

Marine Transportation for Carbon Capture and Sequestration (CCS)

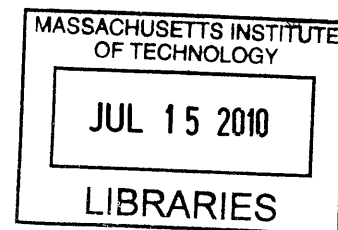
by

Mary-Irene Alexandrakis  
B.Sc. Accounting and Finance  
Athens University of Economics and Business, 2008

and

Bret S. Smart  
B.S. Naval Architecture and Marine Engineering  
Webb Institute, 2009

**ARCHIVES**



Submitted to the Department of Civil and Environmental Engineering  
In Partial Fulfillment of the Requirements for the Degree of  
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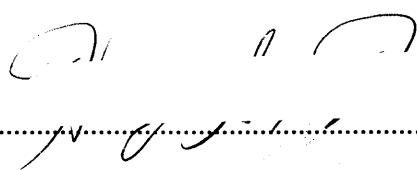
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Signatures of Authors .....  


Department of Civil and Environmental Engineering

May 7, 2010

Certified by .....  


Henry S. Marcus

Professor of Marine Systems, Mechanical Engineering

Thesis Supervisor

Accepted by .....  


Daniele Veneziano

Chairman, Departmental Committee on Graduate Students



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**ABSTRACT**

The objective of this report is to determine whether opportunities to use liquefied carbon dioxide carriers as part of a carbon capture and storage system will exist over the next twenty years. Factors that encourage or discourage the use of vessels are discussed. This study concludes that liquefied carbon dioxide carriers can potentially be used in both the near and long term under different sets of circumstances.

**Thesis Supervisor: Henry S. Marcus**

**Title: Professor of Marine Systems, Mechanical Engineering**





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## **Nomenclature**

CCS	Carbon Capture and Storage
CO <sub>2</sub>	Carbon Dioxide
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
atm	Unit of atmospheric pressure
bar	Unit of pressure
m	Meter
km	Kilometer
nm	Nautical mile
hr	Hour
t	Metric ton (or tonne)
LBP	Length between Perpendiculars
B	Beam
D	Depth
T	Draft
EOR	Enhanced Oil Recovery
EGR	Enhanced Gas Recovery



## **1 Introduction and Purpose**

The marine transportation of carbon dioxide is a complex problem; it has never before been utilized as part of a carbon capture and storage project. This paper aims to give a complete overview of everything relevant to the marine transportation stage. It introduces the universal problem of rising carbon emissions, and highlights some current and planned carbon capture and storage projects that seek to alleviate these emissions. Next, the regulatory framework regarding carbon dioxide sequestration is investigated. Possible marine transportation systems are then identified, along with the pros and cons of each. An analysis of possible locations and market sizing is also completed. With results from market sizing, operating costs, and capital costs, a model is created to gauge the viability of the marine transportation of carbon dioxide.

### **1.1 Carbon Capture and Storage**

The threat of global warming has challenged innovators to find new ways to prevent the emission of green house gases (GHG) into the atmosphere. The biggest culprit contributing to atmospheric GHG is carbon dioxide (CO<sub>2</sub>). Politicians have talked about discouraging CO<sub>2</sub> emissions by initiating a cap and trade system, which would effectively tax parties who pollute the air with CO<sub>2</sub>. For factories and power plants that burn oil or coal, such a tax could be quite significant. One way to potentially avoid the tax while still burning fossil fuels is to ‘capture’ the carbon dioxide and transport it elsewhere for storage. For example, this captured CO<sub>2</sub> could then be stored deep below the ground; this cumulative process is referred to as carbon capture and storage (CCS).

### **1.2 Transporting CO<sub>2</sub>**

The obvious ways to transport large volumes of carbon dioxide are by pipeline or by vessel. The Weyburn-Midale CO<sub>2</sub> Project in southeast Saskatchewan carries captured CO<sub>2</sub> from a coal gasification plant along a 320-kilometer pipeline (Petroleum Technology Research Centre). But for greater distances, ships are more flexible and can be employed elsewhere as needed. The senior vice president of Maersk Tankers believes that transporting CO<sub>2</sub> by ship “is

far more flexible and will not require the same large-scale investments as pipelines” (Kanter). Large tankers currently transport liquefied gases, such as liquefied petroleum gas (LPG) or liquefied natural gas (LNG). Carbon dioxide is also already transported via ship, but on a much smaller scale, for applications in the carbonated beverage industry. One key issue is to investigate the economies of scale realized by shipping CO<sub>2</sub> in larger vessels.

### **1.3 Enhanced Oil Recovery**

The destination of the carbon dioxide is the final piece, geophysically, in the CCS puzzle. One option is to simply pump the CO<sub>2</sub> underground into an empty gas field, where it will occupy the space evacuated by the already-harvested oil. Another option is to use it for enhanced oil recovery (EOR): injecting a gas into an oil field under high pressure. (Enhanced gas recovery (EGR) is a similar concept for accessing depleted natural gas reservoirs; both operations can be collectively referred to as EOR.) The Weyburn-Midale project in Canada is expected to inject 18 million tons of CO<sub>2</sub>, ultimately recovering an additional 130 million barrels of oil and extending the oil field’s life by 25 years (Brown). Thus, such a partially-depleted oil well is an ideal destination for captured CO<sub>2</sub>.

### **1.4 Overall Concept**

This report touches upon all steps of CCS: capture, transportation, and storage. In particular, it focuses on the middle step: transportation. The focus is on CO<sub>2</sub> being carried by vessel, not pipeline. To increase the feasibility of the shipping model, it is assumed that the origin of the harvested CO<sub>2</sub> is a land-based power plant located nearby the water. One possible ultimate destination of the CO<sub>2</sub> is an offshore oil well.

### **1.5 Content Layout**

After the brief overview to CCS projects in this chapter, Chapter 2 presents an in-depth background of existing and proposed CCS projects worldwide and R&D efforts currently underway. Chapter 3 focuses on regulatory frameworks that are being developed to support CCS and to guide the deployment of full scale projects in the future. These provisions are explored for the E.U. and U.S.A. separately. Chapter 4 studies the size of the potential CCS

markets, which provide the opportunities for using marine transportation systems in various locations, in terms of future cargo (CO<sub>2</sub>) and source/storage candidate sites. Chapter 5 further breaks down the marine transportation system's components and lays out the transportation scenarios that will be then tested by the model. This chapter also gives an overview of CO<sub>2</sub> as a cargo; how it is collected, treated, transported and sequestered. Chapter 6 introduces the model that has been developed and shows the output of the analysis made based on the different scenarios and sensitivity analyses. Finally, Chapter 7 presents the conclusions drawn from both qualitative and quantitative analyses.



## **2 Background**

### **2.1 Carbon Emissions**

Worldwide increases in energy demand, coupled with a continued reliance on fossil fuel resources, have contributed to a significant increase in atmospheric levels of carbon dioxide (CO<sub>2</sub>) concentration. This increase shows no signs of slowing. According to the International Energy Agency's (IEA) World Energy Outlook 2007, the projected growth in energy demand will translate to a 130 percent rise in energy-related CO<sub>2</sub> emissions by 2050. Others argue—especially in the recent environment of high energy prices—that global energy demand will be much lower than the IEA forecasts.

Even with rising energy prices, growth in energy use leads to increasing CO<sub>2</sub> emissions in the absence of explicit policies to reduce GHG emissions. However, a multitude of effects, such as the efficiency of appliances, the Corporate Average Fuel Economy (CAFE), and tax policies enacted in 2007 and 2008, have slowed the growth of U.S. energy demand, and as a result, energy-related CO<sub>2</sub> emissions in the Annual Energy Outlook 2009 reference case grow by 0.3 percent per year from 2007 to 2030, as compared with 0.8 percent per year from 1980 to 2007. Under those circumstances, in 2030, energy-related CO<sub>2</sub> emissions would be expected to total 6,414 million metric tons, about 7 percent higher than in 2007.

Slower emissions growth is also, in part, a result of the declining share of electricity generation that comes from fossil fuels (primarily, coal and natural gas) and the growing renewable share, which increases from 8 percent in 2007 to 14 percent in 2030. As a result, while electricity generation increases by 0.9 percent per year, CO<sub>2</sub> emissions from electricity generation increase by only 0.5 percent per year. The largest share of U.S. CO<sub>2</sub> emissions comes from electricity generation.

The U.S. economy becomes less carbon intensive as CO<sub>2</sub> emissions per dollar of GDP decline by 39 percent and emissions per capita decline by 14 percent over that projection. Increased demand for energy services is offset in part by shifts toward less energy-intensive industries, efficiency improvements, and increased use of renewables and other less carbon-intensive energy fuels. More rapid improvements in technologies that emit less CO<sub>2</sub>, new CO<sub>2</sub>

mitigation requirements, or more rapid adoption of voluntary CO<sub>2</sub> emissions reduction programs could result in lower CO<sub>2</sub> emissions levels than are projected here.

Scenarios for stabilizing climate-forcing emissions suggest atmospheric CO<sub>2</sub> stabilization can only be accomplished through the development and deployment of a robust portfolio of solutions, including significant increases in energy efficiency and conservation in the industrial, building, and transport sectors; increased reliance on renewable energy and potentially additional nuclear energy sources; and the deployment of carbon capture and sequestration (CCS). Slowing and stopping emissions growth from the energy sector will require transformational changes in the way the world generates and uses energy.

## **2.2 Definition of CCS**

Coal-fired power stations are at the moment the largest cause of atmospheric pollution with carbon dioxide. Along with transportation activities, burning coal contributes over half of the carbon dioxide in the earth's atmosphere, and it has led to the increase of CO<sub>2</sub> concentration by more than 100 parts per million. This, in turn, leads to global warming (the greenhouse effect) and stimulates climate change for the entire planet. Carbon capture and sequestration (CCS) has been attracting more and more interest as a means to mitigate the increasing concentration of carbon dioxide. CCS refers to the process of capturing carbon dioxide from large point sources, such as fossil fuel (coal, natural gas and oil) power plants, steel manufacturing plants, chemical plants, etc., and injecting it into subterranean reservoirs or into the deep ocean to be isolated from the atmosphere for a long period of time. However, CCS remains at an early stage of development and a low level of public understanding and awareness. There still are many uncertainties regarding the technologies to be used, the supporting infrastructure, the costs, the funding, and time constraints.

Thus far, no complete and full-scale CCS plants and transportation systems have been built. Some companies have been using forms of carbon capture at their plant sites and sequestering the CO<sub>2</sub> underground using pipelines. However, there are many early stage projects in progress around the world. Existing projects include the capture of 100,000 tonnes CO<sub>2</sub>, compression and burial below the Altmark gas field in Germany, the Salah Gas Project carbon strip and storage in Algeria, and the capture from Sleipner West field and storage of CO<sub>2</sub>

in the Ultsira formation in the North Sea. Moreover, for the past decade various plans have been under consideration in countries including the United Kingdom, US, Canada, China, the United Arab Emirates, and Poland.

Even though CCS seems very promising, at the moment the biggest hurdle remains an economic one. Taking CCS from small pilot projects to an industrial scale will require working down the price of the entire operation, which now can add 30% to 60% to the cost of generating electricity. Consulting firm McKinsey figures that adding CCS to the next generation of European power plants could increase their price by up to \$1.3 billion each. But as more utilities adopt the technology, its cost should more than halve by 2030, with even further decreases as it spreads around the world.

### **2.3 Foreseeable Future of CCS Projects**

One useful way to perceive the future of CCS is to assume that there are 2 distinct phases: a demonstration phase (referred to in this report as Phase 1) and a commercial phase (referred to as Phase 2). The figure below gives a visual picture of the timeframe and costs associated with the two phases; it is presented not because the future values it projects are precisely accurate, but because it helps provide a framework for discussion of the research in this report.

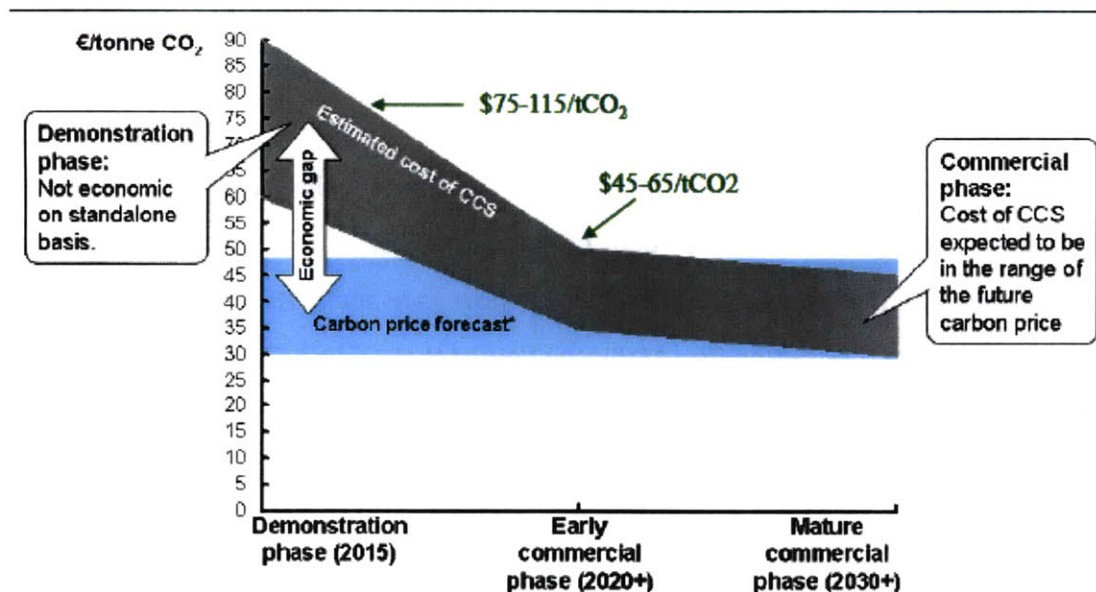


Figure 1: Economic Future of CCS Projects

Source: McKinsey

The cost numbers in the graph above assume that a pipeline, rather than a vessel, is being used as the method for transporting CO<sub>2</sub>, but it is still an excellent graphic to show the state of CCS projects.

As is shown, CCS is currently in the midst of a demonstration phase. McKinsey estimates that early demonstration projects will typically be more costly, due to their smaller scale and lower efficiency, and their main focus on proving technology rather than commercial optimization. These costs include carbon dioxide capture at the power plant, its transport and permanent storage; all told, demonstration projects have an estimated cost of \$75 - \$115 per tonne CO<sub>2</sub>. (The costs shown in dollars on the graph reflect an exchange rate of roughly 1 Euro for every \$1.30.)

It is predicted that the demonstration phase will continue until at least 2020. In reality, this date depends on the success of small-scale demonstration projects that may need the help of subsidies or other beneficial legislation. If these smaller projects are proven to be successful, larger projects may be undertaken; these large projects will both be more economically viable (thanks to economies of scale), and prevent the emission of greater amounts of carbon dioxide into the atmosphere. In the time period before this Phase 2 is reached, subsidies and other



means (such as revenue from EOR or EGR) will help close the gap between the cost of CCS and the social carbon price. McKinsey estimates that the beginning commercial phase will have CCS costs from \$45 - \$65 per tonne CO<sub>2</sub> (about 35 to 50 Euros) in 2020. The mature commercial phase, slated to begin in 2030, will have slightly lower costs of \$40 - \$60 per tonne (30 to 45 Euros).

The other item of import in the figure is the social carbon price forecast, which is shown in the graph as a range from \$40 to \$64 per tonne CO<sub>2</sub> (30 to 47 Euros). As the cost of CCS decreases and nears to this carbon price, CCS projects become more commercially viable. Using all the figures supplied in the graph, the current economic gap ranges from \$12 - \$75, depending on where the carbon price and CCS costs in Phase 1 actually fall within their range.

## **2.4 Existing and Proposed CCS Projects Worldwide**

Many CCS projects are underway around the world. However, most of them are on the research and small-scale pilot scale. The only full-scale plants in operation involve the capture of CO<sub>2</sub> from natural gas, the separation of which is necessary for selling the natural gas. The political support for wide-spread deployment of CCS is nonetheless growing across the world, meaning that it is likely that numerous large-scale demonstration plants will be realized during the coming decade. From 2020 onwards, increased confidence in the technology, combined with appropriate financial incentives and regulations, means that there may be no reason to build large fossil fuel power plants and industrial plants that are not equipped with CCS.

Today, only four small-scale, commercial CCS projects demonstrate the capture and storage of CO<sub>2</sub>: Sleipner, In Salah, Weyburn, and Snøhvit. Several commercial projects have been announced and more CCS projects (including all aspects: capture, transport and storage of CO<sub>2</sub>) should be in operation between 2012 and 2015. The general opinion on CCS from industrial stakeholders is positive. They regard CCS as a very good strategy to reduce CO<sub>2</sub> emissions from factories and coal power plants, because it allows the continued use of fossil fuel. However, industry is very reluctant to pay for the first large-scale CCS plants and thus is asking for substantial public funding towards building the first CCS demonstration plants. Additionally, industry is paying its share: many companies have invested funds, time, and effort in research activities, and some companies have even built pilot plants for CO<sub>2</sub> capture.

## **2.5 Research and Development Activities**

### **2.5.1 Poland's Belchatow Power Plant**

Belchatow Power Plant is Europe's largest coal-fired power plant, located in Poland. It also accounts for Europe's largest amount of CO<sub>2</sub>; in 2008 it emitted a total 31 million tonnes, 4 million in excess of the E.U. limits, thus resulting in a deficit of carbon emission permits it bought. For the next year, Belchatow is expected to have a deficit of 20 million tonnes of carbon credits.

Belchatow has been working for two years on the preparatory task of developing a demonstration scale CCS installation, integrated with its newly-built 858 MW unit. The carbon capture project will compress the CO<sub>2</sub> for transportation by pipeline at supercritical phase. In terms of the CO<sub>2</sub> transport, the associated transportation routes have been identified. These potential routes of the CO<sub>2</sub> pipeline have been notified in the łódzkie Voivodeship Area Development Plans. Concerning the storage component, three potential storage sites have been identified from the various studies and analyses. The detail appraisal of the storage sites is ongoing and final selection will be made by the end of 2010. The research work has been conducted by two contractors: Polish Geological Institute and Schlumberger (Carbon Services Division). This work will comprise high-level characterization of the three potential geological structures and selection of one unique structure by the end of 2010. Bełchatów Power Plant's CCS Project was selected, along with six other European ones, to receive subsidies totaling 180 million Euros; this money comes from designated E.U. funds, the European Economic Plan for Recovery (EEPR) in the field of energy, aimed at stimulating the development of the economic activities under the economic crisis.

In addition to this 180 million Euro grant, Bełchatów is seeking additional funding from sources such as a structural fund allocated to Poland, entitled the Green Investment Scheme. This mechanism enables the allocation of funds coming from purchase and transfer of Assigned Amount Units (AAUs) for targets and projects to combat climate change. These AAUs are resources within the NER 300 (New Entrant Reserve) mechanism to be implemented within E.U. Emissions Trading System, as well as potentially-preferential loans from the European Investment Bank (EIB) and Poland's Environmental Bank (Bank Ochrony Środowiska S.A).

### 2.5.2 Other European R&D Projects

The European Commission is supporting several other R&D projects with an aim of developing CCS technology. A few of these projects are listed below:

**Decarbit:** Aims to develop pre-combustion capture technologies and novel capture technologies. The aim is to achieve a CO<sub>2</sub> capture cost of 15 Euro/tonne CO<sub>2</sub>. The project also includes plans for pilot testing. The project has a 15.5 million Euro budget, 10.2 million of which is funded by the E.U.

**Dynamis:** Aims to develop concepts for electricity and hydrogen production with CCS. Establishing a basis for a demonstration plant – called the Hypogen plant – is part of the project. The budget for the project is 7.4 million Euro, 4 million of which is funded by the E.U.

