifers [19].

Petroleum reservoirs and CO₂ storage go together [20]. Studies indicate that there is enormous potential to store CO₂ in depleted petroleum fields [18, 20]. These fields have proven to be effective hydrocarbon storage reservoirs for millions of years due to favourable essential characteristics required for CO₂ storage, including porosity, permeability, and geological seals, making depleted reservoirs ideal for utilisation for CO₂ injection and long-term storage [21]. In these reservoirs, gaseous CO₂ is injected under pressure into the pore space of the sedimentary rocks [17], and the CO₂ is hydrodynamically trapped in conditions similar to the trapping of hydrocarbons [17].

In addition to depleted petroleum reservoirs, petroleum fields often contain reservoirs above or below the hydrocarbon producing reservoirs that do not contain petroleum themselves, but have the necessary characteristics for storing CO₂, such as cap rock, base rock, permeability, porosity, and containment fractures. These reservoirs are often saline water-bearing reservoir rocks (aquifers) [22], injected with sCO₂ [19].

4. Commercially profitable storage of CO₂ in offshore jurisdictions – the example of Norway

Some commercial-scale sub-seabed CCUS projects have utilised oil-producing formations for CO₂ storage, as depleted petroleum reservoirs are often associated with UCS both due to the use of CO₂ for EOR, and for CO₂ storage. However, given that there is limited capacity in hydrocarbon reservoirs for large-scale CO₂, saline aquifers are an extremely attractive alternative for UCS [23]. Hence, many other UCS projects have injected CO₂ into saline aquifers for storage. These aquifers are usually geological structures associated with petroleum fields [21]. Therefore, what follows is a consideration of CO₂ commercial projects in Norway that have utilised both depleted hydrocarbon reservoirs and saline aquifers.

4.1. Sleipner

The Sleipner field CO₂ storage project was the first global offshore commercial-scale industrial sequestration and storage of CO₂. Commencing in 1996, CO₂ from gas produced in the Sleipner field is injected into an associated reservoir within the Sleipner formation. The injection reservoir is not a depleted hydrocarbon reservoir, but rather an aquifer within the Sleipner hydrocarbon field [24]. Rather than CO₂ injection into an oil-producing formation, it is injected into the Utsira Sand Formation (USF) which lies at a depth of approximately 1000 metres, well above the hydrocarbon producing reservoir located around 3450m depth [24].

The Sleipner project arose because of the high CO₂ content (approximately 9% CO₂) present in the gas produced from the Sleipner West field [25]. To meet export specifications and the purchaser's requirements, the

CO₂ content could not exceed 2.5%. The excess CO₂ was captured during offshore processing, and the CO₂ needed to be disposed of. At the time, the release of CO₂ into the environment was subject to a CO₂ tax in Norway, introduced in 1991, amounting to 1 million Norwegian kroner (NOK)/day. The cost of the CO₂ tax provided the impetus to investigate sub-seabed sequestration of the carbon, making the Sleipner CO₂ injection project economically feasible.

The USF is a regional saline aquifer that stretches approximately 400 kilometres from north to south, and 50-100 kilometres (km) east to west, and is defined by stratigraphic overlap [26]. It is comprised of complex depositional patterns, with a marine depositional environment of approximately 100 metres depth. The USF consists of stacked, overlapping mounds of low relief, fan lobes separated by thin intra-reservoir mudstones, and shaly horizons [26]. The depth of the USF surface varies from 550 to 1500 metres, with depths around 800 to 900 metres near the Sleipner field, and the reservoir is approximately 200 to 300 metres deep [26]. The thickness of the USF means that the Sleipner field can store up to 600 billion tons of CO₂ [26].

Data collection, comprising 770km² of three-dimensional (3D) seismic data, has been interpreted, revealing that the top of the USF generally dips to the south and consists of undulating small domes and valleys [26]. The CO₂ injection occurs through a single well, with the injection point located beneath a small domal feature rising approximately 12 metres above the surrounding area [26]. Shallow fractions of around 5 metres thick, providing significant restriction of CO₂ migration and in treatment of CO₂ in the reservoir. The grain size is fine to medium, with a porosity of 35 to 42.5% as demonstrated by core logs, and porosity of 35-40% occurs over most of the formation. This porosity is ideal for the sequestration of CO₂ [26].

