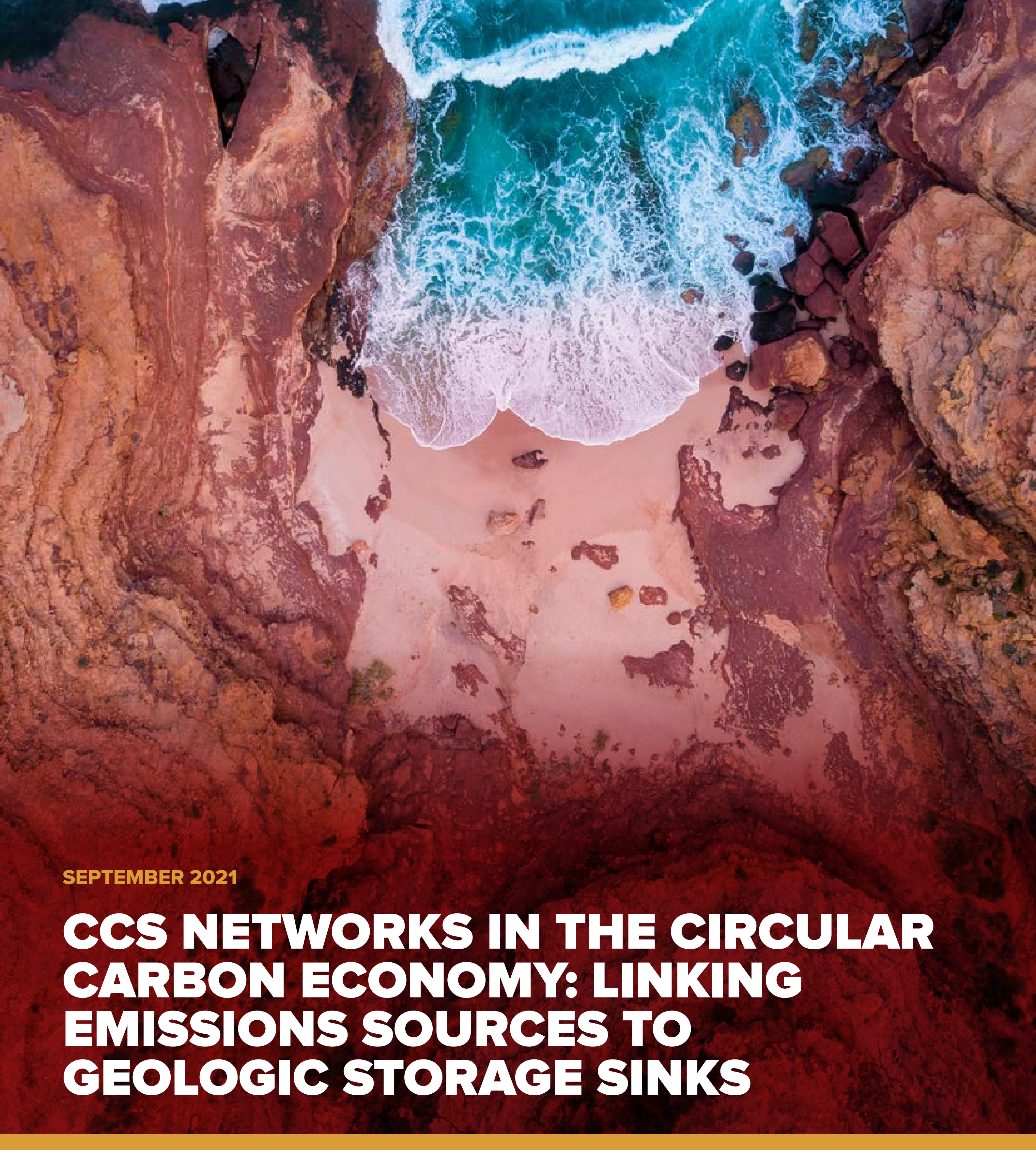


SEPTEMBER 2021

# CCS NETWORKS IN THE CIRCULAR CARBON ECONOMY: LINKING EMISSIONS SOURCES TO GEOLOGIC STORAGE SINKS

**JOEY MINERVINI**
Senior Consultant Storage

**CHRIS CONSOLI**
Senior Consultant Storage

**DAVID KEARNS,**
Principal Consultant CCS Technologies

GLOBAL CCS
INSTITUTE

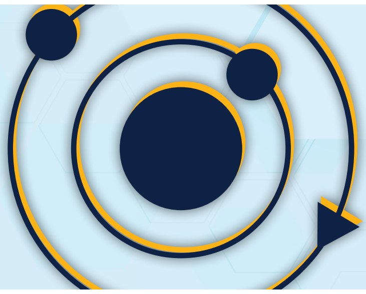
# Acknowledgements

This research was overseen by an Advisory Committee of eminent individuals from government, academia and industry with deep expertise across technology, policy, economics and finance relevant to climate change. The guidance of the Advisory Committee has been invaluable in developing this work.

Thanks are also due to the Center for Global Energy Policy at Columbia University SIPA for their review and input to this report.

**Advisory Committee for the Circular Carbon Economy: Keystone to Global Sustainability Series**

- Mr. Brad Page, CEO, Global Carbon Capture & Storage Institute (Co-Chair)
- Mr. Ahmad Al-Khowaiter, CTO, Saudi Aramco (Co-Chair)
- Dr. Stephen Bohlen, Acting State Geologist, California Department of Conservation
- Ms. Heidi Heitkamp, Former Senator from North Dakota, U.S. Senate, United States of America
- Mr. Richard Kaufmann, Chairman, New York State Energy Research and Development Authority (NYSERDA)
- Ms. Maria Jelescu Dreyfus, CEO, Ardinall Investment Management
- Dr. Arun Majumdar, Director, Precourt Institute for Energy and Stanford University
- Dr. Nebojsa Nakicenovic, Former Deputy Director General/CEO of International Institute for Applied Systems Analysis (IIASA)
- Mr. Adam Siemenski, President, King Abdullah Petroleum Studies and Research Center (KAPSARC)
- Prof. Nobuo Tanaka, Former Executive Director, International Energy Agency (IEA) and Distinguished Fellow, Institute of Energy Economics Japan



**THE CIRCULAR CARBON ECONOMY: KEYSTONE TO GLOBAL SUSTAINABILITY SERIES** assesses the opportunities and limits associated with transition toward more resilient, sustainable energy systems that address climate change, increase access to energy, and spark innovation for a thriving global economy.

# CONTENTS

# EXECUTIVE SUMMARY

Carbon capture and storage (CCS) is a critical part of the portfolio of climate change mitigation technologies and is particularly vital to the decarbonisation of industrial emissions. To achieve a net-zero world, emission-intensive industries have few options beyond applying CCS to their operations.

Currently, CCS networks linking multiple proximate emission point sources to a $CO_2$ transport and storage hub is emerging as the lowest-risk and most cost-effective method of CCS development. A significant number of CCS networks are emerging across North America and Europe, and we expect this trend to grow. Industrial CCS networks require integrated assessment of plant design, $CO_2$ transport infrastructure, and suitable geologic storage resources. Of these three CCS network elements, the characterisation of geologic storage basins and formations severely lacks in most nations.

This report, part of the Circular Carbon Economy project series, has reviewed emissions and storage basins worldwide, seeking to link clusters of emissions-intensive regions to potential geologic storage basins.

The report is in two parts. In part 1, using a single methodology to characterise global emissions and basins, we performed a high-level, regional analysis identifying potential CCS networks by linking suitable storage to intense emissions centres across the globe. In part 2, we present a conceptual approach to designing a $CO_2$ transport network from distributed $CO_2$ sources to a target geological formation for storage, outlining the selection of gas-phase or dense-phase pipeline transport as well as an approach to minimising the cost of pipelines over the network.

Key findings from this analysis include:

Potential CCS networks can be identified in almost every industrialised region of the world.

Those potential networks identified in this report can guide future detailed investigation and planning required for CCS network development.

Each industrialised region of the world has access to storage resources ranked as highly suitable or suitable.

The combination of emission sources in proximity to storage sinks means a global portfolio of CCS networks is technically possible. These networks provide the greatest opportunity to rapidly decarbonise large clusters of power and industrial sources.

Inadequate characterisation of geologic storage resources is the critical limiting factor to CCS network development across the globe.

Comprehensive national assessments are still needed for the majority of nations. Until these assessments are completed, insufficient understanding of geologic storage resources will remain a significant barrier to CCS network development.

Pipeline and compression networks require the development of cost models for piping and compression systems for the specific country and local costs of energy and construction. This provides the quantitative basis for decisions in network design.

Although the approach presented in this report is simplified, it demonstrates how developing cost models for the network in question should be an initial step to guide the network layout and compression system selection, not one conducted at the end of the basic design.

# 1.0 INTRODUCTION

Stopping global warming requires net greenhouse gas emissions to fall to zero and remain at zero thereafter. Put simply, all emissions must either cease, or be completely offset by the permanent removal of greenhouse gases (particularly carbon dioxide - $CO_2$) from the atmosphere. The time taken to reduce net emissions to zero, and thus the total mass of greenhouse gases in the atmosphere, will determine the final equilibrium temperature of the Earth. Almost all analysis concludes that reducing emissions rapidly enough to remain within a 1.5°Celsius carbon budget is practically impossible. Consequently, to limit global warming to 1.5°Celsius above pre-industrial times, greenhouse gas emissions must be reduced to net-zero as soon as possible, and then $CO_2$ must be permanently removed from the atmosphere to bring the total mass of greenhouse gases in the atmosphere below the 1.5° Celsius carbon budget.

This task is as immense as it is urgent. A conclusion that may be drawn from credible analysis and modelling of pathways to achieve net-zero emissions is that the lowest cost and risk approach will embrace the broadest portfolio of technologies and strategies, sometimes colloquially referred to as an "all of the above" approach. The King Abdullah Petroleum Studies and Research Center (KAPSARC) in the Kingdom of Saudi Arabia developed the Circular Carbon Economy (CCE) framework to more precisely describe this approach. This framework recognizes and values all emission reduction options (Williams 2019). The CCE builds upon the well-established Circular Economy concept, which consists of the "three Rs" which are Reduce, Reuse and Recycle. The Circular Economy is effective in describing an approach to sustainability considering the efficient utilization of resources and wastes; however, it is not sufficient to describe a holistic approach to mitigating greenhouse gas emissions. This is because it does not explicitly make provision for the removal of carbon dioxide from the atmosphere (Carbon Direct Removal or CDR) or the prevention of carbon dioxide, once produced, from entering the atmosphere using carbon capture and storage (CCS). Rigorous analysis by the Intergovernmental Panel on Climate Change, the International Energy Agency, and many others all conclude that CCS and CDR, alongside all other mitigation measures, are essential to achieve climate targets.

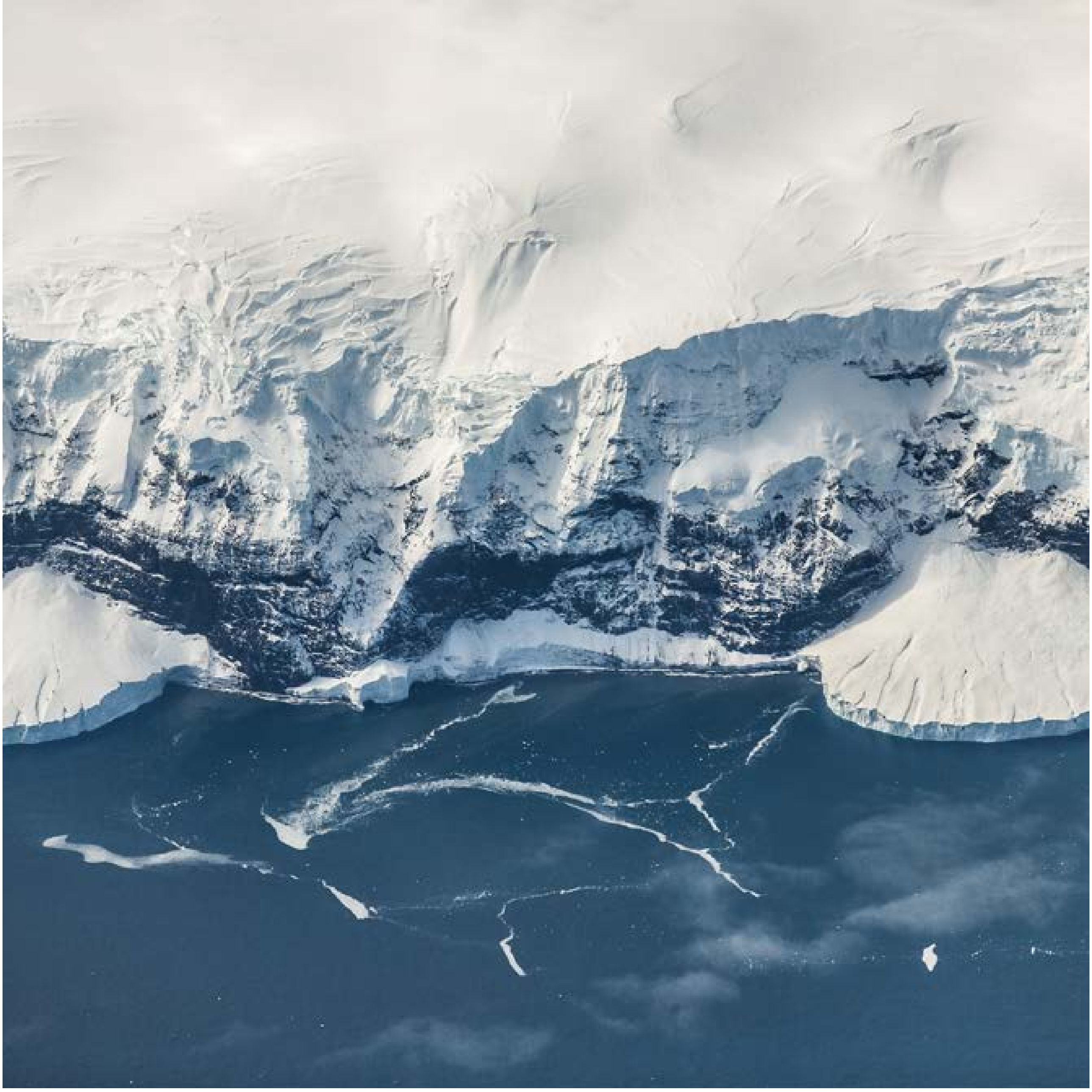
The Circular Carbon Economy adds a fourth "R" to the "three Rs" of the Circular Economy; Remove. Remove includes measures which remove $CO_2$ from atmosphere or prevent it from entering the atmosphere after it has been produced such as carbon capture and storage (CCS) at industrial and energy facilities, bio-energy with CCS (BECCS), Direct Air Capture (DAC) with geological storage, and afforestation.

## CCS Networks

Stand-alone carbon capture and storage (CCS) projects require several elements to come together over a given site to develop and execute a viable project. These elements include storage capacity, concentrated $CO_2$ emissions, transport infrastructure, and regulatory and economic policy support. Unfortunately, the alignment of these elements is uncommon.

Leveraging economies of scale, several $CO_2$ emitting facilities can instead form a CCS network – a collaborative project which links multiple emission point sources to shared $CO_2$ transport infrastructure and a shared storage hub – and significantly decrease project costs. Cost modelling shows that $CO_2$ capture costs for facilities with low partial pressure $CO_2$ flue gas streams can be more than triple those of facilities with concentrated, high partial pressure $CO_2$ flue gas streams (Kearns, Liu and Consoli, 2021). As a result, such facilities benefit considerably from the scale provided by CCS networks. Moreover, CCS networks' shared costs remove economic barriers that otherwise preclude small-scale emitters (those less than 100,000-200,000 tonnes of $CO_2$ per year) from employing CCS.

Several projects across the globe have implemented this network strategy. In Canada, the Alberta Carbon Trunk Line (ACTL) project currently transports $CO_2$ from two facilities in the Edmonton region and stores it in depleted oil and gas fields 240 km away (ACTL, 2021). The $CO_2$ is transported via pipeline designed with excess capacity to connect additional facilities to the CCS network. In Norway, a multi-phase CCS network – the Longship



Project by the Norwegian Government and Northern Lights – is developing the infrastructure to transport (via ships and a storage pipeline from a port), inject, and store up to 1.5 Mt of $CO_2$ annually from regional emitters across Europe by 2024 (Northern Lights, 2021). In the United Kingdom, three consortia – Net Zero Teesside, Northern Endurance Partnership, and Zero Carbon Humber – have secured funding and are planning to build the UK's first decarbonised network on England's east coast (Net Zero Teesside, 2021). Accounting for nearly half of all UK industrial emissions, The Humber and Teesside cluster – collectively named The East Coast Cluster – plan to capture and store up to 27 Mtpa by 2030 (East Coast Cluster, 2021).

Additional projects are in the concept stage. ExxonMobil has proposed a Houston CCS Hub on the Gulf Coast of Texas, which they estimate could capture and store 50 Mtpa by 2030 and 100 Mtpa by 2040 (Blommaert, 2021). A new case study by Columbia University's Center on Global Energy Policy concludes Houston is well-suited for CCS hub development due to its significant industrial $CO_2$ sources, access to infrastructure and storage, and its population of world-class technical expertise in each aspect of the CCS value chain (Friedmann, Agrawal and Bhardwaj, 2021).

# 2.0 PART 1 – GLOBAL $CO_2$ SOURCE/SINK MATCHING

In this section, we identify potential CCS networks across the globe by pairing suitable storage basins (sinks) with $CO_2$ emissions centres (sources).

## Methodology

Our network analysis is regional in scale, but we discuss some local project examples to illustrate network concepts. $CO_2$ sources are abundant worldwide and are not a limiting factor in CCS network development due to rapid industrialisation worldwide and the corresponding increase in fossil fuel utilization.

We have determined that access to high-value storage resources is the determining factor in the commercial viability of early-mover CCS networks. Therefore, the identification of regional networks in this study was guided by understanding a basin's potential for geological storage rather than the region's emissions sources.

### *Basin Suitability*

Suitable geologic storage basins are referred to here, colloquially, as "sinks." The storage suitability of every basin in the world was assessed using the Global CCS Institute's $CO_2$ storage suitability analysis. This analysis incorporates qualitative and quantitative basin suitability criteria, information in English-language published literature, and the expert opinion of the authors of this report. Criteria used in this analysis are critical to the successful deployment of a $CO_2$ storage operation and include:

- Geology – tectonics, basin size, depth, depositional and geothermal history
- Hydrocarbon maturity and prospectivity
- Storage assessment maturity
- Subsurface data and transport infrastructure
- Accessibility

Basins have been assessed as:

- Highly-suitable: Sufficient knowledge to enable the appraisal of viable individual sites for $CO_2$ storage.
- Suitable: Sufficient knowledge to enable the identification of viable individual sites for $CO_2$ storage.
- Possible: Insufficient knowledge to identify viable individual storage sites; however, prominent indications of suitable geology are present, such as a mature oil and gas industry.

It is important to note that basin suitability does not reflect a site's actual injection or storage potential. Site appraisal is not considered here. Basin nomenclature follows the CGG Robertson Sedimentary basins style, using the Robertson Basins and Plays geological sub-regime classification accessed through AAPG (CGG Robertson, 2020).

### *Global Emission Hubs*

Clustered emissions points (aggregated point-sources within 100 km of one another) in this report are colloquially named "sources" and represent the partners to CCS network storage basins – or "sinks." This report utilized the World Resources Institute (WRI) Global Power Plant Database (World Resources Institute 2020) to visualise sources. Though an imperfect dataset to represent emissions across all carbon emissions sectors, we found power plants to be an adequate proxy for this analysis because:

- The WRI data covers the globe and is internally consistent

- Power stations are generally clustered with other industrial plants
- Capture-ready power stations represent an anchor capture plant that can drive a CCS network (Global CCS Institute 2016).

The following steps were taken to modify the original WRI power plant dataset to identify anchor, capture-ready projects.

1. Non-fossil fuel plants were removed.
2. In gigawatt-hours (GWh), estimated generation was converted to $CO_2$ emissions using the IEA WEO estimates for each country. Where a specific country's emissions intensity is not detailed, the region or world average is used.
3. To focus on power plants most amenable to carbon capture retrofit, we removed those plants emitting less than 500,000 metric tons per year.
4. Power plants older than 10 years were removed. This is because retrofit costs increase in older power plants. Given today's policy landscape and conservative economic assumptions, only near- and medium-term potential for carbon capture retrofit or deployment were considered here.
5. Emissions sources within 100 km of one another were then aggregated as a single cluster point.

The results of this analysis can be seen in the figures in each regional section of this report.