**Encap:** Aims to develop and validate a number of pre-combustion CO<sub>2</sub> capture technologies that can result in a CO<sub>2</sub> capture cost of less than 20 Euro/tonne CO<sub>2</sub>, at a CO<sub>2</sub> capture rate of 90%.

**GeoCapacity:** Aims to assess the European capacity of CO<sub>2</sub> storage. The project will focus on applying advanced evaluation techniques and complementing the datasets with emission, infrastructure and storage site mapping as well as undertaking economic evaluations. This will enable source-to-sink matching across Europe. Site selection criteria, standards and methodologies will be created and applied to the project.

**CO<sub>2</sub>sink:** Aims to physically inject carbon dioxide into a storage site in order to investigate the behavior of CO<sub>2</sub> after injection.

**CO<sub>2</sub>ReMoVe:** Aims to monitor and verify techniques for deep subsurface CO<sub>2</sub> storage.

**ECCO:** Aims to investigate possible CO<sub>2</sub> value chains and establish recommendations for how to build CCS infrastructures. The project will identify how CO<sub>2</sub> sources can be linked with CO<sub>2</sub> storage sites. It will also investigate how to deploy early opportunities like CO<sub>2</sub> injection for enhanced oil and gas recovery (EOR and EGR).

### 2.5.3 U.S. R&D Projects

The National Engineering Laboratory (NETL) performs comprehensive research on all aspects of CCS. NETL's primary carbon sequestration R&D objectives are: (1) lowering the cost and energy penalty associated with CO<sub>2</sub> capture from large point sources, and (2) improving the

understanding of factors affecting CO<sub>2</sub> storage permanence, capacity, and safety in geologic formations and terrestrial ecosystems. Once these objectives are met, new and existing power plants and fuel-processing facilities in the U.S. and around the world will have the potential to be retrofitted with CO<sub>2</sub> capture technologies.

The U.S. Department of Energy (DOE) has also created a network of seven Regional Carbon Sequestration Partnerships (RCSPs) to help develop the technology, infrastructure, and regulations to implement large-scale CO<sub>2</sub> sequestration in different regions and geologic formations within the nation. Underlying this regional partnership approach is the belief that local organizations and citizens will contribute expertise, experience, and perspectives that more accurately represent the concerns and desires of a given region, thereby resulting in the development and application of technologies better suited to that region. Collectively, the seven RCSPs represent regions encompassing 97 percent of coal-fired CO<sub>2</sub> emissions, 97 percent of industrial CO<sub>2</sub> emissions, 96 percent of the total land mass, and essentially all the geologic sequestration sites in the U.S. potentially available for carbon storage. The following are the seven major RCSPs:

- Big Sky Regional Carbon Sequestration Partnership (Big Sky)
- Plains CO<sub>2</sub> Reduction Partnership (PCOR)
- Midwest Geological Sequestration Consortium (MGSC)
- Midwest Regional Carbon Sequestration Partnership (MRCSP)
- Southeast Regional Carbon Sequestration Partnership (SECARB)
- Southwest Regional Partnership on Carbon Sequestration (SWP)
- West Coast Regional Carbon Sequestration Partnership (WESTCARB)

*One important thing to note:* none of these aforementioned projects includes marine transportation, at least to date.

## **2.6 Conclusion**

With growth in energy demand slated to rise significantly over the next few decades, planners have looked for ways to decrease the corresponding emission of greenhouse gases such as carbon dioxide (CO<sub>2</sub>). One approach is to develop more alternative sources of energy

that do not emit CO<sub>2</sub>, such as wind power and solar energy. However, for the foreseeable future it is clear that fossil fuels will have to be burned to create energy. A key policy issue is to what extent governments should incentivize the use of alternative energy sources versus the reduction of emissions of CO<sub>2</sub> into the air once that they have been created from existing energy sources, such as coal. Carbon capture and sequestration (CCS) has received a lot of attention as a method of reducing or eliminating the escape of CO<sub>2</sub> into the atmosphere while still allowing for the use of a relatively inexpensive—but polluting-- energy source like coal.

Although the concept of CCS may look good on paper, few actual projects have been implemented. A number of demonstration projects have begun, and some research has been funded to determine what makes a successful CCS system, but ultimately the cost of CCS is currently too high compared to the social carbon price. As more demonstration projects and small-scale projects are begun, some researchers predict that CCS will become more economically viable, moving from its current demonstration phase (referred to in this report as Phase 1) to a commercial phase (referred to as Phase 2). It is convenient to refer to these two phases in order to view the progress of CCS. Energy policies, government subsidies, and carbon taxes will all be significant determinants of the CCS overall costs. In addition, the implementation of enhanced oil recovery as part of CCS will help the CCS economics, and provide incentives to help reach the commercial phase.



### **3 Regulation of CCS**

Here, the existing legal framework for CCS is investigated. An examination of the regulatory environment allows for a better understanding of various opportunities for integrated CCS schemes worldwide.

#### **3.1 Regulation and Legal Framework**

##### **3.1.1 European Union**

On 23 January 2008, as part of a larger announcement on renewable energy and climate change, the European Commission (E.C.) issued a proposal for a directive that establishes the legal framework for “environmentally-safe capture and geological storage of carbon dioxide” in the European Union. Among other things, the CCS directive seeks to ensure environmental security, to address issues of liability, to remove existing legislative barriers to deploying CCS, to provide incentives for deploying CCS, and to provide an enabling framework (as opposed to a mandating one) for CCS. It provides for the use of existing legislation where possible – in particular for capture under the Integrated Pollution Prevention and Control Directive (96/61/EC) and transport under the Environmental Impact Assessment Directive (85/337/EEC) at the member state level. It also proposes new legislation to address CO<sub>2</sub> storage.

On the same day, a communication for “supporting early demonstrations of sustainable power generation from fossil fuels” was released by the European Commission in the context of the European Council’s previous endorsement of a goal to develop up to 12 demonstration plants of sustainable fossil fuel technologies in commercial electricity generation by 2015. In this communication, the Commission proposed the establishment of a European initiative on CCS to demonstrate the viability of CCS by 2020 (i.e. the projected end of Phase 1). It also noted that significant investment will be necessary if demonstration plants are to be financed and that such funding would need to come from public-private partnerships.

As a result of government and industry initiatives, CCS regulations are under development in a number of countries and internationally. Generally, regulatory frameworks in the E.U. are being developed around four main pillars: site characterization, for appropriate

geological storage sites; well construction and operation; monitoring and post-sequestration; and public participation.

The London Protocol (under the United Nations Convention on the Law of the Sea) previously prevented the marine transport (including pipelines) of CO<sub>2</sub> between countries for the purpose of CCS. This was important in Europe, where there are many countries with marine borders. However, the good news is that, in December 2009 the Parties agreed on an amendment, which now allows international trans-boundary shipment of CO<sub>2</sub> for CCS. Thanks are due to the Norwegian delegation, who worked hard to get this passed despite opposition from China and South Africa.

### 3.1.2 United States

In the United States, the Environmental Protection Agency holds the primary jurisdiction over CO<sub>2</sub> injection for enhanced oil recovery, and has asserted jurisdiction over the injection of CO<sub>2</sub> for geologic storage. The majority of the regulations that cover CO<sub>2</sub> storage operational issues are authorized and administered under the underground injection control program established by the U.S. Safe Drinking Water Act. The EOR operations in the US today have all been authorized and/or permitted under the Underground Injection Control (UIC) program by state agencies that have promulgated the necessary regulations that have been approved under the federal statute to implement their applicable state UIC Programs.

In July 2006 the EPA announced that geologic sequestration of carbon dioxide through well injection meets the definition of 'underground injection' of Safe Drinking Water Act (SDWA). After consultations with states and other stakeholders the EPA announced a regulation for commercial-scale CO<sub>2</sub> storage under the UIC program in July 2008. On 17 February 2009, President Obama signed the economic stimulus package which included \$3.5 billion to support CCS development.

A range of other government entities are also involved in CCS activities. The Department of Energy (DOE) leads R&D and demonstration activities and international collaboration on CCS. The Department of Transportation (DOT) is responsible for regulating CO<sub>2</sub> transport pipelines, in conjunction with the states and the Federal Energy Regulatory Commission, which is involved in choosing pipeline sites. Various other legal issues remain to be addressed. These include the



treatment of CCS under the Clean Air Act, accounting for injection and any leakage from CO<sub>2</sub> sites, and long-term liability. It is likely that additional legislation will be needed to manage these issues.

Of all the US states that have introduced or passed CCS-related legislation, the most noteworthy have been Illinois and Texas. (Kansas, Montana, New Mexico, North Dakota, Washington, and Wyoming have all begun actively pursuing CCS activities.) Both states will create incentives for commercial Integrated Gasification Combined Cycle (IGCC) projects with CCS. This could provide a big boost to the industry and especially power plants that utilize IGCC technology used to turn coal into gas. In particular, these plants' suppliers, such as GE Energy and Siemens, would be supported. Illinois' Clean Coal Program Law (CCPL) includes a mandatory clean coal standard requiring local utilities and power sellers to supply 5% of their electricity from coal plants that use CCS.

But there are also some problems to be resolved; the only power plant capable of delivering CCS is the proposed Taylorville plant which is expected to be completed in 2010. If the Illinois General Assembly determines that project costs will not increase Illinois' electricity rates by more than 2%, the project will proceed. Based on 2008 estimates, project costs are expected to meet this requirement, unless there is a significant decrease of natural gas prices, which would weaken the competitiveness of the proposed CCS plant. Based on Illinois' expected power supply requirements, an additional 800 MW of CCS capacity will be needed. To date, no other CCS power projects have been announced in Illinois, although a strong candidate location is the former proposed FutureGen site in Mattoon.

The key provision of the Illinois legislation is that the first facility (the Taylorville plant) is required to capture 50% of CO<sub>2</sub> emitted. The capture level requirement increases to 70% for facilities entering operation between 2015 and 2017, and 90% for facilities starting after 2017. After Illinois, Texas is the second state significantly advancing CCS funding legislation. A Texas House Bill 46 extends up to \$100 million in tax credits per plant to developers of power plants with a capacity of at least 200MW that can capture at least 60% of their CO<sub>2</sub> emissions.

The recently-passed stimulus package of 2008 highlights the U.S. government's desire to accelerate CCS and remain the leading CCS development market globally. Building on existing

programs, the stimulus funding could increase federal CCS support by 70%. This would bring total spending for such development and deployment to over \$8 billion, although how it would be spent remains unspecified.

Across the U.S., more than 15 GW of CCS demonstration projects are at some stage of development. These projects are backed by utility companies that want to get an early-mover advantage ahead of impending carbon policy. Some analysts conjecture that there are 10 projects, each greater than 100 MW, ready to begin construction by 2013 in the US, spurred on by the current political and economic conditions.

### **3.2 Financing options for CCS projects**

#### **3.2.1 Models that Rely on Carbon Markets**

##### *Europe – ETS Auction Revenues*

The European Union has been considering allocating the revenue from auctioning of 300 million E.U. emission allowances (EUA) within the E.U. Emissions Trading System (ETS) for supporting CCS and other novel renewable energy projects, as part of the Phase III of the E.U. ETS. They have also allocated €1.05 billion (\$1.5Bn) from their energy program for economic recovery to support seven CCS projects in Europe. CO<sub>2</sub> that is captured and stored will be acknowledged as "not emitted" under the E.U. ETS starting in 2013. The incentive under the revised proposal will only commence in 2013, but will also be applied to projects in the 2008-2012 time frame under the existing Emissions Trading Directive. However, the price of E.U. during this period (Phase 1) will not be sufficient to launch demonstration projects. The current price of EUAs fluctuates around €25, while Deutsche Bank forecasts a price of €40 for the 2012-2020 period and Societe Generale predicts a price around €79 for 2020; that is when CCS will probably become a profitable investment with wide-spread application (Phase 2).

##### *Europe – CDM Credits*

The United Nations Framework Convention on Climate Change (UNFCCC) has developed the Clean Development Mechanism Credits (CDM) under the Kyoto Protocol. According to this, industrialized countries with a greenhouse gas reduction commitment (called Annex 1

countries) may invest in ventures that reduce emissions in developing countries as an alternative to more expensive emission reductions in their own countries. A crucial feature of an approved CDM carbon project is that it has established that the planned reductions would not occur without the additional incentive provided by emission reductions credits, a concept known as "additionality". The CDM allows net global greenhouse gas emissions to be reduced at a much lower global cost by financing emissions reduction projects in developing countries where costs are lower than in industrialized countries.

During UNFCCC negotiations it has been discussed whether CCS projects could be eligible for CDM credits. If such eligibility were to be achieved, then the CDM price would play the same role as ETS price as incentive for CCS deployment in non-Annex 1 countries. At the moment due to absence of a global post-2012 climate agreement, these CDM prices remain completely uncertain. Supply and Demand for such "securities" and their ability to finance large scale CCS projects is unclear. During the first Kyoto commitment period (2008-2012) forward CDM prices are fixed at around €17-18, significantly lower than EUAs.

Additionally, in recent years, criticism against the mechanism has increased and especially key non-Annex 1 countries have been strongly opposed to this.

### *U.S. – Cap-and-trade System*

In the U.S., the 2009 Waxman-Markey American Clean Energy and Security Act (ACES Act) proposed (in addition to financial support for the first commercial scale CCS demonstration projects) to provide bonus GHG cap-and-trade allowances to subsidize the cost of deploying CCS projects (cumulatively 4% of cap-and-trade allowances are allocated for this purpose through 2050). Through 2010, the U.S. Congress will be debating legislation that could both levy electricity sales and provide bonus allowances. Together this is expected to equal an estimated \$100 billion in incentives for coal use with CCS through 2030 and nearly \$240 billion for 2050. Under the cap-and-trade system, the limited amount of emission allowances issued (the permission to emit 1 metric tonne of CO<sub>2</sub> or its equivalent of another GHG) makes them valuable to emitting sources like coal-fired power plants. Since cap-and-trade allowances will be tradable on an emissions market, free allocation of bonus cap-and-trade allowances to coal

power plants that deploy CCS is equivalent to a cash incentive for CCS where the value of the incentive is the product of the quantity of bonus allowances and their market price. Up to 15% of the cap-and-trade allowances allocated to CCS deployment can be used for industrial CCS projects other than coal-fuelled electricity generation with CCS. The Act will also create a Carbon Storage Research Corporation (CSRC) which will be funded by an electricity levy. For the initial phase of support for first-mover CCS projects, the ACES Act defines a formula for awarding bonus allowances on a first-come, first-served basis equivalent to fixed cash payments for each tonne of CO<sub>2</sub> emissions avoided through CCS technology for ten years. The formula for these bonus allowances rewards coal plants that deploy higher levels of CO<sub>2</sub> capture. In Phase 2, the ACES Act includes incentives such as additional bonus GHG allowances for up to another 66 GW of coal fuelled generating capacity with CCS. The CSRC and the CCS commercial deployment provisions in the ACES Act provide an estimated \$100 billion in incentives for coal use with CCS through 2030 and nearly \$240 billion through 2050.

#### *U.S. - "Feebates"*

According to this option proposed by the Pew Center on Global Climate Change, revenues would be raised by charging a fee directly on unabated fossil fuel use. The funds generated could then be used to support CCS costs. Since the installed capacity of unabated fossil fuel plants is many times greater than the total capacity of CCS plants that would be funded under the program, fee levels would only need to be low to generate the funds needed for commercial-scale CCS demonstration plants. Fees can be applied either to utilities' costs or to customers' bills and can also be used to assist CCS deployment in regions that do not have a direct price on carbon. In the US, a fee of only 0.12 – 0.15\$ /kWh (for large scale projects) could raise \$23.5 – 30.1 billion to support the deployment of 30 commercial-scale CCS demonstration projects and ten CO<sub>2</sub> storage sites from industrial sources (World Coal Institute).

#### *U.S. - Specialized CCS Trust Fund*

The Pew Center Coal Initiative has also proposed using a trust fund option for financing CCS. According to its report, Trust funds can be an attractive option because they offer the

opportunity to raise significant amounts of funds from non-governmental sources and then ensure that those paying into the fund benefit from the program (Pew Center). A specialized CCS Trust Fund can be financed, for example, through fees on coal-based or fossil fuel-based electricity generation targeted to power plants or industrial highly emitting sources. This option could be economically viable and efficient for the following reasons:

- Raise funds at the scale needed to support a number of commercial-scale CCS projects around the country.
- Ensure that the funds raised would be used to demonstrate CCS at commercial scale for a full range of systems applicable to U.S. power plants.
- Establish the true costs, reliability, and operability of power plants with CCS.
- Utilize private-sector business standards for project selection and management to ensure program cost effectiveness.
- Significantly reduce CCS costs within 10 to 15 years by supporting demonstrations that yield substantial national economic benefits as CCS becomes widespread.

The United States has considerable experience with trust funds. Although there is no single existing fund that features all aspects that might be used in a specialized CCS Trust Fund, lessons from prior experience (for example the Federal Highway Trust Fund) can be used to design an effective, efficient mechanism for advancing commercial-scale CCS projects. This experience has pointed out the importance of financial self-sufficiency, private-sector management standards, efficient and targeted allocation of funds, accelerated procedures and termination upon completion of funds' initial goals.

### 3.2.2 Models that Rely on Public Subsidiaries

#### *Europe*

For the first demonstration CCS projects to be deployed in Europe, the main source of funding is probably going to be E.U. funding. In the long run however, industry is going to take over in the form of funding options described above (ex. Carbon allowances allocation and trading). A direct grant will be probably given to demonstration plans directed from the Energy

Technology (SET) plan. Budget allocations from the Commission are determined every seven years through the so-called financial framework. The current plan followed is from 2007-2013. At the moment and until 2013 E.U. budget will be “frozen,” and large funds needed for CCS will not be available. Smaller amounts are available for research and development, but these are minor compared to the needs to kick start CCS in Europe. Instead, funds would need to be drawn from other available sources, such as the following:

- The Research Fund for Coal and Steel program (RFCS)

In July 2002 the European Coal and Steel Community Treaty expired, leaving €1.6bn in its treasury. These funds were then used to establish the RFCS, its task being spending accrued interests from this initial capital (approximately €60mn per year) to support research projects related to the future of coal and steel. Although this amount is not enough to support initial funding of demonstration projects, some argue that the fund should be liquidated and used for CCS, based on the fact that one of RFCS’s priorities is supporting the Zero-Emissions Platform (ZEP) which is highly committed to CCS.

- E.U. economic recovery funds

The Commission proposed to invest a total of €3.5 billion in three different energy sub-programs: gas and electricity interconnections, offshore wind energy projects and CCS technology. The European Council advocated increasing this amount to €3.980 billion. Out of these funds, whatever amount is not spent by September 2010, will be allocated to the advancing of energy projects, such as CCS. Such investment decisions must be made by September 2010 according to the Industry Committee.

- Innovative financial instruments

Members of the European Parliament also suggest that €500 million of the E.U. funds should be contributed to "innovative financial instruments" such as loans, guarantees, equity and other financial products provided by the European Investment Bank, the European Investment Fund and other public long-term financial institutions to support projects in the fields of gas and electricity interconnection, CCS, energy efficiency, renewable energy and

smart cities. The relevant financial institutions would have to contribute an equal amount to the projects, says the amended text.

#### *U.S.A*

The American Recovery and Reinvestment Act (ARRA) of 2009 includes \$3.4 billion in funding to advance research, development and deployment of CCS technologies. Additionally, \$1.52 billion will support industrial CO<sub>2</sub> capture, \$800 million will expand and extend funding under the Clean Coal Power Initiative Round 3, geologic storage site characterization will receive \$50 million, \$20 million will support CCS education and training and \$1 billion is directed to the FutureGen project. In addition to ARRA funds, the U.S. Department of Energy's budget request for its Carbon Sequestration Program in 2010 is \$179.9 million. 2010 funding will support CCS site selection and characterization, regulatory permits, community outreach, and completion of site operations plans for large-scale, geologic carbon storage tests. It will also fund large-scale injection and infrastructure development and pursue research on low-cost/low energy penalty carbon capture technologies for power plants.