Since commencing operation in 1996, Sleipner has sequestered more than 18 million tonnes (Mt) of CO₂. Whilst this may seem like a large amount of CO₂ sequestered, when put into perspective it represents around half of Norway's 2021 CO₂ production [27]. However, the value of Sleipner lies not in the volume of CO₂ sequestered but in determining the commercial viability of CO₂ sequestration, and the data collected, which demonstrates the movement of CO₂ through a reservoir over time.

4.2. Snøhvit

Following on from the success of Sleipner, the Snøhvit offshore gas field and associated gas processing facilities on Melkøya Island near Hammerfest have implemented a similar approach to CO₂ sequestration. Like Sleipner, the Snøhvit involves injecting CO₂ into an associated formation rather than a depleted well, with CO₂ injection occurring concurrently with gas production. The chosen formation for CO₂ injection is the Tubåen Formation (TF), a sandstone saline aquifer located below the gas production reservoir at a depth of 2600-2700m [28].

The injection site selection was based on the suitability demonstrated by data from previous exploration wells (15 wells) [29]. Gas production occurs from the Jurassic-era Stø Formation, which is separated from the above-laying TF by the Nordmela formations [29]. The TF is a sandy formation, comprising five sand intervals of varying quality, with shale cap rock seals. Like the USF found in the Sleipner field, there is an irregular distribution of subordinate shales in the TF, indicating that individual sandstone bodies within the TF overlap and are interconnected vertically and laterally [29], thus enabling good communication during CO₂ injection. Formation zones Tubåen 1- Tubåen 3 occur in the mid and lower parts of the TF and are perforated for CO₂ injection. The porosity of the TF is 10-16%, low compared to Sleipner, but still adequate for CO₂ injection [29]. In the first three years of CCUS, 1.1 million tonnes (Mt) of CO₂ had been captured during gas processing and injected into the TF for permanent storage [29]. Reservoir modelling indicates that the TF will be able to store 23 Mt of CO₂ captured from the well stream over the 30-year project life [29].

4.3. Cross-Border Full-Scale Value-Chain CCUS in Hard-to-Abate Industries: The Longship/Northern Lights Project

The Norwegian *Longship Project* is the Norwegian Government's full-scale carbon capture and storage project. It will be the first ever cross-border, open-source CCUS project. The project aims to capture CO₂ from onshore

industrial sites, initially from Norway, but in the future from across Europe. The captured CO₂ will be transported, injected, and permanently stored in the Eos formation a deep saline aquifer 2,600m below the North Sea seabed [30]. As a world first and publicly funded project, geomechanical modelling and storage reservoir rock characterisation data have been made publicly available. The Longship project was majority funded by the Norwegian government (around three quarters of the cost of the project) [31]. The reasoning for state funding of the project is to support Norway's Nationally Declared Contribution (NDC) under the Paris Agreement, to contribute to strengthening climate solutions (that is, demonstrating that it is possible to store carbon from hard-to-abate industries such as cement), and to secure and create new jobs within the petroleum industry [12].

The *Northern Lights* component of the Longship project comprises the storage of CO₂ on the Norwegian Continental Shelf. The Longship Project offers companies across Europe the opportunity to store CO₂ safely and permanently underground. Phase one of the project will be completed in mid-2024 with a capacity of up to 1.5 Mt of CO₂ per year.

The full-scale Longship project, as set out in the Storting Report No. 33, 2019-20 [32] includes capturing CO₂ from industrial capture sources in the Oslo fjord region in eastern Norway (including cement and waste-to-energy), liquefaction of this CO₂, and shipping the liquid CO₂ from industrial capture sites to an onshore terminal at Øygarden on the Norwegian west coast. From there, the liquified CO₂ will be transported by pipeline to CO₂ storage reservoirs in the Johansen Formation for permanent storage.

Construction of the Northern Lights terminal began in 2021, with the first phase expected to be complete by mid-2024, providing an initial storage capacity of 1.5 Mt of carbon dioxide per year over 25 years. The aim of phase two is to increase storage capacity to 5-7 Mt per year by 2026.