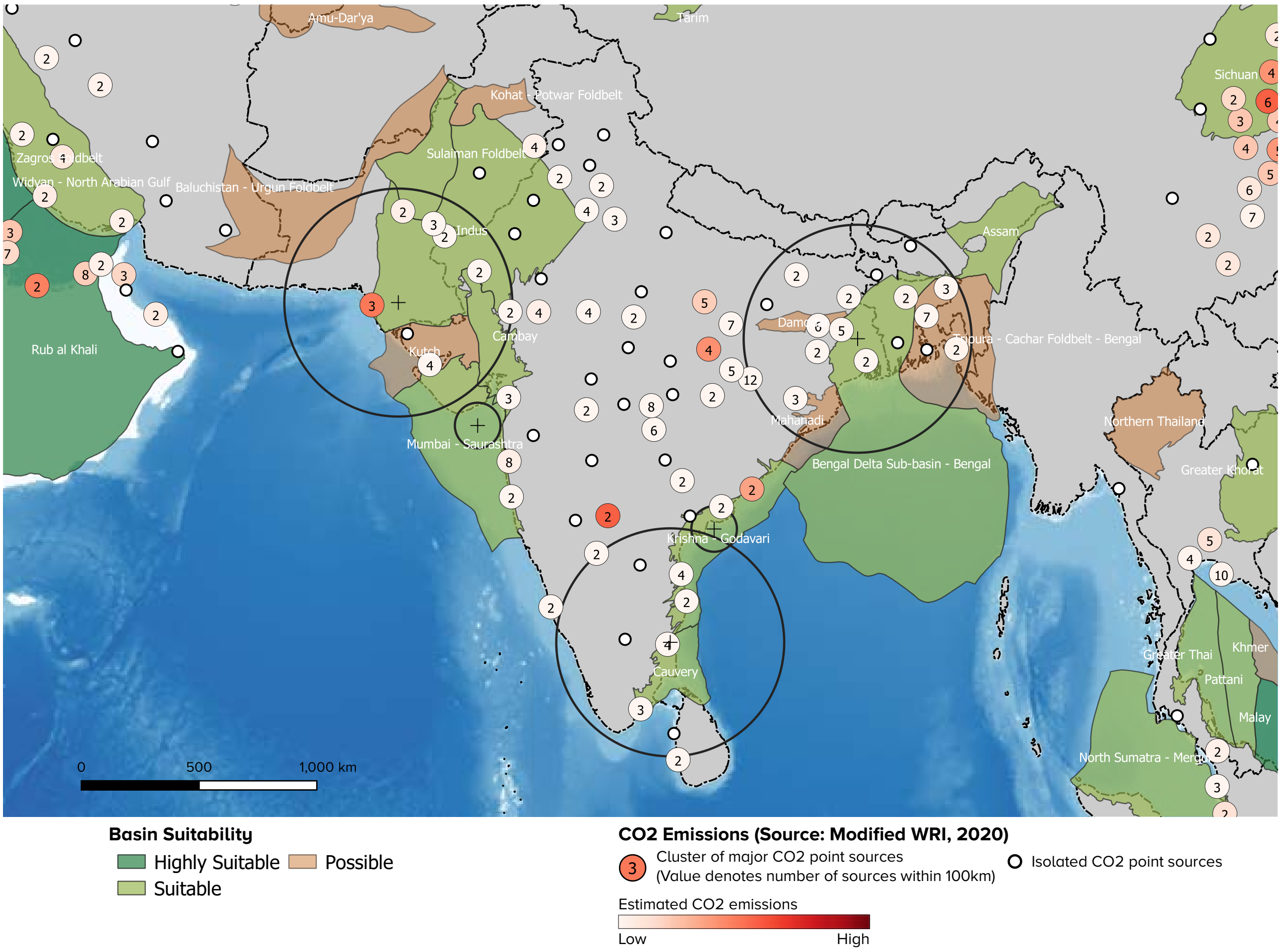
## Source-Sink Network Analysis

$CO_2$ source-sink matching is the process of spatially connecting emission hubs (sources) to suitable storage basins (sinks). The general workflow employed in this study is outlined here:

1. Potential sink points were located within basins where it is understood a sufficient sediment thickness (>800 m) is present to contain a suitable storage reservoir and caprock (seal). Sink points are not intended to serve as exact storage site locations. For this regional analysis, one discrete point was chosen to represent the sink. A more in-depth analysis should represent sinks as a polygon defining suitable storage areas.
2. Circles illustrating viable pipeline transportation distances were drawn around potential sink points using the following conservative techno-economic estimates of pipeline construction feasibility (shipping excluded):
    a. 500 km radius onshore source to onshore sink
    b. 100 km radius onshore source to offshore sink
3. Possible source-sink pairs were identified where sufficient estimated cumulative emissions fall within viable transportation distances to suitable storage resources.

# Indian Subcontinent

**Figure 1 - $CO_2$ emissions clusters and potential CCS networks for the Indian Subcontinent. Known suitable geologic storage sites are located primarily along the coastal and offshore regions of Pakistan, India, and Bangladesh.**



The geological storage potential of the Indian Subcontinent has only been characterised at the regional level. These regional assessments and storage estimates used broad assumptions and limited data.

India's suitable storage basins are generally limited to the coastal margins of the continent, the majority of which are offshore. Significant work is required to assess India's storage resources comprehensively. Much of the required data for characterisation exists – due to India's long history of oil and gas operations in both onshore and offshore basins. High-level estimates of India's storage resources include more than 1000 $MtCO_2$ in oil fields, 345 $MtCO_2$ in coal formations, and crude estimates exceeding 63,000 $MtCO_2$ in saline aquifers (IEAGHG, 2008).

India is the world's third-largest emitter of $CO_2$. Coastal emissions clusters can likely access India's large storage sites offshore. Interior emissions centres, however, are limited to less favourable storage options - either storage within India's old onshore rift basins, in basalts via mineral carbonation, or via transportation to the larger basins offshore.

India's most suitable storage basins are situated along India's west coast (onshore Cambay, offshore Mumbai-Saurashtra Basins) and east coast (Krishna-Godavari, Cauvery, Bengal Basins). Additional storage potential is ranked possible in several other Indian basins, including Kutch and Mahanadi; however, these basins require basic storage suitability analysis to define their storage resources. The Assam Basin in India's far northeast is suitable, but emissions sources are sparse in this region.

Coal-burning power plants in India's interior have limited, poorly characterised storage options. The NE region of Madhya Pradesh state is coal-rich and a major source of $CO_2$ emissions. Point sources in this region are adjacent to the Vindhyan and Rewa Basins – old (Proterozoic and Paleozoic, respectively) sedimentary basins with adequate sedimentary thickness, but may lack the necessary porosity and permeability to economically store large quantities of $CO_2$. According to the CarbFix Mineral Storage Atlas, storage via mineral carbonation in basalts is also limited in this region (CARBFIX, 2020).

Other interior emissions centres located in northern Andhra Pradesh state are situated within the Prahnita-Godavari Basin. Like the Vindhyan and Rewa Basins desribed above, this old (Proterozoic) interior rift basin contains adequate sedimentary thickness and favourable lithologies for geologic storage; however, formation porosity and permeability may be unviable.

While India's old, interior rift basins may have storage inadequacies, they cannot be discarded as potential storage sites until fundamental storage suitability analysis is completed for each basin.

The Deccan Traps are a major flood basalt province onshore and offshore western and central India. These vast basalt formations could provide a significant $CO_2$ mineralisation storage opportunity, which has yet to be characterised.

Emissions sources within Pakistan have access to suitable storage in the Indus Basin, both onshore and offshore. Additional potential storage exists in the Sulaiman Foldbelt and the Baluchistan-Urgun Foldbelt.

Limited studies have been completed for the basins of Bangladesh. The Bengal Basin is one of the thickest sedimentary basins in the world, in parts exceeding 10 km. With numerous onshore gas fields, the potential for storage resources in Bangladesh is high. Physical storage in structural traps is likely within the Tripura-Cachar Foldbelt.

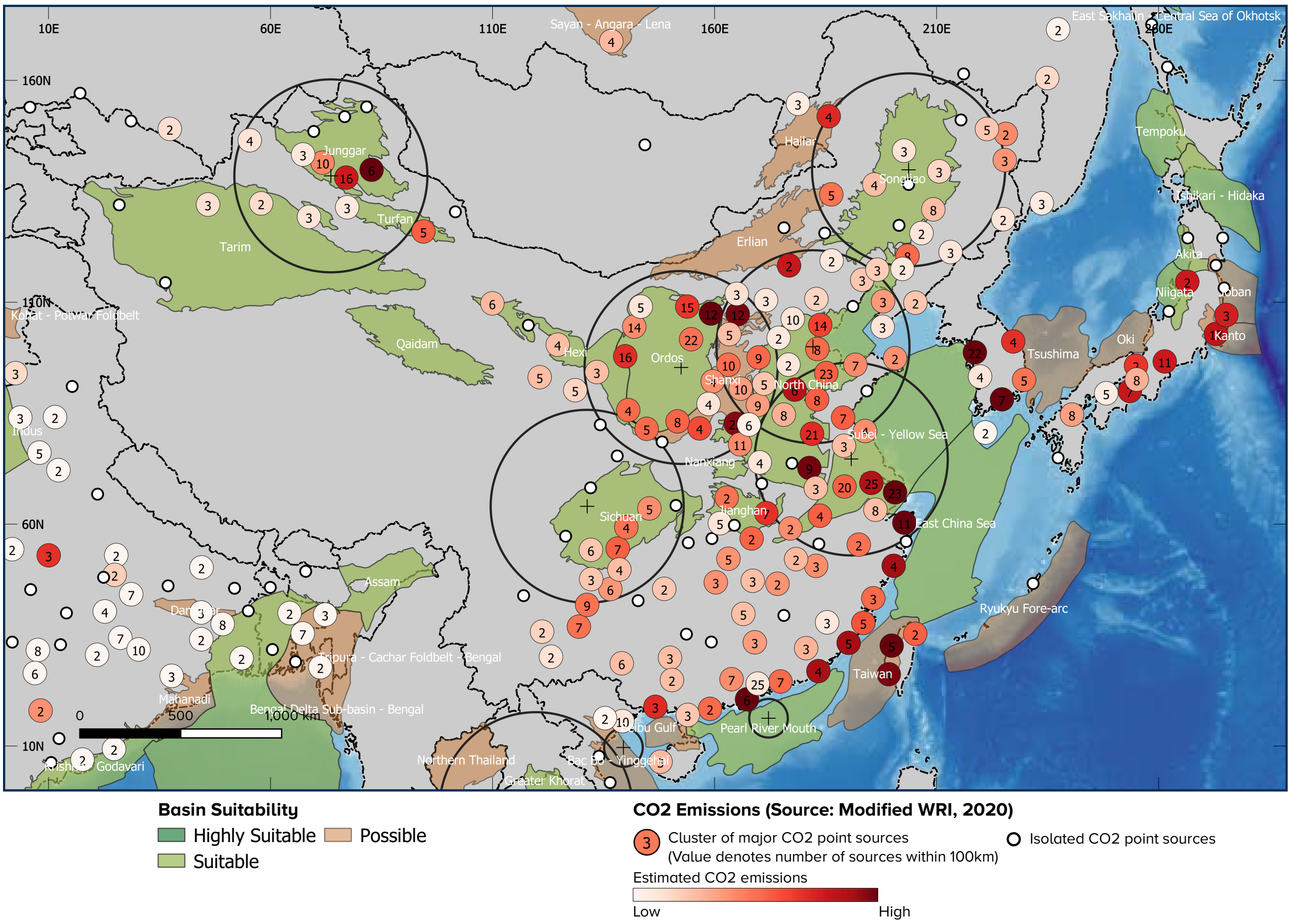
Access to subsurface geologic data in the region is highly restricted, but enough published data exist to identify five potential $CO_2$ source-sink networks across the Indian Subcontinent (Figure 1):

1. Coastal Gujarat and Mumbai regions – Offshore Mumbai Basin
2. Coastal Andhra Pradesh – Offshore Krishna-Godavari Basin
3. Kolkata region – Onshore Bengal Basin
4. Chennai and surrounds – Cauvery-Palar Basins
5. Central Pakistan – Indus Basin

Each of these clusters requires fundamental storage assessments targeting prospective formations within the basins. Major oil and gas basins (offshore Mumbai, Cambay, Indus, Tripura-Cachar Fold Belt, and Krishna-Godavari) have inherently lower storage risk because reservoirs and seals are tacitly proven and supported by data from oil and gas operations.

# East Asia

**Figure 2 - $CO_2$ emissions clusters and potential CCS networks for East Asia. Emissions clusters are concentrated in eastern China and overly suitable storage basins in most cases. South Korea and Japan have more limited storage options, primarily offshore.**



At over 3,000 $GtCO_2$, the geological storage potential of China is well-characterised and abundant (Dahowski et al., 2009). Multiple national, basin, and formation-scale studies have been published. China has completed a number of pilot and demonstration projects (Global CCS Institute, 2020a). Three commercial operations are capturing $CO_2$ from chemical and petrochemical facilities and storing it in the Songliao, North China, and Junggar Basins.

China is the world's largest emitter of $CO_2$, the largest producer of steel and cement, and the world's manufacturing hub. As such, emissions point sources are distributed across the heavily populated eastern regions of the nation.

China has a mature oil and gas industry that operates in roughly a dozen sedimentary basins throughout the country. These basins are suitable or highly suitable for $CO_2$ storage and exist both onshore and offshore.

Geologic storage resources of the Tarim and Qaidam basins of west-central China could be significant, but these basins are far from the major emission clusters in eastern China and $CO_2$ transportation costs may be prohibitive. The Ordos Basin is a petroliferous basin with existing CCS projects; however, formation permeabilities in this basin are generally low.

Emissions sources in northeast China have better access to onshore storage sites than those south of Shanghai. A large number of $CO_2$ point sources exist in southeast China – particularly around Hong Kong. Unfortunately, because proximate onshore storage basins are not present in southeast China, these regions will incur higher $CO_2$ transportation costs. Emissions clusters in Hong Kong, for example, are just over 100 km from depocenters of the Pearl River Mouth Basin and will either have to transport $CO_2$ by ship or by pipelines exceeding 100 km in order to reach the offshore storage resources. The high concentrations of $CO_2$ emissions centred in and around Hong Kong could make the techno-economics of a longer pipeline feasible.

China keeps access to its subsurface geologic data highly restricted; however, existing published data allows identification of seven potential $CO_2$ source-sink networks (Figure 2):

1. Far northwest Xinjian Province – Junggar Basin
2. Far northeast – Songliao Basin
3. Shanxi Province – Ordos Basin
4. Sichuan Province – Sichuan Basin
5. Henan Province/Beijing/Tianjin – Ordos and North China/Bohai Bay Basins
6. Shanghai – Subei / South Yellow Sea Basin
7. Hong Kong – Pearl River Mouth Basin

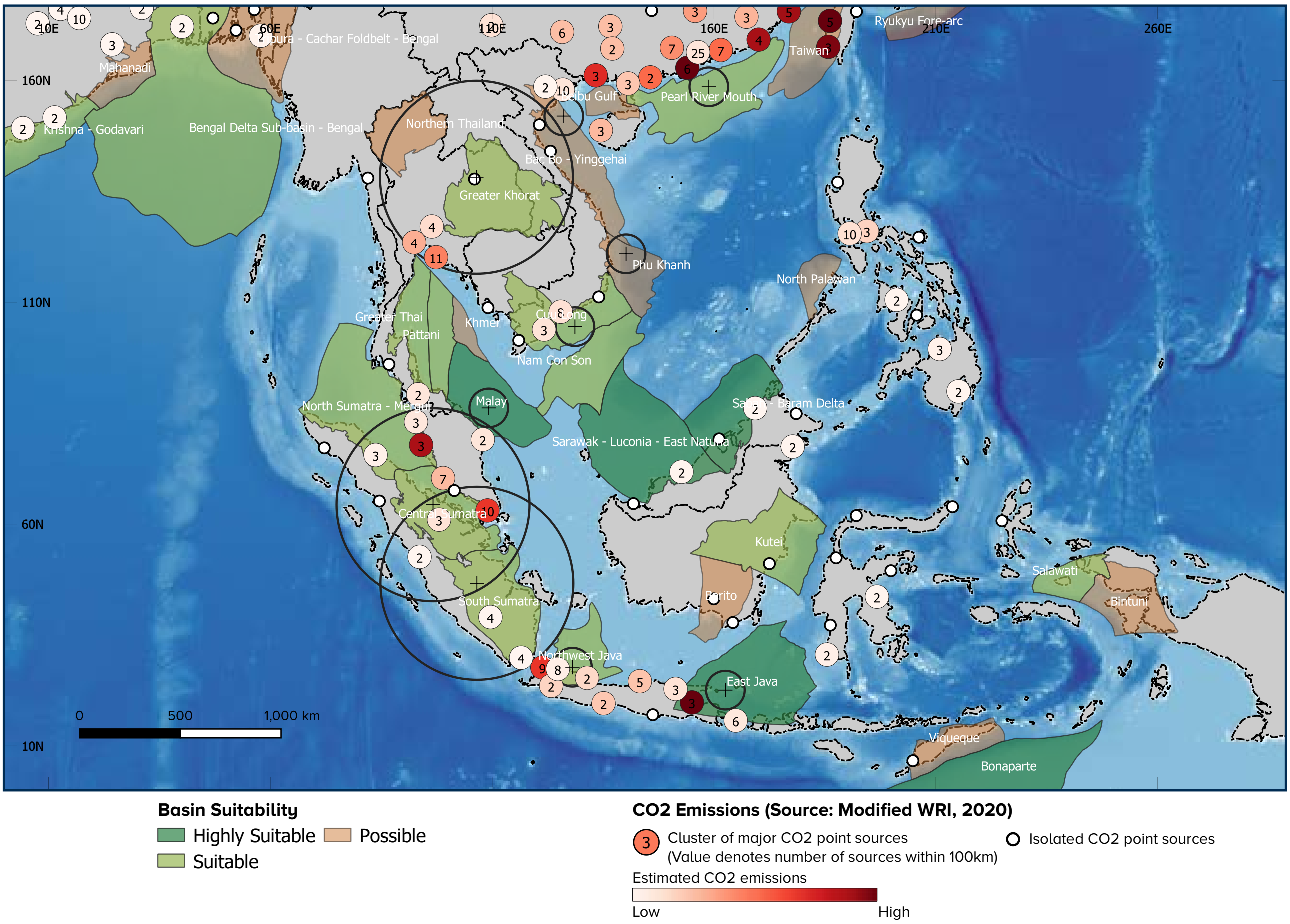
The geological storage potential of Japan and South Korea is moderately characterised with national, basin, and site-level assessments. Japan's storage potential is estimated to be 146 $GtCO_2$ (Takahashi et al., 2009a). Estimates for South Korea range from 100 to 200 $GtCO_2$ (Global CCS Institute, 2020a). The most suitable storage sites for both nations will be offshore. Japan has hosted a number of pilot and demonstration projects. The largest – the Tomakomai Project – injected 300,000 $tCO_2$ into the Ishikari – Hidaka Basin.

In northern Japan, emissions could be stored in the offshore Niigata Basin to the west, and the offshore Kanto Basin to the east. The latter is an important sink for Tokyo Bay heavy industry. Southern Japan, however, has limited storage options, particularly around Nagoya, Osaka, and Hiroshima. Prospective sedimentary basins exist in the offshore in southern Japan, but public domain characterisation of their storage suitability has not been completed. This may be due to a lack of available subsurface data, typically derived from the oil and gas industry – which has not been significantly active in southern Japan.

The geological storage potential of the offshore basins of South Korea is also largely unknown and uncharacterised in English-language published literature. Some oil and gas operations have taken place in the Ulleung and South Yellow Sea Basins, so storage resources likely exist in these basins. Trans-boundary transfer of $CO_2$ into other offshore basins may need to be considered if Korea deploys CCS at full scale.

# Southeast Asia

**Figure 3 - $CO_2$ emissions clusters and potential CCS networks for East Asia. Suitable and highly suitable geologic storage is present in both onshore and offshore regions of Malaysia and Indonesia.**



The geological storage potential for southeast Asian nations has only been reviewed at the regional or basin-scale, but these assessments identify several suitable storage basins across the region.

Both Indonesia and Malaysia have robust and mature oil and gas sectors. Correspondingly several suitable or highly suitable storage basins are present in onshore and offshore locations in both countries. The Indonesian islands of Sumatra and Java both host suitable storage basins near emissions centres. Indonesia is estimated to have between 1.4 and 2 Gt of $CO_2$ storage resources (World Bank, 2015). Malaysia's primary emissions centres are located adjacent to highly suitable storage offshore in the Malay Basin. Malaysia's Sarawak and Sabah-Baram Delta Basins – offshore Borneo – are highly suitable as well. For example, in Sarawak Basin's Luconia Province alone, researchers estimate between 56 and 75 $GtCO_2$ of storage resources exist (Hasbollah and Junin, 2017). While the country's emissions near these basins are relatively low, these extensive storage resources may provide Malaysia with an opportunity to commercialise transboundary $CO_2$ storage.