#### **3.2.3 Renewable Energy-Type of Support Models**

The cost of electricity generation from power plants that employ CCS technology already compares favorably to the cost of electricity generated from renewable sources. For example price support for renewable energy today ranges from \$73 per tonne of CO<sub>2</sub> for onshore wind to \$1000 for solar power. On the other hand CCS demonstration project costs are in the range of \$80-120 per tonne of CO<sub>2</sub> and expected to decline to \$45-70 by 2020. The difference in funding between CCS and renewables is repeated at the regional level. For example, the E.U. has committed to meet 20% of its energy needs with renewables by 2020 at an annual cost of €13 – 18 billion. In comparison, the total cost of E.U. investment in the first 10 to 12 CCS demonstration projects (the Flagship Program) is expected to cost between €5 – 13 billion. However, deployment of CCS cannot be left to the market. The substantial experience with designing and implementing renewable energy technology support schemes (in around 60 countries worldwide) is directly relevant in determining how to best incentivize development and deployment of commercial-scale CCS.

## *Europe*

- Mandatory CCS quotas for member states

An often-used policy adopted by the E.U. has been setting specific targets for the member states to meet, through issuing directives, for example the directive on renewable energy sources (RES) of 2008. The same has been proposed to be done for funding CCS projects, and specifically by setting a kind of RES target for member states to be reached by 2020, where the targets will be set by taking into account their GDP per capita.

Economic operators will have the freedom to trade Guarantees of Origin (GOs) across the E.U. and this way imported GOs will count against the country's target while exported GOs will be deducted. If the Flagship Program is launched then this will mean deploying 10-12 CCS facilities at power plants, each of 300-800MW in capacity, that will equal approximately 2% of E.U. electricity generation and this objective would be shared among the member states according to their GDP per capita. Since in the early stage of CCS in Europe, only a number of countries will be able to support CCS, the other members will have to purchase GOs to meet their specific targets. This mechanism, if proven well, will help to accelerate the adoption of CCS technology and also meet environmental targets.

- Feed-in tariffs

The E.U. has set and regulated tariffs for RES successfully in most of the member states, generally known as 'feed-in tariffs'. They guarantee RES suppliers a certain price for the electricity they generate, sell and distribute that reflects, and usually exceeds what is necessary to make investments in RES commercially viable. Tariffs provide incentives for adopting RES and are set at different levels for different RES and guaranteed for a long time period (generally 10-20 years) with a certain reduction scheduled over time. Feed-in tariffs exist in two main variations: In Germany, a guaranteed tariff is set. It effectively eliminates all financial risk for the investor on the revenue side. The other variant, applied in Spain for example, regulates only the level of the 'RES premium' that comes on top of market electricity rates. The difference of tariffs with conventional energy sources is thus guaranteed, while the effective tariff paid to suppliers will vary. A similar system could be introduced for the Flagship Program, by having member states guarantee investors for selected CCS projects a certain tariff for their electricity.



## United States

Feed-in tariffs are also placed in the U.S., depending on the RES and the state where used. Their mechanism is the same as described above and could potentially benefit CCS deployment. The table below shows the different levels of feed-in tariffs that already exist in the E.U. and the U.S.

**Table 5. Comparison of Renewable Energy Feed-in Tariffs**

Feed-in Tariffs (US c/kWh)		Wind	Biomass	Solar	Hydro	Landfill Gas	Geothermal
Europe	Germany	8 - 12 Onshore 11 - 12 Offshore 20	11 - 13	61 - 83			
	Netherlands	10 - 13					
	Spain	12		13 - 40			
	Austria	10	4 - 22	63 - 80	5 - 8		
	France	Onshore 11 Offshore 17		40 + construction bonus 33	8		12
United States	Minnesota	10.5 - 25	10.5 - 14.5	50 - 71	6.5 - 10	8.5 - 10	
	Rhode Island	10.5 - 11.5	10.5 - 14.5	48 - 54	6.5 - 10	8.5 - 10	9 - 19
	Michigan	10.5 - 25	10.5 - 14.5	50 - 71	6.5 - 10	8.5 - 10	9 - 19
	Hawaii					45 - 70	
	Illinois	10.5 - 25	10.5 - 14.5	50 - 71	6.5 - 10	8.5 - 10	9 - 19

Source: Anderson 2006 'Costs and Finance of Abating Carbon Emissions in the Energy Sector', & Rickerson, Bennhold, Bradbury 2008 'Feed-in Tariffs and Renewable Energy in the USA - a Policy Update'

Figure 2: Feed-in Tariffs in E.U. and U.S.

### 3.3 Markey-Waxman Draft (ACESA 2009)

On 31 March 2009, Chairmen Markey and Waxman released a discussion draft, which essentially is the draft of a comprehensive energy and greenhouse gas reduction bill. The draft was revised and renamed the American Clean Energy and Security Act 2009, which was passed by the U.S. House in June 2009. This bill provides an integrated regulation framework for all energy-related issues for the future. The draft consists of four titles: Clean Energy, Energy Efficiency, Reducing Global Warming Pollution, and Transitioning to a Clean Energy Economy.

Out of all the provisions included in the Markey-Waxman Draft 2009, the following are the key points of regulation that concern CCS (Under the Provisions for Coal section in Title 3):

- **Interagency report will be drafted that identifies legal and regulatory barriers** to commercial CCS deployment. Report must provide recommendations to the President and Congress for new legislation and regulations that would address these barriers. A task force study to design a legal framework for geologic storage sites is also established.
- **CO<sub>2</sub> geologic storage site regulations:** Amends the Clean Air Act (CAA) and the Safe Drinking Water Act (SDWA) to establish standards. Standards must include rules on financial responsibility of injected CO<sub>2</sub>, monitoring, record keeping, public participation and certification rules, among other things. Rules must minimize redundancy between CAA and SDWA authority. Certified and uncertified geologic storage sites are covered entities under the cap and trade program.
- **R&D and early deployment of CCS**
  - **Carbon Storage Research Corporation:** Established to oversee and direct R&D of CCS capture and storage technologies by issuing grants and financial assistance. This program is identical to Rep. Rick Boucher's (D-VA) proposal.
  - **Funding:** Secured through assessments on utility sales of electricity from fossil fuels with annual nationwide limit of \$1 billion per year for no more than 10 years.
  - **Financial assistance eligibility:** Commercial-scale projects undertaken by private, public, academic and non-profit organizations are eligible with an emphasis on supporting a diversity of technologies and fuels.
  - **Other provisions** deal with governance, government oversight, sharing of information and intellectual property.
- **Incentives and Standards for commercial deployment of CCS**
  - **Incentives:** Provides fixed payments to facilities for tonnes of CO<sub>2</sub> captured and sequestered. Amount per tonne to be determined by administrator of the EPA, based on incremental cost of CCS and other factors over a fixed amount of years. To be eligible, facilities

must be a coal- or petroleum coke-fired electric generating unit with 250 MW or greater nameplate capacity or be an industrial source that will emit more than 250,000 tonnes of CO<sub>2</sub> per year absent any emissions capture.

- **Performance standards:** Amends the CAA to require new coal fired power plants to meet performance standards. The EPA administrator must review standards and may tighten them depending on the performance of commercially available technology. Details include:

- Standards apply to all plants permitted after Jan. 1, 2009 where 30% or more of their fuel is coal and/or petroleum coke. Standards vary based on the year in which the plant is permitted along with other factors.
- Plants permitted from 2009 through 2014 must emit no more than 1,100 lbs of CO<sub>2</sub>/MWh by no later than 2025 and potentially earlier depending on the level of commercial deployment of CCS technology.
- Plants permitted from 2015 through 2019 must emit no more than 1,100 lbs/MWh at start
- Plants permitted from 2020 onward must emit no more than 800 lbs/MWh at start

Overall, the American Clean Energy and Security Act of 2009 (ACESA) provides a number of important provisions that will facilitate the demonstration and deployment of CCS technologies. It lays a strong foundation for moving CCS technology to scale by reducing costs and providing funding for demonstrations. The ACESA has the following strengths:

- **Develops a comprehensive national strategy for deployment.** The bill requires Federal agencies, with EPA leadership, to develop a comprehensive strategy for commercial deployment and deliver a report to Congress within one year. The report will identify barriers and regulatory challenges and will recommend regulation, legislation, and other actions to facilitate CCS deployment.
- **Establishes regulations for geologic storage.** Amends the Clean Air Act and Safe Drinking Water Act to establish regulations for geologic storage. Requires EPA to finalize the rules for carbon dioxide geologic sequestration wells, including financial

responsibility requirements, within one year. The bill also requires EPA to identify a coordinated process for certifying and permitting geologic storage sites within two years.

- **Requires emissions reporting for geologic storage sites.** Geologic storage sites are regulated under the cap and trade program. Mandatory emissions reporting is required beginning in 2011.
- **Requires a formal report and evaluation of regulatory framework every three years.** The bill requires EPA to formally report data on geologic storage sites, evaluate the performance of the geologic storage sites, and reassess the regulatory framework for geologic storage sites to Congress once every three years.
- **Establishes a task force to design legal frameworks.** The bill establishes a task force to provide recommendations to Congress within two years that include a study of the ability of existing laws and insurance mechanisms to manage risks associated with CCS, the implications and considerations for different models for liability assumption, and subsurface property rights.
- **Promotes R&D and early deployment of CCS.** The bill establishes a Carbon Storage Research Corporation to be run by the Electric Power Research Institute. The Corporation would use funds collected through a feed-in tariff to issue grants and financial assistance for commercial-scale CCS demonstrations. Funding is capped at \$1.1 billion per year for no more than 10 years. The bill also includes provisions for governance, government oversight, information sharing and intellectual property for both the Corporation and projects it would undertake.
- **Provides bonus allowances for stored carbon dioxide.** The bill provides bonus allowances to the first facilities that implement capture and secure geologic storage that result in a 50 percent reduction in annual carbon dioxide emissions. Payment is available for electric generating units fired by coal or petroleum coke at least 50 percent of the time and with a nameplate capacity of 200MW or greater, and to industrial sources that emit more than 50,000 tonnes of carbon dioxide per year and do not produce liquid transportation fuel. Funds will be divided into tranches with the payment on sliding

scales with higher payments for greater percentage capture. This program provides a mechanism for offsetting the technical risk assumed by early-adopters and a financial incentive to capture and store greater percentages of carbon dioxide than is required under the performance standards.

- **Sets performance standards for new coal-fired power plants.** The bill amends the Clean Air Act to require new coal-fired power plants to meet performance standards. The EPA Administrator must review the standards and may tighten them depending on the performance of commercially-available technology.
  - Standards apply to all plants permitted after January 1, 2009 where 30% or more of their fuel is coal and/or petroleum coke.
  - Plants permitted from 2009-2020 must achieve a 50 percent reduction in annual emissions by 2025 or earlier (depending on the level of commercial deployment of CCS technology).
  - Plants permitted from 2020 onward must achieve a 65 percent reduction in annual emissions from the unit.
- **Allows for retrofits of existing plants to apply for bonus allowances.** The bill provides criteria for retrofit facilities and specifies that such facilities should apply CCS to at least 200 MW with a 50-65 percent annual reduction in carbon dioxide emissions from the portion of the unit that has been retrofitted (as proposed in the Congressman Space amendment).

Specifics of the bonus allowance payments are outlined below:

**Phase I (first 6 GW of CCS equipped plants)**

- Units achieving capture and storage of 85% or more of the carbon dioxide that would have otherwise been emitted would receive \$90 bonus allowance value for each tonne of CO<sub>2</sub> captured and sequestered.
- Bonus allowance payment for lower percentage capture will be determined by the EPA administrator, with a minimum payment of \$50 per tonne of CO<sub>2</sub> captured and sequestered for a 50 percent reduction in carbon dioxide.

- An extra \$10 per tonne bonus allowance is given for early-adopters, or those that begin operating at a 50% capture and storage rate before 2017.
- A lower but undefined bonus allowance will be given to projects that combine geologic storage with enhanced oil recovery.

## **Phase II (6-72GW)**

- Allowances are distributed through an annual reverse auction (unless otherwise decided by the EPA) with bids based on the desired level of incentive for 10 years of geologic storage.
- Allowances will be divided into a series of 6 GW tranches.
- Value of allowances will be on a sliding scale with higher values for greater percentage capture. Precise values will be determined by the administrator and re-evaluated every 8 years.

### **3.4 American Recovery and Reinvestment Act 2009 provisions for CCS**

The American Recovery and Reinvestment Act of 2009—the \$787.2 billion economic stimulus package proposed by President Barack Obama and passed by Congress in mid-February 2009—is intended to put America back to work and to help shorten the recession. The document includes a number of provisions that aim to promote what has been labeled as “Green Economy”, a promising advance after the 2007 recession. More than \$71 billion will be invested in green initiatives, from energy conservation and efficiency to environmental cleanup, using methods as CCS, along with \$20 billion in green tax incentives. These provisions highlight the U.S. Government’s desire to accelerate CCS and remain the leading CCS development market globally. Building on existing CCS programs, the stimulus funding could increase federal CCS support by 70%.

The Senate version of the stimulus package initially included \$50 billion in loan guarantees for the nuclear industry and \$4.6 billion for carbon-capture-and-sequestration technologies for coal-fired power plants. Both provisions were dropped when the House and Senate went into conference to craft the compromise legislation that Congress later passed and

the president signed into law. Despite the lack of these provisions, the stimulus package still includes \$3.4 billion for CCS programs.

Specifically, the detailed summary of the stimulus package posted by the House Appropriations Committee says the \$3.4 billion is “for carbon capture and sequestration technology demonstration projects.” This funding will provide valuable information necessary to reduce the amount of carbon dioxide emitted into the atmosphere from industrial facilities and fossil fuel power plants and the opportunity to deploy large scale CCS. Most likely, the final decision on how that money gets spent will fall to Energy Secretary Steven Chu, who called coal his “worst nightmare” before Obama nominated him for the nation’s top energy job. More recently, at his confirmation hearing, Chu expressed a more positive view of coal and CCS technology and their place in America’s energy future.

### **3.5 Ship Financing as part of CCS**

Financing the special purpose CO<sub>2</sub> carrier will require special attention. In Phase 1 it is expected that financing the vessels, as part of the whole marine transportation system integrated in CCS, will be done mainly through subsidies, tax credits and other support mechanisms. These will aim to get demonstration projects running in order to test the overall systems before launching commercial projects. During Phase 2 however, the projects will be financed through banks. The challenge then will be to persuade the banks to finance the vessels using the asset itself as collateral. The challenge lies in the fact that the ship is especially designed to carry carbon dioxide. In the case of default, the bank will not easily sell the vessel to owners who could economically use it for other cargos. In contrast, with a more-conventional liquid or dry bulk ship, the world market presents many potential buyers who could use the vessel for its intended purpose. Thus, the terms on which the ships will be financed, as well as how this financing will be related to the overall CCS projects, must be determined. Generally, the liquefied CO<sub>2</sub> vessels would have to be financed as part of the overall CCS project with a long term contract for their use.

### **3.6 Conclusion**

The regulation of carbon emissions is a current concept that might potentially favor the rise of CCS and other emission-reduction programs. Both the European Union and United States have taken big steps to approach the greenhouse gas problem. Technologies like CCS are highly encouraged, and a number of financial incentives have been promised to projects that propose to use CCS. There are three key issues to be addressed by regulating bodies: integrate existing laws and regulations, provide incentives for CCS deployment, and assess liability in the case of leakages and other safety measures. As such subsidies are given to CCS projects around the world, CCS will see its economic viability increase, and will likely move closer towards Phase 2, where full-scale commercial projects are possible. Furthermore, if a legal framework is completed by 2015, this will also encourage CCS planners that a commercial phase may be within reach.



## **4 Market Sizing**

### **4.1 Overview**

This section aims to define the current market for CCS. Understanding the market size and the location of power plants will provide insight on the characteristics of feasible origin-destination pairs for marine transportation of CO<sub>2</sub> as part of CCS projects. First, an overview of carbon emissions globally, broken down by energy source and region is presented. Then the focus is directed at fossil-fuel power plants (especially coal-fired power plants) in areas where there is a potential for CCS development that might include marine transportation.

### **4.2 Background**

Sustainable economic growth going into the future requires large amounts of energy supplies, which must also be reliable and affordable. At the same time increases in associated carbon dioxide emissions globally, and the associated risk of climate change, are a cause of major concern. The IEA analysis in *Energy Technology Perspectives 2008* (ETP) projects that the CO<sub>2</sub> emissions attributable to the energy sector will increase by 130% by 2050 in the absence of new policies set in place or supply constraints on the fossil fuels used. To address this problem, analysts talk about increasing renewable energy usage, energy efficiency, and other technologies such as nuclear power and the near-decarbonization of fossil fuel-based power generation. Nonetheless, fossil fuel usage is expected to continue to play a major role in delivering global energy supply, with the latest IEA projections showing a global increase in fossil fuel usage through 2030. Energy efficiency and renewable energy will be vital in mitigating carbon emissions.

But the IEA also estimates that even if policies currently being considered to increase renewable energy generation and energy efficiency are implemented, there will still be a 20% increase in CO<sub>2</sub> emissions by 2030. In other words, renewable energy and energy efficiency will not decrease emissions quickly enough to prevent climate change. This makes CCS an essential bridge between today's energy system (dependent on fossil fuels) and the long-term goal of relying solely on renewable energy. The only technology available to mitigate GHG emissions from large-scale fossil fuel usage is CCS.

In order to maintain power supplies, industry worldwide needs to replace large quantities of power generation plants that have reached the end of their lives. It is also expected that a significant quantity of extra capacity will be required in some rapidly growing economies. In the reference scenario of the IEA's 2006 World Energy Outlook, 5087 GW of new and replacement power plant capacity, mostly using fossil fuels, is projected to be built between 2005 and 2030.

Coal represents an economically attractive option for new plants due to the high and volatile prices of oil and gas and is also available in vast amounts in markets such as China, India and the U.S.A., where many of the power plants are likely to be built, as seen in Figure 2. In the IEA's reference scenario, coal-fired generation capacity is projected to increase to 2565 GW in 2030. CO<sub>2</sub> can be captured from fossil fuel fired power plants, but it is not currently economically feasible to build power plants fitted with CO<sub>2</sub> capture. The concept of a 'capture ready' power plant, therefore, comes into being. A capture ready plant is a plant which can be retrofitted with CO<sub>2</sub> capture when the necessary regulatory or economic drivers are in place.

### A coal-fired world

The world has been on a tear building coal-fired power plants in the past five years, creating an added 1 billion tons of carbon dioxide per year. In the next five years, even after Kyoto limitations kick in, more coal-fired power is expected to come online, adding 1.2 billion tons of CO<sub>2</sub> per year. China is set to slow its buildup. The United States and, to a lesser extent, nations that face Kyoto limits on greenhouse gases, plan to accelerate their buildup dramatically.

	2002-06		2007-11		
	New electric capacity from coal-fired plants, in gigawatts	Tons of CO <sub>2</sub> produced annually	Expected new capacity from coal-fired plants, in gigawatts	Tons of CO <sub>2</sub> produced annually	Percent change
<b>China</b>	112,613	739,867,410	55,490	364,569,300	-50.7%
<b>India</b>	12,138	79,747,974	36,477	239,651,591	200.5
<b>US</b>	2,660	17,472,915	37,723	247,840,110	1,318.4
<b>EU Countries</b>	2,508	16,477,823	12,856	84,463,920	412.6
<b>Other Kyoto Nations</b>	19,824	130,244,337	33,455	219,796,722	68.8
<b>Non-Kyoto Nations</b>	8,977	58,976,919	2,045	13,435,650	-77.2

Figure 3: Coal-Fired Plants throughout the World

Source: *Energy Information Administration (Report: DOE/EIA-0383 2009)*

### 4.3 Carbon Emission Statistics

Fossil fuels and especially coal are an important source of energy and the need for them as part of electricity generation is growing. The combustion of coal, however, is also the greatest pollutant in terms of carbon dioxide emissions, adding more CO<sub>2</sub> per unit of heat energy than any other fossil fuel. The amount of heat emitted during coal combustion depends largely on the amounts of carbon, hydrogen, and oxygen present in the coal and, to a lesser extent, on the sulfur content. The figure below shows the breakdown of energy-related GHG emissions into emitting fuel sources. Emissions from coal are now the dominant fossil fuel emission source, surpassing 40 years of oil emission prevalence.