Longship's first sub-project is a carbon-capture plant at a cement factory located in Brevik, owned by Norcem-Heldelberg. The project aims to use surplus heat to capture 400,000 tonnes of CO₂ annually, which accounts for one-third of the emissions from the production of 1.2 Mt of cement per year. The second sub-project is the Hafslund Oslo Celsio waste-to-energy plant located in Oslo. This sub-project will also capture 400,000 tonnes of CO₂ per year from the waste combustion process. The captured CO₂ from the two east coast plants will be transported by ship to the Northern Lights reception terminal in Øygarden municipality on the Norwegian west coast, and then by pipeline to the injection well where storage will take place beneath the seabed. The transport and storage infrastructure component of the Longship Project (known as Northern Lights) aims to become commercially profitable based on a tariff paid by emitting firms for transporting and storing their captured carbon dioxide.

In a cross-border first [33], Yara and Northern Lights have completed a binding CO₂ transport and storage agreement with Northern Lights to transport CO₂ captured from Yara's Sluiskil ammonia and fertiliser plant in the Netherlands, and permanently store it beneath the seabed off the coast of Norway [32]. Beginning in early 2025, 800,000 tonnes of CO₂ will be captured, compressed, and liquefied in the Netherlands, then transported by ship to the Øygarden terminal in Norway for storage in the deep-sea Johansen reservoir (2,600m) [32].

The Longship project reflects the Norwegian government's ambition to develop a full-scale CCUS value chain in Norway by 2024, demonstrating the potential of this decarbonisation approach to Europe and the world. The Norwegian Government has exhibited long-standing leadership in realising full-scale CCUS and realistic decarbonisation opportunities for Norwegian and European industries.

4.4. Future CO₂ Storage on the Norwegian Continental Shelf

In some jurisdictions the hydrocarbon industry and petroleum regulators are integral in CCUS and UCS technologies as a tool, independent of hydrocarbon extraction and EOR, that will assist in attaining NZE2050. The clear leader in Norway. Since the early 2010s, the Norwegian Petroleum Directorate (NPD) has compiled and regularly updated its CO₂ Storage Atlas, which maps potential CO₂ storage geology [34]. In addition, Norway established a comprehensive legal framework for UCS in 2014.

Given Norway's extensive experience in CO₂ management, there has been a continuous and growing interest in acreage for injection and storage of CO₂ on the NCS. This demand and the response from the Norwegian government have moved UCS from an activity of limited potential to one designed to regulate the large-scale UCS of CO₂. The commerciality of UCS is further demonstrated by the NPD granting three CCUS licences in the North and Barents Sea in April 2022, awarded pursuant to the *Regulations of 5 December 2014 No. 1517 relating to the exploitation of subsea reservoirs on the continental shelf for storage of CO₂ and relating to the transportation of CO₂ on the continental shelf*. These licences were announced in rounds separate from hydrocarbon activities, demonstrating how formations for UCS are often separate from hydrocarbon production. In 2022, three exploration licences for storage of CO₂ were awarded, one in the Barents Sea and two in the North Sea. Similarly, in 2023 licences were granted for CO₂ storage on the Norwegian continental shelf. The primary objective of these licences is to determine whether these areas are suitable for commercial CO₂ storage.

Of critical importance in the licencing of CO₂ acreage has been two innovative and important development by the Norwegian government, in cooperation with industry. The first is the establishment of a CO₂ storage Atlas for the Norwegian sector of the North Sea [31]. Prepared by the Norwegian Petroleum Directorate and assembled utilising pre-existing petroleum data collected over the previous 40 plus years, this innovative, one-of-a-kind atlas demonstrates a CO₂ storage capacity of about 70 billion tonnes storage in the Norwegian North Sea alone. The objective of this atlas is to provide an overview of existing geological structures suitable for securing long-term CO₂ storage, so that knowledge regarding reservoir properties, sealing rocks, migration paths, storage capacity, and monitoring methods can be implemented in new projects [31].

The second innovative and important development by the Norwegian government was to develop and utilise a standard for the geological storage of CO₂ - *ISO 27914:2017 Carbon dioxide capture, transportation, and geological storage — Geological storage*, and the related *ISO 27916:2019 Carbon dioxide capture, transportation, and geological storage* [35]. The standards are complementary rather than overlapping [31], and together the two ISO's promote the use of geologic storage in a commercial, safe, and long-term manner through containment in geological systems [35]. The implementation of these industry standards for CCS supports industry CCS project developments and guide permitting and approval of UCS with the standards used to guide processes for evaluating technical challenges in alignment with existing and developing best practice [35].