Four possible source-sink networks can be identified in the following areas (Figure 3):

1. Jakarta – South Sumatra and Northwest Java Basins
2. East Java – East Java Basin
3. Central Sumatra (possibly Singapore) – Central Sumatra Basin
4. Peninsular Malaysia – Malay Basin

The Asian Development Bank estimates Vietnam could hold 12 $GtCO_2$ of storage resources (Asian Development Bank, 2013). Vietnam launched two pilot $CO_2$ - enhanced oil recovery (EOR) projects, injecting $CO_2$ into fractured basement (crystalline rock) reservoirs of the Cuu Long Basin. The storage potential of one fractured basement reservoir was found to be approximately 7 – 100 $MtCO_2$ (Thanh et al., 2019). Additional work is needed to characterise deep saline formation storage offshore Vietnam; however, suitable and possible basins are present along its coastal margin basins (Bac Bo-Yinggehai, Phu Khanh, and Cuu Long). Two possible source-sink networks can be readily identified (Figure 3):

- Southern Vietnam – Cuu Long Basin
- Northern Vietnam – Song Hong-Yinggehai Basin

Geological storage in Thailand has been estimated at 2.2 $GtCO_2$ (Choomkong et al., 2017). This resource estimate is conservative and unlikely to be a true reflection of actual storage resources in Thailand. Suitable storage exists offshore in the Gulf of Thailand and is likely suitable onshore in the Khorat Basin. The Gulf of Thailand comprises several north-south trending rift basins – the largest of which is the Pattani Basin. The Pattani Basin has suitable geology for storage, but is problematic because it is situated more than 100 km from emissions centres in Bangkok, and, more importantly, it lies within a geopolitically disputed zone between Thailand and Cambodia. The onshore option for Thailand maybe its best storage solution. One possible source-sink network can be identified (Figure 3):

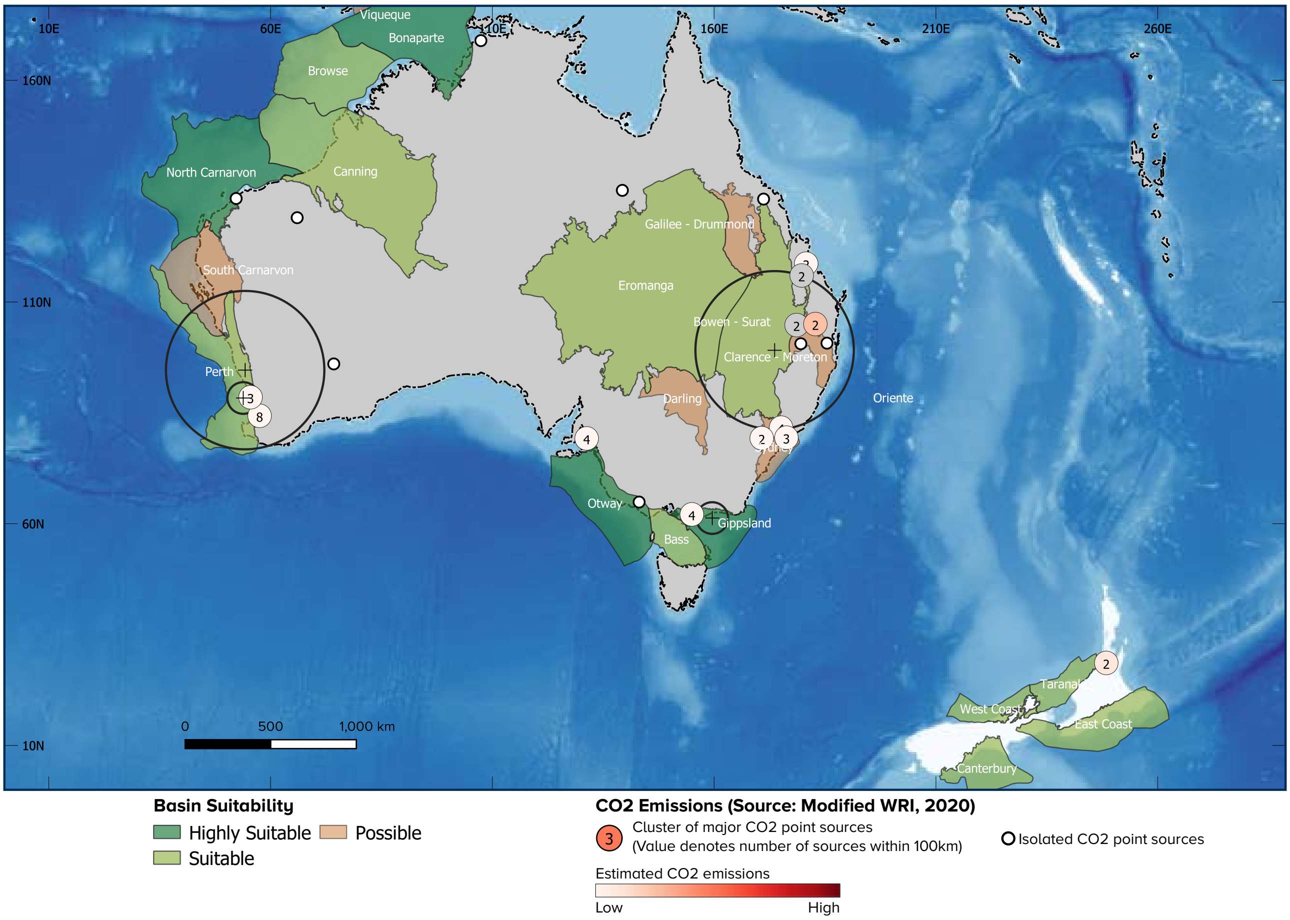
- Bangkok- Khorat Basin

The Philippines has access to potentially significant but, as yet, uncharacterised storage basins offshore Palawan Island (Palawan Basin) and in the Sulu Sea (East Palawan and Sandakan Basins). One regional assessment estimated that 23 $GtCO_2$ of storage resources are present (Asian Development Bank, 2013). In addition, some smaller, uncharacterised, onshore and nearshore basins are also present across the archipelago. The country's major emissions centres are located around Manila, on Luzon Island, but the largest potential storage basins are likely more than 200 km offshore in the North Palawan Basin.

Singapore is unique in SE Asia in that it has a high level of emissions – 55 Mtpa – for its size, yet it has no significant geologic storage available within its borders. Singapore's only storage option is transboundary $CO_2$ transport exceeding 100 km.

# Australia, New Zealand, and Oceania

**Figure 4 - $CO_2$ emissions clusters and potential CCS networks for Australia and New Zealand. Vast suitable and highly suitable geologic storage is available along the margins of the Australian continent. CCS networks will be most viable along the east and west coasts, where $CO_2$ emissions sources are clustered.**



The geological storage potential of Australia is well-characterised with multiple national, basin, and site-level assessments in key regions. The northwest, north, and southeast regions offshore Australia feature very large sedimentary basins (Northern Carnarvon, Browse, Bonaparte, and Gippsland Basins, for example). These offshore basins, along with those onshore basins in east-central and western Australia, present the best opportunities for geologic storage of $CO_2$ for the country. The latest national study estimated an effective storage resource of 227 to 702 $GtCO_2$ in 26 of Australia's highest-ranked or strategically important basins (e.g. adjacent to high emission sources) (Carbon Storage Taskforce, 2010).

The Gorgon $CO_2$ Injection Project on Barrow Island, off Australia's northwest coast, is currently the world's largest operating commercial-scale CCS project and represents the only stored $CO_2$ at such scale in Australia. The project has injected 5 million tonnes of $CO_2$ since 2019 (Chevron Australia 2021). A number of smaller CCS pilot projects have also been carried out across Australia.

While the basins along the northwest continental shelf of Australia likely have enormous storage potential, their geographic isolation from the major emissions point sources in eastern and southwest Australia make them unfavourable sinks for CCS networks in Australia.

Four possible source-sink networks of variable suitability can be identified in Australia (Figure 4):

1. Southeast Victoria – Gippsland Basin
2. Central Queensland – Surat Basin
3. Perth (Western Australia) – Perth Basin (onshore/offshore)
4. Coastal New South Wales –Surat Basin

New Zealand's major emissions hubs are proximate to the suitable Taranaki Basin. The offshore portion of the basin comprises major depleted hydrocarbon fields with potential for storage (Edbrooke et al. 2009).

The $CO_2$ storage potential of the Islands of Oceania are unknown; however, Papua New Guinea is a major regional gas producer and has uncharacterised onshore and offshore storage resources.

# Russia and Central Asia

**Figure 5 - $CO_2$ emissions clusters and potential CCS networks for western and central Russia. Large sedimentary basins and numerous oil and gas fields underly emissions clusters of central Russia. Suitable storage closer to Moscow may be present, but more characterisation is need to identify those storage resources.**

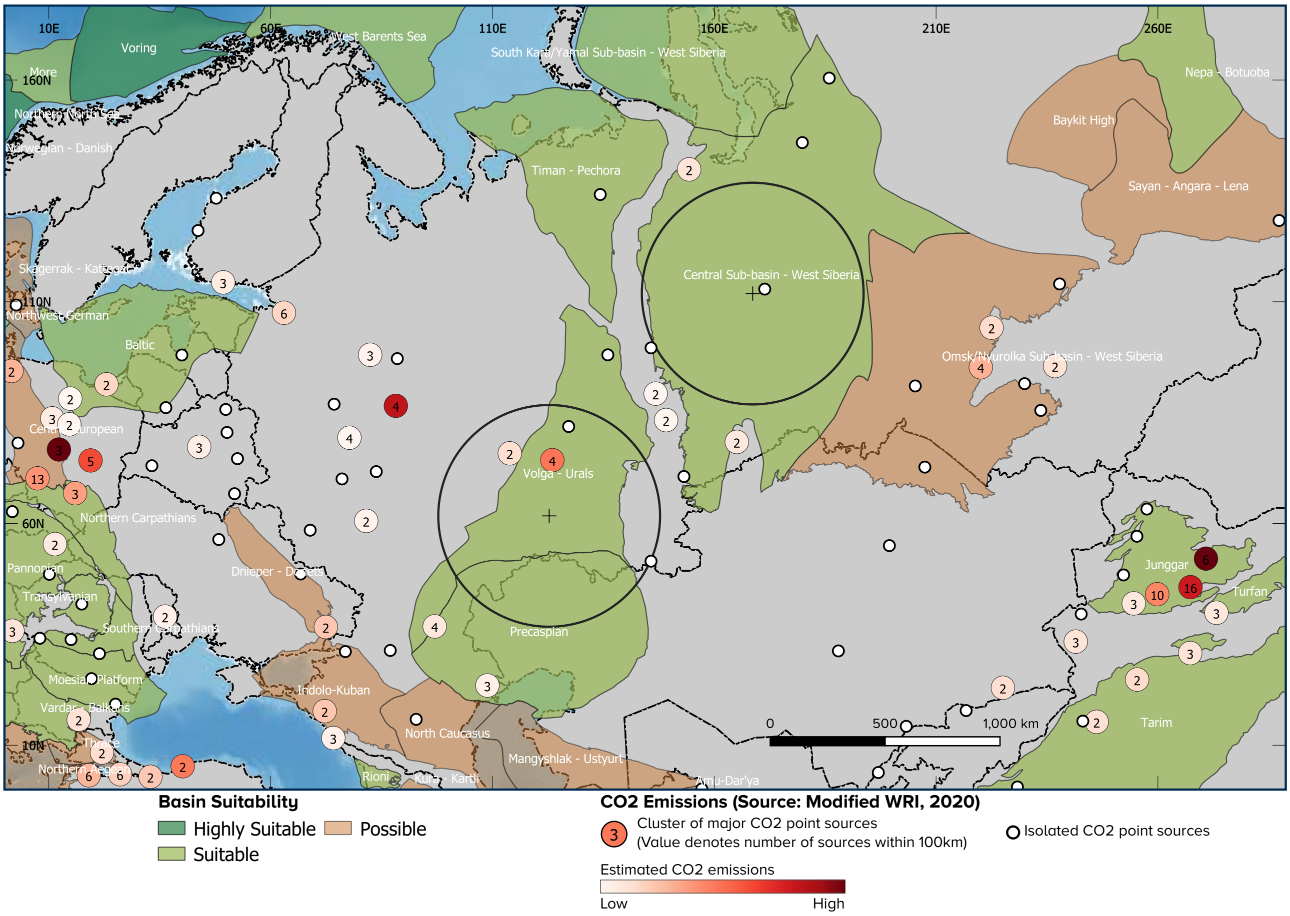
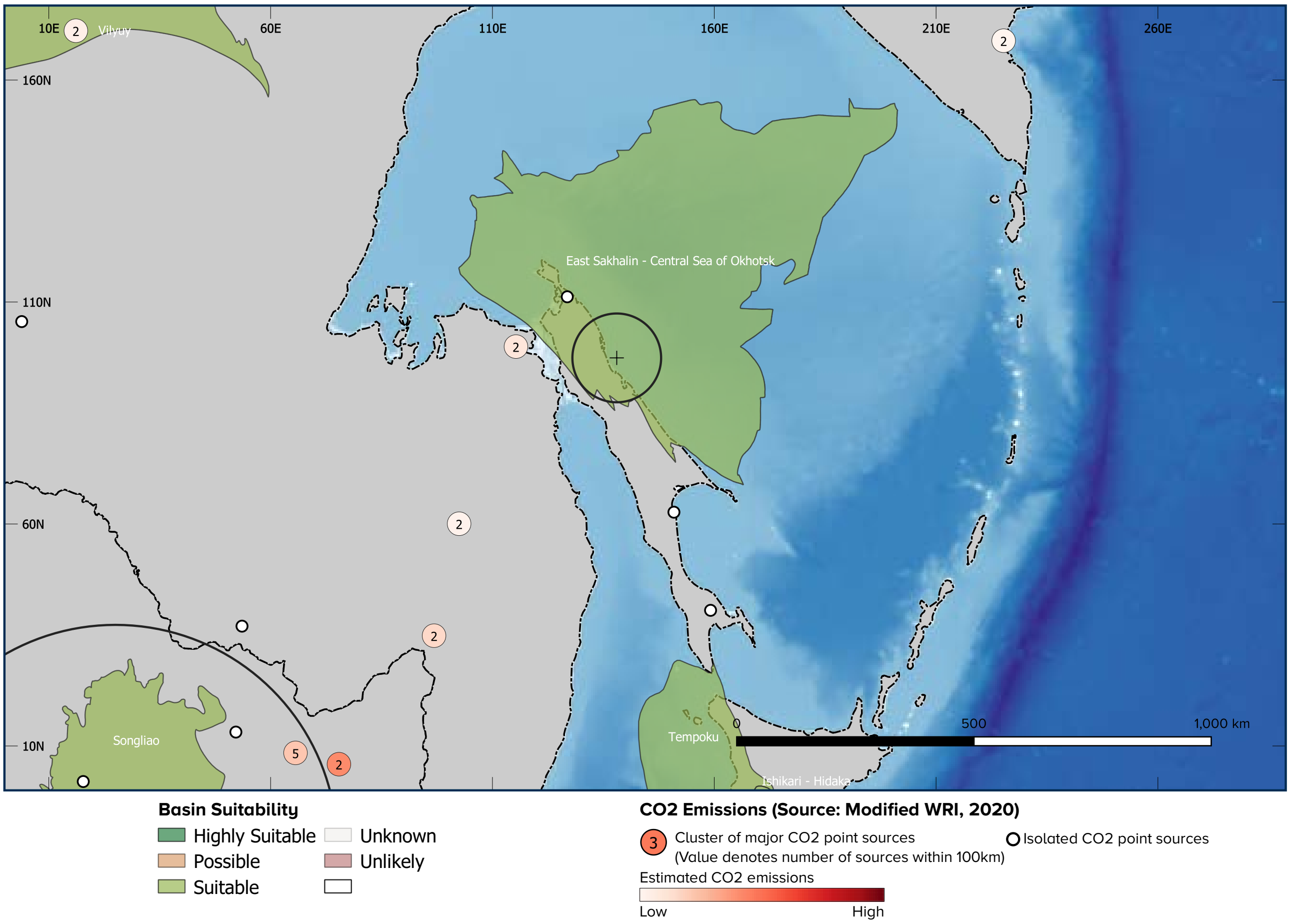


Figure 6 - $CO_2$ emissions clusters and potential CCS networks for Sakhalin Island in eastern Russia. Suitable storage and several oil and gas fields underly emissions point sources in this region.



Russia is the world's fourth-largest emitter of $CO_2$. Emissions are concentrated in the more densely populated regions of west, southwest, and south-central Russia.

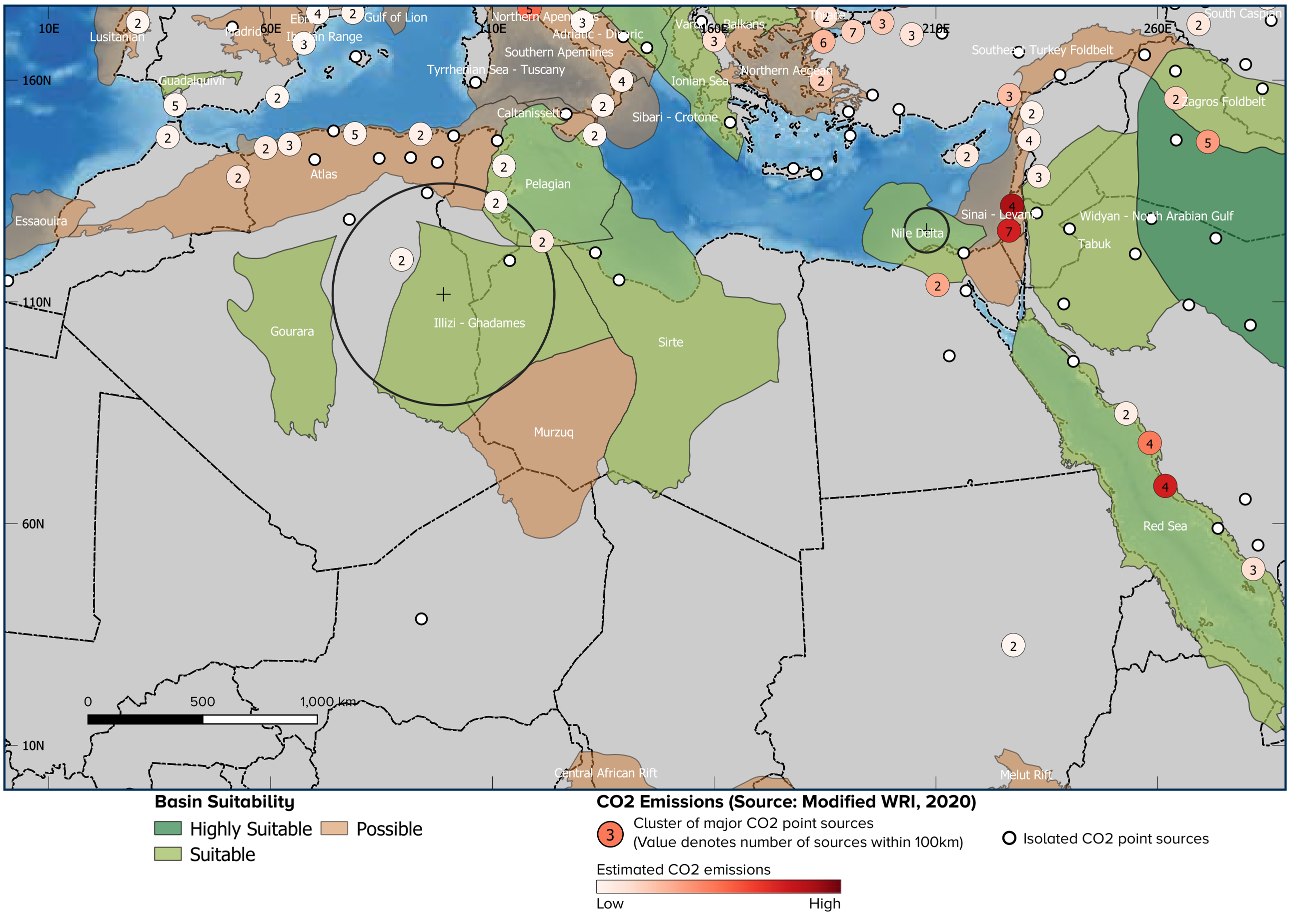
The geological storage potential of Russia and central Asia is significant but largely uncharacterised in published English-language literature. High-level estimates of storage resources in Russia exceed 56 $GtCO_2$ (UNECE, 2021). A mature oil and gas industry operates in Russia; however, several of the country's hydrocarbon-bearing regions, and correspondingly suitable basins, are located far from emissions centres. Four possible source-sink networks can be identified (Figures 5 and 6):

1. Moscow region – Precaspian and Volga-Ural Basins (transportation exceeds 500km)
2. Southwest Russia – Volga-Ural Basin
3. South-Central Russia – West Siberia Basin
4. Sakhalin Island – East Sakhalin Basin

The geological storage potential of Central Asia is unknown, but sedimentary basins exist in Mongolia with a total sedimentary thickness exceeding 3 km. Modest hydrocarbon exploration and production operations are present in eastern Mongolia, indicating some amount of suitable storage resources exist.

