

CARBON CAPTURE AND STORAGE IN DEEP OCEAN SPACE FOR THE 21ST CENTURY

GUIDELINES FOR IMPLEMENTATION IN CHINA

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FOREWORD

The Lloyd's Register Educational Trust (The LRET) in collaboration with the University of Southampton instituted a research collegium in Advanced Ship and Maritime Systems Design in Southampton between 11 July and 2 September 2011.

The LRET is an independent charity that was established in 2004. Its principal purpose is to support advances in transportation, science, engineering and technology education, training and research worldwide for the benefit of all. It also funds work that enhances the safety of life and property at sea, on land and in the air. The LRET focuses on four categories:

- **pre-university education:** through appropriate organisations (but not individual schools), promotes careers in science, engineering and technology to young people, their parents and teachers
- **university education:** provides funding for undergraduate and post-graduate scholarships and awards at selected universities and colleges (does not fund students directly)
- **vocational training and professional development:** supports professional institutions, educational and training establishments working with people of all ages.
- **research:** funds existing or new centres of excellence at institutes and universities.

This year's collegium has focused on The LRET's research-led education agenda. Successful ship and maritime systems design depends on the collaborative application of a broad range of engineering competences as the drive for improved efficiency and environmental performance places greater demand on the design community. This aspect needs to be reflected in the education of naval architects, marine engineers and others who are the active contributors to the ship design processes.

The aim of the research collegium has been to provide an environment where young people in their formative post-graduate years can learn and work in a small, mixed discipline group drawn from the maritime community to develop their skills whilst completing a project in advanced maritime systems design. The project brief that initiates each project will set challenging user requirements which will encourage each team to develop an imaginative solution, using their individual knowledge and experience, together with learning derived from teaching which will form a common element of the early part of the programme.

The collegium format provided adequate time for the young people to enhance their knowledge through a structured programme of taught modules which will focus on the design process, advanced technologies, emerging technologies and novel marine solutions, regulatory and commercial issues, design challenges (such as environmental performance and climate change mitigation and adaptation) and engineering systems integration. Lecturers have been drawn from academic research and industry communities to provide a mind-broadening opportunity for the young people, whatever their original specialisation.

The subject of the 2011 collegium has been systems underpinning carbon capture and sequestration (CCS) in ocean space. The 19 scholars attending the 2011 collegium were teamed into four groups. The project brief included: (a) quantification of the environmental challenge; (b) understanding of the geo-political legal-social context; (c) possible techniques for sequestration; (d) one engineering system to achieve carbon storage in ocean space; (e) economics and logistics challenges. While all the groups addressed the items (a) to (c), each team focused on just one engineering system in dealing with items (d) and (e). This volume presents the findings of one of the four groups.

Mr. Michael Franklin (The LRET) and Professors Ajit Shenoi and Philip Wilson (University of Southampton)
Southampton
22 August 2011

PREFACE

Since the original findings of the Swedish Nobel laureate Arrhenius in 1896 linking the temperature of the Earth to the gaseous composition of our atmosphere we have come a long way. However, one of the most startling observations is the increasing mean carbon dioxide concentration at Mauna Loa, Hawaii. Recordings from 1960 to the present show a total increase of almost 80 ppm CO₂ to the present value of 392 in July 2011. Even without the implications on climate change, the simple fact that anthropogenic contributions of CO₂ are obligation enough to seek solutions to solve the issue at hand. However the sequestration of CO₂ is a multi-dimensional problem with no simple solution to be offered. It is likely dependent on the individual nation, the most accessible storage site both logistically and economically will be a driving factor in the decision making process. It is with this that attention is placed on the preliminary suggestion by Marchetti in 1977, who thought of sequestering CO₂ in the path of ocean currents where natural processes would disperse it further, thus mitigating the problem. Ever since then, the concept of ocean storage of CO₂ has received mixed views. Although many are currently championing the concept of geological storage, the authors believe that ocean storage, though risky, should be considered nonetheless as a viable alternative. Case in point is China with its extended coastline and relatively close access to open sea as well as deep basins makes it a prime choice. China's continued dependence on fossil fuels for power generation and startling economic growth are additional incentive for the authors to put forward views on CCS in its current state of development.

This report serves to outline some high level views in the form of possible future guidelines for a complete solution of the CCS value chain. The report is organised into eight chapters that meticulously address different elements of a CCS system. Chapter One introduces the implications of climate change as well as the project design. System characterisation is addressed in Chapter Two and Three where an effort to give a broad overview of the project, inclusive of public concerns, is made. The authors propose a complete solution that encompasses the capture of carbon dioxide (CO₂) effluents. Chapter Four focuses on the arrangements for transporting carbon dioxide via pipelines and liquid bulk shipment of CO₂ to offshore platforms. Potential risks were identified and mitigation measures were proposed in Chapter Five. Sequestration in ocean space, proposed dilution rate as well as perceived effects associated with ocean acidification form the main argument in Chapter Six with specific application to China. The proposed solution allows for a measure of flexibility to the readers and the authors deem such an approach being necessary as CCS implementation is still in its infancy. With the capture of CO₂ from coal-fired power plants by means of traditional and emerging technologies, both retrofitting of existing plants or the continued use of coal in more efficient greener plants can be considered.

The choice of ocean space for sequestration purposes was primarily based on the desire to stimulate further study as there are little known effects of CO₂ at great ocean depths. By addressing this topic the authors also accede to the fact that there are challenges and risks (Chapter Seven and Eight) to this storage solution that deserved further examination. As a result, public engagement strategies that are essential in getting the public interested about CCS should be actively supported. Lastly, CCS solutions in the long run should endeavor to achieve a zero carbon footprint while accommodating the steady strong development of the Chinese economy.

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1 INTRODUCTION

Climate change, in particular the increasing problem of global warming, has led to many scientists forecasting potential detrimental impacts on the biodiversity on Earth and on human lives (IPCC, 2005, Miles et al., 2004). The consequences are deemed to be unacceptable by leading international organisations and therefore, breeding discussions and debates on the various mitigating mechanisms and strategies by experts as well as country representatives. In the Kyoto Protocol, many nations have pledged to limit their level of greenhouse gases emissions in an attempt to stabilise CO₂ concentrations in the atmosphere to 350ppm (UN, 1998). Among the suggestions and proposals raised, CCS has been identified as a transitional mechanism which countries dependent on fossil fuels for power generation and highly unlikely to be able to switch to cleaner renewable energy within a short period of time can adopt. CCS is a system which has been in operations for two decades (but not predominantly for the purpose of removing carbon from the atmosphere) and is regarded as one of the abatement mechanisms which can be adopted to reduce the amount of greenhouse gases emissions into the atmosphere from large point sources (IPCC, 2005, Stern, 2007).

CCS involves the capturing of CO₂ from large point sources such as power plants, heavy industries like cement and steel, transporting the captured CO₂ to a storage site, which is often located away from the capturing site, and finally being injected into the storage site. Close monitoring has to be continued for a long period of time (in excess of a thousand years) to ensure the integrity of the site and the stored CO₂ has minimal leakage recorded. Storage of CO₂ can occur either onshore or offshore. Onshore storage includes injecting the CO₂ into geological formations such as saline aquifers where the perimeter rocks are strong enough to trap the CO₂ within. Offshore storage involves subsea geological formations as well and in addition, there is an option for direct injection. Direct injection represents a procedure whereby the captured CO₂ is converted into its supercritical state and injected into the ocean directly, at depths beyond 3,000 metres, such that the pressure and temperature at that point would prevent the CO₂ from floating towards the surface or turning back into gas. There are currently limited studies on direct injection of CO₂ as compared to known techniques of onshore geological storage due to the lack of information with regards to the short term and long term environmental impacts of such activities.

Implementation of CCS is a tremendous task as it requires more investment into further research as there are plenty of unresolved issues such as regulatory, financial, social, engineering and environmental uncertainties. These issues act as obstacles which hinder the full scale global deployment of the system. While there is existing technology and lessons for CCS to emulate and refine, further studies with regards to unfamiliar grounds has to be undertaken. Thus the creation of a regulatory framework which is able to impose liabilities spanning more than one thousand years and also the long term impacts on the environment and ecosystems of the deep ocean if CO₂ is injected directly must be addressed. While onshore and offshore subsea geological storage of CO₂ are better understood and surveyed compared to the conditions and characteristics of Deep Ocean, this report focuses on exploring the prospects and viability of direct injection as a method of storage for CO₂.

CCS, as an emerging technology, has attracted serious attention from China who is the largest emitter of CO₂ since 2007. China has displayed a strong desire to explore cleaner alternatives to coal as an energy source through the promotion of their environmental protection agency into a full-fledged ministry as well as making promises to reduce emissions at international environmental conferences and engaging global partners in collaborative CCS projects. These projects provide China with initial funding for CCS trial projects, transfer of technology and knowledge for regulatory and engineering issues. The main considerations for China in identifying CCS as one of the top priorities for science and technology research in 2006 was due to China's reliance on coal for energy production.

Coal is a relatively cheap source of energy for China due to the significant availability of coal reserves within China and the technology for harnessing energy from coal is well-understood and cost effective. However, due to coal's chemical composition, it is also the most pollutant energy source among the fossil fuels. China will continue to use coal as the demand for energy increases

due to unprecedented economic development and increasing standards of living experienced in the past three decades. Current levels of renewable energy are unable to replace electricity production in China in its entirety without adverse impacts on her economy. Therefore, in order to balance her energy demands and environmental protection objectives, CCS offers China a resolution to the mammoth task of achieving both targets.

China has limited expertise on matters concerning CCS presently thus there are several essential areas which she has ample potential to improve and build up on. They include regulatory framework, international relations, social engagement, economic concerns, technical issues of storage, transportation, capture, and monitoring and risks management. Safety aspects, cost effectiveness and risks mitigation procedures would be discussed in this report as well. While a stringent regulatory framework can adequately safeguard the public's welfare, it discourages private participation in CCS due to increased liabilities and costs of implementing additional safety features, thus resulting in retarded growth of innovations in CCS technologies. However, if societal concerns are ignored in preference of a speedy CCS implementation, the lack of support from the public will result in the system's ultimate failure as well. Thus, each of these aspects is fundamental to the creation of a resilient, compassing and balanced strategy which would ensure the successful deployment of CCS in China as a key carbon abatement mechanism for the rest of the century.

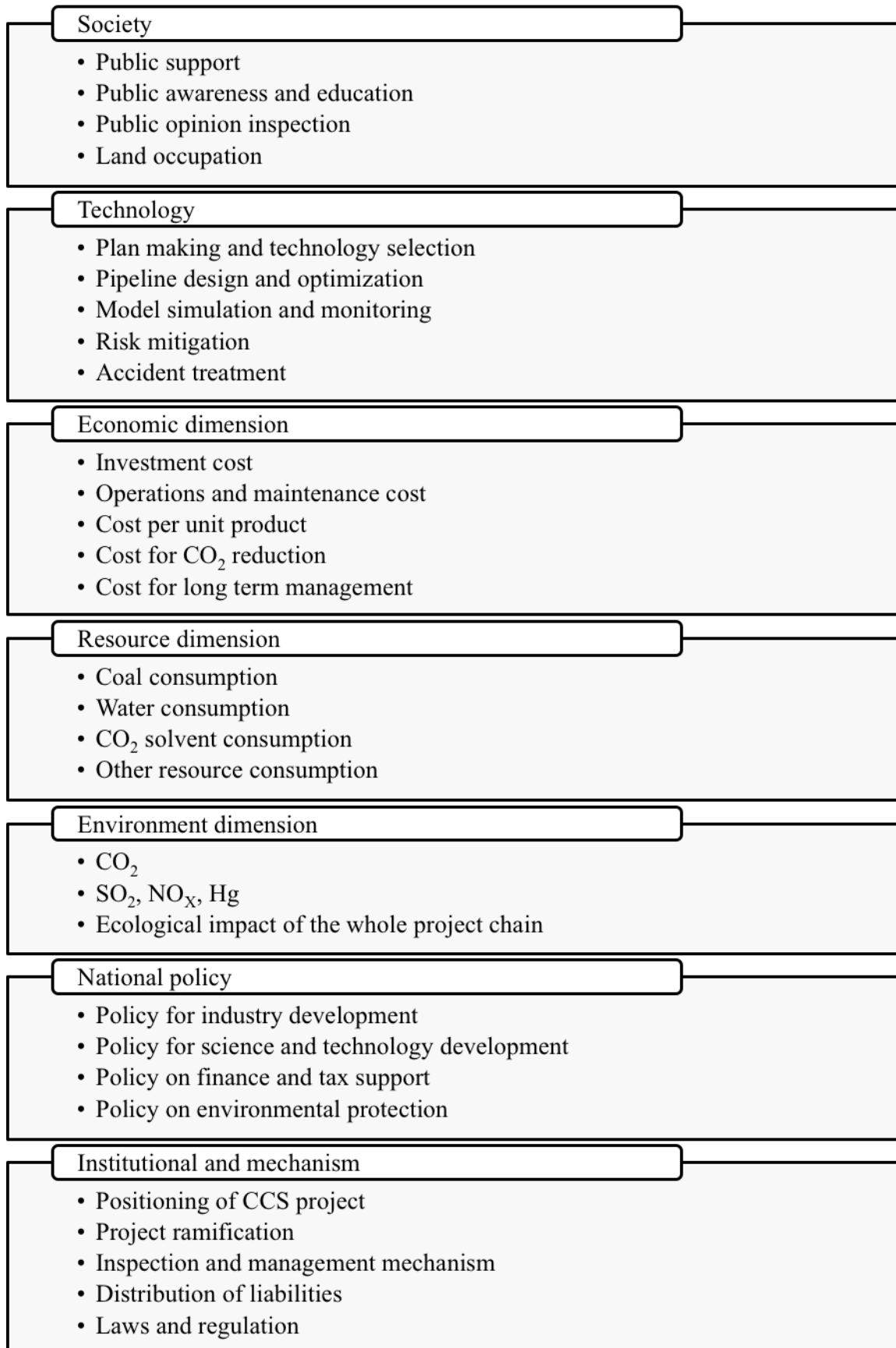


FIGURE 1-1: ISSUES RELATING TO THE IMPLEMENTATION OF CCS

2 SYSTEM CHARACTERIZATION

Towards the end of the last century, economic reforms led by Deng Xiaoping propelled China to international recognition and prominence as one of the global economic powers alongside the traditional G8 nations. From 1978 to 2010, China's economy has been developing at a rate of 9.5% per annum. The economic growth was supported by rapid primary and secondary industrialization, which in turn triggered urbanization and elevation in living standards.

Primary industries, comprising of activities such as food production and mining, provide raw materials for the secondary industries which manufactures end-products for local consumers or overseas demand. This export-driven economy is the main reason behind China's rapid growth in trade volumes with global trading partners. China's trade surplus has grown to USD 183.1 billion for the year of 2010 and the main trading partners includes: the European Union (EU); the United States of America (US) and the Association of Southeast Asian Nations (ASEAN) (Wang and Yao, 2010).

As employment opportunities increase within and around major cities and special economic zones, there is strong inclination for Chinese citizens to move from rural areas towards the more urban areas. In addition, people were able to gain access to electricity, improved transport and housing, healthcare, education and recreation facilities. Due to this, China is experiencing an overall increase in standards of living. Inevitably, in order to support the population, industries, infrastructure and services, China's power sector had to grow at a similarly rapid rate. Electricity output between 2005 and 2009 alone grew by 1,213TWh, an increase of 48.5% (Jaccard and Tu, 2011).

The increasing demand for electricity in China has been predominantly met by fossil fuel power plants. In particular, China's reliance on coal is palpable: 66.5% of the total energy produced in 2008 comes from coal and peat (IEA, 2010a). According to the National Bureau of Statistics (NBS), coal-fired generated electricity had been increasing at 12% annum since 2000 and coal-produced electricity presently stands at 77.3% in 2010 (National Bureau of Statistics, 2010, Jaccard and Tu, 2011). Coal is a valuable resource for China because:

- It has plentiful of coal in proven reserves (13.3% of world reserve);
- The technology required to harness energy from coal is well-developed in China;
- Coal provides additional reliability and security compared to renewables;
- Coal is cheaper than other fossil fuels while offering a moderate level of energy content; and
- Coal dominates 93% of China's proven fossil fuel reserves (BP, 2011).

Hence, with more than half of China's current power grid being focused on coal and an increasing number of coal-fired power plants being in the pipeline, it would take more than 3 decades to replace coal with renewables and cleaner energy sources in China, based on the planned operational period of thirty to forty years for all of the existing power plants. Unfortunately, this worsens the problem of environmental protection and global warming as coal is considered as the most polluting form of fossil fuel. It has the smallest carbon-hydrogen ratio (1:1) and emits the highest amount of carbon dioxide (CO₂) per unit combusted. Therefore, the rapid industrialization and economic growth has also resulted in China leapfrogging the US as the top carbon emitting country in the world in 2007 and the emissions amount is projected to be accelerating (IEA, 2010b).

With the newfound 'fame', China now faces the consequences of this sudden rise to prominence. The international community, as a whole, has begun to focus on reducing the amount of CO₂ present in the atmosphere in view of the potential perils brought about by global warming. CO₂ is documented as one of the greenhouse gases (GHG) which contributes to global warming, alongside other gases such as methane, water vapour, ozone and nitrous oxide (Environmental Protection Agency, 2011). Therefore, the focus is on reducing the amount of anthropogenic CO₂, which is the additional amount generated as a consequence of human activities on top of natural occurring CO₂, in the atmosphere. China, being the top carbon emitting country in the world, inevitably comes under

pressure from the international community, non-governmental organisations (NGO) and environmental protection groups to reduce its carbon footprint.

While protesting the partiality of penalising China on the basis of total emissions instead of per capita emissions as well as the consideration that it has yet to reach the level of economic and social development of a developed nation, China has acknowledged the fact that it will play an integral role in the global efforts to impede the accelerating rate of CO₂ emissions in the midst of rising expectations from other countries. Thus, China's increasing economic dominance has placed itself in an ideal position to take up additional socio-political responsibilities and leadership in the community so as to protect her strategic interests. In order to do that, one of the key objectives of the Chinese government will be to develop a comprehensive strategy and roadmap to solve the GHG emissions issue.

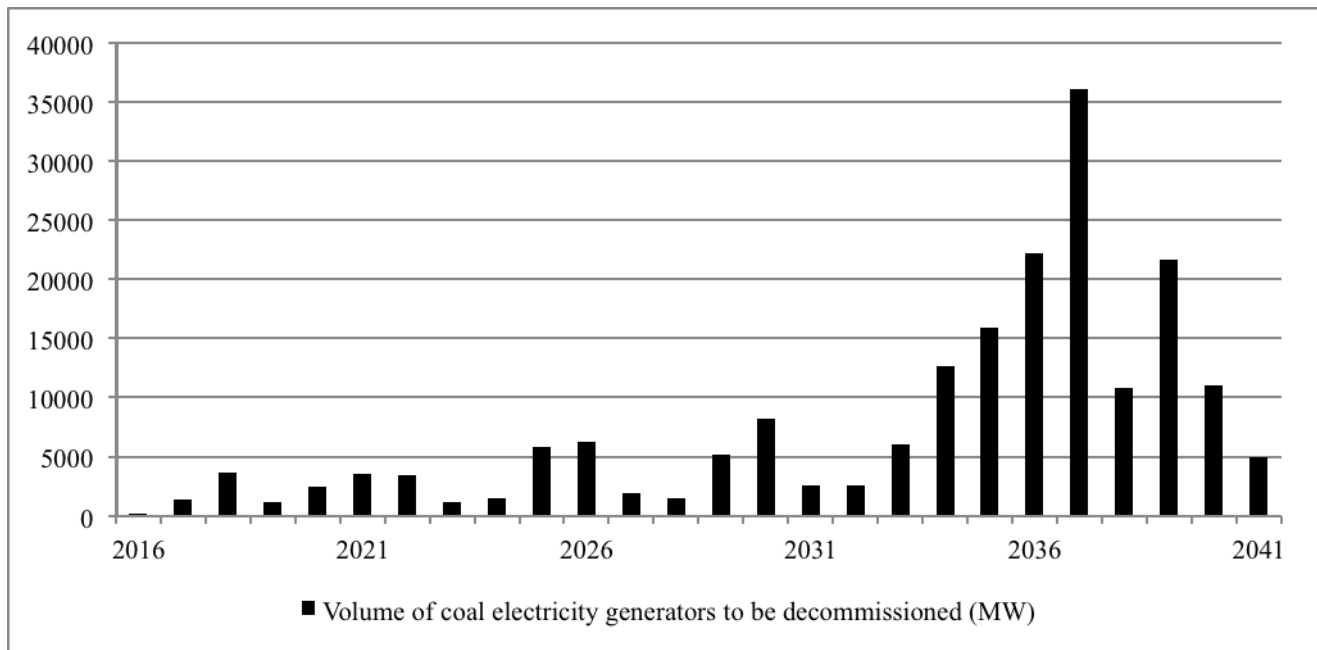


FIGURE 2-1: VOLUME OF CURRENT COAL POWERED GENERATORS APPROACHING 30 YEARS OF OPERATIONS. SOURCE: ANALYSIS BY AUTHORS. DATA: PLATTS UDI WORLD ELECTRIC POWER PLANTS DATA BASE.

For China to reduce CO₂ emissions significantly within the next couple of decades while not penalising economic and social growth, it will either have to ramp up renewable energy production to replace fossil fuels entirely or equip current and future fossil fuel power plants with carbon capture and sequestration (CCS) technologies (Jaccard and Tu, 2011, Chen, 2011). Figure 2-1 shows that majority of the coal-driven electricity generators are not due for decommissioning until after 2030. Hence it would be uneconomical and implausible that the power plant operators would immediately cease operations. On the other hand, the technology for renewable energy is not presently feasible at the required scale to provide sufficient power demanded by China's population and economy. If the proportion of renewable energy sources is excessively inflated at this current juncture, the costs involved for the government and end-users would be prohibitive for economic and social development as many of the cost-effective sites have already been utilized in previous development projects. Therefore, CCS provides a good compromising platform for China to exploit existing coal and other fossil fuel reserves to support its growth and development while minimizing damage to the environment and meeting international pressure to reduce its global warming footprint. More importantly, CCS would be able to buy China valuable transition time before she develops clean and renewable energy to a point when absolute replacement of fossil fuels is possible.

The journey towards equipping all of China's fossil fuel driven power plants with CCS capabilities is littered with obstacles. Important issues to be resolved include:

- Political will and leadership;

- Development of regulatory frameworks for the allocation of responsibilities and accountabilities;
- Economic feasibility and financial instruments;
- Social acceptance; and
- Technical challenges (Fan et al., 2011, Zhu and Fan).

In 2006, the State Council of China has identified CCS as a state-of-the-art technology and prescribed for the research of clean, efficient and low-emissions technology for fossil fuel power as part of the country's overall science and technology drive in the next fifteen years. One of the targets determined for GHG control is to ease China's contribution of GHG emissions by 20% by 2020 (20-20-20) (Odeh and Haydock, 2009). In addition, the State Council issued the first governmental policy, China's National Climate Change Programme (CNCCP), dedicated to combat climate change in the following year. This document mainly highlights key focus areas for China to fulfil its international and environmental obligations in accordance with the United Nations Framework Convention on Climate Change (UNFCCC). CNCCP endeavour to limit the emission of GHG, boost China's proficiencies in acclimatizing to the changes in climate, elevating the level of research and development as well as the quality of various institutions and instruments and not the least, to educate the public on climate change (People's Republic of China, 2007). This top-down development guide plan has generated much hype in the country as several number of pilot and research projects were launched in the next two to three years, many led by the Ministry of Science and Technology of China (MOST). MOST initiated the China's Scientific and Technological Actions on Climate Change in 2007 as a collaborative effort between itself and other ministries and governmental agencies to achieve long term goals identified in the above two policies through highlighting important elements and embarking on pilot projects (Odeh and Haydock, 2009). One of the key objectives is earmarking for the growth in level of expertise for limiting GHG emissions through focusing on the various aspects of CCS: capture; exploitation and storage (NZEC, 2009).

The various approaches and initiatives by the Chinese government to reduce the reliance on coal has led scholars and experts projecting coal-based power plants to decrease from the current contribution levels to 50% of the overall power generation in China by 2030 (Best and Beck, 2011). In addition to governmental efforts, active participation in CCS from private sectors, scientists and institutions to resolve the technical complications involved with economic considerations is as vital. CCS is an additional feature (and cost) to electricity production which the general public has no prior encounter with. Previous experience with the initial introduction of cleaner yet slightly dearer renewable energies (wind, solar and hydro predominantly) had shown that time and patience for educating the public was essential to their eventual acceptance and implementation of the favourable technology.

As with most industries, innovative solutions and engineering state-of-the-art technologies will become the basis for competition and survival of CCS operating companies. There are available patent and proprietary laws in China to protect intellectual property rights of companies and institutions engaging in CCS research and development. Hence, for CCS technology to establish itself for extensive implementation, Chinese regulatory organisations would have to direct their attention towards framing a visionary and encompassing set of guidelines, especially for the storage of carbon dioxide.

There have been numerous cases around the world of sudden and concentrated release of carbon dioxide from natural sources, resulting in losses of human and animal lives. Hence, storage of carbon dioxide, especially in the oceans, is expected to incur initial disapproval and misgivings from the general public that are aware of the potential negative impacts when carbon dioxide are released at significant concentrations. To ensure that artificial storage of carbon dioxide can be contained and its integrity maintained to a satisfactory level acceptable by the public, regulatory bodies would have to construct CCS protocols alongside technical developments to ensure sufficient understanding of the CCS technology and customised crafting of the protocols. Appropriate supervision by the relevant authorities will also provide for the safeguarding of societal interests in the long run as well as the protection of natural resources for future generations' exploitation.

Organic growth in CCS competency may not offer the best scenario for China's deployment of the system as there is an element of catch up that must be played with the rest of the world. The USA has 68.4% share of the patents for various aspects of CCS while China contributed 0.4% in 2006 (Lee et al., 2009). Therefore, China has to look overseas for already available and proven technology while directing internal efforts to fill the gaps as an efficient and integrated strategy for CCS implementation. There are several means through which China is able to secure technologies for deployment: outsourcing the performance of CCS to foreign companies; purchase rights/license for specific patents; joint ventures between local and foreign companies and through aids and transfer of technology from the developed nations (Best and Beck, 2011, Liu and Liang, 2011).

China, in particular, belongs to the group of emerging economies which are rapidly increasing their GHG emissions as they strive for economic growth. As many of the developed nations are concerned about the worrying trend of global warming, pressure is placed upon the developing nations to limit their emissions. However, developing nations contend that the developed nations are responsible for 30% of the carbon already in the atmosphere and that they should be exempted from any GHG emission controls until they achieve the same level of economic maturity as the developed nations (Jaccard and Tu, 2011). To allow for both economic expansion and GHG emissions restrictions to materialise in developing countries, there are calls for developed nations transfer clean and efficient energy expertise in addition to providing financial assistance to support the developing countries in reducing their carbon footprint.

Multiple collaborative efforts between China and developed nations have materialised in terms of funding for research, student exchange, information sharing and pilot studies. Joint projects include:

- The UK-China Near Zero Emissions Coal (NSEC) initiatives;
- Cooperation Action within CCS China-EU (COACH) initiatives;
- The China-Australia CAGS Project;
- The US-China Clean Energy Research Centre (CERC);
- Nordic-China research collaboration;
- Carbon Sequestration Leadership Forum (CSLF);
- The China-Canada Enhanced Coal CBM project, and
- The global CCS institute (NSEC, 2007, Gao et al., 2011, COACH, 2007, CSLF, 2008, CAGS, 2009, CERC, 2011, Global CCS Institute, 2011).

These global projects will assist China in accelerating the process towards full CCS implementation. Furthermore, handling the issue of global warming requires international cooperation, synergy and frequent dialogue between the developed nations and developing nations. This will encourage CCS's integral role in mitigating GHG emissions within the near future. One of the underlying reasons for global interests in China can be simply explained by the fact that if all of China's polluting industries are equipped with CCS technologies, the following percentage of the world's production of essential raw materials would experience a much lighter carbon footprint: 49% of flat glass; 48% of cement; 35% of steel and 28% of aluminium (Rosen and Houser, 2007).

2.1 Social Consideration

CCS is an emerging technology for carbon abatement and as with most new technologies, they face an uphill task in garnering support for implementation from key stakeholders such as policy makers, and the general public (Oltra et al., 2010). Acceptance by the society as a whole is an important factor in inspiring an eventual successful exploitation and dispersion of new technologies (Reiner et al., 2006). Hence, one of the essential agenda for CCS advocates is to convince the general public to accept, support and eventually, participate in CCS. Factors under considerations by the public include other alternative technologies and perceived risks. This section will analyse the need to engage the general public in decisions regarding science and technology with particular application to China and her efforts in adopting CCS.

There are studies done in China to develop a deeper understanding to ascertain barriers and incentives with regards to a full scale CCS deployment as well as to garner feedback on the perceptions and opinions of the general public in China (Dapeng and Weiwei, 2009, Liang et al., 2011, Wilson et al., 2011). In order to appreciate the results of the surveys conducted, one should be mindful of the facts that each individual's appraisal of technological issues reflects their cultural background: values; social interactions and experiences. Hence, policy makers have to be mindful of these factors when dealing with the public who come from different locations and of different cultural background.

Much effort has been spent to engage the public. There are consequences as a result of global warming and CCS is a tool for reducing the rate of global warming. Therefore, there is a moral obligation to the public to seek their recognition and feedback on important topics which may be overlooked by the policy makers (Braun and Schultz, 2010). However many CCS advocates worldwide face a similar obstacle when engaging the public: With the technology being relatively immature and insufficient information are faced by even experts themselves, there are many questions which the public would raise that cannot be answered with certainty. For example, there are conflicting interests among experts on determining the best storage sites for CO₂ and all of them involve incurring some risks which cannot be accurately quantified. Therefore, it remains a challenge to convince the public in supporting CCS as a carbon abatement strategy under current limitations.

Traditionally, acceptable knowledge in science and technology has involved processing the actual knowledge into processes which the public can digest better (Collins and Pinch, 1998). Therefore, to initiate meaningful discussions and debates on CCS issues, basic understanding of the general concepts of CCS as well as its benefits and other conflicting interests can be related to the public to create a foundation for arguments and propositions. Characteristics of CCS which are generating concerns in China includes the deficiency in financial support, high costs of adopting CCS and the lack of a solid regulatory framework (Duan, 2010). Proposition by the studies conducted in China encouraged the use of public education via various platforms as well as the establishment of proper regulatory guidelines and policies in addition to imposing carbon tax and trading systems to encourage private investments in CCS (Duan, 2010, Dapeng and Weiwei, 2009).

For a successful public engagement strategy in China for CCS, there are eight elements which warrant attention and investments in. From Figure 2-2, the eight elements are:

- Role of CCS experts;
- Focus groups;
- Risk communications;
- Credibility;
- Platforms for public debate;
- Assurances;
- Trade-offs; and
- The media.

Together, they generate synergy in convincing the public through various means, including education and transfer of information.

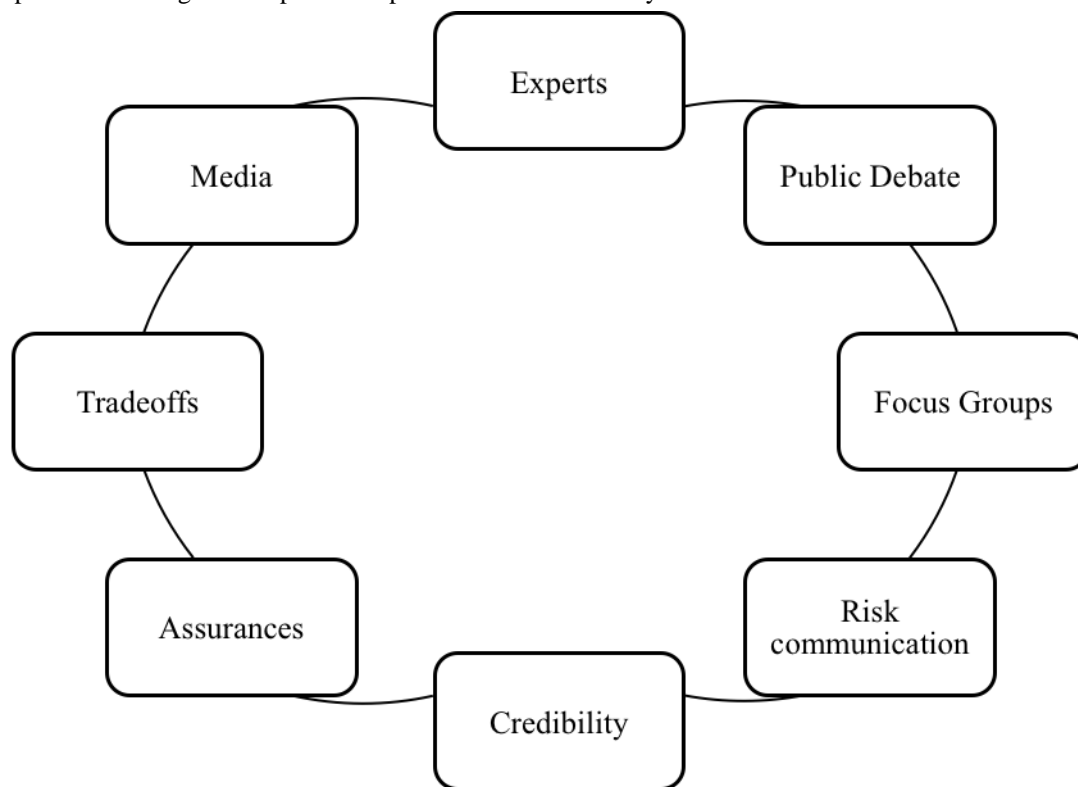


FIGURE 2-2: IMPORTANT ASPECTS OF A PUBLIC ENGAGEMENT STRATEGY

Since CCS is a relatively new technology, broadening and recognizing a wider range of experts taking part in public forum discussions should be encouraged. Interdisciplinary collaboration is particularly important in this context since a more heterogeneous set of experts lead to new forms of evidence being introduced, new standards of proof being accepted and new domains of expertise could be developed. Evans and Plows (2007) recognises that even though expert forums remain the most suitable institutions for resolving complex and contested matters of fact, there remains a need for these activities to be undertaken within the context of a broader public scrutiny. Thus the citizen jury model, with its implicit distinction between ‘expert witnesses’ and ‘citizen jurors’, provides one mechanism through which such deliberation and scrutiny by non-experts can be encouraged (Evans and Plows, 2007). CCS stakeholders therefore should organise and sponsor such forums throughout universities and research institutions in China. During such forums, concerns about CCS should not overshadow the substantive benefits of CCS, which is to provide immediate solution to the GHG emissions and therefore, mitigating climate change.

A two part solution to public engagement strategy could be adopted. Firstly, the technical phase relies on expert knowledge to evaluate the credibility and reliability of CCS knowledge-claims. Secondly, the democratic phase during which decisions will be taken based on majority rule. Thus technical phase should focus more on empirical evidence and rational argument with particular emphasis on success stories of CCS technology. In order to widen the depth of information filtration, the public can be connected with technical experts through traditional and emerging social media. CCS stakeholders have to be mindful that science and technology can no longer be seen as autonomous; therefore, technical issues and choices must be subjected to greater oversight and participation from the public. Following on expert consultations and debates a democratic or political phase in which the process of public engagement is subjected to a democratic voting process or other feedback mechanisms. Any decisions and concerns identified have to be incorporated and addressed through the development of policies and regulatory frameworks by CCS stakeholders. Technical debates on uncertainties are to take place within the guidelines of policy frameworks and through which key policy makers can be held accountable. If uncertainty and controversy prevails during forum discussions and debates then a strategy should be devised such that concerns shape the kinds of research that are prioritized in response to the uncertainties.

Focus groups can be engaged by CCS stakeholders for part of the feedback mechanism where the main aim would be to investigate current concerns and develop additional strategies to convey the advantages and risks of CCS. The linkage between climate change and power generation will be one of the issues addressed as there is evidence that the Chinese public have a better understanding of global warming (Duan, 2010). In particular, 86.4% of the respondents recognised that burning fossil fuels was the major cause of climate change and that the impact of remaining status quo was well understood too. Duan (2010) also determined that 76% of the respondents believed climate change is a serious problem and 98% believed the Chinese government has a moral duty to take action to mitigate the effects of climate change. Therefore, this study highlighted the willingness and demands of the public for actions to be taken in combating climate change. Based on this, CCS is explored as an important abatement tool and should be thoroughly evaluated by the public prior to its eventual deployment. In this case, focus groups can then act as a catalyst in fuelling the public's continual interests on climate change issues.

While the need to communicate risks can be viewed as a measure of credibility, caution should be taken since human nature has a tendency to defend their locality against perceived threats. One of the best approach therefore is to minimise the threat perception and maximise the perception of benefits during communications to the public (Desbarats et al., 2010). However, this is not equivalent to misinforming or concealing facts from the public. It is about inaugurating a resilient team of experts who are actively involved in CCS and are able to perform beneficial outreach activities with the public as they are able to recapitulate the key aspects of CCS for the public, in view of the tremendous amount of widely available information (Desbarats et al., 2010). The public engagement team, based on their respective expertise, can communicate with credibility as well as presenting an assuring presence to the public.

Trust and credibility are major contextual characteristics which influences the endorsement and appreciation of scientific messages and perception of risks by the public (Wynne, 1992). Specifically to China, trust in authority and concerns about the equitable nature of CCS implementation procedures are the two most important issues for the general public (Duan, 2010). Therefore to educate the public, CCS advocates need to be mindful that public trust and credibility are not set in concrete but embedded within changing social relationships and thus, are conditional and open to renegotiation (Wynne, 1992, Wynne, 1980). Nothing should be taken for granted even with initial success with regards to engagement of the public for CCS and continual efforts should be invested throughout the lifespan of the various projects. For instance, the success of project Ketzin CCS storage in Germany was attributed to trust in the project developer and the fact that the public was consulted at the early stages of the project planning process (Desbarats et al., 2010).

Assurance and trust are complementary traits that have to be conveyed so that a gradual introduction and adoption of CCS will be carried out, thus enabling operators to fully grasp and mitigate the potential risks involved. Policy makers and CCS operators should also reassure the general public that research and development would continue on all fronts (green energy as well as CCS technology) and as new information becomes available, it shall be disseminated. While coal-fired power plants add economic value to the Chinese people by means of meeting their energy demands as well as providing employment opportunities and raising living standards, the GHG emissions from such industrial activities will result in detrimental effects to the global environment if left unchecked. With unrelenting research, development and phased implementation, CCS can contribute in ensuring that the energy security of China is safeguarded, economic activities and social development are powered and the environmental is protected for sustainable exploitation by future generations. Thus, public assurance is crucial if CCS deployment has to align with other global and national development goals.

By taking the additional costs required for CCS into account, it is evident that trade-offs are unavoidable and tough decisions on compromises (as well as sacrifices) would have to be made as well from political, economic and social perspectives. For the political side, cooperation between relevant ministries such as the Ministry of Science and Technology (MOST), National Development

Reform Commission (NDRC) and state-owned utilities as well as influential coal industry stakeholders is paramount for the successful deployment of CCS due to the issue of scarce resources being left to be distributed to each organisation after increased efforts being invested into CCS. As a result, the conflict between development priorities such as maintaining affordable electricity prices and safeguarding strategic energy security against the cost of deploying CCS should shape and balance China's strategic debates for the future (Wilson et al., 2011). As the increase in electricity prices would be felt by the public and companies, significant efforts in motivating the public on the fact that CCS would be worthwhile as a transitional mechanism for the eventual low-carbon and clean energy technologies which forms a sustainable energy system. This can include highlighting ground-breaking work and pilot projects for latest developments in clean energy in conjunction with CCS developments. An example of such work being in the pipeline is that of the Shenhua Group which set up a low-carbon energy laboratory with four research focus areas:

- 1) CCS and CO₂ management;
- 2) coal switching technologies including coal-to-liquids (CTL) and power plant efficiency;
- 3) hydrogen energy from coal; and
- 4) renewable energy such as wind, solar and thermal (IEA, 2009b).

The role of traditional and emerging social media cannot be overstated when dealing with debatable science and technology ideas such as CCS. The importance of CCS advocates and regulators engaging the media in disseminating information on ideas is underlined by the fact that the media have issues of objectivity when dealing with reports on science (Dean, 2008). Especially for CCS where accurate and precise information is scarce and many potential risks have yet to be fully examined, it is paramount for experts in this field to provide journalists with up-to-date and reliable materials and rely on them (the journalists) to produce well-balanced articles which the public are better able to appreciate, largely because it may be counter-productive if reports were based on spurious claims. Therefore, with objective reports that are educational and rationally persuasive, the general public can be empowered to make informed decisions and meaningful contributions.

Information provided by experts should include those which are of interests to key stakeholders: social, environmental and economic. There are potential for improvements and increased coverage of CCS in China by the state media and also through emerging social media as CCS was relatively anonymous and poorly understood compared to other clean energy technologies in 2009 (Duan, 2010). In the study by Duan (2010), respondents indicated a supportive attitude towards CCS as a global warming reduction mechanism after they were provided with introductory information and aims of the CCS. With initial groundwork indicating that support for CCS can be garnered from the public with an increased flow of information, Chinese regulators and CCS operators have to engage the media, which will allow the public to be better educated in CCS issues and hopefully, strong support will be the eventual outcome. Instead of delaying till the time when the technology matures, it is recommended to commence public engagement in this early stage, despite concerns with respect to technological maturity, risk factors, efficiency and capability of CCS to achieve significant CO₂ reductions, to ensure that the current substantial investments are not wasted.

Despite the technical uncertainties associated with CCS implementation, a combination of energy needs and GHG emissions mitigation targets could necessitate its increased endorsement (Desbarats et al., 2010). Hence, to complement the completed initial quantitative studies, a cross pollination of qualitative research methods as well as statistical methods could form the focal points of future studies on public perceptions in China. With the conclusive causal relationships formed between all stakeholders, an effective public engagement strategy would allow for the swift implementation of CCS.

2.2 Legal Considerations

2.2.1 International

China had taken notice of the escalating environmental issues about two decades ago and the first major milestone in the environmental protection efforts was their representation in the United Nations Framework Convention on Climate Change (UNFCCC) since 1992 as a non-Annex I party (UNFCCC). In fact, China has ratified or agreed to a total of 17 international environmental conventions and treaties since 1981 (Huang et al., 2010). None of the conventions applies specifically to CCS operations. However, five are of certain association with CCS:

- Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Dumping Convention 1972);
- International Convention for the Prevention of Pollution from Ships (MARPOL 73/78);
- The United Nations Convention on the Law of the Sea (UNCLOS 1982);
- The United Nations Framework Convention on Climate Change (UNFCCC 1992);
- The Kyoto Protocol and the 1996 Protocol to the London Convention 1972 (London Protocol 1996).

The objectives of UNCLOS are to promote legal and peaceful use of the seas and oceans through regular communications between the signatory parties as issues concerning the seas and oceans often require consensus among numerous states. MARPOL seeks to enhance preventive measures and expertise in relation to the pollution of the seas while the Kyoto Protocol is related to UNFCCC and it applies specific targets for countries to achieve the ultimate aim of reducing GHG emissions (UN, 1998, IMO, 2011a). The London Convention, replaced by London Protocol in 2006, focuses on the deterrence of dumping of wastes in the seas and oceans (IMO, 2011b).

TABLE 2-1: INTERNATIONAL CONVENTIONS RELATING TO CARBON CAPTURE AND STORAGE.
SOURCE: (DUCROUX AND BEWERS, 2005, UN, 1998, IMO, 2011B, IMO, 2011A, UNCLOS)

Conventions	Focus	Status for CCS	Approval for Direct injection
UNCLOS	Peaceful, equitable use of the seas for all	Scientific research only	Scientific research only
UNFCCC/ Kyoto	Reduction of GHG emissions	Recommended	No
London Convention/ Protocol	Control of dumping in seas and oceans	Approved	No
MARPOL	Prevention of pollution by ships	No	No

In view of the potential of CCS in mitigating global warming, amendments were made to the London Protocol in 2006 to add CO₂ into the list of materials which may be permitted for ‘dumping’ in the seas and oceans. More specifically, it mentioned that captured CO₂, in a relatively pure form, is to be stored within a subsea geological formation (IMO, 2011b). The Kyoto Protocol has admitted CCS into the list of probable options for countering global warming. As seen from Table 2-1, two of the four conventions and protocols have made amendments for CCS. The last revision to MARPOL was made in 1997 for the addition of Annex VI and the importance of MARPOL for CCS is gaining the option of injecting CO₂ via ships or floating platforms. Under the present articles contained in the Conventions, direct injection either from offshore structures or ships are not specifically permitted under the London Protocol and Kyoto Protocol (Ducroux and Bewers, 2005). Therefore, direct injection of CO₂ into the deep seas and oceans can only be carried out under the namesake of scientific research at a very small scale. Until more information about the precise environmental

impacts of direct injection and higher capabilities of containing CO₂ within a certain area of the deep oceans are attained, it is unlikely that governments would be comfortable in accepting direct injection into the four conventions and protocols.

2.2.2 *National*

In order to ensure that the environmental objectives and rules stated in the conventions are adequately implemented and regulated, the National Environmental Protection Agency (NEPA), previously in charge of environmental protection, was upgraded twice, in 1999 and 2008, to a full-fledged ministry known as the Ministry of Environmental Protection (MEP) (Qiu and Li, 2009, SEPA, 2006). Henceforth, there can be an increased amount of available resources to carry out any plans and reforms for the current structure in China as a result of the increasing prominence and significance attached to environmental protection. In addition, the reorganisation can lead to improved governance to rectify previous issues such as ineffective execution by local agencies which are acting in the interest of economic development and limited effectiveness due to organisational oversight especially in the rural areas (Huang et al., 2010, Qiu and Li, 2009). As China has been developing its economy on a “pollute first, clean up later” approach, there is no doubt that compromises between environmental protection and economic development would have to be realised during the overhaul of the current models. With the enhanced status of environmental protection in the country’s top councils, there can be more far-reaching initiatives carried out.

Whilst MOST is aggressively promoting the development of technical expertise for CCS in China, it is MEP’s responsibility to work in tangent with the progress in CCS developments locally as well as abroad to construct a resilient and comprehensive framework. CCS regulations are generally regarded as a new branch of regulations in many countries even though they already have stringent emissions controls in place. This is largely due to the sheer amount of CO₂ required for sequestration and the long periods necessary before the CO₂ no longer poses a threat to safety of life. China has had no previous experience of such procedures hence it would be beneficial for its regulatory bodies to develop the framework as CCS technology progresses. Furthermore, as either onshore or offshore storage facilities may extend beyond national borders, it would be in the interests of the international community to formulate a standard set of guidelines and regulations for streamlined efforts in policing and learning.

There are several platforms through which China is actively involved in the discussions with regards to creation of CCS-specific protocols, such as the Intergovernmental Panel on Climate Change (IPCC), CSLF and the World Resource Institute (WRI). The IPCC advises China on the expansion and amendment of current laws required to regulate CCS while the CSLF offers countries updates on regulations for the favourable development of CCS (CSLF, 2008). The sponsored collaborative project between WRI and the Tsinghua University of China is focused on formulating a set of guidelines for CCS as well (Forbes, 2009). A rigid set of CCS regulations is fundamental to the eventual implementation of the technology in China as it would ensure that the society’s concerns are well taken care of and that the operators can be clear of their responsibilities and liabilities. Subsequently, the operators can design their systems to be within the legal requirements and be aware to any potential issues. Hence, the coordinated efforts in constructing a rigid CCS framework in China would be of pronounced help in expediting the possibility of CO₂ ocean storage (Odeh and Haydock, 2009).