5. Australian Offshore Opportunities for UCS

5.1. Overview

Australia's climate policy, set by the Australian government as required under international law commitments, has committed to legally binding greenhouse gas emissions reduction targets, as set out in the *Commonwealth Climate Change Act 2022 (CCA)*. Section 10(1) of the CCA sets two targets: a reduction in Australia's net greenhouse gas emissions to 43% below 2005 levels by 2030, and a reduction in Australia's net greenhouse gas emissions to zero by 2050.

As illustrated in Fig. (1) below, there is only one operational CCS project in Australia that undertakes UCS, with another proceeding after final investment decision (FID) occurred in 2023, and a further 14 projects in various phases of feasibility studies. Also, of critical importance for the future implementation of CCUS and UCS in Australia is the pilot/demonstration facility at the Otway CO₂ CRC international test centre, which to date has provided excellent data for the capacity of CCUS to be operational in Australia's sedimentary basins.

Although there are few commercial projects operating to date, there is a history of research in CCUS in Australia. A trial for carbon capture from coal-fired generation (ZeroGen project) was undertaken in the early 2010s. The Queensland (Qld) based ZeroGen project was to comprise of a 400 MW commercial scale power generation facility, with an integrated coal gasification power plant for the capture and storage of CO₂ emissions while generating low-emissions base-load electricity for the national electricity market [36]. Located in central Queensland, the geo-sequestration of the CO₂ was to be into the northern Denison Trough. As part of the project GHG exploration permits were awarded to the project proponent under the *Greenhouse Gas Storage Act 2009 (Qld)*, which was implemented for the project to proceed [36].