# Africa

**Figure 7 - $CO_2$ emissions clusters and potential CCS networks for northern Africa. Emissions clusters are located along the Mediterranean coast and can access suitable geologic storage onshore and offshore Algeria, Libyia, Tunisia, and Egypt.**



## North Africa

The geological storage potential of northern Africa is poorly characterised in comparison to southern Africa. Further characterisation is required as most analyses are based on single, basin-level studies or global reviews.

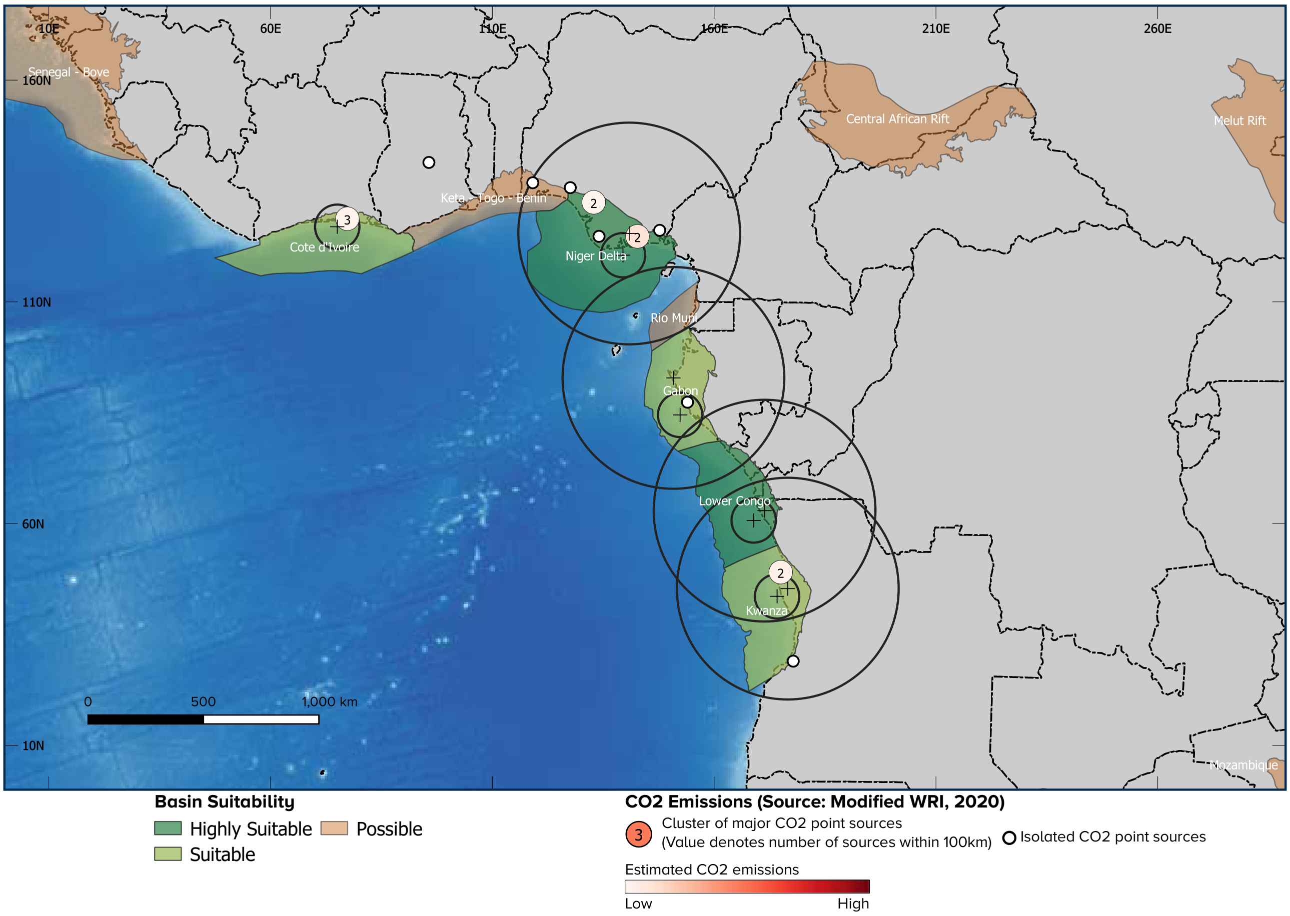
In Northern Africa, primary emissions are clustered along the Mediterranean coasts of Morocco, Algeria, Tunisia, and Egypt. The geologic storage potential of onshore and offshore basins adjacent to these emission sources is largely uncharacterised. Wood Mackenzie, however, recently studied the storage capacity of two offshore depleted hydrocarbon fields in the Nile Delta Basin, and an estimated 178 $MtCO_2$ can be stored in these two fields alone (Nandurdikar and Bowe, 2021). High geologic pore pressure (specifically, overpressure – which is reservoir pore pressure exceeding a hydrostatic pressure at a given depth) in the deeper, sub-salt stratigraphic section of the Nile Delta Basin will need to be considered when planning CCS projects in this basin.

In eastern Algeria, the Ghadames and Illizi Basins are petroliferous and comprise sufficient thickness and favourable reservoir and seal/cap rock lithologies for geologic storage. Estimates for total storage resources in Algeria range from 1 to 7 $GtCO_2$ (IEAGHG, 2009; Aktouf and Bentellis, 2016). The challenge for Algeria's coastal emissions sources will be developing a $CO_2$ transportation solution to these suitable basins. Two potential source-sink networks can be identified (Figure 7):

1. Cairo – Nile Delta Basin
2. North Algeria – Western Ghadames Basin (transportation may exceed 500 km)

# *Western Africa*

**Figure 8 - $CO_2$ emissions clusters and potential CCS networks for western Africa. Suitable or highly suitable storage basin are situated along the west African continental margin. Some storage is available onshore. CCS networks are possible in many countries including Cote d'Ivoire, Nigeria, Gabon, and Angola.**



Western Africa is one of the world's most prolific hydrocarbon provinces, featuring large sedimentary basins along nearly the entire length of the continent, from Angola through Nigeria to Sierra Leone.

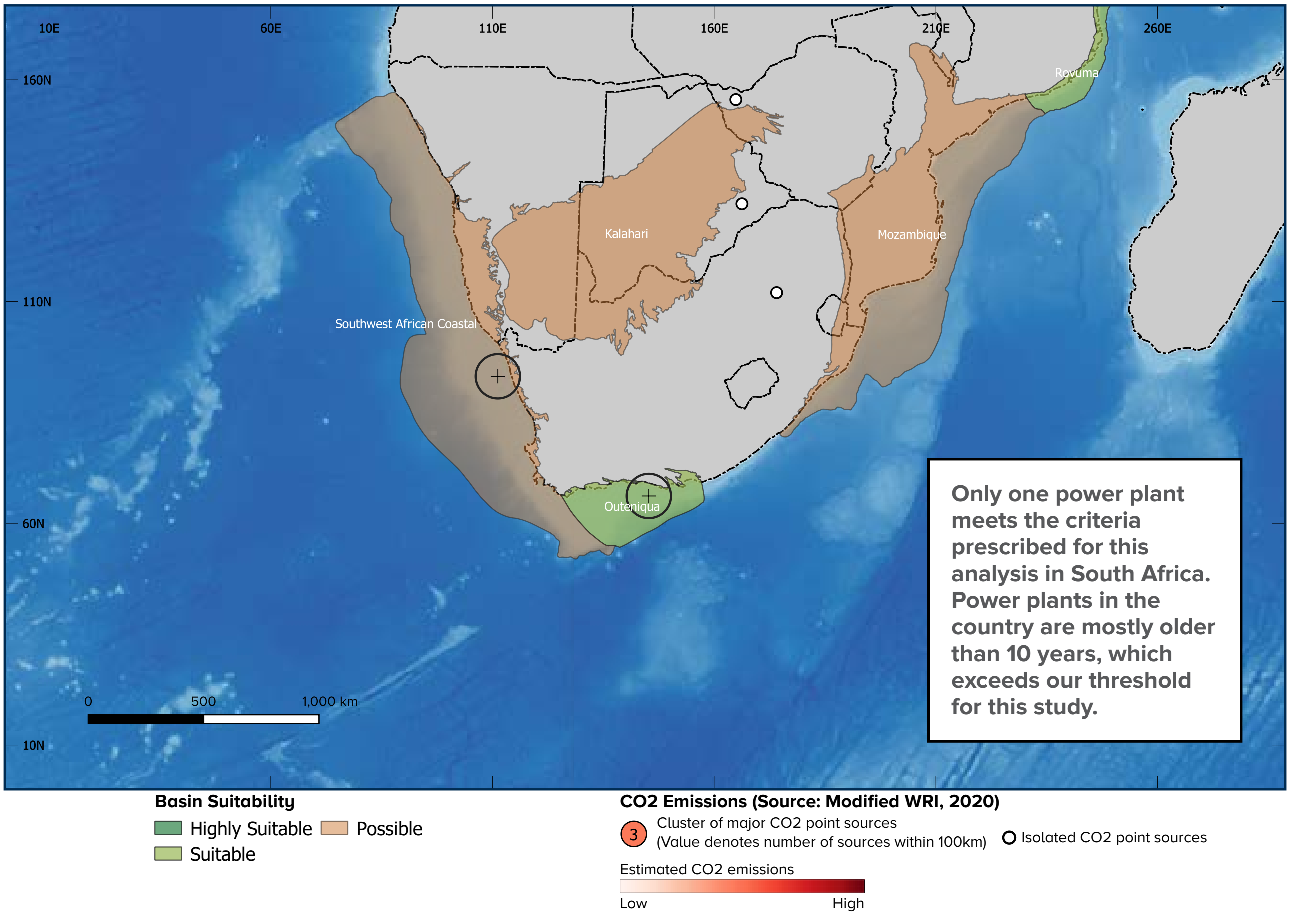
The majority of emissions sources in Western Africa are located in the Niger Delta region. The Niger Delta Basin is a highly suitable basin for storage. It comprises a significant thickness of suitable sedimentary fill, numerous oil and gas fields – including several giant fields. A CCS network could be developed for refineries and industrial facilities in Lagos, Warri, and Port Harcourt regions of Nigeria, utilising storage in onshore and offshore hydrocarbon fields and saline reservoirs.

Similarly, emissions clusters of the West African Transform Margin, Gabon, and Angola match well with suitable or highly suitable storage in their respective Tano, Gabon, and Lower Congo/Kwanza Basins. The Gabon, Lower Congo, and Kwanza Basins have both onshore and offshore storage potential. Four possible source-sink networks can be identified (Figure 8):

1. Coastal Nigeria – Niger Delta Basin
2. Coastal Cote d'Ivoire – Tano Basin (Cote d'Ivoire)
3. Coastal Angola – Lower Congo and Kwanza Basins
4. Coastal Gabon – Gabon Basin

## *Southern Africa*

**Figure 9 - $CO_2$ emissions clusters and potential CCS networks for South Africa. Most suitable storage exists offshore. Possible CCS networks can be identified in the Western Cape province.**



**Only one power plant meets the criteria prescribed for this analysis in South Africa. Power plants in the country are mostly older than 10 years, which exceeds our threshold for this study.**

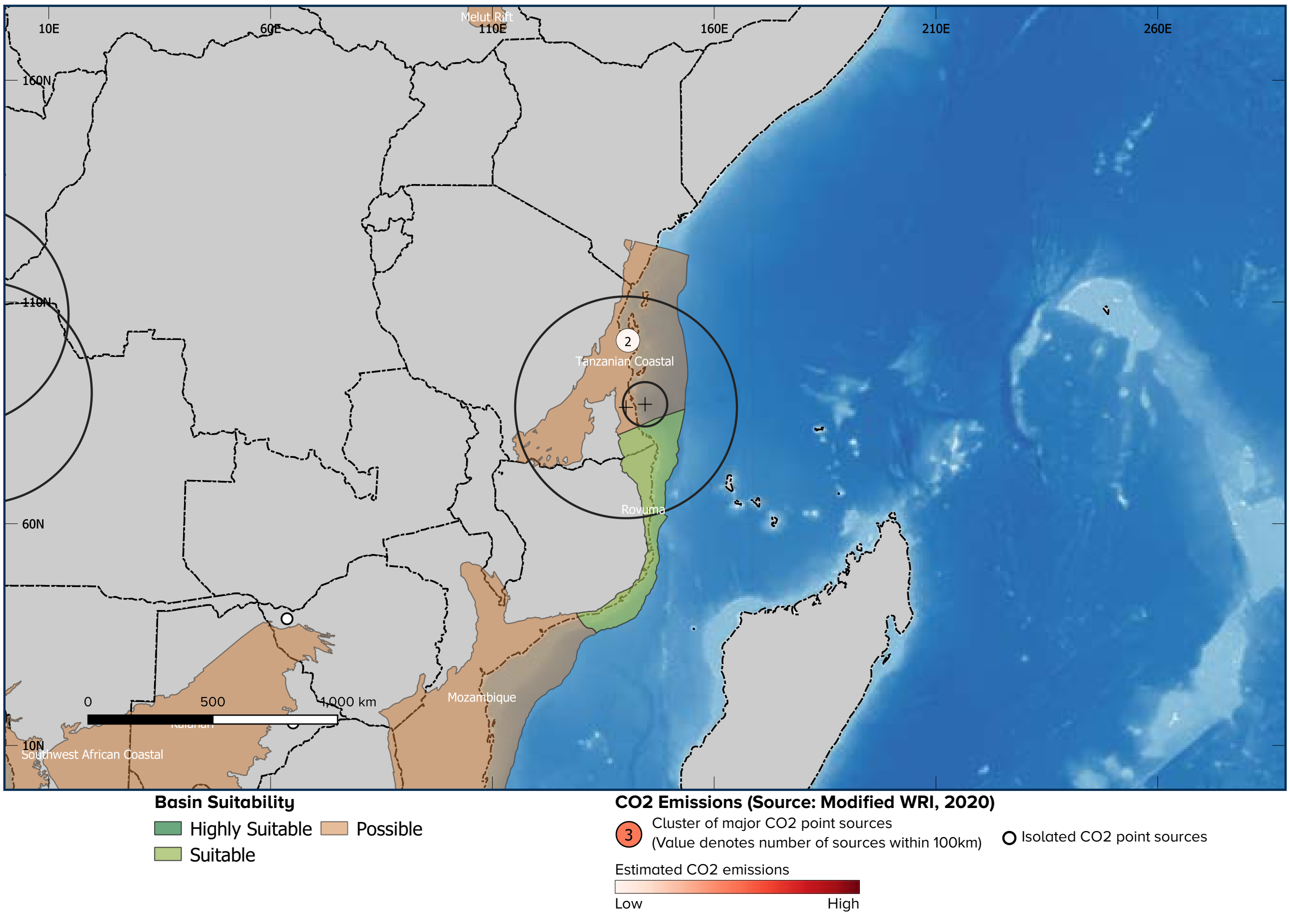
Suitable storage basins in South Africa are located offshore the south and southwest margins of the continent. A nationwide assessment estimates more than 150 $GtCO_2$ of storage resources are present, mostly in offshore saline formations (Viljoen, Stapelberg and Cloete, 2010). Suitable lithologies and sedimentary thickness exist onshore in the western Karoo Basin; however, low porosity and permeability in its sandstones may preclude economic storage. Further characterisation is needed.

The offshore Orange and Outeniqua Basins offer suitable storage for emissions clusters located in the Western Cape region of South Africa. Metocean conditions (i.e., wind, waves, ocean currents) offshore South Africa can be extreme and will need to be considered when considering the development of offshore storage in the Outeniqua Basin. Interior emissions centres in Gauteng and Limpopo have no proximate storage sink. $CO_2$ in these interior areas will likely have to be aggregated and transported significant distances to the Western Cape for storage. Therefore, only two potential source-sink network can be identified at this time (Figure 9):

- Western Cape – Southwest African Coastal Basin (Orange Basin)
- Western Cape – Outeniqua Basin

## East Africa

**Figure 10 - $CO_2$ emissions clusters and potential CCS networks for eastern Africa. Suitable storage is present in the Rovuma basin. Suitable storage likely extends north into Tanzania, where a CCS network is possible either offshore or onshore.**



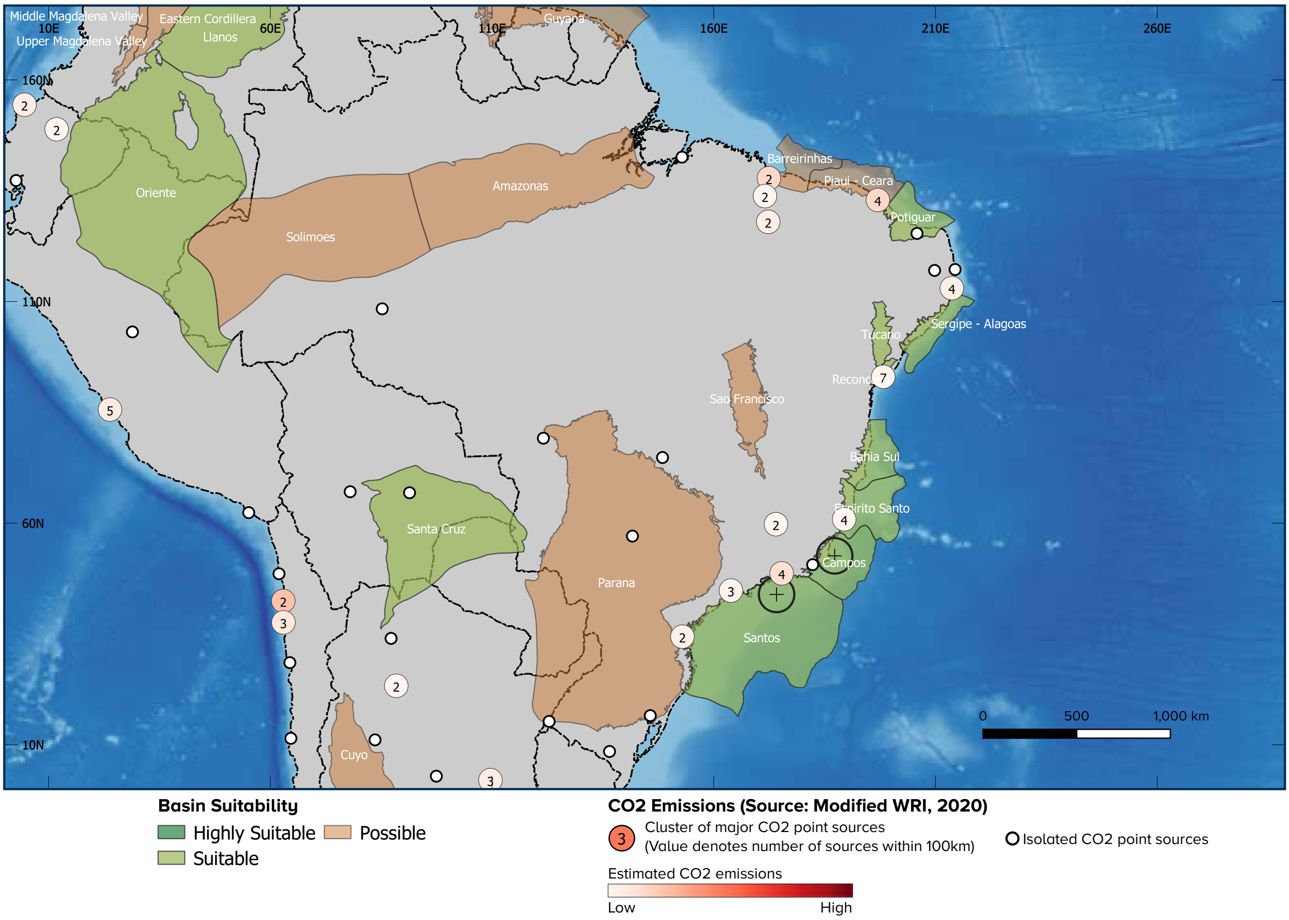
The geological storage potential of East Africa is poorly characterised apart from Mozambique, which is has been the subject of one national assessment (DNV, 2013). This assessment identified significant storage resources of 2-228 Gt $CO_2$ across four formations (DNV, 2013). Recent giant gas field discoveries in the Rovuma Basin, offshore Mozambique, indicate favourable storage resources are present. The geology underpinning these resources likely extends north into southern and central Tanzania, both onshore and offshore. Emissions centres in Dar es Salaam, Tanzania, therefore, may have possible storage resources in the Mafia Basin, Mandawa Basin, and northern portions of the Rovuma Basin. While additional analysis is required, one possible source-sink pair can be identified (Figure 10):

- Dar es Salaam – Tanzanian Coastal Basins (Mafia, Mandawa, and North Rovuma Basins)

# Americas

## *Central and South America*

**Figure 11 - $CO_2$ emissions clusters and potential CCS networks for Brazil. CCS networks are possible in the Santos and Campos Basins. Additional CCS networks are possible in other suitable basins, but additional storage characterisation is required.**



The geological storage potential of Central and South America is largely uncharacterised, apart from basins in Brazil and, to a lesser extent, Colombia and Trinidad and Tobago. Analogous to the West African continental margin, a series of enormous offshore sedimentary basins extend along the eastern margin of South America – from Argentina, through Brazil, and north to Suriname and Guyana.