For the coastal areas, including territorial waters and exclusive economic zones (EEZ), MEP would have to insert concise regulations for CCS operations within China’s jurisdiction to protect other interests like commercial fishing, established shipping routes, undersea pipelines and cables as well as the extraction of natural resources from beneath the seabed. A transparent and clear licensing system should be established for the benefit of the administrators and potential CCS operators. Before a license can be issued, several key aspects must be addressed by the applicant in the form of a written project plan. The projects would have to adhere to the current applicable laws concerning the output and wastes generated by carbon capture, transportation and storage. For example, under

the China Environmental Impact Assessment Law, a written assessment of the environmental impacts brought about by CCS projects with respect to the capture plants, transportation modes and storage sites have to be submitted for approval by relevant authorities (Odeh and Haydock, 2009). In addition to current regulations, it is recommended that financial assurance in the forms of insurance, environmental bonds or letters of guarantee from banks be imposed as a one of the prerequisite conditions. Safety considerations for the welfare of humans and fauna and flora are also to be held at highest regard and thorough evaluations of all operations, monitoring and response strategies must be conducted to ensure that risks for the general public and environment are kept to the minimal. Regulations governing the post-injection period are crucial to CCS especially, in view of the uncertainties and uneasiness of the society with regards especially to the consequences of high concentration leakage of CO₂ in the ocean. Amendments to the Marine Environment Protection Law of China, following the revision of the London Protocol in 2006, would have to take place in order to legitimise carbon storage in the ocean space within and beyond China's territorial waters (Standing Committee Of People's Congress, 1983).

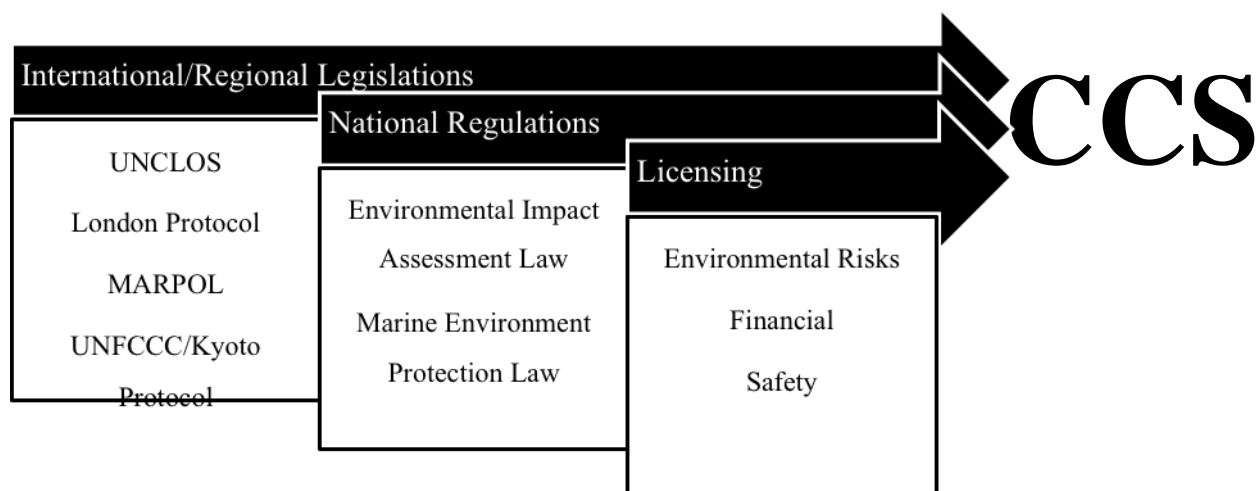


FIGURE 2-3: CHINA'S REGULATORY ROADMAP TOWARDS FULL SCALE CCS IMPLEMENTATION

Figure 2-3 displays the roadmap required for CCS legislations to mature in China. Firstly international and regional agreements would have to be achieved and this is still pending with regular efforts in communication between various ministries, governments and institutions. Next, China's national laws will have to be kept up-to-date with the revision of any Convention she is signatory to as well as the progress of research and additional information garnered from trial projects. The final step towards CCS in ocean space is for the creation of a capable licensing scheme which would provide sufficient supervision of the CCS operators within China.

2.3 Geopolitical Considerations

China has a vast coastline of 14,500km with many of her power plants and industries located along the shore and one of the main water bodies she has access to is the South China Sea (CIA, 2011). The South China Sea is home to some of the busiest shipping lanes including the Straits of Malacca and the Sunda Straits as well as natural resources such as fish stocks and fossil fuels (McDowell, 2011). In addition to China, the South China Sea is also accessible from many countries, including those from the Association of Southeast Asian Nations (ASEAN) such as Vietnam, The Philippines, Singapore, Cambodia, Malaysia, Indonesia and Brunei. China has been increasing communication and links with ASEAN, mainly in terms of trade and economic cooperation, through regular talks and discussions with ASEAN members for the past two decades (ASEAN, 2010).

There are, however, conflicts existing between China and other nations, majority from ASEAN, with regards to claiming of territorial waters and islands present in the South China Sea historically. Skirmishes between non-governmental organisations and civilians were not uncommon in the bid to secure and declare sovereignty over the disputed islands and land formations in the seas, which are

generally grouped into four archipelagos (Joyner, 1999). The enthusiasm exhibited by eight nations in claiming part or all of the archipelagos is largely due to the desire for securing the control of major shipping routes and rights to exploit natural resources present on and around the islands, inclusive of those underneath the seabed. Armed conflict, last encountered in 1988 between Vietnam and China, resulted in regions around the islands being left largely un-explored and –surveyed for the actual reserves of natural resources throughout the years to avoid further bloodshed as commercial activities in close proximity were regarded as an act of hostility by other nations (Chang, 1990). Relationships seemed to have thawed following close ties in trade with the “Declaration on the conduct of parties in the South China Sea” by ASEAN and China in 2002 to attempt in resolving the differences in a peaceful manner (ASEAN, 2002). This declaration contained a specific clause inserted to allow for “cooperative activities which may include marine scientific research”. However, there were no significant development since, apart from inconclusive talks and statements released from respective foreign ministries reiterating sovereignty over the islands.

Even so, CCS trial and demonstration projects are still probable to be implemented in the South China Sea, if sufficient support were garnered from the relevant nations. None of the ASEAN nations are signatories to the London Convention and Protocol which had recently added CO₂ to the list of exceptions for materials disallowed for dumping into the sea (IMO, 2011c). It may indicate a lack of interest or initiative from ASEAN as a whole towards matters concerning CCS or environmental protection of the oceans. Hence, it may require an incredible amount of effort and time from China, which had ratified the Convention in 2006, in order to influence the other ASEAN countries to jointly explore the potential of developing CCS technology in the South China Sea for ocean storage of CO₂.

As shown in the Antarctica Treaty, valuable scientific research can commence without prejudice to unresolved sovereignty claims (Joyner, 1999). Therefore, a regional assembly comprising of all stakeholders should be formed to provide a dedicated platform for the discussion of CCS matters in the South China Sea.

2.4 Economic Considerations

According to the Stern Report published in 2006, carbon emissions will be costing the world 5% of its GDP annually as a result of the negative impacts on the global climate and there can be savings of more than \$60/tCO₂ if CCS technology is developed early. In addition, IPCC has predicted that CCS could potentially absolve the global community of 70% of the total cost required to abate carbon dioxide in the atmosphere (IPCC, 2005). However, despite the optimistic predictions from relevant authorities regarding climate change, there are many uncertainties for companies to adopt an all-out approach towards researching and developing technologies in CCS. As a result, despite being researched upon and deemed feasible in the 1980s, CCS have not reached full deployable scale yet even though the technologies required to perform the various operations are already present in the oil, food and chemical industries. Current levels of capturing and transporting carbon dioxide can be deemed to be insignificant compared to the scale required for CCS.

To accomplish the goal of bringing CCS to a commercially viable scale and operational level in the next half of 21st Century, IEA has recognised that a much more aggressive investment and research approach has to be taken by the global community, especially with the developed countries occupying a leading role (EurActiv, 2009). More than half of the proposed \$4 billion contributions from developed countries should be directed to developing countries as funding to establish full scale trial and pilot projects. China’s present position in the world can be considered unique, as she is expanding so quickly that she is ranked 3rd globally in 2009 in terms of GDP, behind the US and Japan (The World Bank, 2011). Yet, she cannot be regarded as a developed country as her colossal population size had led to many aspects and living standards indicators exhibiting the features of a developing country. Therefore, although China is currently enjoying limited benefits as a result of this proposal at the CSLF conference in 2009, the current levels of funding and foreign aid on CCS is insufficient considering the projected amount of carbon she is due to emit in the near future. In order

to attract more funds for the implementation of CCS in China, the Chinese have to not only involve other sovereign nations in their project, their overall strategy should also encompass private companies. To do so, policies which will remove some of the uncertainties facing interested private companies should be engaged.

One of the main underlying uncertainties of CCS is the price of carbon in the future. Carbon prices are vital concerns for companies associated with CCS because of a straightforward reason: CCS will only be economically viable in the future as a result of the introduction of artificial market mechanisms that places a penalty on carbon emissions. The mechanisms can be in the form of emission trading (cap-and-trade) schemes (ETS) or carbon taxes and they are commonly used in other applications for the purpose of discouraging activities which generate negative externalities. China has displayed interests in adopting this system of controlling carbon emission as she has begun trials on a system of carbon trading in five of its provinces (AAP, 2011).

An established carbon trading system, the European Union Emissions Trading Scheme (EU ETS), was created in view of limiting the quantity of carbon emissions from the industries located in the EU. The EU ETS was linked to the Kyoto Protocol's Clean Development Mechanism (CDM) in 2003 with the belief that certain decline in costs can be achieved while attaining the same level of carbon reductions (Nazifi, 2010). However, as prices fluctuate within the carbon market and with no additional knowledge of the future carbon credits quantity being available, private companies and institutes are unable to make any reliable forecast for the prices of carbon. The quantity of future carbon credits would be dependent on the targeted CO₂ concentration agreed upon by the global community and the prices would reflect the degree of reduction necessitated. Hence a very limited number of CCS research and funding are initiatives of for-profit companies. Therefore, in short, the capricious nature of carbon prices affects the magnitude of investments in CCS as there is strong tendency for businesses to adopt a wait-and-see approach (Celebi and Graves, 2009).

On the other hand, taxes are considered a more inefficient cousin, both from economics' and the administration's perspective as there are costs involved with enforcement. However, tax rates could not be changed at an instance and any prudent cabinet or government usually requires time to decide on any modifications as there are significant implications on the attractiveness of the country to foreign investors and the competitiveness of local industries as compared to their foreign rivals. Hence, by having a relatively fixed carbon tax, companies interested in developing CCS can be reasonably assured of the potential savings or earnings available to them in the future. Once companies gain confidence about the viability of CCS as a critical tool for carbon abatement, participation rate and investment quantity from private companies will significantly increase. In addition, for this system to enjoy the same flexibility as ETS in terms of rebates from abatement projects, governing bodies should cater for equivalent amounts of tax waiver in the tax procedures to encourage private investments in pilot demonstrations and eventual full scale operations.

Additional income from carbon credits and taxes can be allocated for good use to alleviate negativities, mainly consequential of the additional monetary burden, during initial stages:

1. The income can be used to propagate CCS technologies to greater heights for lower operational costs (and hence, lower tax rates). At the current maturity of CCS technical knowledge and process, it is projected that full scale implementation will only be possible from 2030 or even 2050 onwards (Celebi and Graves, 2009, WCI, 2008, IEA, 2008). Therefore it is crucial that more resources are made available to encourage research institutions, private companies and universities in directing their efforts towards CCS.

Government-led efforts are always crucial during the early periods of introducing cleaner yet relatively expensive energy sources to the public. This can be in the form of guidelines for future development, subsidies on CCS pilot projects or build-operate-transfer (BOT) projects. Subsidies are prevalent in today's CCS scene with numerous developments involving governmental participation and call-for-proposals undertakings (WCI, 2008).

As CCS is not the only carbon abatement strategy offered, there are strong advocates of alternate approaches towards alleviating global warming and therefore, one of the techniques to attract attention is through the availability of funds. Private and public-listed companies usually invest in shorter term projects which offer shorter payback periods or instant results. Therefore, since CCS is deemed to be commercially feasible by 2030 or even 2050, governments and international organisations have to provide the initial investments to entice private businesses to engage in CCS research and pilot projects.

2. The income can be used for enhancing present renewable energy technologies to allow for a quicker complete replacement of fossil fuel-driven electricity production, which should be the ultimate aim of all carbon abatement strategies.
3. The income can be used in developing countries like China for the operation of CCS systems. As a result, the additional costs of carbon abatement would not be passed on to the end-users located within the developing regions. Thus, clean and efficient energy development will ensue while not penalising economic and social growth.
4. Developed countries can make use of the additional income to satisfy the quota for contributions recommended by IEA to finance the transfer of CCS and efficient energies technology for the benefit of developing countries.

Another means to generate cash flow from CCS operations is through the sale of carbon credits for the amount of carbon sequestered. Once a target concentration level of CO₂ is agreed upon, quantity of CO₂ required to be removed from the atmosphere can be determined as accountability of emitting CO₂ becomes increasingly transparent and documented in many countries. When there is more CO₂ sequestered than obligated, it should be allowed for the operator to gain carbon credits to his benefit. This may result in the formation of new business models constructed specifically to target this niche segment of environmental innovation. However, it should not be a 1:1 ratio for the awarding of carbon credits to avoid encouragement of the view that CCS will be a perpetual solution for irresponsible carbon emission and it should be tagged to the overall security and management rating of the site.

As shown in Table 2-2, the two countries which had carbon taxes effected (Australia and Norway) have relatively substantial investments and actual implementation of CCS compared to the rest of the countries and regions. China's level of investments still pale in comparison with the other developed nations hence there is a need to increase the level of investments initiated by the government. It may be prudent for China to impose an introductory carbon tax soon for its most polluting industries in order to send a clear message across to the businesses located within its borders. In addition, private participation and investments would likely to increase in China, speeding up the process of equipping most power plants and industries with CCS technology. When there are sufficient activities involving CCS research and employment, China can consider converting the carbon pricing mechanism to an ETS as it has proved to be an effective cost minimising tool for mitigating carbon as the costs of mitigation varies significantly between companies (Grubb and Sato, 2009).

The second main uncertainty concerning CCS is the extent of potential future costs savings that can be practically reaped on account of present investments and economies of scale. From a business' perspective, the overall costs incurred for performing CCS operations must be lower than the actual carbon tax or credit prices for any profits, if any, to be made. Figure 2-4 shows the comparison of current costs of CCS against future carbon abatement costs by oil majors, consultancy firms and a university. Majority of the projections revolve around the range of \$30-\$40/tCO₂ with the most optimistic figure being \$20/tCO₂ and the most conservative being \$55/tCO₂ while current costs hover from \$45/tCO₂ to \$125/tCO₂. The large gap difference can be attributed to a lack of studies conducted at realistic scales and it also highlights the fact that each CCS system is customized for a specific site and the costs involved can vary significantly location to location. Hence, this observation further reinforces IEA's push for a rapid increase in CCS pilot projects by end of 2020 to

Carbon Capture and Storage in Deep Ocean Space for the 21st Century
 establish sufficient knowledge and information for informed decisions on designing and executing a cost-effective CCS systems (EurActiv, 2009).

TABLE 2-2: LEVEL OF INVESTMENTS IN CCS FROM PRIVATE AND PUBLIC SOURCES. SOURCE: (WCI 2008), (IEA 2009), (NZEC 2009)

Country	Level of private investments (in Billions of U.S. Dollars)	Level of public investment (in Billions of U.S. Dollars)
Australia ⁶	0.86	2.65
Canada	-	3.1
EU	-	14.4
Japan	-	0.116
Norway ⁶	Oil companies engage in CCS	0.935
US	-	3.4
China	0.0313	0.0368

In addition, it has been examined that costs savings from improving current know-hows tend to be more limited as compared to developing revolutionary technologies (Al-Juaied and Whitmore, 2009). Therefore, not only does the up-scaling of current technologies for economies of scale may be profitable for CCS companies but exploring ground-breaking ideas and design can be very valuable indeed. Last but not the least, applicable regulations of different regimes can diverge considerably in terms of specifications and requirements of the CCS systems and this will result in varying costs for the companies engaging in CCS within the borders. In view of preserving the competitiveness of the local industries and free trade obligations, China can actively participate in the several leadership forums for CCS to achieve an agreed set of regulations for CCS to avoid confusion and promote easier transfer of technology, manpower and expertise (CSLF, 2008, Global CCS Institute, 2011).

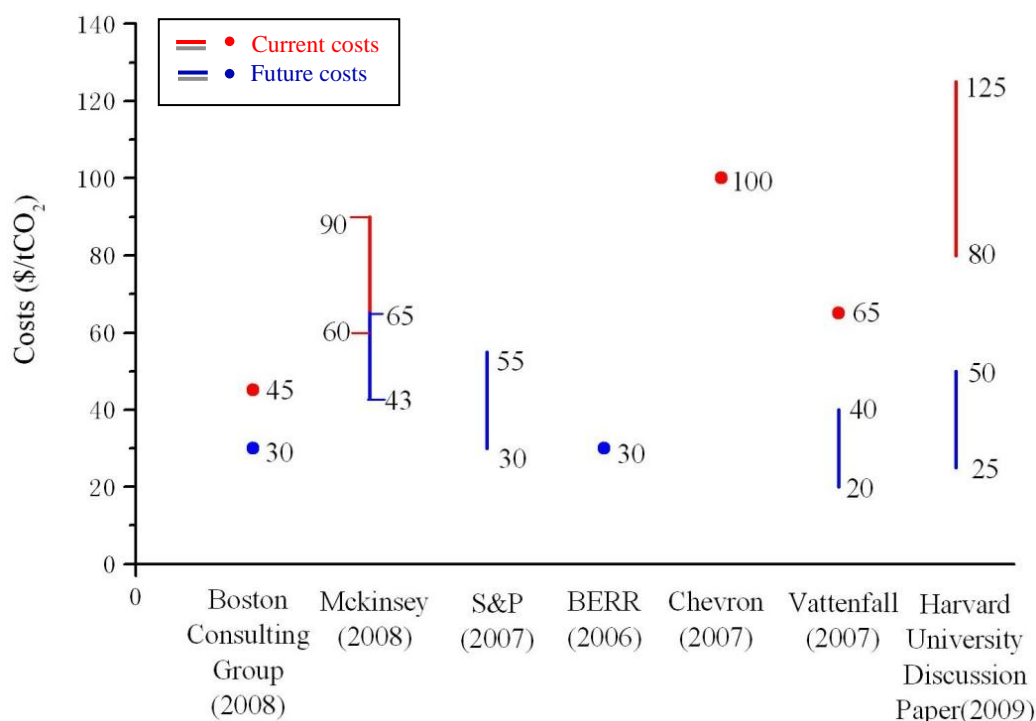


FIGURE 2-4: MEASURES OF CURRENT AND FUTURE CARBON ABATEMENT COSTS. SOURCE: (CHANGE 2005; STERN 2007; AL-JUAIED AND WHITMORE 2009)

The third uncertainty of CCS concerning private businesses is the opportunities available to mitigate the downsides to their investments and operations of CCS systems. Each CCS configuration has a

⁶ Countries which implemented carbon tax/levies

restrictive operational duration due to the lifespan of fossil fuel power stations being 25 to 30 years as well as the pre-designated storage space containing limited volume. But the physical storage site will hold injected CO₂ for 1,000 to 10,000 years before the CO₂ can mineralised. Therefore, there must be requirements for the continual monitoring and assessment of all storage sites for a very long period and also, the issue of accountability and liability exists for any potential incidents. The extent of liabilities incurred by the companies with regards to the integrity of the stored CO₂ will be determined by the respective national and regional regulations. Regulators have to keep in mind the average lifetime of commercial companies and it is definitely not as long as the time taken for CO₂ to mineralise. In addition, since CCS can involve placing CO₂ in the ocean space, be it through direct injection or subsea geological formations, any potential incidents can incur widespread consequences which are hardly constrainable within a nation's borders or seas. Therefore, a mechanism which allows for the reimbursement of remedial action and compensation not limited to international boundaries has to be established.

Firstly, since CCS systems encounter relatively similar categories of risks, a common system of mutual insurance and risks spreading similar to the Protection and Indemnity (P&I) clubs for ship owners can be created for CCS operators. CCS operators can pay a sum of contribution to the CCS mutual club annually to be indemnified by the club in case of any covered incidents. In return, the operator would have to ensure that the management of the CCS system is up to the highest standards accessible at that time and which are acceptable by the mutual club. Rules of the club would be decided by the representatives of the members or members themselves. When accidents do occur, the amount of compensation would be paid for by the club on behalf of the member using the funds built up over the years from individual member's contribution. In this case, the society can be assured of the CCS industry being self-regulated at optimal levels and that any suffering victims would enjoy a higher chance of being compensated for their losses. Furthermore, there is less chance for a CCS operator to be bankrupted by any single incident and CCS operations would not be abruptly disrupted. A separate fund for governments can be created for long term CO₂ storage protection. Secondly, there are propositions of imposing environmental bonds for operators and the paid-up amount will be refunded if there is no incidents occurring within 20 years after operations at the storage site had ceased (Gerard and Wilson, 2009). This model assumes the respective governments taking control of the storage sites after they are filled to capacity. Ultimately, all citizens are paying for the sequestration of CO₂ and any governmental intervention required would be funded by taxpayers. Therefore, it would be logical for the commercial CCS companies to transfer the monitoring of the site back to the government, which will have full knowledge of the site and its characteristics prior to, during and after the active CCS operations. The actual monitoring can be outsourced to professional companies under the close supervision of government officials. Thirdly, individual CCS companies can seek out profit-making insurance corporations which are interested in offering customized products (Zurich, 2009). As public perception presently may regard CCS in ocean space as a form of legitimised ocean pollution, putting a safety net arrangement in place early would help to garner support and momentum in promoting CCS.

For the general public, one of the concerns for the implementation of CCS is that it results in higher operational costs for power plants. Additional cost components are usually passed on to the end-users through charging of higher tariffs on the usage of electricity by industries and households. This may result in the loss of competitiveness of the companies which practices CCS as compared to those which do not. Furthermore, if CCS is eventually implemented on a global scale, the resultant rising electricity prices will result in even higher living expenses and inflation for the public. Costs of electricity have been already increasing for the past decades due to the expanding dominance of renewable energy in the world's energy portfolio. Therefore, for CCS to gain wider acceptance from the public and to be deemed feasible, the overall costs will have to be kept within the difference between the costs of electricity from renewables and from fossil fuels. In addition, investments in renewable energy have reached 150 billion U.S. dollars in 2009 while CCS is lagging far behind at about 26 billion U.S. dollars in total investments (REN21, 2010). There is a substantial gap to fill between the current developments and the projected requirement of 2.5-3 trillion U.S. dollars

Carbon Capture and Storage in Deep Ocean Space for the 21st Century required by 2050 (IEA, 2009a). China is already one of the world leading investors on renewable energy alongside Germany in 2009 hence it is likely that she would pick up pace on CCS in the near future (REN21, 2010).

2.5 Engineering Requirement

A complete integrated carbon capture and storage system is composed of three distinct steps:

- *Capture*, or the separation of CO₂ from flue gas. Capture is generally required to be able to economically transport and store the CO₂.
- *Transport*, or the movement of the CO₂ from its source to the final storage location.
- *Storage*, or depositing CO₂ into the storage location. The main storage reservoirs under consideration today are geological formations. Other potential reservoirs include the deep ocean, ocean sediments, and mineralization (conversion of CO₂ to minerals).

Figure 2-5 shows a more detailed breakdown of the integrated CCS system with five steps listed. This mirrors the design that is proposed for China. The design flowchart for the system can be seen in Figure 2-6. Two alternatives are proposed for CO₂ capture: amine and membrane separation based on when the retrofit will occur. Additionally, two alternatives are available for storage in ocean space, however, only direct injection into the deep ocean is considered here.

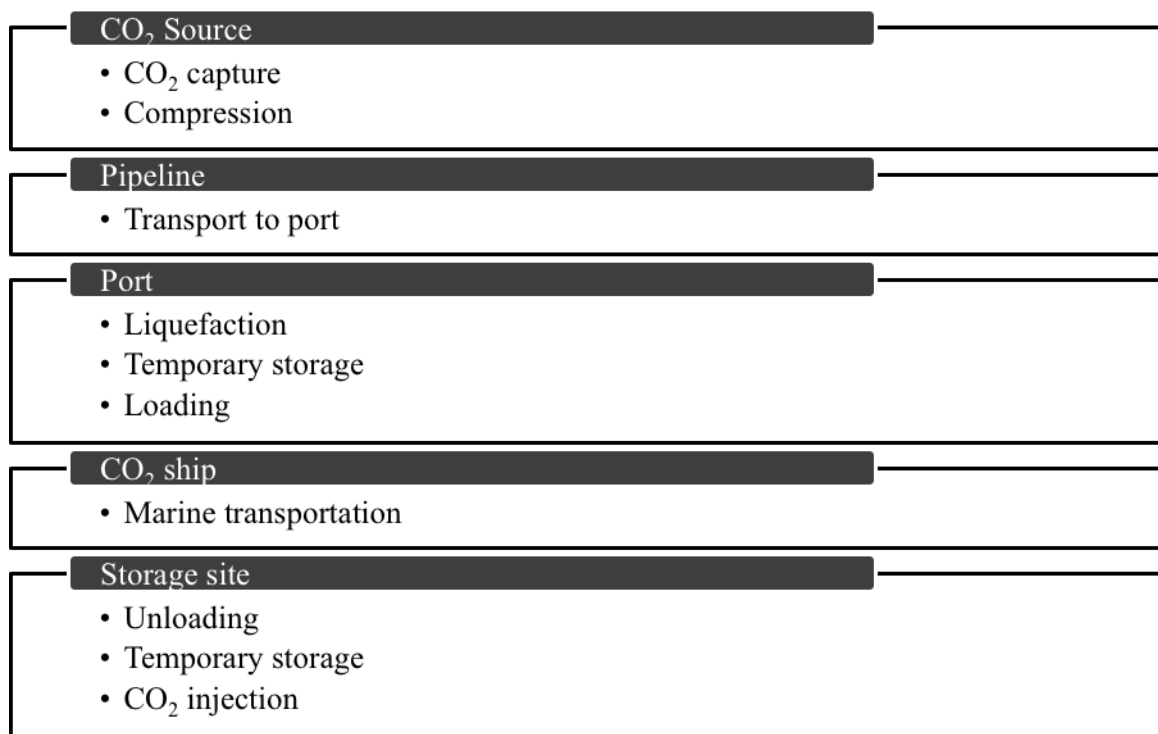


FIGURE 2-5: GENERAL DIAGRAM OF CO₂ CAPTURE, SHIP TRANSPORT AND OFFSHORE GEOLOGICAL STORAGE

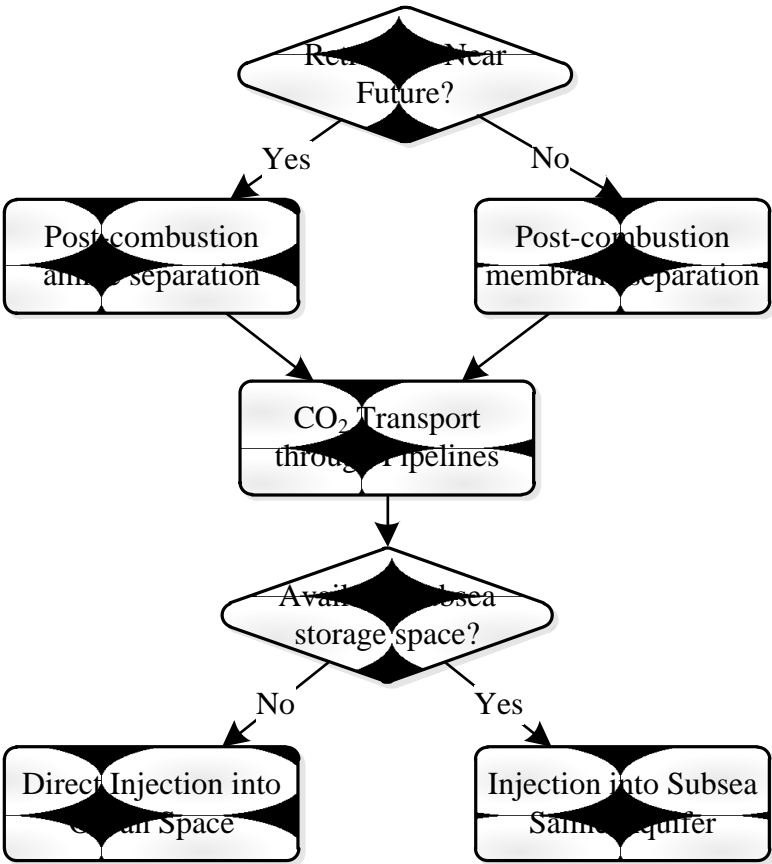


FIGURE 2-6: DESIGN PATHWAYS FOR IMPLEMENTATION OF CCS IN CHINA

3 CARBON CAPTURE

The first step in a complete CCS system is carbon capture (for the purposes of this report, compression of the CO₂ stream after capture will also be included in this stage). There are three primary approaches for capturing CO₂:

- Post-combustion capture: where the CO₂ is separated from the flue gas after combustion and applies primarily to coal combustion plants. Instead of the flue gas being discharged directly to the atmosphere, it is passed through equipment which separates most of the CO₂. The CO₂ is sent for compression and transport, and the remaining flue gas is discharged to the atmosphere;
- Pre-combustion capture: where the CO₂ and carbon is removed from the fuel (not flue gas) prior to combustion and this applies primarily to gasification plants. Pre-combustion capture involves reacting a fuel with oxygen or air and/or steam to give mainly a 'synthesis gas' (syngas) or 'fuel gas' composed of carbon monoxide and hydrogen; and
- Oxyfuel combustion capture: where the fuel is burned in pure oxygen stream allowing for complete combustion. This can be used with either coal or gasification plants. Oxygen is normally produced through low temperature air separation though advances in membrane and chemical looping are being explored.

The primary impediment to carbon capture and storage lies with the large cost of the capture step, where up to 80% of the total cost lies. Current commercial systems using any of the above approaches can achieve approximately 85-95% capture efficiency, but have not been scaled up to larger power plants (> 500 MW). Figure 3-1 shows the schematic for carbon separation via all three mechanisms. In the diagram, it is clear that post-combustion requires processing after combustion, while the other two focus on generating either a pure stream of oxygen for combustion, or a synthetic gas that does not contain carbon. Additionally, the figure only indicates geological storage as an option. The advantages and disadvantages of each individual approach are highlighted in Table 3-1.

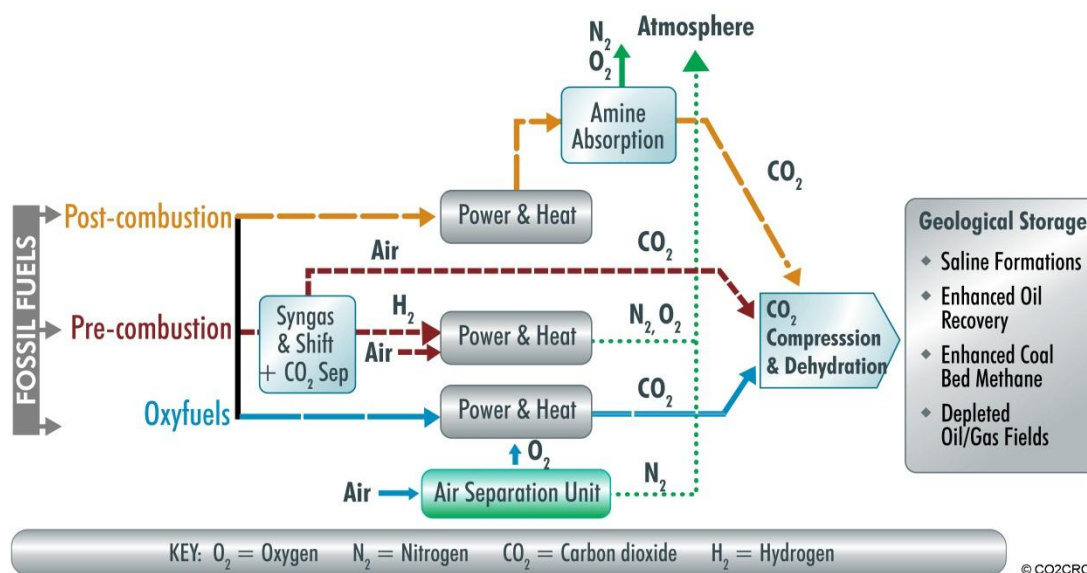


FIGURE 3-1: CAPTURE APPLICATIONS (AFTER CO₂C CAPTURE PROJECT AND IEA GHG R&D PROGRAM)

SOURCE: CO2CRC.COM.AU/IMAGELIBRARY3/CAPTURE.PHP

TABLE 3-1: ADVANTAGES AND LIMITATIONS FOR CARBON CAPTURE APPROACHES AND ASSOCIATED TECHNOLOGIES (ADAPTED FROM FIGUEROA ET AL. (2008)).

	Advantages	Limitations
Post-combustion	Applicable to existing coal-fired power plants (retrofit is possible) Utilizes existing technologies (60 years of experience with amine solvents) Technology is already in use for soft drink industry	Flue gas is very dilute (~13% CO ₂) and at ambient pressure High operating costs for the absorber and degraded solvent replacement Requires a scale-up of 10x for commercial power plants
Pre-combustion	Potential reduction in compression loads, leading to reduction in costs Proven industrial applications in oil refineries (scale-up of only 3x) 90-95% of CO ₂ emissions can be captured Applicable to natural gas and coal-fired integrated gas combined cycle plants Provides the lowest technology risk	Primarily applicable to new plants (few gasification plants in existence) Requires chemical processing prior to combustion in gas turbine High investment cost in new plants Increased NO _x emissions (require scrubbers, increasing cost) Efficiency of H ₂ turbines is lower than conventional turbines
Oxyfuel combustion	Very high CO ₂ concentration in flue gas Potential for 100% CO ₂ capture Limited other pollutant emissions due to more complete combustion Potential for retrofit onto modified coal-fired power plants	Large cryogenic O ₂ production is required Recycle of CO ₂ into the combustion chamber is required to limit temperatures High energy penalty without chemical looping Process is at large development stage (not commercial)

Coal-based industries should be the focus for CO₂ capture implementation in China, including the power, coal chemical, cement, and steel industries. Among these, electric power industry is the sector with the largest amount of CO₂ emission. If China is to implement CCS to realize significant reduction of CO₂ emissions, CO₂ will be captured by appropriate technologies from coal-fired power plants.

TABLE 3-2: COAL-BASED POWER GENERATION TECHNOLOGY IN CHINA

Technology	Efficiency	Cost (\$ per kW)	Status
Subcritical	30%-36%	500-600	Main base of China's current generating fleet
Supercritical	41% ⁷	600-900	About half of current new orders
Ultra-supercritical	43%*	600-900	Two 1000 MW plants in operation
IGCC	45-55%	1100-1400	Twelve units waiting for approval by NDRC

Based on the limitations identified in Table 3-1 and the projected reliance of China on coal for the foreseeable future, post-combustion capture was determined to be the best solution. Within this approach, there are several methods for achieving gas separation. The three primary types are:

- Separation with sorbents/ solvents: Separation is achieved by contacting the gas stream with a liquid solvent or solid sorbent. The solvent/ sorbent is then transported to a separate vessel where it is regenerated, causing the liberation of the CO₂ through a change in pressure or temperature. A continuous supply of solvent/ sorbent is required as degradation in the presence of contaminants is common (SO_x, NO_x, etc.). A schematic of this process is seen in Figure 3-2: a.

⁷ Indicates current efficiency. Improvements are expected in the future.

- Separation with membranes: Membranes are designed to allow selective transport across their surface for the targeted substance. The transport is often driven by a pressure difference. Several types of membranes are already in use for separation CO_2 from H_2 , such as polymeric, metallic and ceramic. A schematic of this process is seen in Figure 3-2: b.
- Distillation of a liquefied gas stream: the gas stream can be liquefied through a series of compression, cooling and expansions steps, and once liquefied can be separated through distillation or refrigerated separation. A schematic of this process is seen in Figure 3-2: c. Due to the high cost of these systems, they are not considered in any depth within this report.

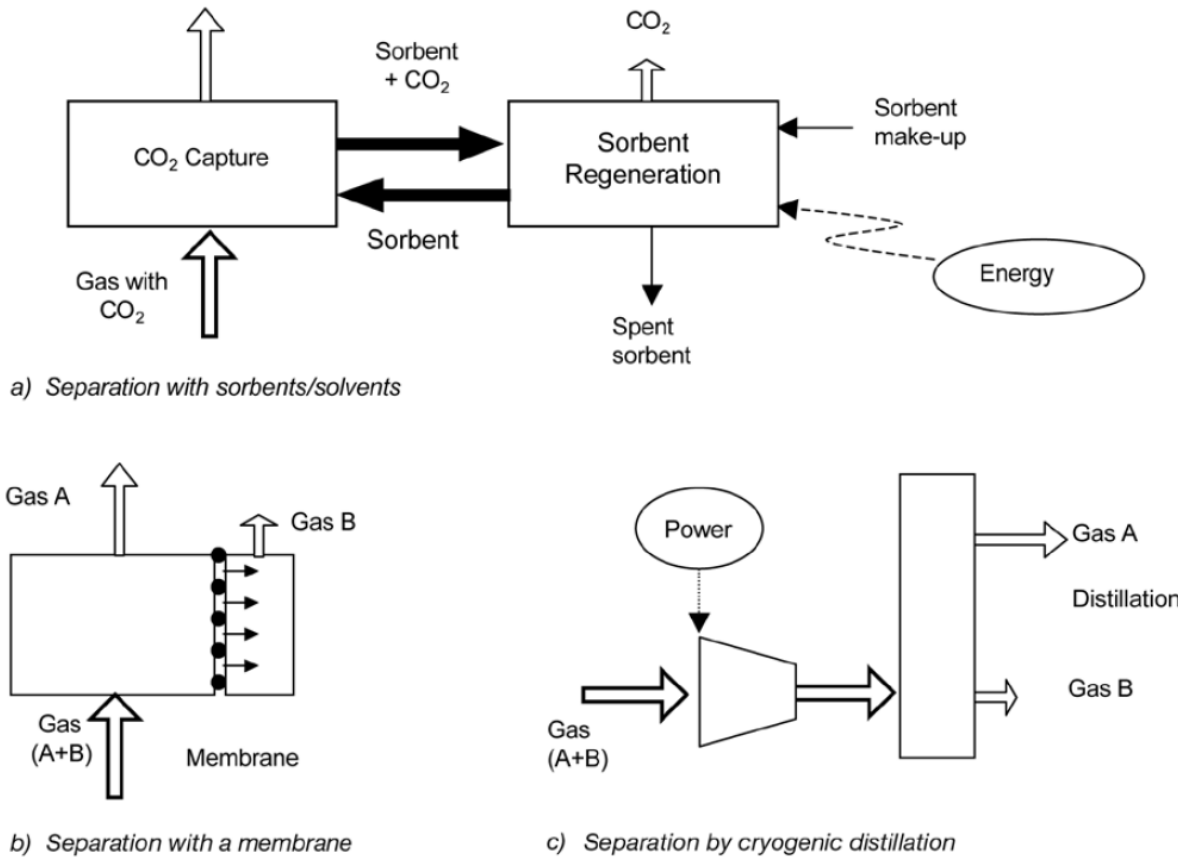


FIGURE 3-2: GENERAL SCHEMES OF THE MAIN SEPARATION PROCESSES FOR CO_2 CAPTURE. SOURCE: IPCC (2005).

3.1 Capture Requirements

With respect to the CO_2 capture rate for power plants, the active demonstration plants in current operation have all chosen 90% as the acceptable capture rate (for every 10 parts of CO_2 generated, only 9 are captured by the process). The other requirement for the process is to provide a high purity stream of CO_2 for transport. Carbon dioxide is highly acidic in the presence of water and corrodes steel pipes; therefore, the free water content of the stream needs to be eliminated.

Primary energy use increases with the use of carbon capture plants (energy is necessary to drive the separation of the flue gas, or the generation of a pure stream of oxygen in the case of oxyfuel combustion). The emissions for a given power plant with a capture system depend primarily on the type of fuel, the removal efficiency of the CO_2 and the overall efficiency of the plant. The energy penalty is steep for these processes and can lead to a 30-40% reduction in usable power. The pollutants released by a power plant with and without carbon capture can be seen in Table 3-3. The sulphur emissions are decreased in both technologies due to a need for flue gas desulphurization in post-combustion plants to prevent fouling of the sorbent or membranes, and the complete combustion in oxyfuel systems. However, in amine-base post-combustion systems the release of NH_3 is increased due to degeneration and release of some of the sorbent.

TABLE 3-3: AVERAGE, MINIMUM, AND MAXIMUM VALUES FOR THE EMISSIONS FACTORS FOR PULVERIZED COAL POWER PLANTS AND CO₂ CAPTURE SYSTEMS (ADAPTED FROM (KOORNNEEF ET AL., 2010B))

Capture Technology	No-capture	Oxyfuel combustion	Post-combustion
CO ₂ (g/k Wh)	826 (706-1004)	47 (0-147)	143 (59-369) ⁸
NO _x (mg/k Wh)	374 (159-620)	172 (0-390)	537 (205-770)
SO ₂ (mg/k Wh)	414 (100-1280)	25 (0-98)	9 (1-13)
NH ₃ (mg/ k Wh)	7 (3-10)	n.a.	209 (187-230)
VOC (mg/k Wh)	10 (9-11)	n.a.	n.a.
PM (mg/k Wh)	39 (7-51)	3 (0-10)	52 (9-74)

TABLE 3-4: TYPICAL POST-COMBUSTION FLUE GAS COMPOSITION (COAL POWER PLANT) AND RANGE OF TARGET PURIFICATION VALUES (ADAPTED FROM FAVRE, 2011; ZHAO ET AL., 2011)

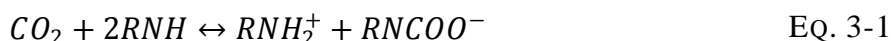
Compound	Flue gas composition (coal power plant)	Acceptable range for transport in pipeline
CO ₂	~14%	>90% or >95.5%
N ₂	~71%	<4% (together with all other non-condensables)
H ₂ O	~11%	10-500 ppm
O ₂	~4%	10 ppm (EOR) to 4% (aquifer)
NO _x	150-300 ppmv	100-1500 ppm
SO ₂	50-100 ppmv	100-1500 ppm
Ar	1%	<4% (together with all other non-condensables)
CO	--	100-4000 ppm
Particulates	--	0.1 – 10 mg/N m ³

3.2 CO₂ Separation through Chemical Absorption

Chemical absorption is the most widely used process for separation of carbon dioxide from gas streams. Absorption is a common process in the chemical industry and it is used among others in the treatment of the industrial gas streams containing acid gases like H₂S, NO_x and CO₂ (Majchrowicz et al., 2009). In these gas treating processes, aqueous solutions of particularly alkanolamines are commonly used (Dame et al., 2006b (Damen et al., 2007) (Kaggerud et al., 2006); (Gibbins and Chalmers, 2008). Separation is achieved through a reversible reaction between carbon dioxide and an alkaline reagent.

The most common reagents are alkanolamines, such as monoethanolamine (MEA), diethanolamine (DEA), and diisopropanolamine (DIPA). Potassium carbonate and sodium hydroxide are two examples of non-amine reagents.

For an amine with functional group *R*, the basic reaction that occurs requires two moles of amine for every mole of CO₂. The products are a cationic amine species and an anionic carbamate species as seen in



This reaction proceeds via a non-elementary mechanism and is approximately first order with respect to both CO₂ and amine concentrations. Water can also be added to the above reactions as a reactant, forming a bicarbonate ion:



⁸ The high maximum value is considered to be an outlier as in that study (IPCC, 2005) it is assumed that an auxiliary gas fired boiler is used to provide the energy required for the CO₂ capture process. The CO₂ emissions from this boiler are not captured, hence the high CO₂ emissions.

The overall forward reaction is exothermic (reaction proceeds faster at lower temperatures). The opposite is true for the regeneration of the solvent, as the reaction is endothermic requiring very high temperatures. Typical operating conditions for the absorption step are 40°C and at atmospheric pressure, while regeneration generally occurs at 120° and slightly higher pressures (up to 2 atm).

3.2.1 Process

The process flow for a typical amine absorption process is simple as seen in Figure 3-3. The operations of the main unit consist of an absorber tower, a stripper column, and a heat exchanger to recover heat from the hot regenerated solvent. The flue gas enters from the bottom of the absorber while the cooled lean solvent is pumped in from the top of the tower. The gas contacts the solvent and CO₂ is absorbed; the remaining flue gas exits at the top of the tower, and the CO₂ rich solvent leaves out the bottom. From there, the solvent passes through the heat exchanger, where it is heated slightly before entering the stripper column. A reboiler at the bottom of the stripper column heats the solvent using steam to reverse the absorption reaction and regenerate the solvent. The hot lean solvent is recycled back through the heat exchanger and a cooler before it is pumped back to the top of the absorber. The CO₂ product stream from the top of the stripper column is saturated with water at nearly atmospheric pressure, and must be dehydration and compressed if it is sent to a pipeline for transport to a consumer or sequestration site.

A system for post-combustion capture of CO₂ by a chemical solvent is shown in Figure 3-3. The flue gas is usually cooled before entering the absorber column at the bottom. As the flue gas rises, the CO₂ is absorbed by a solvent in counter-current flow. The CO₂-free gas is vented to the atmosphere. At the bottom of the absorber, the CO₂-rich solvent is collected and pumped through a heat exchanger, where the CO₂-rich solvent is preheated before entering the regenerator. In the regenerator, the CO₂-rich solvent flows downward. While it's flowing down, the temperature increases, thereby releasing CO₂, which rises to the top of the column and is removed.

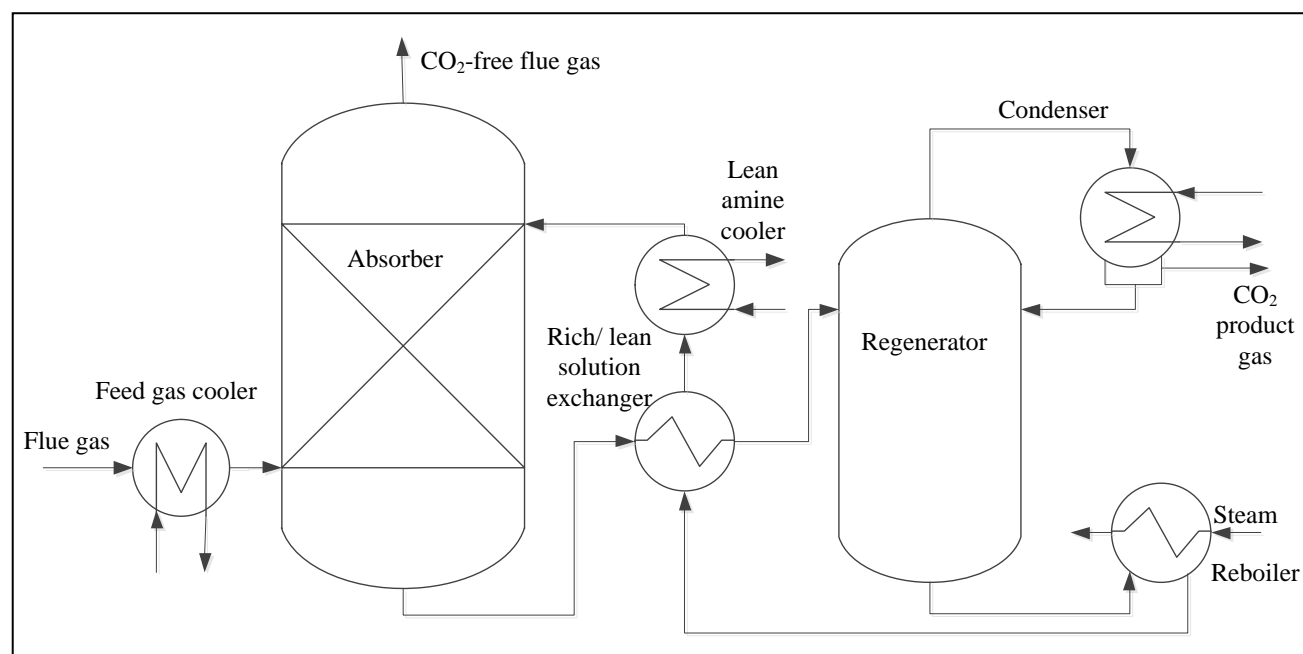


FIGURE 3-3: SCHEMATIC DIAGRAM OF A POST-COMBUSTION CAPTURE PLANT WITH CHEMICAL ABSORPTION

The majority of the operating cost is due to the large amount of steam required for regeneration of solvent. Corrosion of the process equipment can be a serious problem. To prevent corrosion, it is necessary to either use stainless steel for construction or to add corrosion inhibitors to the solvent. Because the stripping process is carried out at around 120°C, which is above the boiling point of water, a large amount of solvent is lost to evaporation. The solvent also degrades in the presence of oxygen to form heat stable salts. Not only must fresh solvent be added to make up for this, the salts

have to be periodically removed from the system to prevent clogging or other damage to the process equipment.