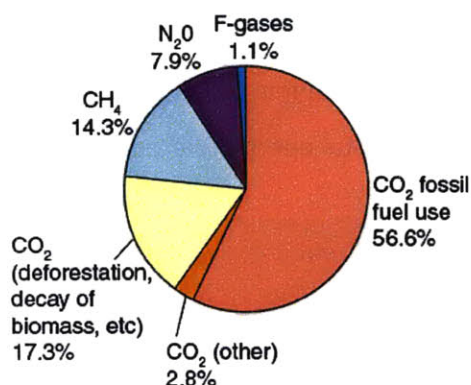


Figure 4: Energy-Related GHG Emissions

Source: *Energy Information Administration (Report: DOE/EIA-0383 2009)*

Researchers from the University of East Anglia report that CO<sub>2</sub> emissions from the burning of fossil fuels increased by two percent from 2007 to 2008, by 29 percent between 2000 and 2008, and by 41 percent between 1990 (also the reference year of the Kyoto Protocol) and 2008. They have also proved that the 2007 financial crisis had a small but discernable impact on emissions growth in 2008, with a 2% increase compared with an average 3.6% increase over the previous seven years. Emissions from emerging economies such as China and India have more than doubled since 1990 and developing countries now emit more greenhouse gases than developed countries.

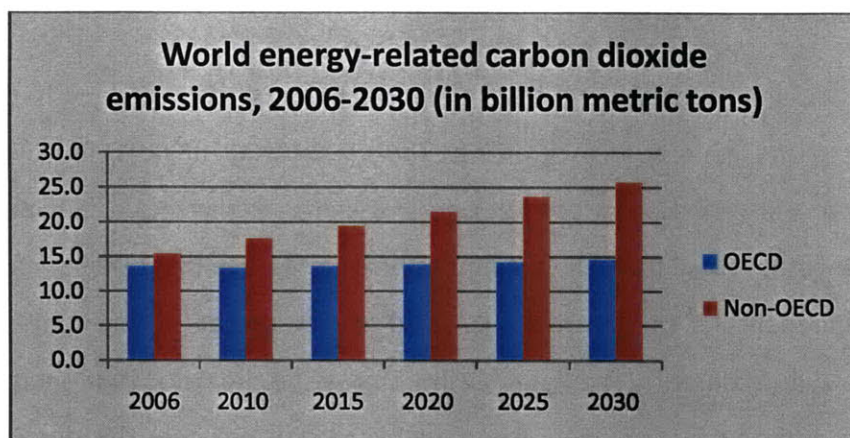


Figure 5: World Carbon Dioxide Emissions

Source: Energy Information Administration (Report: DOE/EIA-0383 2009)

The following graph indicates the total volume of CO<sub>2</sub> emissions from coal combustion and the corresponding percentage as part of total energy-related emissions.

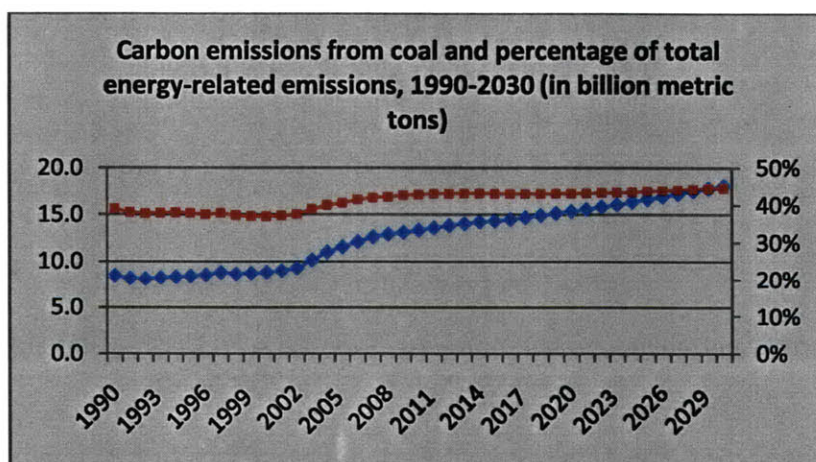


Figure 6: Projected Increase in Coal Usage

Source: Energy Information Administration (Report: DOE/EIA-0383 2009)

#### 4.4 Origins and Destinations

In order to gain insight into the characteristics of origins and destinations for a CO<sub>2</sub> vessel system, the methodology is broken down to the following three parts:

- (a) ***Examination of possible origins.*** Possible origins are coal-fired power plants that, first of all, are equipped with capturing technology and have a sufficient amount of CO<sub>2</sub> captured in discrete times, which would justify the use of ships for transportation. Second, the power plants must be coastal or have some kind of immediate access to the sea, so that a proper dockside could be constructed (or already exists). CCS chains for which it makes more sense to use ships instead of pipelines are defined by factors such as distance (long distances reflect economics of ships over pipelines), difficulty in laying pipeline (ocean's depth and fishing area limitations), degree of stability of volume over lifetime of investment, and the level of flexibility desired (pipelines will be used for a single purpose through their useful lives). By looking at the following map of highest CO<sub>2</sub> emitting power plants worldwide, provided by CARMA, we can immediately see that the most feasible origins are clustered in North America, Northern regions of Europe, India and China.
- (b) ***Examination of possible destinations.*** Destinations are slightly more difficult and uncertain to identify. The three most interesting alternatives for storing CO<sub>2</sub> from fossil-fueled power plants are: existing oil fields, depleted gas reservoirs and deep saline aquifers:
- Existing oil fields. The oil industry has been injecting CO<sub>2</sub> into oil fields to enhance the recovery of oil from existing production wells for many years. More than 70 enhanced oil recovery (EOR) projects around the world are now underway.
  - Depleted oil and gas fields. These geological formations have proven their capability to hold oil and gas over millions of years and, therefore, have great potential to serve as long-term storage sites for CO<sub>2</sub>.
  - Deep saline aquifers. Saline aquifers are underground rock formations that contain salty water. Suitable aquifers for storage are typically located at least



800 meters underground and contain water that is not potable. The CO<sub>2</sub> partially dissolves in the formation water and in some cases the CO<sub>2</sub> slowly reacts with minerals to form carbonates, thereby permanently trapping the CO<sub>2</sub> underground.

#### 4.4.1 Data Collection

Data has been collected from a number of sources. Carbon emissions statistics have been taken from the U.S. Energy Information Administration, processed and shown in the charts above. Additionally, information has been extracted from Bellona Foundation studies on CO<sub>2</sub> emission sources, available storage sites as well as current and potential CCS projects. This data will be used later on as part of a case study. The most important and detailed data about power plants, their locations, operations and GHG emissions have been collected by Carbon Monitoring for Action. CARMA is a large database containing information on the carbon emissions of over 50,000 power plants and 4,000 power companies worldwide. The following, provided by CARMA, is a snapshot of an interactive map, which shows the highest emitting power plants worldwide. The data on global power plants available online by CARMA can also be imported into the Google Earth program, which allows for a full-scale interactive map and provides the following data:

- Power plant locations worldwide and their labeling according to energy and pollution intensity, ranging from clean to dirty
- The same labeling for countries
- The information above is available from 1989 (historic data) to 2019 (forecasts)



Figure 7: Largest CO<sub>2</sub> Power Plants in the World

#### 4.4.2 Market Sizing Estimates

The first step in our market sizing efforts is to find the number of power plant that could be used as origins. The following chart using data from CARMA, shows the total number of power plants per continent, independent of their capacity or CO<sub>2</sub> emission intensity.

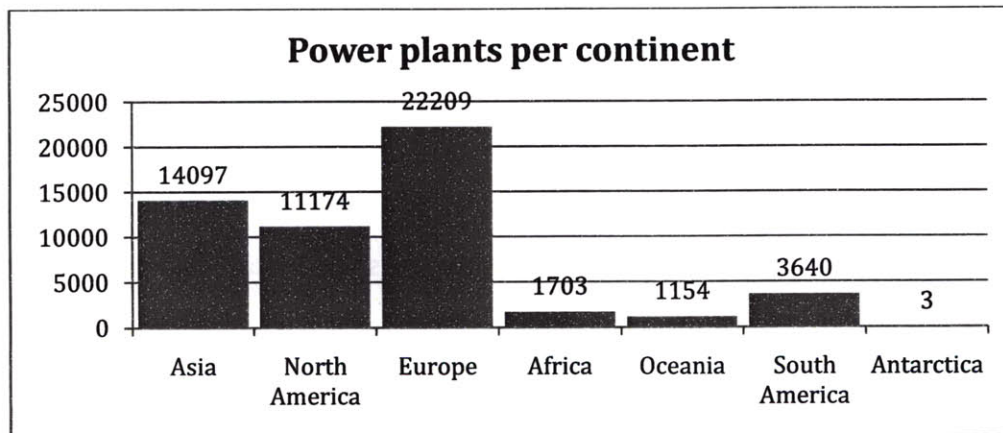


Figure 8: Power Plants per Continent

Source: CARMA ([www.carma.org](http://www.carma.org))

However, for a marine transportation system to be attractive (as well as feasible) as part of CCS can only be developed in larger power plants due to large volumes of available “cargo”. The

following table shows the number of carbon dioxide source types that could support CCS and have emission volumes over 1 million tonnes CO<sub>2</sub> per year.

Table 1: Carbon Dioxide Sources

(over 1mn tonnes CO <sub>2</sub> emitted per year)	
<b>CO<sub>2</sub> Source type</b>	<b>Number</b>
<i>Coal power plants</i>	1,137
<i>Gas power plants</i>	332
<i>Refineries</i>	319
<i>Cement factories</i>	270
<i>Chemical products</i>	259
<i>Oil power plants</i>	238
<i>Iron and steel factories</i>	144
<i>Oil and gas processing</i>	8
<i>Other</i>	11
<i>Undefined</i>	492
<b>Total</b>	<b>3,210</b>

Out of these sources the most attractive type of origin is, of course, coal-fired power plants. Out of these 1,137 plants, four already have operating small-scale CCS technology (though all use pipeline transportation to the storage site), 26 are under consideration for developing within the next 5-10 years and 57 have been classified as possible, fulfill the requirements and can be launched within the same time period.

#### 4.5 “Capture-Ready” Power Plants

The IEA defines a capture-ready power plant as a plant which can include CO<sub>2</sub> capture when the necessary regulatory or economic drivers are in place. According to the 2007 report “CO<sub>2</sub> capture ready power plants” by the IEA, the requirements for these plants are the following:

- Coal-fired power plants using Integrated Gasification Combined Cycle or Pulverized Coal Combustion technologies to generate electricity



- Sufficient space to accommodate the capture equipment (scrubbers, compressors, oxygen production plant etc), additional facilities including cooling water and electrical systems, safety barrier zones and pipework.
- Carbon dioxide would need to be transported to storage sites either by pipeline or ships. Requirements change depending on which mode is chosen. For the purpose of this study we will focus on ship transportation. In this case the power plant must also be coastal, or have easy access to the sea.
- Financial ability to pre-invest in setting up the CCS system originating from specific power plant and to compensate for any downtime during construction.

#### **4.6 Locations- Coastal Power Plants and Available Storage Sites**

##### **4.6.1 Europe- North Sea**

A few different options come to mind as possible locations for a carbon capture and sequestration operation. A number of studies have been performed in the North Sea to gauge how exploration, development, and management of potential sites could be carried out safely and effectively. The United Kingdom Energy Minister, Ed Miliband, predicts that “there's enough potential under the North Sea to store more than 100 years worth of CO<sub>2</sub> emissions from the UK's power fleet” (Gray).

Also, in a paper by Markussen *et al.* (2002), it is mentioned that if some of the most mature candidate fields of the North Sea Continental Shelf (NSCS) were to adopt CO<sub>2</sub> for oil recovery, then with a 25-year economic lifetime the project could conservatively produce 2.1 billion barrels of incremental oil while sequestering 680 million tonnes of CO<sub>2</sub> in secure depositories. In 2002, the CO<sub>2</sub> for EOR in the North Sea (CENS) project also began, with the collaboration between regional major oil and gas operators, country energy departments, trade associations and NGOs, to identify opportunities for CO<sub>2</sub> transportation in the North Sea and EOR opportunities.

Europe currently has 22,209 power plants, whose CO<sub>2</sub> emissions per year span 0 to 37,000,000 tonnes per year. It seems that Europe has a very high percentage of carbon-free facilities (alternative energy sources); only 7,979 out of the 22,209 will be polluting in the next decade (35%). Out of these, only 491 will have CO<sub>2</sub> emissions over 1,000,000 tonnes per year in

the next decade and 241 are coastal<sup>1</sup>. The following snapshot represents these power plants in an interactive map:

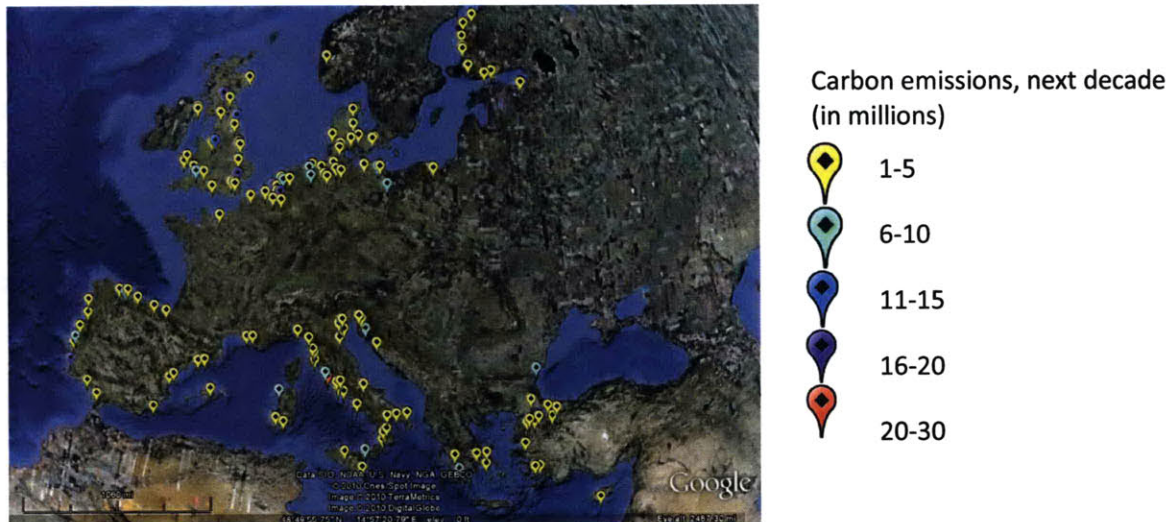


Figure 9: Coastal Power Plants and their Carbon Emissions in Europe

It is observed that the majority of coastal power plants are clustered around the North Sea, in Northern Europe (Netherlands, Belgium, Germany, Denmark, UK) and the Baltic Sea (Finland). This fact presents opportunities for marine transportation in two ways: first, CO<sub>2</sub> can be transported and stored in deep sea geological formations, such as the operational Sleipner depleted oil field and second, CO<sub>2</sub> can easily be transported to other sites nearby for EOR purposes (Kentzin, K12B for example). These opportunities can be illustrated in the map below:

<sup>1</sup> Coastal means either they have immediate access to the sea or are located less than 50km from the shore.

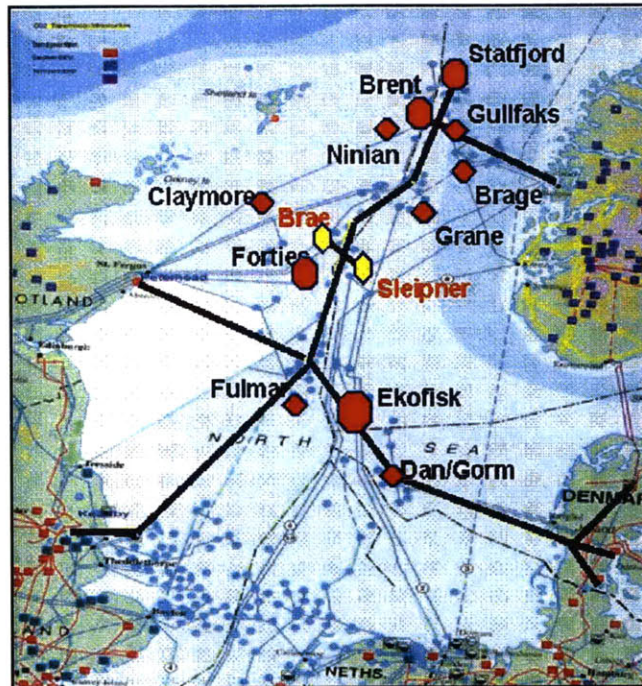


Figure 10: Proposed EOR locations in the North Sea and Their Connections (CENS project 2002)

*Source: Mechanisms and Incentives*

Maersk Oil has identified the North Sea as a possible location for CCS coupled with EOR. A new project from Maersk aims to capture, transport, and store volumes in excess of 1.2 million tonnes of CO<sub>2</sub> each year in the Danish North Sea. The Meri-Pori coal-fired power plant which will be used in this project is located on the west coast of Finland, has an installed capacity of 565 MW and is equipped with Siemens' proprietary post-combustion capture technology. Meri-Pori's demonstration project will be the only one so far to combine shipping, cross border transportation between countries and EOR. This project, which seeks qualification for funding under the E.U.'s CCS Demonstration Programme (expected by 2011), is slated to be in operation by 2015 (Maersk).

#### 4.6.2 U.S.A

Here the same methodology is used to identify potential origins. In the U.S. there are 9,472 power plants whose CO<sub>2</sub> emissions per year span from 1 to 43,100,000 tonnes per year. Out of these only 309 are located in coastal states and 142 are coastal. The following snapshot represents these power plants in an interactive map:

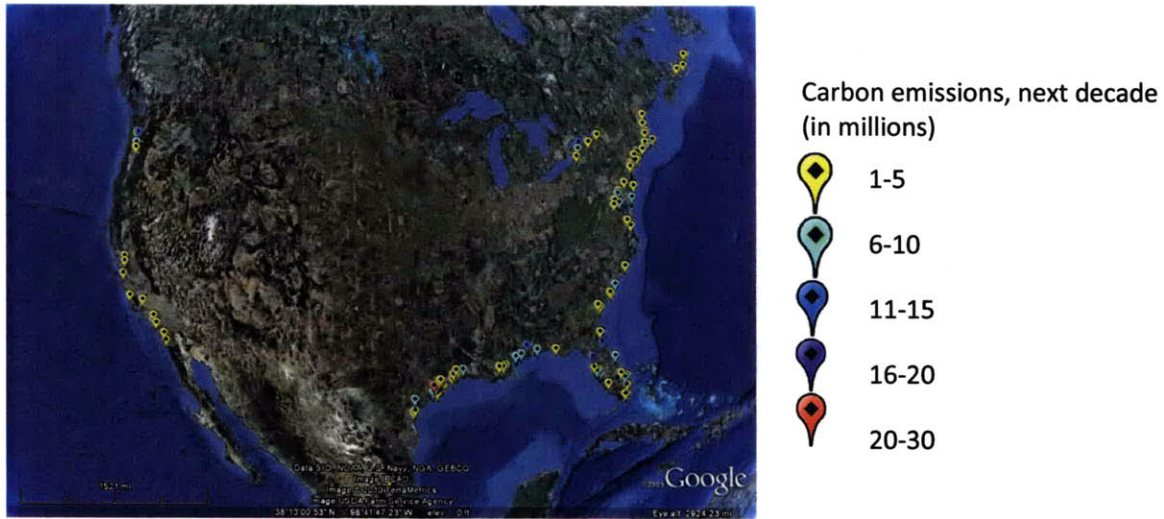


Figure 11: Coastal Power Plants and their Carbon Emissions in the U.S.A

Here, highly emitting power plants are clustered in the south (Texas, Louisiana, Mississippi, Alabama, and Florida), which is also promising for transporting CO<sub>2</sub> for EOR purposes in Texas, the Gulf of Mexico and potentially Trinidad and Lake Maracaibo, as shown below:





Figure 12: Existing/Proposed CO<sub>2</sub> Storage Sites

Source: IPCC Special Report on Carbon Dioxide Capture and Storage, Edward S. Rubin Carnegie Mellon University, Pittsburgh, PA

Specifically, the Gulf of Mexico is another prime location. The location of multiple power plants located nearby the shore, along with scores of oil wells in the Gulf of Mexico (GOM), are ideal for a relatively short shipping route. The GOM region can also benefit from environmental incentives that are being introduced in the United States; for instance, in June, 2009, President Barack Obama announced a \$1 billion revamp of a near-zero-emissions coal plant in Illinois (Science News).