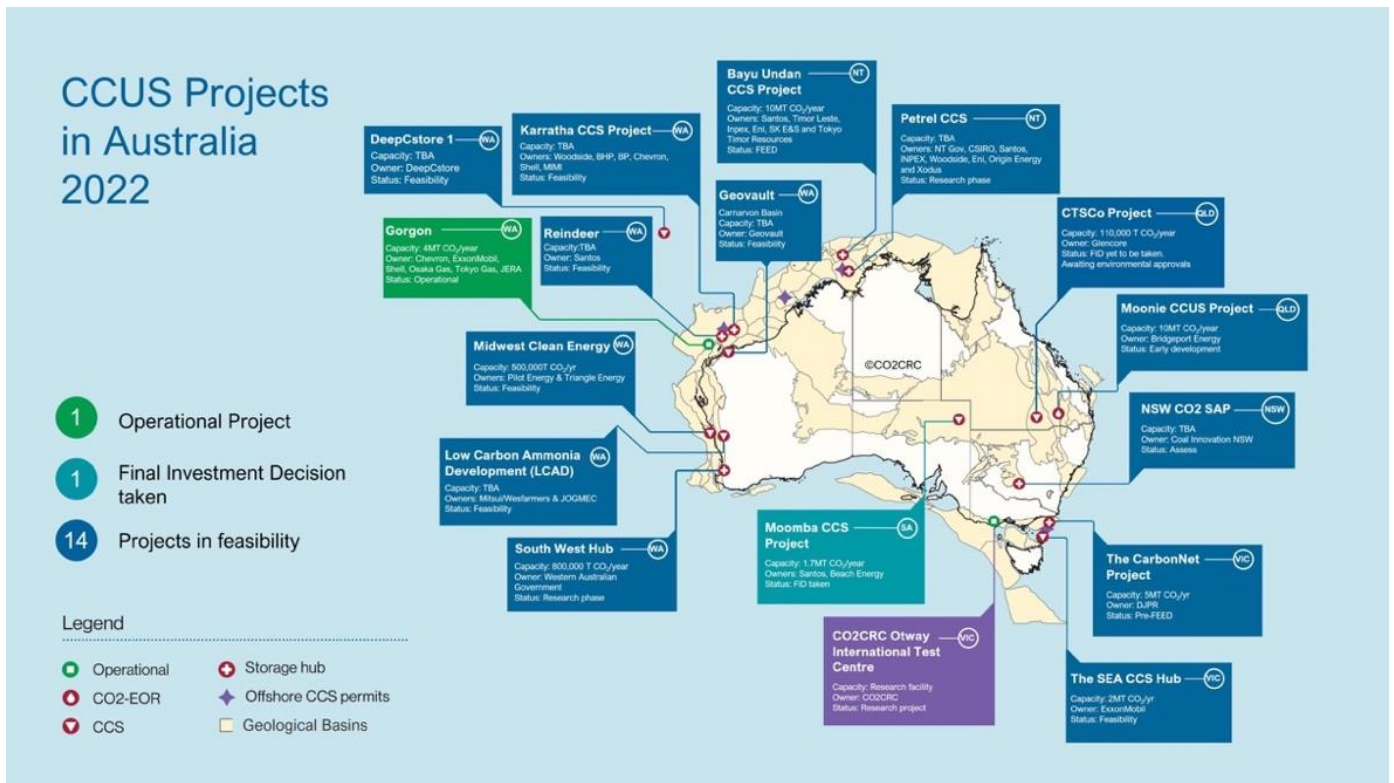


Figure 1: CCUS projects in Australia (Source: CO₂ CRC <https://co2crc.com.au/?s=ccs+projects>)

Depending on the literature consulted, the ZeroGen project was either an overwhelming success [37], or a spectacular failure [38]. Although the project was due to progress to the demonstration phase by 2015, with a full-scale plant by 2020, the ZeroGen project was placed in liquidation in 2011, and officially cancelled. The full history of the ZeroGen project, including the failures, is an important lesson for carbon capture projects, and that full-scale deployment of a project is preferable to trial phase [36].

In Australia, CO₂ EOR has been increasingly used, with the practice commencing in the 1970s. CO₂ injection for EOR has been viewed as an attractive on-ramp for CCUS and UCS, and Chevron’s Gorgon Project on Barrow Island, is currently the only profitable large-scale permanent carbon sequestration in Australia.

Results in the US suggesting that CO₂ injection into the formation as a liquid or super critical fluid can restore reservoir pressure to near original conditions [39]. Achieving this super critical state requires pressures exceeding 7.3 MPa, and temperatures more than 31.1 degrees Celsius [40], where CO₂ density increases to values comparable with oil, and viscosity remains low, preventing the CO₂ from rising to the top of the reservoir. Experience suggests that CO₂ will remain in this super critical state at a depth exceeding 800m [40].

5.2. Western Australia

5.2.1. Gorgon

The only fully commercial Australian UCS project is Chevron’s Barrow Island in Western Australia (WA). This project falls under Western Australian jurisdiction and is regulated under a state agreement since the pre-combustion carbon capture was part of the overall Barrow Island CCS project.

The Gorgon project captures CO₂ at the liquefied natural gas (LNG) processing facility on Barrow Island, and then disposes of the captured CO₂ through injection into the Dupuy Formation, a deep saline reservoir 2km beneath Barrow Island [41]. Reservoir characterization was initially utilised to select the target formation, however further seismic studies, seismic modelling, and a comprehensive appraisal including the drilling of an appraisal well, were utilised to confirm the target reservoir. In addition, a suite of robust subsurface models was utilised to

gauge the impact of CO₂ injection. However, a lack of knowledge meant that a flexible development plan for CO₂ disposal was required to ensure CO₂ sequestration occurred.

The target Dupuy Formation is characterised by fine to medium- grained blocky sandstone, capped by a fining upward unit at the top, the upper massive sand, thought to be a slope deposit, and containing important intra-reservoir siltstone baffles such as the Perforans 'Shale', a very low permeability siltstone. The upper Dupuy Formation is bioturbated siltstone with minor interbedded sandstone lenses, forming the barrier at the top of the Dupuy Formation, and therefore not an injection target. Immediately above the Dupuy Formation is the Basal Barrow Group Shale, a deltaic shale unit at the base of the Barrow Delta, found in every well that penetrates to the top of the Dupuy Formation on Barrow Island, and therefore considered to be a regionally extensive and continuous barrier, enabling injection into the Dupuy Formation to occur [41].

Comprehensive geomechanical modelling was developed for the Dupuy Formation based on numerous data sources: pore pressures, modified leak off tests, mini-frac data, image log data from the Gorgon CO₂ data well, fault geometric mapping from seismic data, and rock mechanics data from core analysis. This modelling was significant in the evaluation of the Dupuy Formation for subsurface disposals of CO₂. In addition, the modelling significantly influenced well placement and well trajectory, has identified constraints on formation containment, and provided well operability limits for injection pressure [41].