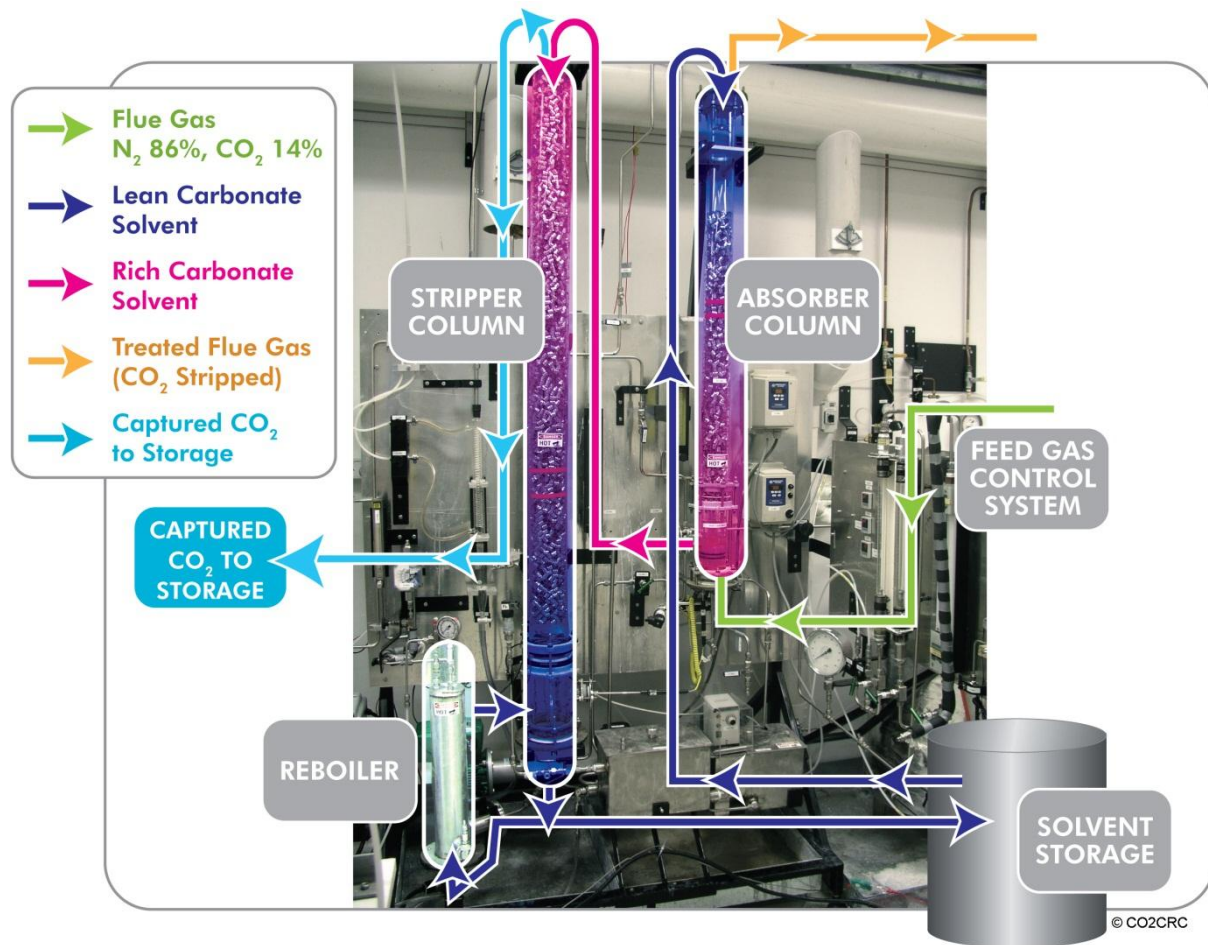


FIGURE 3-4: ABSORPTION CAPTURE: CO₂ SOLVENT REMOVAL PLANT

SOURCE: CO2CRC.COM.AU/IMAGELIBRARY3/CAPTURE.PHP

3.2.2 Commercial Technologies

There are several commercial amine absorption processes available for CO₂ removal from flue gases. The most widely used, with 21 plants built, is the Fluor Daniel Econamine FG process. Second is the Kerr-McGee/ ABB-Lummus Amine process with 3 plants. The most recently developed technology is the Mitsubishi Heavy Industries KS-1 process, which is used at a single plant built in 1999.

- The Fluor Daniel Econamine FG process uses an inhibited 30 wt% MEA solution. This process can recover between 85-90% of the CO₂ in a typical flue gas stream, while producing a product of >95% pure CO₂. Proprietary inhibitors are added to prevent corrosion and allow for the widespread use of carbon steel construction materials. Capacities of the 21 plants constructed range from 6 tonnes to 1200 tons of CO₂ recovered per day.
- The Kerr-McGee/ ABB-Lummus Amine process uses a 15-20 wt% MEA solution with no inhibitors. The lack of inhibitors requires the use of stainless steel equipment, and limits the concentration of the amine in the solution to 20%. This process can recover >96% of the CO₂ from a typical flue gas, with a product stream of 95-98% pure CO₂. The plant capacities range from 200 tonnes to 800 tonnes of CO₂ per day.
- Mitsubishi Heavy Industries KS-1 process was developed to address some of the key problems encountered with conventional amine absorption. The solvent is a proprietary sterically-hindered amine solution. The solvent can achieve 90% recovery from a flue gas stream with a lower solvent circulation rate than other amine technologies. A lower solvent circulation rate means that less energy is required to regenerate the solvent and the equipment

Carbon Capture and Storage in Deep Ocean Space for the 21st Century
sizes can be smaller leading to lower capital costs for the plant. The solvent also has low corrosivity and degradation rates without the use of inhibitors. The one plant in commercial operation has a capacity of 160 tonnes of CO₂ per day.

3.2.3 *Costs*

Based on the capital expenditure analysis of the conventional MEA process; the absorption column is found to be the principal component with around 50% of the total capture equipment costs. In addition, the CO₂ compression is responsible for around 30% of the total investment cost. In operational expenditure, the fuel requirement is responsible for more than 50% of the overall cost, from which 55 to 70% is required for solvent regeneration.

3.2.4 *Issues*

However, there are drawbacks for absorption (Knudsen et al., 2009):

- i. The applied solvents have limited cyclic CO₂ loading capacity;
- ii. They promote the corrosion of the equipment (high corrosion potential of the solvent);
- iii. Solvent regeneration requires high energy consumption;
- iv. Degradation of the solvent due to SO_x and NO_x forming nonregenerable, heat-stable salts;
- v. A significant amount of solvent is lost by evaporation; and
- vi. The solvent degrades in an oxygen rich atmosphere.

3.2.5 *Research Gaps & Probable Breakthroughs*

R&D pathways to improved amine-based systems include:

- Modified tower packing to reduce pressure drop and increase contacting,
- Increased heat integration to reduce energy requirements,
- Additives to reduce corrosion and allow higher amine concentrations, and
- Improved regeneration procedures.

3.3 *Membrane Separation*

Membranes have been widely used in various industrial separations for the last two decades. Industrial applications are currently dominated by polymeric membranes. Recent research directed at the development and application of inorganic membranes is advancing faster because of the demand in new application fields, such as fuel cells, membrane reactors, and other high-temperature separations. Inorganic or polymeric membrane separation processes are expected to be more efficient than conventional CO₂ separation processes (Damle and Dorchak, 2001, Xu et al., 2002).

The diffusional characteristics of a particular gas through a given membrane depend on the membrane's physical and chemical properties (the nature of the permeant species). The third factor, interaction between membrane and permeant, refers to the sorptivity or solubility of the gas in the membrane (Shekhawat, 2003). In membrane separation technology, a membrane separates two phases from each other and acts as a selective interface that separates preferred materials from the feed. The membrane material can consist of nonporous solid, microporous or macroporous solid with liquid or gas in the pores, gel or a combination of these.

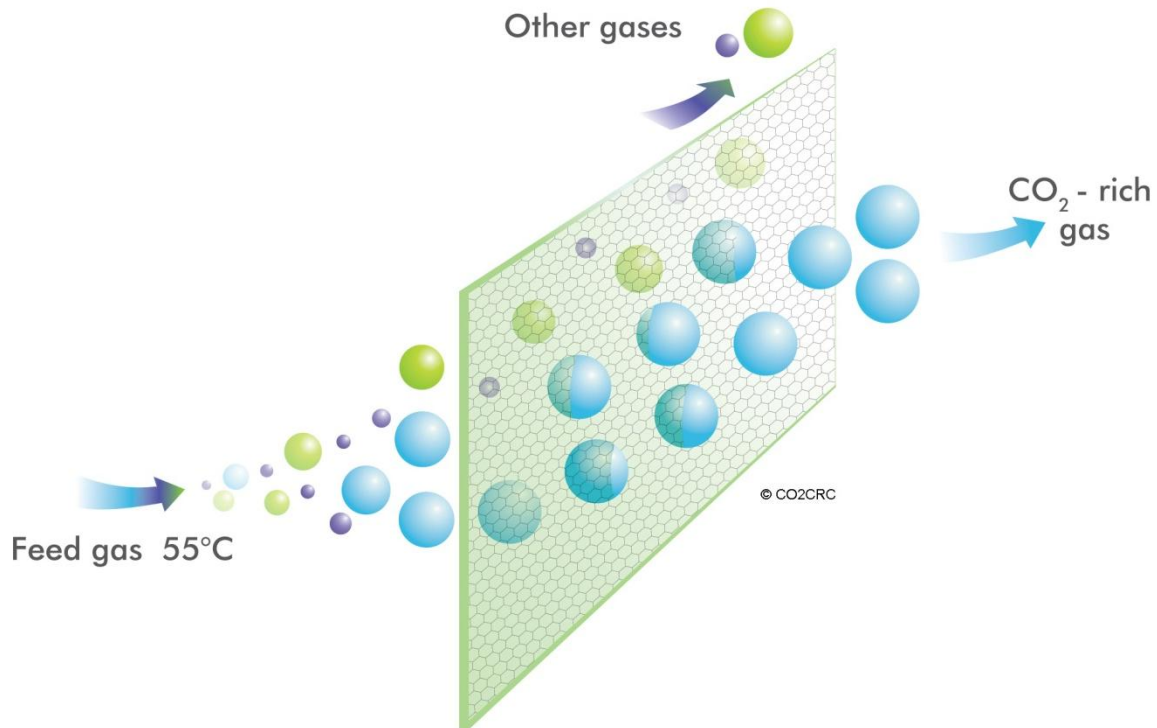


FIGURE 3-5: FLATSHEET MEMBRANE: GAS SEPARATION MEMBRANE: FLATSHEET MODULE. SOURCE: CO2CRC.COM.AU/IMAGELIBRARY3/CAPTURE.PHP

The basis for any membrane separation system is shown in Figure 3-6. One stream leaving the membrane system is enriched of CO₂ (the species that needs to be separated) while the other stream is depleted of CO₂.

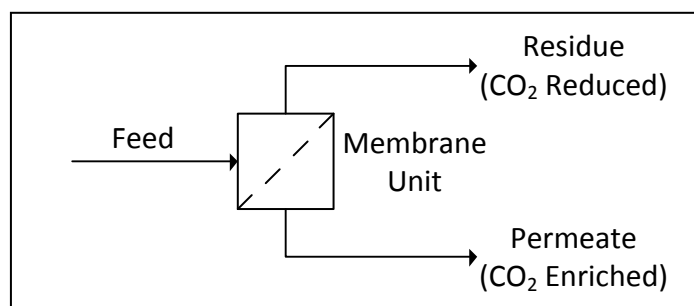


FIGURE 3-6: SINGLE STAGE MEMBRANE UNIT

The movement of materials across the membrane can take place due to several driving forces. The driving force can either be due to a chemical potential or an electrical potential. A chemical potential can occur because of a concentration gradient or a pressure gradient or both. The gas separation membrane systems rely on the pressure gradient by setting the stream fed to the membrane at a higher pressure and by setting the stream leaving the membrane at a lower pressure. The pressure gradient provides the driving force for the materials to diffuse across the membrane.

Various species in the stream have different diffusivities through a given membrane material; therefore, each species diffuses at a different rate across the membrane and leads to separation into

two streams. Molecules with larger molecular weights diffuse slower than molecules with smaller molecular weights. If the pores of the membrane are too large, convective flow of molecules will occur through the membrane and therefore, no separation will occur. If the pores of the membrane are quite small, larger molecules will not pass through the membrane and will be separated due to molecular sieving. If the pore diameters are smaller than the mean free path of the gas molecules entering the membrane by Knudsen diffusion. In solution-diffusion membranes, selective gas molecules will dissolve into the membrane material and then diffuse across the membrane.

3.3.1 Types of Membranes

For a membrane to be useful for carbon dioxide capture, it should possess a number of properties, namely (Powell and Qiao, 2006, Brunetti et al., 2010)

- High carbon dioxide permeability;
- High carbon dioxide/ nitrogen selectivity;
- Thermally and chemically resistance;
- Plasticisation resistance;
- Aging resistance;
- Cost effective; and
- Ability to be cheaply manufactured into different modules.

It is important to construct membranes into a practical configuration. Most polymeric membrane gas separation studies are performed on dense homogeneous membranes. Such a configuration provides the permeability with a closer relationship to the intrinsic permeability of the polymer. However, the construction of a gas separation module in practical applications requires a more complex membrane structure. Dense membranes tend to be significantly thicker than the selective layer of asymmetric membranes. This leads to dense membranes possessing considerably lower gas fluxes than alternative membrane structures. Often used in asymmetric composite hollow fiber or flat sheet configuration.

The performance of some polymeric membranes are summarized in Table 3-5 mainly separating post-combustion flue gas with CO₂/ N₂ being the main components (Powell and Qiao, 2006). Single-stage membrane systems are not capable of high capture efficiency and CO₂ can be further concentrated by a second membrane stage.

TABLE 3-5: PERFORMANCE OF POLYMERIC MEMBRANES SEPARATING CO₂/N₂ (POWELL AND QIAO, 2006)

Material	Permeance (m ³ / m ² ·Pa·s)	Selectivity $\alpha_{\text{CO}_2/\text{N}_2}$
Polyimide	735	43
Polydimethylphenylene oxide	2750	19
Polysulfone	450	31
Polyethersulfone	665	24.7
Poly(4-vinylpyridine)/ polyetherimide	52.5	20
Polyacrylonitrile with poly (ethylene glycol)	91	27.9
Poly (amide-6-b-ethylene oxide)	608	61

Two common ways to construct membrane modules are the hollow fiber module and the spiral-wound module.

- A hollow fiber module is a collection of cylindrically shaped fibers. The feed flows through the cylinders and the selective material from the feed diffuses across the fiber material while the rest of the feed material keeps flowing through the cylinders. The material that diffuses

across the fibres leaves as the permeate stream from one side and the material that do not diffuse leaves as the residue stream from another side of the membrane.

- In a spiral-wound module, the feed flows axially across the membrane envelope and the selective feed material permeates through the membrane envelope radially inward to the collection tube and exits. The material in the feed that is not selective to the membrane will continue to flow axially across the membrane envelope and exit from the opposite side.

3.3.2 Process

The engineering considerations for membrane gas separation of CO₂ are:

- Operating flexibility: the ability to operate under variable feed quality conditions, either on a short- or long-term basis. The flexibility of the absorption process is moderate. The flexibility of the membrane system depends on the composition of the flue gas, but it's response time is instantaneous and correction action has immediate results.
- Turndown: Capability of the system to operate at reduced capacity. Membranes are highly capable of operating at upto 10% of the initial design. Absorption on the other hand can only maintain both recovery and product purity between 30-100% of the design.
- Reliability: Membranes are highly reliable with respect to the on-stream factor. The membrane separation process is continuous and has few control components which can cause a shutdown. Absorption systems on the other hand are moderately reliable due to the large equipment associated with the process and the corrosion products generated.
- Ease of expansion: Membrane system expansion is very easy since this only requires the installation of identical modules. Absorption systems can also be expanded, but this requires additional design considerations and adds cost to the initial design of the project.
- Energy intensity: A key feature for all CO₂ capture systems is the energy requirement and resulting loss of efficiency on the power cycles.

TABLE 3-6: COMPARISON AMONG IMPORTANT DESIGN CONSIDERATIONS FOR MEMBRANES AND ABSORPTION PROCESSES (ADAPTED FROM (BRUNETTI ET AL., 2010))

	Membrane system	Absorption
Operating flexibility	High (%CO ₂ >20%) Low (%CO ₂ < 20%)	Moderate
Response to variations	Instantaneous	Rapid (5–15 min)
Start-up after the variations	Extremely short (10 min)	1 h
Turndown	Down to 10%	Down to 30%
Reliability	100%	Moderate
Control requirement	Low	High
Ease of expansion	Very high (modularity)	Moderate
Energy requirement	0.5–6 MJ/kg CO ₂	4–6 MJ/kg CO ₂

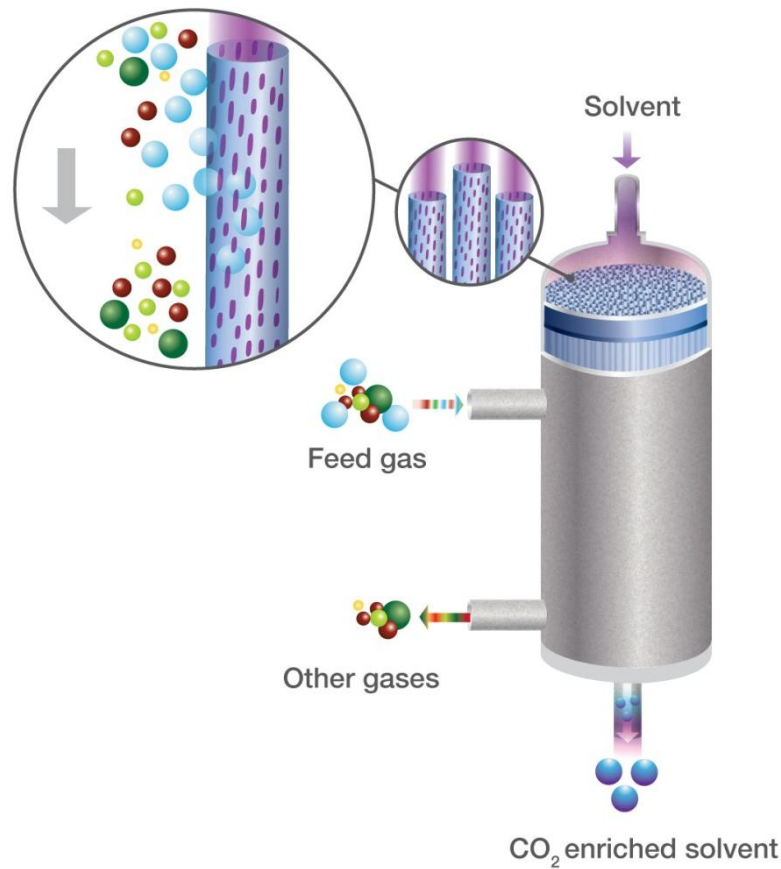


FIGURE 3-7: MEMBRANE GAS SEPARATION: SPIRAL WOUND MEMBRANE
SOURCE: CO2CRC.COM.AU/IMAGELIBRARY3/CAPTURE.PHP

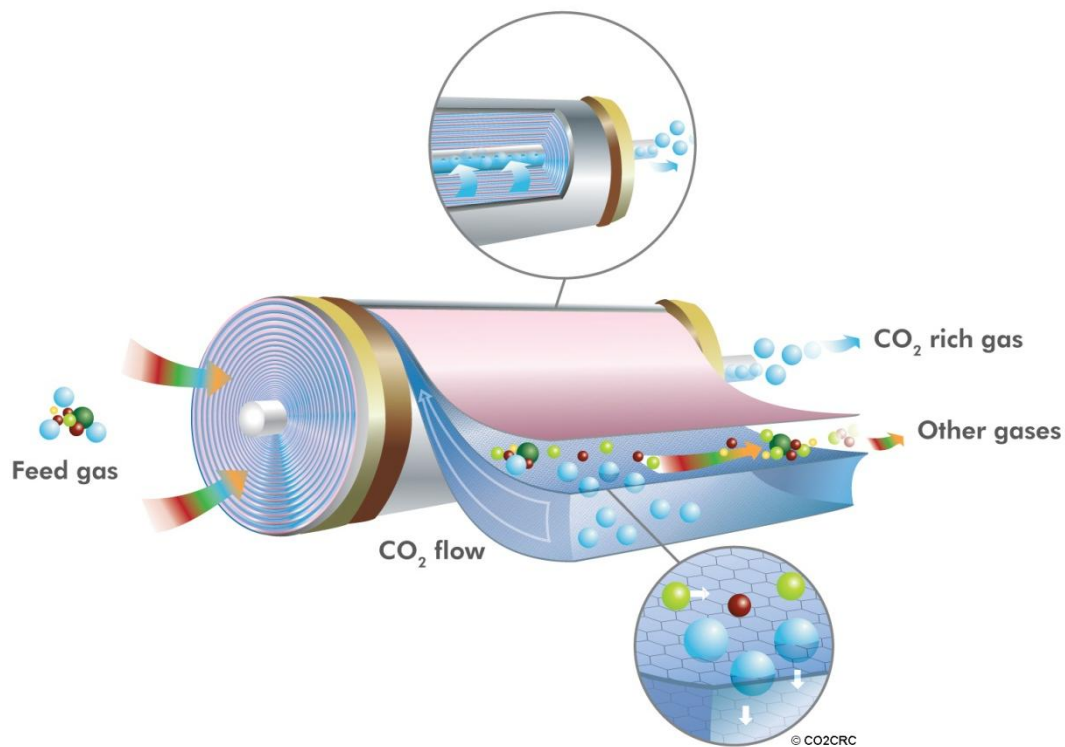


FIGURE 3-8: MEMBRANE GAS ABSORPTION: HOLLOW FIBRE MODULE
SOURCE: CO2CRC.COM.AU/IMAGELIBRARY3/CAPTURE.PHP

3.3.3 Costs

TABLE 3-7: ILLUSTRATIVE PARAMETERS NECESSARY FOR DEVELOPING A COST ESTIMATE FOR A GAS SEPARATION MEMBRANE SYSTEM (ADAPTED FROM (MERKEL ET AL., 2010))

Category	Value	Units
Compressor, turbo expander, and vacuum pump efficiency	0.80	–
Compressor and turbo expander cost	500	\$/kW
Membrane CO ₂ permeance	1000	gpu
Membrane CO ₂ /N ₂ selectivity	50	–
Membrane skid cost	50	\$/m ²
Membrane equipment installation factor	1.6	–
Capital depreciation/interest	20	%/year
Cost of power	0.04	\$/kW
Capacity factor	85	%
Power plant lifetime	25	Years
Power plant size	600	MW _e
Flue gas flow rate	500	m ³ /s
Flue gas composition (wet gas): 11.6% CO ₂ ; 11% H ₂ O; 73% N ₂ ; 4.4% O ₂		

3.3.4 Advantages of using membrane

TABLE 3-8: MEMBRANE PROCESSES FOR POST-COMBUSTION CCS APPLICATION: A TENTATIVE SYNOPTIC (ADAPTED FROM FAVRE, 2011)

Target	Membrane process	Main characteristics
Intensified gas liquid absorption	Membrane contactor (hydrophobic porous membrane)	Membrane stability (non wetting conditions) has to be ensured for long term operation Regeneration step non-achievable Effective intensification factor remains to be clearly evaluated
Carbon dioxide capture	Gas separation membranes: physical (GS) (usually a dense polymer)	Numerous materials investigated, few technico-economical studies, almost no pilot scale processes on real flue gas Water in flue gas is a problem Require multi-stage processes in order to achieve purity target
	Chemically reactive membranes (FSCM)	Require water, on both sides of the membrane, to be effective May be applicable through a single stage process if a high selectivity is attained Industrial feedback on real flue gas is still not achieved
	Liquid membranes (LM)	Very high selectivity can be achieved Require water, on both sides of the membrane to be effective Solvent losses due to volatility can be a problem, possibly solved by ionic liquids Effective driving force, stability and effective permeability in a real post-combustion situation remains to be proven
Flue gas or concentrated CO ₂ drying	Membrane gas separation	Water will always permeate faster than CO ₂ The incidence of water permeation on CO ₂ permeability depends on polymer type Competitiveness compared to other operation

	(absorption molecular sieves) remains to be proven
--	--

Several studies have been published comparing the performance of amine absorption-based and membrane in the CO₂ capture from flue gases (Bounaceur et al., 2006, Favre, 2007, Okabe et al., 2008). The gas permeation processes have several advantages:

- i. Higher separation energy efficiency relative to equilibrium-based processes;
- ii. Current application to industrial processes (air separation, hydrogen recovery and carbon dioxide capture from natural gas); and
- iii. High packing density which requires small installations.

Polymeric membranes are of particular interest in gas separation applications. They separate gases based on solution-diffusion mechanism and are typically limited by the well-known relationship between permeability and selectivity. The polymeric membranes present several advantages:

- i. Low cost;
- ii. High performance separation;
- iii. Easy of synthesis;
- iv. Mechanical stability (Scholes et al., 2009, Xomeritakis et al., 2009).

Some advantages of membrane separation systems over absorption and adsorption processes include lower operating costs because membranes do not need to be regenerated. In addition, the operation is simple and can be left for long periods of time. The capital costs for the membrane module itself is lower than other separation processes, but large pre-treatment units can increase the total capital costs for these installations. Some membrane units require more than one stage with pretreatment units and compressors.

Membrane units do not require as much space as the other types of acid gas removal systems because the equipment used for membrane units are comparatively smaller.

3.3.5 Issues

The separation of CO₂ from N₂ was already studied and is easily performed by membranes with high CO₂ permeance and CO₂/N₂ selectivity. However, the treatment of an enormous flow rate of flue gas emitted by power plants requires a very large membrane area and consequently increases the cost of this capture technology. Another drawback is the need of very large membrane area and consequently increases the cost of this capture technology. Another drawback is the need of very large, expensive and energy-consuming compression equipment. This limits the maximum pressure ratio attainable by feed compression and/or permeate vacuum to about 10.

TABLE 3-9: CAPTURE CHARACTERISTICS FOR MEMBRANE AND ABSORPTION SYSTEMS (ADAPTED FROM (MERKEL ET AL., 2010))

	Membrane system	Absorption
Feed composition (CO ₂ %)	>15%	>5%
CO ₂ purity	80–95%	>95%
CO ₂ recovery	60–80%	80–95%

Membranes are a low cost means of separating gases when high purity is not vital. There are number of issues associated with the capture of carbon dioxide from flue gas which limit the use of membranes. The concentration of carbon dioxide in flue gases is low, which means that large quantities of gases will need to be processed. The high temperature of flue gases will rapidly destroy a membrane, so the gases need to be cooled to below 100°C prior to membrane separation. The membranes need to be chemically resistant to the harsh chemicals contained within flue gases, or

these chemicals need to be removed prior to the membrane separation. Additionally, creating a pressure difference across the membrane will require significant amounts of power.

Polymer-based membranes, in comparison to other separation techniques, such as pressure swing absorption, are less energy intensive, require no phase change in the process, and typically provide low-maintenance operations (Berchtold, 2006, Zhou, 2006). A polybenzimidazole (PBI) membrane under development at DOE's Los Alamos National Laboratory (LANL) has demonstrated long-term hydrothermal stability up to 400°C, sulphur tolerance, and overall durability while operating in simulated industrial coal-derived syngas environments for over 400 days at 250 °C.

Key technical challenges to the use of membrane systems include processing large flue gas volumes, relatively low CO₂ concentration, low flue gas pressure, flue gas contaminants, and the need for high membrane surface area.

3.3.6 Research Gaps & Probable Breakthroughs

There are a variety of options for using membranes to recover CO₂ from flue gas. In one concept, flue gas would be passed through a bundle of membrane tubes, while an amine solution flowed through the shell side of the bundle. CO₂ would pass through the membrane and be absorbed in the amine, while impurities would be blocked from the amine, thus decreasing the loss of amine as a result of stable salt formation. Also, it should be possible to achieve a higher loading differential between rich amine and lean amine. After leaving the membrane bundle, the amine would be regenerated before being recycled. R&D pathways to an improved system include increased membrane selectivity and permeability and decreased cost (Falk Pederson et al., 2000).

Several issues have to be clarified before the most relevant place and role of membranes is identified. In general, more research should be conducted in the following areas:

- Studies which combine materials and engineering aspects
- Proof of concept studies, as well as pilot studies, on flue gas from a real post-combustion environment.

3.4 Retrofitting an Existing Plant: Post-combustion System

This process involves extracting CO₂ from the flue gas following combustion of fossil fuels or biomass. Several commercially available technologies, some involving absorption using chemical solvents, can in principle be used for carbon capture. It can be typically built in to existing industrial plants and power stations (known as retro-fitting) without significant modifications to the original plant. This is the type of technology favoured by the UK Government in its competition for state support.

There are several methods that can be used to capture the CO₂. The most common method is passing the CO₂ through a solvent and adsorbing the CO₂ with an amine solvent. A change in temperature and/or pressure will then release the CO₂. Another process in development is calcium cycle capture where quicklime is used to capture the CO₂ to produce limestone, which can then be heated to drive off the CO₂ and quicklime which can then be recycled. All of these require additional energy input to drive off the CO₂ from the solvent - this typically results in extra energy costs of 20-30% compared to plants with no capture. New solvents are under development to reduce these penalties to 10%.

Existing plants use air, which is almost four-fifths nitrogen, for combustion and generate a flue gas that is at atmospheric pressure and typically has a CO₂ concentration of less than 15%. Thus, the thermodynamic driving force for CO₂ capture from flue gas is low (CO₂ partial pressure is typically less than 0.15 atm). Other post-combustion possibilities, currently being researched, include cryogenically solidifying the CO₂ from the flue gases, or removing CO₂ with an adsorbent solid, or by passing CO₂ through a membrane.

TABLE 3-10: POST-COMBUSTION CAPTURE TOOLBOX (CO₂/N₂) SOURCE: IPCC 2006

Capture Technologies	Current	Emerging
Solvents (Absorption)	Chemical solvents	Improved solvents Novel contacting equipment Improved design of processes
Membranes	Polymeric	Ceramic Facilitated transport Carbon contractors
Solid sorbents	Zeolites Activated carbon	Carbonates Carbon based sorbents
Cryogenic	Liquefaction	Hybrid processes

Table 3-11: Results of China Coal fired Power and CO₂ Capture Techno-Economic Assessment (Adapted from Senior et al. 2011) Table 3-11 summarises the calculated technical and economic performance of a range of coal fired power plant types with CO₂ capture under Chinese conditions. A coal cost of 16 RMB/GJ and a discount rate of 10% over a plant life of 25 years was assumed. The load factor is taken at 85% (67.5% in first, commissioning year). Costs do not include financing and taxes. The cost of transport, storage, and monitoring were not included.

TABLE 3-11: RESULTS OF CHINA COAL FIRED POWER AND CO₂ CAPTURE TECHNO-ECONOMIC ASSESSMENT (ADAPTED FROM SENIOR ET AL. 2011)

Plant Type	Units	Advanced Supercritical 800 MW	Oxyfiring	Post-combustion MEA	Post-combustion Ammonia	Pre-combustion IGCC	Existing 600 MW Supercritical	Post-combustion MEA	Post-combustion Ammonia
Net Output	MWe	824.3	672.5	621.5	670.3	661.7	574.1	398.1	435.6
Net efficiency	%LHV	43.9	35.6	33.1	35.7	36.8	40.3	27.9	30.6
Capture Penalty	--	--	--	10.8	8.2	--	--	12.35	9.7
CAPEX-specific	RMB/kW net	5850	8646	10735	9000	10049	5258	11110	9041
Levelized COE	RMB/MWh	271.3	368.9	463.2	398.3	412.5	270.1	512.4	431.9
CO₂ Emissions	g/kWh	796.6	98.2	105.6	98.0	95.4	868.2	125.2	114.4
CO₂ Captured	g/kWh	--	884.1	950.8	881.6	859	--	1126.9	1029.9
Cost of CO₂ Abatement	RMB/tCO ₂ v PC Plant	--	139.7	277.8	181.7	201.4	--	326.2	214.6
	US \$/tCO ₂	--	20.4	40.7	26.6	29.5	--	47.8	31.4

3.5 Technology Readiness

Of the ninety-two post-combustion CO₂ capture processes assessed, fifty-two (57%) are absorption based, fourteen (15%) are adsorption based, seven (8%) are membrane based, and nineteen (21%) are mineralization or biofixation based. Another observation is that the most common and most mature PCC process are absorption based technologies. This was expected considering that absorption-based gas separation processes have the longest history of use in the chemicals and oil and gas industries. Most of the leading PCC vendors have taken mature solvents and process designs and created derivative forms for use on coal-fired flue gas applications. There is a double peak of absorption technologies with the first peak occurring at TRL 3-4 and another at TRL 6. The PCC processes in TRL 6 group all use the most mature capture chemistries (e.g. amines) while those in the lower TRL stages use fundamentally new chemistries, supporting processes or both (e.g. ionic liquids, self-concentrating solvents, etc.).

TABLE 3-12: TRL DEFINITIONS AS APPLIED BY EPRI FOR USE WITH CO₂ PROCESSES

Demonstration	9	Normal commercial service
	8	Commercial demonstration, full-scale deployment in final form
	7	Sub-scale demonstration, fully functional prototype
Development	6	Fully integrated pilot tested in a relevant environment
	5	Sub-system validation in a relevant environment
	4	System validation in a laboratory environment
Research	3	Proof-of-concept tests, component level
	2	Formulation of the application
	1	Basic principles observed, initial concepts

Following these trends, the membrane and adsorption based systems are starting with arguably less industrial gas separation experience and therefore, will likely take more time in the research technology readiness levels as more time is needed to evaluate the fundamental material performance and designing new processes. There simply isn't as much industrial operation experience to draw upon. This fact is reflected in the distribution of these technology types in the TRL ranks. The distribution of PCC technologies across ranks show TRL distribution for all technologies is as follows: 2%, 14%, 27%, 24%, 11%, 17%, and 4% for TRLs 1-7 respectively.

3.6 CO₂ Compression Technologies

The CCS chain is divided into capture, transport and storage. In further detail, the capture stage is divided into a CO₂ capturing stage from the source and later in to a CO₂ compressing stage having suitable pressure for pipeline transport (typically about more than 10 MPa or 20 MPa). It is a conventional approach to compress the CO₂ using multiple stage centrifugal compressor. Meanwhile, CO₂ has to be liquefied to render it possible for transport by ship which is not necessary in pipeline transport. This liquefaction stage makes CO₂ shipping economically less competitive to pipeline.

4 CARBON TRANSPORT

A complete CCS system requires safe, reliable, and cost effective solutions for transmission of the CO₂ from the capturing facility to the location of permanent storage. For transmission of large quantities of CO₂ over moderate distances, pipelines are considered the most cost-effective solution. Onshore pipelines for transmission of CO₂ have existed in North America for several decades. CO₂ transport is the necessary link between CO₂ capture and storage. The present focus on safety, flexibility, reliability, and cost reductions has created a demand for new solutions that can compete with pipeline transport.

Due to limited information regarding large-scale ship-based transport of CO₂, it is compared with technologies for the transport of other liquefied gases. Liquefied petroleum gas (LPG) is found to have many similarities with CO₂ and provides a useful starting point for the development of a CO₂ transport system. Thus, the design of the ship, tank farm, and onshore loading system, while innovative in its application to CO₂, starts from existing technology in LPG.

CO₂ is heavier than air and may displace air in low areas if there is a leakage. Care must be taken when designing large-scale CO₂ liquefaction systems and storage tanks, especially in harbour areas. Procedures for loading and unloading liquid CO₂ near the triple point are developed to avoid dry ice formation. Dry ice may form during pressure letdown in the offshore transfer system.

4.1 Transport Requirements

The transport chain considered in this project comprises seven main processes as shown in Figure 4-1: liquefaction and gas conditioning, initial storage, pipeline transport to harbour, intermediate storage, loading, ship, offshore unloading, and CO₂ storage.

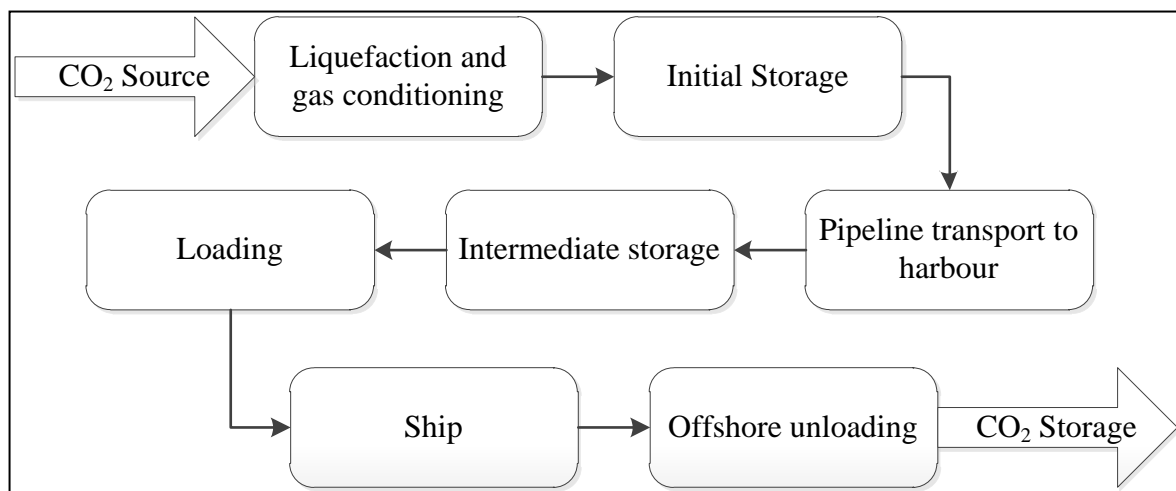
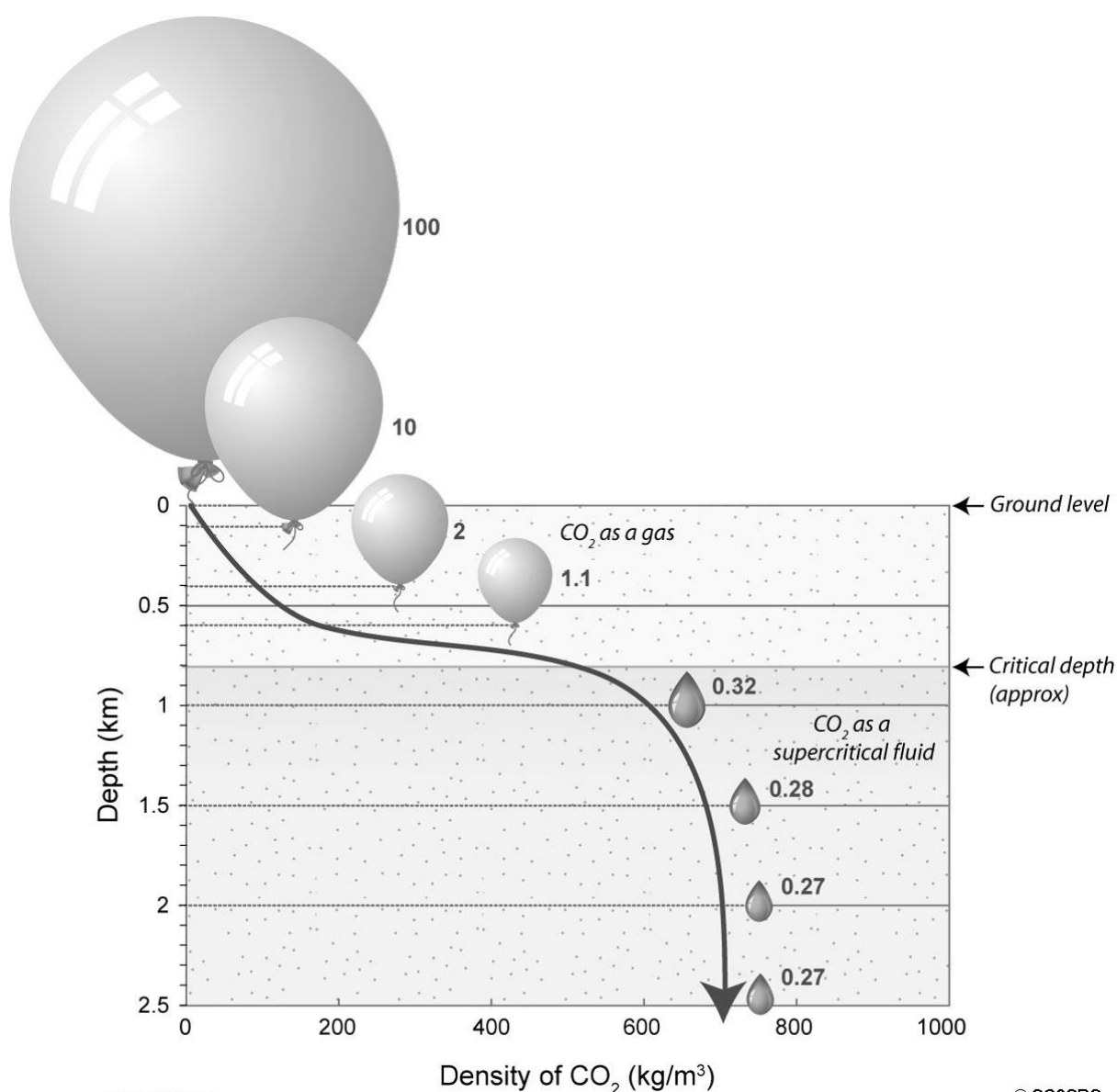


FIGURE 4-1: MAIN PROCESSES IN THE TRANSPORT SYSTEM

The transport of CO₂ is a mature technology as the technical requirements are similar to those applied to other gases transport. Commonly, the CO₂ is not stored in the same place where it is captured. Thus, it should be transported and, depending on the distance between the two places (from point of capture to storage site), this could be done by pipeline, ship or tanker trucks. To transport large volumes of CO₂, pipelines are considered to be the most cost-effective and reliable method (McCoy and Rubin, 2008, Haugen et al., 2009). However, in some situations or locations, CO₂ transport by ship may be economically attractive, particularly when the CO₂ has to be moved over large distances or overseas. Vandeginste and Piessens (2008) published a review about the CO₂ pipeline transportation and revealed that the pipeline diameter is the crucial parameter for cost estimation of this transport method. Additionally, quantitative risk assessment for CO₂ pipeline transportation was evaluated in several studies, some of them in the context of CCS projects (Chrysostomidis et al., 2009, Koornneef et al., 2009, Koornneef et al., 2010b).

Several millions of tonnes of CO₂ are already transported by pipelines, most of it being transported to enhanced oil recovery (EOR) fields. Pipelines linking several industrial regions can be shared, allowing the greatest emission reductions for the lower cost. A computer tool for economic analysis was developed within EU-funded GeoCapacity project to evaluate the CO₂ transportation systems based on low-cost pipeline networks to connect sources of CO₂ and storage reservoirs (Kazmierczak et al., 2009). Additionally, an engineering-economic model was proposed to evaluate the cost per ton of transporting CO₂ for a range of CO₂ flow rates, over a range of distances in the United States (McCoy and Rubin, 2008). Atmospheric dispersion of carbon dioxide after sublimation from a dry ice bank is of concern when dealing with safety criteria for the transportation of carbon dioxide in Carbon Sequestration projects (Mazzoldi et al., 2009, Chrysostomidis et al., 2009).



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FIGURE 4-2: EQUIVALENT VOLUMES OF CO₂ AT VARYING DEPTHS: CO₂ INCREASES IN DENSITY WITH DEPTH AND BECOMES A SUPERCRITICAL FLUID BELOW 0.8 KM. SUPERCRITICAL FLUIDS TAKE UP MUCH LESS SPACE, AS SHOWN IN THIS FIGURE, AND DIFFUSE BETTER THAN EITHER GASES OR ORDINARY LIQUIDS THROUGH THE TINY PORE SPACES IN STORAGE ROCKS. THE GREY NUMBERS IN THIS FIGURE SHOW THE VOLUME OF CO₂ AT EACH DEPTH COMPARED TO A VOLUME OF 100 AT THE SURFACE.

SOURCE: CO2CRC.COM.AU/IMAGELIBRARY3/CAPTURE.PHP

Before being transported, the CO₂ stream is conditioned to remove impurities and compressed into supercritical form. Captured CO₂ may contain impurities such as water vapour, H₂S, N₂, methane, O₂ and hydrocarbons. The water should be reduced to a lower percentage, as it reacts with CO₂ and other acidic compounds to form acids, which are corrosive (Koornneef et al., 2010a). The CO₂ transport in supercritical form (at pressures ranging 80-150 bar, CO₂ behaves as a compressible liquid with a density of gaseous CO₂ and relatively high pressure drops per unit of length (McCoy and Rubin, 2008, Haugen et al., 2009). Applying pressures higher than CO₂ critical pressure, temperature fluctuations along the pipeline will not result in the formation of gaseous CO₂ and difficulties encountered with two phase flow. The energy requirement for the conditioning processes will depend on the composition and pressure of the CO₂-rich stream and the selected transport process and is typically between 90 and 120 kWh/ton-CO₂ (Aspelund and Jordal, 2007). In ship transport most of the volatiles must be removed in order to avoid too cold temperatures and dry ice formation in the liquid CO₂. For pipeline transport, removal is not necessarily required; however, it makes sense from an economic point of view.

4.2 Pipeline Transport

An infrastructure must be developed to move CO₂ from its source to the storage site. Transporting large quantities of CO₂ is most economically achieved with a pipeline within a reasonably moderate distance. An important technical consideration in the design of CO₂ pipelines is that CO₂ should remain above its critical pressure. This can be achieved by recompressing the CO₂ at certain points along the length of the pipeline. Recompression is often needed for pipelines over 150 km (90 mi) in length. However, it may not be needed if a sufficiently large pipe diameter is used.

Natural gas pipelines are a good analogue to a CO₂ pipeline network for purposes of understanding costs. A survey of North American pipeline project costs yields several pertinent observations. First, for a given pipeline diameter, the cost of construction per unit distance is generally lower, the longer the pipeline. Second, pipelines built near populated areas tend to be more expensive. Finally, road, highway, river or channel crossings and marshy or rocky terrain also greatly increase the cost (True, 1998). Based on these data (cost for natural gas pipelines), Heddle et al. (2003) estimated costs for CO₂ transport. Economies of scale are reached with CO₂ flow rates in excess of 10 million metric tons per year (equivalent to CO₂ emissions from about 1500 MW_e of coal-fired power). At these flow rates, transport costs are under \$1 per metric ton CO₂ per 100 km.

Implementing pipeline networks is a classic “chicken and egg” problem. It is not worth building a pipeline network without a critical mass of capture plants to feed CO₂ into the network. However, without the transport infrastructure in place, it is much more difficult to develop CCS projects. CO₂ pipelines are not presently governed by regulatory regimes like those for oil and natural gas pipelines. However, as CO₂ pipeline networks grow, they will face increasing regulation.