Brazil's two major sedimentary basins are the Santos and Campos Basins, offshore Sao Paulo and Rio de Janeiro states. They are both well-suited for storage (Ketzer et al., 2015); however, the giant oil and gas fields in these basins are situated in deep water (1000 – 2000 m) and are therefore likely unviable sinks for near-term storage of onshore emissions sources. The Petrobras Santos $CO_2$-EOR CCS Project is currently injecting over 4 Mtpa $CO_2$ from a cluster of floating, production, storage and offloading (FPSO) vessels. Onshore emission hubs will have to utilise the smaller hydrocarbon fields and saline formations present in shallower water depths. Two possible source-sink networks can be identified (Figure 11):

- Sao Paulo – Santos Basin
- Rio de Janeiro – Campos Basin

Additional source-sink clusters are almost certainly possible for the Espiritu-Santo, Sergipe-Alagoas, Tucano, and Potiguar Basins, but additional analysis is required. Similarly, Brazil's onshore Paraná Basin requires further characterisation, but is likely a suitable storage basin.

The Maracaibo Basin in Venezuela is one of the most prolific hydrocarbon-producing basins in the world. The country hosts a mature oil and gas industry. Gulf of Venezuela emission sources – mainly from power generation and oil and gas processing and refining – can likely be stored in depleted oil and gas fields in the Maracaibo Basin.

Trinidad and Tobago emissions sources (power generation and gas refining) are surrounded by suitable offshore storage basins; however, most of the country's oil and gas fields are still producing, so depleted field storage capacity is limited (Nandurdikar and Bowe, 2021). Small-scale $CO_2$-EOR projects have been carried out in the country, with future projects planned. Additional characterisation is needed to understand the storage potential in the country's saline reservoirs.

Both Venezuela and Trinidad and Tobago have complex tectonic histories. Active tectonism and faulting in these basins are unfavourable characteristics for long term $CO_2$ storage and will need to be considered when planning CCS projects in these regions.

Western South America is a tectonically active, convergent continental margin, making its offshore basins largely unsuitable for permanent $CO_2$ storage. As a result, emissions clusters in coastal regions of Peru and Chile may need to seek transboundary transportation or onshore storage options.

---

## *North America*

**Figure 12 - $CO_2$ emissions clusters and potential CCS networks for the United States. Potential CCS networks can be identified in every emissions-heavy region of the country.**

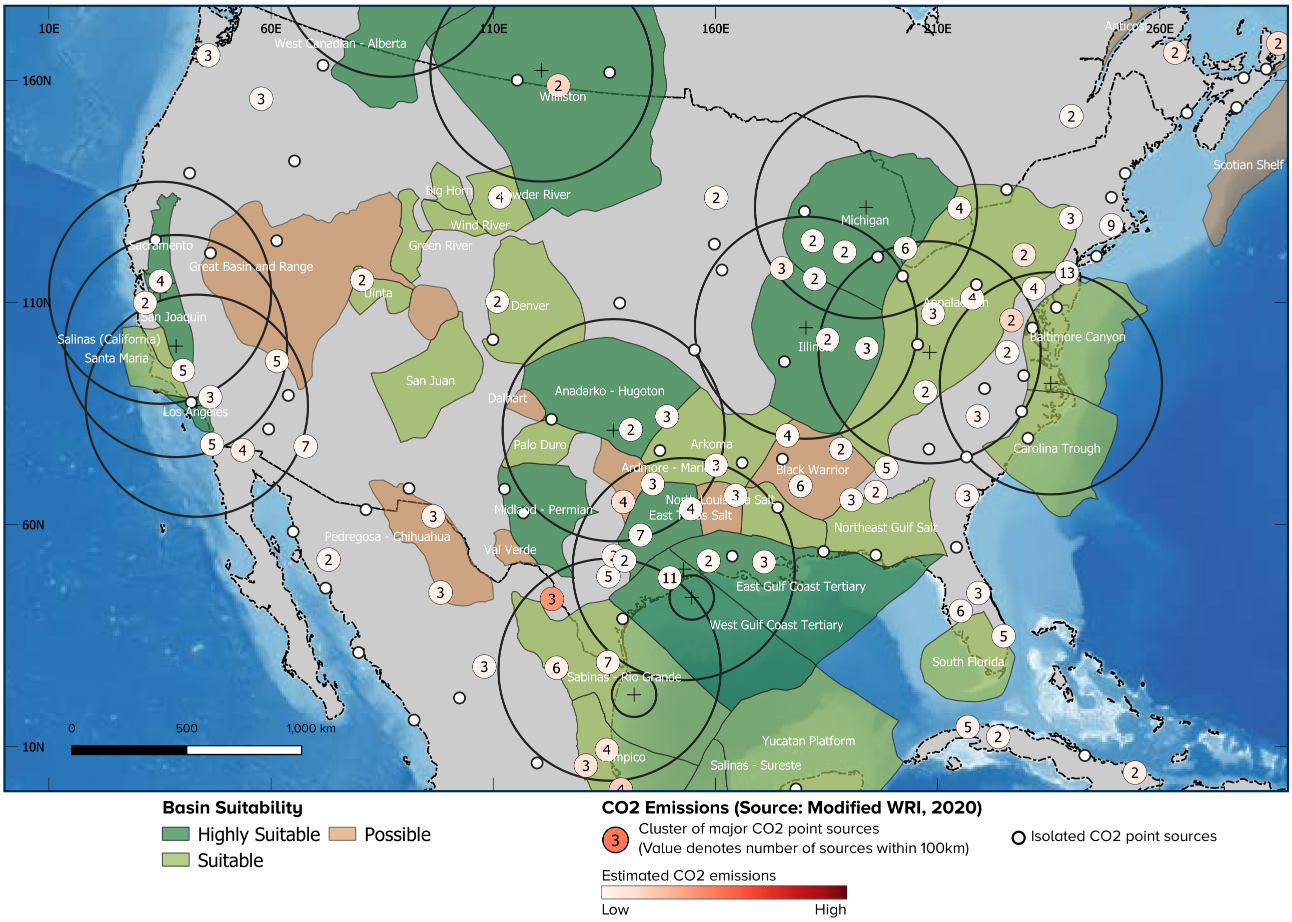
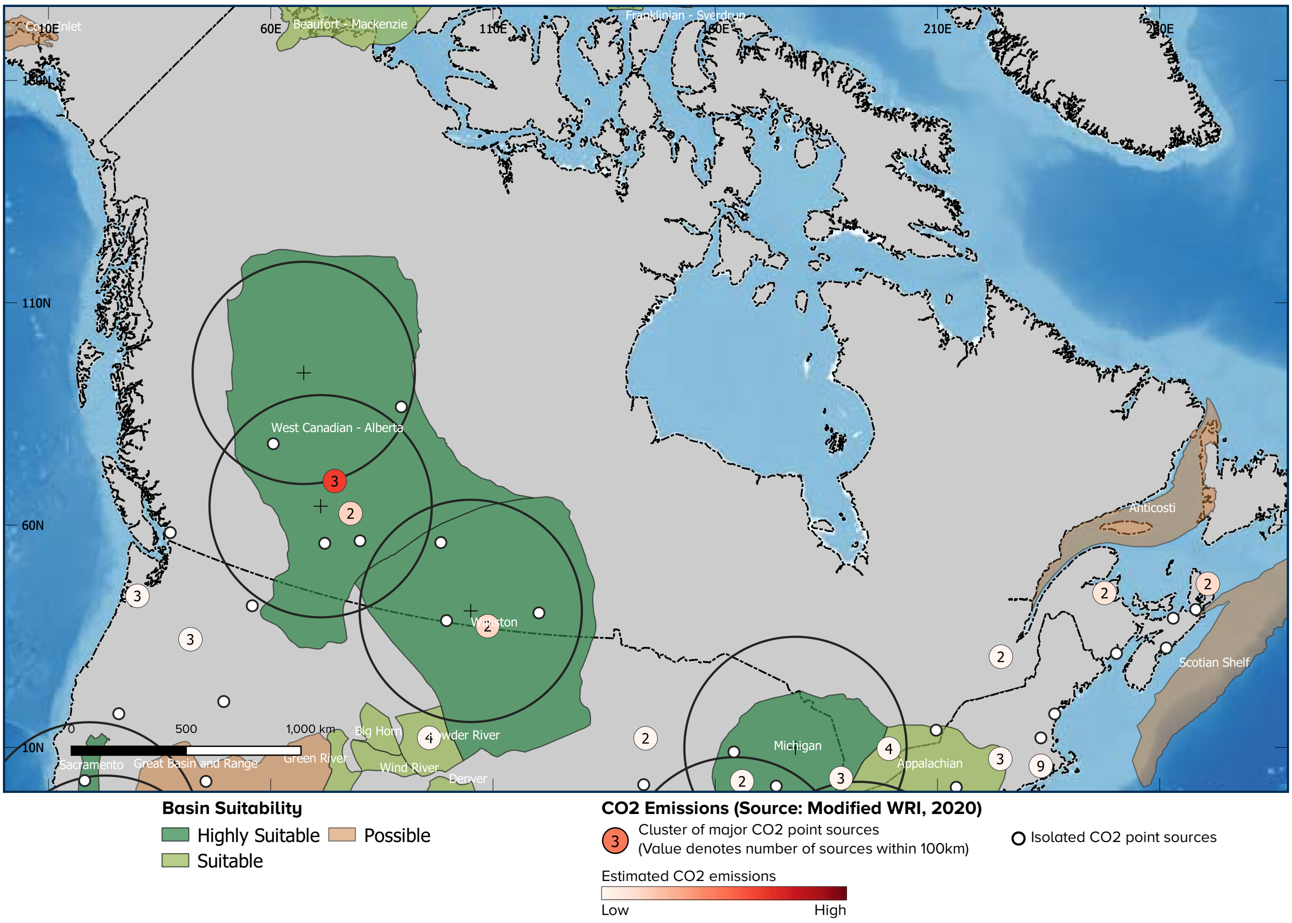


Figure 13 - $CO_2$ emissions clusters and potential CCS networks for Canada. CCS networks are possible and currently operating in Alberta's Williston and Alberta Basins. Additional networks may be possible in the Canadian portions of the Michigan Basin.



The geological storage potential of North America is well-characterised, with multiple assessments ranging from national-scale through to basin-scale simulations and site-scale appraisal programmes. (Sener, no date; Bachu, 2003; DOE, NRCan and SENER, 2012; US DoE/NETL, 2015). Both dedicated geological storage and $CO_2$-EOR opportunities have been reviewed in characterisation studies.

The latest storage resource estimate lies between 2,000 and 20,000 $GtCO_2$ for the United States. According to the Global CCS Institute's $CO_2$RE database, the majority of the world's CCS facilities are located in the United States (Global CCS Institute, 2020a).

In the western United States, significant volumes of oil and gas have been discovered and produced from onshore and offshore reservoirs of the San Joaquin, Sacramento, Ventura, and Los Angeles Basins of California. These basins have been well-studied, comprise thick sequences of porous reservoirs and cap rock (top seal), and are all suitable or highly suitable for storage. California Resources Corporation has begun front-end engineering and design (FEED) for the state's first commercial CCS project – CalCapture – which could capture up to 4,000 $tCO_2$ per day for enhanced oil recovery in the San Joaquin Basin (OGCI, 2020). While the Los Angeles Basin is suitable for CCS, its high geologic heat flow and densely populated urban setting present a challenge for CCS project planning in the basin.

One notable geologic feature in the northwestern United States is the Columbia River Basalt Group, which is an extensive deposit of basalt formations extending across Idaho, Washington, and Oregon. These formations could provide a large storage resource for mineral carbonation in basalts, but fundamental storage characterisation is still required.

Three source-sink networks can be identified for the western United States (Figure 13):

- San Francisco – Northern San Joaquin and Sacramento Basins

- Central Valley of California – San Joaquin Basin
- Los Angeles – Los Angeles or southern San Joaquin Basins

Similarly, in the southern United States, the Gulf of Mexico Basin has produced enormous volumes of oil and gas, comprises thick, favourable sandstone and mudstone sequences, and is highly suitable for storage. The region's highest emissions directly overly the basin and match well. Several CCS projects in the Gulf Coast region are currently operational, including the Air Products Steam Methane Reformer in Texas, the Cranfield Project in Mississippi, the Fuel Cell Carbon Capture Pilot Plant in Alabama, the NET Power Clean Energy Large-Scale Pilot Plant in Texas, and the PCS Nitrogen facility in Louisiana.

In April of 2021, ExxonMobil proposed a CCS hub concept for the Texas Gulf Coast. They expect a Houston-based CCS hub could capture and store 50 Mtpa from the region's petrochemical sector by 2030 and increase that amount to 100 Mtpa by 2050 if favourable CCS policies are in place (Blommaert, 2021).

It is worth noting the Gulf of Mexico Basin is not without storage site challenges. Both the high reservoir pore pressure in the sub-salt stratigraphic section and the tremendous number of wells across the basin will be problematic for site selection. Exploration for storage potential outside of the overpressured (i.e., regions where reservoir pore pressure exceeds a hydrostatic pressure for their given depth) portions of the Gulf of Mexico Basin should be conducted.

Emission clusters in northeast Mexico have access to onshore and offshore portions of the Gulf of Mexico Basin.

The east coast of the United States has long been protected from offshore oil and gas operations, but onshore portions of east coast basins and southern coastal plain regions could serve as good storage sinks and do not share the well density problem facing the central Gulf of Mexico Basin.

In the Midwest of the United States, the Appalachian Basin underlies emissions sources of Ohio, West Virginia, and Pennsylvania. The basin is petroliferous, with a mature oil and gas industry, and is suitable for storage. Additionally, in the Midwest, the highly suitable Michigan and Illinois basins offer significant opportunities for source-sink clusters with multiple emission clusters overlying both basins. A number of characterisation studies have been completed for these basins, but with pilot and commercial facilities currently operating, both basins are proven for CCS.

Six possible source-sink networks can be identified for basins east of the Rocky Mountains (Figure 12):

1. Houston – Gulf of Mexico Basin (detailed site characterisation needed)
2. Northeast Mexico – Sabinas and Gulf of Mexico Basins
3. East Coast – Onshore Carolina Trough and Baltimore Canyon Basins
4. Midwest (Ohio, Pennsylvania, West Virginia) – Appalachian Basin
5. Midwest (Illinois) – Illinois Basin
6. Upper Midwest (Michigan) – Michigan Basin

The sedimentary basins of Canada have been well-characterised. Canada's Alberta and Williston basins are major hydrocarbon producing basins with thick successions of favourable sandstones and mudstones; both ranked highly suitable for storage. The region's largest sources of emissions match well with these basins, which currently host several long-running CCS projects in Alberta and Saskatchewan.

The Alberta Carbon Trunk Line (ACTL) is notable as it is currently the world's largest capacity pipeline for anthropogenic $CO_2$ (ACTL, 2021). The ACTL established an expandable $CO_2$ transportation and storage network linking a petrochemical refinery and fertiliser plant north of Edmonton, Alberta, to an enhanced oil recovery (EOR) oil field 240 km away.

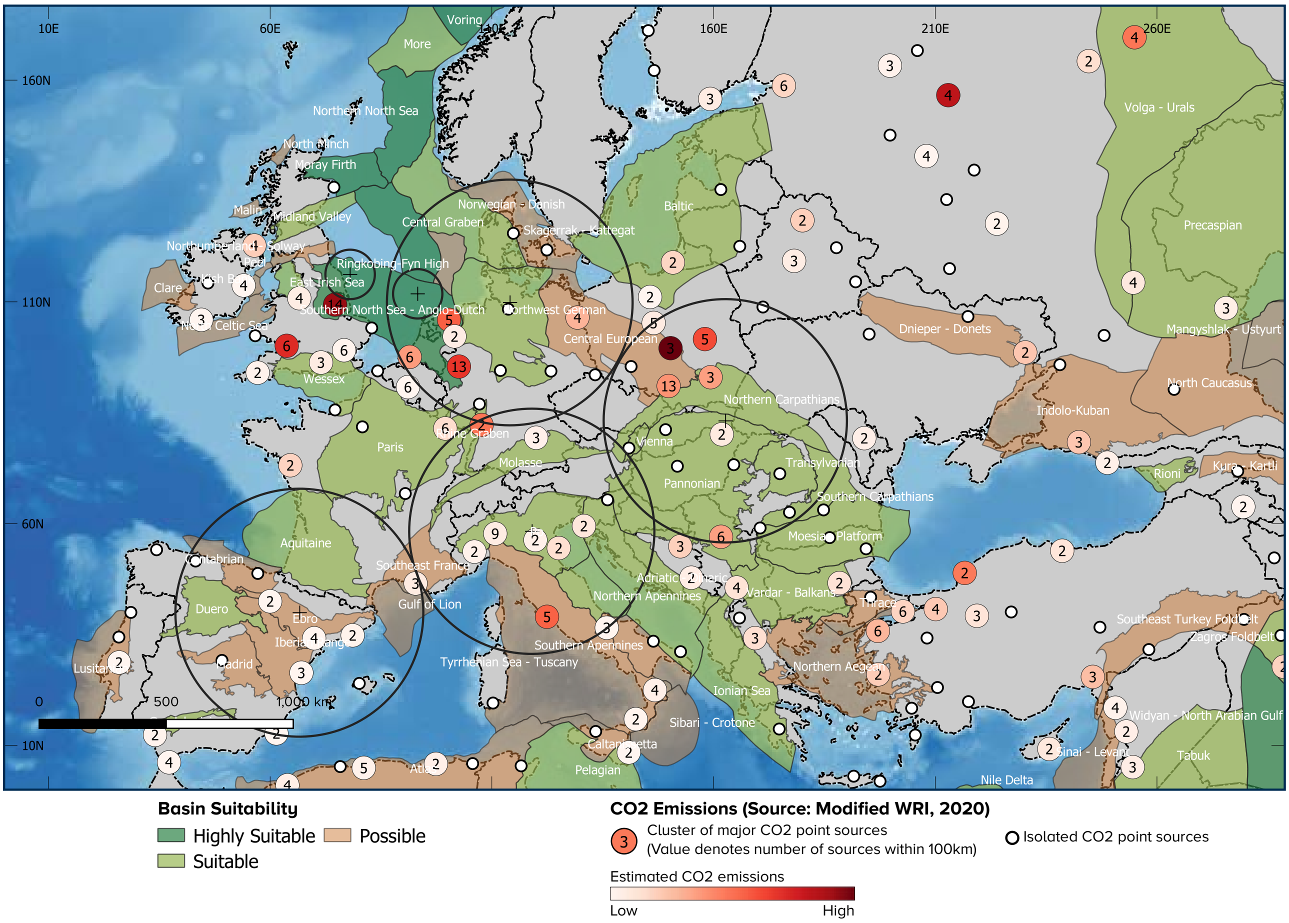
The Michigan and Appalachian basins extend into Canada, and, according to several assessments, host viable deep saline formations despite thinning of the basins across the international border with the USA.

Two possible source-sink networks have been identified (Figure 13):

1. Edmonton – Alberta Basin
2. Southern Saskatchewan – Williston Basin

# Europe and UK

**Figure 14 - $CO_2$ emissions clusters and potential CCS networks for Europe and the UK. Several networks are possible in suitable and highly suitable storage basins, both onshore and offshore, across the region.**



The geological storage potential of Europe and the United Kingdom is well-characterised, with multiple national assessments. The majority of sub-basins and depocenters underlying the North Sea between the United Kingdom and Norway are highly suitable for storage and are prolific hydrocarbon producing provinces. The majority of Western Europe's emissions centres are distributed along its coastal regions. All match well with North Sea storage sites.