Hydrodynamic studies were also undertaken and were an important component of the containment assessment process. These studies explained formation faults and their ability to seal or be part of a communication network and confirmed the integrity of the top seal. The pressure and salinity data acquired demonstrated that aquifer pressure separation and salinity differences of at least 20,000 parts per million total dissolved solids (PPM TDS) equivalent between the Dupuy and the overlying aquifers existed, indicating the existence of hydraulic separation between the aquifers over the production time span, and demonstrating that at least one, and possibly two, competent regional seals were present above the Dupuy Formation [42].

Although extensive data acquisition, geomechanical modelling and hydrological studies were undertaken to identify and assess the target formation, the Gorgon CCS has not been entirely successful. Since the commencement of CO₂ injection at Barrow Island in August 2019, Chevron has injected 5,000,000 tonnes of greenhouse gases. Although this volume of injection is large, surpassing the annual injection rates of the Norwegian Sleipner commercial CCS project, it has fallen well short of the estimated target of almost 10 million tonnes of GHG. Independent analysis estimates that this shortfall of around 4.6 million tonnes will cost Chevron around \$100 million to offset via carbon credits. An analysis of the cause of this shortfall in sequestration points to a failure in engineering and technology applications and frequent inefficiencies [42], all contributing to the ongoing failure to inject predicted volumes of carbon.

5.2.2. Pilot Energy - Cliff Head Oil Basin - Conversion from Production Field to CO₂ Storage

Due to reservoir properties which include thick and competent overlying geological seals, as well as existing petroleum infrastructure, Pilot Energy (Pilot) identified the potential to convert the depleted Cliff Head oil field (Cliff Head), into a site for UCS of CO₂. Located in Production Permit WA-31-L in the northern Perth Basin, offshore Western Australia. The Cliff Head oil field is in Commonwealth waters approximately 12 km offshore, and 20 km south-southwest of Port Denison and Dongara. Water depth is on the order of 15-20 m. The project is scheduled to commence capturing and storing CO₂ from 2025-6, with a storage potential of 50 Mt of CO₂, injected at a rate of 665,000-1Mtpa for 15 years [43].

The Cliff Head CCUS Project aims to be the first commercial offshore CCUS/UCS in Australian Commonwealth Waters [43]. The project is based on the conversion of the late-stage, mature Cliff Head Oil Field, and its associated offshore and onshore infrastructure, into a permanent CO₂ storage facility [43]. To guide both the project proponent and the regulator, both of whom are novices in the conversion of a petroleum platform to a CCS injection platform, the use of *ISO 27914:2017 Carbon dioxide capture, transportation, and geological storage — Geological storage*, and the related *ISO 27916:2019 Carbon dioxide capture, transportation and geological storage* [35, 44]. Together, these will guide the project proponent in the necessary steps for COS storage but also aid the

regulator given that there are many similarities in the regulation of petroleum activities and CO₂ storage activities (and that the regulation of both activities occurs in the same legal instrument, the Commonwealth *Offshore Petroleum and Greenhouse Gas Storage Act 2006* [44]).

The petroleum production platform at Cliff Head will require substantial modifications. Typically, offshore petroleum production demands large amounts of utilities, usually supplied by low-efficiency energy systems, such as simple cycle gas turbines (SCGT) with waste heat recovery units (WHRU) [45]. Any adaptation of an offshore petroleum installation for CO₂ injection must be mindful of both weight and weight distribution across the platform, with a need to undertake a new risk analysis considering the modifications required. New risks include leakage of CO₂, utilising ISO 27914:2017 and ISO 27916:2019 for best practice, as well as well integrity standards (such as NORSOK DS-010) [46].

5.3. South Australia

In 2018 the South Australian Department for Energy and Mining undertook a study on the potential for CO₂ EOR in the Cooper and Eromanga Basins. The study demonstrated that the Cooper-Eromanga Basin system appears to be an ideal location for CO₂ EOR, since the fields in the region are deep, contain light oil which is favourable for miscible CO₂ flooding [47]. This is critical given that the basin system produces considerable volumes of CO₂, presently being vented during processing. The implementation of CO₂ EOR could therefore assist in greater recovery of hydrocarbons, whilst at the same time reducing the CO₂ footprint of the field [47].