Pipeline transmission of CO₂ over longer distances is most efficient when the CO₂ is in the dense phase, i.e. in liquid or supercritical regimes. This is due to the lower friction drop along the pipeline per unit mass of CO₂ compared to transmitting the CO₂ as a gas or as a two-phase combination of both liquid and gas. For CO₂ to transform from liquid to gas, heat must be added in the same way as heat must be added to convert liquid water to steam. For a pipeline, the heat ingress from the ambient is determined by the difference between the ambient temperature and the temperature of the CO₂ inside the pipeline, combined with the insulation properties of the pipeline. Above the critical temperature there is no noticeable phase change, hence when pressure is reduced from above to below critical pressure, a smooth enthalpy change occurs from super critical fluid to gas. Pure CO₂ has a triple point at -56.6°C and 5.18 Bara, which determines the point where CO₂ may co-exist in gas, liquid and solid state.

4.2.1 Design Requirements

A CO₂ onshore pipeline can, to a large extent, be planned and constructed in the same way as natural gas transmission pipelines. For both types of pipeline systems the following issues have to be considered:

- Routing
- Topography along the route (e.g. bedrock, flat or hilly terrain)
- Numbers of road and river crossings (e.g. micro tunnelling)
- The relationship between desired transport capacity, pipeline dimensioning (diameter), inlet and outlet pressure, steel quality and pipeline wall thickness
- Internal and external corrosion protection
- Compressors and/or pumps
- Rights of way (e.g. difference between agriculturally used area, sparsely populated or uninhabited areas and populated areas)
- Pigging.

The implications of the type and amounts of contaminants are not only limited to the individual effects but also how the different contaminants react with each other. Combined with free water, H₂S, NO_x, and SO_x, will form acids which may significantly increase corrosion rates. At the right combination of pressure and temperature and presence of free water, hydrates may form in a similar way as for natural gas.

The critical design parameter for a pipeline is the operating pressure. In addition, the temperature, gas composition, gas corrosivity, ambient temperatures and pipeline control are also important. The CO₂ will be transported as supercritical fluid to maximize the volume that can be transported. The CO₂ will be transported as a supercritical fluid in order to maximize the volume that can be transported. The gas composition depends on how good of a separation can be achieved from the flue gas of the power plant. Contaminants include H₂O, SO_x, NO_x, methane, and traces of other gases.

During the design of CO₂ pipelines, the Chinese can learn from two sources: from the U.S. engineering experience with CO₂-EOR pipeline construction and the American Petroleum Institute's recommendations; and from its own engineering experience from completing over 20,000 km of natural gas pipelines domestically.

Pipeline construction through geological hazard zones (earthquake prone regions, landslide prone regions, permafrost zones, etc.), geographically harsh zones (mountains, rivers, deserts, marshes, etc.), and densely populated regions should be avoided to minimize transportation risks and costs. If CO₂ transport pipelines must pass through sensitive areas (residential areas, ecologically fragile areas, or areas of frequent geological activity), the project operators need to take additional protective measure to ensure safe and stable pipeline operation. Possible methods include reducing the distance between pipeline shut-off and other operational valves, increasing pipeline burial depth, conducting added evaluation of pipeline seals, and increasing monitoring frequency.

- To guarantee the safety of pipeline transportation of CO₂, China should formulate CO₂ pipeline material standards, referring to the current Chinese natural gas pipeline standards and U.S. CO₂-EOR pipeline standards.
- Before formal implementation of CCS, China needs to specify which government departments will oversee CO₂ pipeline construction, ensuring the smooth implementation of different components.
- CO₂ pipelines must be closely monitored closely. Pipeline monitoring technology for CO₂ pipelines is fundamentally the same as that for natural gas pipelines. Monitoring methods include both uses of monitoring instruments as well as manual monitoring.
- In the case of a CO₂ pipeline accident affecting a body of water and/or the local soil, necessary recovery measures should be employed. (Zhaofeng et al., 2011)

It should be noted that the experience gained with transporting CO₂ on a large scale in the USA may not directly be applicable to other regions or situations. For instance, most CO₂ pipelines in the USA are situated in remote areas with low population densities. This influences the external safety and precaution measures taken. The deployment of CCS in other regions, e.g. Northwest Europe, will imply that a large network of CO₂ pipelines is needed which will be located in densely populated areas.

Pipeline control is important for providing continuous monitoring of the pipeline system. The system should be able to respond quickly to emergency situations. It should monitor key parameters such as the operating temperature and pressure of the pipeline, as well as the flow rate of gas through the pipeline system. The control system should be able to detect leaks and also provide predictions on the fatigue of the system. In order to ensure safety, block valves should be placed along the pipeline about every 10 miles. This prevents loss of pressure integrity of the entire pipeline, whereby sections can be isolated, limiting the amount of CO₂ released into the atmosphere. The ability of CO₂ to collect in depressions and other low-lying areas near the pipeline present a significant hazard if leaks continue undetected.

Another concern in pipeline design is the formation of hydrates in the pipeline. These can build up in the pipeline and cause the flow rate to drop or block off the pipe. With low percentage of water and methane in the system, this should not be a major problem but it must be addressed. Scrapers or “pigs” can be used to clean out the inside of the pipe. Pig launchers and receivers should be placed every 10 miles in order to speed up the pigging process and make shut down as short as possible. Injecting inhibitors such as methanol or salt solutions during the pigging process can minimize the hydrate formation. To transport the CO₂ from the point of capture to the site of storage, high-pressure pipelines are typically used. Carbon dioxide pipelines have been in use for many years. The optimal pipeline design under the required conditions can be calculated using an economic optimum:

$$D_{i,opt} = 0.363m_V^{0.45}\rho^{0.13} \quad \text{EQ. 4-1}$$

Where:

$D_{i,opt}$ = economic inside diameter (inches)
 m_V = required volumetric flow rate (MMscf/day)
 ρ = supercritical density of CO₂ (lb_m/ft³)

The Barlow and Lamé equation (Department Of Transportation, 2004) can be used to calculate the required wall thickness under the required condition:

$$t_m = \frac{PD_o}{2(SE + PY)} + C \quad \text{EQ. 4-2}$$

Where:

t_m = pipe wall thickness (inches)
 P = design pressure (psia)
 D_o = outside diameter of pipe (inches)
 S = basic allowable stress
 E = quality factor
 Y = yield strength

TABLE 4-1: PIPELINE DIAMETER CALCULATION ASSUMPTIONS(GAO ET AL., 2011)

Parameter	Symbol	Value
CO ₂ mass flow rate (t/d)	M	4000
Average Temperature (°C)	T _{ave}	14
CO ₂ inlet pressure (MPa)	p ₁	15.2
CO ₂ outlet pressure (MPa)	p ₂	10.3
Altitude difference (m)	h ₂ -h ₁	0
Pipe length (km)	L	300

Rubin's model (McCoy and Rubin, 2008) concludes an iterative methodology for calculating CO₂ pipeline diameter. A series of equations is illuminated in the publication (Boyce, 1997, Zigrang and Sylvester, 1982, Mohitpour et al., 2003), and here we only list the kernel equation for pipeline diameter (D):

$$D = \left\{ \frac{-64Z_{ave}^2 R^2 T_{ave}^2 f m^2 L}{\pi^2 [MZ_{ave} R T_{ave} (p_2^2 - p_1^2) + 2gP_{ave}^2 M^2 (h_2 - h_1)]} \right\}^{\frac{1}{5}} \quad \text{EQ. 4-3}$$

where Z_{ave} is the average compressibility factor; R is the universal gas constant (Pa m³/mol K); f is the Fanning friction factor; P_{ave} is the average pressure (Pa).

Whenever CO₂ pressure is lower than 10.3 Mpa during the transportation, a booster is needed. With pipe nominal diameter settled based on equation (1), the max length of pipeline without booster can be calculated:

$$L_{max} = \frac{(D_o - 2t)^5 \pi^2 [MZ_{ave} R T_{ave} (p_2^2 - p_1^2) + 2gP_{ave}^2 M^2 (h_2 - h_1)]}{-64Z_{ave}^2 R^2 T_{ave}^2 f m^2} \quad \text{EQ. 4-4}$$

Also, with a settled pipeline length, based on equation (1), the actual CO₂ outlet pressure (p_{2a}) can be calculated:

$$p_{2a} = \left\{ \frac{\left[\frac{-64Z_{ave}^2 R^2 T_{ave}^2 f m^2 L}{(D_o - 2t)^5 \pi^2} - 2gP_{ave}^2 M^2 (h_2 - h_1) \right]}{MZ_{ave} R T_{ave}} + p_1^2 \right\}^{1/2} \quad \text{EQ. 4-5}$$

In consideration of longer distance transport cases, a balance should be made between pipeline diameter and the number of booster stations (if required).

4.2.2 Operations

The importance of continuous monitoring of the water content in the CO₂ stream at the inlet to the pipeline is essential to prevent several of the most likely failure modes. Existing CO₂ pipelines in operation applied automatic shut-down if the dewatering system does not meet the water content specification, which has proven to be efficient in preventing both internal corrosion and hydrate formation. Another concern is to control and monitor additional impurities from a mixture of several CO₂ streams, such as methane (CH₄), hydrogen (H₂), nitrogen (N₂), sulphur oxides (SO_x), nitrogen oxides (NO_x), which may affect the CO₂ with respect to flow, pressure, water drop out and hydrate formation. The effects of contaminants may also have implications on the pipeline response during shut-in and/or depressurization.

Based on operational experience with existing CO₂ pipelines, one of the main concerns related to pipeline depressurization is the potential risk for formation of solid state CO₂. If solid CO₂ is formed, a considerable amount of time may be required for the CO₂ to sublime. The sublimation time will depend on the ambient temperature and the pipeline insulation properties. A too rapid depressurization will also cause a rapid cool down of the pipeline, potentially causing detachment of external coating when the pipe diameter contracts. Formation of solid state CO₂ may be prevented by appropriate setting of the depressurization rate. Hence, depressurization of a longer section of a CO₂ pipeline may take a considerable amount of time, and have a significant impact on the availability of the pipeline.

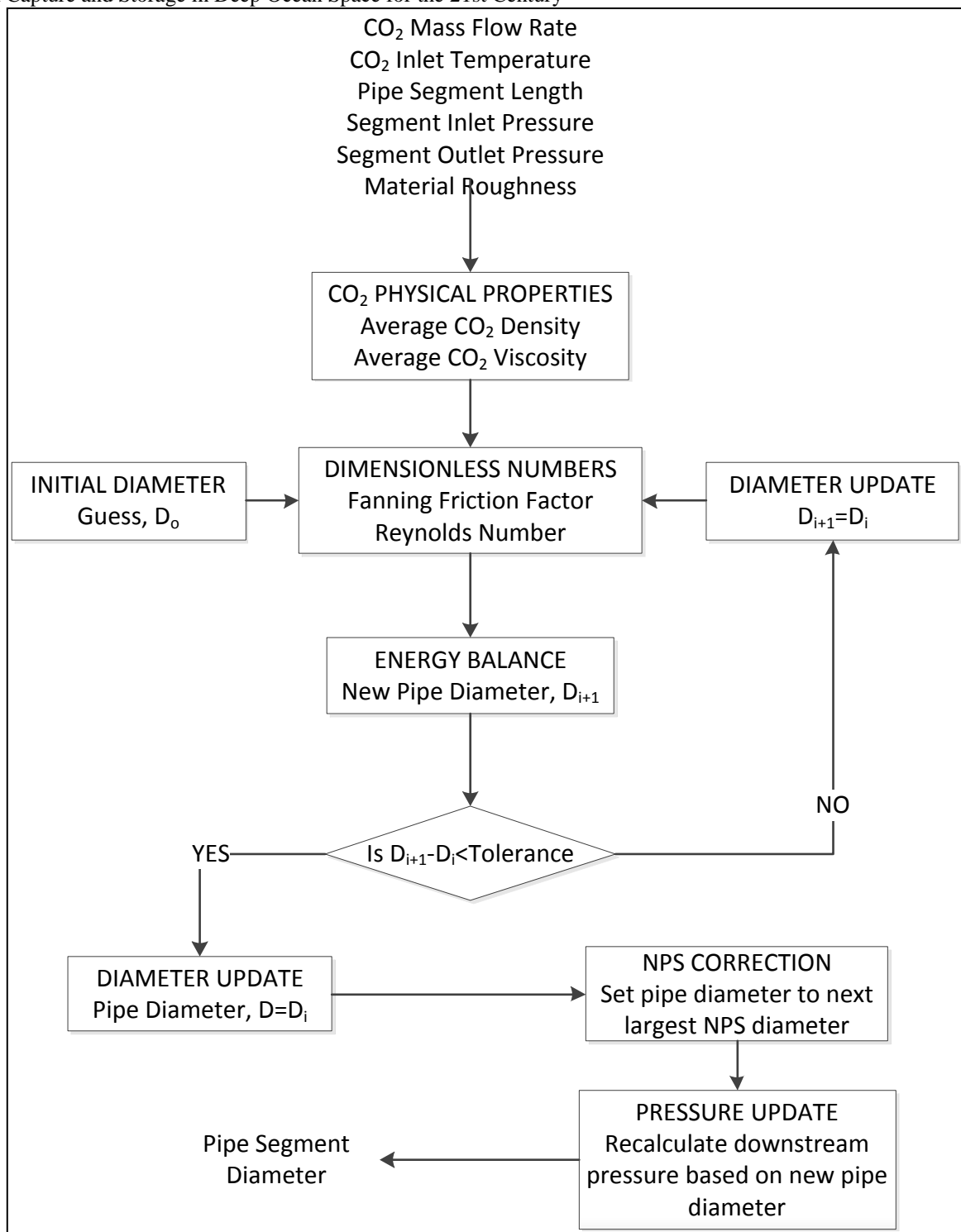


FIGURE 4-3: FLOWCHART ILLUSTRATING THE CALCULATION METHOD USED TO ESTIMATE THE PIPELINE DIAMETER (ADAPTED FROM (MCCOY AND RUBIN, 2008))

4.2.3 Corrosion Issues

For a carbon steel pipeline, internal corrosion is a significant risk to the pipeline integrity in case of insufficient dewatering of the CO₂ composition. Free water combined with the high CO₂ partial pressure will give rise to extreme corrosion rates, primarily due to the formation of carbonic acid. Presence of other contaminants/ impurities such as H₂S, NO_x, or SO_x will also form acids which in combination with free water will have a significant effect on the corrosion rate.

Internal corrosion may lead to a pin-hole leak that can be detected by a leak detection system. The time it takes to depressurize the pipeline may be significant depending on the size and length of the pipeline and/ or the distance between block valves. In worst case, internal corrosion may cause pipeline rupture with a subsequent large instantaneous release of CO₂. Because an acid gas is being transported through the pipeline, corrosion must be checked biannually at intervals no greater than 7.5

months. Adding inhibitors or preventative coating to the inside surface of the pipeline via pigging can reduce this corrosion. If this corrosion is not caught as soon as possible, the lifespan of the pipeline will be greatly reduced and it will have a negative impact on the overall economics (Robertson, 2007).

From the long operational experience with onshore CO₂ pipelines in North America, internal corrosion is not experienced as a significant pipeline failure mode. According to the U.S. Department of Transportation's Office of Pipeline Safety, there are no reported pipeline damages caused by internal corrosion. Based on discussions with the pipeline operators this is mainly due to the high focus on measured water content in the CO₂ before the stream enters into the pipeline, and the strict procedures for shutting down the line in case the dewatering system cannot meet the specifications. Application of corrosion resistant steels for longer pipeline sections is generally not considered feasible from a cost perspective. However, it may be an option for shorter pipeline sections considered particularly critical.

4.2.4 Safety of CO₂ pipelines

In the case of pipeline leakage, the greatest risk for workers and residents in the immediate vicinity is the leakage of H₂S involved in CO₂ stream. Therefore, extra attention should be given to H₂S hazards and strict limits should be placed on H₂S contents in the pipeline. For projects transporting CO₂ with high H₂S contents, additional H₂S-specific monitoring equipment and inspection frequency may be required.

At present, China does not have regulations specific to CO₂ pipeline. Under the existing legal system, CO₂ pipelines would be classified as "pressurized pipelines" and fall under the jurisdiction of the "pressurized pipelines safety management and supervision requirements". However, CO₂ pipeline management safety provisions can also refer to oil and gas pipeline safety rules and regulations. Additionally, the relevant department may respond for the CO₂ pipeline supervision and management.

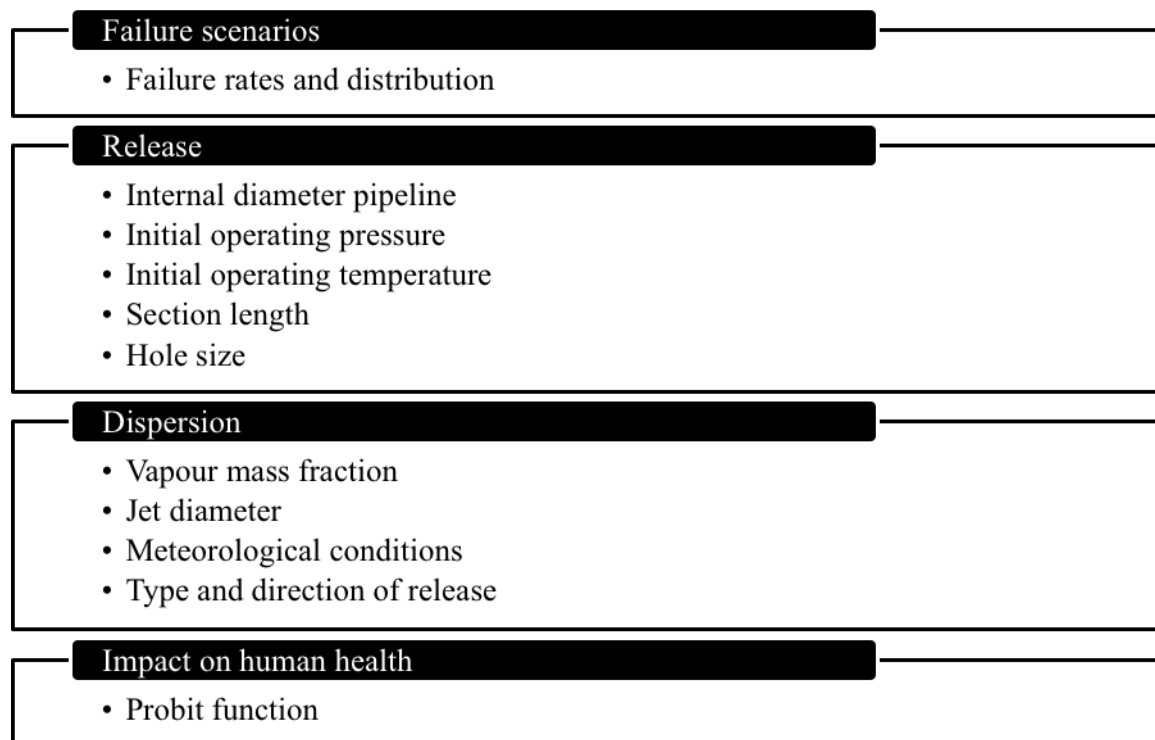


FIGURE 4-4: OVERVIEW OF IMPORTANT STEPS TO BE CONCLUDED IN A QUANTITATIVE RISK ASSESSMENT. PER STEP THE METHODOLOGICAL CHOICES ARE INPUT PARAMETERS EVALUATED IN THIS STUDY ARE SHOWN

In addition to technical efforts, concerted efforts to raise public awareness of the CO₂ pipeline and associated risks amongst local residents is critical for obtaining public acceptance of the project and reducing the probability of accidents for potential hazards.

4.2.5 Risk Mitigation

Risk can be defined as the product of the probability and effect of an accidental adverse event. Performing a quantitative risk assessment (QRA) for CO₂ pipelines first involves the determination of failure scenarios. These failure scenarios have a certain probability attributed to them based on expert judgment or heuristics: in this case experiences with pipeline operations and failures. To estimate the effect, or impact, of a failure scenario, dedicated models are used to calculate the release and dispersion of escaping CO₂. The exposure of local residents to CO₂ is then modelled by estimating the concentration of CO₂ at a certain location after an elapse of time. With a probit function the relationship between exposure at CO₂ and the effect on human mortality rates can be integrated into the calculations.

Two types of failure scenarios are considered in general when performing a QRA for pipelines, namely a puncture and a full pore rupture. A failure is caused predominantly by third party interference, corrosion, construction or material defects (e.g. welds), ground movement or operator errors. Overall, cumulative failure rates assumed in studies on the risks of CO₂ pipeline ranges from 0.7 to 6.1 per 10,000 km per year. The fact that failure rates assumed are often based on natural gas pipelines or pipelines in general is a shortcoming. Natural gas pipeline failure rates may not be valid for CO₂ pipelines due to its properties during transport. In addition, failure rates for CO₂ pipelines based on historical accidents cannot be compared straightforwardly with those of natural gas pipelines given the limited cumulative experience with CO₂ pipelines.

Typical properties of CO₂ transport that may justify using different, i.e. higher, failure rates for CO₂ pipelines are the acidity of the CO₂ when dissolved in water and the presence of impurities in the CO₂ stream. Both may lead to corrosion. At least three of the 36 incidents between 1994 and 2007 concerning CO₂ pipelines in the USA were caused by corrosion (IPCC, 2005). Minimizing water content in the CO₂ flow is therefore important. Experience with pipelines suggests that corrosion rates are very low if the free water content is sufficiently low. Next to free water content other impurities such as SO_x, NO_x, O₂, and H₂S may increase corrosion rates which may lead to higher failure frequencies if not addressed properly.

Typically, a dispersing heavy gas will form a cloud that moves close to the ground, its progress being influenced heavily by local topography and obstructions. The dispersion of a heavy gas is different from gases that are lighter than air, e.g. natural gas. According to Britter and CPR, the following reasons can be identified for difference:

- The substance is typically stored in a liquid phase which represents a very large volume of gas.
- The release is usually transient and can be a mixture of phases.
- The formation of the gas cloud typically involves phase changes.
- Heat and mass transfer with underlying surface are likely to occur.
- The substance encounters gravity-induced spreading.
- The density variations may reduce vertical mixing by stratification of the dispersing cloud.

These characteristics certainly apply to the dispersion of CO₂ as the substance is likely to be transported in a liquid phase. As a consequence, during release, phase transitions are expected to occur which may result in the transfer of heat and mass with the surface, e.g. in the case of dry ice fallout.

The limitation of the dense gas dispersion model and the release model is that they have not been specifically developed for CO₂. Moreover, they have been developed for the gas/liquid phase only and are therefore not equipped to address the solid phase appropriately.

Risk-mitigation measures are typically aimed at:

- 1) Reducing the exposure to a failure mechanism;
- 2) Increasing the resistance to a failure mechanism;
- 3) Mitigating the effect of a failure; and
- 4) Limiting the impact of a failure on the environment.

The first two are focussed on reducing the probability of failure and the latter two on mitigation or remediation of the consequences of a failure. The mitigation of risk is possible by implementing available technical, administrative and social-psychological measures that may address any of these goals.

Whether the risks of CO₂ pipelines are formally or legally acceptable will strongly depend on local conditions like population density and other risk-bearing activities. Whether the risks are socially acceptable will depend on public attitude. This is determined by psychological factors merely a quantified representation of the risk presented in the form of an individual risk contour.

4.2.6 *Costs*

The cost of pipeline transport will be controlled by the pipeline route with the physical and geographical constraints playing important roles, as well as the characteristics of the pipeline itself, such as the pipeline length, diameter, material, amount and sharpness of bends and the need and number of booster stations (IPCC, 2005). Researchers have claimed different cost estimates (Liu, 2007, Bock, 2003). Diameter calculation is considered as a crucial step in the cost estimation of CO₂ pipeline transport by many researchers (McCoy and Rubin, 2008, Vandeginste and Piessens, 2008, Bock, 2003). One plausible method is the calculations that are based on hydraulic laws. Regulations to the compositions of the transported CO₂ have been specifically explained by many researchers (Vandeginste and Piessens, 2008).

4.2.7 *Issues*

In concentrations of approximately 5% (50,000 ppm) the gas causes an increase in respiration along with a number of other symptoms, such as headache, breathing difficulty, palpitation, dizziness and weakness. Consequently, 5% concentrations are assumed to be the lower limit for adverse human effects. Above 10 vol% (100,000 ppm) the gas causes instantaneous unconsciousness and will be lethal unless the victim is quickly removed. Consequently, 10% can be considered as the upper limit for survival. If the concentration is 20% or above the gas is instantaneously fatal.

Immediately after release the concentration will be highest in the centre of the gas cloud with falling gradients to the sides because of intensive mixing with ambient air. Due to the wind the plume is dispersed the most at the rear edge, whereas high concentration gradients persist at the front edge of the plume. The criterion for a safe distance to the pipeline is based on the time dependence concentration profile, where the lower limit (50,000 ppm) as well as the time of exposure for this concentration are emphasized. During the time of exposure concentrations higher than 50,000 ppm will occur. In order to prevent serious adverse effects the maximum exposure time is not to exceed a defined maximum of 1 minute for concentrations higher than 50,000 ppm, regardless of the distance from the pipeline.

The emission from the pipeline has been determined on the basis of physical and thermodynamic calculations of the gas/ liquid as it escapes the pressurized pipeline. As a rupture is in effect a large leak, the period of time taken for a large amount of CO₂ to be discharged would be short, i.e. adiabatic expansion of the CO₂ occurs. In the modelling studies, a worst-case emission is assumed, defined by a complete pipe rupture right between two check valves causing outflow from two pipe ends.

When transported in liquid form the CO₂ escape scenario is not very different. Initially there will be a large pressure drop in the pipeline as the liquid is virtually incompressible, the pressure will fall until

liquid becomes a mixture of saturated vapour/liquid. In the vicinity of the rupture, liquid CO₂ will escape and immediately vaporize and expand, some of the liquid will even sublime into dry ice, which will precipitate onto the ground. This will take place over a very short period of time. After the pressure fall the flow profile of the escaping gas will almost be as described for gaseous CO₂ transport.

The segment is equipped with check valves at both ends. Along the pipe sensor devices are installed registering the rupture, which will cause actuators to seal the pipe and throttle down the compressors. Until the valves are completely shut, gas/liquid will continue to flow into the damaged segment. This flow has been disregarded in the calculations because it will have no influence on the amount included in the initial puff. However, it will increase the total amount released from the segment. (Kruse and Tekiela, 1996)

4.3 Liquefaction

Large scale liquefaction of CO₂ is best achieved in an open cycle, using the CO₂ feed as refrigerant where the refrigeration is partly or fully provided by the feed gas itself. The CO₂ feed is first compressed in stages to a pressure higher than the transport pressure. The CO₂ is cooled by ambient air or water after each compressor stage. At the highest pressure height is rejected from the CO₂ through contact with an external cooling circuit (heat exchanger typically utilizing seawater).

Water must be removed to avoid hydrates, freezing of the water and corrosion. The solubility of water in CO₂ gas decreases with high pressure and lower temperatures. Therefore, most of the water should be removed after compression and cooling with gas scrubbers. The last free water is removed at a pressure between 20 and 40 bar and at a temperature close to the hydrate formation curve. The CO₂ gas is dried to ppm level by adsorption. (Aspelund et al., 2006a, Aspelund et al., 2004)

4.4 Intermediate Storage

The CO₂ is stored at the bubble point in semi-pressurized storage tanks until the ship berths at quay. The design of the storage facility has to be flexible regarding size, place and ground conditions as the need for storage volume, and variations in geographical location. The total storage capacity should be set to 1.5 times the capacity of the ship. Semi-pressurized storage is common for other liquefied gases, such as LPG and ethylene. The most common method is using semi-pressurized spheres, semi-pressurized cylindrical tanks or underground storage in caverns. The pressure vessels can be placed above the ground on racks or they can be placed on the ground where they are partly or fully covered. (McGurie and White, 2000)

4.5 Loading System

The loading system at quay transfers liquefied CO₂ from the storage tanks at the liquefaction plant to the ship. The loading system includes all the necessary piping between tanks and ship, as well as pumps, marine loading arm and export building. The recommended solution consists of two parallel product pipes between the tanks and the loading arm for export of CO₂ and a return line for CO₂-vapour generated at the ship.

The loading system equipment and materials have been carefully chosen by looking at their resistance to corrosion and low temperature, the need for maintenance, costs and availability. Also procedures for loading are developed to prevent operational problems with dry-ice formation or problems with thermal cycling.

4.6 Ship Transport

There are several key factors that make shipping CO₂ attractive.

- The initial investment required for this method of transport is much less expensive than pipeline construction.
- CO₂ shipping is a discrete transport solution that offers more flexibility in transporting over long distances, compared to a pipeline that maintains a continuous flow.
- Shipbuilding can be customized to suit client's demand and do not require much lead-time.
- CO₂ shipping has less stringent regulatory approval issues when compared to pipelines, for which said approvals can represent significant problems in CCS project development.

In spite of these advantages, ship transport has been regarded as a short-term measure only for demonstration projects because pipelines are considered a more economical solution, especially for short distances and large amounts of CO₂ transport.

IPCC SRCCS and other research concluded that the break-even distance, i.e. the distance for which the costs per transport mode are the same, is in the range between 1,000 km and 1,500 km for transporting 6 Mt/yr. This paper will review recent technical development which can make CO₂ shipping more cost effective and will suggest that CO₂ shipping should be considered as a competitive alternative for CO₂ transport in shorter distance than 1,000 km as well.

Semi-pressurized ships are usually designed for a working pressure of 5-7 bara and operate at low temperatures (-48°C for LPG, -104°C for ethylene). This is the most frequent type of ship for LPG transport up to nearly 20,000 m³. Such vessels have normally two to six tanks, and each tank may have a capacity of 4500 m³. It may be possible to convert existing LPG ships for CO₂ transport. However, since CO₂ is transported at slightly higher pressures and densities, and lower temperatures than LPG, some difficulties may arise.

The design of a tanker ship is dictated to a large extent by the international maritime regulations, class regulation as well as the conventional ship design parameters that control drag, manoeuvrability, weight, stability, freeboard and relative strength. In addition, the shipyard production line may affect the dimensions of the ship.

The concept suggested is a combined LPG/ CO₂ semi-refrigerated ship with a total capacity of 20,000 m³, adapted to both submerged turret loading (STL) unloading offshore and direct terminal/terminal service. The reasons for choosing a combined LPG/ CO₂ ship are increased remaining value, and the possibility of improving ship utilization. The need for re-condensation equipment on board depends on whether the ship will also be used for LPG transport and on the distances for CO₂ transport. The ship is equipped with the necessary elements (heat exchanger, pump, and so on) so that CO₂ can be heated to 0°C previous to unloading offshore.

In fully refrigerated conventional LPG and LNG ships the cargo is kept in liquid phase at atmospheric pressure by refrigeration only. CO₂, however, cannot exist as a liquid at atmospheric pressure due to its triple point at 5.2 bar and -56.6°C. At lower pressures or temperatures, CO₂ will exist either as vapour or in solid state as dry ice. The sublimation point of CO₂ at atmospheric pressure is -78°C. The density of solid CO₂ is approximately 1500 kg/m³. Solid CO₂ can be transported as dry cargo on ships, but seems economically unfeasible mainly due to complex loading and unloading procedures.

In semi-pressurized ships the gas to be transported is kept in liquid phase on the saturation line by a pressure higher than atmospheric pressure and a temperature lower than ambient temperature. CO₂ exists in liquid form between 5.2 bar (triple point, TP) and 73 bar (critical point, CP). The density of saturated liquid will range from 1200 kg/m³ at the TP to 600 kg/m³ at the CP. So in a fixed volume vessel almost two times more CO₂ can be transported at low pressures near the TP than at high pressures near the CP. (Aspelund et al., 2006b)

Additionally, the lowest pressure possible is desirable to minimize production cost of the pressure vessels on the ship. The required energy to liquefy CO₂ at lower pressure, though this is marginal compared to the benefits of higher transport capacities and less costly vessels. (National Institute of Standards and Technology, 2005)

In order to assess the costs and feasibility of CO₂ transport by ship aiming the use for CCS, the International Energy Agency Greenhouse Gas R&D Programme (IEA GHG) performed a study of “Ship Transport of CO₂” in 2004 (IEA, 2004, Ozaki et al., 2004), and the results were referred in the chapter of “Transport of CO₂” in IPCC Special Report on CCS (IPCC, 2005). For large-scale temporary storage and transport of liquefied gas, the design pressure of cargo condition tends to be determined as modest as possible with trading off against necessary low temperature. Referring the phase diagram of CO₂, the cargo conditions for such large ship were set around -50°C in temperature and 0.6 to 0.7 MPa in pressure.

4.6.1 Shipping Advantages

- Ships can be added to or removed from the transport fleet to meet fluctuations in demand, while a pipeline need be sized for future transportation growth during its initial construction.
- Shipping CO₂ is a flexible option. The vessels can be used after the CCS project is completed and be converted to the standard gas tanker trade.
- Shipping CO₂ is flexible throughout the life of the project, as it allows the client to alter the loading and unloading locations as needed.
- The lead-time of the shipping solution is usually less than the construction of a pipeline.
- China has sufficient port infrastructure to accommodate any CO₂ shipments

4.6.2 Costs

Here, the cost includes both of capital and operating due to CO₂ compression, liquefaction, temporary storage at port, and shipping.

- The cost depends mainly on the ship size and the transport distance. Larger ships result in lower costs per ton-CO₂, but the scale merit seems saturated when the ship size reaches a certain scale.
- The cost of short distance transport depends weakly on the distance. It is because the running cost of the liquefaction system accounts for a significant portion of the cost and the impact of ships and storage tanks are not so large in total.
- Pipeline costs are mainly determined by CAPEX (capital expenditure) and are roughly proportional to distance. They therefore benefit significantly from economies of scale and full capacity utilisation.
- Ship transport costs are less dependent on distance and on scale of transport. CAPEX is proportionally lower than for pipelines and ships have a residual value in hydrocarbon gas transportation which significantly reduces the financial risk.
- Combining pipes and ships for offshore networks could provide cost-effective and lower risk solutions, especially for the early developments of clusters.
- For large-scale transport, long range and central planning can lead to significantly reduced long-term costs.

TABLE 4-2: MERITS AND DEMERITS OF CCS BY MEANS OF SHUTTLE SHIPS AND SOCKET BUOYS

Merits	Demerits
<ul style="list-style-type: none"> • Flexibility for plan change, e.g. route, injectivity, stepwise expansion of CCS project • Water depths and transport distance could be easily increased • Decommissioning is easy • Relocation and reuse of the system is easy • System redundancy is high 	<ul style="list-style-type: none"> • Cost is higher than optimized pipeline transport • Shipping skill is necessary • Operation is affected by sea conditions • Additional CO₂ will be emitted from ship engine

5 CARBON STORAGE INJECTION METHODS

Long-term storage of CO₂ is the final step in carbon management. Although the cost of storage accounts only for a small portion of the total cost, it may well be the most difficult step in the value chain for carbon management. The challenge will grow over time as the volumes that will need to be stored increases rapidly. At present the world is releasing about 8.5 Gt/year of carbon, or about 30 Gt of CO₂, into the environment. As mentioned before, storage volumes over the century could easily amount to several thousand gigatons of CO₂. Many different technologies have been suggested for long-term CO₂ storage. These include storing CO₂ in the ocean, in geological formations, and through mineral sequestration, which involves the formation of solid carbonates from CO₂ and minerals.

Power plant designs and CO₂ storage are usually very distinct operations. The requirement of the power plant operator is to deliver a stream of concentrated CO₂, which typically will have to be pipelined to the site of disposal. Any capture scheme can be combined with any disposal scheme. There are a few exceptions in which the sorbent used in the power plant is directly disposed of.

Although the CCS technology is still too new to settle on a single approach, any storage option that would be useful beyond small niche markets must possess the following properties: have a large capacity, be safe, be environmentally benign, and guarantee the long-term stability of storage. Storage lifetime constraints will become more stringent over time.

5.1 Offshore Platform Types

Offshore structures are used worldwide for a variety of functions and in a variety of water depths, and environments. As the right selection of equipment, types of platforms and method of drilling and accompanied by adequate planning, design, fabrication, transportation, installation and commissioning of petroleum platforms are all dependent on water depth and the environmental design conditions, it is critical that they are carefully examined. Different types of offshore oil rigs and platforms are used depending on the offshore water depth and environmental situation. Several types of offshore structures are described below.

5.1.1 Semi-submersible platforms/rigs

This is an offshore oil rig that has a floating drill unit that includes columns and pontoons that, if flooded with water, will cause the pontoons to submerge to a predetermined depth. Semi-submersible rigs are the most common type of offshore drilling rigs, combining the advantages of submersible rigs with the ability to drill in deep water. Semi-submersible rigs work on the same principle as submersible rigs; through the 'inflating' and 'deflating' of its lower hull. The rig is partially submerged, but still floats above the drill site. When drilling, the lower hull, filled with water, provides stability to the rig. Semi-submersible rigs are generally held in place by huge anchors, each weighing upwards of ten tons. These anchors, combined with the submerged portion of the rig, ensure that the platform is stable and safe enough to be used in turbulent offshore waters. Semi-submersible rigs can also be kept in place by the use of dynamic positioning. Semi-submersible rigs can be used to drill in much deeper water than the rigs mentioned above. Now with a leap in technology, depths of up to 6,000 feet (1,800 m) can be achieved safely and easily.

5.1.2 Seastar platforms

Seastar platforms are like miniature tension leg platforms. The platform consists of a floating rig, much like the semi-submersible type discussed above. A lower hull is filled with water when drilling, which increases the stability of the platform against wind and water movement. In addition to this semi-submersible rig, however, Seastar platforms also incorporate the tension leg system employed in larger platforms. Tension legs are long, hollow tendons that extend from the seafloor to the floating

platform. These legs are kept under constant tension, and do not allow for any vertical movement of the platform. However, their flexibility does allow for side-to-side motion, which allows the platform to withstand the force of the ocean and wind. Seastar platforms are typically used for smaller deep-water reservoirs, when it is not economical to build a larger platform. They can operate in water depths of up to 1200 meters.

5.1.3 Tension leg platforms

Tension leg platforms are larger versions of the Seastar platform. The long, flexible legs are attached to the seafloor, and run up to the platform itself. As with the Seastar platform, these legs allow for significant side to side movement (up to 20 feet), with little vertical movement. Tension leg platforms can operate as deep as 7,000 feet.

5.1.4 Subsea system

Subsea production systems are wells located on the sea floor, as opposed to at the surface. As in a floating production system, the petroleum is extracted at the seafloor, and then can be connected to an already existing production platform. The well can be drilled by a moveable rig and instead of building a production platform for that well, the extracted oil and natural gas can be transported by a riser or even undersea pipeline to a nearby production platform. This allows a single strategically placed production platform to service many wells over a reasonably large area. Subsea systems are typically in use at depths of 7,000 feet or more, and do not have the ability to drill, only to extract and transport.

5.2 Summary of Offshore Construction Project stages

Similar to the other fields of activities, the offshore platform construction services can be provided on a turn-key basis, i.e. covering investment feasibility studies, basic and detailed design, procurement, installation of steel structures and equipment, and commissioning. All or any of the above listed work stages can be performed under the supervision of an independent certifying authority followed by the issue of a certificate of class.

Basically an offshore platform construction project includes the following phases:

- Investment feasibility studies
- Construction site survey including diving inspections of installation locations
- Conceptual, basic and detailed design
- Platform element strength calculations
- Design approval by the regulating authorities
- Procurement
- Fabrication of steel structures
- Preparation of platform elements transportation and offshore installation procedures
- Loadout, transportation and installation operations
- Commissioning

The design and analysis of offshore platforms must be done after taking a number of factors into consideration, including the following parameters:

- Environmental (initial transportation, and in-place 100-year storm conditions)
- Soil characteristics
- Code requirements (e.g. American Institute of Steel Construction “AISC” codes)
- Intensity level of consequences of failure

The successful design and operation of floating production units involves consideration of the environmental conditions and the appropriate evaluation of the environmental loads that prevail during

transportation, installation and operation. There is a trend subscribed by the classification societies to extend the relevant classification notes to include guidance for specific contributions from environmental loadings, which have usually been ignored in the past.

5.3 Design Considerations

Some of the key parameters influencing the selection process of a FPS configuration are:

- Water depth
- Environmental conditions
- Preferred hull type(s) and construction material(s)
- New-build vs. conversion
- Transportation and installation
- Service life
- Storage requirements
- Regulatory requirements for re-use

Each of these parameters is described below.

- a. Water depth: Horizontal excursion of the mooring system is influenced by the water depths as different mooring systems have different depth capabilities. Some hull types may have a minimum water depth requirement.
- b. Environmental Data: Performance of different concepts depends on the harshness and characteristics of the environment. For example, a FPS with long natural periods would exhibit less wave-induced motion than one with shorter natural periods and, therefore, would have less downtime due to weather. A FPS with a low natural period may experience a large number of cyclic loadings in normal environmental conditions, which may result in significant fatigue damage. Vortex induced motions may also influence the design of some systems. Thus, in the selection process, the performance characteristics of various concepts in a site specific environment should be evaluated and considered in the design process.
- c. Preferred hull type and construction material: Based on a FPSOs functional requirements, design environmental conditions, preferred well system configuration, capability and availability of fabrication facilities, consideration of new-build vs. conversion, and project economics, the owner/operator may have preference of one hull type over the other. Although the hull construction material is very likely to be steel, its properties may vary depending on the type of application. For example, steel used for a ship hull designed for operating in warm Gulf of Mexico climate may not be suitable for use in the colder environment of the North Sea.
- d. New build vs. conversion:

Reusing an existing ship or column stabilized vessel may provide an economically viable alternative under certain circumstances. In many cases, schedule and cost considerations may lead to the decision of converting an existing vessel to a FPS. There are other situations where a new purpose-built FPS may prove to be economical in the long run.

Both new purpose-built facilities and converted existing facilities are valid options for FPSs. The following are some of the considerations for deciding whether to convert or build a new vessel:

1. Field-specific considerations
 - i. Expected field life
 - ii. Field development schedule
 - iii. Coastal governmental regulations
 - iv. Mission requirements
 - v. Environmental conditions
2. Overall economic considerations
 - i. Availability of a suitable existing vessel
 - ii. Construction/modification and installation cost
 - iii. Operating cost

- iv. Delivery time
 - v. Functional capability
 - vi. Expected service life
 - vii. Environmental and personnel safety issues
- e. Transportation and installation: Fabrication location, distance to the offshore location, and available marine installation equipment are all factors that should be taken into account when selecting the hull type.
- f. Service Life: This can affect environmental design return periods and fatigue performance requirements, outfitting for corrosion protection, in situ inspection philosophy, etc. Some configurations may be better suited for long service lives in harsh environments. Some configurations are also better suited for relocation and reuse

The FPS is likely to face issues related to equipment interfaces between dissimilar systems, both for conversion and new-build FPSs. An example of this is the interface between the electrical systems on a ship and that of the production equipment, well control equipment, and connections to a platform. Some of the major interface areas are:

- Electrical
- Cargo handling systems
- Air, water, and drainage utility systems
- Ballast and bilge systems
- Fire protection/gas detection
- Lighting
- Fuel system and source
- Emergency shutdown systems
- Lifesaving appliances
- Personnel safety equipment

5.4 Engineering Requirements

The CO₂ will arrive at the oil field in the ships at 6.5 bar and -52°C. In order to overcome the reservoir pressure and avoid hydrate and wax formation, the inlet conditions to the wellhead will be at 200-300 bar and 15-20°C. The offshore unloading system will be connected to the platform via a riser and a seabed pipeline for transfer of the CO₂, and must be able to keep the vessel at a safe distance from the platform. The availability of the unloading system is of high importance to ensure a cost-effective transport chain. Furthermore a high unloading rate is important to reduce the vessel's turnaround time and hence reduce the total transport costs.

The offshore unloading system basically includes:

- A submerged turret loading (STL) system;
- A submerged carbon pump in the cargo tank and a booster pump on the ship deck;
- A CO₂ heating system on the ship and/or a waste heat recovery system at the platform;
- A flexible riser from the ship to the seabed;
- A pipeline at seabed;
- A pipeline from seabed to platform deck;
- A pumping system on the platform for pressure increase up to injection pressure; and
- An expansion system on the platform to avoid pressure build-up in the transfer lines between transmissions. ([Aspelund et al., 2006](#))

In the most flexible solution the CO₂ is pumped to a pressure somewhat higher than the injection pressure, before it is heated to ambient temperature and transferred to the injection manifold on the platform for re-injection. This solution is valid for most offshore installations. In warm waters the heating can be provided by heat exchangers using seawater as heating media. In the North Sea, with temperatures as low as 5°C, heating with seawater is not technically preferable due to icing in the heat

exchangers. Therefore, heating of the CO₂ will require a separate heating system, which will increase both the capital and operational costs. Moreover, there will be a significant increase in CO₂ emissions due to burning of fuel for the heating process. To avoid high-pressure transfer lines, pumping from 60 bar to the required injection pressure may take place on the platform.

If waste heat and sufficient space for an additional heat exchanger and pumps are available on the platform, the CO₂ should be heated on board the platform. The liquid CO₂ is pumped by the booster pump to 50-60 bar in order to avoid flashing of CO₂ in the transfer system. The cold CO₂ is unloaded through the transfer system at -45°C. On the platform, the CO₂ is heated to 10-20°C by waste heat before it is pumped to 200-300 bar. The main advantage is the utilization of excess waste heat on the platform. At as low temperatures as -50°C many materials become brittle. Hence, it is a challenge to design a flexible riser for such cold liquids. Icing in the STL and on the flexible riser may also cause problems if not properly designed for. Moreover, ice formation on the subsea transfer lines will act as an insulating layer and reduce the heat transfer to the pipeline significantly.

Also depressurization of the transfer line is a challenge when unloading CO₂ at low pressures and temperatures. The ship is an important part of the total costs in the transport chain and an efficient utilization is necessary. Therefore continuous unloading from the ship will be too costly. Technically an intermediate storage of CO₂ could be a possibility; however, this is cost-intensive. Hence, in order to keep the unloading time at a minimum, the CO₂ will be injected in batches at high rates while the CO₂ ship is connected to the transfer system. Between the batches of CO₂, produced water may be injected. Batch-wise injection of CO₂, water and natural gas may actually be favourable, from a reservoir standpoint. (Aspelund et al., 2006)

To avoid depressurization of the unloading system between each discharge operation, the system is kept at transmission pressure. As cold liquid CO₂ is heated from the surrounding seawater the density of the CO₂ will decrease and hence the volume will expand. To avoid venting of CO₂ to the atmosphere an expansion system, which accumulates liquid CO₂ in the period between each discharging operation is included.

5.4.1 Floating Platform Design

Considering the economy, particularly for deep water applications, socket buoy is proposed in this study. The "socket" buoy concept is that the platform is supported by a buoy system and can be "plugged" into the ship when it arrives on site. It is assumed that no offshore facilities for temporary storage are mounted, and hence the ship provides the injection function so that there is no offshore personnel requirement for operation.

There are various technological options for the socket buoy as follows, and more detailed study is necessary considering water depth, weather and sea conditions, seabed conditions, etc.

- Case using floating structure
 - Floating body: hull-type, semi-submersible type, SPAR, TLP, etc.
 - Loading: loading arm, floating hose, suspension hose, etc.
 - Injection line to well: vertical steel pipe, steel catenary pipe, flexible pipe, etc.
- Case attaching and detaching with ship
 - Connecting measure: submerged turret buoy, submersible flexible steel pipe, etc. (Ozaki and Ohsumi, 2011)

For deep sea direct injection of CO₂ where the seabed depth is at least 3km, a floating or semi-submersible platform would more desirable due to their flexible nature and ability to withstand the forces of nature present. Platforms are usually built for specific locations and will be well-equipped to handle any foreseeable risks and tasks. This can include a potential power generating module which contains renewable energy components.