#### 4.6.3 Using Ships vs. Pipelines

However, marine transportation is not the only solution for transporting CO<sub>2</sub>; vessels are also competing against pipelines over short distances. The figure below gives a rough estimate of where marine transportation of CO<sub>2</sub> becomes cheaper than pipelines. Again, the figure shows a framework for discussing shipping and pipeline costs, not to present precisely accurate costs.

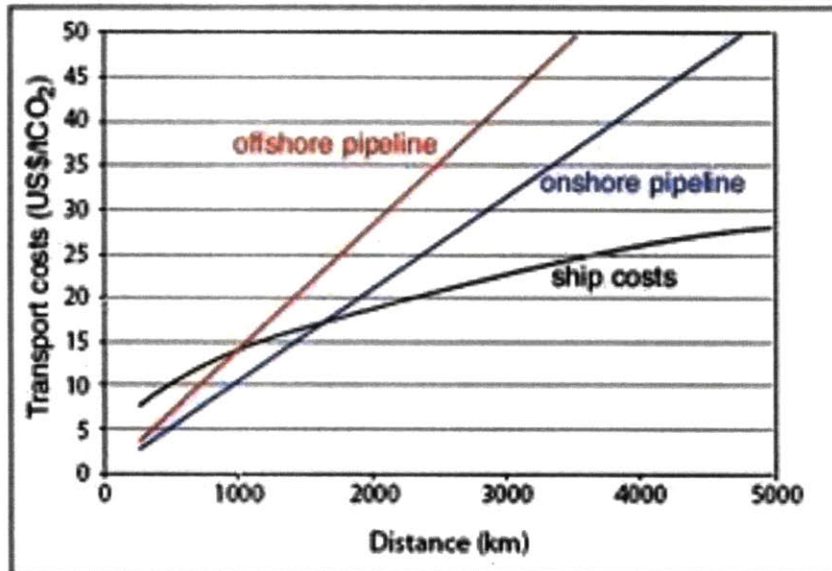


Figure 13: Pipeline vs. Ship Costs

Source: *Green Facts*

The figure quotes a distance of roughly 1000 km (540 nautical miles) as the point where shipping costs are less than pipeline costs. Clearly, other modes of transportation must be considered before deciding to use ships, depending on the route distance.

In a number of situations, however, transporting CO<sub>2</sub> via special-purpose vessels could have significant advantages against pipelines for a number of reasons. Ships provide great flexibility in terms of locations. On one hand, they can move around and collect cargo from a number of different sources and deposit it in a number of available storage sites around the globe. On the other hand, there is evidence that suggests these ships can carry other cargo, such as LPG or LNG, in the backhaul; a feature that does not exist in pipelines. In addition, as the distance gets larger and the water depth increases, economics might favor vessels over pipelines.

Another interesting reason is that there are some high carbon-emitting areas, where CCS could be used, do not allow for laying pipelines on the ocean bed. Such an example is in Japan, where the underwater seismogenic geology forbids the use of pipelines for transporting and storing CO<sub>2</sub>. In the greater eastern Asia area, the fisheries' unions also prohibit the use of

pipelines, reasoning that potential leakages in the pipeline networks would have a devastating effect in the area's marine life.

Finally, there is also a time dimension of advantages. Especially in the initial phases of CCS, ship transportation could be the best alternative since pipelines take a long time to construct and the ships could help get the first projects started. Moreover, ships are better used for enhanced oil recovery because EOR operations are limited to a specific number of years, and it may be impractical to make such a large investment in a long lasting pipeline infrastructure.

#### **4.7 Conclusion**

A market sizing estimate is helpful in the process of investigating possible locations for a CCS project. One must consider the yearly carbon output from the initial power plant, as well as its distance from a potential carbon sequestration site. The market certainly exists: the International Energy Agency forecasts a 130% increase in energy-attributable CO<sub>2</sub> emissions by 2050 if policies like CCS are not implemented. Large coastal plants are particularly of interest for a CCS project that uses vessels as the mode for transporting carbon dioxide.

In order to make a significant difference in the total amount of CO<sub>2</sub> emissions, power plants with annual emissions of at least one million tonnes of carbon dioxide are a plausible source for a CCS project; these can be either coal- or fossil-fuel-powered plants. In particular, coal-fired power plants are particularly of interest because they account for 1/3 of the world's total CO<sub>2</sub> emissions, and they emit more CO<sub>2</sub> than the same amount of other fossil fuels. On the receiving end, the carbon dioxide can be stored in underground geological formations or used as part of enhanced oil recovery (EOR). Potential sites have been identified in the North Sea, where some CCS projects have already begun, as well as in the Gulf of Mexico. In particular, there are 241 such coastal power plants in the North Sea and approximately 63 in the Gulf of Mexico, expected to emit collectively over 100 million tonnes CO<sub>2</sub> and over 70 million tonnes in the next decade, respectively.

The decision to use a vessel instead of a pipeline is another important question that depends on the particular situation. In situations where high volumes are guaranteed to be moved between a specific origin and destination for decades into the future, pipelines would

appear to be the obvious choice. Very long distances over very deep water would favor vessels over pipelines. The most important characteristic—particularly during Phase 1—is the length of time for which certain volumes can be guaranteed. To the extent that the economics of the system depends on temporary subsidies or carbon taxes of an unpredictable level, the flexibility of vessels is a great advantage. If high volumes between a particular origin-destination pair cannot be guaranteed for long enough to provide an economic return on the building of a pipeline, vessels—which can be easily moved to another location—look more promising. In the demonstration phase, vessels could also be used to gather small volumes from many different sources. Although this system may not be the most economic in the long run, it might make for an interesting demonstration project. There may also be certain circumstances that prevent the use of pipelines, such as earthquake zones and fishing areas.



## 5 Marine Transportation Systems

### 5.1 Overview

This section discusses various scenarios for how CO<sub>2</sub>-carrying vessels could be deployed, all of which are studied further in the model. It also introduces a number of possible vessel designs that have been proposed for the vessels. Additionally, this section explains how carbon dioxide acts as a cargo throughout the CCS process.

### 5.2 Vessel Scenarios

#### 5.2.1 Base Case

A number of possible scenarios is investigated for transporting the carbon dioxide. The simplest option is to carry liquefied CO<sub>2</sub> in one direction, deliver it to an offshore site, and return to the power plant empty. As the tanker returns to the shore-based plant with empty tanks, it will most likely be necessary to fill up the ballast tanks. This configuration, while it does help alleviate the carbon dioxide emissions of the power plant, does not optimize the use of the ship during the return trip.

#### 5.2.2 Direct Return with Liquefied Gas

To optimize the use of the ship's capacity and mobility, another idea has been presented. After unloading CO<sub>2</sub>, the vessel subsequently picks up a cargo of LNG or another liquefied gas from the sequestration site, and returns to shore. This configuration is theoretically ideal: the ship travels back and forth between two points, without any course deviations; and it also has a payload in each direction. The route would take more time than the base case, with the CO<sub>2</sub>-carrier also loading and unloading LNG, but it would then be unnecessary to use the ballast tanks.

Another consideration with this option is the extra time needed to clean the tanks each time a different cargo is transported. It is important to keep the liquefied gas uncontaminated, so this option raises the question of purity of the cargo. If unique tanks are used for each cargo, this additional cleaning time would not be an issue. Furthermore, purging the CO<sub>2</sub> tanks is a potentially expensive and complex process that could be avoided by the use of unique cargo tanks.

In reality, although the concept of a backhaul is financially attractive, it would be very complicated to enact seamlessly. The timing, volumes, and sequestration sites would all have to match perfectly for the backhaul concept to work out. Additionally, the origin and destination would have to have ready use for the cargos delivered.

#### 5.2.3 Triangular Route

A twist on the previous configuration would be to add a third site. The ship begins at port A, picks up a load of CO<sub>2</sub>, and drops it off at the sequestration site, port B. Then the vessel continues on to port C, where it receives a load of gas cargo, such as liquefied natural gas, and transports it back to the gasification plant at port A. This may occur because port C is the ideal source of natural gas to deliver to the power plant, or because port B has ideal conditions for sequestration, etc. Again, tank cleaning would be an issue whenever cargo is swapped, unless there are unique tanks. And unlike the direct return with natural gas, more time and distance must be covered to arrive at the third port in the triangle.

#### 5.2.4 Tug and Barge

A final scenario employs a tug and barges, rather than ships, in a classic “drop and swap” scheme. This scenario could also be considered as a different vessel design. But a tug and barge system would add more flexibility to the entire operation. A single tug and multiple barges could potentially be constructed, with the tug accompanying one barge at a time. Construction costs and operating costs for these articulated tug-barges (ATB) may differ from a tanker with the same capacity. Also, the loading and unloading times may be reduced since one barge can be loaded while the tug is powering a different barge. In this approach, one or more barges could be used to replace the need for shore-based intermediate storage.

### 5.3 **Vessel Designs**

Today’s CO<sub>2</sub> carriers are small compared to other gas-carrying vessels, as the demand is currently quite low. The *Coral Carbonic*, for instance, is 1250 m<sup>3</sup> with a length between perpendiculars of 74 m and a beam of 13.75 m; her cargo is used solely in the carbonated beverage industry. Its outboard profile is shown below.



Figure 14: CO<sub>2</sub> Carrier *Coral Carbonic*

Source: Anthony Veder

Delivered in 1999 and operated by Anthony Veder, this ship has a design speed of 12.5 knots with a loading rate of 250 m<sup>3</sup>/hr. All cargo is transported in a single cylindrical tank with half-spheres on either end (referred to as bilobe tanks); she trades around the Baltic and in northwest Europe.

Other simple designs have been presented. Audun Aspelund offers a design with a set of 10 similarly shaped bilobe tanks, shown in the following figureFigure 15. This ship can carry liquefied CO<sub>2</sub> in one direction with a backhaul cargo of LNG in a separate set of tanks. (It also requires a small tank dedicated to liquid inert nitrogen, or LIN, which Aspelund proposes to use in order to help liquefy the LNG.)

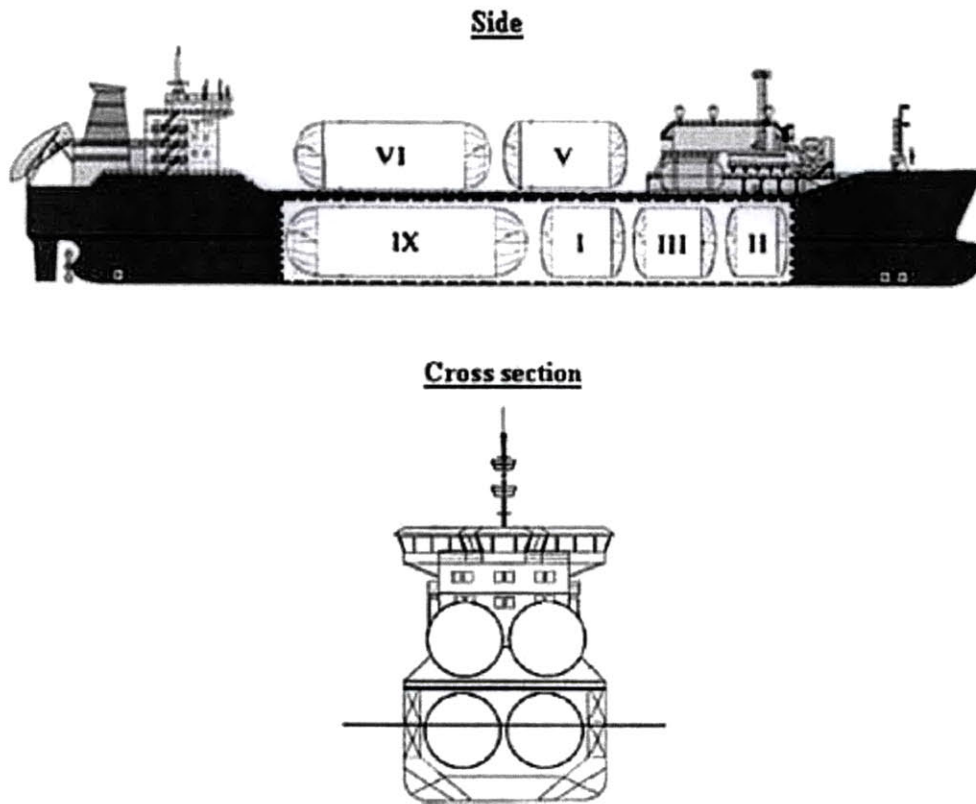


Figure 15: CO<sub>2</sub> Possible Tank Arrangement

Source: Aspelund

Each tank in the design has a diameter of 9.2 meters and is constructed of stainless steel.

Another option is to emulate current designs in LNG and liquefied petroleum gas (LPG) carriers. Mitsubishi Heavy Industries sets forth a 156-meter vessel with a conventional set of spherical tanks, shown below.

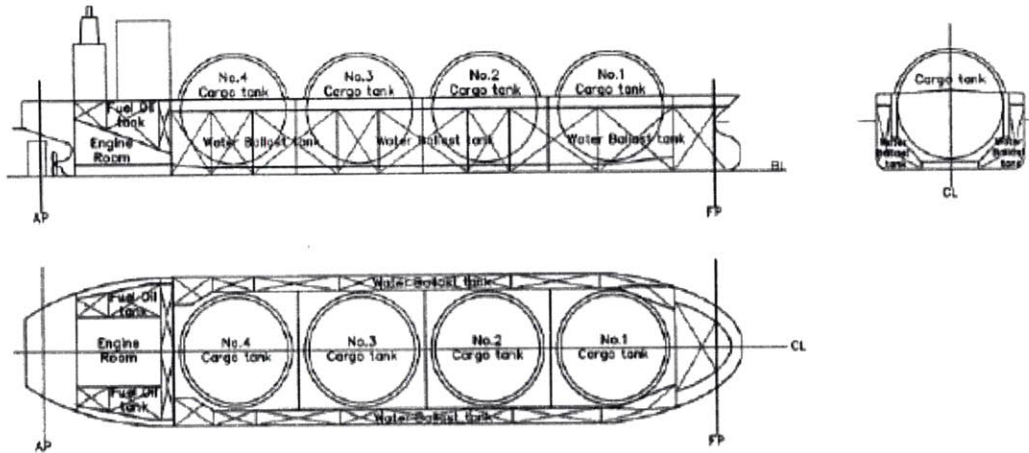


Figure 16: Mitsubishi Conceptual Design for CO<sub>2</sub> Carrier

Source: Mitsubishi Heavy Industries

One final alternative for transporting carbon dioxide by ship is to stack many small pressure vessels of CO<sub>2</sub> in its compressed form. The ship would carry hundreds of pressure “bottles” stacked vertically. Knutsen OAS has developed a prototype for such a vessel, labeled the PNG (pressurized natural gas) carrier. The figure below shows the vertical storage units and how they are integrated into the vessel.

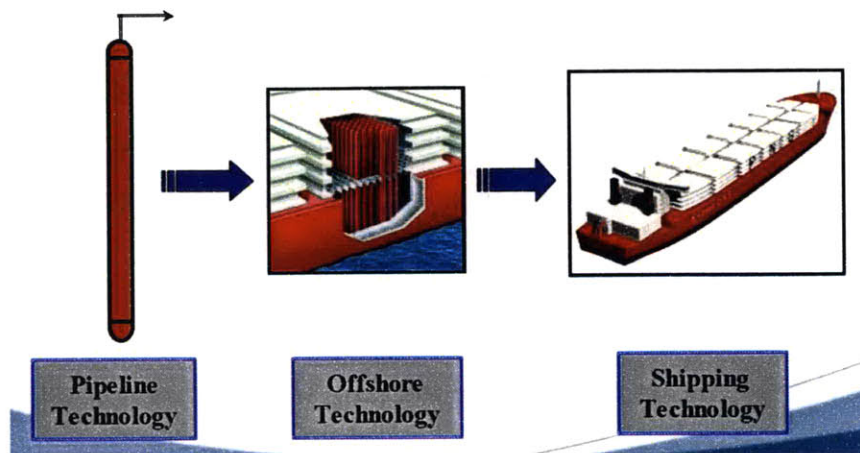


Figure 17: PNG Carrier Concept

Source: Knutsen PNG

## 5.4 Carbon Dioxide as a Cargo

### 5.4.1 Collection and Treatment

The simplest way to collect CO<sub>2</sub> from shore is to use a post-combustion method, separating carbon dioxide from flue gases produced by the power plant. Currently, the energy industry performs post-combustion separation by dissolving the CO<sub>2</sub> into a liquid solvent such as amines. This flexible procedure can even be retrofitted to existing power plants (CO<sub>2</sub> Capture Project). The construction of a new power plant with carbon collection capabilities, or a simpler retrofit, both constitute a significant initial investment.

### 5.4.2 Intermediate Storage

Intermediate storage facilities would also need to be built at the CO<sub>2</sub> source location, since the production of pure, liquefied CO<sub>2</sub> is a continuous process, whereas the loading of the vessels is distinct. Berger, Kaarstad and Haugen propose building facilities with a total capacity of 150 percent of the loading capacity of the ship, so for example for a 20,000 m<sup>3</sup> vessel the intermediate storage should be 30,000 m<sup>3</sup>. Others have suggested a ratio high as 250 percent. (To be conservative, a factor of 250% for intermediate storage needs is used in the model.)

Intermediate storage could be composed of either steel tanks (cylindrical or spherical) or rock caverns. Substantial experience exists in the Nordic countries for storing propane at a temperature of -43°C in rock caverns specifically designed and constructed for this purpose. At present, it seems that rock cavern storage would be a cost-reducing option for large storage volumes exceeding 50,000 m<sup>3</sup> of CO<sub>2</sub>.

### 5.4.3 Transport

The next step is the transportation of the CO<sub>2</sub>. The triple point of carbon dioxide is at 5.3 bar and -56.6° Celsius, at which point it may become unstable. The phase diagram of CO<sub>2</sub> is shown below.

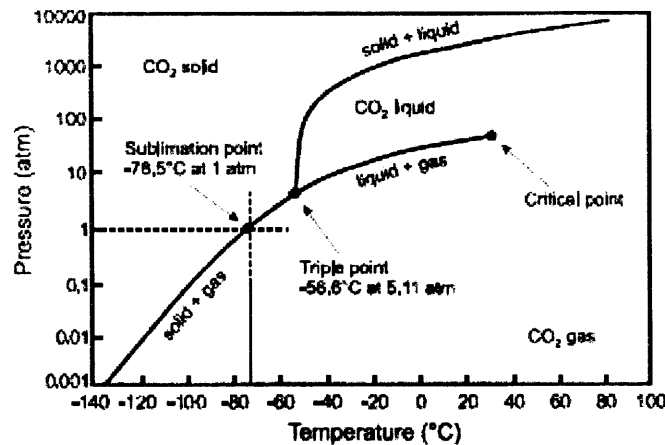


Figure 18: Phase Diagram of Carbon Dioxide

Source: Shakhshiri

In a feasibility study of carbon dioxide ships, Mitsubishi Heavy Industries recommends a pressure of 7 bar and a temperature of -50° Celsius to keep it as a liquid (Mitsubishi). Audun Aspelund suggests a slightly lower pressure and temperature, 5.5 bar and -54.5° Celsius, putting the CO<sub>2</sub> at a density of 1167 kg/m<sup>3</sup> (Aspelund). Such pressures and temperatures would maximize the amount of CO<sub>2</sub> cargo while retaining its liquid state.