Outside of the SA report, there is scant academic literature regarding CO₂ EOR in the Cooper-Eromanga, and even less literature for the adjoining Pedirka Basin. An examination of the NT geological reports on the Pedirka and Cooper Basins demonstrates geological and stratigraphic similarities between the basins [48, 49], therefore indicating that CO₂ EOR may also be successful in the Pedirka Basin.

5.3.1. Moomba Gas Field - Chevron

Encouraging research results regarding CO₂ EOR in the Cooper-Eromanga Basin drove Santos to investigate the suitability of sediments within the Moomba gas field for UCS. With a start-up date of 2024, the Moomba CCS project is on target to commence receiving CO₂ for storage. The project has a target annual rate of sequestration of 1.7 million tonnes annually, and if successful, could usher in a tide of projects that are presently at the feasibility stage.

5.4. UCS in Commonwealth Waters

In Australia, the disposal of CO₂ through CCUS and UCS at sea is regulated under several commonwealth instruments. When a project proponent intends to dispose of CO₂ by UCS at sea, they are required to obtain a dumping permit under the Commonwealth's *Environment Protection Sea Dumping Act 1981* (EPSDA). To grant a sea dumping permit for the purpose of UCS, the minister or delegate must be satisfied that the material for dumping meets the criteria set out in the 1996 London Protocol to the London Convention. This particularly pertains to the composition of the CO₂ stream and any contaminants found within that stream. Permits will also be required for the storage loading, transportation, and sequestering at appropriate offshore sites to ensure that there are no significant adverse impacts on human health or the marine environment.

An offshore UCS permit application form under the EPSDA is currently being developed, and the former considers Australia's international obligations under the London convention in practice and reflects the criteria set out in *Annex 2 of the London Protocol*; *Revised 2012 Specific Guidelines for Assessment of Platforms or Other Man-Made Structures at Sea*; and *Risk Assessment and Management Framework for CO₂ Sequestration in Sub-Seabed Geological Structures*.

To inject into a reservoir in Commonwealth Waters (for Commonwealth waters see [50, 51]), the project proponent will need to hold a Greenhouse Gas injection licence under the Commonwealth's *Offshore Petroleum and Greenhouse Gas Storage Act 2006* (OPGGSA) and its regulations. Typically, a project proponent commences with a greenhouse gas (GHG) assessment permit, which enables a permit holder to drill a well and inject air, water, or

petroleum to determine if the reservoir is suitable for CO₂ injection. An assessment permit is granted either by work-program bidding (ss296-300 OPGGSA), or via cash bid (ss303-307 OPGGSA).

After examining the results of assessment wells and seismic modelling (both two and three dimensional) the assessment permit holder, if believing the assessed licence area is capable of holding CO₂, will provide a *declaration of identified greenhouse gas storage formation* as required under s312 of OPGGSA. As in the case of a declaration of a petroleum discovery, the title holder is obligated to apply for a greenhouse gas injection licence under ss361-364 of OPGGSA.

As specified in s318 of OPGGSA, an assessment title holder, an injection title holder who has not carried on any injection or storage of CO₂, an unsuccessful applicant for a GHG injection lease, or the holder of a petroleum retention lease can apply for a GHG holding lease, which is akin to a petroleum retention lease under s 141-146 of OPGGSA. To obtain a GHG holding lease, the identified GHG storage formation must be wholly situated in the permit area and the applicant is currently 'not in a position' to inject and permanently store a GHG substance but is likely to be in such a position within 15 years. These generous terms for retaining the right to inject GHG provide the project proponent with the ability to plan sequestration projects, as well as utilising the current *method* for CCUS to obtain Australian Carbon Credit Units [52] whilst also producing petroleum (although not using the CO₂ for enhanced oil recovery).

In August 2022, two offshore UCS exploration permits were awarded in the Northern Territory and Western Australia. The permits are for area G-7-AP over GHG21-1 in the Bonaparte Basin, a joint venture between INPEX, Woodside Energy and TotalEnergies, and for area G-8-AP over GHG21-3 in the Browse Basin for Woodside Energy.

Importantly, Minister King noted:

Carbon Capture and Storage has a vital role to play in helping Australia meet its net zero targets. Australia is ideally placed to become a world leader in this emerging industry, with large, stable offshore geological formations for greenhouse gas storage [53].