On a general scale, the platform/FPSO would experience forces on its deck and hull/floater, in the forms of wind, currents and waves. Such forces may result in stresses on the structure, causing fractures, fatigue or even failure. Hence, careful considerations would have to be given many essential aspects of the platform: height of the top deck; level of water clearance; centre of gravity of the structure; weight/buoyancy uplift of the hull/floater and the acceptable allowance for vertical and horizontal movements.

5.4.2 Positioning

Mooring lines and cables can fixate a platform/FPSO to the seabed so as to minimise its movements. However, considering the depth at which the direct injection has to occur (3.8km), the massive weight of the steel cables would pose as a burden to the platform structure/hull structure. In addition, the platform/FPSO has to consider the impact on its buoyancy and centre of gravity.

Since mooring lines are secured to the seabed and this design project is focused on direct injection of CO₂ into the sea to form a CO₂ lake at the bottom, mooring lines would have to be attached to the platform/FPSO at a higher angle to avoid disturbing the stability/settling down of the CO₂ lake. As a result, longer mooring lines are needed and a larger area of safety zone is required around the platform/FPSO.

Dynamic positioning (DP) is a supplement or alternative to mooring lines. It is a system which adopts a combination of Global Positioning System (GPS) as well as radar and acoustics equipment to maintain the platform/FPSO at a pre-determined location. As it is a passive system, the engines and systems would have to be kept running 24/7, if there is no mooring system in place. Hence, energy requirements and running costs would be higher than a mooring arrangement in the long run.

Vertical position and horizontal position allowances would have to be determined.

5.4.3 Installation

As the injection pipe is of considerable length, it is recommended that the pipe be prefabricated elsewhere and connected in-situ. Adoption of a FPSO would reduce the complexity of installation as the various modules required for injection and storage can be readily installed at the dry docks during conversion or construction.

5.4.4 Power requirements

Usually, offshore platforms are powered by an on-board generator fuelled by some of the gas or oil which is extracted from subsea geological formations, with the resultant emissions released in-situ. In order to reduce the carbon footprint of the proposed system, the platform can be powered by renewable energy (solar, wind or waves), gas engines (H₂ or natural gas) with in-situ capture or OTEC technologies which maximise the benefits of the substantial water depth at which the proposed system would be operating in. Once the energy requirements of the main pumps, pressurizing and cooling systems are determined, the amount of area required by power generation can be evaluated.

Current wind-power technology is being experimented in regions with depths of up to 700m. It may be a far cry from the depths of 3.8km which the CCS system we are designing which have to achieve but the possibility to locate wind power stations in deep seas can be said to be significant enough for this option to be considered.

5.4.5 Carbon transport requirements

As carbon dioxide would form hydrates at temperatures below 15°C, sufficient heating systems have to be put in place to ensure that the transporting temperature remains above 15°C to prevent clogging and wearing off of the pipelines. When heat is applied, density of the CO₂ falls and volume subsequently increases. Such physical changes would affect the actual mass being transported into the CO₂ lake and

affect the flow rate required in the pipe. This heating process can be powered by a seawater exchanger.

5.4.6 *Pump specification*

1. Pipe diameter
2. Mass flow rate/flow capacity
3. Density
4. Pressure drop
5. Pipe length
6. Difference in elevation
7. Pump efficiency
8. Friction loss
9. Long radius elbows
10. Gravity considerations

5.4.7 *Interface with vessels (shuttle tankers and supply vessels)*

For cargo operations, it would be relatively safer for the ships to receive/deposit CO₂ via a single point buoy system than conduct ship-to-ship (STS) transfer, although the procedures for STS is quite established in the tanker industry. Fenders would be required if the ships were designed to moor right next to the platform/FPSO.

6 DEEP OCEAN SEQUESTRATION

Since 1977, when the first concept of direct ocean sequestration of CO₂ was introduced, significant research efforts have taken place to continue solving its unique challenges. The ocean is a large natural sink for CO₂ and spontaneously absorbs a significant fraction of the fossil CO₂ emissions. In equilibrium, the partitioning of CO₂ between ocean and atmosphere is roughly 4 to 1. It would, however, take thousands of years for this equilibrium to be reached naturally. Even though the ocean contains 39,000 Gt of carbon as carbonate and bicarbonate, its uptake capacity is far smaller. An addition of 1,000 Gt of carbon would already severely change ocean chemistry. Several of the methods for ocean sequestration can be seen in Figure 7-1.

In spite of these limitations, estimates for ocean storage capacity in excess of 10,000 billion Gt C have been cited. Such numbers would be feasible only if alkalinity (e.g., NaOH) were added to the ocean to neutralize the carbonic acid. Over thousands of years, the dissolution of calcareous oozes at the bottom of the ocean could provide such alkalinity.

A number of CO₂ injection methods have been investigated. One is to dilute the dissolved CO₂ at a depth below the mixed layer where carbon can be stored for decades to centuries, although capacities are limited by environmental ramifications. Another approach is to form lakes of CO₂ at the bottom of the ocean. Below 2,700 meters, the density of the compressed CO₂ is higher than that of seawater, and therefore, CO₂ sinks to the bottom. In addition, CO₂ will react with seawater to form a solid clathrate, which is an ice-like cage structure with approximately six water molecules per CO₂.

Methods of ocean storage

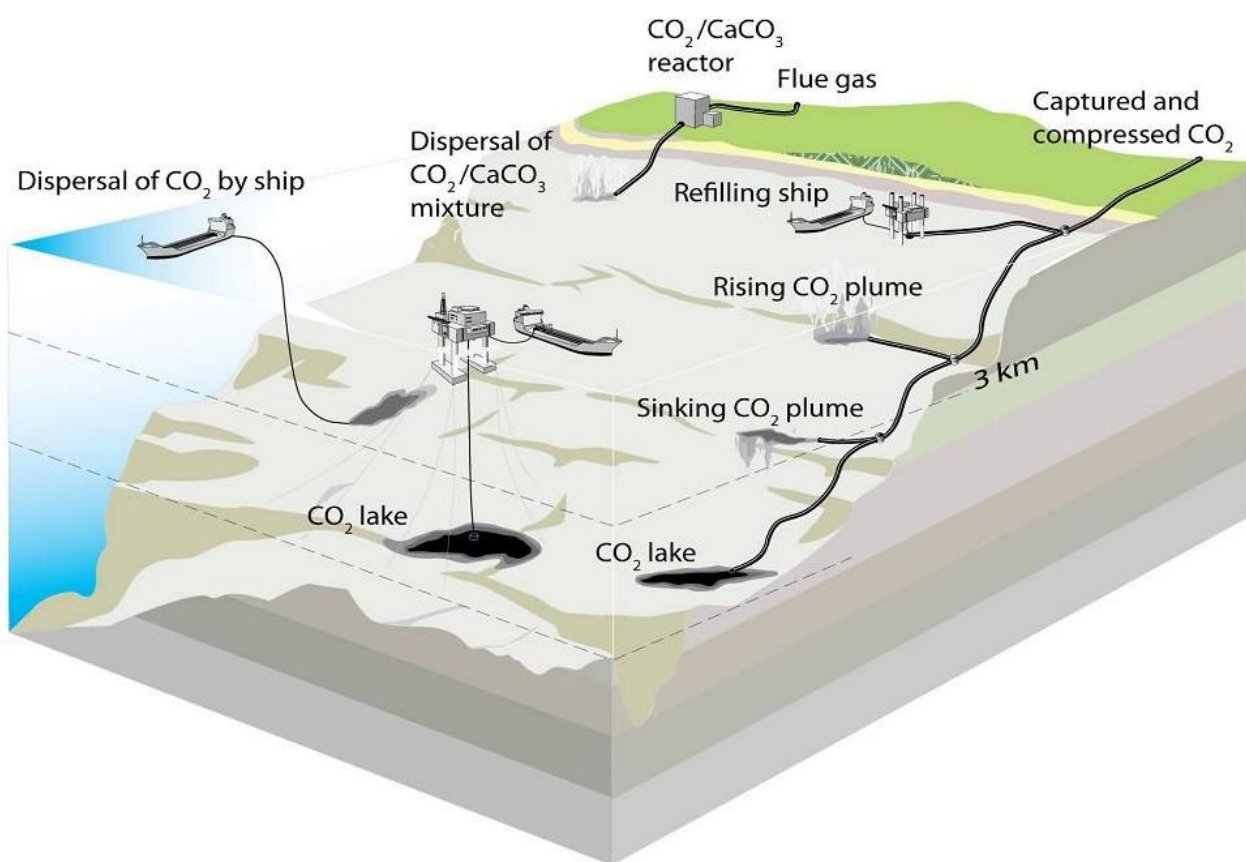


FIGURE 6-1: ILLUSTRATION OF SOME OCEAN STORAGE STRATEGIES. SOURCE: IPCC (2005)
FIGURE 6.1 (ARTWORK COURTESY OF SEAN GODDARD, UNIVERSITY OF EXETER)

Estimates of the cost of the direct disposal of CO₂ in the oceans range from \$1-6 per ton of CO₂ to \$5-15 per ton of CO₂. The main hurdle to the acceptability of ocean storage is the environmental

Carbon Capture and Storage in Deep Ocean Space for the 21st Century

concerns related to long-term chronic issues of altering the ocean chemistry as well as on the local effects of low pH (as low as 4) and its effect on marine organisms (e.g., stunting coral growth). It does not help to replace one environmental problem with another.

CO₂ sequestration refers the long-term CO₂ storage to reduce the emissions of CO₂ to atmosphere. Their principles are:

- i. Storage must be safe;
- ii. The environmental impact should be minimal;
- iii. Storage must be verifiable; and
- iv. Storage liability is indefinite (Lackner and Brennan, 2009).

The ocean storage consists of the CO₂ injection at great depths where it dissolves or forms hydrates or heavier-than water plumes that sinks at the bottom of the ocean. This process accelerates the transfer of CO₂ to the ocean that occurs naturally with an estimated rate of 2 Gton/ year (Khoo and Tan, 2006). The ocean is considered to be the largest store of CO₂. It is estimated that the ocean contains 40,000 Gton of carbon, contrasting with 750 Gton in the atmosphere and 2200 Gton in the terrestrial biosphere. Several techniques were tested to perform the CO₂ transfer to the ocean:

- i. Vertical injection;
- ii. Inclined pipe;
- iii. Pipe towed by pipe; and
- iv. Dry ice (Khoo and Tan, 2006).

However, the increase of CO₂ concentration in the ocean can have serious consequences in marine life. CO₂ leads to the ocean acidification, affecting the growth rate of corals.

6.1 Storage reservoir modelling & analysis

The world's oceans represent the largest potential sink for CO₂ produced by human activities, but the scientific knowledge to support active ocean sequestration is not yet adequate. Oceans already contain the equivalent of an estimated 140 trillion tons of CO₂. Natural carbon transfer processes in oceans span thousands of years and will eventually transfer 80 to 90 percent of today's manmade CO₂ emissions to the deep ocean. This natural CO₂ transfer may already be adversely affecting marine life and may also be altering deep ocean circulation patterns.

Compared to terrestrial and geologic sequestration, the concept of ocean sequestration is in a much earlier stage of development. No commercial-scale applications of deep ocean injection have yet been conducted. Research is focused on learning more about the ocean carbon cycle and deep ocean ecosystems, assessing the environmental impacts of CO₂ storage, and understanding the mechanisms by which CO₂ hydrates form.

Once the CO₂ has been captured, the next step is to select a suitable storage site. Presently there are several options for storing CO₂ in various locations in the lithosphere which may either be subterranean or sub-sea geological formations. The storage of large amounts of CO₂ may also be diluted into the ocean or stored in dense liquid form in deep waters forming CO₂ lakes in surface depressions. All the storage methods rely on the interaction of CO₂ with its surroundings in one way or another to form a trapping mechanism which prevents the return of the CO₂ into the atmosphere. In this section, the focus is constrained to the storage of CO₂ in deep ocean lakes similar to the concepts proposed by Nakashiki (1997). Ocean direct CO₂ injection at depths greater than 3000 m produces liquid CO₂ denser than the ambient seawater. In this section, we describe the physical and chemical processes of CO₂ in seawater. With that, we investigate the current and future potential of deep ocean storage reservoirs (> 3000 m) for a long term storage system of CO₂ in China's waters.

6.2 CO₂ processes in deep waters

CO₂ exists naturally in seawater, even more so in the deeper portions of the ocean. This is because the oceans are a natural sink of CO₂ from the atmosphere. However, the purposeful injection of CO₂ into the water column will lead to several processes occurring due to the interaction of CO₂ with seawater. The CO₂ reacts with seawater by dissolving into the water body to form bicarbonate and carbonate ions resulting in acidification. If conditions are suitable, a thin film of gas clathrates or carbon dioxide hydrates will form instead. This film becomes a semi impermeable barrier which slows the rate of diffusion of the CO₂. Several experiments and model studies have been conducted to understand better the lifespan and effects of ocean storage of CO₂ over large timescales on the chemistry of the water body and the biological impact of the resulting acidification.

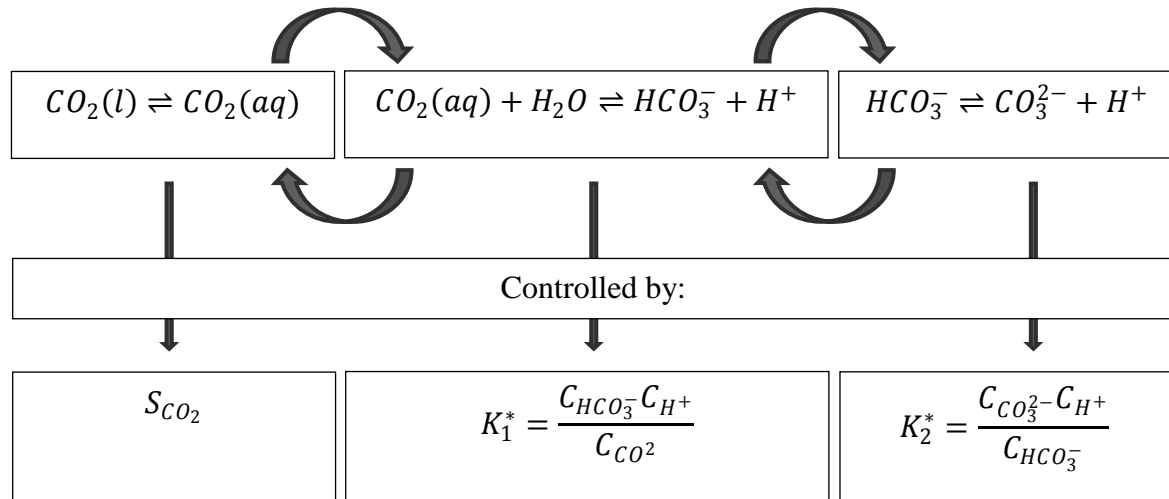


FIGURE 6-2: THE DISSOLUTION STAGES OF CO₂ FROM LIQUID TO IONIC STAGES. ALSO SHOWN ARE THE SOLUBILITY OF CO₂ (S_{CO_2}), THE FIRST DISASSOCIATION CONSTANT (K_1^*), AND THE SECOND DISASSOCIATION CONSTANT (K_2^*). $C_{HCO_3^-}$ IS THE CONCENTRATION OF BICARBONATES, ETC.

6.2.1 Dissolution of CO₂

CO₂ reactions with seawater can form one of four products; aqueous CO₂, bicarbonate (HCO₃⁻), carbonate (CO₃²⁻) and a small amount of carbonic acid (H₂CO₃) refer to Figure 6-2. The disassociation of the components of CO₂ leads to the acidification of the water due to the reduction in total alkalinity.

Laboratory experiments conducted by Aya et al. (1997) to study the solubility of CO₂ at 30 MPa. They found that solubility of CO₂ decreases with temperature and the dissolution rate of a CO₂ droplet in seawater increases linearly with temperature when hydrates are present. The dissolution rate of pure water without the presence of hydrates occurs almost independent of temperatures (> 3°C).

6.2.2 Mechanics of Dispersion/Dissolution

It has been shown by Gabitto and Tsouris (2006) that models which assume the structure of a hydrate is pseudo homogenous does not accurately predict the dissolution characteristics of CO₂ in seawater based on comparisons with experimental data Brewer et al (2002). Instead the structure can be assumed to be a permeable hydrate layer separating the CO₂ phase and the seawater phase with inter-crystalline diffusion of CO₂ (Teng et al., 1996) or an impermeable layer (Mori and Mochizuki, 1997) with diffusion through capillaries.

Modelling the dispersion of CO₂ through a hydrate film over a droplet has been analysed by Gabbito and Tsouris (2006). There are three general approaches to modelling the dissolution rate:

- Assuming a quasi-homogenous material comprising of liquid CO₂ and hydrates

- Assuming a three phase approach with hydrate formation on the CO₂ phase and the dissolution occurring on the water face
- As before but the hydrate is a porous layer that draws water into the pores via capillary action

Although they approached the problem for a case of droplets, the principle can be applied in the same way for reservoir dissolution characteristics by assuming droplet radius to be approaching infinity. The drag force over the droplet due to the flow around the droplet is analogous to a pressure difference over a finite length.

Storage of CO₂ into trenches and depressions reduce the rate of dissolution as the dissolved CO₂ forms density stratification and the stagnant waters reduce the rate of vertical mixing. The hydrate layer also reduces the rate of dissolution but the formation of hydrates is exothermic and this might result in instabilities of the density stratification which is capping the CO₂ reservoir. Hydrate formation also causes the idea of a homogenous lake of CO₂ improbable as studies have shown that injection of CO₂ in hydrate forming conditions because grape-like formations as the droplets coalesce (Teng et al., 1996).

6.2.3 *Field experiments*

Several in-situ experiments have been conducted to observe the dissolution of liquid CO₂ and the formation and dissolution of CO₂ hydrates. One particular experimental campaign is the one conducted in Monterey Bay using the Ventana ROV (Brewer et al., 1998, Brewer et al., 1999, Brewer et al., 2000, Brewer et al., 2002, Rehder et al., 2004, Brewer et al., 2005) to study the hydrate formation, dissolution and characteristics of CO₂ at various depths in the water column. The formation of hydrates occurs easily and rapidly even in field conditions however the solubility of CO₂ in water leads the hydrates to be a temporary delay mechanism to the complete dissolution of CO₂ (Brewer et al., 1998).

Brewer et al. (1999) showed that the formation of hydrates can occur at rather shallow depths but the density of CO₂ at those depths is less than the ambient seawater. The CO₂ will then be positively buoyant and rise through the water column. The investigators also report two interesting findings. First, the formation of hydrates dramatically increased the volume of the original CO₂ by a factor of 4 to 7 times the original as it is possible that the hydrate lattice was not completely occupied. Further explanation is provided in the stability of hydrates section of the appendices. The second finding is at the interface, a possible combination of salt rejection and heat release from the formation of the hydrate and the dissolution of the CO₂ was visible from heterogeneities in the density of the fluid. This disruption in the density of the overlying seawater is important when considering a trapping mechanism for a potential CO₂ storage area.

Brewer et al. (2000) showed in their field experiments that the method of injection of CO₂ influences the pH reduction and hydrate formation significantly. Energetic injection leads to a large pH reduction in the vicinity of the reservoir in comparison to slow injection where the interface of CO₂ and water was kept low. In order to track the dissolution in the field of a droplet of CO₂ as it is injected into the water column, Brewer et al. (2002) released liquid CO₂ droplets into an enclosure with glass panels opened at the top and bottom to at 800 m depth. From the footage captured they were able to determine the dissolution rate of the CO₂ droplet.

Brewer et al. (2005) also conducted flume experiments at 3941 metre depth to study CO₂ plume generation. The experiment simulates the behaviour of a possible CO₂ reservoir in terms of pH reduction and hydrate formation albeit at small scale. They commented that the hydrate formation was suspended when current velocities transporting diffused CO₂ exceeded the nucleation rate of the hydrates. When flow across the flume was stopped the hydrate film reformed via propagation from existing hydrate “rafts” which collected on the downstream of the flume. This experiment showed that the use of pH sensing electrodes was not adequate for sensing CO₂ concentrations and the interpretation of the results would be difficult. However, the development of in-situ Raman

spectroscopic meters would be able to measure the concentration directly and would be an excellent tool in the study of plume dynamics and monitoring (Uchida et al., 1997).

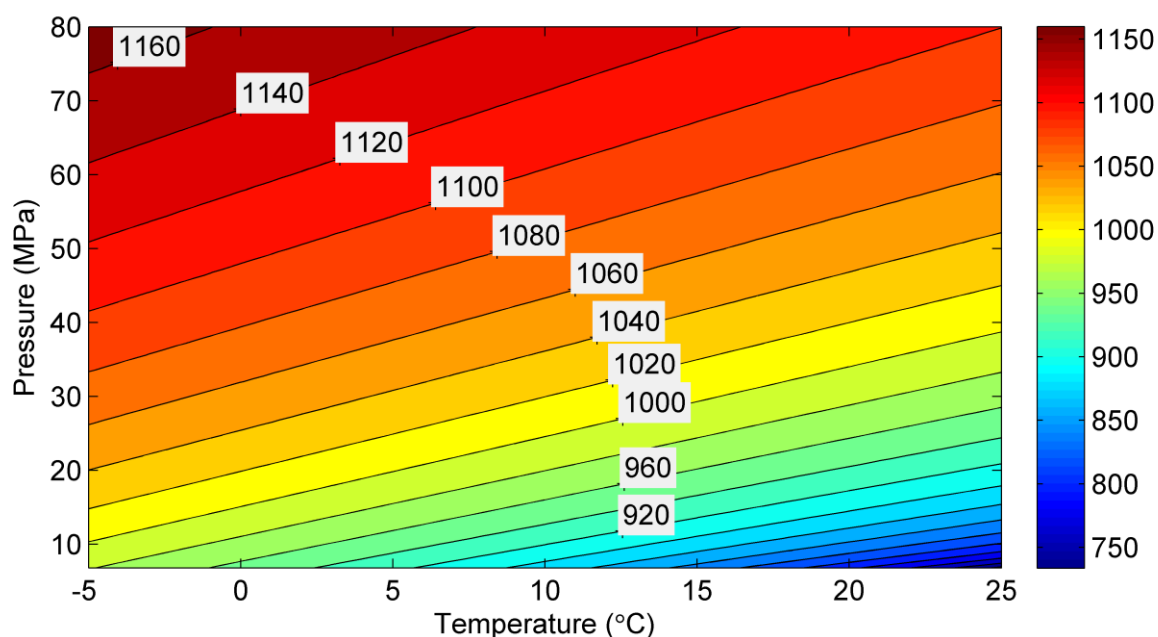


FIGURE 6-3: COLOUR CONTOUR PLOT OF LIQUID CO₂ DENSITY AS A FUNCTION OF TEMPERATURE AND PRESSURE. DATA WAS OBTAINED FROM THE NIST CHEMISTRY WEBBOOK ([HTTP://WEBBOOK.NIST.GOV/CHEMISTRY/](http://webbook.nist.gov/chemistry/)).

6.3 Reservoir analysis

The complete process of dissolution of stored liquid CO₂ into seawater is a complex combination of simultaneous processes as shown in the previous sections. CO₂ is soluble in water and eventually disassociates to form carbonate ions and eventually acidifies the ambient water. CO₂ also reacts with water to form hydrates. Hydrates release heat during formation and consume heat during collapse. The heat released interferes with the density stratification producing buoyant plumes. Hydrates also diffuse CO₂ although at a lower rate than pure CO₂-seawater contact. The concentration field is also strongly affected by convection by the ambient currents. Excessive shear stress leads to turbulence and increases the mixing rate as well as damages the fragile hydrate layer. Flows are also periodic and may be in excess of 0.2 m/s in the event of benthic storms⁹.

6.3.1 Location selection

Three possible regions are within China's reach for ocean storage of CO₂:

- South China Sea
- North Pacific Ocean
- East China Sea

⁹ Benthic storms are defined as periods in which deep ocean currents in deep water become very fast and generate turbulence which increase vertical and horizontal mixing. Field observations of benthic storms have shown storm durations of 1-2 weeks with 1-3 month frequency.

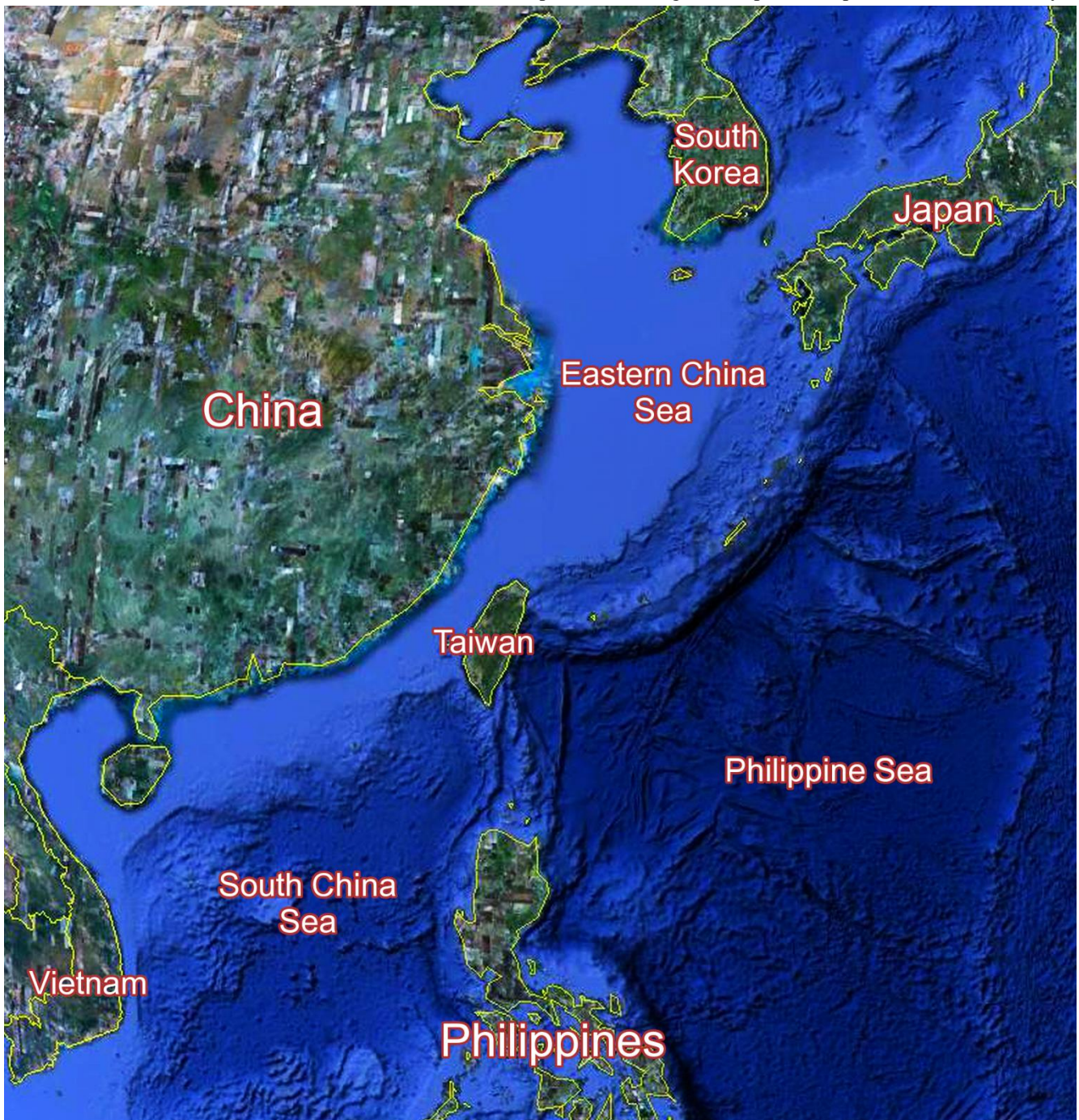


FIGURE 6-4: SATELLITE IMAGE OF THE WATER BODIES ACCESSIBLE TO CHINA FOR OCEAN STORAGE

A contour plot of the waters around the island of Hainan, China is shown in Figure 6-5. The data was obtained from the British Oceanographic Data Centre's (BODC) General Bathymetric Chart of the Oceans (GEBCO) bathymetric data at a 1 minute resolution. The land is represented in deep red and the wide orange contour represents depths less than 3,000 metres. In order for CO_2 to be sequestered in dense liquid form the required depth of the reservoir should exceed 3,000 m. This effectively rules the East China Sea out as an option as the depths in the East China Sea do not have the required depth. The North Pacific Ocean has reservoirs with adequate depth for the most part. However, it is not an accessible option for a few reasons:

1. The depths are very deep and conditions would require depositing the CO_2 as a sinking plume. Control of the dissolution and spreading of the plume is not possible and direct injection would not be economical.
2. The accessible areas are within close proximity to the tectonic ridges and therefore pose a certain level of risk.

3. The distance from China to the North Pacific waters for sequestration purpose are more than 500 km.

In the South China Sea, areas of the basin are owned by multiple countries namely the Philippines and Vietnam as it lies within their EEZ. With regards to reservoir potential, a number of zones have been identified south of Hainan as shown in Figure 6-5. These zones have sufficient depth, and are enclosed depressions which can safely isolate the CO₂ lake. All three zones are within close proximity and are located close to a shelf (south of Zone 2). This can potentially be a place to place a platform if

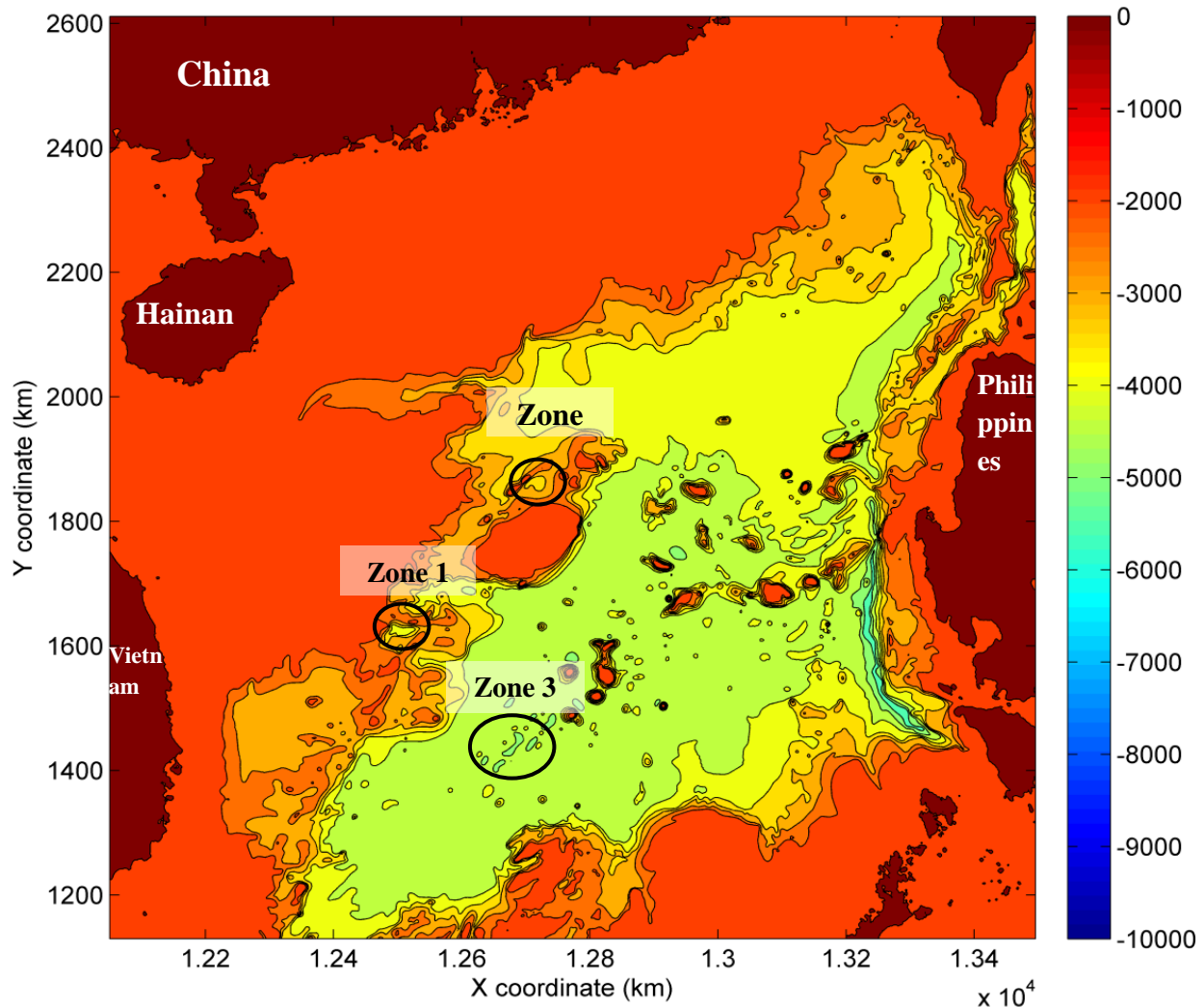


FIGURE 6-5: LOCATION OF THE THREE POSSIBLE ZONES WHERE SEQUESTRATION OF CO₂ IN DENSE FORM IS FEASIBLE

the economics are beneficial. Zone 1 and Zone 2 is more favourable as they are surrounded by shallower waters and closer to China. Zone 3 is in deeper waters and further away from the mainland. Data¹⁰ from the open ocean is used as a benchmark for estimating the conditions within the reservoirs as in situ data is not presently available. In Table 6-1, five sets of sample data is shown to give an indication of the conditions which exist at 3,000 m deep waters. Although not shown in the table, the pH values tend to reduce with increasing depth, initially starting at pH of 8. The pH data is only sampled at 250 m at its deepest. Temperature also declines with depth.

At 3000 m depth, the pressures are approximately 30 MPa and the density of CO₂ at that depth is 1050 kg/m³. Due to the compressibility of CO₂ the densities can increase up to 1070 kg/m³ at 4 MPa. However for our design purposes we will use a conservative density of the former for all volumetric calculations.

¹⁰ Obtained from the National Oceanic Data Centre (NODC)

TABLE 6-1: SAMPLE DATA INDICATIVE OF CONDITIONS EXPERIENCED AT 3000 METERS DEPTH

	Data 1	Data 2	Data 3	Data 4	Data 5
Longitude	130.100	126.527	127.99	165.975	129.9928
Latitude	11.003	9.955	10	7.998	13.026
Date	1986	1986	1986	1986	1991
Temperature(°C)	1.63	1.62	1.53	1.65	1.615
Salinity(pss)	34.666	34.666	34.671	34.665	34.668
pH	7.93(250m)	8.08(250m)	8.08(250m)	7.78(250m)	N/A
Oxygen(ml/l)	2.33	3.28	3.4	3.05	3.16

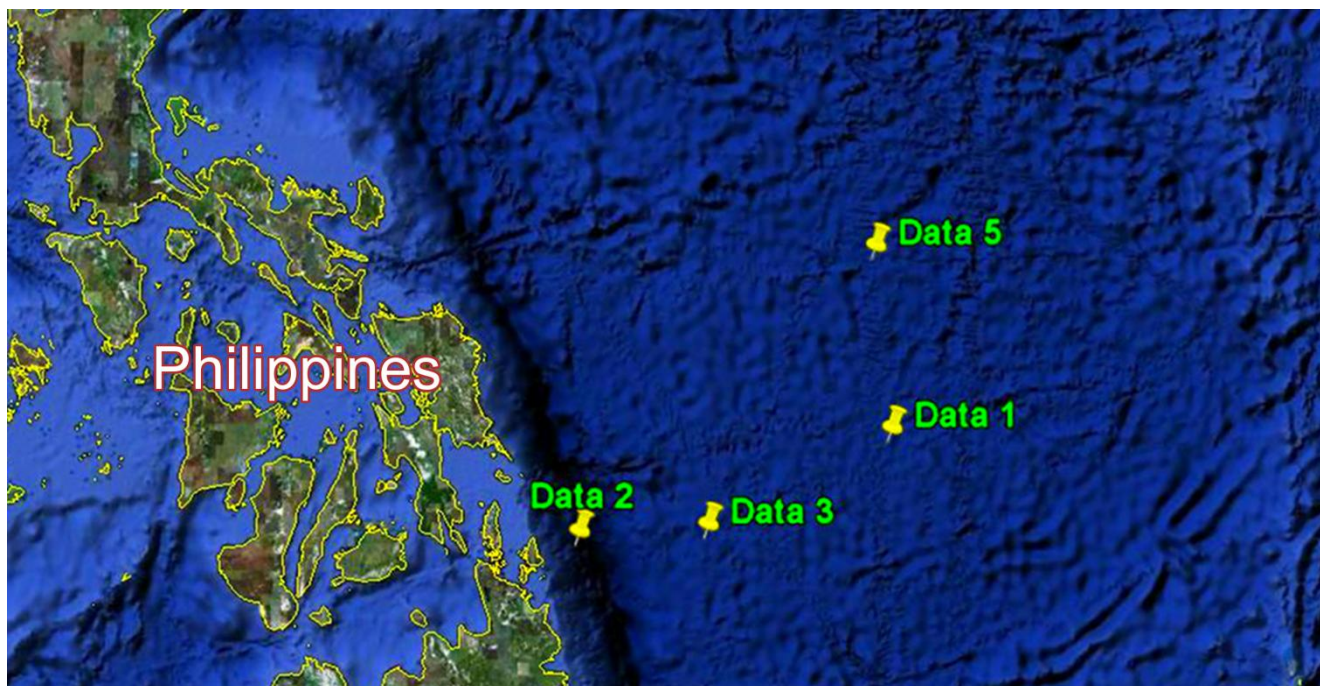


FIGURE 6-6: LOCATIONS CORRESPONDING TO THE SAMPLES LISTED IN TABLE 6-1. POINT 4 IS LOCATED WITHIN THE VICINITY OF THE MARSHALL ISLANDS AND IS NOT SHOWN.

The most vital aspect of all undersea geological features for carbon dioxide storage is simply the raw reservoir capacity. Without external action there is no possible way stopping the dissolution of the CO₂ lake into the surrounding water body. However the premise of our design is to form a slow release chamber in which the CO₂ released from the mouth of the reservoir is in very dilute conditions and would have minimal impact to the far field ecosystems.

The performance of our reservoirs will be based on the findings of numerical models of Enstad et al. (2008) and Rygg et al. (2009). Their findings will be used to obtain the volume of water which is affected by the CO₂ lake as “steady” state. Although three zones have been selected as potential storage sites, only one will be analysed here as a representative case study. The volumetric capacities of all three sites will however, be calculated. The numerical model of Enstad et al. (2008) of the lake dissolution rate is not similar to the conditions observed in our reservoir (refer to Appendix E), however, they demonstrated that the volume of pH reduced seawater achieved steady volume after a period of time. Using that steady volume values, we can loosely estimate the volume of seawater affected by pH reduction. Figure 6-7 shows the volume affected by a corresponding pH reduction for case 2 with the presence of hydrates in their simulations. The data points are the maximum values of the volume for each pH reduction. The data was found to fit a 4-order polynomial equation and the values < 0.6 pH drop were extrapolated. The main difference between their model and the design of this reservoir would be the duration required to achieve that condition. This is dependent on the hydrodynamics within the trench itself which may suppress or enhance mixing. From Grubb and Sato (2009), we observe that the effect of topology reduces the rate of dissolution of the CO₂ lake. Although they only modelled a gap of 20 m, the effects were still significant.

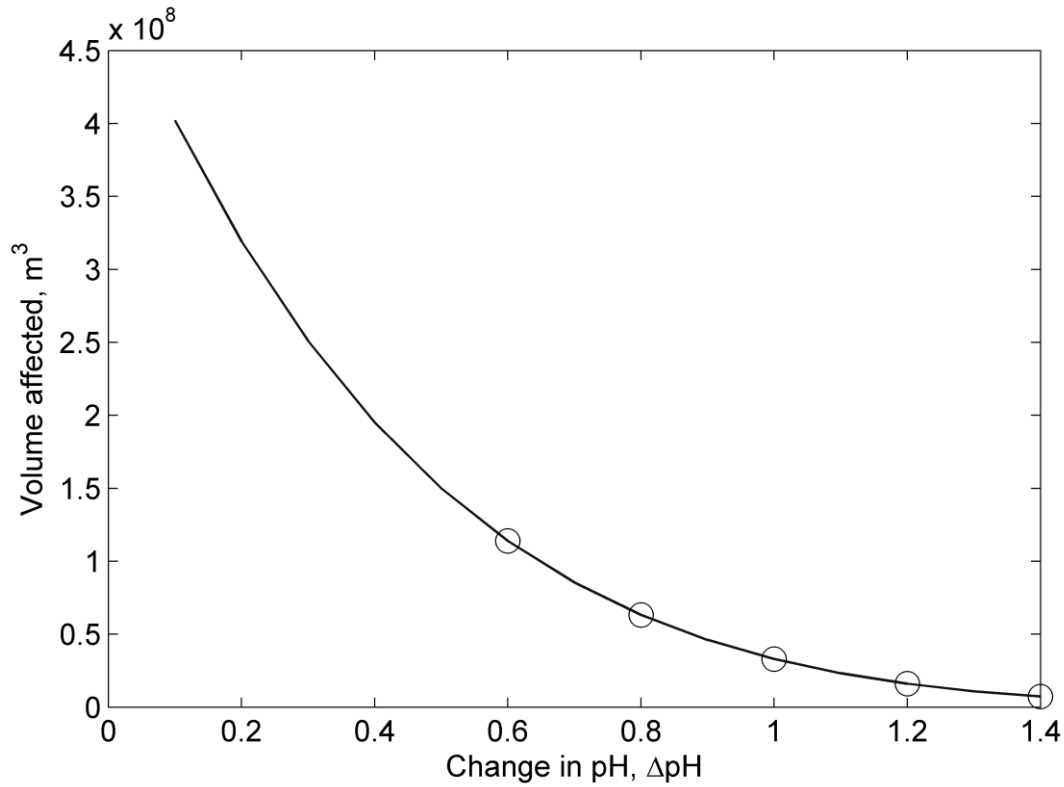


FIGURE 6-7: VOLUME OF SEAWATER WITH REDUCED pH AT STEADY STATE. CIRCLES CORRESPOND TO MAXIMUM VALUES OF VOLUME FOR A GIVEN pH. DATA TAKEN FROM ENSTAD 2008 FOR CASE 2H, $U=10$ CM/S WITH THE PRESENCE OF HYDRATES.

Dissolution is also a function of the surface area of the interface between the liquid CO_2 and seawater. In their simulations, Enstad 2008 modelled a 500 by 500 meter sized lake. By correlating the depth at which the interface occurs to the surface area and volume in the reservoir an estimate to the pH reduction volumes based equivalent 500 m by 500 m units can be made.

6.3.2 Required volume of to be stored CO_2

First the required amount of CO_2 to be stored needs to be determined. Assuming a 500 MW coal fire plant emits 2.9 Mt CO_2 per year and emissions increase linearly for larger plants. (IPCC, 2005) Therefore ten 2500 MW plant emits,

$$M_{\text{CO}_2} = 10 \text{ plants} \times 14.5 \times 10^9 \text{ kg year}^{-1} \times 30 \text{ years} = 4.35 \times 10^{12} \text{ kg}$$

In 30 years which is the common life expectancy of a power plant. Assuming a density of 1050 kg m^{-3} for liquid CO_2 the volume required to store the CO_2 is,

$$V_{\text{CO}_2} = \frac{M_{\text{CO}_2}}{\rho_{\text{CO}_2}} = \frac{4.35 \times 10^{12} \text{ kg}}{1050 \text{ m}^3} = 4.143 \times 10^9 \text{ m}^3$$

The reservoir is assumed to absorb all the injected CO_2 and losses during injection due to dissolution while the liquid CO_2 descends to the accumulating lake is ignored. (i.e. dissolution of CO_2 considered to only occur at the lake for volumetric calculations).

6.3.3 Zone A Reservoir

Figure 6-4 is plotted in degrees longitude and latitude which is inconvenient for calculating metric volumes. Therefore we make an assumption that 1 degree latitude and longitude is equal to 111.12 km. This conversion is true for all lengths across the latitude, the lengths across longitudes at the equator. The latitudinal length between longitudes however varies depending on the latitude. Due to the relatively small area of the storage sites the vertical variations at the south and north of the reservoir is assumed to be small. The resulting plot is shown in Figure 6-8 with the storage reservoir located

within the dashed circle. The contours begin at 2500 m depths at 100 m intervals. The reservoir is about 3700 m at its deepest point. The volumes also do not consider the spherical nature of the earth which in more detailed studies should be accounted for.

By converting a continuous colour into a gray-scale image the depths can be estimated at every point. At every depth, there is an associated surface area at the interface and a corresponding volume underneath the interface. The depths are represented by a simple vector from the reservoir top (3000 m) to the deepest point at regular intervals. The frequency of each depth multiplied by the resolution of the grid defines the area associated at each depth. The product of that value multiplied with the actual depth yields the volume under that area. By making a cumulative sum in the order of decreasing depth the area of interface and volume is known if the depth at which the interface occurs is known and vice versa.

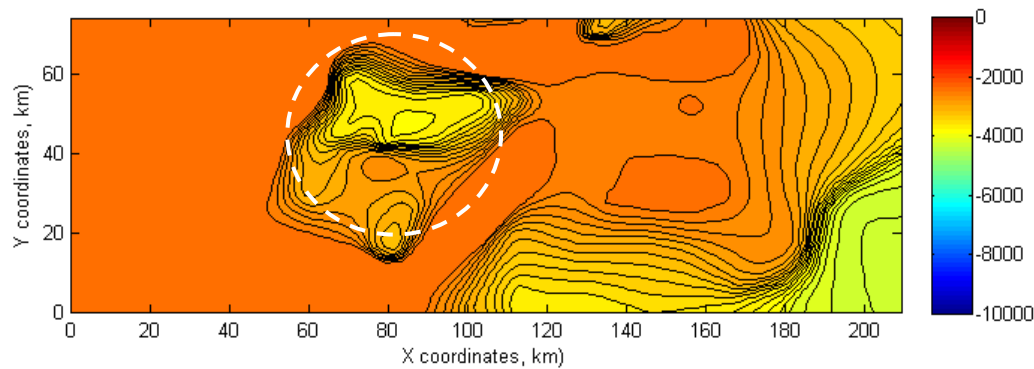


FIGURE 6-8: ZOOM-IN VIEW OF ZONE A

6.3.4 Calculation of capacity

The amount of CO_2 that needs to be stored is $4.143 \times 10^9 \text{ m}^3$. From Figure 6-9, the area of the interface will be $5.6 \times 10^6 \text{ m}^2$. Relative to the lake modelled by Enstad this lake is 22.8 times larger and is estimated to have the same multiple of required reservoir water. From Figure 6-9, the volume of water which is acidified by 0.1 pH per unit lake (1 unit = $500 \times 500 = 250000 \text{ m}^2$) is 4×10^8 . Assumption is that the liquid CO_2 is being replenished as fast as it dissolves. The total volume of acidified water is then $9.12 \times 10^9 \text{ m}^3$. The sum of acidified water plus CO_2 (l) is $1.3264.143 \times 10^{10} \text{ m}^3$. The total capacity of the reservoir is $3.93 \times 10^{11} \text{ m}^3$. Thus there is an excess of 96.5 % of the reservoir unaffected severely. The percent unaffected will reduce drastically when the surface area is increased.