From examination of the phase diagram in above, it is apparent that refrigeration alone (*i.e.*, refrigeration but not pressurization) will not allow the CO<sub>2</sub> to reach a liquid state; rather, it must be pressurized to at least 5.11 atm, or about 5.2 bar. As the phase diagram shows, it is possible to highly pressurize the CO<sub>2</sub> without refrigeration; however, as the temperature of liquid CO<sub>2</sub> is allowed to increase, the required pressure must also increase exponentially. For instance, at a temperature of 20° Celsius, it must be at 56 bar to retain its liquid state. For such large quantities of CO<sub>2</sub> that would be moved via ship, the combination of refrigeration and pressurization is ideal.

For the base case identified earlier, where the cargo tanks only carry CO<sub>2</sub>, the ship can be designed to these requirements. However, for the other cases where the ship also transports LNG, the liquefied natural gas may become the limiting factor. In refrigerated LNG tankers today, cargo is carried at extremely low temperatures around -162° Celsius, kept cold by expensive, insulated tanks. LNG has a density of roughly 450 kg/m<sup>3</sup>. Thus, if these CO<sub>2</sub>

carriers are built to LNG standards, there should be no further temperature considerations necessary to accommodate the cargo of CO<sub>2</sub>.

#### 5.4.4 Tank Sizing

The most prevalent approach in the ethylene tanker market is to use independent Type C tanks. They are self-supporting pressure vessels, with neither a secondary barrier required nor any restriction concerning partial filling.

The largest Type C tanks built to date are 6,000 m<sup>3</sup> for cylindrical tanks and 7,500 m<sup>3</sup> for bilobe tanks. The maximum diameter for the cylindrical design is 13 m, and 15 m for the bilobe design. These limits are related to economics, welding issues and the minimum design pressure. It may be possible to build tanks with larger diameters, but technical problems abound and cost increases exponentially. For example, distributing the saddle load into the hull becomes a major issue. Therefore, wall thickness is directly proportional to diameter and pressure and inversely proportional to allowable stress.

#### 5.4.5 Sequestration

Once the CO<sub>2</sub> is transported to the offshore depleted oil well, it is then pumped below the surface (in the base case, for storage only). Maersk indicates two options for offshore discharge operations. The first is for the vessel to connect to an offshore buoy, which is in turn connected to the offshore platform by a submerged turret system below the ships. This solution is very stable when it comes to adverse weather conditions and would be useful for locations with rough weather conditions, like the North Sea. The second option is a single-anchor bow system, where the cargo is discharged across the bow while the vessel is linked to an offshore buoy directly connected to the platform. Here, installation costs would be comparatively lower than for the first option (Maersk). In areas with mild weather it should be possible for the tanker to dock at an offshore platform.

It should be noted that some adjustments in the pressure or temperature of the carbon dioxide are typically necessary for this sequestration process. A common concern among environmentalists is that trapped CO<sub>2</sub> may somehow suddenly escape to the atmosphere. To combat this possibility, the US Environmental Protection Agency (EPA) has begun an



“Underground Injection Control (UIC) Program for Carbon Dioxide Geologic Sequestration (GS) Wells” (U.S. EPA).

Enhanced oil recovery sequesters the carbon dioxide while bringing up additional oil from an older oil field. Revenue from EOR highly depends on the current price of oil; estimates place potential revenue anywhere from \$8 up to \$30/tonne of CO<sub>2</sub> (U.S. Department of Energy). Howard Herzog from MIT puts the price, on average, at \$20 per tonne of CO<sub>2</sub>. For EOR, It is estimated that it takes roughly between 0.52 and 0.64 tonnes of CO<sub>2</sub> to recover a barrel of oil (Biello).

## **5.5 Conclusion**

After selecting a location for a CCS project to be used with a marine transportation system, the next step is to choose an appropriate vessel. Various designs have been presented, from a single tank design to a design with multiple bilobe tanks. Other designers have suggested a LNG-type design with spherical tanks, as well as a few other novel ideas. Furthermore, a number of transportation scenarios are possible for the transportation of CO<sub>2</sub>. These have been divided into (1) a base case, where a vessel carries CO<sub>2</sub> in one direction, (2) a direct return with LNG, (3) a triangular route, and (4) a tug-barge setup.

Another important concern in a CCS project is ensuring the safe delivery of the cargo, carbon dioxide. Either retrofitted or newly-built power plants can be used to capture the CO<sub>2</sub> initially. The carbon dioxide is cooled and pressurized sufficiently into a liquid stage, for ease of transportation. Intermediate storage tanks are located on shore to hold the cargo temporarily (or, additional barges are used in a tug-barge system). Finally, the CO<sub>2</sub> is pumped below ground, either as part of EOR or into a geological formation.



## **6 Analysis**

### **6.1 Overview**

The goal of this section is to analyze a number of different trade-offs in the transportation of liquefied carbon dioxide; the model is run and its results are discussed and analyzed. A brief explanation of the model is given, detailing inputs and assumptions. Then a number of cases are explored to determine how the costs of CCS projects change as various inputs are altered. First, the length of the trade route is altered to view its effect on the cost of CO<sub>2</sub> shipping. Varying volumes of CO<sub>2</sub> coming from the original power plant are also considered. The vessel's design and size will both be analyzed to see how economies of scale decrease the cost of shipping. These results are discussed, with the goal of highlighting the scenarios that are least expensive, and are most likely to begin a Phase 2 (the commercial phase) of CCS.

Other scenarios are possible, but are not explored in this analysis. For instance, the possibility exists that a single large ship could collect carbon dioxide from a number of low-outputting coastal power plants until it is full, and then head to an offshore site for sequestration. In terms of cost per tonne, this scenario would not be as efficient as serving a single larger power plant.

### **6.2 Explanation of the Model**

The model produced to perform the analysis was created in Microsoft Excel. It is composed of spreadsheets containing data concerning vessel logistics and costs of all facets of a CCS operation. Appendix A contains the instructions for using the model. Appendix B contains data values and their sources for construction cost, operating cost, and voyage cost. The user inputs values for type of route, distances between each point, and amount of carbon dioxide to be sequestered per year.

The model costs are broken into four sections. The first section designates non-vessel costs; this includes industry rates for carbon capture and sequestration per tonne, as well as the cost of intermediate storage containers. The other three categories are typical of a marine transportation project: capital costs (the cost of a vessel, based on its size, given by a 25-year loan at 8%); operating costs (also based on size); and individual voyage costs, which include fuel

consumption and estimated harbor fees. The construction cost of a dock at the origin or unloading facilities at the destination were not included. Costs reflecting the international marketplace were used; operations in the U.S. domestic Jones Act trade were not considered.

With regards to cost projections, it is difficult to accurately predict the costs for all sizes of CO<sub>2</sub> vessels. Large carbon dioxide tankers have never been built before, and there are not necessarily economies of scale for the CO<sub>2</sub> tanks aboard. Therefore, significant uncertainty exists with the construction cost estimates for the larger CO<sub>2</sub> vessels. A factor of 35% has been added to the cost of LPG vessels to approximate the initial construction cost. Operating costs and voyage costs are also difficult to predict. However, estimates are made based, in part, on the costs of other liquefied carriers.

Using the model, a number of various cases have been implemented to see the effect of changing variables on the final output; these cases are identified in a sensitivity analysis. Recall that the model contains three cases: (1) a base case, (2) a case where the vessel returns with LNG, and (3) a case where the vessel returns with LNG from a third point along the route. Note that in the model, for this last case with the triangular route (Case 3), the distance between Points B and C has been set as 1/3 of the distance from A to B; for instance, for a route distance of 600 nautical miles, the distance from B to C is set at 200 miles.

Another feature of the model is LNG capacity, particularly important for Cases 2 and 3. If the user inputs a ship with a capacity of 30,000 m<sup>3</sup>, it is assumed that half of this capacity is devoted to LNG and the other half is devoted to CO<sub>2</sub>; unique tanks are used. This is due to the extensive time that is necessary for cleaning non-unique tanks. Thus, a ship in Case 2 can carry only half as much as the same size ship in Case 1. When the final cost for each scenario is displayed (in costs per tonne), this indicates the cost of moving one tonne of either CO<sub>2</sub> or LNG. In other words, the capital, operating, and voyage costs are spread out over all of the tonnes moved annually.

However, when a tug-barge carries out Case 2, unique tanks are *not* used; instead, the barge is purged after delivering its CO<sub>2</sub> cargo to the offshore site. Exact data on tank-cleaning costs is unavailable, since no dual CO<sub>2</sub> carriers exist that would require any measures to ensure

the purity of LNG cargo as well. In order to be conservative, a value of \$2.50 per cubic meter is assigned to the cost of tank cleaning.

Intermediate on-shore storage of carbon dioxide is another necessary facet of the marine transportation model. The ratio of land storage to vessel size in this model is set to 2.5, a typical ratio for LNG trades (Lewis). For example, if the vessel capacity is 20,000 m<sup>3</sup>, then the land storage capacity must be at least 50,000 m<sup>3</sup>. In reality, shore-based storage tanks in use today have a certain capacity, and only a discrete number of them could be used. However, in the model, the tank costs are modeled as a continuous variable, in order to avoid awkward bumps in the results. (It is assumed that in any CCS project, tanks would be custom-built to the correct size to accommodate the necessary intermediate CO<sub>2</sub> storage.) Furthermore, in the tug-barge scenario, less intermediate storage is unnecessary because some of the barges can be used to hold the cargo, until they are ready to be shipped to the sequestration site.

A final note about the model: in each case, carbon capture costs (\$50/tonne) and sequestration costs (\$10/tonne) are constant, as these are industry estimates (Mohan). Thus, before any marine transportation costs are estimated, the cost per tonne of CCS is already \$60/tonne. Model results will be reported with these capture and sequestration costs included, of which the user should be aware.

### 6.3 Basic Scenario

For this initial analysis, a set of parameters similar to the existing trade of the *Coral Carbonic* were chosen to get a reasonable idea of the cost of current carbon dioxide transportation systems. Since its yearly CO<sub>2</sub> delivery is unknown, this figure was set at 225,000 tonnes per year, a relatively low value compared to shore-based power plants, but more realistic for the *Coral Carbonic's* beverage CO<sub>2</sub> trade. (This annual output of 225,000 tonnes also fully optimizes the capacity of the 1250-m vessel in Case 1.)

The following table displays the parameters selected, and results in annual cost of \$25 million. A breakdown of these costs is displayed in the pie chart below.

Table 2: Initial Parameters

Item	Value
Yearly CO <sub>2</sub> Output	225,000 tonnes
Ship Capacity	1250 m <sup>3</sup>
Route Distance	360 nm (one-way)
Fuel Cost	500 \$/tonne

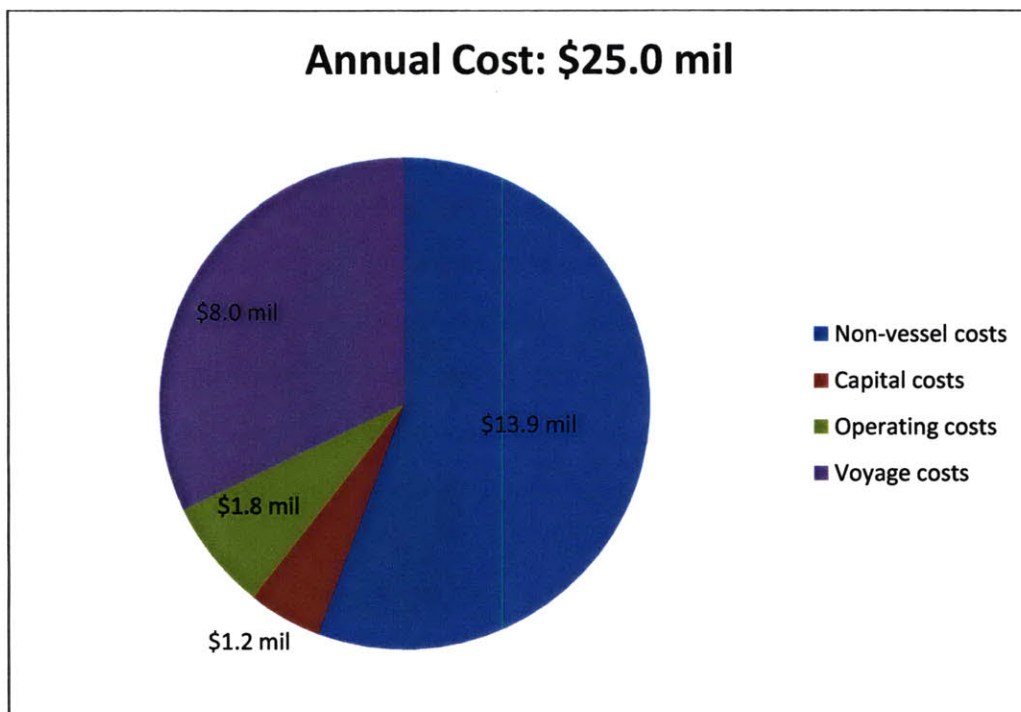


Figure 19: Cost Breakdown, Basic Scenario

With such a low volume of CO<sub>2</sub> moved and such small ships, the majority of the overall cost (56%) goes into the non-vessel costs. Recall, the *Coral Carbonic's* route is an example of a Case 1 scenario: delivering CO<sub>2</sub> in one direction without the capability to handle LNG. In Case 1, the current cost is quite expensive: \$111.2 per tonne of CO<sub>2</sub>.

For a CCS system, the costs would need to be significantly lower to approach the range of carbon pricing (projected from \$40 - \$64 per tonne of CO<sub>2</sub>, as shown in Figure 1). To achieve a cost reduction, it would be reasonable to look at a number of cost components; the first option is to increase vessel capacity and evaluate the effect of economies of scale.

#### 6.4 Altering Ship Capacity

With the low volume explored in the previous section, it was reasonable to use a correspondingly small ship. However, the CO<sub>2</sub> output from a large shore-based power plant produces is significantly greater than the amount necessary for the beverage industry. Table 1, for instance, showed that there at least one thousand power plants worldwide with yearly emissions exceeding 1 million tonnes.

For the following analysis, the CO<sub>2</sub> output is initially set to 6 million tonnes annually, or about 16,500 tonnes daily. To investigate the effects of varying ship capacity, the following parameters were used. Ship capacity was varied from 1250 to 100,000 m<sup>3</sup> (these values are converted into tonnes accordingly in the model using the density of CO<sub>2</sub> liquid, 1167 kg/m<sup>3</sup>).

Table 3: Inputs, Varying Ship Capacity

Item	Value
Yearly CO <sub>2</sub> Output	6 million tonnes
Ship Capacity	1250 – 100,000 m <sup>3</sup>
Route Distance	360 nm (one way)
Fuel Cost	500 \$/tonne

The figure below demonstrates the necessary number of vessels in Cases 1 and 2 as ship capacity increases. (Case 3 is not shown because it yields an almost-identical curve as for Case 2.)

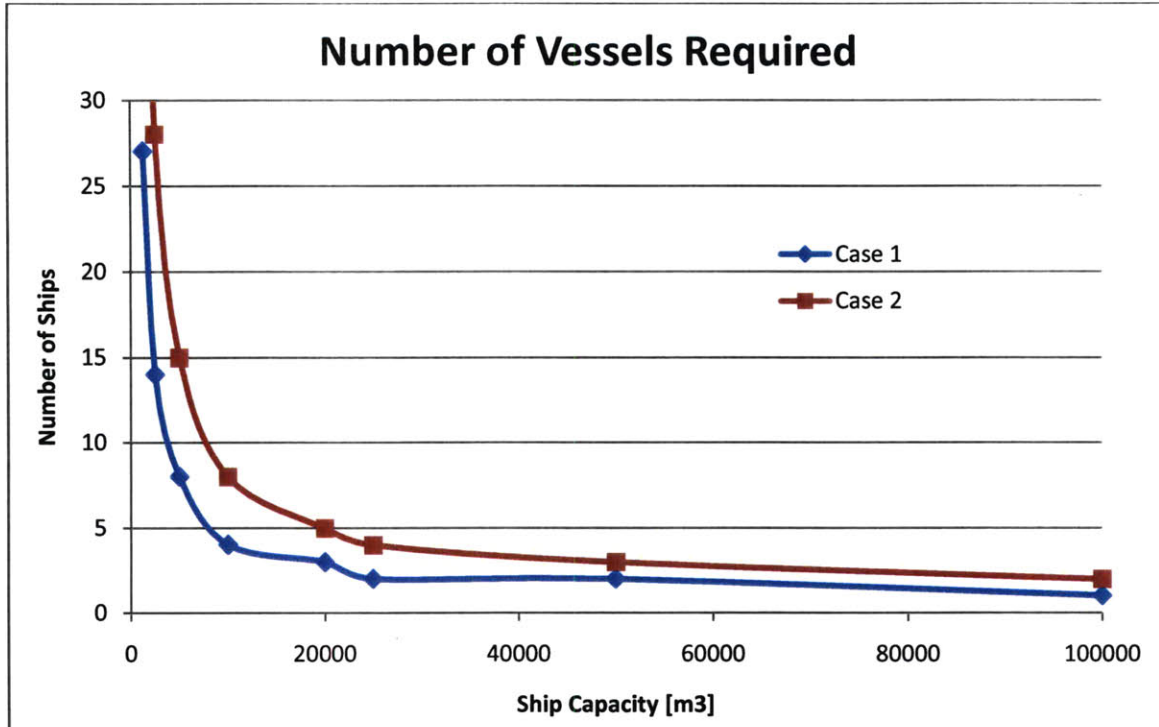


Figure 20: Effect of Varying Vessel Size on Fleet Size

(The data points for the 1250-m<sup>3</sup> vessel are not displayed since they are far off the graph; Case 1 would require 27 of these small vessels, while Case 2 would require 54.)

Overall, as the ship capacity increases, the annual output of 6 million tonnes of CO<sub>2</sub> can be handled with fewer vessels. If extremely large vessels of 100,000-m<sup>3</sup> capacity are built, only 1 vessel (in Case 1) or 2 vessels (in Case 2) are necessary. One of the most important points is that in each case, twice as many vessels are required in Case 2 as in Case 1. Inherently, this makes sense, because only half of the tank capacity in Case 2 vessels is devoted to CO<sub>2</sub>, while the other half is used for a liquefied gas backhaul cargo.

Rather than using the same-sized vessel in Cases 2 and 3 (and thereby requiring twice as many ships), another possibility is to use vessels twice the size of Case 1 vessels, which would deliver the same amount of CO<sub>2</sub> per trip. By using larger vessels in Cases 2 and 3, economies of scale from vessel size could potentially be realized. To gauge the benefit of using larger vessels, the effect of varying vessel capacity on each case is analyzed. The figure shown below demonstrates the decreasing transportation cost as larger vessels are used in Case 1.