Furthermore, Minister King stated, 'The award of G-7-AP is one of two acreage permits awarded in the past eight years and will help make Darwin's ambitions as a Carbon Capture and Storage Hub a reality' [53]. Minister King reiterated her view that 'Australia has the capacity to continue to be an energy export leader, at the same time as developing a domestic offshore UCS industry' [53]. This capacity will rely on north-western Australia, including the North West Shelf, to continue to be a producer, whilst also a location of UCS.

5.5. Bayu-Undan UCS Field

In March 2022, Santos announced that it had entered the front-end engineering and design (FEED) phase for the proposed Bayu-Undan UCS project. This project involves the export of carbon dioxide from Australia via pipeline to the Bayu-Undan gas field, located across the Australian/ Timor Leste maritime boundary.

In May 2023, Santos announced it signed four Memoranda of Understanding (MOU) for the proposed storage of CO₂ emissions from *third parties* to underpin the initial development of the Bayu-Undan carbon capture and storage (CCUS) project, where front end engineering design work is nearing completion is now nearing completion. The four non-binding MOUs for CO₂ supply to Bayu-Undan CCUS have been executed with potential upstream gas and LNG projects offshore the Northern Territory, in Darwin, and an energy and industrial conglomerate in Korea.

These MOUs indicate that demand for Bayu-Undan storage at Bayu-Undan CCUS could exceed 10 million Tonnes per annum (Mtpa). It is expected that the Bayu-Undan CCUS project with CO₂ piped offshore to the reservoir from Darwin, will offer a relatively low-cost carbon solution, staying within the Australian Government's proposed price cap on Australian Carbon Credit Units.

The importance of the Bayu-Undan CCUS project is that it has the potential to reduce the absolute emissions and emissions intensity of Australian gas and LNG projects and other industrial activities in the Northern Territory. It achieves this by providing permanent CO₂ storage and providing a potential Scope 3 emissions solution for

Australia's exports to Asia. Furthermore, large customers in countries such as Korea are also considering Bayu-Undan as a location for storing captured energy and industrial emissions, with the possibility of shipping the CO₂ to Australia for sequestration.

The Bayu-Undan CCUS project is located offshore Timor-Leste, with Darwin set to be an important regional hub for CO₂ capture, transfer, and storage to Bayu-Undan as well as to other potential CCUS locations offshore the Northern Territory, which are still in the exploration and feasibility stages. However, previous tensions regarding maritime boundaries [54] and Australia's conduct towards Timor Leste [55] may influence the progression of the project.

6. Conclusion

Innovation and technological development concerning CCUS and UCS are continuing at a fast pace, evidenced by the Norwegian Longship project funded by the Norwegian government. What was once considered a fanciful and dreamed of technology is now proving to be within the grasp of all states. Indeed, CCUS and especially UCS as a tool in the global response to climate change is both proven and essential. Petroleum reservoirs and associated geological structures are critical for the successful deployment of UCS. Although depleted petroleum reservoirs are utilised for the sequestering of CO₂, it is sedimentary reservoirs associated with petroleum deposits in a field that holds the key to widescale deployment of UCS, as demonstrated in both the Sleipner and Snøhvit UCS projects, and the granting of CO₂ storage licences on the Norwegian continental shelf.

Yet there continues to be an assumption that the underground storage of captured carbon will not be successful, a view that currently prevails in Australia on the back of the poor performance of the Gorgon CCUS project on Barrow Island. Such views are likely to prevail in light of unsuccessful projects such as Gorgon [56]. However, as commercial projects in Australia, Norway, and North America commence operations, and successfully store the predicted volumes, CCUS and UCS may very well be utilised as a tool in attaining net zero emissions by 2050.

This analysis has demonstrated that the leadership of the Norwegian government in developing a CO₂ storage atlas, and the development of ISO standards for carbon capture, transport, storage, and technology have significantly contributed to the advancement of UCS. In developing new UCS projects, Australian project proponents and regulators need to engage with and implement the ISO standards to ensure best practice. In addition, the development of a CO₂ Storage atlas, akin to that developed by the Norwegian Petroleum Directorate, will provide a timely and critical aid for the Australian, and other governments who seek to utilise appropriate geological formations associated with petroleum fields for UCS.

Conflict of Interest

The author declares no conflict of interest.

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