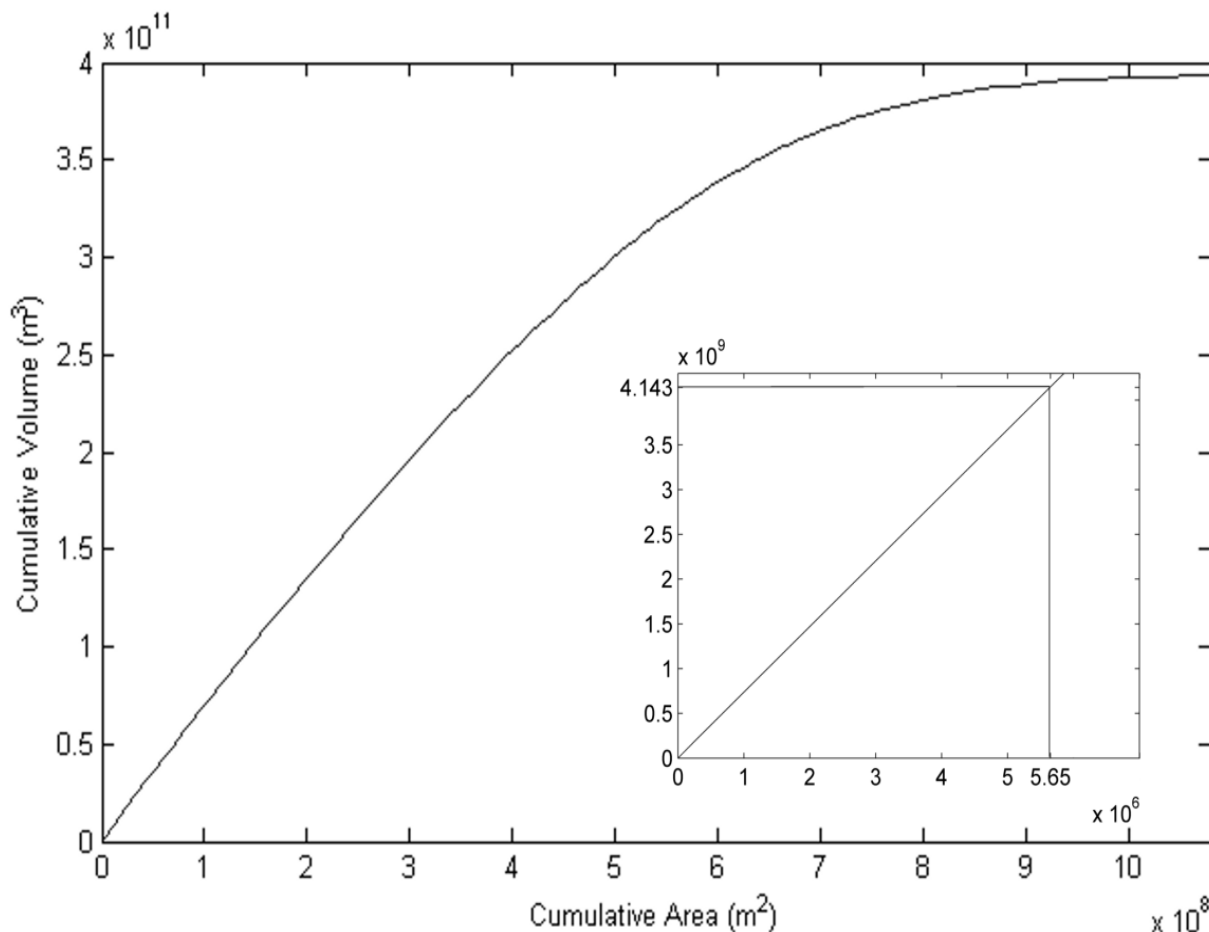


FIGURE 6-9: THE CUMULATIVE VOLUME OF RESERVOIR (M³) TO ASSOCIATED AREA (M²) FOR THE ZONE 1 RESERVOIR. THE INSET SHOWS THE RESERVOIR VOLUME CONSUMED BY OUR DESIGN CONDITIONS AND THE ASSOCIATED CO₂-SEA WATER INTERFACE AREA.

6.3.5 Conclusion

The storage of CO₂ in deep ocean reservoirs is a potential alternative to the storage of CO₂ for the long term to increase the amount of stored CO₂ per annum. It is expected that a combination of efforts would be best in reducing the total amount of emissions in a year which in turn would reduce the amount of additional carbon dioxide released into the atmosphere. By storing CO₂ into the deep ocean the normal route of CO₂ through the pelagic layer is bypassed reducing the rate of acidification on the surface layer as the turnover of the CO₂ at those depths may exceed 1000 years. This is a manner of protecting the near surface ecosystem which is both an important economic and natural resource. The idea of ocean storage is an intermediate tactic to allow technology to catch up and provide a solution which will allow the permanent storage of the CO₂ in deep ocean space.

The storage of CO₂ in deep ocean space is possible as an alternative to geological storage. However in order to confirm this statement further experiments, field studies and possible pilot scale projects should be performed. The level of uncertainty with the processes and behaviour in deep oceans is very high which reduces the reliability of any estimate of reservoir performance.

7 RISK ASSESSMENT

Although it is not classified as “toxic”, CO₂ is more than just an asphyxiant and causes psychological effects including increased breathing rate and acidosis. Other potentially hazardous properties include low temperatures on release or blowdown and the propensity to dissolve in elastomers, causing potential damage to elastomer seals on decompression.

TABLE 7-1: EXAMPLE OF CCS HAZARDS

Component of CCS Chain	Example Hazards
Capture	Enhanced combustion leading to fire or explosion as a result of loss of containment of oxygen
	Fire due to loss of containment of amine (or other flammable solvent used for CO ₂ capture)
	Explosion due to loss of containment of synthesis gas (pre-combustion capture), possibly made worse by congestion introduced by retrofit of CCS.
Transport	Loss of containment of CO ₂ from pipeline causing a hazard to people due to its toxicity and low temperature.
	Loss of containment of CO ₂ from refrigerated intermediate storage causing a hazard to people due to its low temperature and high concentration toxicity.
Injection (into storage)	Loss of containment of CO ₂ from delivery or injection riser causing a hazard to people due to its toxicity and low temperature, especially given semi-confinement. Possible escalation to hydrocarbon systems (causing fire/ explosion) or platform structure due to cold embrittlement.

TABLE 7-2: KEY ISSUES IN THE ASSESSMENT OF ENVIRONMENTAL IMPACTS REGARDING CO₂ CAPTURE, TRANSPORT AND STORAGE AS IDENTIFIED AND CHARACTERIZED WITH THE USE OF THE DPSIR FRAMEWORK

	Indicator (DPSIR) ¹¹	Models/tool (1, 2, 3, 4) ¹²	Regulations (α , β , γ , δ) ¹³
Capture	<p>P. Atmospheric emissions quantified but uncertain. Cobenefits (PM, SO_x, HCl, HF) and trade-offs (NO_x, NH₃) probable due to application of CO₂ capture. Depends on applied capture technology</p> <p>P. Emissions of solvents and degradation products (focus: post-combustion)</p> <p>P. Limited quantitative data available on emissions to water and solid waste streams</p> <p>P. Water consumption increase due to capture</p>	<p>1. No reliable emission factors for emissions to water and air. No model seems available that models waste generation for capture technologies (focus recommended: coal fired post-combustion and oxyfuel).</p> <p>2. Possibly adaptation of emission models is required to cope with 'new' emissions due to capture.</p> <p>1, 2, 3. See transport for issues of release and dispersion modelling of CO₂ from the engineered system.</p>	<p>α. No BREF and BAT.</p> <p>β. No PSR that takes into account efficiency penalty.</p> <p>γ. Emission and concentration norms for solvent emission and their degradation products should be formulated.</p> <p>δ. Uniform atmospheric concentration limits CO₂ to be used in RA.</p>
Transport	<p>P. Characteristics of released content are, within boundaries, uncertain. Maximum reported release rate is 22 t/s</p> <p>S. Concentration of CO₂ and impurities in surrounding of a failed pipeline is assessed to be above concentration thresholds at up to 7.2 km</p> <p>I. Impact (1*10⁻⁶ risk contour) of CO₂ pipelines is assessed to be possible up to 3.3 km based on a concentration threshold. With a preliminary probit function this contour extends up to 124 m.</p>	<p>1. Probability of infrastructure failure requires scrutiny.</p> <p>1. Release models should include impurities and thermophysical properties</p> <p>2. Release/ dispersion model validation for high-pressure CO₂ release.</p> <p>3. Dose-response models (e.g. probit function) for target species (or ecosystems) should be developed depending on environmental compartment. Currently, these models are not (yet) available.</p>	<p>α. Pipeline standards are absent, although work is performed in this area.</p> <p>β1. In QRA no standardized failure scenarios are formulated.</p> <p>βp. No formal limits for release of CO₂ and impurities.</p> <p>γ. Uniform atmospheric concentrations limits for CO₂ to be used in RA.</p> <p>δ. No formally adopted safety distances for CO₂ pipelines.</p>

¹¹ DPSIR: Driver, Pressure, State, Impact and Response.

¹² 1, 2, 3, 4: Indicate model/tools that are used to measure or model DPSIR indicators. 1= models to determine linkage between Driver and Pressure; 2= models to determine linkages between Pressure and State; 3= models to determine linkage between State and Impact; 4= models to determine linkage between Impact and Response.

¹³ α , β , γ , δ : indicate formal Responses in the form of regulations that regulate Driver, Pressure, State and Impact indicators, respectively.

	Indicator (DPSIR) ¹¹	Models/tool (1, 2, 3, 4) ¹²	Regulations (α , β , γ , δ) ¹³
Storage	<p>P. Characteristics (total amount and speed) of fluxes (e.g. CO₂ and brine) between environmental compartments can be quantified, although with high uncertainty. Maximum release rate from storage activity in reviewed risk assessments is 0.5 t/s</p> <p>S. The State (CO₂ concentration, pH) of a compartment is not frequently reported.</p> <p>I. Impact indicators per compartment are reported in RAs although sparsely for risks caused by failure of the geological storage system. No risk contours can be drawn as not all leakage pathways are known.</p> <p>PSI: No clear performance indicators per environmental compartment.</p>	<p>1b. Failure scenarios are typically: leakage along well and wellhead failure, caprock failure and leakage through faults or fractures and leakage along spill point.</p> <p>2. CO₂ dispersion and transport models, reservoir models are not validated for long-term CO₂ storage.</p> <p>2. Integration of models for subsurface and biosphere is at an infant stage.</p> <p>1, 2, 3. See ‘transport’ for issues of release and dispersion modelling of CO₂ from the engineered system.</p> <p>RA Tools rely highly on expert panel to (depending on approach):</p> <ul style="list-style-type: none"> • Identify and select failure scenarios; • Characterize/ quantify failure rates; • Characterize consequences. 	<p>α. Best practice manuals for CO₂ injection are being developed.</p> <p>β1a. Monitoring and reporting guidelines for, and prescription the exact characteristics of the injected CO₂ are not formulated.</p> <p>β1b. Standardized methodology for the development of failure scenarios and reporting.</p> <p>βp. Monitoring/ reporting standards and limits for fluxes between compartments are absent.</p> <p>γ. Monitoring/ reporting standards and State limits dependents of compartment are absent.</p> <p>δ. Standard Safety distances not formulated.</p>

There are risks present in all decisions made in our daily lives due to the presence of uncertainties. In that sense, CCS is considered particularly risky as there are many unanswered questions and incomplete information with regards to various components of its entire value chain, in addition to the inherent risks. However, it would be irresponsible to remain in a status quo condition because there are risks involved in CCS as a tool for mitigating global warming. Since risks involved with CCS already exists, thus the impact of carbon emissions on the planet as having detrimental effects is well known; doing nothing about carbon emissions therefore is a risk in itself. Taking on a risk is rational if the eventual magnitude, coupled with risk alleviating activities, comes within an acceptable level. Hence, risk management and response is essential to the success of CCS on a global scale and they are an important step in assisting all stakeholders to understand the entire chain of operations as well as to estimate any probable consequences (Walentek et al., 2011). In addition, by assessing the risks involved, regulators can construct a detailed framework which allocate liabilities to various responsible parties and also to determine if the operator be allowed to commence operations (Standing Committee Of People's Congress, 1983, Wilday et al.). As CCS can be operated fully by private firms in the future, there are many risks which they may face that are common to present businesses such as natural catastrophes, anthropogenic calamities, terrorism, economic shocks and longer term ones such as environmental (Kirchsteiger, 2008).

According to the UK Environmental Agency 2011 report on risk assessment for Carbon Capture and Storage, the purpose for producing a risk assessment is to identify best existing practices and to prevent the impact of risk on property, personnel and environment as well as reducing it when prevention is not practicable. Thus a systematic framework for listing all generic risks, evaluating their significance and determining possible measures to reduce risk to acceptable levels should be in place. Some characteristics of CCS with regards to risks management (Wilday et al., Environment Agency, 2011):

1. CCS technology is relatively new resulting in the difficulty in ascertaining their impact on environment.
2. If CCS incorporate existing technology such as use of pipelines and ships, risks can be easily assessed based on established principles associated with these technologies.
3. Staged implementation can be adopted as a measure to assess CCS risks.
4. CCS system operation and control is likely to involve three different operators for capture, transport and storage located hundreds of kilometres apart resulting in differing standards being applied by different operators.
5. CCS is an emerging risk

Therefore, it is clear that more information has to be gained from trials and demonstration projects or be transferred from existing procedures and operations in order to develop a comprehensive assessment and management plan for the direct injection of CO₂ into the oceans.

As seen from Figure 7-1, the main shore-based operations of CCS such as capturing and transporting the CO₂ from the flue gas of power plants are not entirely new. In fact, there are already well-defined regulations and procedures for chemical plants which are of similar nature to CO₂ capturing sites which deals with large amounts of chemicals such as the amines as well as the other wastes contained within the flue gas (Clarkson University, 2011). Attaining sufficient financing for CCS projects can be conducted through traditional financing such as loans or bonds. Likewise for the governments and regulatory bodies, financial instruments such as a bank guarantee or mutual club guarantee can be commanded before the issuance of operating license to provide a minimum safety net for potential victims. Pipeline transportation of CO₂ is well understood, particularly in the US, and the same goes for global understanding of transporting liquefied gas using tankers. Techniques for accessing and evaluating subsurface and subsea geological formations are available especially with oil majors. There are no similar operations conducted in the direct injection of CO₂ into the oceans. In addition,

Carbon Capture and Storage in Deep Ocean Space for the 21st Century even with a full scale on-going project, it would be a colossal task to monitor and document detailed data from the project as well as to accurately measure any long-term environmental consequences. One point to note, though, is that due to the uniqueness of each storage site, the knowledge garnered from the trial projects may not be directly applicable to other locations.

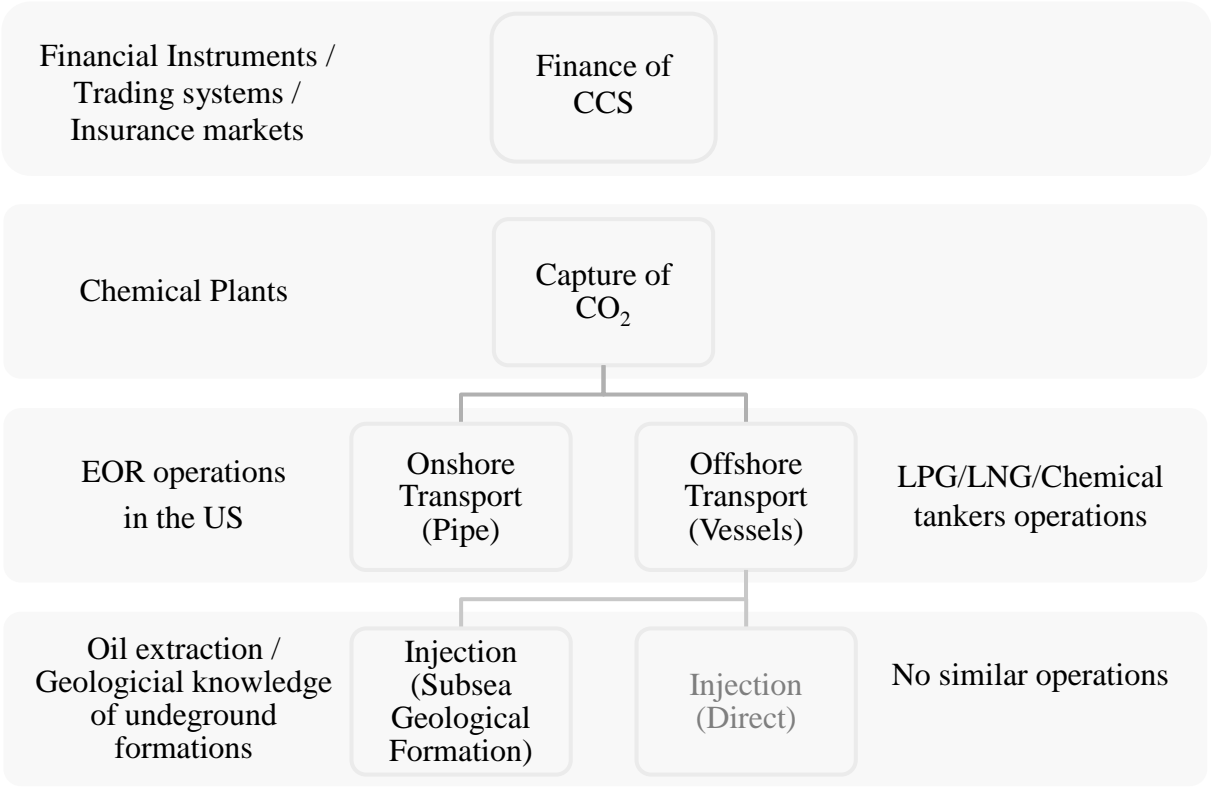


FIGURE 7-1 ASPECTS OF CCS WHICH HAVE SIMILARITIES TO PRESENT PROCESSES

In order to make a decision between alternatives available for CCS, risks assessments of remaining status quo has to be done as well in order to provide a clearer picture of the necessity and urgency to act. As more information becomes available, a key issue to be evaluated is that whether would the substitution of global atmospheric symptoms with localised symptoms (within the oceans) be justifiable and acceptable.

7.1 Hazard identification

A common model for determining a particular risk is by means of taking multiple of frequency and the consequences of a particular hazard. Therefore, to mitigate any risks, either the impact or frequency or both would have to be reduced. For CCS, there are three main types of hazards which can be identified: Financial, Environmental and Social (as seen in Figure 7-2). Each of these categories represents impacts on different groups and specific interests and has to be studied in detailed to ensure that any foreseeable risks are adequately dealt with through preventive and avoidance measures. There are many studies on risks assessments of CCS with regards to its wide-ranging effects and at this present level of information availability for CCS, financial risks are the most mentioned as compared to environmental and social risks (Walentek et al., 2011).

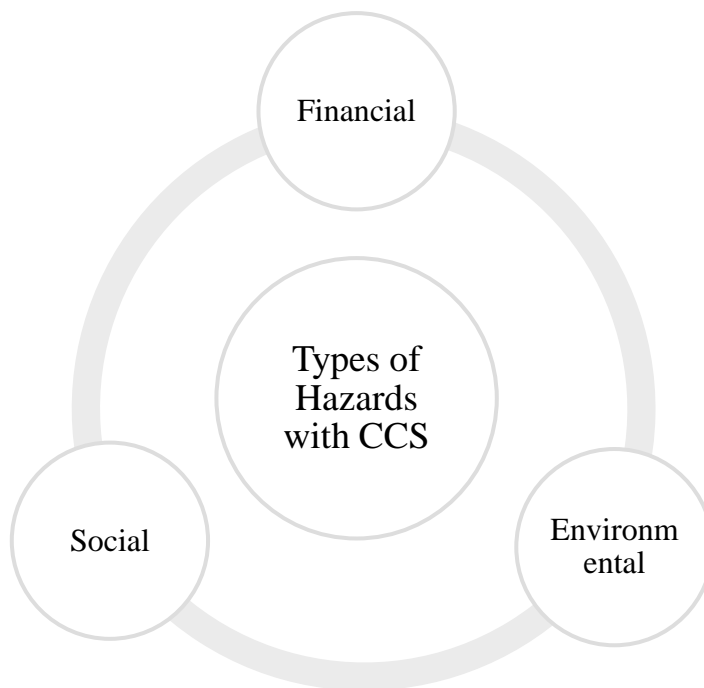


FIGURE 7-2: FOUR MAIN TYPES OF CCS-RELATED HAZARDS. *SOURCE: (IPCC, 2005, IEA, 2008, ENVIRONMENT AGENCY, 2011)*

7.1.1 Financial risks

As mentioned in the economics section, CCS would only be financially feasible with the implementation of carbon taxes or carbon trading schemes at rates higher than the costs of CCS on a global scale. The artificial pricing of emissions and uncertainties present in the levels of carbon emissions permissible in the future had led commercial firms speculating if they can breakeven, or even make a profit, by engaging in CCS. Unless the financial risks for CCS are deemed to be within acceptable levels, commercial firms would instead place their investments elsewhere to make up for the costs of purchasing carbon credits. The following table displays the various financial risks which CCS operators may encounter during the lifecycle of their CCS operations.

TABLE 7-3: FINANCIAL RISKS ATTRIBUTED TO THE CAPTURE STAGE OF CCS

Hazard identification	Who/what might be affected	Likely cause	Impact	Probability of occurrence	Possible remedial action
Lack of Funding (Walentek et al., 2011)	CCS operators	Blurry risk profile of business leading to financial institutions' reluctance in lending	Delayed construction or cancellation of projects	Low	Government part-ownership in demonstration projects; Set up an intergovernmental fund catered for CCS
Changing political landscape	CCS operators, power plants, carbon trading firms, CCS investors	Social disapprovals; Political interests moving away from carbon abatement	Delayed construction or cancellation of projects	Medium – High	Active social engagement; Regular dialogues with regulatory bodies
Sluggish permit application process	CCS operators, power plants, carbon trading firms	Inexperience regulators handling CCS approvals and checks	Delays in project; Loss of income/carbon credits	Medium	Training of governmental officials; Active participation in information sharing of other countries which are more advance in CCS development
Higher interests rates	CCS operators	Tightening of financial markets; Reduction of liquidity in market	Increased costs of CCS; Project becomes obsolete due to higher costs compared to carbon credits	Medium – High	Secure bank's or government's guarantee of loans at attractive interests rates
Decreased value of carbon credits	CCS operators, carbon trading firms	Improvement in carbon reduction processes for industries; Increased upper limit for CO ₂ atmospheric concentration; Higher cost effectiveness of clean renewable energy	Loss of income; Negative cash flow and losses; CCS become obsolete	Medium – High	Tighten carbon credits issuance; Early formation of carbon concentration limits plan
Accidents resulting in casualties	CCS operators, employees at CCS plants,	Equipment failure; Human negligence; Natural disasters	Compensation; Fines	Low – Medium	Insurance policies for employees; Sufficient cash reserves for one-off payments

Hazard identification	Who/what might be affected	Likely cause	Impact	Probability of occurrence	Possible remedial action
Accidents resulting in work stoppage	CCS operators, carbon trading firms	Equipment failure; Human negligence; Natural disasters	Work stoppage; Loss of income; Compensation	Low – Medium	Best practices sharing between CCS plants; Training of workers; Adequate maintenance plans
Increased costs of CCS operations	CCS operators and investors	Poor management; chemicals for capturing CO ₂ increases in price; Increases in manpower costs	Loss of income; CCS become	Medium	Upstream value chain integration of CCS;
Loss of assets	CCS operators and investors	Poor maintenance; Natural disasters ; Terrorism	Loss of income; Outflow of funds for replacement; Loss of public confidence	Low	Vigilant security systems; Adequate maintenance plans; Insurance
Migration of fish stocks	Human (Fishing companies)	Higher concentration of CO ₂	Compensation	Medium	Early communications to assist in increasing the employability of those affected.

7.1.2 Environmental risks

By preventing CO₂ in the flue gas of power plants from escaping into the atmosphere, sites located all over the world has to be surveyed and determined if they are suitable for long term storage of the captured CO₂. As with most anthropogenic activities, carbon sequestration would bring about impacts and risks to the areas around the storage sites. And one of the consequences of direct injection which has generated much discussion is acidification of the oceans.

The result of direct ocean storage of CO₂, whether intentionally released through direct injection as a storage proposal or accidental is ocean acidification. According to studies, ocean acidification has already occurred as the concentrations of atmospheric CO₂ is higher than the content in the oceans and is likely to increase if anthropogenic activities do not change (Raven et al., 2005). The current stated change in acidity of the oceans is 0.1 units and a further 0.3 units will occur by 2050 with a further 0.5 units change by 2100 (Caldeira and Wickett, 2005). This decrease in pH has detrimental effects on shell forming marine organisms. Thus, the increase in CO₂ content in the waters surrounding the creatures will lead to corrosive conditions for such calcifying organisms, making it difficult to build and maintain their carbonate skeletons (Kurihara, 2008, Orr et al., 2005). With the reduction in the population of such creatures, biodiversity and ecological balance in the deep seas will be adversely affected. Although deep sea biodiversity have not been studied under the same light as its terrestrial cousin and thus the actual impacts being unknown, it is clear that avoiding increases in global temperature will save 43% of biodiversity in the terrestrial ecosystem (Miles et al., 2004). In addition, the IPCC Special Report on *Carbon Dioxide and Storage* looked at environmental risks from the effects of CO₂ on cold-blooded water breathing animals, the impacts of CO₂ on pH levels in the oceans, effects of CO₂ at high concentrations and long term impacts of CO₂. Therefore, scientists are very much concerned about the potential risks involved with the method of direct injection.

In addition to acidification of the oceans through deliberate direct injection, any accidental release of liquid CO₂ in limited amounts into the oceans will likely to result in a localised “dead zone” that would last for a period of time depending on the amount and concentration of CO₂. Injection of CO₂ to a depth beyond 3,000m requires constant pressurizing to keep it in a liquefied form and this requires a sizable capacity of machinery and pumping systems. There are likelihoods that the equipment and pipes will fail during operations and result in leaks or even oilspills thus they should be considered in the risks assessment as well.

7.1.3 Social Risks

Public acceptance, support and participation are crucial for CCS to materialise at a global scale. Therefore the social aspect of risk management has to be tackled through precautionary measures, education and information transfer as well as a comprehensive public engagement strategy. This is also an issue which governments and non-governmental organizations (NGO) would be very interested in. Important aspects of social risks to address are risks of injuries and welfare of society. As many of the risks involving the environment causes detrimental effects to humans, the following table contains both environmental and social risks.

7.2 *Decision making recommendations*

With such wide-ranging effects of CO₂ direct injection, risks involved no doubt will add to the already severe consequences. Governments have to determine to what extent the consequences impacting deep ocean ecosystems is considered acceptable. For the retardation of global warming, companies can then evaluate and determine the risk mitigation and prevention strategies based on the acceptable limits (Gerstenberger et al., 2009). With the probable hazardous impacts of CCS identified and yet insufficient studies has led to inconclusive risk assessment of the impacts, a complementary risk management strategy known for its deterministic and conservative nature called the *precautionary principle* can be applied (Kirchsteiger, 2008).

TABLE 7-4: RISKS ASSOCIATED WITH THE ENVIRONMENTAL AND SOCIAL ASPECTS OF CCS

Hazard	What or who is affected	Possible Causes	Likely effects	Probability of occurrence	Possible remedy
Concentrated release of CO ₂	Environment; Human	Raptured pipelines; Sabotage; Geological disturbances; Accidental collisions	Asphyxiation; Plants may be frozen in the vicinity of the releases; Lethal if concentration increases CO ₂ content in the air by 7-10%	Low – Medium	Material verification; Pipeline inspection and monitoring; Emergency procedures; Maintenance plan; Avoid erecting pipeline in residential; Monitoring of flanged joints; Further study of system parameters for CO ₂ pipeline failure
Release of chemicals from capture tower	Environment; Human	Equipment failure; corrosion; improper disposal of wastes;	Pollution of the air, water sources or land; Health hazard to humans	Low-Medium	Proper guidelines and standard operating procedures of emergency response; Regular maintenance and disposal programme
Leakage (smaller amounts)	Environment; Human	Geological disturbances; Pipeline damage; Corrosion; Equipment failure	Health risks to people sensitive to increased concentration of CO ₂ ; Underground aquifers polluted if leakage occurs over a long period	Low – Medium	Periodic inspections; Quality assurance of pipes; Adequate monitoring systems of pipeline pressure and temperature
	Environment; Human	Fire and explosion on-board vessel could result in system leakage	Health hazard to crew;	Low	Training of crew; Adequate maintenance
	Environment; Humans	Loading stresses; Collisions; Age-related deformations; Bad weather	Health hazard to crew and port workers; Limited amounts of CO ₂ returning to the atmosphere; Localised acidification of sea surface	Medium	Adherence to shipboard Safety Management Systems (SMS) and maintenance systems; Training of crew; Observance of Class Society rules
	Environment; Humans	Damage due to dynamic pressure, sloshing and slamming	Health hazard to crew; Localised acidification of sea surface; Limited	Low – Medium	Adequate tanks design; Constant monitoring of cargo tanks

Hazard	What or who is affected	Possible Causes	Likely effects	Probability of occurrence	Possible remedy
			amounts of CO ₂ returning to the atmosphere		
	Environment	Fatigue of the pipes due to stresses from waves, currents and water pressure	Increase in the concentration of CO ₂ and acidification in the immediate vicinity of the leak with both near and far field effects.	Medium	Routine maintenance of delivery systems
Shipboard accidental releases of CO ₂ during loading/unloading	Environment	Tsunamis; Storm surges; Swaying; Mooring failure causing pipes to break	Hazardous to crew and port workers. Port waters acidified.	Medium	Ensure barriers are in place and monitor warning systems. Observe good seamanship techniques
	Human and marine life	Distortion causing valves and/or piping to fail and/or rupture	Hazardous to crew; Limited amounts of CO ₂ returning to atmosphere	Low – Medium	Inspection during construction; Adequate maintenance systems
Clogged injection pipeline	Environment; Human	Carbonate hydrates forming within a pipe	Explosion at the injection point; Release of CO ₂ into the atmosphere and seas; Probable injuries to workers and crew; Disruption to operations	Medium	Constant monitoring systems; Installation of hydrate inhibitors and safety valves
Upwelling	Environment	Deep sea storms; Deep sea currents	Large area of high CO ₂ concentration; High mortality rates for animals; Dispersion of CO ₂ beyond allocated area;	Medium	Enlarge the perimeter for monitoring; Collaboration between oceanography centres for information sharing; Conduct long-term surveys within vicinity of storage sites; Measurements of current profiles; Detection of extreme events such as temperature oscillations
Physical	Environment	Saturation of CO ₂ may	Unexpected sudden release	Medium	Ensure the reservoir is given a

Hazard	What or who is affected	Possible Causes	Likely effects	Probability of occurrence	Possible remedy
changes in stored CO ₂		lead to exothermic formation of hydrates and generate chain reactions with surroundings	of CO ₂ with reduction of reservoir performance due to exothermic reactions damaging the density stratification of the reservoir. Life expectancy of reservoir is reduced.		large amount of additional space for sufficient time to alkalise
“Excessive” ocean acidification	Environment; Human	Faster dissolution rate than expected. Deep sea storms and currents can accelerate the process	Lethal effects on ocean species dependent on intensity. Reduction in calcium ion concentrations	Medium	Careful selection of site as well as alkaline buffering solution/precipitation.

8 MONITORING

The monitoring for the Carbon Capture and Storage (CCS) system will take place from the point of emission through injection and storage in a deep ocean reservoir. The point of emission for the designed system is a coal power plant. The carbon dioxide must be separated and compressed from the flue gas. Monitoring is required for process control as well as reporting to national and/or regional authorities on emissions levels. After compression, the CO₂ must be transported to a port where it is liquefied and loaded onto a CO₂ ship, similar to the Coral Carbonic. During pipeline and shipping transport, it is necessary to monitor the process to ensure leaks are prevented and minimize damage to the infrastructure through corrosion and other mechanisms. Once the CO₂ has been shipped to the floating offshore structure for injection into the deep sea reservoir, monitoring is critical for ensuring that CO₂ is isolated from the atmosphere for the designed life cycle. Monitoring is an important tool in the overall risk management strategy for CCS projects. In many cases, standard procedures or protocols have not been developed specifically for CCS projects. However, knowledge in other sectors can be used to guide development, i.e., design and monitoring of deep sea sewage disposal.

The environmental, monitoring, risk and legal aspects associated with carbon dioxide as a product for chemical processing plants is well developed. However, CCS targets much higher volumes than CO₂ processing. On both the local, national and global scale, additional emergency response and other regulatory frameworks can be expected in the near future. For carbon dioxide, the United States Occupational Health and Safety Act standards (OSHAS) exist for safe handling of carbon CO₂ and for the reagents and catalyst used in the various separation and compression processes. In addition there are international standards such as ISO 14001 (for the environment) and ISO 9001 (for quality) and OSHAS 18000 exist to provide assurances that all steps are taken to ensure needed safety, health and quality management systems are in place.

8.1 CO₂ Capture Monitoring Methods

Monitoring CO₂ capture systems do not present any new technical challenges, as many countries worldwide have already implemented rigorous standards for monitoring and reporting emissions on NO_x and SO_x. For these and other pollutants there are existing procedures and protocols for reporting emission levels and documenting the health, safety and environmental risks associated with failure to comply with standards. To date, China has no specific regulations for monitoring CO₂ capture processes. It is recommended that until this is remedied, power plants utilizing CO₂ capture implement the highest existing standards that are economically practical; see Maximum Achievable Control Technology (MACT)¹⁴ guidelines under the Clean Air Act in the United States.

This includes following the World Bank guidelines and other financial institutions requirements to reduce risk (World Bank Group and United Nations Industrial Development Organization, (1999)). These guidelines are especially important in developing countries where there is little emphasis on monitoring and regulatory control. Additionally, regulations for plant design and specifications for monitoring emissions levels can be utilized from other countries, such as those used in the United States and overseen by their Environmental Protection Agency.

Plants with CO₂ capture systems are designed to produce a concentrated stream of CO₂ for storage. The stream must continually be monitored for impurities as they may impact the transport and final storage of the CO₂. In addition, several of the impurities have potential health, safety and environmental impacts. Capture from most processes contains moisture which has to be removed to avoid corrosion and hydrate formation in the pipeline and ships during transport. Continuous monitoring is required to ensure the water content is below the specification for transport. Existing CO₂ pipelines in operation apply automatic shut-downs if the dewatering system does not meet the specification; this has proven an efficient means of preventing internal corrosion and hydrate

¹⁴ See <http://www.cdphe.state.co.us/ap/mact.html> for a description of Maximum Achievable Control Technology Standards.

formation. Several additional impurities must be monitored as well, such as methane (CH_4), hydrogen (H_2), nitrogen (N_2), sulphur oxides (SO_x), nitrogen oxides (NO_x). These may affect the transport of CO_2 with respect to flow, pressure, water drop out and hydrate formation.

8.2 Pipeline and Ship Transport Monitoring

In all transportation options there are risks, both calculable and perceived. Pipeline and marine transportation systems both have established safety records. Comparison of the requirements of a CO_2 transport system with existing oil and gas transport systems (long distance pipelines and ship transport) indicates that the risks should be comparable. The existing transport systems in general are perceived to have acceptable risk levels (aside from several prominent disasters such as the *Exxon Valdez* in 1989, *Torrey Canyon* in 1967, *Braer* in 1993 and *Deepwater Horizon* in 2010). Based on this, CO_2 transport systems should be built within the monitoring framework that is currently acceptable for oil and gas transport.

Carbon dioxide transport (whether by ship or pipeline) must be monitored to ensure that there is little to no release into the atmosphere. For transport, operations include daily maintenance, scheduled planning and policies for inspections, maintaining and repairing all equipment on the line, pipeline and the ship, as well as all of the support equipment.

8.2.1 Onshore Pipelines

CO_2 pipelines must be monitored closely. The technology for this is fundamentally the same as that for natural gas pipelines and should include both the use of monitoring instruments (automated) as well as manual monitoring (visual inspection). Pipelines in operation are monitored internally by pigs (internal pipeline inspection devices, discussed below) and externally by corrosion monitoring and leak detection systems. In addition, patrols are also conducted on foot and by aircraft to detect unauthorized excavation or construction before damage occurs to the pipeline. The monitoring interval for visual inspections is agreed upon by the operator and the relevant regulatory authorities. External inspections can detect leakages in buried pipelines. The pressure decrease due to a phase change of CO_2 can result in a significant temperature decrease of the surrounding environment which results in freezing of the humidity in the soil and air, causing the formation of large ice bulbs. CO_2 operators in the United States that reported ice bulbs with a size of 1-2 m^3 .

Key parameters for monitoring are the operating temperature and pressure of the pipeline, the flow rate of gas through the pipeline, and the stream composition. The control system should also be able to detect leaks and provide predictions for locations of fatigue.

- The flow rate can be determined by standard flow restriction metering (orifice or Venturi), however accurate temperature monitoring and control is also necessary due to the density dependence for CO_2 on pressure and temperature.
- While compositional analysis of the CO_2 can be accomplished using gas chromatography (identical to that used in natural gas transport). The components to identify will depend on the specification for the purity of CO_2 in the pipeline.
- Water content is the primary component of concern in the CO_2 stream. Instead of a dew point measurement, experience show that it is more suitable to use a moisture analyser to measure the water content. There are several commercially available sensors for this. Moisture analysers can detect in the range of 0.1-2500 ppm and with an accuracy of 10%.

In-line inspection tools need to be compatible with the pressures and phases of CO_2 that may be present along the CO_2 pipeline. Difficulties specific to the pipeline transport of CO_2 include material compatibility, high pressures, diffusion of high pressure CO_2 into electronic components, speed control and cup wear. Pipelines are cleaned and inspected by 'pigs' (Tiratsoo, 1992, Wang et al., 2001, Phipps, 2009, Bubar, 2011). They are piston-like devices driven along the line by the gas pressure. 'Pigs' have reached a high level of sophistication, and can measure internal corrosion, mechanical deformation, external corrosion, the precise position of the line, and the development of spans in underwater lines.

Long-distance pipelines are instrumented at intervals so that the flow can be monitored. The monitoring points, compressor stations and block valves are tied back to a central operations centre. Computers control much of the operation, and manual intervention is necessary only in unusual upsets or emergency conditions. The system has inbuilt redundancies to prevent loss of operational capability if a component fails. Some pipelines have independent leak detection systems that find leaks acoustically or by measuring chemical releases, or by picking up pressure changes or small changes in mass balance. This technology is considered available and routine and need only be applied to CO₂ transport.

8.2.2 *Offshore Pipelines*

Currently, underwater pipelines are monitored by remotely operated vehicles, small unmanned submersibles that move along the line and make video records, and in the future, by autonomous underwater vehicles that do not need to be connected to a mother ship by a cable. Some pipelines have independent leak detection systems that find leaks acoustically or by measuring chemical releases, or by picking up pressure changes or small changes in mass balance. This technology is available and routine. Marine pipelines are monitored internally by inspection devices such as 'pigs', and externally by regular visual inspection from remotely operated vehicles. Similar to onshore pipelines some have independent leak detection systems.

8.2.3 *Ship Transport*

Monitoring for ship transport is two-fold: the ship itself must be inspected to ensure it meets all required standards and complies with all relevant safety regulations, and the potential to monitor the system should a leak occur. Ship and tank inspections are already well-documented for use with oil and gas tankers and similar methodologies should be used for carbon dioxide transport.

In general, strandings are the greatest source of public concern. These can be controlled by careful navigation along prescribed routes, and the highest standards of operation. Position of the ship along with other ships and navigational hazards can be monitored using existing technology. Liquid natural gas tankers, while potentially dangerous, have had no accidental losses of cargo and there is no reason this cannot continue with CO₂ transport.

Should an accidental release of CO₂ take place from ship transport, the CO₂ would accumulate on the surface of the sea. The release of CO₂ should not have the long-term environmental impacts that are commonly associated with oil tankers; however, it will have localised and immediate impacts. Its interaction with the sea could cause hydrate and ice formation. The temperature difference between the liquid CO₂ and the ocean could also induce strong currents. The liquid CO₂ will evaporate into the atmosphere and a portion of it will dissolve into the sea. In calm conditions and with a temperature inversion, the evaporated cloud of CO₂ could lead to asphyxiation and may also stop the ship's engines.

8.3 *Storage Monitoring*

Monitoring the storage portion of the CCS system is used to identify the movement of CO₂ which can provide information regarding the reliability and day-to-day operations of the injection as well as long-term safety and security of storage system. Monitoring during the injection and post-injection phase can utilize the same techniques, albeit at different time scales. In both cases, there are no established protocols for monitoring, i.e. the responsible party, duration and frequency of sampling, and the purpose.

So long as all of the regulatory requirements have been met, Keith and Wilson (2002) have proposed that the responsible party for long-term monitoring are the governments whom control the storage location (after the active phase of the project or post-injection). It has been suggested that monitoring may be required for thousands of years (White et al. 2003). Until requirements and the purpose of the

monitoring plan is determined (Stenhouse et al. 2005), it is not possible to determine the optimal mix of technology.

8.3.1 *Monitoring of Injection*

Prior to beginning injection, an initial monitoring survey will be conducted to assess the baseline site properties. This will encompass all of the methods described in the following section. Once the injection has started, the surveys are repeated at specific time intervals to create a time-lapse dataset of the site properties. The results of the surveys can be used to build up a picture of how properties are changing with time. Monitoring begins prior to injection, continues through the injection period, and into the final storage phase (post-injection). This is to ensure that the system is behaving as predicted.

Parameters such as injection rate and pressure will be measured continuously, and the instruments to monitor these parameters are available commercially. Measurements will need to be taken at the surface and the end of the pipe to ensure the integrity of the injection pipe. Pressure gauges can be installed along the injection pipe, with continuous data streaming to a central control room on the floating platform. Surface pressure gauges are often connected to shut-off valves that will stop or curtail injection if there is a drop in pressure as a result of a leak. Combined with temperature measurements, the collected parameters will provide accurate accounting for inventories, reporting and verification, as well as for inputs into modelling.

8.3.2 *Storage Reservoir Monitoring*

Monitoring the injection through the pipe is relatively simple and utilizes well established technologies. Monitoring protocols for open ocean disposal depend on whether the plume is rising or sinking. The method proposed here is a dense CO₂ lake residing in the bottom of a deep ocean trench (which is most similar to sinking plume monitoring). Monitoring is done for several purposes, including gaining specific information relating to a particular CO₂ storage operation and to gain general scientific understanding. The monitoring program should quantify the mass and distribution of CO₂ from each point source and relate them to biological and geochemical parameters.

Using an array of pH and conductivity sensors at a depth of 4-km, Brewer et al. (2005) were able to detect a plume of CO₂. Measurements of ocean pH and current profiles at a high resolution (both spatially and temporally) can evaluate the rate of CO₂ release, local accumulation and transport away from the designated CO₂ storage area (Sundfjord et al., 2001). The sound velocity contrast between liquid CO₂ and sea water (300 m/s and 1,500 m/s respectively) provide a means for utilizing acoustic techniques such as sonar.

A combination of the above methods (pH, conductivity, velocity, and acoustic sensors) as well as underwater vehicles, the placement of CO₂ in the lake can be verified. Undersea vehicles will likely play a key role in any successful monitoring and verification program. Autonomous vehicles have been developed that can follow complex trajectories, but their ability to sense pH in a changing pressure and temperature field cannot be verified (Simonetti, 1998). Deep-sea pH monitoring from tethered vehicles has been shown to be very precise (Brewer et al., 2004), and these vehicles can routinely collect precisely located samples for later analysis.

Similar to the method proposed by the IPCC (2005), a combination of chemical, biological and current sensors should be used (see Figure 8-1). The difference between the figure and the system under consideration is the use of a floating platform to inject the CO₂ into a lake, rather than a pipeline connected to the shoreline. An array of moored sensors will be used to monitor the injection of the CO₂ followed by verifying the location and size of the CO₂ lake for the duration of post-injection monitoring. An autonomous underwater vehicle can be used to monitor the near-field effects of the lake. Moored systems both underwater and on the surface can be used to monitor the lake on a near-continuous basis. In conjunction with the moored buoys (stationary source with high temporal frequency), ship-based surveys can be used to monitor areas of interest based on either numerical models or anomalous findings from one of the buoys. While technology currently exists that can be

used for the monitoring schemes mentioned above, it is recognised that the extreme environment (depths greater than 3500 m) will greatly increase the economic cost of any monitoring plan as well as increasing safety risks to involved personnel.

In general, there is very little data concerning deep-sea ecosystems, let alone the impacts of CO₂ injection on them at full scale. Therefore, it is difficult to determine with any degree of accuracy the necessary monitoring to minimize environmental impacts. Because large amounts of pure CO₂ have never been injected into the ocean, conclusions regarding risk must be drawn from laboratory and



FIGURE 8-1: SCHEMATIC OF POSSIBLE APPROACHES FOR MONITORING THE INJECTION OF CO₂ INTO THE DEEP OCEAN VIA A PIPELINE. THE GREY REGION REPRESENTS A PLUME OF HIGH CO₂ /LOW pH WATER EXTENDING FROM THE END OF THE PIPELINE. SOURCE: IPCC (2005) FIGURE 6.22 ON PAGE 309.

small scale in-situ experiments along with critical analysis of conceptual and mathematical models.

Introduction of CO₂ into the ocean as a lake on the sea floor will result in changes in dissolved CO₂ at injection area and near the CO₂ lake. Dissolving CO₂ in sea water increases the partial pressure of CO₂ (pCO₂), which causes decreased pH (more acidic) and decreased CO₃²⁻ concentrations (less saturated). This can lead to dissolution of CaCO₃ in sediments or in shells of organisms. The spatial extent of the waters with increased CO₂ content and decreased pH will depend on the amount of CO₂ released and the technology and approach used to introduce that CO₂ into the ocean.

TABLE 8-1: RELATIONSHIP BETWEEN ΔpH , CHANGES IN pCO_2 CALCULATED FOR MEAN DEEP-SEA CONDITIONS. SOURCE IPCC (2005) (ADAPTED FROM TABLE 6.3 ON PAGE 313)

pH change ΔpH	Increase in CO_2 partial pressure ΔpCO_2 (ppm)	Seawater volume to dilute 1 tCO_2 to ΔpH (m³)	GtCO_2 to produce ΔpH in entire ocean volume
-0.1	150	656,000	2,000
-0.2	340	340,000	3,800
-0.5	1,260	141,000	9,200
-1	5,250	54,800	24,000
-2	57,800	6,800	190,000

Strategies that release liquid CO_2 close to the sea floor will affect two ecosystems: the ecosystem living on the sea floor, and deep-sea ecosystem living in the overlying water. Storage in a topographically confined 'CO₂ lake' (within a trench and investigated here) would limit immediate large-scale effects of CO_2 addition, but cause the death of most organisms under the lake that are not able to flee and of organisms that wander into the lake. CO_2 will dissolve from the lake into the bottom water, and this will disperse around the lake, with effects similar to direct release of CO_2 into the overlying water. The changes in pH expected in the near field are well within the scope of those expected to exert significant effect on marine biota, depending on the length of exposure.

The cost of a monitoring and verification program for the deep ocean will involve purchasing, deploying and maintain a large array of sensors in the ocean, ship-based sampling, as well as research into new and novel methods to quantify biological impacts. While the technology exists for this type of monitoring, it is typically only used for research activities and may not be appropriate for long-term (decades to centuries) of use. Prior to 2005, there were no cost estimates of near-field monitoring of ocean injection (IPCC, 2005).

9 CONCLUSIONS

China has seen a remarkable rise in its economy in the past four decades and has now recognised the accruing costs of growth and development at the expense of the environment. Coal has been and will continue to dominate the power industries in order to support China's economy and social development beyond 2030. China has displayed commitment in resolving climate change through numerous regulatory policies and guidelines targeted at developing expertise in energy efficiencies and clean energy production. Therefore CCS, which China has placed as one of the priorities of its latest science and technology road-map, will offer an ideal avenue for the continual usage of coal as an energy source whilst reducing greenhouse gas emissions into the atmosphere. From preliminary studies, it appears that China has the potential for a full scale deployment of CCS in ocean space in view of the proximity of many power plants to the coastline and potential sites for storage. Indeed, there is much work left to be completed in addition to evaluation of site integrity. There are several completed and on-going collaborative projects in which developed countries are partnering China to stimulate her interests and expertise in CCS. Funding, information and technical knowledge transfer as well as regulatory consultancy are among the main activities of the joint projects. Increased intensity and level of collaboration are required to enable China to advance to a more mature stage in CCS development in areas such as direct injection of CO₂ into the oceans.