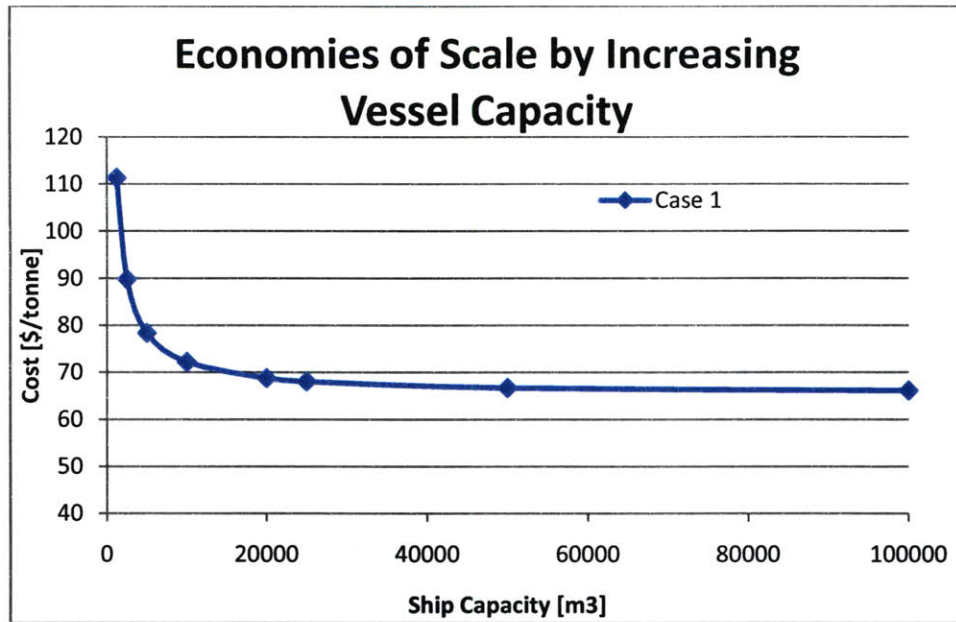


Figure 21: Effect of Varying Vessel Size on Case 1

As larger ships are used, the cost per tonne of transporting CO<sub>2</sub> is reduced in Case 1, leveling out around \$66 per tonne. It is clear from the figure that the economies of scale have been almost fully realized with the 50,000-m<sup>3</sup> vessel. When doubling capacity from 50,000 to 100,000 m<sup>3</sup>, the cost drops by only an additional \$0.5 per tonne of cargo. Thus, for the remainder of the analysis, there is no reason to continue analyzing such a large vessel, especially since the largest liquefied CO<sub>2</sub> vessels in existence today are less than 5,000 m<sup>3</sup>. In addition, the 100,000 m<sup>3</sup> ships would appear to involve unnecessary risks in construction and operating costs as well as with limited flexibility of use.

To display the associated economies of scale in Cases 2 and 3, the following chart is used. This time, a vessel in Case 1 is compared with a differently-sized vessel (twice as large) in Cases 2 and 3, since they both carry the same amount of CO<sub>2</sub> per voyage.

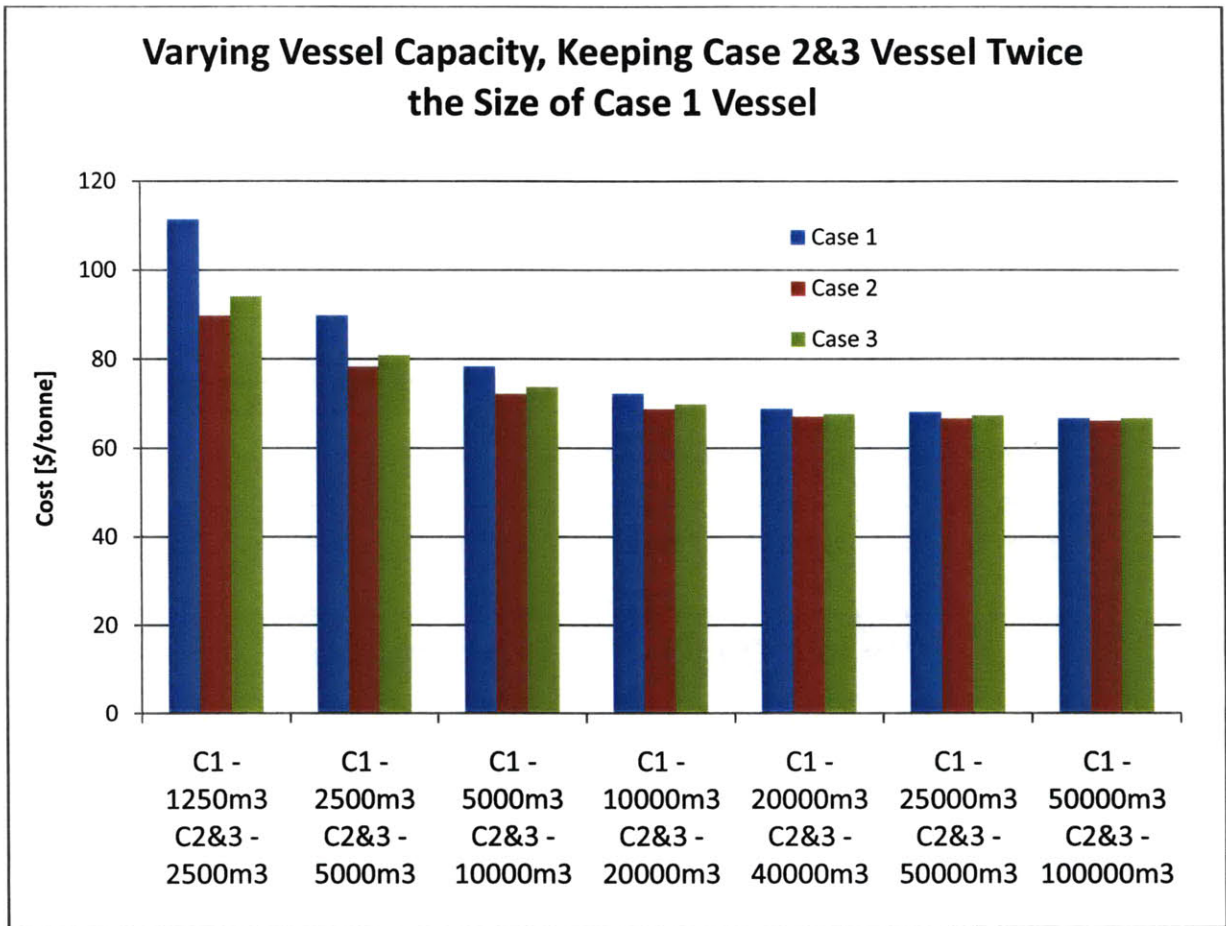


Figure 22: Effect of Varying Ship Size; Case 2&3 Vessel Twice the Size of Case 1 Vessel

It is clear that the same trends occur in Cases 2 and 3 as in Case 1; furthermore, the costs per tonne for Cases 2 and 3 are even lower than the cost for the Case 1 vessel. Thus, there are economies of scale from using the larger vessels in Cases 2 and 3 (rather than twice as many same-sized vessels). In future comparisons, it is reasonable to compare a given vessel in Case 1 with a vessel in Cases 2 and 3 that is twice its size.

## 6.5 Altering Annual CO<sub>2</sub> Emissions

Since the major goal of carbon capture and sequestration is to remove as much CO<sub>2</sub> from the atmosphere as possible, it is interesting to look at power plants with varying volumes of carbon dioxide output per year. From the ship capacity analysis, a smaller ship is selected for Case 1 with a capacity of 10,000 m<sup>3</sup>, and yearly CO<sub>2</sub> output is varied from 2.5 million tonnes per

year to 100 million tonnes per year. As discussed, it is appropriate to compare the costs of this vessel with vessels twice as big in Cases 2 and 3; thus, a 20,000-m<sup>3</sup> vessel is used for these two cases. The other inputs are shown in the table below.

Table 4: Inputs, Varying Annual CO<sub>2</sub> Output

Item	Value
Yearly CO <sub>2</sub> Output	2.5 million – 100 million tonnes
Ship Capacity	10,000 m <sup>3</sup> for Case 1 20,000 m <sup>3</sup> for Cases 2&3
Route Distance	360 nm (one-way)
Fuel Cost	500 \$/tonne

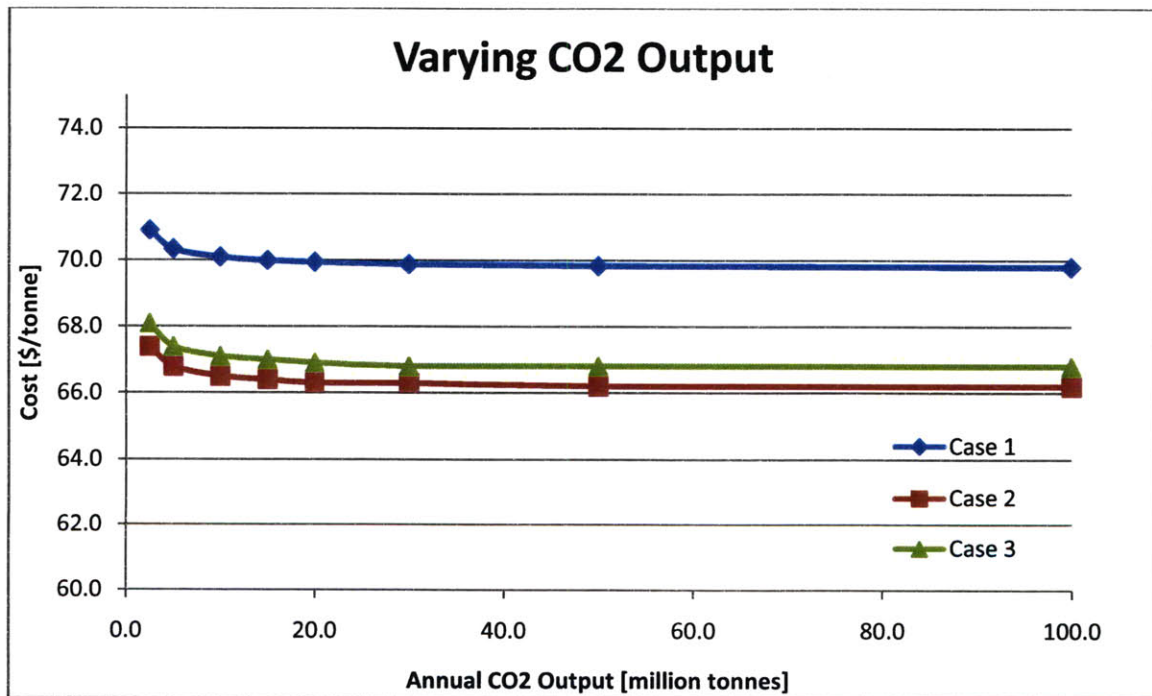


Figure 23: Effect of Varying CO<sub>2</sub> Output; Case 1 - 10,000 m<sup>3</sup>, Cases 2 & 3 - 20,000 m<sup>3</sup> Vessel

As more CO<sub>2</sub> is transported annually, the cost per tonne decreases very minimally. It is evident that the cost of transport levels off in each case, even with extraordinarily large volumes like 100 million tonnes of CO<sub>2</sub> annually. (Because the shore-based storage is fixed at 2.5 times the vessel capacity, increasing the throughput results in lower costs per tonne

moved.) The cost for Case 1 at 100 million tonnes annually is \$69.8 per tonne CO<sub>2</sub>, versus Cases 2 and 3, which level off lower around \$66.5 per tonne of cargo.

As Phase 2 looms in the future, the possibility of using larger vessels becomes more likely. For a 40,000-m<sup>3</sup> vessel with the same inputs, the trends are the same: virtually horizontal lines, just at lower costs per tonne. For all vessel sizes, there is very little, if any, effect of varying the CO<sub>2</sub> output of the plant on the transportation cost per tonne. Clearly, the economies of scale are present in the size of the vessel, not the volume of the power plant's emissions.

## 6.6 Altering Route Distance

An important issue in a CCS project is the distance between capture site and sequestration site; the shorter the distance, the less time and lower fuel costs. For this analysis, this distance is first varied to gauge the effect on cost. Then, the location of the intermediate point (which is only present in Case 3) is altered to see if Case 3 remains economically competitive. In one possible scenario, the yearly CO<sub>2</sub> output is set at 6 million tonnes and the ship capacity for Case 1 is kept at 10,000 m<sup>3</sup> and 20,000 m<sup>3</sup> for Cases 2 and 3. (This represents a plausible situation for a Phase 1 project (i.e. the demonstration phase), with a relatively small vessel and a medium amount of yearly CO<sub>2</sub> emissions.) Route distances are varied from a short six-hour, one-way trip of 90 nautical miles, to a long voyage of 2400 nautical miles. The results are as follows:

Table 5: Inputs, Varying Route Distance

Item	Value
Yearly CO <sub>2</sub> Output	6 million tonnes
Ship Capacity	10,000 m <sup>3</sup> for Case 1 20,000 m <sup>3</sup> for Cases 2&3
Route Distance	90 – 2400 nautical miles (one-way)
Fuel Cost	500 \$/tonne

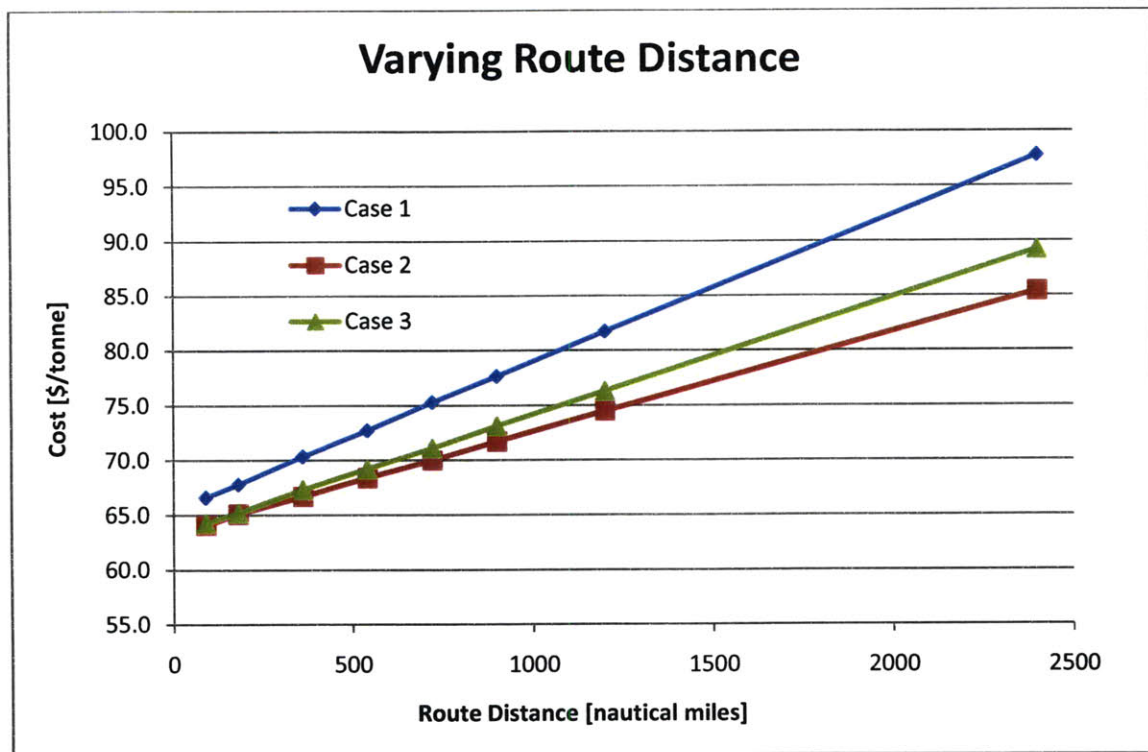


Figure 24: Effect of Varying Route Distance; Case 1 - 10,000 m<sup>3</sup>, Cases 2 & 3 - 20,000 m<sup>3</sup> Vessel

As is expected, as the route distance increases, the cost of transportation increases significantly. Additionally, the number of vessels in the fleet expands considerably throughout this range: for the distance of 90 nm, 2 vessels are necessary in Case 1; at 2400 nm, 21 ships are required. In Case 2 (which has 20,000-m<sup>3</sup> vessels), 3 vessels are necessary for 90 nm, and 22 for 2400 nm – roughly the same fleet sizes as Case 1. In Case 3 with a one-way distance of 2400 nm, 25 vessels are required.

Notably, as the route distance increases, Case 3 (whose 3<sup>rd</sup> leg is set at one third of the distance from coastal power plant to offshore sequestration site) becomes less viable in comparison to Case 2 as additional vessels are required. Since Case 2 uses roughly the same number of vessels as Case 1, the effect of varying the route distance causes similar cost increases, which is seen as the two cases have similar slopes in the figure above.

Using this same scenario, the viability of Case 3 is explored by varying the distance between the sequestration point and the gas pick-up point (called Leg 3 in the model). Heretofore, this number had been set at one-third of the distance from shore-based power



plant to sequestration site. Now, the route distance is set to 1200 nautical miles, and Leg 3 is varied. The resulting cost differences between Case 2 and Case 3 are then reported.

Table 6: Inputs, Varying Leg 3 Distance

Item	Value
Yearly CO <sub>2</sub> Output	6 million tonnes
Ship Capacity	20,000 m <sup>3</sup> (for Cases 2&3)
Route Distance	1200 nm (one-way)
Fuel Cost	500 \$/tonne
<b>Leg 3 Distance</b>	<b>0 – 1200 nautical miles</b>

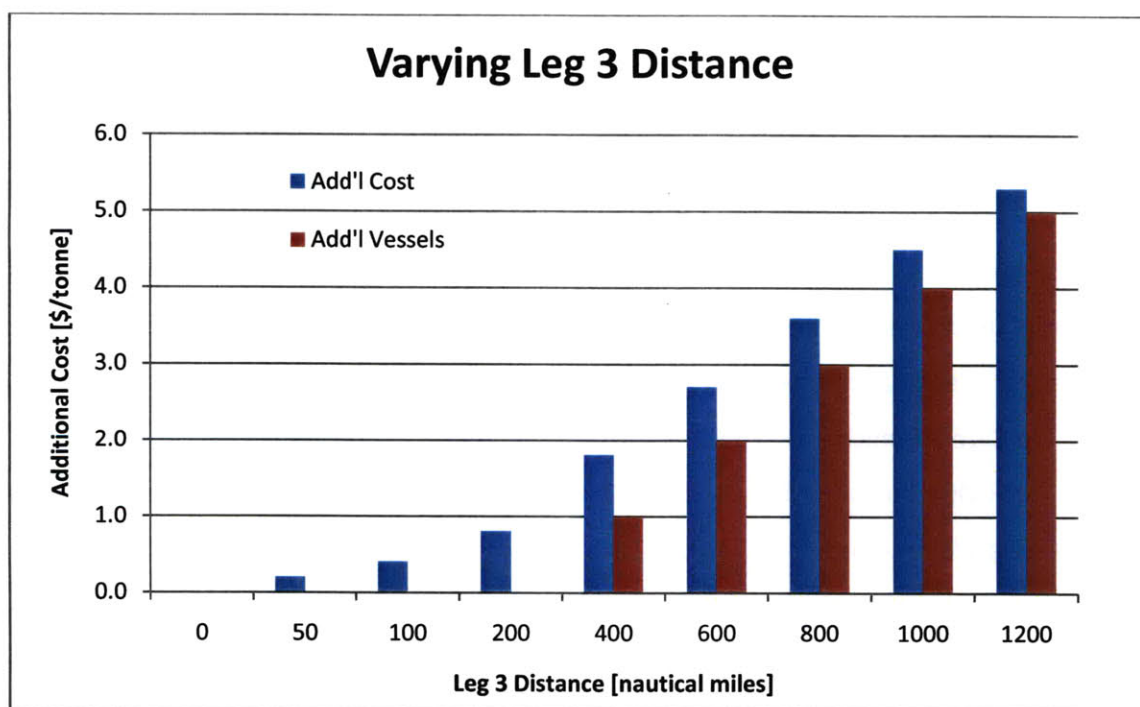


Figure 25: Effects of Varying Leg 3 Distance on Case 3 Cost

In this scenario, additional vessels become necessary as the Leg 3 distance increases, and the cost per tonne also increases significantly. Clearly, keeping the Leg 3 distance as short as possible is the most economically-practical strategy.

## 6.7 Altering Fuel Cost

Heretofore, fuel has been held constant at \$500 per tonne, but due to its fluctuating nature, large increases in price may carry corresponding increases in voyage costs. A possible Phase 1 scenario is identified below, again with a smaller vessel for Case 1 (10,000 m<sup>3</sup>), a vessel twice as big for Cases 2 and 3 (20,000 m<sup>3</sup>), and a carbon dioxide output of 6 million tonnes; the fuel price is varied. (Note that the Leg 3 distance for Case 3 has been re-set at one-third of the route distance.)