Onshore basins in northern Europe are suitable for storage and match well with dense emissions centres in onshore France and Germany; however, public resistance to onshore storage options in these countries is persistent. These mainland European countries may need to seek transboundary storage options in the North Sea. In Spain, researchers have identified suitable storage structures and potential CCS network hubs in the northwest and northeast portions of the country (Sun et al. 2021). We rank the Iberian basins as possible for storage, but with additional characterisation they could be ranked suitable or highly suitable

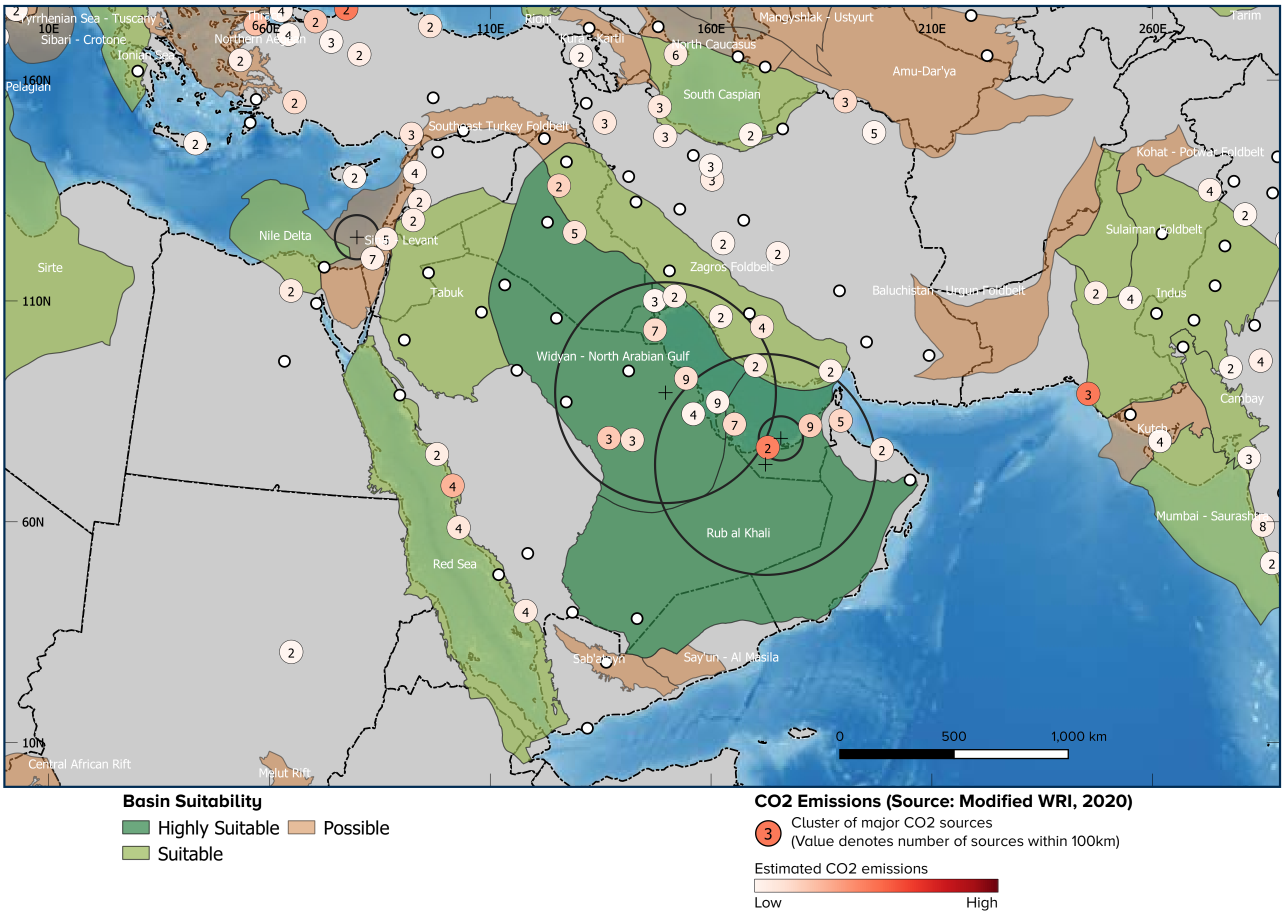
The North Carpathians and Pannonian Basins in eastern Europe are suitable for storage and are adjacent to dense emissions centres in Poland, Hungary, Serbia, and Croatia. High geologic heat flow in the Pannonian Basin will need to be considered when appraising sites for storage.

For Europe, six source-sink networks can be identified (Figure 14):

1. Eastern England – North Sea Basin
2. Netherlands/Denmark/Germany – North Sea Basin (transportation >100 km)
3. Hungry and Poland – North Carpathians and Pannonian Basins
4. Northern and Central Italy – Po and Northern Apennines basins
5. Central Germany – Northwest German Basin
6. Northeast Spain – Iberian Range/Ebro Basins

# Middle East

**Figure 15 - $CO_2$ emissions clusters and potential CCS networks for the Middle East region. CCS networks are possible in the highly suitable storage basins of Saudi Arabia and the United Arab Emirates. Most nations have access to suitable storage, so additional CCS networks are possible.**



The Middle East is a prolific hydrocarbon province with abundant storage available onshore and offshore. Emissions are primarily from power, refining, and chemical sectors and match well with available storage in Saudi Arabia, Qatar, United Arab Emirates, Iraq, Iran, and Kuwait. The Widyan and Rub al Khali Basins in central-eastern Saudi Arabia are highly suitable and are currently utilised to store $CO_2$. Three CCS facilities are currently operating in Gulf States, capturing 3.7 Mtpa of $CO_2$ (Global CCS Institute, 2020b).

The Red Sea Basin is suitable for storage, but the shallow sedimentary section is dominated by a substantial thickness of evaporite deposits, rather than a preferable succession of sandstone or carbonate reservoir rocks (Lindquist, 1999; World Petroleum Resources Project, 2010). Although several oil and gas fields exist, it may prove challenging to identify storage reservoirs at suitable geologic depths. Additionally, high geologic heat flows in the basin can degrade reservoir quality. Exposure to elevated reservoir temperatures may increase rates of cementation, which decreases reservoir porosity and permeability (Bjorlykke & Egeberg 1993; Bjørkum et al. 1998). One option worth exploring for point source emissions in western Saudia Arabia is mineral carbonation storage in basalt formations onshore, but additional work is required to characterize this storage technology and local formation suitability.

Israel has access to offshore storage in the Levant Basin, which hosts several gas fields, including one giant field. We rank the basin as possible for storage, but with additional characterisation it could be ranked suitable or highly suitable.

Three primary source-sink networks can be identified across the Middle East region (Figure 15):

- Isreal – Levant Basin
- Eastern Saudi Arabia / Qatar – Widyan Basin
- UAE – Rub al Khali basins

# 3.0 PART 2 – $CO_2$ COMPRESSION AND PIPELINE NETWORK DESIGN

This section demonstrates an approach to design the shared infrastructure of a CCS network, given a specific set of industrial $CO_2$ sources and a nearby $CO_2$ storage resource. The example map and facilities provided in this section are fictional and are for demonstration purposes only.

## Basis

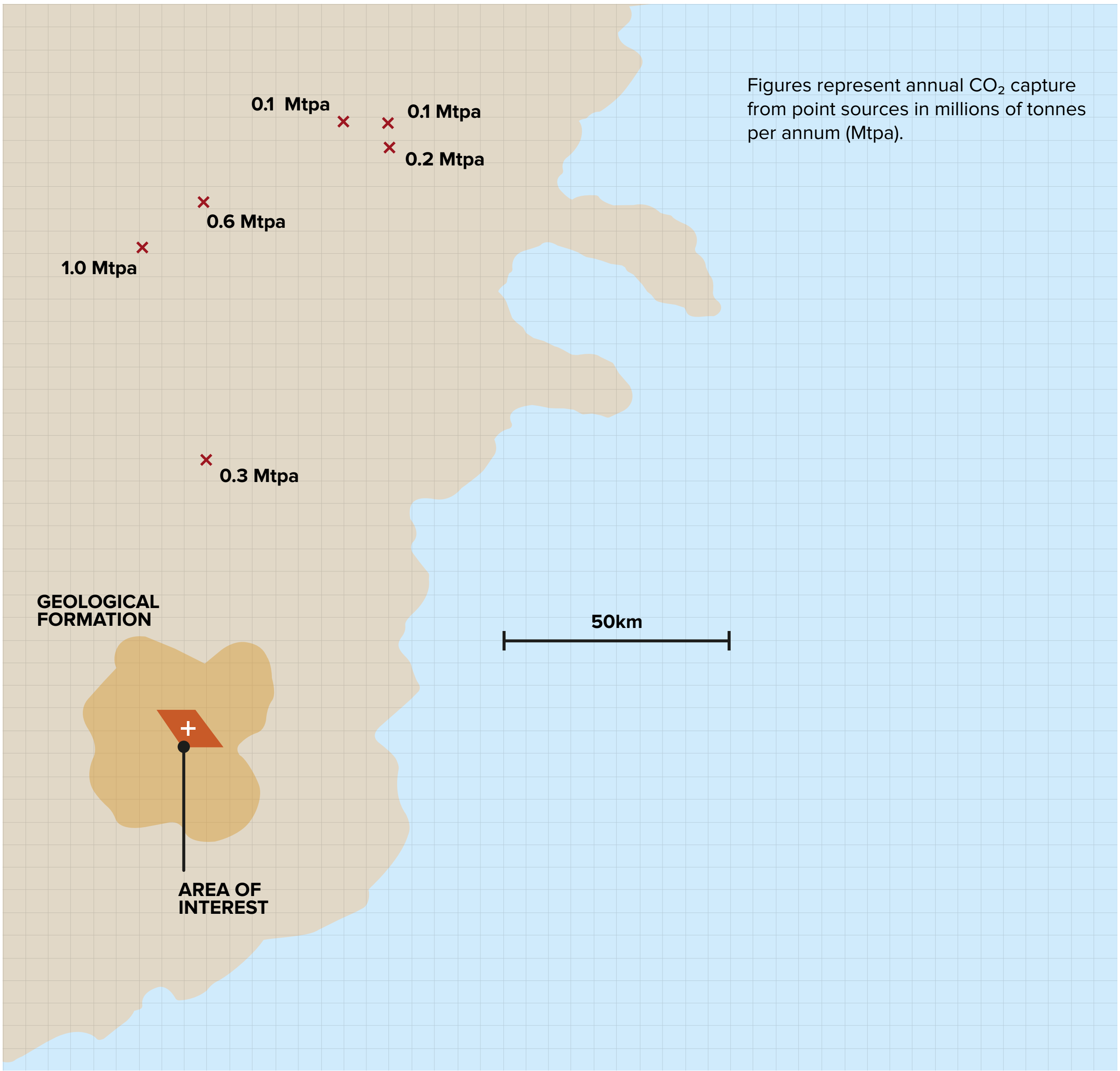
The industrial cluster is located near the east coast of the fictional nation of Carbonlandia. The relevant region is approximately 80 km North to South, and approximately 70 km East to West. The nearest suitable $CO_2$ storage basin is located around 60 km south of the southernmost $CO_2$ source in the region. The area of interest for storage (the plus symbol near the bottom of the map) lies within the broader geologic formation to be used for storage. The objective is to design a network to compress and transport $CO_2$ from all point sources to this target area of interest.

A sketch of this land is shown in Figure 16:

Each "X" represents a $CO_2$ capture source, with the number representing the annual volume in millions of tonnes per annum (Mtpa).

The network design is intended to be a first-pass attempt to minimise the overall transport system cost to deliver $CO_2$ from all sources to the target storage site in the south of the map.

Figure 16 – Map of the east coast of Carbonlandia



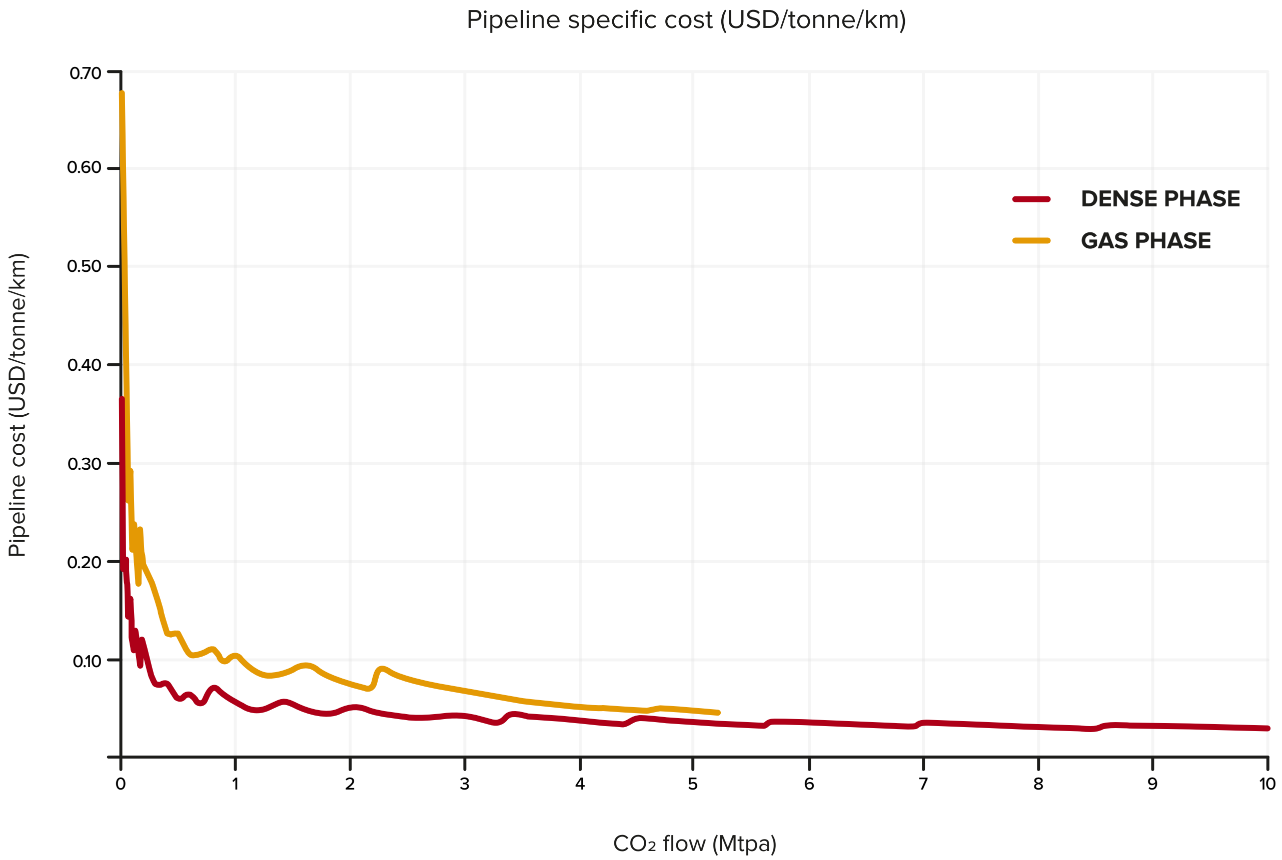
Figures represent annual $CO_2$ capture from point sources in millions of tonnes per annum (Mtpa).

## Cost bases

Network design is strongly influence by cost trends for pipelines and $CO_2$ compression. The first step in laying out a new network is to understand these cost trends.

A previous Global CCS Institute report (Kearns, Liu & Consoli 2021) outlined cost trends for $CO_2$ pipelines. Indicative pipeline costs per kilometre-tonne were outlined for gas-phase and dense-phase (>74 bar pressure) $CO_2$ pipelines (Figure 17). The figures are based on data from Australia but represent the sort of trends expected in any location, even if the specific costs are not exactly the same.

**Figure 17 – Total pipeline cost per km-tonne for $CO_2$ pipelines (gas phase and dense phase)**



Based on costs in Figure 17, we can see that it is desirable to aggregate flows to greater than 0.5 Mtpa and ideally above 1.0 Mtpa where possible. At this point, most of the economies of scale available have been exploited. This means that every effort should be made to keep smaller capacity pipelines short, and aggregate $CO_2$ streams as soon as possible to reach 0.5-1.0 Mtpa or greater.

**Guideline 1:** Pipeline routes carrying less than 0.5 - 1 Mtpa should be made as short as reasonably possible, with the objective of joining larger capacity pipeline routes before covering large distances.

In all cases, dense phase $CO_2$ pipelines are lower cost than gas phase pipelines of the same flow capacity. However, this does not mean that all $CO_2$ transport should be in the dense phase. The cost of gas compression also needs to be taken into account.

Typically, captured $CO_2$ first emerges from its capture plant at close to ambient pressure (~1 bar abs). For dense phase transport, this would need to be compressed in a multi-stage compressor to the critical pressure (73.8 bar) and then be pumped to the final required pressure for transport. For this exercise, this final pressure is assumed to be 150 bar.

An alternative option is to carry out compression for smaller scale flows in two steps. First, modest compression (assumed to be 1-9 bar) for gas-phase transport to a shared compression facility. The shared facility would then do the rest of the compression. This approach enables economies of scale for the shared compression facility, by aggregating multiple $CO_2$ streams.

We have estimated the total cost of compression for three options:

1. Gas compression from 1 bar ($CO_2$ source pressure) to 9 bar for gas-phase transport.
2. Compression from 5 bar (from gas-phase pipelines) to 150 bar for dense-phase transport.
3. Compression from 1 bar ($CO_2$ source pressure) directly to 150 bar for dense phase transport.

The gap between outlet pressure in (1) and inlet pressure in (2) is to allow for gas-phase pressure drop in the gas-phase pipeline.

We assumed a power price of USD 80/MWh, and a capital recovery factor of 9.75%. Compression energy was estimated using Aspen HYSYS, with an assumed motor efficiency of 90%. Capital cost estimates for the $CO_2$ compressors and pumps were obtained using formulae in Mccollum & Ogden (2006).

The total costs (capex plus opex) of these options vary with $CO_2$ flow, and are summarised in Table 1.

**Table 1 – Total compression cost per tonne of $CO_2$ (numbers in bold text refer to Options 1 and 2 described in the following pages)**

| $CO_2$ FLOWRATE (Mtpa) | 1-9 bar GAS PHASE (USD/t) | 5-150 bar GAS TO DENSE PHASE (USD/t) | 1-150 bar DENSE PHASE (USD/t) |
|---|---|---|---|
| 0.01 | 48.95 | 62.41 | 96.68 |
| 0.02 | 33.83 | 43.30 | 67.08 |
| 0.03 | 27.52 | 35.39 | 54.77 |
| 0.04 | 23.89 | 30.86 | 47.71 |
| 0.05 | 21.48 | 27.86 | 43.02 |
| 0.06 | 19.74 | 25.69 | 39.64 |
| 0.07 | 18.41 | 24.04 | 37.06 |
| 0.08 | 17.36 | 22.73 | 35.01 |
| 0.09 | 16.50 | 21.66 | 33.34 |
| 0.10 | **15.78** | 20.77 | **31.94** |
| 0.11 | 15.16 | 20.01 | 30.75 |
| 0.12 | 14.63 | 19.35 | 29.72 |
| 0.13 | 14.17 | 18.78 | 28.82 |
| 0.14 | 13.76 | 18.27 | 28.02 |
| 0.15 | 13.39 | 17.82 | 27.32 |
| 0.16 | 13.06 | 17.41 | 26.68 |
| 0.17 | 12.77 | 17.05 | 26.10 |
| 0.18 | 12.50 | 16.71 | 25.58 |
| 0.19 | 12.25 | 16.41 | 25.10 |
| 0.20 | 12.02 | 16.13 | 24.66 |
| 0.30 | 10.45 | 14.20 | 21.62 |
| 0.40 | 9.55 | 13.09 | 19.88 |
| 0.50 | 8.95 | 12.35 | 18.72 |
| 0.60 | 8.52 | 11.82 | 17.88 |
| 0.70 | 8.19 | 11.41 | 17.24 |
| 0.80 | 7.93 | 11.09 | 16.74 |
| 0.90 | 7.71 | 10.83 | 16.32 |
| 1.00 | 7.53 | **10.61** | 15.97 |
| 1.20 | 7.25 | 10.26 | 15.42 |
| 1.40 | 7.03 | 9.99 | 15.00 |
| 1.60 | 6.86 | 9.78 | 14.67 |
| 1.80 | 6.72 | 9.61 | 14.39 |
| 2.00 | 6.60 | 9.46 | 14.17 |
| 2.20 | 6.50 | 9.34 | 13.97 |
| 2.40 | 6.41 | 9.23 | 13.80 |
| 2.60 | 6.34 | 9.14 | 13.66 |
| 2.80 | 6.27 | 9.06 | 15.00 |
| 3.00 | 6.21 | 8.98 | 14.83 |
| 3.10 | 6.18 | 8.95 | 14.74 |
| 3.20 | 6.16 | 8.92 | 14.67 |
| 3.30 | 6.13 | 8.89 | 14.59 |
| 3.40 | 6.11 | 8.86 | 14.52 |
| 3.50 | 6.08 | 8.83 | 14.46 |
| 3.60 | 6.06 | 8.80 | 14.39 |
| 3.70 | 6.04 | 8.78 | 14.33 |
| 3.80 | 6.02 | 8.75 | 14.28 |
| 3.90 | 6.00 | 8.73 | 14.22 |
| 4.00 | 5.99 | 8.71 | 14.17 |

To demonstrate the potential cost advantage of short-run gas-phase transport for smaller scale sources, an example is worth exploring.