A transparent and resilient regulatory framework is essential for the further development and the eventual deployment of CCS. China is signatory to three international conventions which are not against CCS and with more say in the highest Chinese regulatory body, the Ministry of Environmental Protection can develop a comprehensive framework that governs CCS and is able to safeguard the general public's and private businesses' interests. For CCS to take place in the South China Sea, dialogue with regional neighbours in ASEAN has to take place so that cooperative efforts in CCS trials and site surveys can be conducted even beneath the looming subject of continental shelf claim disputes.

In addition to protecting the public, China has to embark on an active public engagement strategy at an early stage to earn the public's trust, support, acceptance and eventually, participation in CCS. The role of traditional and emerging social media in educating and persuading the public is instrumental as with the creation of platforms on which forums and discussions can be held for constructive debates on controversial issues and for assuring influences from credible sources to be influenced on the public during such forums. Even at later stages, continual efforts in engaging the society are paramount to the ultimate success and retirement of CCS. A recommendation for China's engagement strategy is to adopt an approach which focuses on the facts on benefits and rational perspective of potential threats.

CCS is only viable when there are artificial pricing mechanisms introduced upon carbon emissions, such as carbon tax and carbon trading systems. Therefore, there has to be foreseeable and realistic projections of the carbon concentration levels permitted in the future for companies to determine if CCS is indeed economically viable or even profitable. If the economics become viable, the much needed private investments would increase in China to continue the development of CCS. In view of the high risks involved, public participation would be crucial to the swiftness at which China can deploy CCS on a large scale. In addition, to make CCS an attractive avenue for investments by private firms, instruments such as private insurance and mutual insurance or governmental loans at low interest rates can be introduced to mitigate the financial risks involved.

With regards to the technical aspects of CCS, capture of CO₂ many demonstration plants have determined an acceptable carbon capture rate to be at 90%. The eventual process is required to provide a relatively pure stream of CO₂ for cost-efficient transportation due to the fact that CO₂ is highly acidic in the presence of water. Hence, the free water content in the stream has to be eliminated to reduce corrosion on the steel pipes. Technology for absorption of CO₂ from the flue gas using chemicals is well-understood and commercially viable. China has to take into considerations the future benefits of partaking in membrane separation systems which boast higher capital costs but much lower operation costs and simpler operating procedures, as compared to lower investments in chemical

absorption which would account for a large percentage of the energy penalty for CCS due to the temperature shift required for regeneration of the solvent.

For the power plants along the coast of China, pipelines are considered the most cost-efficient solution for the transportation of CO₂. Transportation chains involve the following steps: liquefaction and gas conditioning, initial storage, pipeline transport to harbour, intermediate storage, loading, shipping, and offshore unloading. Critical parameters of pipeline design are operating pressure, temperature, gas composition and corrosiveness as well as ambient temperatures. Storage in the deep ocean requires a sea voyage to the transportation chain and shipping acts as an alternative with lower capital costs and higher flexibility. In addition, the unit costs per tCO₂ reduce with the increase in vessel capacity, up to a certain size. With the building up of the Chinese fleet by the state-owned shipping companies, this will become an attractive option.

One alternative option for storage of CO₂ is in the deep ocean and this method is particularly sensitive as it may result in consequences for neighbouring nations with access to the same body of water. Therefore, deep ocean storage is under developed due to limited knowledge on the detrimental processes which would occur at large scale. Conceptually, a CO₂ reservoir is regarded as a large vat for the eventual dilution of CO₂ into ocean space which would occur naturally however bypassing the surface layers were the marine organisms have a larger sensitivity and economic potential in comparison to the deep depths. By slowing the rate of dilution, the amount of buffer required per unit time is reduced thus making the idea of carbon fixing also more feasible. In addition, less amounts of fixing materials are required and the probable spread of thirty years allows technology to catch up, resulting in lower costs and higher efficiencies. A deciding factor for the use of direct injection would be the moral debate of whether the protection of biodiversity in the terrestrial system would warrant the sacrificial of an ecosystem contained within a relatively small ocean floor area. There is indeed sufficient capacity for storage of China's CO₂ in the deep ocean and further studies in this niche area would increase knowledge about the deep ocean ecosystem, fluid dynamics, chemical interaction and limiting measures of an adaptive system over a long period.

Monitoring systems are crucial to the value chain of the entire CCS system as part of risk mitigation and they should encompass not only the CO₂ characteristics but the effects on the surrounding environment as well. The risks of remaining in a status quo scenario (instead of employing CCS) has been examined and regarded as unacceptable. Ultimately, there has to be an agreed amount of trade-offs and compromise to be made in order to compensate for the excess CO₂ in the atmosphere and CCS seems to be providing most of the answers for China.

10 WORKS CITED

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11 APPENDICES

Appendix A. Existing and Planned Power Plants in China

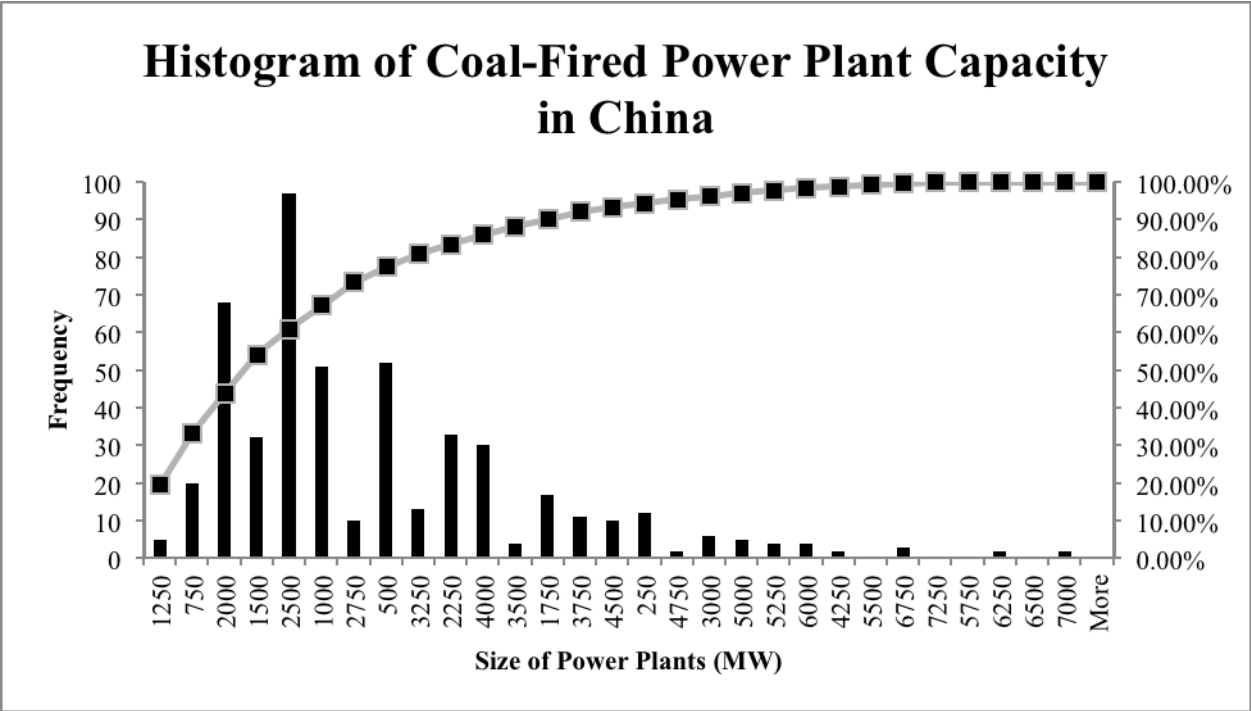


FIGURE 11-1: HISTOGRAM OF COAL-FIRED POWER PLANTS IN CHINA (TOTAL CAPACITY IN MW) DATA

SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

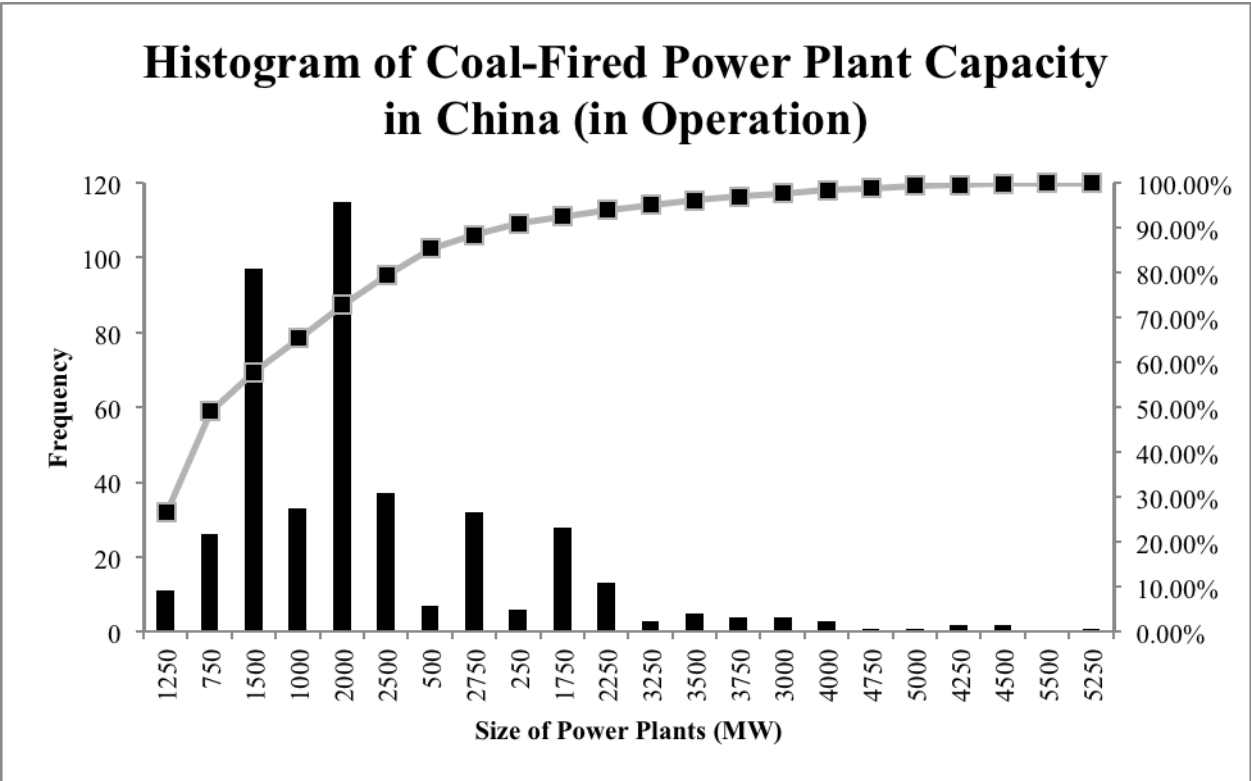


FIGURE 11-2: HISTOGRAM OF COAL-FIRED POWER PLANTS IN CHINA (OPERATIONAL CAPACITY IN MW) DATA

SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

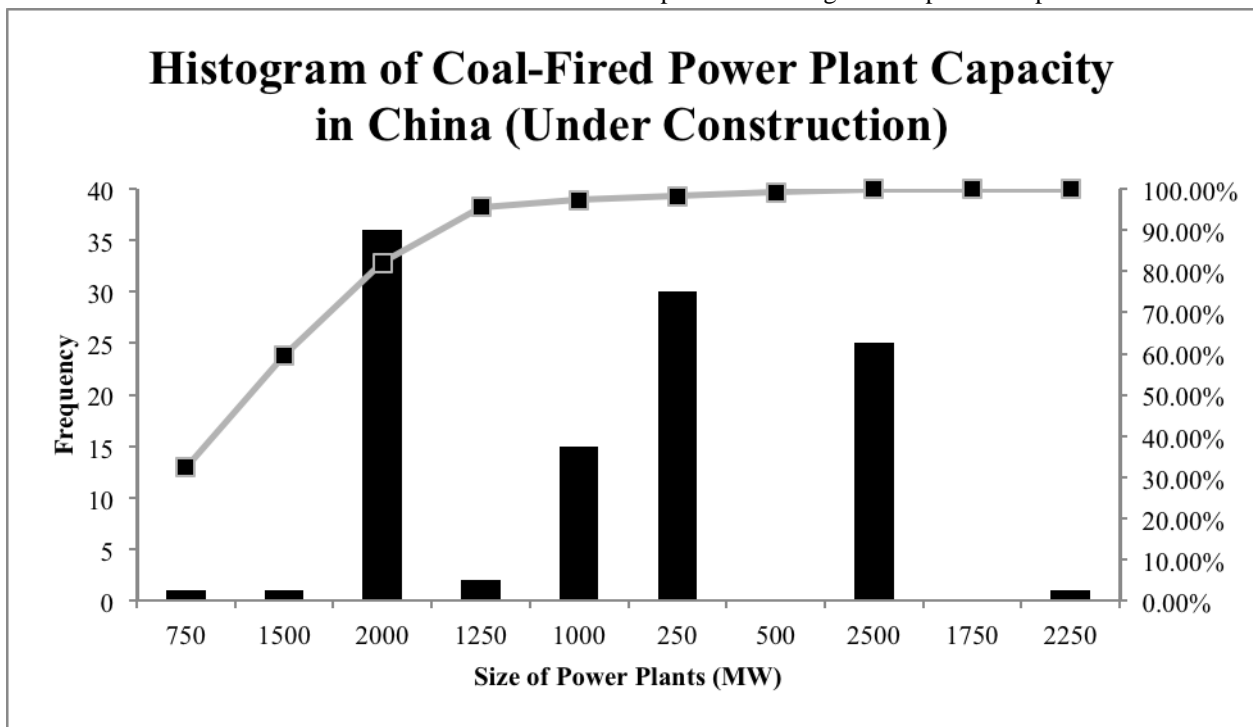


FIGURE 11-3: HISTOGRAM OF COAL-FIRED POWER PLANTS IN CHINA (CAPACITY UNDER CONSTRUCTION IN MW) DATA

SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

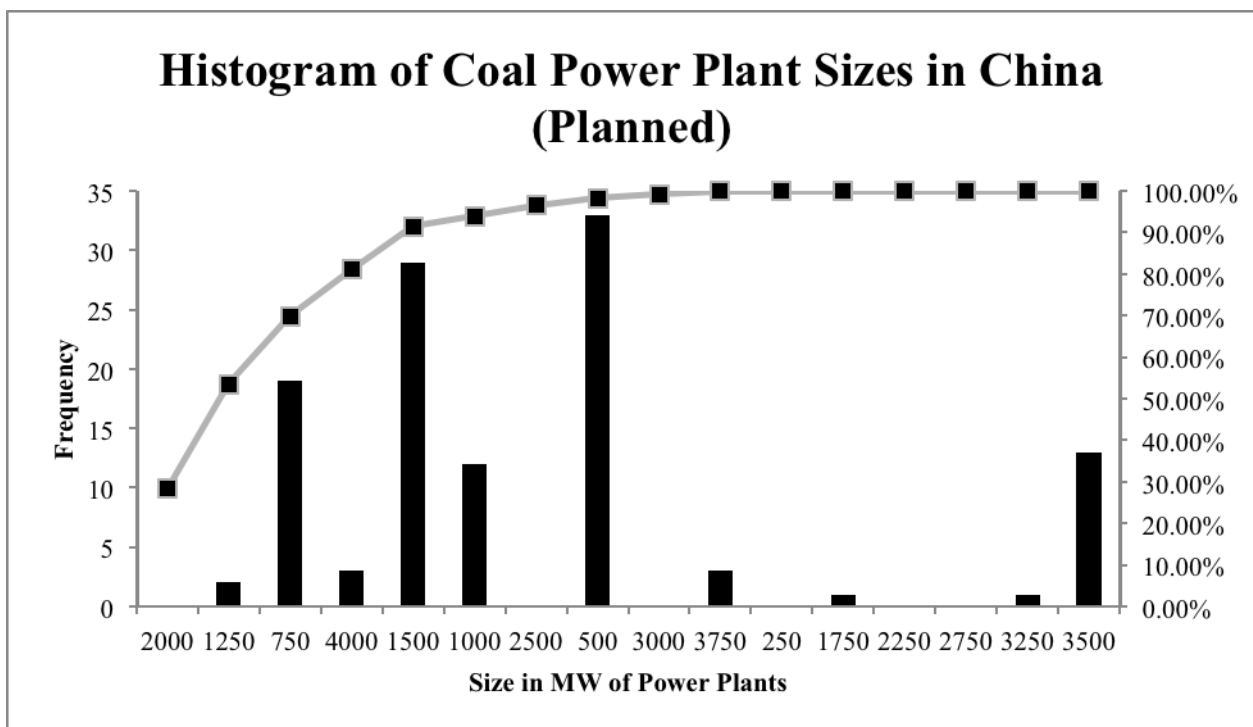


FIGURE 11-4: HISTOGRAM OF COAL-FIRED POWER PLANTS IN CHINA (PLANNED CAPACITY IN MW) DATA

SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

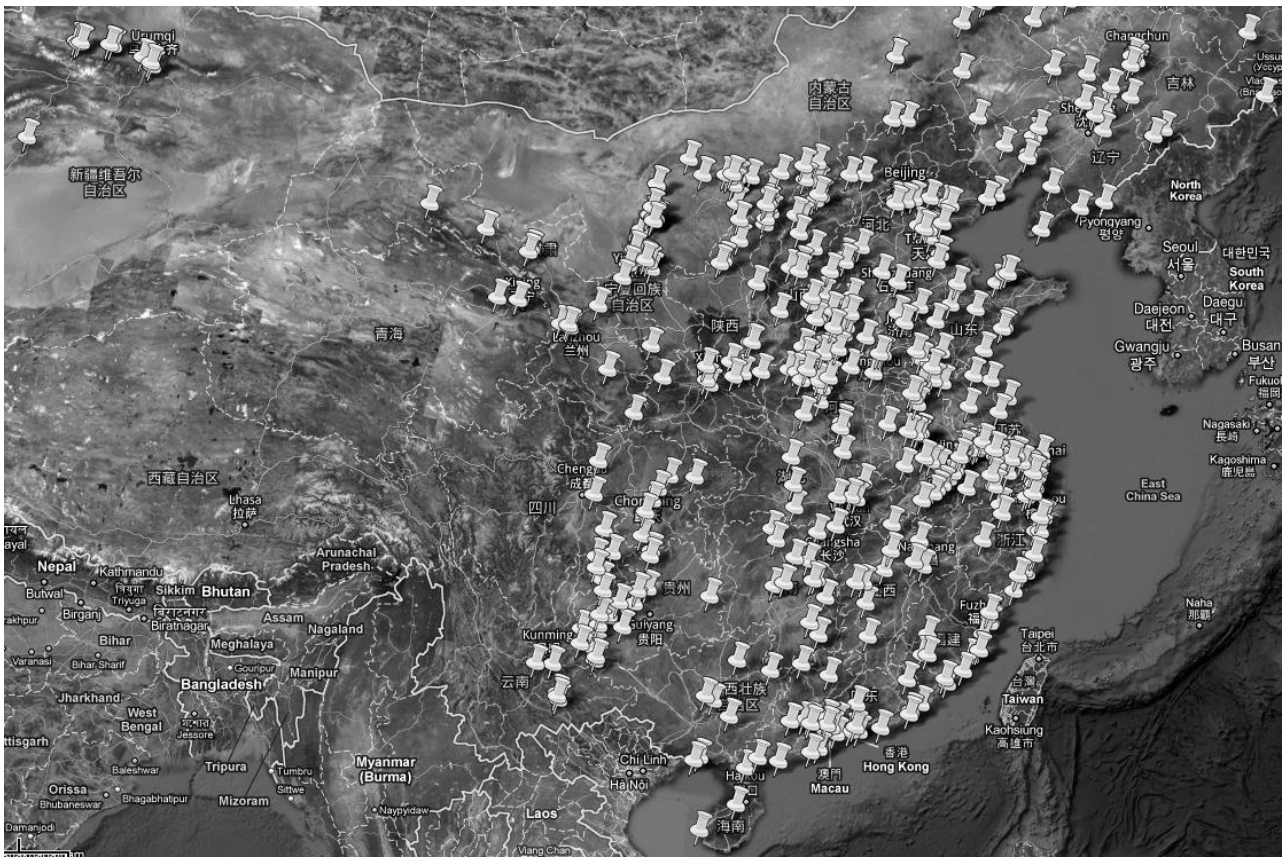


FIGURE 11-5: LOCATION OF ALL COAL-FIRING POWER PLANTS IN CHINA. SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)



FIGURE 11-6: LOCATION OF COAL-FIRING POWER PLANTS IN CHINA WITH RELATION TO THE SOUTH CHINA SEA NEAR THE ISLAND OF HAINAN .
SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)



FIGURE 11-7: LOCATION OF COAL-FIRING POWER PLANTS IN CHINA WITH RELATION TO THE EAST CHINA SEA NEAR BEIJING

SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

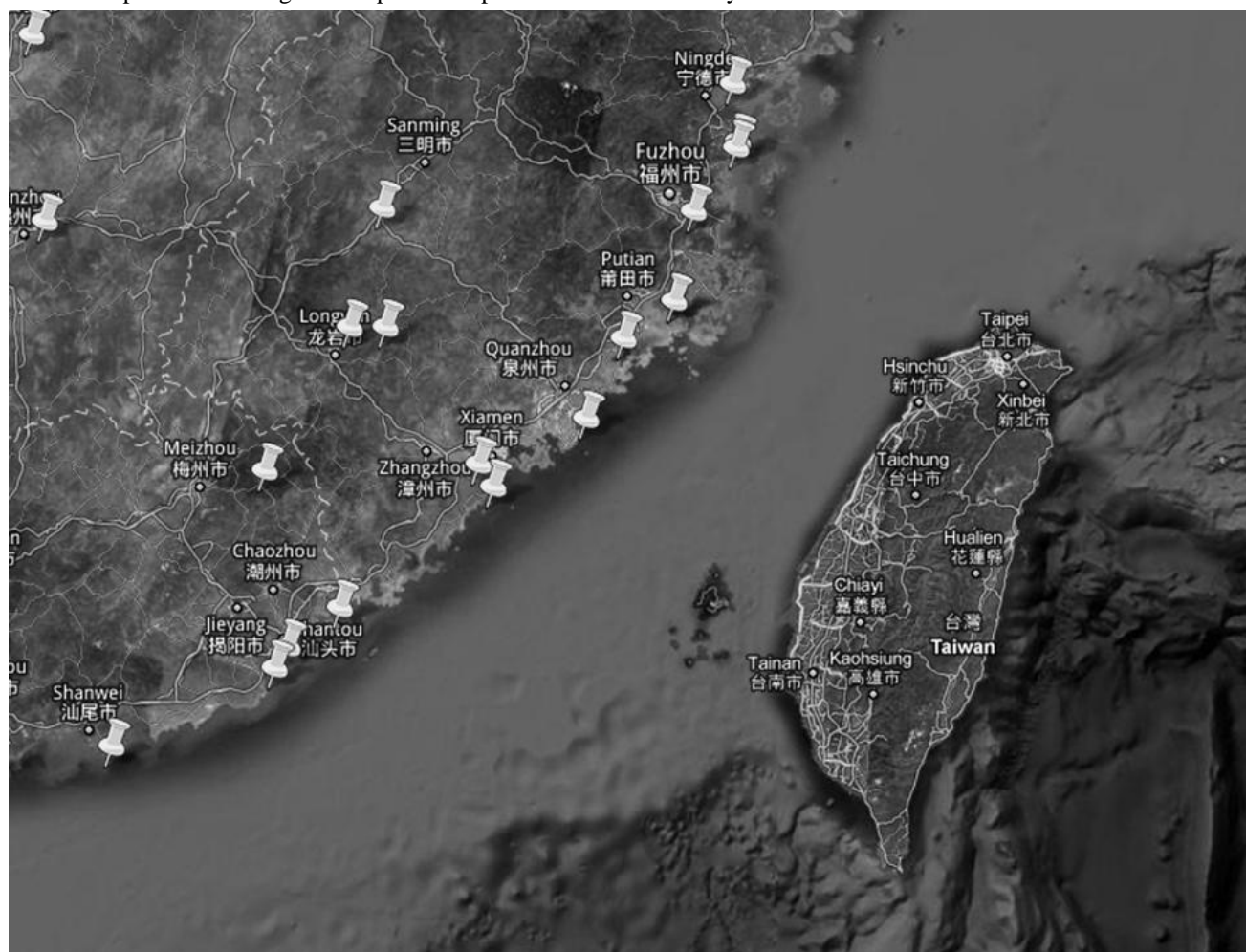


FIGURE 11-8: LOCATION OF COAL-FIRING POWER PLANTS IN CHINA WITH RELATION TO THE PHILLIPINE SEA AND THE NORTH ATLANTIC (NEAR THE ISLAND OF TAIWAN) .

SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

TABLE 11-1: LOCATION AND CAPACITY OF COAL-FIRED POWER PLANTS IN CHINA
 SOURCE: [HTTP://EN.WIKIPEDIA.ORG/WIKI/LIST_OF_POWER_STATIONS_IN_CHINA](http://en.wikipedia.org/wiki/List_of_power_stations_in_China)

Station	Latitude	Longitude	Capacity (MW)
Kuqa Power Station	41.74	82.89	270
Kuitun Power Station	44.41	84.93	270
Dushanzi Power Station	44.38	84.87	375
Wusu Power Station	44.44	84.76	660
Tianfu South Power Station	44.36	86.04	930
Manas Power Station	44.32	86.17	1230
Tianye Power Station	44.36	86.04	1340
Weihuliang Power Station	43.85	87.65	250
Changji Power Station	43.99	87.31	910
Hongyanchi Guodian Power Station	43.74	87.66	880
Hongyanchi Huadian Power Station	43.74	87.66	800
Jiuquan Steel Power Station	39.80	98.31	600
Xihai Power Station	36.97	100.91	250
Zhangye Power Station	39.07	100.45	600
Datong Power Station	36.91	101.71	600
Qiaotou Power Station	36.90	101.71	1225
Yongcang Power Station	38.37	102.10	860
Jinchuan Group Power Station	38.49	102.17	300
Kunming 2nd Power Station	25.01	102.33	600
Xigu Power Station	36.13	103.62	1115
Yangzonghai Power Station	24.96	103.03	1000
Xiaolongtan Power Station	23.84	103.20	600
Fanjiaping Second Power Station	36.08	103.68	60
Honghe Power Station	23.74	103.22	600
Xunjiansi Power Station	23.96	103.19	600
Chalco Lanzhou Power Station	36.16	103.33	900
Jiangyou Power Station	31.80	104.77	1260
Gongxian Power Station	28.27	104.67	5200
Jintang Power Station	30.70	104.57	3600

Station	Latitude	Longitude	Capacity (MW)
Zhengxiong Power Station	27.49	104.95	1200
Shuicheng Power Station	26.68	104.81	600
Jingyuan Power Station	36.73	104.76	2000
Qujing Power Station	25.66	104.06	1200
Diandong Power Station	25.20	104.68	2400
Faer Power Station	26.33	104.77	2400
Pannan Power Station	25.47	104.59	2400
Yuwang Power Station	25.09	104.62	2400
Panxian Power Station	26.01	104.52	1000
Xuanwei Power Station	26.19	104.11	1800
Fuxi Power Station	28.66	104.68	2400
Weixing Power Station	27.88	104.88	1200
Gangu Power Station	34.76	105.10	600
Zhongning Power Station	37.59	105.71	660
Luzhou Power Station	28.78	105.28	2400
Baima Power Station	29.53	105.01	2100
Dafang Power Station	27.10	105.56	2520
Daba Power Station	37.98	105.93	2400
Anshun Power Station	26.22	105.71	1200
Nayong First Power Station	26.65	105.18	1200
Nayong Second Power Station	26.60	105.18	1200
Lueyang Power Station	33.35	106.14	330
Haibowan Power Station	39.32	106.86	1260
Lingzhou Power Station	38.14	106.57	270
Anwen Power Station	28.64	106.75	960
Wuhai Thermal Power Station	39.71	106.83	400
Xixia Power Station	38.44	106.12	1060
Haibowan Gangue Power Station	39.37	106.89	400
Jinhai Gangue Power Station	39.37	106.89	1200
Wuda Power Station	39.48	106.74	3000
Daba Power Station	30.16	106.55	1920

Station	Latitude	Longitude	Capacity (MW)
Mengxi Power Station	39.71	106.83	600
Wansheng Power Station	28.84	106.78	600
Wusitai Power Station	39.47	106.70	600
Maliantai Power Station	38.17	106.57	1980
Lingwu Power Station	38.15	106.35	5200
Qipanjing Power Station	39.39	106.97	2460
Shuidonggou Power Station	38.21	106.54	5320
Yuanyanghu Power Station	38.06	106.69	1320
Dawukou Power Station	39.04	106.39	1100
Qianbei Power Station	27.48	106.26	1700
Pingliang Power Station	35.50	106.79	1200
Qianxi Power Station	27.05	106.12	1200
Yaxi Power Station	27.58	106.65	1200
Guang'an Power Station	30.53	106.83	2400
Luohuang Power Station	29.35	106.43	2640
Shizuishan Power Station	39.29	106.79	1980
Ningdong Power Station	37.85	106.79	4660
Huayinshan Power Station	30.89	107.05	600
Jinneng Thermal Power Station	40.38	107.00	1200
Linhe Thermal Power Station	40.38	107.00	600
Wanyuan Power Station	31.32	107.49	600
Baoji No2 Power Station	34.50	107.22	1200
Wulashan Power Station	40.65	108.77	1800
Baihe Power Station	31.27	108.46	600
Heshan Power Station	23.83	108.87	660
Dongfang Power Station	19.05	108.64	1400
Fangchenggang Power Station	21.59	108.39	3120
Qin Zhou Power Station	21.71	108.61	3200
Tongchuan Power Station	34.85	108.89	1200
Weihe Power Station	34.43	108.91	1200
Wuyuan Power Station	41.12	108.23	1200

Station	Latitude	Longitude	Capacity (MW)
Baqiao Power Station	34.29	109.05	850
Baotou No2 Thermal Power Station	40.68	109.89	2200
Baotou No1 Thermal Power Station	40.66	109.66	1800
Dalong Power Station	27.30	109.01	600
Laibin Power Station	23.69	109.16	2520
Guigang Power Station	23.11	109.77	3200
Hengshan Power Station	38.04	109.42	1100
Baotou East Hope Aluminum Smelter Plant Power Station	40.59	109.78	1320
Qinling Power Station	34.53	109.94	1400
Shenghua Yili Power Station	40.36	109.97	800
Pucheng Power Station	34.98	109.80	2520
Dalate Power Station	40.37	110.00	3180
Yuheng Power Station	38.13	109.54	1200
Maoming Power Station	21.68	110.88	1700
Shenghua Coal liquefaction Thermal Power Station	39.33	110.15	500
Baotou Donghua Thermal Power Station	40.58	110.07	2600
Yongfu Power Station	25.10	110.07	870
Baotou No3 Thermal Power Station	40.62	110.00	600
Dongsheng Power Station	39.82	110.03	1360
Haikou Power Station	19.96	110.05	1212
Hejin Power Station	35.61	110.66	1900
Hexi Power Station	39.82	110.03	4400
Hancheng No2 Power Station	35.60	110.56	1200
Zhanjiang Power Station	21.31	110.41	2400
Jinjie Power Station	38.74	110.17	2400
Liulin Power Station	37.42	110.83	1400
Salaqi Power Station	40.58	110.62	600
Yuncheng Power Station	34.65	110.29	1200
Jinqiao Power Station	40.71	111.74	1200
Zhungeer Dafanpu Pithead Power Station	39.79	111.16	4400

Station	Latitude	Longitude	Capacity (MW)
Suancigou Power Station	39.83	111.27	1800
Chuangyuan Power Station	29.20	111.56	600
Lianyuan Power Station	27.77	111.89	600
Sanmengxia Power Station	34.69	111.03	2800
Tuoketuo Power Station	40.20	111.36	6600
Hequ Power Station	39.38	111.19	2400
Jinzhusan Power Station	27.63	111.48	2400
Yangxi Power Station	21.54	111.67	2400
Fugu Power Station	39.20	111.12	1200
Shimeng Power Station	29.58	111.39	1200
Zhungeer Energy Power Station	39.85	111.25	1320
Huozhou Power Station	36.55	111.69	1200
Hezhou Power Station	24.74	111.35	4000
Weijiamao Power Station	39.56	111.37	1200
Taiyuan 1st Power Station	37.78	112.48	1275
Jingmeng Power Station	31.03	112.23	1840
Yushe Power Station	36.98	112.95	800
Yuelian Power Station	24.98	112.55	1720
Shouyangshan Power Station	34.73	112.76	2200
Leiyang Power Station	26.39	112.86	1000
Nanhai 1st Power Station	22.89	112.92	1600
Jingzhou Power Station	30.28	112.28	600
Yichuan No3 Power Station	34.41	112.55	600
Yunfu Power Station	22.97	112.11	1120
Luoyang Thermal Power Station	34.68	112.39	1005
Gujiao Power Station	37.90	112.09	1800
Yiyang Power Station	28.60	112.27	1800
Xiangtan Power Station	27.83	113.00	1900
Yahekou Power Station	33.31	112.64	1900
Huilai Power Station	23.01	112.61	7200
Changsha Power Station	28.49	112.80	1200

Station	Latitude	Longitude	Capacity (MW)
Hengyi Power Station	23.02	112.84	1200
Wuxiang Power Station	36.82	112.83	1200
Xuangang Power Station	38.91	112.48	1320
Taiyuan 2nd Power Station	37.99	112.52	1800
Yichuan No2 Power Station	34.41	112.50	600
Zhuozi Power Station	40.92	112.64	800
Pingshuo Gangue Power Station	39.47	112.32	1200
Xiangfan Power Station	31.91	112.17	2400
Qinbei Power Station	35.17	112.72	4400
Daihai Power Station	40.52	112.67	2400
Taishan Power Station	21.87	112.92	5000
Xin'an Power Station	34.74	112.06	1410
Shengtou Power Station	39.36	112.55	4600
Yangcheng Power Station	35.47	112.57	3300
Mengjin Power Station	34.87	112.53	1200
Qiaoyuan Power Station	22.97	112.11	1200
Linzhou Power Station	36.06	113.79	850
Jiaozuo Wanfang Aluminum Plant Power Station	35.25	113.37	1120
Datong 1st/Yungang Thermal Power Station	40.06	113.22	1310
Jining Thermal Power Station	41.02	113.16	300
Guangzhou Huarun Thermal Power Station	22.86	113.51	660
Xinxiang Power Station	35.40	113.93	3270
Shaoguan Power Station	24.58	113.58	3200
Puqi Power Station	29.66	113.87	2600
Xinmi Power Station	34.50	113.60	2600
Dengfeng Power Station	34.39	113.20	1800
Hengyun Power Station	23.06	113.50	1120
Liyujiang Power Station	25.94	113.22	600
Xinfeng Thermal Power Station	40.47	113.09	600
Zhangshan Power Station	36.33	113.08	1440
Yueyang Power Station	29.45	113.16	2525

Station	Latitude	Longitude	Capacity (MW)
Zhuzhou Power Station	27.86	113.12	620
Luohe Power Station	34.17	113.36	1860
Yuzhou Power Station	34.17	113.36	2020
Datong Tashan Pithead Power Station	39.93	113.08	2520
Liyujiang B Power Station	25.94	113.19	1200
Longshan Power Station	36.60	113.69	1200
Wangqu Power Station	36.35	113.19	1200
Xinxiang Baoshan Power Station	35.32	113.50	3320
Zhuhai Power Station	21.97	113.18	4600
Shajiao Power Station	22.75	113.68	3880
Lianfu Power Station	34.79	113.08	900
Shenzhen Qianwan Power Station	22.51	113.85	1170
Huangpu Power Station	23.08	113.50	850
Zhangze Power Station	36.32	113.08	840
Jiaozuo Power Station	35.22	113.20	2470
Hanchuan Power Station	30.66	113.92	3200
Yangquan 2nd Power Station	37.77	113.63	1200
Zhujiang Power Station	22.81	113.57	1200
Yaomeng Power Station	33.74	113.24	3800
Zhengzhou Thermal Power Station	34.77	113.59	1000
Datong 2nd Power Station	40.03	113.29	3720
Fengzhen Power Station	40.40	113.14	2400
Mawan Power Station	22.98	113.89	1800
Dingxiang Power Station	38.47	113.02	2000
Luyang Power Station	34.82	113.01	2000
Youxian Power Station	27.24	113.46	1200
Zuoquan Power Station	37.07	113.36	1200
Qingshan Thermal Power Station	30.63	114.43	1522
Fenyi Power Station	27.78	114.62	640
Matou Power Station	36.49	114.42	1620
Hebi Power Station	35.85	114.18	4200

Station	Latitude	Longitude	Capacity (MW)
Puyang Power Station	35.75	114.98	420
Xinyu Power Station	27.78	114.91	1640
Zhumadian Gucheng Power Station	32.87	114.04	2600
Ezhou Power Station	30.55	114.64	1800
Huayu Power Station	32.11	114.14	1920
Xisaishan Power Station	30.55	114.64	1800
Huai'an Power Station	40.65	114.41	660
Zhumadian Thermal Power Station	33.05	114.06	660
Shang'an Power Station	38.06	114.20	2620
Kaifeng Power Station	34.81	114.43	1200
Heyuan Power Station	23.57	114.64	3200
Dabieshan Power Station	31.14	114.90	2400
Dingzhou Power Station	38.51	114.84	2520
Hanfeng Power Station	36.47	114.15	2640
Huizhou LNG Power Station	22.76	114.61	1050
Shenzhen East Power Station	22.58	114.44	1050
Anyang Power Station	36.12	114.28	1200
Xibaipo Power Station	38.24	114.22	2400
Yangluo Power Station	30.69	114.54	2400
Xingtai Power Station	37.01	114.48	1920
Shalingzi Power Station	40.66	114.95	2400
Pinghai Power Station	22.61	114.74	6000
Huizhou Power Station	22.75	114.63	660
Shahe Power Station	36.85	114.33	1200
Heze (Guodian) Power Station	35.24	115.53	1510
Jingangshan Power Station	27.05	115.02	1920
Ruijin Power Station	25.92	115.10	700
Heze (Huarun) Power Station	35.25	115.68	1200
Shanwei Power Station	22.71	115.55	6520
Fuyang Power Station	33.00	115.85	1200
Minquan Power Station	34.62	115.29	1200

Station	Latitude	Longitude	Capacity (MW)
Xinchang Power Station	28.86	115.98	1320
Hengshui Power Station	37.75	115.60	1200
Fengcheng Power Station	28.19	115.71	2520
Beijing 3rd Thermal Power Station	39.81	116.14	150
Beijing Thermal Power Station	39.89	116.53	1768
Haimen Power Station	23.19	116.65	6000
Jiujiang Power Station	29.74	116.04	1350
Huaibei Power Station	33.97	116.78	1050
Xilinhote Power Station	43.98	116.13	600
Shantou Power Station	23.33	116.74	1200
Huaibei Guo'an Power Station	33.87	116.86	1960
Sanhe Power Station	39.95	116.85	1300
Suzhou Power Station	33.65	116.98	3200
Fengtai Power Station	32.76	116.65	2520
Liu'an Power Station	31.67	116.50	2520
Huangjinbu Power Station	28.45	116.86	1200
Shijingshan Power Station	39.92	116.14	880
Shiheng Power Station	36.21	116.51	1200
Dezhou Power Station	37.45	116.24	2670
Zouxian Power Station	35.33	116.93	4540
Pingwei Power Station	32.68	116.90	4400
Shangdu Power Station	42.22	116.03	3720
Liaocheng Power Station	36.49	116.24	2400
Gaojing Power Station	39.94	116.13	600
Duolun Power Station	42.22	116.57	3600
Dapu Power Station	24.40	116.59	1200
Huaibei Hushan Power Station	33.87	116.86	1320
Xilinhote Datang Power Station	44.00	116.15	1320
Shiliquan Power Station	34.81	117.57	1325
Hefei Power Station	31.92	117.25	1200
Chentanghuang Thermal Power Station	39.05	117.24	835

Station	Latitude	Longitude	Capacity (MW)
Beijiang Power Station	39.22	117.93	4000
Pengcheng Power Station	34.38	117.18	3280
Tengzhou Power Station	35.07	117.12	1000
Huangtai Power Station	36.71	117.09	1300
Guixi Power Station	28.29	117.22	1800
Tianjiaan Power Station	32.67	117.03	600
Anqing Power Station	30.54	117.17	1200
Chizhou Power Station	30.75	117.59	1800
Tongling Wanneng Power Station	30.89	117.75	2920
Lubei Power Station	38.08	117.74	660
Hefei No2 Power Station	31.79	117.51	1400
Yangliuqing Power Station	39.15	117.04	2620
Panshan Power Station	39.98	117.46	3400
Tongling Guodian Power Station	31.07	117.96	3200
Kanshan Power Station	34.41	117.58	3200
Wangtan Power Station	38.31	117.88	3200
Bangbu Power Station	32.78	117.11	2400
Chaohu Power Station	31.64	117.82	2400
Tianji Power Station	32.67	117.03	2520
Feixian Power Station	35.32	117.90	1200
Sanbaimen Power Station	23.57	117.10	7200
Huanghua Power Station	38.31	117.88	2520
Jingdezhen Power Station	29.19	117.09	1320
Zhangping Power Station	25.28	117.40	1000
Longyan Pithead Power Station	25.28	117.16	1140
Xuzhou Power Station	34.39	117.26	3460
Junliangcheng Power Station	39.05	117.41	1500
Xutang Power Station	34.35	117.93	3200
Laicheng Power Station	36.26	117.67	1200
Luohe Power Station	32.69	117.08	3400
Dagang Power Station	38.78	117.49	1314

Station	Latitude	Longitude	Capacity (MW)
Yong'an Power Station	26.00	117.38	850
Weishanhu Power Station	34.62	117.37	1200
Xuancheng Power Station	30.88	118.87	1200
Douhe Power Station	39.77	118.27	1200
Banqiao Power Station	31.95	118.63	2070
Shengli Oil Field Power Station	37.40	118.53	1000
Huaiyin Power Station	33.60	118.96	1760
Xingdian Power Station	36.78	118.24	2250
Fengrun Power Station	39.81	118.09	600
Hongshan thermal Power Station	24.73	118.75	3200
Baiyinhua Jinshan Pithead Power Station	44.93	118.71	2400
Wuhu Zhongdian Power Station	31.44	118.35	1320
Wuhu Huadian Power Station	31.24	118.15	3320
Maanshan No3 Power Station	31.54	118.41	1320
Maanshan No2 Power Station	31.75	118.48	1200
Songyu Power Station	24.45	118.03	1200
Masteel Power Station	31.73	118.49	525
Huaneng Nanjing Power Station	32.21	118.75	640
SINOPEC Yangzi Petrochemical Power Station	32.25	118.79	360
Houshi Power Station	24.30	118.13	4200
Maanshan Power Station	31.73	118.49	1320
Daban Power Station	43.59	118.70	1200
Yuanbaoshan Power Station	42.30	119.32	2100
Taizhou Power Station	32.19	119.91	4000
Yixing Power Station	31.37	119.77	270
Qinhuangdao Power Station	39.95	119.64	1600
Xinhai Power Station	34.58	119.13	3100
Yangzhou Power Station	32.43	119.48	1100
Nanpu Power Station	25.44	119.34	1940
Luanhe Power Station	39.95	119.64	660
Weifang Power Station	36.64	119.23	2000

Station	Latitude	Longitude	Capacity (MW)
Rizhao Power Station	35.34	119.51	2060
Jinling Power Station	32.17	119.02	2000
Yimin Power Station	48.55	119.77	3400
Huolinhe Pithead Power Station,	45.46	119.54	1800
Jiangying Power Station	25.44	119.34	2400
Changzhou Power Station	31.96	119.99	2520
Ningde Power Station	26.76	119.74	4520
Yangzhou No2 Power Station	32.27	119.42	2460
Zhenjiang Power Station	32.19	119.27	3700
Changxing Power Station	30.99	119.93	2400
Hongjun Power Station	45.51	119.65	2400
Fuzhou Power Station	25.99	119.48	2720
Putian LNG Power Station	25.22	119.00	1560
Kemen Power Station	26.37	119.76	5400
Lanxi Power Station	29.19	119.51	2400
SINOPEC Yizheng Chemical Fiber Power Station	32.28	119.11	600
Jianbi Power Station	32.19	119.27	3800
Luoyuan Power Station	26.41	119.78	3320
Yizheng Natural Gas Power Station	32.26	119.14	600
Jurong Power Station	32.21	119.21	2000
Baorixile Power Station	49.35	119.72	1200
Ewenke Power Station	48.73	119.94	1200
Chenjiagang Power Station	34.42	119.79	1320
Nanshan Group Power Station	37.73	120.45	2000
Longkou Power Station	37.68	120.31	1000
Zhangjiagang Power Station	31.89	120.60	250
Huangdao Power Station	36.04	120.22	2050
Qishuyan Power Station	31.74	120.04	400
Wangting Power Station	31.44	120.44	1920
Penglai Power Station	37.68	120.31	2000
Nantong/Tianshenggang Power Station	32.03	120.75	2660

Station	Latitude	Longitude	Capacity (MW)
Xiaoshan Power Station	30.05	120.23	260
Shazhou Power Station	31.99	120.68	3200
Suizhong Power Station	40.08	120.01	3600
Banshan Power Station	30.36	120.14	1420
Yancheng Power Station	33.40	120.12	560
Sheyanggang Power Station	33.82	120.47	1870
Xiagang Power Station	31.92	120.20	1216
Wenzhou Power Station	28.00	120.84	2520
Qingdao Power Station	36.11	120.33	1800
Changshu Power Station	31.76	120.98	3000
Ligang Power Station	31.94	120.08	3600
Cangnan Power Station	27.50	120.66	6000
Laizhou Power Station	37.43	120.02	2000
Yanshanhu Power Station	41.52	120.32	1200
Jingjiang Power Station	32.03	120.38	1320
Baosteel Power Station	31.44	121.44	1200
Keyouzhong Power Station	44.98	121.42	300
Caojing Power Station	30.76	121.40	4000
Taicanggang Power Station	31.58	121.26	5170
Datang Jinzhou Thermal Power Station	41.14	121.22	1200
Taizhou Power Station	28.70	121.46	1260
Wujing Power Station	31.06	121.47	3600
Taichang Power Station	31.66	121.18	1800
Jiaxing Power Station	30.63	121.15	5000
Dalian Power Station	39.01	121.72	1400
Leqing Power Station	28.17	121.09	2520
Fuxin Power Station	42.00	121.66	1400
Yuhuan Power Station	28.12	121.14	4000
Fuxin Jinshan Coal Gangue Power Station	41.78	121.43	600
Fengxian LNG Power Station	30.98	121.50	720
Zhenghai Power Station	29.94	121.69	860

Station	Latitude	Longitude	Capacity (MW)
Waigaoqiao Power Station	31.36	121.60	5000
Shidongkou Power Station	31.46	121.40	3600
Wushashan Power Station	29.51	121.66	4400
Ninghai Power Station	29.48	121.51	4400
Lüsigang Power Station	32.06	121.73	2640
Beilun Power Station	29.94	121.81	5000
Jinzhou Power Station	41.27	121.25	1200
Minghang Power Station	30.99	121.37	815
Shanghai Petrochemical Power Station	30.70	121.28	375
Yangshupu Power Station*	31.27	121.55	359.2
Yingkou Power Station	40.30	122.10	3040
Baicheng Power Station	45.53	122.78	3320
Tongliao Power Station	43.67	122.15	1400
Kangping Power Station	42.70	123.37	2400
Zhuanghe Power Station	39.68	123.21	1200
Shuangliao Power Station	43.53	123.47	1800
Tieling Power Station	42.34	123.80	2400
Fulaerji Power Station	47.19	123.61	1425
Liaoning Power Station	41.92	124.09	2250
Siping Power Station	43.15	124.40	2100
Jilin Thermal Power Station	47.38	124.05	1350
Qiqihaer Thermal Power Station	47.38	124.05	600
Dandong Power Station	39.84	124.15	700
Qinghe Power Station	42.53	124.14	1800
Liaoyuan Power Station	42.87	125.16	860
Changchun No3 Power Station	43.78	125.14	1400
Changchun No4 Power Station	44.04	125.22	1400
Changchun No2 Power Station	43.88	125.39	1900
Erdaojiang Power Station	41.78	126.02	600
Harbin No3 Power Station	45.97	126.66	2200
Hunjiang Power Station	41.97	126.45	1000

Station	Latitude	Longitude	Capacity (MW)
Harbin Thermal Power Station	45.71	126.70	600
Harbin No1 Thermal Power Station	45.71	126.47	1200
Beihai Power Station	41.78	126.02	1920
Mudanjiang No2 Power Station	44.66	129.65	1230
Huichun Power Station	42.90	130.29	2060
Jiamusi Power Station	46.83	130.40	600
Hegang Power Station	47.10	130.30	1200
Shuangyashan Power Station	46.56	131.67	3230
Shuangyashan Datang Thermal Power Station	46.68	131.17	400
Qitaihe Power Station	45.76	131.05	1900

Appendix B. Economic Guidance from NETL*11.1.1 General Guidelines*

In 2005, the U.S. National Energy Technology Laboratory issued a set of guidelines for the analysis of carbon capture and sequestration technologies to allow consistent evaluation between separate studies and technologies. The guidelines provide a means of conducting an energy system study. Guidance is provided on specifications for feedstocks, products, and processes, estimating performance, documentation of assumptions and methodology, definition of measures, cost estimation guidance based on standard industry practices, and guidelines for reporting overall economic performance.

Carbon capture and sequestration system analysis should include at a minimum (according to NETL 2005):

- Process Flow Diagrams (PFD) that show how process streams flow among the major components in the overall energy system.
- Stream Tables that list by stream number the significant properties of each stream at design point conditions (each PFD should be accompanied by a stream table). At a minimum the following properties should be included: temperature, pressure, vapour fraction, enthalpy, volumetric flow (for gases), total mass flow (for liquids and solids), and chemical composition.
- Component descriptions of each process, sub-process and major piece of equipment.
- Capital and O&M Costs for each major component or subsystem, including the project and/or contingency applied to each. The costs should be accompanied by the basis for each estimate, e.g., a programmatic cost target; a factored analysis based on a similar system, vendor estimates for commercial equipment, etc.
- CO₂ Quality that includes at a minimum: % CO₂, H₂S (ppm), oxygen (ppm), water (lbs/MMCF), glycol (gal/MMCF), nitrogen (minimum miscibility pressure or MMP), hydrocarbons (MMP), and temperature (Fahrenheit).
- Techno-economic Performance of the system as determined by calculating \$/ton of CO₂ avoided, \$/ton of CO₂ removed, % parasitic load, % increase in cost of electricity (COE), etc. The baseline data for the plant (without capture) will be required to complete these calculations. Sensitivity scaling curves for plant sizes between 200 and 1000 MW should be included, that illustrate the impact of implementing this technology relative to the cost of electricity (\$/kWh) for specified capacity factors (multiples curves expected for capacity factors within the 65% to 85% range in 5% increments) plant efficiency, capture system footprint (ft²), plant capital cost, \$/ton of CO₂ avoided, % CO₂ captured, and % increase in COE.
- Environmental Performance of the system, including a characterization of any liquid or solid waste streams, and a listing of air emissions on the basis of mass per unit of input fuel energy, e.g. kg/MWh.
- Expected Year of Commercialization for the technologies explored. The projection should be supported by a brief narrative describing the current development status of the technology and time line (e.g. concept, bench-scale, pilot-scale, demonstration plant, pre-commercialization unit, etc.).

11.1.2 Transport Guidelines

Carbon dioxide (CO₂) whether being sold for chemical processing or sequestered, is to be supplied as liquid and must meet the pipeline specification shown in

Table 11-2.

TABLE 11-2: CARBON DIOXIDE PIPELINE SPECIFICATION

Pressure	152 bar
Water Content	233 K (-40°F) dew point
N ₂	< 300 ppmv
O ₂	< 40 ppmv
Ar	< 10 ppmv

11.1.3 Estimating Capital, Operating & Maintenance Costs

Estimated plant capital costs should reflect full turnkey outlays, including cost allowances for site engineering, permitting and licensing, installation, land, transportation, taxes, contingencies, financial and legal fees, construction, startup, commissioning, spares, and operator training. The design basis of estimated capital costs for each major subsystem should be explicitly stated, whether known costs for a similar system, a factored analysis based on sizing of major equipment, or a detailed estimate based on full design drawings and vendor quotes. Break down the plant capital cost by major plant section, with both a process contingency and a project contingency applied to each.

11.1.3.1 Process Contingency:

Process contingency is designed to compensate for uncertainty in cost estimates caused by performance uncertainties associated with the development status of a technology. Application of a process contingency to each plant section based on its technology status at the time the cost estimate is prepared according to Table 11-3.

TABLE 11-3: AACE STANDARDS FOR PROCESS CONTINGENCY

Technology Status	Process Contingency
New technology, little or no test data	40% +
New technology, prototype test data	20-35%
Modifications to commercial technology	5-20%
Commercial technology	0-5%

11.1.3.2 Project contingency

Project contingency is designed to compensate for uncertainty in cost estimates caused by an incomplete technical definition. Project contingencies are typically applied to the entire project, but NETL recommends applying the contingency to each plant section, based on the stage of technical definition at the time the cost estimate is prepared according to Table 11-4.

TABLE 11-4: AACE STANDARDS FOR PROJECT CONTINGENCY

Design Stage	Level of Project Definition (% of complete definition)	AACE Estimate Class	Project Contingency
Concept Screening	0-2	5	50%
Feasibility Study	1-15	4	40%
Budget Authorization	10-40	3	30%
Project Control	30-70	2	15%
Bid Check	50-100	1	5%

11.1.3.3 Operating and Maintenance Costs

Assume a capacity factor of no more than 85% for power plant O&M purposes. The assumed capacity factor should be based on a realistic assumption of system availability. Explicitly state the cost of consumables (fuels, catalysts, sorbents, and water), labour rates, interest rates, etc., used in estimating O&M costs. The byproduct credits and waste disposal costs, including estimated tonnages and assumed rates in O&M costs.

11.1.3.4 Capacity Factor and Availability

When forecasting the total output of an energy system and calculating the associated O&M costs, an annual capacity factor for the energy system must be set:

$$\text{annual capacity factor \%} = \frac{\text{total output in one year}}{(\text{rated output capacity})(8760 \text{ hours})}(100\%)$$

The annual capacity factor of an energy system depends upon both its duty cycle and its availability. A baseload energy plant that is dispatched as much as possible could have an annual capacity factor that is nearly equivalent to its availability. On the other hand, the annual capacity factors of “intermediate” or “peaking” energy systems could be much lower than their availabilities, since market demands or other factors limit how often they are required for service.

You should assume that the capacity factor for fossil-fuelled, baseload energy systems is the lesser of 80% or the system availability.

Energy system studies should conform to the following definitions when addressing measures of energy system reliability and availability.

$$\text{on} - \text{stream}\% + \text{product unrequired}\% + \text{planned outage \%} + \text{unplanned outage}\% = 100\%$$

Where

on – stream% = percentage of year that the system was operating and supplying product in a quantity useful to the customer.

product unrequired % = percentage of year that the primary product was not required, and therefore the system was not operated.

planned outage% = percentage of year that the system was not operated because of outages that were scheduled at least one month in advance, including yearly planned outages as well as maintenance outages with more than one month notice.

unplanned outage % = percentage of year that the system was not operated because of forced outages that had less than one month notice, including immediate outages as well as maintenance outages with less than one month notice.

$$\text{forced outage rate}\% = \frac{\text{unplanned outage \%}}{(\text{on} - \text{stream \%}) + (\text{unplanned outage \%})}(100\%)$$

$$\text{availability}\% = (\text{on} - \text{stream}\%) + (\text{product unrequired}\%) \left[1 - \frac{\text{forced outage rate \%}}{100} \right]$$

11.1.4 Reporting Capital Economic Performance

This section details costs associated with capital expenditures, specifically, anything to do with purchase, siting, and startup of working equipment. The costs are broken into three areas: total plant cost, total plant investment, and total capital requirement.

11.1.4.1 Total Plant Cost (TPC)

- Process plant cost (PPC)- Plant section subtotal
- Engineering fees- 10% of PPC
- Process contingency- Plant-section dependent
- Project contingency- Plant-section dependent

11.1.4.2 Total Plant Investment (TPI)

The TPI is the total of TPC and

An interest and inflation-adjustment factor (dependent on construction interest rate, inflation rate, and construction time frame) multiplied by the TPC.

11.1.4.3 Total Capital Requirement (TCR)

The TCR is the total of TPI and:

- Prepaid royalties- 0.5% of PPC for new technology, a capital charge
- Initial catalyst and chemical inventory- 30 day inventory
- Startup costs
 - 2% TPI
 - 30 days chemical and operating labor
 - 7.5 days fuel inventory
- Spare parts- 0.5% of TPC
- Working capital
 - 30 days fuel and consumables
 - 30 days byproduct inventory
 - 30 days direct expenses
- Land

11.1.5 Reporting Operating Costs

Operating costs are costs associated with the day-to-day operation of the plant. Maintenance and consumables are accounted for in this section. Byproducts and any credits for byproducts are also reported in this section.

11.1.5.1 Total operating costs

- Consumables- 1 year at capacity factor
 - Fuel
 - Chemicals
 - Catalysts disposal- cost of ash/ sorbent disposal
- Maintenance costs- 2.2% TPC
 - Plant labour
 - Operating labour
- Supervisory/ clerical- 30% of operating labour and 12% of maintenance costs

11.1.5.2 Byproduct credits- Credit for salable materials

Byproduct sales should be fully described and referenced.

- Material description
- Amount per unit time
- Market price per unit amount

11.1.5.3 Net Operating Costs (NOC)

NOC is the total of TOC and byproduct credits.

11.1.6 Economic Assumptions

To enhance the consistency of NETL-sponsored energy system studies, this section provides “default” specifications for certain assumptions that may be required to evaluate the economic performance of energy systems. In the absence of any compelling market-, project-, or site-specific requirements, follow these guidelines:

- Project Life- 20 years
- Book Life- 20 years
- Tax Life- 20 years
- Federal and State Income Tax Rate- 38%
- Tax Depreciation Method- Accelerated Cost Recovery System (ACRS)
- Investment Tax Credit- 0.0%
- Construction Interest Rate- 11.2% for the construction period
- Financial structure- both current and constant dollars

For low-risk projects, the financial structure in Table 11-5 would be adequate:

TABLE 11-5: FINANCIAL STRUCTURE FOR LOW-RISK PROJECTS

Type of Security	% of Total	Current Dollar Cost %	Current Return %	Constant Dollar Cost %	Constant Return %
Debt	80	9.0	7.2	5.8	4.7
Preferred Stock	0	3.0	0.0	0.0	0.0
Common Stock	20	20.0	4.0	16.5	3.3
Discount Rate (Cost of Capital)	--	--	11.2	--	8.0

For high-risk projects, the financial structure in Table 11-6 would be adequate:

TABLE 11-6: FINANCIAL STRUCTURE FOR HIGH-RISK PROJECTS

Type of Security	% of Total	Current Dollar Cost %	Current Return %	Constant Dollar Cost %	Constant Return %
Debt	45	9.0	4.1	5.8	2.6
Preferred Stock	10	8.5	0.9	5.3	0.5
Common Stock	45	12.0	5.4	8.7	3.9
Discount Rate (Cost of Capital)	--	--	10.3	--	7.1

- Inflation rate- 3.0%
- Real escalation rates
 - Fuel
 - Coal- 0.5% over inflation (EIA 2003)
 - Natural Gas- 0.3% over inflation, low growth case (EIA 2003)
0.5% over inflation, high growth case (EIA 2003)
 - O&M – 0% over inflation

Appendix C. Wave Conditions in South China Sea

The wave data has been collected from visual observations at sea from 1854 – 1984 and data is more dense along shipping routes. This is because of the Voluntary Observing Fleet (VOF) contribution to the database. The data is also denser in recent years in the time range in comparison when the data was first collected. The quality of wave statistics have been improved by a numerical model called NMIMET. NMIMET uses the recorded wind data to improve the reliability of the wave statistics. The data is provided as joint distribution tables of significant wave height and zero-crossing period separated into 9 directional categories -all directions and the eight major direction in 45° bins i.e. N, NE,E etc.-. The data is also provided as an annual distribution and a quarter annual distributions.

Annual Analysis

Common wave condition is zero crossing period, T_0 of 5-6 seconds with significant wave height, $H_s = 1-2$ m. 4.5 % Occurrence of wave height in excess of 5 m with the highest recorded 10 – 11 m through the range of 5 – 11 seconds. Common annual direction is NE with 33.22% with discounting unknown direction data (1.3 %) with the most aggressive waves present at this time. Majority of the most aggressive waves occur in the NE quadrant.

Aggressive Seasons

Wave conditions are most aggressive in this region from September to February with the strongest waves point northeast most frequently (>40%). From June to August the majority of the waves are in the SW quadrant with relatively milder conditions. (Waves being less than 8 meters high)

TABLE 11-7: ANNUAL JOINT DISTRIBUTION OF H_s - T_0 FOR ALL DIRECTION IN PARTS PER THOUSAND.

	T_0 (s)	< 4	4 - 5	5 - 6	6 - 7	7 - 8	8 - 9	9 - 10	10 - 11
H_s (m)									
8 – 9		0	0	0	1	1	1	0	0
7 – 8		0	0	0	1	2	1	1	0
6 – 7		0	0	1	3	3	2	1	0
5 – 6		0	0	3	8	8	5	2	1
4 – 5		0	1	9	19	17	9	3	1
3 – 4		0	4	26	45	34	15	4	1
2 – 3		0	14	64	85	52	19	5	1
1 – 2		2	41	118	108	47	12	2	0
0 – 1		13	64	76	36	9	2	0	0

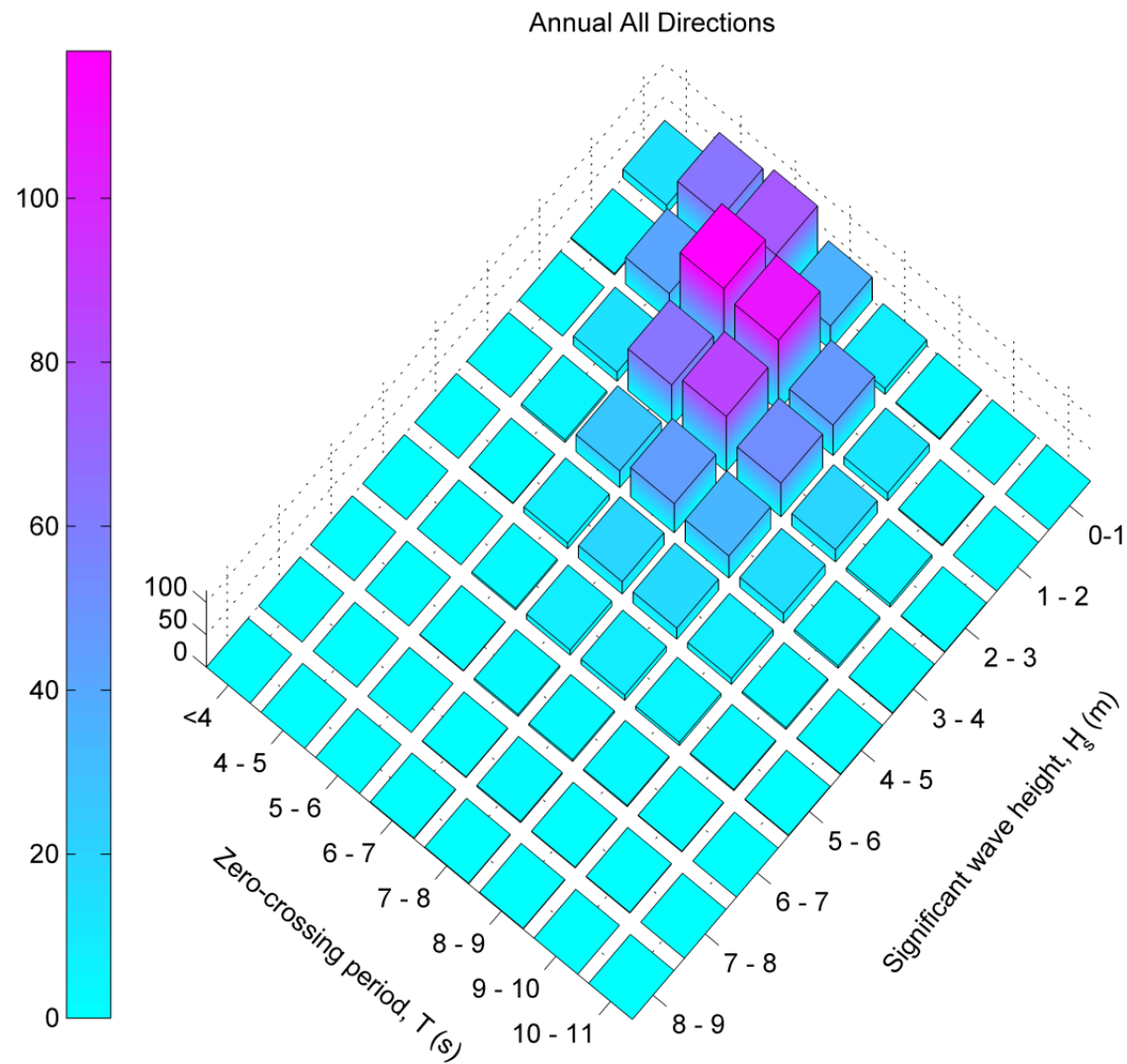


FIGURE 11-9: ANNUAL JOINT DISTRIBUTION OF H_s - T_0 FOR ALL DIRECTION IN PARTS PER THOUSAND.

Appendix D. CO₂ Hydrate Mechanics

Formation of Hydrate:

At the interface between seawater and liquid CO₂, the second physical transformation occurs. CO₂ molecules are encased in a hydrogen bonded lattice known as a hydrate with an 8 CO₂:46H₂O configuration when fully occupied (Sloan, 2003). Common CO₂ hydrates are built out of two basic cell structures, two pentagonal dodecahedra 5¹² (12 pentagonal faces) and six tetrakaidecahedra, 5¹²6² (12 pentagonal faces and 2 hexagonal faces).

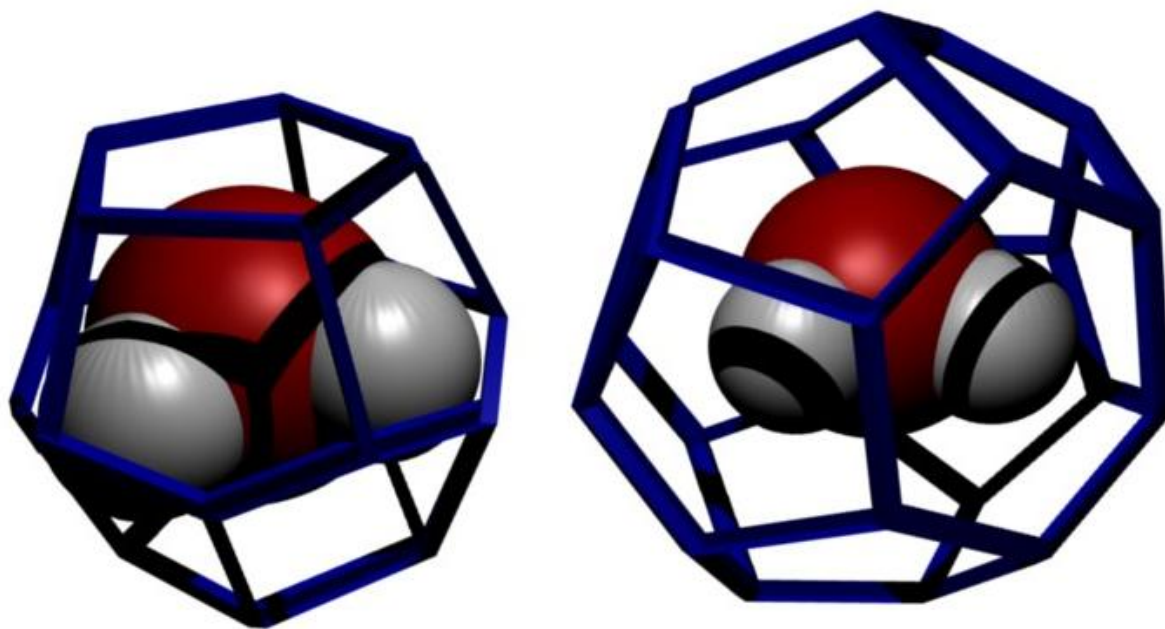


FIGURE 11-10: INDICATIVE STRUCTURE OF THE TWO BASE COMPONENTS OF A STRUCTURE I HYDRATE LATTICE (NOT TO SCALE). (LEFT) PENTAGONAL DODECAHEDRA (12 PENTAGONAL FACES). (RIGHT) TETRAKAIDECAHEDRA (12 PENTAGONAL FACES & 2 HEXAGONAL FACES).

The more common hydrate lattice (Structure I) is made up of two base components – two pentagonal dodecahedra (12 pentagonal faces) and six tetrakaidecahedra (12 pentagonal faces & 2 hexagonal faces) – which can house at most a single guest molecule (in this case CO₂). The “cage” is made up of weak hydrogen bonds between water molecules represented by the blue bars stemming from each node in the cage. The CO₂ is enclathrated during or after the formation of the lattice during hydrate forming conditions. At most each lattice will hold eight guest molecules but as the pentagonal dodecahedra has a smaller radius the guest molecule can only enter at the formation stage of the lattice. The lattice will remain stable however as long as five out of six of the secondary cages are filled and the primary cages are empty.

The molecular diameter, Å for the former is 4.92 and 5.76 respectively and the molecular diameter of CO₂ is 5.12. (Sloan, 1990) from (Teng et al., 1996). Hence, the CO₂ molecules can enter one structure easier than the other. The former may encase a CO₂ if it was trapped during the formation of the hydrate film. Therefore under real conditions, the hydrate is seldom fully occupied and therefore does not have a uniform composition or density and is dependent on the saturation of CO₂. This also implies that the hydrate is a non-stoichiometric compound. A formulation for the density of hydrate is given by Teng et al. (1996) as:

$$\rho_H = 46 \frac{M_{CO_2}}{N_A a^3} \left(0.409 + \frac{x_{CO_2}^H}{1 - x_{CO_2}^H} \right) \quad \text{EQ. 11-1}$$

Where M_{CO_2} is molar mass in kg/kmol, N_A is the Avogadro's constant in molecule/kmol and $a = 12 * 10^{-10}$ m as the lattice constant.

Kimuro et al. (1993) conducted laboratory experiments on the formation of hydrates by simulating the ambient conditions at various water depths. At that pressure, by injecting liquid CO₂ into a pressure vessel to pressures equivalent to 3000 m depth (31.4 Mpa) they observed the reaction between the liquid CO₂ and the artificial seawater and noted three qualitative observations. A hydrate formed at the base, interface and around the CO₂ droplet as it was injected showing that hydrates can naturally form at any interface between liquid CO₂ and water. The amount of dissolved CO₂ was also shown to depend on the injection velocity. Higher velocities tended to increase amount of dissolved CO₂. The turbulent diffusion is probably accelerates the dissolution of the CO₂ into the surrounding water. North et al. (1998) also conducted laboratory experiments to determine the minimum ratio of CO₂ molecules needed for hydrates to form. With deionized water at 55 bar and 5° C, a mol fraction of 0.03 CO₂ in an agitated water-CO₂ mixture was required to form hydrates and that it only occurs after a critical value. For seawater, the fraction is higher at 0.043. The higher the pressure the higher the ratio that is required, as solubility of CO₂ increases with rising pressure. Formations of hydrates are exothermic and retards the dissolution of CO₂ (Aya et al., 1997).

Stability of Hydrate:

The stability of hydrates is described in detail by Teng et al. (1996). The stability of the lattice comes from the presence of a CO₂ molecule which provides a repelling force to the hydrogen bonded water molecules. This provides rigidity to the lattice by minimising the distortion angles among the bonds. Therefore, the stability of the hydrate is a function of the occupancy or mole fraction of CO₂ in the hydrate. The minimum mole fraction required for stability of the hydrate is 0.098 where 5 out of 6 of the 5¹²6² cages are occupied.

Dissolution or collapse of hydrate:

Hydrates stored in the deep ocean eventually dissolve completely, and this phenomena has been observed both in laboratory (North et al., 1998) and field settings (Brewer et al., 1998). According to Teng et al. (1997), the hydrate film is only stable when the ambient water is saturated with CO₂. This corresponds to the liquid CO₂ interface with the hydrate film, on the other face however, the concentration of CO₂ in seawater is very low leading to an imbalance in chemical potential leading to a net mass transfer to the phase with a lower saturation. The collapse of the layer can be seen to occur in the following process. CO₂ molecules diffuse out of the hydrate structure due to the difference in chemical potential. This leaves the hydrate in an unbalanced state due to the low occupancy (i.e. $x_{CO_2}^H \leq 0.098$). The hydrate structure collapses releasing the remaining CO₂ molecules. Rehder *et al.* (2004)'s field experiments support the analysis of (Teng et al., 1997) that hydrates are not likely to form an effective trapping mechanism for the dissolution of CO₂ for permanent storage as the hydrate film is denser than the liquid CO₂ (above 5000 m depth) and the formation of stable hydrates over a large area is unlikely. The trapping would most likely be produced from the density stratification of the dissolved CO₂ over the reservoir.

Appendix E. Dispersion/Dissolution Numerical Modelling

One key concern of ocean storage schemes is the duration that the CO₂ will remain and the rate at which the reservoir contents disperse and dissolve into the water column. Numerous studies have already been conducted to study the behaviour of CO₂ (i.e. the dispersion, dissolution and possible trapping from the formation of hydrates at the interface). Ideally, full- or pilot-scale experiments should be conducted to properly observe the mechanics and reactions of the CO₂ interface under field conditions. However, since the level of uncertainty is quite and costs required are high and the potential to cause significant damage to the surrounding ecosystem both in the near and far fields, the scale of field studies so far have been small. In its place, numerical models have been used to model the dissolution and associated pH reductions within the vicinity of a simulated reservoir.

Fer and Haugan (2003) conducted numerical simulations: With 2D advection diffusion: At 3000 m deep, domain 20 km x 200 m and 500 m length. Reservoir boundary is at 1.5 km to 2 km from the upstream boundary. Study the interaction between CO₂ lake, presence of hydrates, boundary layer with a flat bottom. Hydrates modelled with the Mori and Mochizuki (1997) method which uses rate of water permeation through capillaries and the rate of CO₂ diffusion through the water phase interface (look at the original formula). Total 10 simulations 5 with hydrates and 5 without. Source concentration is 1500 mol/m³ which is the solubility at $t = 5$ degrees C and Salinity = 35. Density, boundary layer and various diffusion characteristics: Boundary layer velocity profile use law of the wall approximation. The pH field is calculated to determine the near field acidification. By estimating the steady state piston velocity the dissolution rate can also be determined.

Discussion of results: On average presence of hydrates reduce dissolution rates by 2.7 over case 1-3 when density is neglected. The effect of density stratification suppresses the dissolution rate with an average reduction of 1.6 with the presence of hydrates.

Haugan and Alendal (2005) conducted numerical simulations: With the 1D General Ocean Turbulence Model (GOTM). GOTM only accounts for salinity and temperature in its transport equations, so a carbon concentration tracer was added which accounts for density increments at higher CO₂ concentrations. The turbulent length scales are calculated by the ISPRAMIX model. The computational domain is at 3000 m depth and is 10 km long with a 500 m lake at 2.5 km from the upstream face. Twelve simulations were conducted. The effects of internal waves which occur due to instabilities in the gravitational and buoyant restoring force occur due to density stratification of the water column are accounted for in half of their simulations. Half of their simulations included a salinity gradient of $\Delta S = 0.001$ over the deepest 100 m of the computational domain. The presence of hydrates was not accounted for

Discussion of results: Internal waves for low velocity conditions enhance the mixing rate and lead to a larger area being acidified however it is sensitive to the cut off rate at which the internal wave model is activated. The model uses a very basic advection system and may not represent the transport and horizontal propagation of CO₂ enriched seawater accurately. They suggest that a full non-hydrostatic solver be used to account for all the processes in further studies.

Enstad et al. (2008) coupled the MIT General Circulation Model (MITgcm) and with GOTM to predict the dissolution rates and pH reduction effects within the vicinity of the CO₂ lake. The MITgcm is a numerical ocean model which provides the shear and buoyant frequency to the GOTM model. The GOTM provides the vertical eddy viscosity and eddy diffusivity. The study models a channel 30 km x 20 km x 240 m where the dimensions of the lake are 500 m x 500 m located 3500 – 4000 m downstream of the upstream boundary. The study comprises of three pairs of simulations with velocities of 0.05, 0.10 and 0.2 ms⁻¹ and with and without the effect of hydrate formation.

Discussion of results: The use of a quasi – 3D model allows for the dissolution to occur faster due to the “reduction of turbulent damping produced by lateral spreading”. The increase in density of water due to the dissolution of CO₂ causes both upward and lateral advection in the vicinity of the CO₂lake. The simulations also showed that for locations that had very high pH changes, steady state conditions

were achieved much sooner than locations with lower pH reductions. By releasing passive tracers at various distances from the centre line, it shows that any organisms which are carried by the ambient flow into the middle of the lake centre will experience a large increase of pH as opposed to being released at some distance away from the centre line. However, downstream of the lake the organism would be under the very similar levels of pH reduction.

Rygg et al. (2009) conducted 2D numerical simulations with the MITgcm (z-coordinate model) and the Bergen Ocean Model (BOM) (σ -coordinate model) to study the topographical effects of CO₂ dissolution rates. The bottom boundary is set as a source term of CO₂. The lake is 500 m long and is located 5.5 km downstream of the upstream boundary. The ambient velocity in the model is 0.1 m/s and two different vertical eddy viscosities were used 10^{-2} m²/s and 10^{-6} m²/s while the horizontal eddy viscosity is set to 10 m²/s. The BOM model with topography, however, has zero horizontal viscosity. The terrain following model (σ -model) generally gives large volumes of acidified water than the MITgcm. Rygg et al (2009) believes this is due to the nature of terrain following models which enhance mixing and possibly over estimates the amount. Z-coordinate models however may underestimate the mixing by having very small velocities within the trench.

Discussion of results: They have shown that the introduction of topography can significantly reduce the rate of dissolution of the CO₂. Additionally, the simulation shows that increased viscosity setting reduce the rate of dissolution as well as turbulent mixing is dampened.

TABLE 11-8: MODEL TYPES

Source	ID	Velocity (m/s)	Flux ($\mu\text{mol}/\text{cm}^2\text{s}$)	Dissolution (cm/year)	rate	Dissolution (year)	time	Hydrate	Boundary layer
(Fer and Haugan, 2003)	1	0.05		169		29.6			No
	1H	0.05		61		82.4			No
	2	0.05		99		50.4			Yes
	2H	0.05		37		135.6			Yes
	3	0.20		450		11.1			No
	3H	0.20		170		29.5			No
	4	0.05		18		280.3			Yes
	4H	0.05		12		407.7			Yes
	5	0.20		317		15.8			Yes
	5H	0.20		162		30.9			Yes
Haugan and Alendal (2005)	U05NIW	0.05	0.06	79/59					Yes
	U05SIW	0.05	0.05	66/55					Yes
	U10NIW	0.10	0.07	92/69					Yes
	U10SIW	0.10	0.19	251/193					Yes
	U20NIW	0.20	0.46	607/468					Yes
	U20SIW	0.20	0.42	557/421					Yes
	U05N	0.05	0.07	92/66					Yes
	U05S	0.05	0.06	79/58					Yes
	U10N	0.10	0.06	79/64					Yes
	U10S	0.10	0.06	79/57					Yes
	U20N	0.20	0.34	449/340					Yes
	U20S	0.20	0.30	396/303					Yes
Enstad et al. (2008)	I	0.05	0.08	105		74.3		No	Yes
	IH	0.05	0.057	75.2		66.5		Yes	Yes
	II	0.10	0.32	422		11.8		No	Yes
	IIH	0.10	0.20	259		19.3		Yes	Yes
	III	0.20	1.04	1373		3.6		No	Yes
	IIIH	0.20	0.57	752		6..6		Yes	Yes
Rygg et al. (2009)	1	0.1	0.31	415					
	2	0.1	0.11	147					

Source	ID	Velocity (m/s)	Flux ($\mu\text{mol}/\text{cm}^2\text{s}$)	Dissolution (cm/year)	rate	Dissolution (year)	time	Hydrate	Boundary layer
	3	0.1	0.10	129					
	4	0.1	0.08	109					
	5	0.1	0.11	147					
	6	0.1	0.10	129					
	7	0.1	0.34	452					
	8	0.1	0.23	307					
	9	0.1	0.01	14					
	10	0.1	0.15	203					
	11	0.1	0.21	279					
	12	0.1	0.10	134					

The flow field for all the previous simulations have all been allowed to develop before the initiation of CO₂ dissolution.

Appendix F. Alternative Design Procedure

In the main body of the document, we determined the effected water volume with a pH decrease of 0.1 pH unit. That procedure is useful for determining the volume required when the CO₂ lake is known. Also, note that the percentage occupancy is very small, approximately 3.5%. It would be better if we could determine the full capacity of a reservoir. Therefore, the following iterative procedure is suggested:

1. Determine the maximum depth of the reservoir from 3000 m depth in Figure 11-11. Approximately 750 m for the Zone 1 reservoir.
2. Take 10 % of that value (75 m) and find the associated area (Figure 11-11) and volume occupied by the liquid CO₂ (Figure 11-12).
3. From the area, find the volume of pH reduced seawater and sum it with the initial volume to find the total volume of the reservoir occupied. From this the percentage occupancy can be determined.
4. As a suggestion, if the percentage occupation is more than 50 %, repeat steps 1 – 3 by increasing the depth at which the CO₂ interface occurs. The percentage occupancy will rise significantly as the volume increment reduces per unit area added is lower when the amount of stored CO₂ is increased and the returns from storing the excess CO₂ diminishes from the additional dissolved CO₂ to be dealt with.

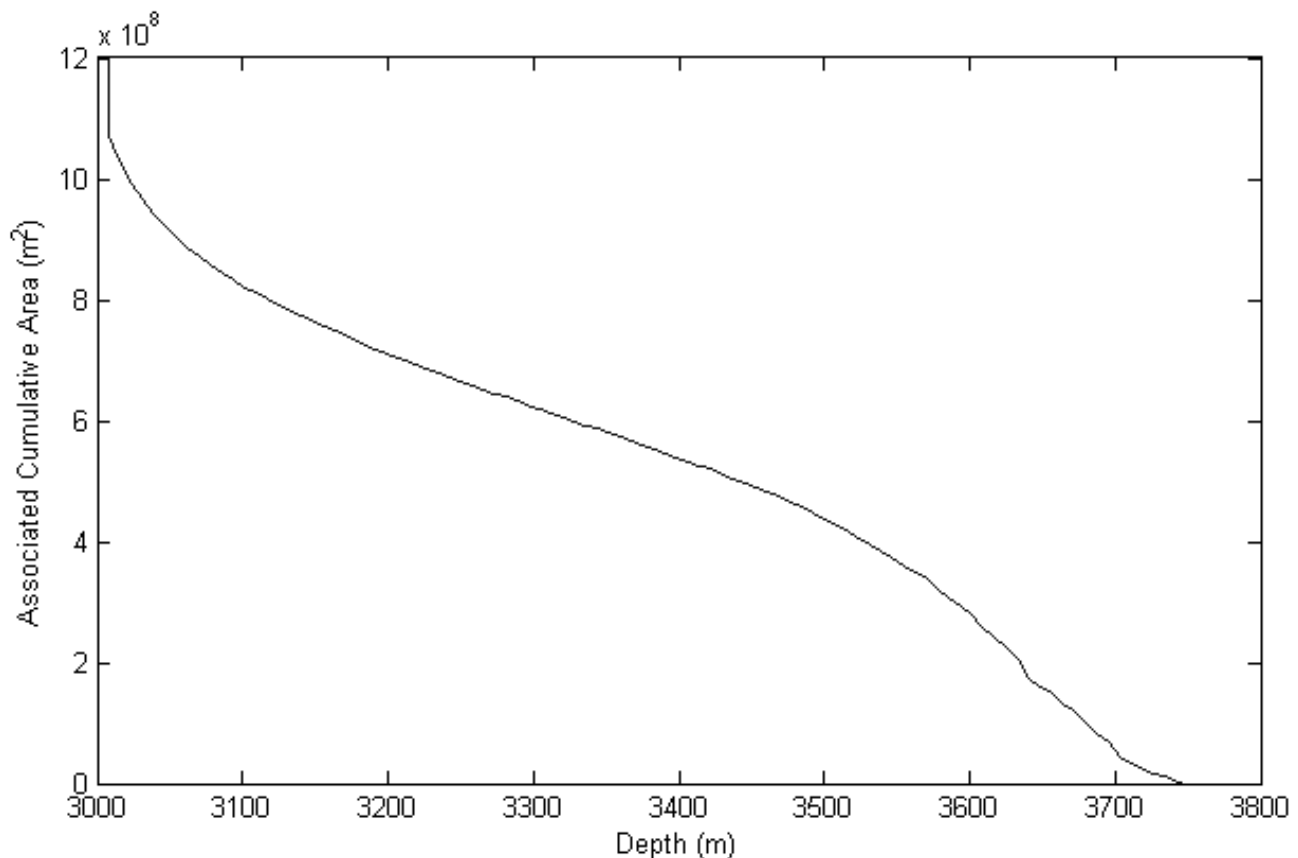


FIGURE 11-11: THE ASSOCIATED CUMULATIVE AREA (M²) WITH REDUCING DEPTH OF CO₂ - SEAWATER INTERFACE (M) FOR ZONE 1

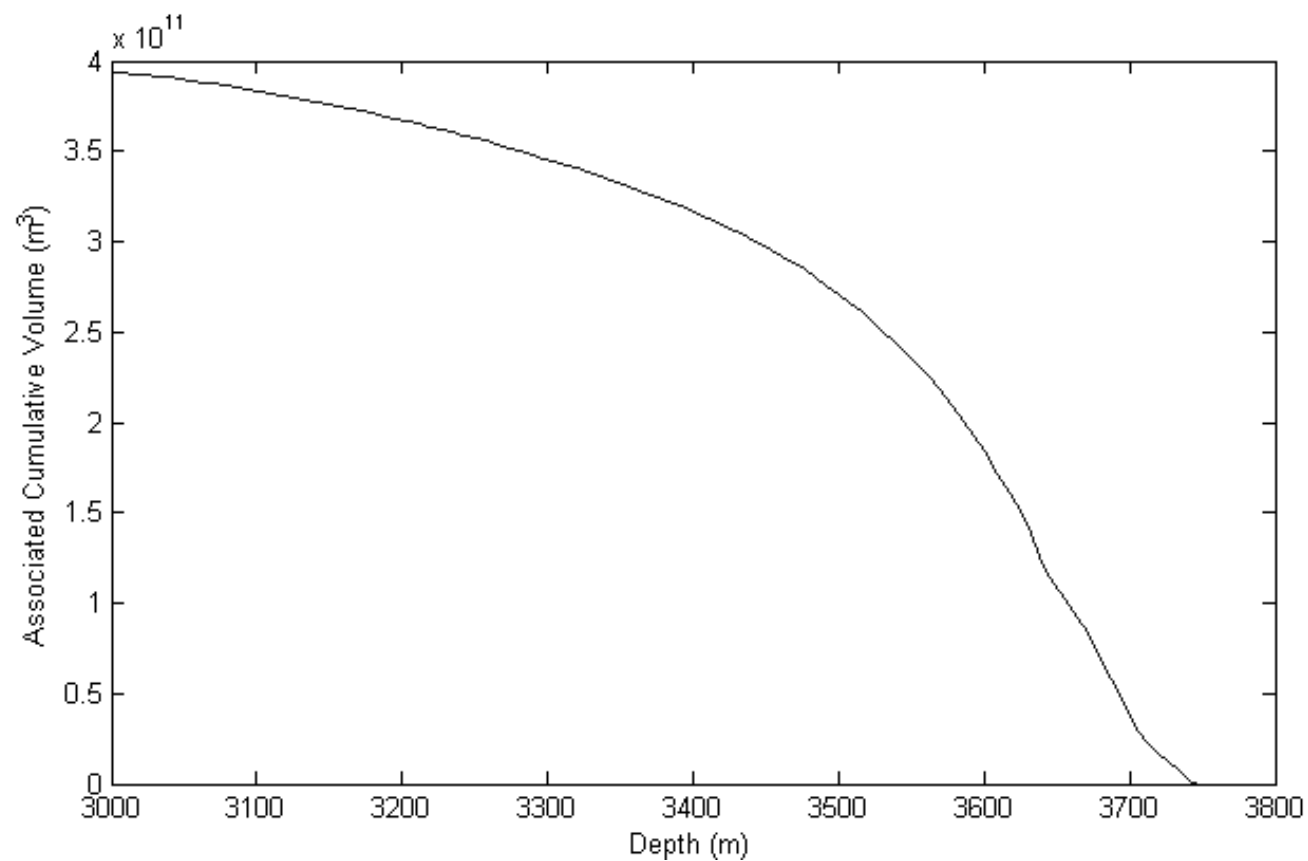


FIGURE 11-12: THE ASSOCIATED CUMULATIVE VOLUME (m^3) WITH REDUCING DEPTH OF CO_2 - SEAWATER INTERFACE (M) FOR ZONE 1.

Appendix G. *Crazy Idea for Monitoring and Sequestration*

During the course of the collegium, a large number of ideas were brainstormed and considered, what follows is one of the ideas that was not pursued due to limitations of time and potential engineering feasibility problems.

While pursuing the concept of deep ocean storage, the predominant impediment to adopting the technique was the potential irreversible changes made to the pH of the ocean and its impact on marine ecosystems across the globe. As a means of combating this, a preliminary design was considered for covering the deep CO₂ lake on the bottom of the ocean. The intent was to place a spherical dome over the cover constructed with triangle members for strength (see Figure 11-13). The surface of the lake and the separation device would have a large volume of water between them (due to the dome-like shape of the proposed covering). This water would be allowed to freely mix with CO₂ lake.

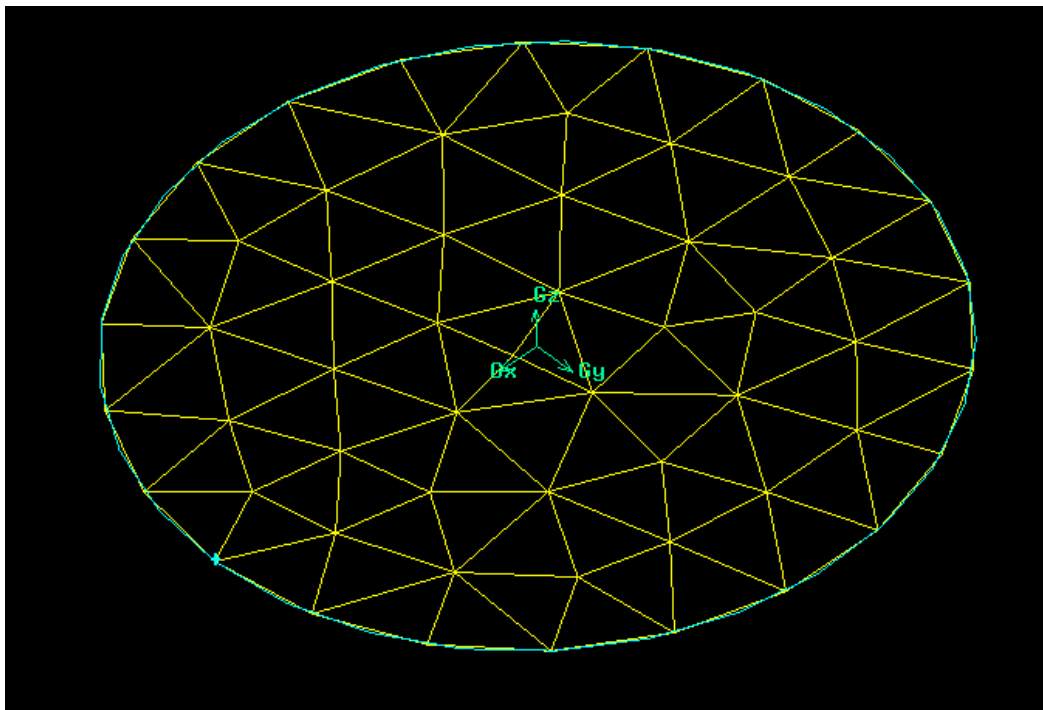


FIGURE 11-13: THE WALL BUILT BY MANY SMALL PARTS

It is realized that there are severe technical issues with implementing such a solution due to the extreme depth of the lake, as well as the forces caused by currents along the bottom of the ocean. The fabrication of the elements (in triangular sections) should not pose a significant challenge. However, installation and maintenance are not currently technically feasible.

A zoomed-in view of the structure can be seen in Figure 11-14. The hole between the connecting members are intentional. Through them monitoring is possible to determine if any CO₂ is dispersing through the water column. Additionally, without holes the membrane is not as structurally stable. Expansion of the CO₂ would cause the structure to break down or rupture without them. The primary issue for the design is the use of materials that will prove durable in the extreme environment of the deep ocean.

As mentioned previously, this was one of many extreme and outside-the-box ideas that were generated for the purpose of the collegium.

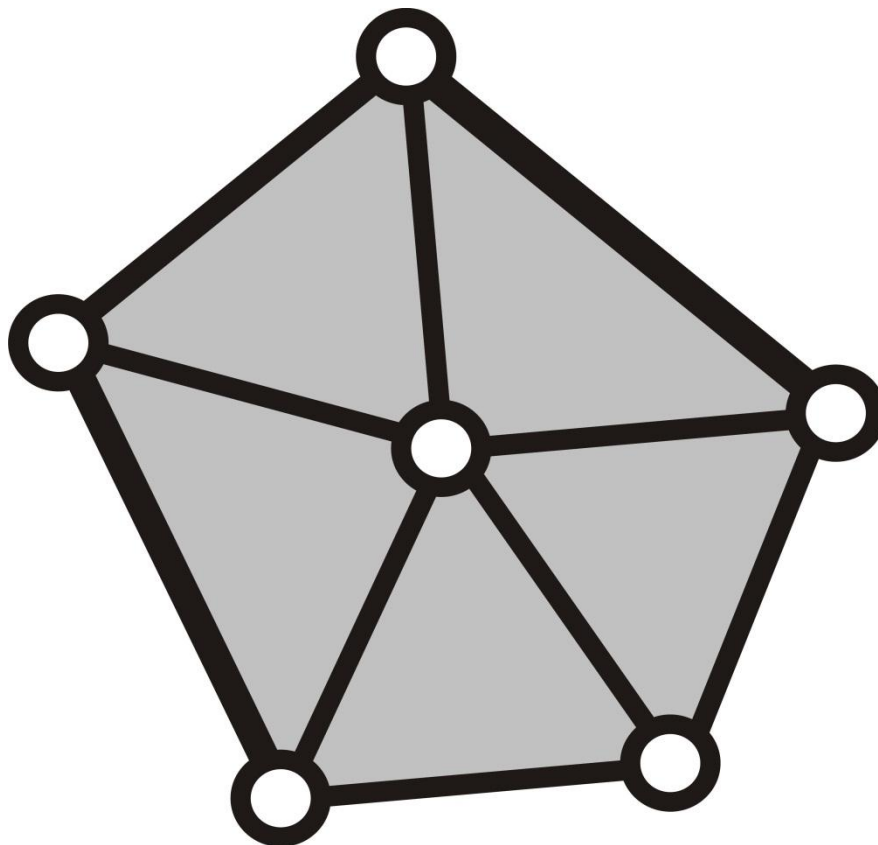


FIGURE 11-14: THE HOLES USED FOR SAFETY AND MONITORING