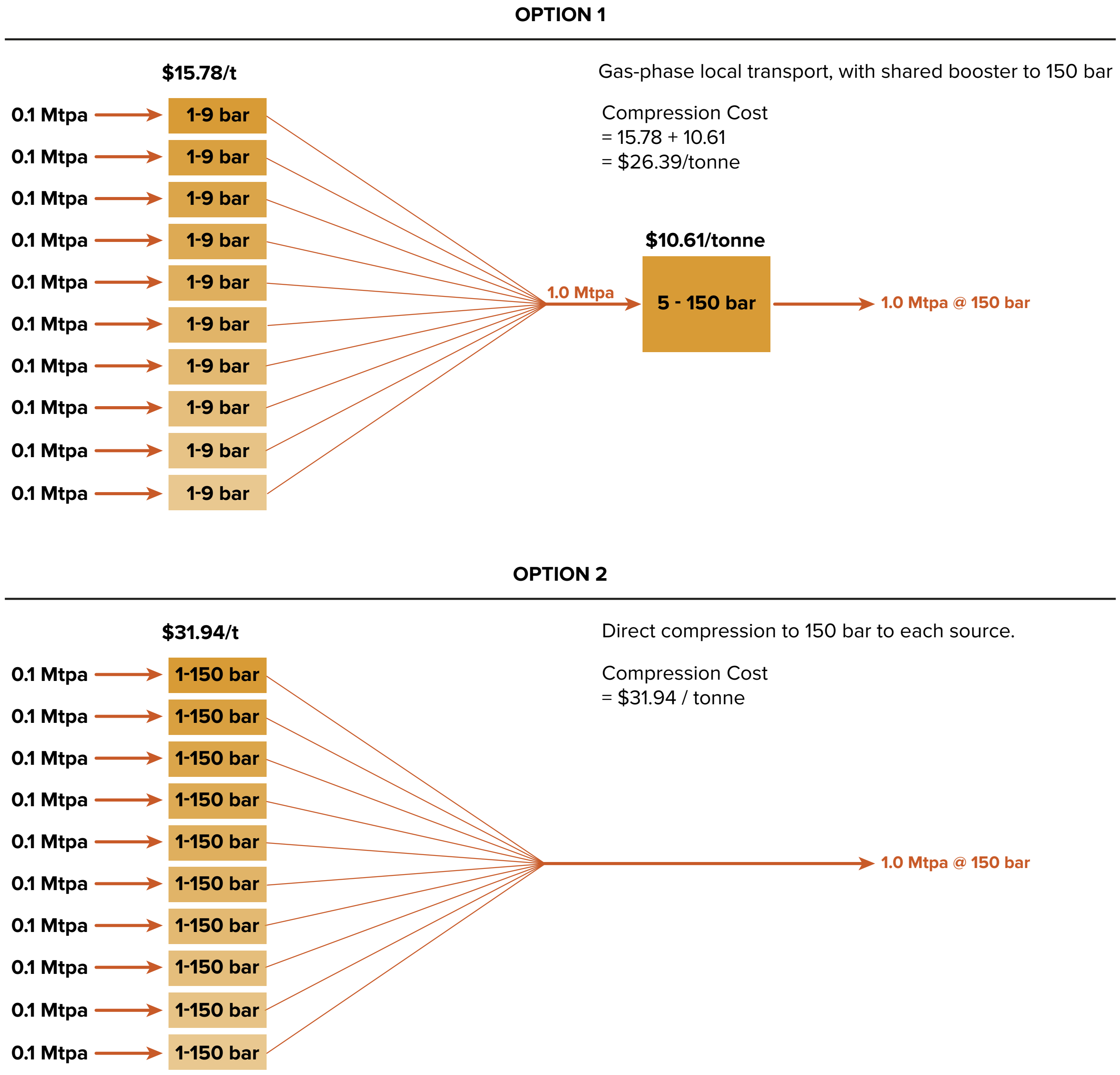
As an example, let us assume there are ten $CO_2$ sources of 0.1 Mtpa each, and it is required to boost each 1 bar source up to the dense phase at 150 bar for transport.

Two options have been proposed for $CO_2$ compression:

1. Local compression to 9 bar for short-range gas-phase transport, followed by a shared compression facility to boost an aggregated $CO_2$ stream to 150 bar.
2. Directly compressing each point source of $CO_2$ to 150 bar, with no shared compression facility.

Figure 18 gives an impression of each compression arrangement.

**Figure 18 – two step compression (with shared compression to dense phase) vs separate compression of each point source to dense phase.**



Option 1: a gas-phase compressor boosts the pressure of each 0.1 Mtpa source to 9 bar. After short-run gas-phase pipeline transport, these streams are aggregated into a 1.0 Mtpa stream, before entering a shared 5-150 bar system to boost the pressure of the aggregated stream for bulk transport.

Compression costs would be (reading relevant figures bolded in Table 1):

10 x gas-phase (1-9 bar) @ 0.1 Mtpa = $15.78 / tonne

Plus 1 x gas-dense phase (5-150 bar) compressor @ 1.0 Mtpa = $10.61 / tonne

Total compression cost = $15.78 + 10.61 = $26.39 / tonne.

Compare this to the cost of running 1-150 full compression at each of the ten 0.1 Mtpa sources (i.e. all transport in the dense phase):

10 x gas-to-dense phase (1-150 bar) @ 0.1 Mtpa = $31.94 / tonne

For this example, using separate gas-phase 1-9 bar compressors followed by a shared 5-150 bar compressor, yields a compression cost saving of $5.55.

This cost advantage of two-step compression disappears at higher source flowrates. Table 2 summarises the cost advantage (shown by negative differences in costs) between 2-stage compression vs doing all compression to 150 bar at the source. Note that the cost saving depends not only on the scale of each $CO_2$ source, but also on the scale of the aggregated stream flowing to the shared 5-150 bar compression system.

**Table 2 – Difference in per-tonne cost of compression between full scale (1-150 bar) at source and split (1-9 bar at source, 5-150 bar at shared facility). Negative numbers indicate that split compression is cheaper. All cost differences are in USD/tonne.**

| Scale of $CO_2$ source (1-9 bar) (Mtpa) | Scale of shared $CO_2$ compression (5-150 bar) (Mtpa) | | | |
|---|---|---|---|---|
| | 0.5 | 1.0 | 1.5 | 2.0 |
| 0.01 | - 35.39 | - 37.13 | - 37.86 | - 38.27 |
| 0.02 | - 20.90 | - 22.64 | - 23.37 | - 23.79 |
| 0.03 | - 14.90 | - 16.64 | - 17.37 | - 17.79 |
| 0.04 | - 11.47 | - 13.21 | - 13.94 | - 14.36 |
| 0.05 | - 9.19 | - 10.93 | - 11.66 | - 12.08 |
| 0.06 | - 7.55 | - 9.29 | - 10.02 | - 10.44 |
| 0.07 | - 6.30 | - 8.04 | - 8.77 | - 9.18 |
| 0.08 | - 5.30 | - 7.05 | - 7.77 | - 8.19 |
| 0.09 | - 4.49 | - 6.23 | - 6.96 | - 7.38 |
| 0.1 | - 3.81 | - 5.56 | - 6.28 | - 6.70 |
| 0.2 | - 0.29 | - 2.03 | - 2.76 | - 3.18 |
| 0.3 | **1.18** | - 0.56 | - 1.29 | - 1.71 |
| 0.4 | 2.02 | **0.28** | - 0.45 | - 0.87 |
| 0.5 | 2.58 | 0.84 | **0.11** | - 0.30 |
| 0.6 | 2.99 | 1.25 | 0.52 | **0.10** |
| 0.7 | 3.30 | 1.55 | 0.83 | 0.41 |
| 0.8 | 3.54 | 1.80 | 1.07 | 0.65 |
| 0.9 | 3.74 | 2.00 | 1.27 | 0.86 |
| 1.0 | 3.91 | 2.17 | 1.44 | 1.02 |

The orange cells in Table 2 indicate the point where the cost difference becomes positive; in other words, when the point source is large enough to justify its own 1-150 bar compressor, rather than using shared infrastructure.

From this table we can derive a second guideline for this exercise:

**Guideline 2:** If a $CO_2$ source is smaller than 0.3 Mtpa, it should be transported in the gas phase to a shared compression system downstream for boosting to dense phase.

If the $CO_2$ source is in the 0.3-0.5 Mtpa range, the choice of compression arrangement will need to be on a case-by-case basis.

If the $CO_2$ source is greater than 0.5 Mtpa, full compression to dense phase at the source for transport should be done.

We can now apply these guidelines on pipelines and compression to our theoretical example of an industrial cluster to develop a new CCS network.

## Applying guidelines to the Carbonlandia network design

This exercise is intended to show one approach to minimising the overall cost of the pipelines and compression systems across a cluster of industrial $CO_2$ sources. Simplifying assumptions, such as all pipelines running in straight lines from place to place, would need to be reviewed in light of real-world factors such as the location of private properties, geographical obstacles (rivers, mountains etc), and suitable land for pipeline construction.

### Sources A, B and C

Our starting point is the close grouping of small point sources in the north of our map (refer Figure 16). Applying guideline 2, all three sources (A, B and C) are small enough to benefit from 2-stage compression (gas-phase at the source, boosted to dense phase at a central shared facility).

From Figure 2, gas phase pipeline costs are:

0.1 Mtpa: USD 0.23 / tonne / km

0.2 Mtpa: USD 0.20 / tonne / km

Multiplying out by tonnage, these costs become:

0.1 Mtpa pipeline: $0.23 \times 0.1 \times 10^6$ = USD 23,000 / km

0.2 Mtpa pipeline: $0.20 \times 0.2 \times 10^6$ = USD 40,000 / km

Although costs per tonne-km are higher for the 0.1 Mtpa streams (A and B), the straight per-km costs are substantially lower thanks to the smaller volumes. The compression station should be located at the spot where the total costs of all gas-phase lines supplying it are minimised.

The three sources are located on a grid 10 km east-west and 5 km north-south. The shared compression station will need to be at some location between these coordinates. The basis will be the minimisation of the gas-phase pipeline costs across all three sources.

The three $CO_2$ sources are as follows (grid coordinates are km from origin at source A):

A – located at (0,0) on the grid – 0.1 Mtpa

B – located at (10,0) on the grid – 0.1 Mtpa

C – located at (10,5) on the grid – 0.1 Mtpa

We can locate the shared compression station (indicated as a star) at an arbitrary (x,y) position between the three $CO_2$ sources, where x is km east of source A, and y is km south of source A. This is represented in Figure 19.

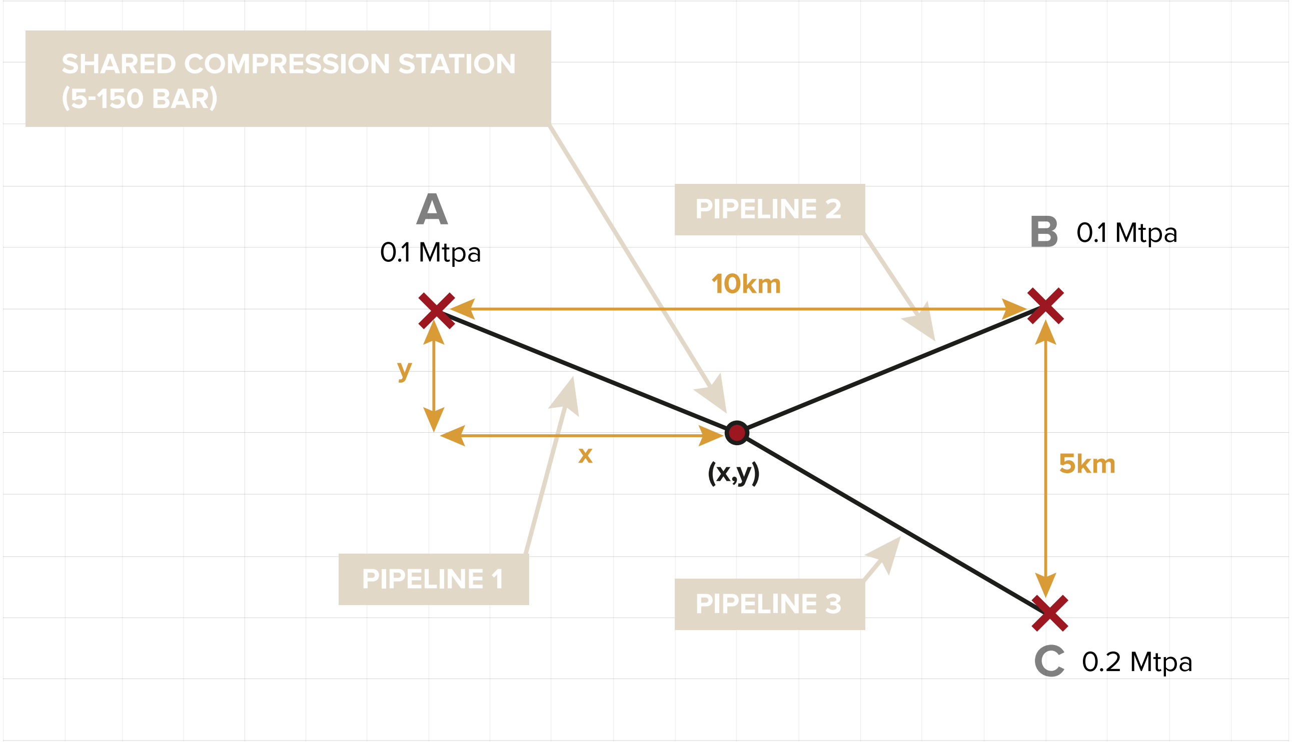
Assuming all pipelines can be straight lines from their source to the shared compression station, the costs of each of the three gas-phase lines are as follows:

Cost of pipeline 1 from A to shared station = 23,000 USD/km x $\sqrt{(x^2 + y^2)}$

Cost of pipeline 2 from B to shared station = 23,000 USD/km x $\sqrt{((10-x)^2 + y^2)}$

Cost of pipeline 3 from C to shared station = 40,000 USD/km x $\sqrt{((10-x)^2 + (5-y)^2)}$

Figure 19 – Optimising the location of shared compression station for smaller emissions sources in Northern Carbonlandia



We applied a GRG non-linear method using the Solver module in Excel to minimise the total cost of all three gas-phase pipelines, allowing both x and y to vary.

The minimum cost was found to be when the compression station is located at (10,5) – in other words, co-located at emissions point C. Although this means that pipeline 1 (from source A) will backtrack approximately 11 km in the opposite direction from the downstream pipeline, it still is the best choice.

Therefore, locate the shared 0.4 Mtpa 5-150 bar compression station adjacent to source C.

Pipeline from source C to source D:

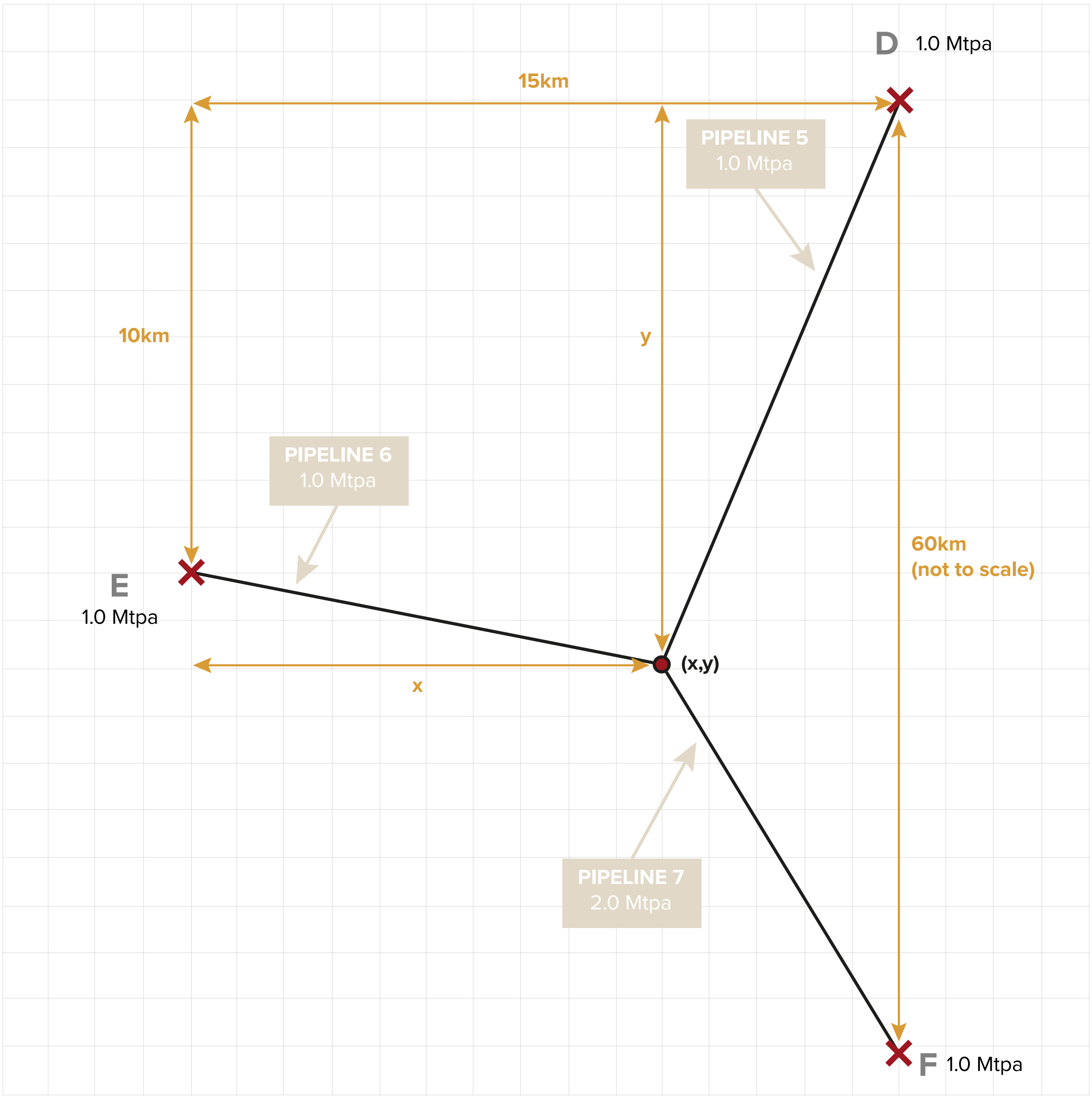
This pipeline (which we call pipeline 4) is a straight run from C to D. The pipeline is sized for 0.4 Mtpa (the sum of sources A, B and C).

Pipelines from sources D and E and a combined flow to F

The arrangements of sources D, E and F are shown in Figure 20. Pipeline 5 from D has a capacity of 1.0 Mtpa (the sum of $CO_2$ from sources A-D). Pipeline 6 from source E is a 1.0 Mtpa line.

The combined flow from D and E flows in a 2.0 Mtpa line to meet the source F, 60 km south of D.

Figure 20 – determining merger point for pipelines 5 and 6.



Source D, being above our 0.5 Mtpa threshold from guideline 2, has its own dedicated 1-150 bar (dense phase) compression station. Likewise, source E (1.0 Mtpa) has its own dedicated 1-150 bar compression system as per guideline 2.

As before, the intersection point of pipelines 5, 6 and 7 is an arbitrary x,y point on the map.

From Figure 2, dense phase pipeline costs are:

1.0 Mtpa: USD 0.057 / tonne / km

2.0 Mtpa: USD 0.052 / tonne / km

Multiplying out by tonnage, these costs become:

1.0 Mtpa pipeline: 0.057 x 1.0 x $10^6$ = USD 57,171 / km

2.0 Mtpa pipeline: 0.052 x 2.0 x $10^6$ = USD 104,388 / km

The costs of each of pipelines 5-7 is as follows:

Cost of pipeline 5 from A to shared station = 57,171 USD/km x $\sqrt{((15-x)^2 + y^2)}$

Cost of pipeline 6 from B to shared station = 57,171 USD/km x $\sqrt{(x^2 + (y-10)^2)}$

Cost of pipeline 7 from C to shared station = 104,388 USD/km x $\sqrt{((15-x)^2 + (60-y)^2)}$

Applying GRG nonlinear optimisation again, the lowest cost for the three pipelines is obtained when the intersection is located at (9,23) – a position 9 km east of source E and 23 km south of source D.

**Source F**

Although source F is a small 0.3 Mtpa source, there are no other small sources nearby with which to aggregate the flow. Therefore, it will require its own 1-150 bar compression system.

**From source F to the target storage site**

The final pipeline 8 from F to the storage site needs a capacity of 2.3 Mtpa (enough for all sources in this network). The pipeline runs 57 km the south and 5 km to the west, for a total length of 57.2 km.

**Summary**

The network consists of the following:

| | |
|---|---|
| 0.1 Mtpa gas-phase pipelines: | 16.2 km |
| 0.4 Mtpa dense-phase pipelines: | 41.8 km |
| 1.0 Mtpa dense-phase pipeline: | 33.0 km |
| 2.0 Mtpa dense-phase pipeline: | 37.1 km |
| 2.3 Mtpa dense-phase pipeline: | 57.2 km |

2 x 0.1 Mtpa 1-9 bar compression stations.

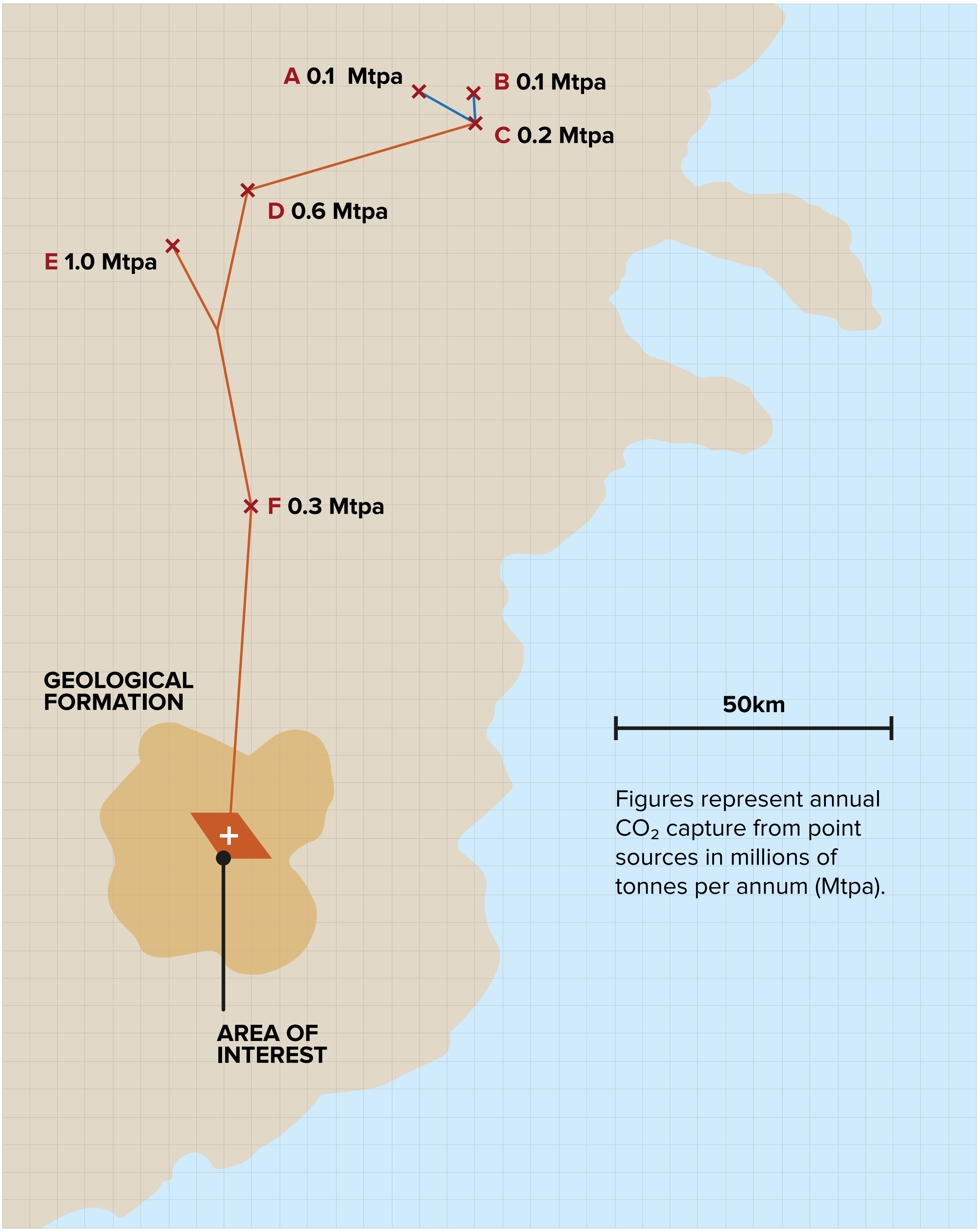
1 x 0.3 Mtpa 1-150 bar compression station.

1 x 0.4 Mtpa 1-150 bar compression station.

1 x 0.6 Mtpa 1-150 bar compression station.

1 x 1.0 Mtpa 1-150 bar compression station.

**Figure 21 – Carbonlandia network pipeline layout**



The approach proposed here for network design is simplified. Nevertheless, it does demonstrate that with a modest amount of effort to characterise cost trends in the country of interest, and some basic optimisation of pipeline costs, it is possible to design a $CO_2$ compression and transport network while making a reasonable effort to keep costs contained.

# 4.0 FINDINGS AND RECOMMENDATIONS

**Finding 1: CCS networks are possible for the majority of global emissions clusters.**

Emission sources are prevalent on each continent and in many countries. To achieve net-zero scenarios, these emission clusters will become critical centres for CCS deployment. $CO_2$ point sources inherently form clusters because industries – such as power generation, refining, chemical processing – often develop together around ports, urban centres, and shared infrastructure corridors.

Fortunately, highly suitable or suitable basins for storage are present in nearly all emissions-intensive regions of the world. Conventional reservoirs which are favourable for $CO_2$ storage are common and typically present at multiple stratigraphic levels in basin assessments. Moreover, emerging storage technology in basalt rock, utilising mineral carbonation, may dramatically increase available storage across the globe. Nevertheless, well-characterised assessment of geologic storage resources is severely inadequate for the majority of nations.

The most viable regions for the establishment of CCS networks are those regions adjacent to well-characterised storage basins. Typically, these are mature hydrocarbon provinces. Fortunately, these regions are generally centres of intense industrialisation and host a number of potential networks including: the North Sea (Humber/Rotterdam), Alberta, Gulf of Mexico, Mumbai, Niger Delta, Sumatra, eastern seaboard of China, Persian Gulf, amongst others.

**Recommendation from Finding 1:** Governments (data-keepers) and corporations (project developers) should proactively work together on planning and organising CCS networks for their suitable and highly-suitable storage basins.

**Finding 2: Rigorous characterisation of geological storage resources and site screening are on the critical path to CCS network deployment.**

CCS networks require three fundamental elements: emissions centres, transportation infrastructure, and storage resources. Of these elements, emissions are abundant and $CO_2$ capture and transportation technologies are advanced and well-understood across the globe. In the vast majority of nations, however, the potential for $CO_2$ storage – even at the basin level – is unknown or insufficiently characterised. Where storage characterisation has been completed, and the basin is ranked as highly suitable, large-scale CCS networks may not be viable until significant additional, detailed subsurface analysis is completed. This analysis includes developing an understanding of:

1. the distribution of storage resources within a basin
2. the $CO_2$ fluid behaviour in each basin's unique pressure and temperature conditions (i.e., $CO_2$ injectivity)
3. each storage compartment's volume and risks
4. the formation cap rock (or seal)
5. the in-situ formation fluids (water, oil, gas).

Storage exploration and appraisal is time-intensive and requires integration of well data, seismic and geophysical surveys, core analysis, subsurface mapping, and more.

The paucity of site-specific analysis is significant in two ways:

- A nation's true ability to employ CCS to achieve its emission reduction and net zero targets may be less or greater than expected until rigorous characterisation of its geological storage resources is complete.
- Engineering of CCS networks – including costs estimates, infrastructure requirements, well planning, and injection timelines – cannot proceed until storage resources are understood.

Characterisation of geological storage resources remains limited for rising economies, such as the Indian Sub-continent, Southeast Asia, and Sub-Saharan Africa, as well as for large, fossil fuel-producing regions, such as Russia and the Middle East. Of the nations with advanced geological storage development, only the UK, USA, and Norway have progressed to formation-level evaluation on a national scale.

For these reasons, geological storage characterisation and site screening are on the critical path to deployment of CCS networks.

**Recommendation from Finding 2:** Characterisation of the storage resource at the basin- and formation-scale must be re-energised and prioritised for emissions-intensive countries.

**Finding 3: Basin characterisation methodology, level of detail, and transparency vary greatly across the globe.**

Reliable assessment of storage resources underlies a nation's ability to develop a robust $CO_2$ emissions abatement strategy. Published national storage assessments exist for roughly 80% of the world's nations, but the methodology, quality, transparency, and level of detail of this work varies greatly. For example, the national assessment of Japan does not discuss storage potential or resource estimates for individual basins, but rather only provides a single, national storage assessment value (146 $GtCO_2$) (Takahashi et al., 2009b). Mexico and Brazil are other examples of national storage resource estimates without any attribution to their basins. The US provides storage estimates by state rather than basin, which makes further characterisation and source-sink network analysis challenging.

Basin characterisation using public, published data is often sufficient for a high-level characterisation of storage suitability. However, because of variability in methodology used to perform these high-level assessments, storage resources can rarely be compared at a global scale.

Comprehensive basin characterisation should utilise a "show your work" approach and include separate estimates for saline formations and depleted oil and gas fields. Each of these storage categories require unique treatment because of the processes and storage mechanisms operating in each type of storage formation. We recommend the methodology presented by US DOE National Energy Technology Laboratory (NETL 2017).

**Recommendation from Finding 3:** Complete a comprehensive characterisation programme across a prioritised list of data-rich basins using a consistent methodology.

**Finding 4: Additional work is necessary to characterize $CO_2$ transport infrastructure requirements.**

In this study, broad assumptions are made when matching $CO_2$ emissions sources to storage sinks. This approach is fit for the purposes of this report – guiding decision-makers to recognize regional CCS network potential – however, more work can be done to identify the most viable networks of those we have identified. For example, shipping has been overlooked as a transportation option, but is increasingly being viewed as a viable option for longer distances.

The next phase of analysis on CCS networks should include simulated optimised $CO_2$ transport infrastructure. The initial focus of this work should be linking cost-effective, high-impact sources to storage locations. Whilst transportation distance and pipeline capacity are fundamental aspects of planning $CO_2$ transport, transport options and costs are also impacted by:

- existing infrastructure
- scale of individual $CO_2$ sources within the network
- terrain
- populated areas
- access restrictions
- existing natural resources

**Recommendation from Finding 4:** Examine transport routes across a prioritised list of CCS networks, focusing on impacts of local conditions.

**Finding 5: Network design should be holistic and include an assessment of gas-phase and dense-phase transport, as appropriate for the scale of individual $CO_2$ sources.**

Network design is not simply a case of layout of pipelines on a map. The selection of compression options also has a material impact on overall transport system cost. Gas-phase transport should always be considered for smaller-scale $CO_2$ sources, allowing aggregation to a more economic scale for compression to dense phase and for bulk pipeline transport.

# 5.0 REFERENCES

1. ACTL (2021) The ACTL System. Available at: https://actl.ca/actl-project/about-actl/.
2. ADB (2013) Prospects for carbon capture and storage in Southeast Asia.
3. Aktouf, A. and Bentellis, A. (2016) “$CO_2$-storage assessment and effective capacity in Algeria,” SpringerPlus, 5(1), pp. 1–24. doi: 10.1186/s40064-016-2682-7.
4. Asian Development Bank (2013) Prospects for Carbon Capture and Storage in Southeast Asia.
5. Bachu, S. (2003) “Screening and ranking of sedimentary basins for sequestration of $CO_2$in geological media in response to climate change,” Environmental Geology, 44(3), pp. 277–289. doi: 10.1007/s00254-003-0762-9.
6. Beck, B. and Kulichenko-lotz, N. (2017) “ScienceDirect World Bank CCS Program activities in Botswana – Results and lessons learned,” 00, pp. 14–18.
7. Blommaert, J. (2021) Energy Factor - The Promise of Carbon Capture and Storage, and a Texas-Sized Call to Action. Available at: https://energyfactor.exxonmobil.com/insights/partners/houston-ccs-hub/.
8. Bjørkum, PA, Oelkers, EH, Nadeau, PH, Walderhaug, O & Murphy, WM 1998, ‘Porosity Prediction in Quartzose Sandstones as a Function of Time, Temperature, Depth, Stylolite Frequency, and Hydrocarbon Saturation’, AAPG Bulletin, vol. 82, no. 4, pp. 637–647.
9. Bjorlykke, K & Egeberg, PK 1993, ‘Quartz cementation in sedimentary basins’, American Association of Petroleum Geologists Bulletin, vol. 77, no. 9, pp. 1538–1548.
10. CARBFIX (2020) Mineral Storage Atlas, https://www.carbfix.com/atlas.
11. Carbon Storage Taskforce (2010) National Carbon Mapping and Infrastructure Plan – Australia, Australian Government.
12. CGG Robertson (2020) Robertson Basins and Plays geological sub-regime classification.
13. Chevron Australia 2021, ‘Chevron Australia $CO_2$ Injection Milestone’, accessed from <https://australia.chevron.com/news/2021/$CO_2$-injection-milestone>.
14. Choomkong, A. et al. (2017) “A study of $CO_2$ Emission Sources and Sinks in Thailand,” Energy Procedia, 138, pp. 452–457. doi: 10.1016/j.egypro.2017.10.198.
15. Co, P. et al. (2013) “D ET N ORSKE V ERITAS A Preliminary CO 2 Storage Atlas of Saline Aquifers in the Mozambique Basin,” pp. 1–37.
16. Dahowski, R. T. et al. (2009) “Regional Opportunities for Carbon Dioxide Capture and Storage in China,” (December), p. 85.
17. DOE, NRCan and SENER (2012) “The North American Carbon Storage Atlas,” Nacsa, p. 52.
18. East Coast Cluster (2021) The Humber and Teesside join forces to form the East Coast Cluster and decarbonise almost half of UK industrial cluster emissions. Available at: https://eastcoastcluster.co.uk/press-release/the-humber-and-teesside-join-forces-to-form-the-east-coast-cluster-and-decarbonise-almost-half-of-uk-industrial-cluster-emissions/.
19. Edbrooke, S, Arnot, M, Funnell, R, Bland, K & Field, B 2009, ‘New Zealand Carbon Dioxide Storage Site Assessment : Phase 1’, , no. June.
20. Friedmann, S. J., Agrawal, M. and Bhardwaj, A. (2021) Evaluating Net-Zero Industiral Hubs in the United States: A Case Study of Houston.
21. Global CCS Institute (2020a) $CO_2$RE, $CO_2$re.co.
22. Global CCS Institute (2020b) $CO_2$RE Database. Available at: https://$CO_2$re.co/.
23. Global CCS Institute 2016, Understanding Industrial CCS Hubs and Clusters,.
24. Hasbollah, D. Z. A. and Junin, R. (2017) “Assessment of geological $CO_2$ storage potential in central Luconia province,” International Journal of ADVANCED AND APPLIED SCIENCES, 4(2), pp. 44–48. doi: 10.21833/ijaas.2017.02.008.
25. IEAGHG (2008) A regional assessment of the potential for $CO_2$ storage in the Indian subcontinent.
26. IEAGHG (2009) $CO_2$ storage in depleted oilfields: Global application criteria for carbon dioxide enhanced oil recovery, IEA Greenhouse Gas R&D Programme (IEA GHG), Technical Study Report No. 2009/12.
27. Kearns, D, Liu, H & Consoli, C 2021, TECHNOLOGY READINESS AND COSTS OF CCS, accessed from <https://circularcarboneconomy.co/resources/>.
28. Ketzer, J. M. et al. (2015) Brazilian Atlas of $CO_2$ Capture and Geological Storage.
29. Lindquist, S. J. (1999) The Red Sea Basin Province: Sudr-Nubia(!) and Maqna(!) Petroleum Systems, United States Geological Survey.
30. Mccollum, DL & Ogden, JM 2006, ‘Techno-Economic Models for Carbon Dioxide Compression , Transport , and Storage Correlations for Estimating Carbon Dioxide Density and Viscosity’, , no. 530, p. 87, accessed from <http://its.ucdavis.edu/>.
31. Nandurdikar, N. and Bowe, A. (2021) Horizons - Location, location, location: the key to carbon disposal. Available at: https://www.woodmac.com/horizons/location-location-location-the-key-to-carbon-disposal/.
32. NETL 2017, Best Practices: Site Screening, Site Selection, and Site Characterization for Geologic Storage Projects,.
33. Net Zero Teesside (2021) Funding secured to accelerate development of UK’s first decarbonised industrial clusters on the east coast of England. Available at: https://www.netzeroteesside.co.uk/news/funding-secured-to-accelerate-development-of-uks-first-decarbonised-industrial-clusters-on-the-east-coast-of-england/.
34. Northern Lights (2021) About the Longship Project. Available at: https://northernlightsccs.com/about-the-longship-project/.
35. OGCI (2020) No Title. Available at: https://www.ogci.com/ogci-climate-investments-invests-in-elk-hills-carbon-a-project-to-design-and-permit-californias-first-carbon-capture-and-sequestration-system/.
36. Sener, M. (no date) “Overview of Mexico´s storage potential.”
37. Sun, X, Alcalde, J, Bakhtbidar, M, Elío, J, Vilarrasa, V, Canal, J, Ballesteros, J, Heinemann, N, Haszeldine, S, Cavanagh, A, Vega-Maza, D, Rubiera, F, Martínez-Orio, R, Johnson, G, Carbonell, R, Marzan, I, Travé, A & Gomez-Rivas, E 2021, ‘Hubs and clusters approach to unlock the development of carbon capture and storage – Case study in Spain’, Applied Energy, vol. 300, no. July, p. 117418.

38. Takahashi, T. et al. (2009a) “Estimation of $CO_2$ Aquifer Storage Potential in Japan,” Energy Procedia, 1(1), pp. 2631–2638. doi: 10.1016/j.egypro.2009.02.030.
39. Takahashi, T. et al. (2009b) “Estimation of $CO_2$Aquifer Storage Potential in Japan,” Energy Procedia, 1(1), pp. 2631–2638. doi: 10.1016/j.egypro.2009.02.030.
40. Thanh, H. V. et al. (2019) “Integrated workflow in 3D geological model construction for evaluation of CO 2 storage capacity of a fractured basement reservoir in Cuu Long Basin , Vietnam,” International Journal of Greenhouse Gas Control, 90(April), p. 102826. doi: 10.1016/j.ijggc.2019.102826.
41. UNECE (2021) Geologic $CO_2$ storage in Eastern Europe, Caucasus and Central Asia: An initial analysis of potential and policy.
42. US DoE/NETL (2015) Carbon Storage Atlas.
43. Viljoen, J. H. A., Stapelberg, F. D. J. and Cloete, M. (2010) TECHNICAL REPORT ON THE GEOLOGICAL STORAGE OF CARBON DIOXIDE IN SOUTH AFRICA. doi: 10.1350/enlr.2009.11.3.057.
44. Williams, E 2019, ‘Data Insights Achieving Climate Goals by Closing the Loop in a Circular Carbon Economy’, King Abdullah Petroleum Studies and Research Center (“KAPSARC”, pp. 1–13.
45. World Bank (2015) The Indonesia Carbon Capture Storage (CCS) Capacity Building Program.
46. World Petroleum Resources Project (2010) Assessment of Undiscovered Oil and Gas Resources of the Red Sea Basin Province.
47. World Resources Institute 2020, ‘Global Power Plant Database’, Global Power Plant Database.

# GET IN TOUCH

To find out more about the Global CCS Institute including Membership and our Consultancy services, visit globalccsinstitute.com or contact us.

---

**AMERICAS**

Washington DC, United States

americasoffice@globalccsinstitute.com

**EUROPE & MIDDLE EAST**

Brussels, Belgium

europeoffice@globalccsinstitute.com

**AUSTRALIA**

Melbourne, Australia

info@globalccsinstitute.com

**UNITED KINGDOM**

London, United Kingdom

ukoffice@globalccsinstitute.com

**CHINA**

Beijing, China

chinaoffice@globalccsinstitute.com

**JAPAN**

Tokyo, Japan

japanoffice@globalccsinstitute.com

The information in this document is supplied by the Global Carbon Capture and Storage Institute Ltd (Global CCS Institute) and is subject to the provisions outlined in this section. The receipt of this document by the persons or entity named at the front of this document or any other recipient (Recipient) evidences acceptance of these provisions. This document is addressed solely to the Recipient and is for their sole review only and may not be provided or disclosed to any other person without the prior written consent of Global CCS Institute. If these provisions are not agreed and accepted by the Recipient, this document and any copies of it must be immediately returned to Global CCS Institute or otherwise destroyed.

This document has been made available to the Recipient for information purposes only and is not intended to be and does not constitute any form of offering document, advice or recommendation. To the maximum extent permitted by law, Global CCS Institute and its affiliates, associates, related bodies corporate, shareholders, officers, employees, partners, representatives, agents, advisers and consultants (each a Relevant Person) expressly disclaim all liability for any loss or damage (including but not limited to for negligence, default or lack of care) for use or reliance on the information in this document or any information which is made available in connection with any further or related enquiries, including any commercial or investment decisions made on the basis of information provided in this document.

This document has been prepared on the basis of publicly available information or other information known to Global CCS Institute at the time this document was compiled and the accuracy of such information has not been independently verified by the Global CCS Institute or any Relevant Person. Global CCS Institute does not guarantee that the information in this publication is totally reliable, accurate or complete and therefore the information in this document must not be relied upon when making commercial, investment or other decisions. Neither the Global CCS Institute nor any Relevant Persons make any representation or warranty (express or implied) as to the accuracy, sufficiency or completeness of the contents of this document and accept no liability for use or reliance of any information in this document.

This document is based on information available as at the date of this report, unless specified otherwise. The Recipient acknowledges that circumstances may change and the contents of this document may become outdated as a result. Neither Global CCS Institute nor any Relevant Persons will be under any obligation to provide the Recipient with access to any additional information, to update this document or to correct any inaccuracies that may become apparent in this document after the date of its issue.