Table 7: Inputs, Varying Fuel Cost

Item	Value
Yearly CO <sub>2</sub> Output	6 million tonnes
Ship Capacity	10,000 m <sup>3</sup> – Case 1 20,000 m <sup>3</sup> – Cases 2&3
Route Distance	360 nautical miles (one-way)
Fuel Cost	100 – 1000 \$/tonne

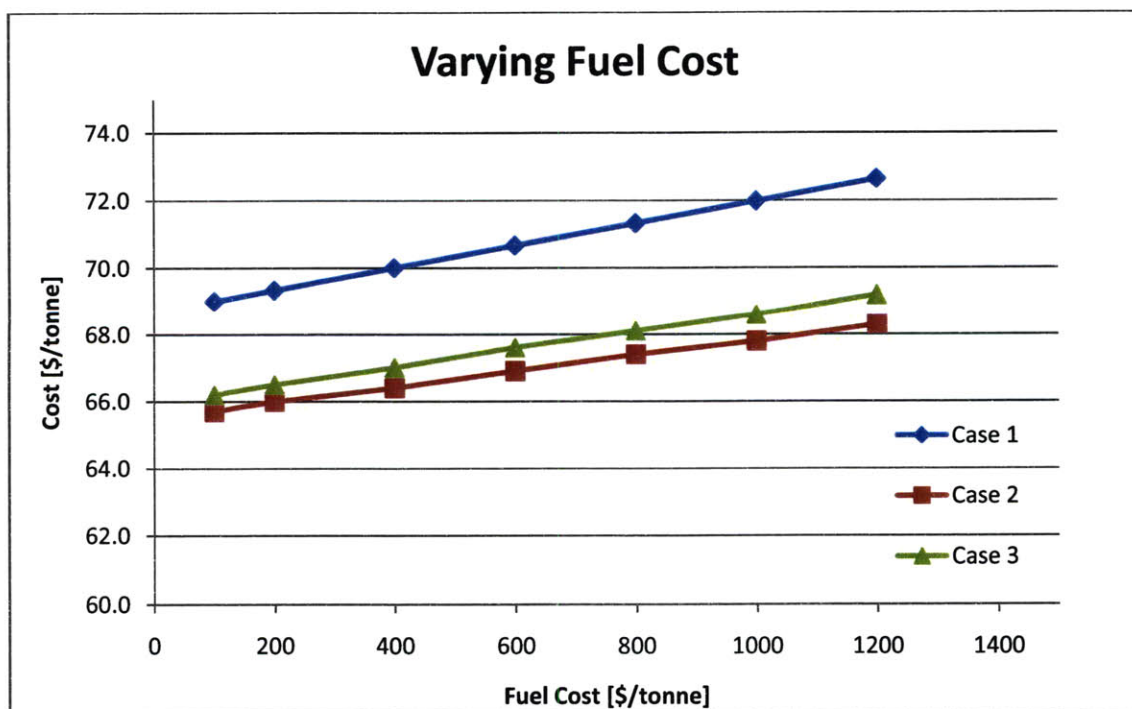


Figure 26: Effect of Varying Fuel Cost; Case 1 - 10,000 m<sup>3</sup>, Cases 2 & 3 - 20,000 m<sup>3</sup> Vessel

For the most part, the increase of fuel prices causes a linear increase in overall cost per tonne. In Case 1, for instance, the increase of fuel price from \$100 to \$1200/tonne yields an overall increase in overall prices from \$69.0 to \$72.6/tonne. Though difficult to see, there is an increasing gap between Cases 2 and 3; this difference in slope between Case 2 and Case 3 exists because the Leg 3 distance is set to 120 nautical miles. The slope of the line for Case 3 in the figure above would be steeper (for longer distances of Leg 3) or shallower (for shorter distances of Leg 3).

## **6.8 Tug-Barge**

For routes with short distances and in locations with predictably good weather, an alternative to building a tanker is to construct a tug and some barge units. One major difference is the construction cost of the tug and barges, which is slightly cheaper than that of a tanker. Another difference is the logistics of “drop-and-swap,” which shortens loading and unloading times while necessitating the presence of more barges than tugs.

In the model, the tug-barge scenario is especially attractive for Cases 2 and 3. With a tanker in Case 2, half of the capacity is devoted to CO<sub>2</sub> while the other half is devoted to LNG. Using a barge, the entire barge can be filled with CO<sub>2</sub> and simply dropped off at the sequestration site. Then, as the tug picks up another barge full of LNG, the first barge can be cleaned at the sequestration site, in preparation for being re-filled with a cargo of LNG. The barges themselves can be used as storage units as well, reducing the capacity needed for the shore-based intermediate CO<sub>2</sub> storage tanks.

Because tank-cleaning time is long and expensive, additional costs are included for tank cleaning within the tug-barge model. Recall that in the model, this figure is set at a relatively high value of \$2.50 per cubic meter of the tank, in order to be conservative. This value is used only for a tug-barge unit in Cases 2 & 3, where barges are cleaned before being loaded with a liquefied gas cargo.

To compare the tug-barge setup with a traditional tanker, the scenario shown in the following table was selected. The route distance is varied as before from 90 to 2400 nautical miles. The first comparison is made between the costs for a tanker and a tug-barge in Case 1, with results shown in the figure below.



Table 8: Inputs, Tug-Barge Analysis

Item	Value
Yearly CO <sub>2</sub> Output	6 million tonnes
Ship Capacity	10,000 m <sup>3</sup> for Case 1 Tanker and Case 1 & 2 Barges 20,000 m <sup>3</sup> for Case 2 Tanker
Route Distance	90 to 2400 nautical miles
Fuel Cost	500 \$/tonne

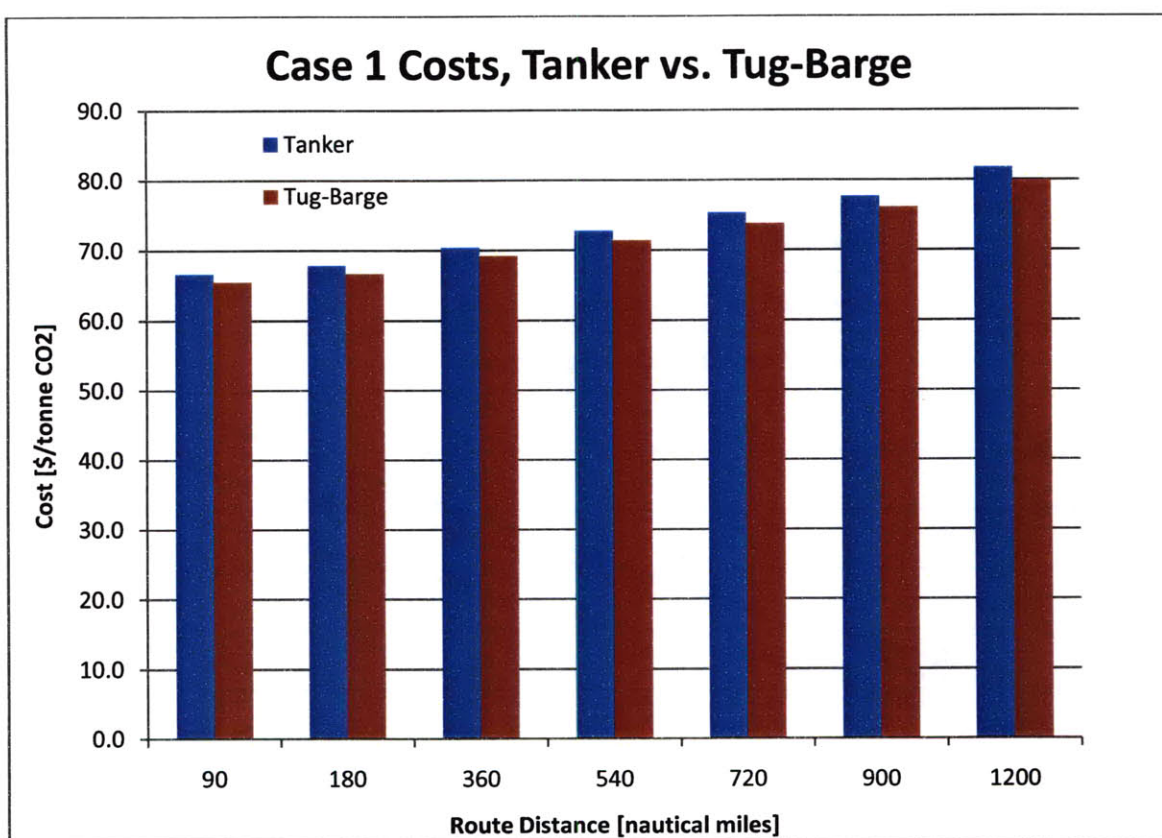


Figure 27: Effect of Varying Route Distance in Case 1, Tanker vs. Tug-Barge

This graph shows that the tug-barge is virtually the same as tanker, regardless of distance. The tug-barge unit is slightly cheaper than the tanker (roughly 85% of the initial cost), and does not require time at either point for loading or unloading of its carbon dioxide cargo; these two factors give it the small cost advantage over the tanker.

The real merit for using a tug-barge would be in Cases 2 or 3. The time required for loading and unloading the cargo on either end would be avoided by using multiple barge units. Furthermore, each barge unit can be solely devoted to a single cargo, whereas a tanker in Cases 2 or 3 must have half of its unique tanks devoted to each of its cargos. Accordingly, the model is updated to assume that the tug-barge is transporting both CO<sub>2</sub> and LNG. The tug-barge is set at a capacity of 10,000 m<sup>3</sup>, while the tanker in Cases 2 and 3 is set at 20,000 m<sup>3</sup>. Furthermore, two cases are run for the tug-barge to view the effect of tank cleaning costs. In one case, cleaning costs are set at \$2.50 per cubic meter; and in the other, the cleaning costs are a much lower value of \$0.50. Results are shown graphically below.

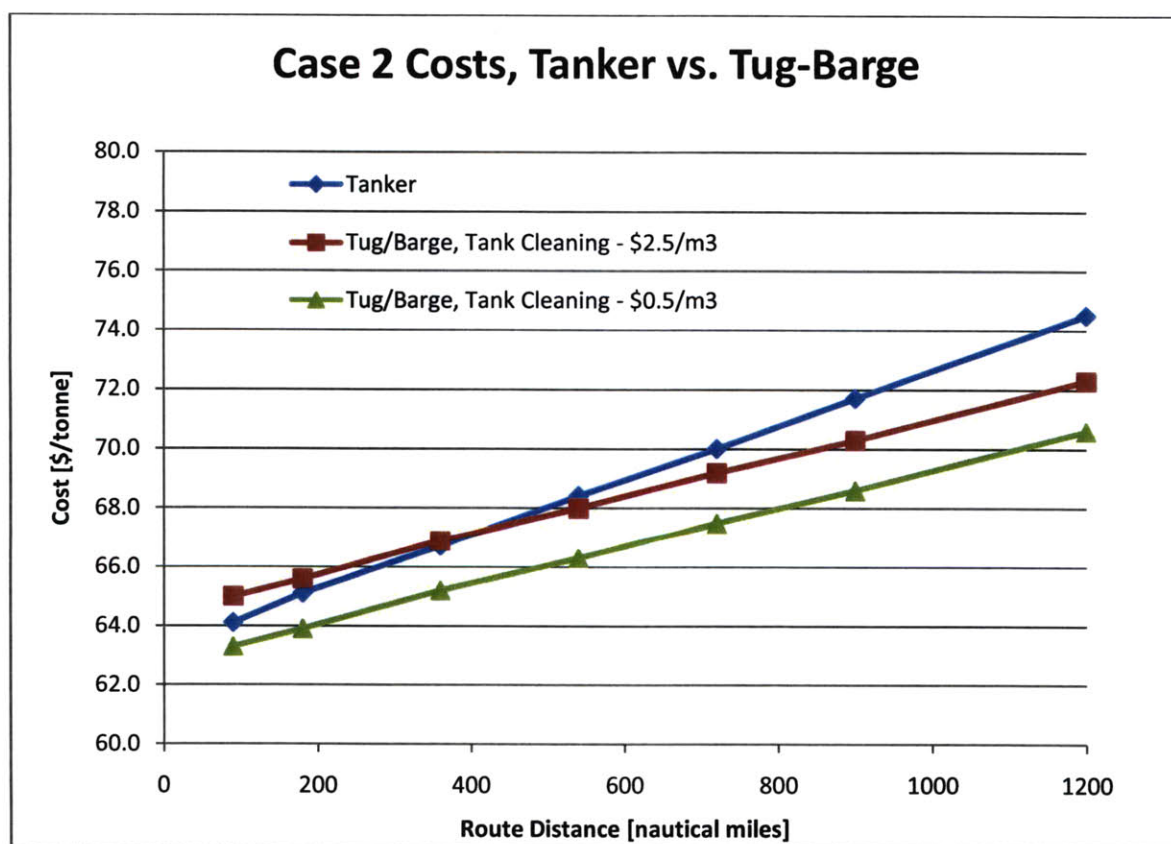


Figure 28: Effect of Varying Route Distance in Case 2, Tanker vs. Tug-Barge

(The Case 3 costs for both the tanker and tug-barge are not shown, since they are virtually the same as Case 2, just slightly higher, as was seen before in the tanker route distance sensitivity analysis.)

Although the tanker and tug-barge start out at similar costs for short distances, the tug-barge indeed becomes cheaper over longer distances. The slopes of both tug-barge options are less steep than that of the tanker. Due to the “drop and swap” capability of the tug-barge, no time of the tug-barge’s voyage is devoted to loading or unloading cargo, and thus less vessels are necessary; this advantage is exploited at longer route distances.

In the comparison between tug-barges, it is shown that the tank cleaning cost merely affects the starting point of the curve. Thus, even though the exact cost of tank cleaning per cubic meter is unknown, the cost for a tug-barge will always maintain that same slope as shown in the figure above as route distance increases. The cheaper the cost of tank cleaning, the more attractive an option the tug-barge becomes.

## **6.9 Conclusion**

In order to draw some conclusions about ideal conditions for a CCS project (and to gauge how close CCS is from Phase 2), a model was created with inputs for vessel size, yearly carbon dioxide output, distance from capture site to sequestration site, and fuel cost. The results from the analysis above indicate some conclusions for prospective CCS planners. After running a number of cases in the model, it is now possible to see where each case fits, vis-à-vis Phase 1 and Phase 2. It is convenient to redisplay the figure of the two phases that was introduced earlier, now with conclusions to be drawn about CCS economics.

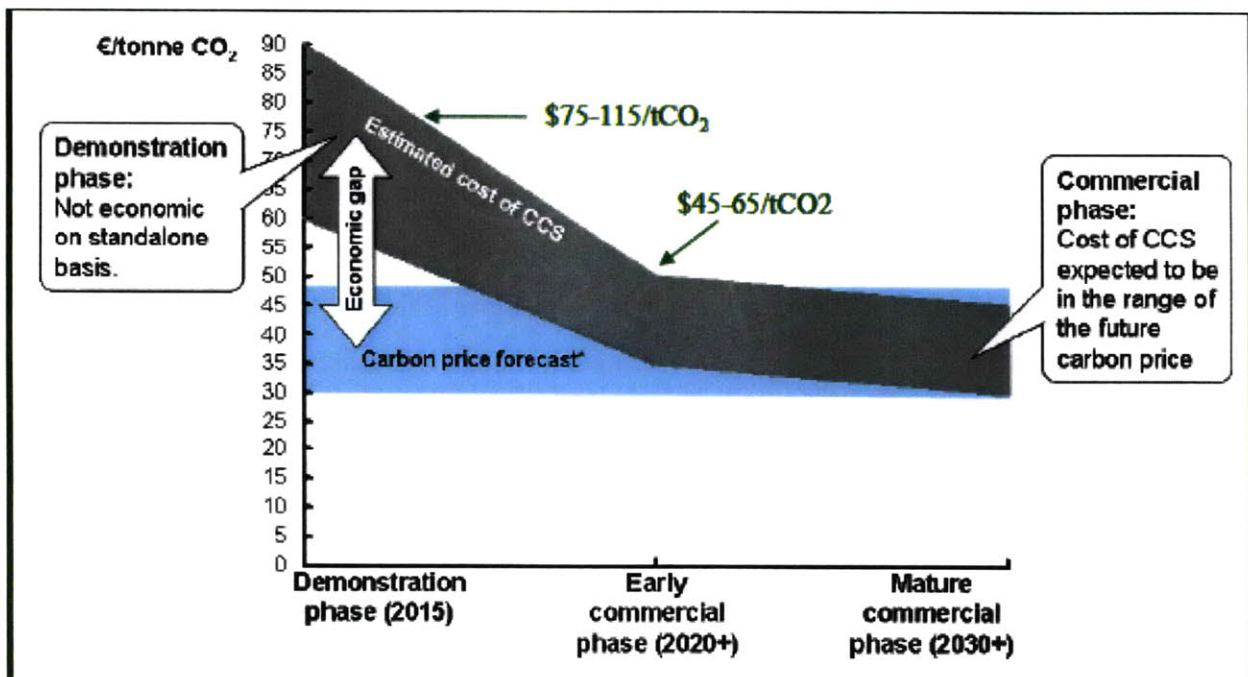


Figure 29: Economic Future of CCS Projects (Redisplayed)

Recall the projected costs of each phase: the demonstration phase and early commercial phase are shown in green, while the mature commercial phase (from 2030 onwards) is estimated at \$40 - \$60 per tonne of CO<sub>2</sub>. Future carbon pricing is projected from between 30 and 47 Euros per tonne, or \$40 - \$64 per tonne of CO<sub>2</sub>. As such, the current economic gap is at least \$12 per tonne of CO<sub>2</sub> (and that is only if the upper bound on the carbon price and the lower bound on the CCS cost are used in the calculation; otherwise, the economic gap is as much as \$75 per tonne).

The demonstration phase, Phase 1, consists of small-scale projects, particularly vessels with smaller capacities and low annual volumes of CO<sub>2</sub>. One such situation could use 5,000-m<sup>3</sup> CO<sub>2</sub> carriers to service a power plant annually outputting one million tonnes of CO<sub>2</sub>, with a one-way route distance of 360 nm. From the model, the resulting cost is \$77.2 per tonne of CO<sub>2</sub>, certainly still at the lower-cost end of Phase 1 in 2015. Revenue from EOR (which on average is about \$20 per tonne CO<sub>2</sub>) allow the cost to decrease to \$55.2 per tonne.

In contrast, larger ships and larger volumes bring a potential for economic success, and a resulting sustainable commercial phase. Assuming a larger vessel (50,000 m<sup>3</sup>) with the capacity to carry both CO<sub>2</sub> and LNG, and a greater carbon dioxide output (10 million tonnes

annually) over the same distance, the new cost becomes \$64.4 per tonne of cargo. Now this cost sits at the upper-cost end of Phase 2 in 2020. And with additional EOR revenue, the cost would drop even further, to \$44.4 per tonne.

The breakdown for each case of these last two scenarios is shown in the table below, with and without the added revenue from EOR. (Note that for the Phase 1 scenario, a 5,000-m<sup>3</sup> vessel is used for Case 1, and a 10,000-m<sup>3</sup> ship is used for Cases 2 and 3; for Phase 2, the ship sizes are 25,000 m<sup>3</sup> and 50,000 m<sup>3</sup>, respectively.)

Table 9: Effect of EOR Revenue on CCS Costs

	Cost [\$/tonne]		
	Case 1	Case 2	Case 3
<b>Phase 1</b>	77.2	70.9	71.9
<i>w/EOR</i>	57.2	50.9	51.9
<b>Phase 2</b>	66.2	64.4	64.8
<i>w/EOR</i>	46.2	44.4	44.8

In all cases, EOR revenue brings an additional \$20 per tonne, making an appreciable difference overall.

Figure 29 showed a so-called “economic gap” between the cost of CCS and future carbon pricing, which is initially projected from 30 to 47 Euros (or about \$40 - \$64) per tonne. It is interesting to plot the results from Table 9 and see how they compare with this carbon pricing projection. The figure below does precisely this, showing the cost of CCS for each phase and a carbon pricing of \$50 per tonne of carbon dioxide (which is towards the middle of the range predicted in Figure 29).



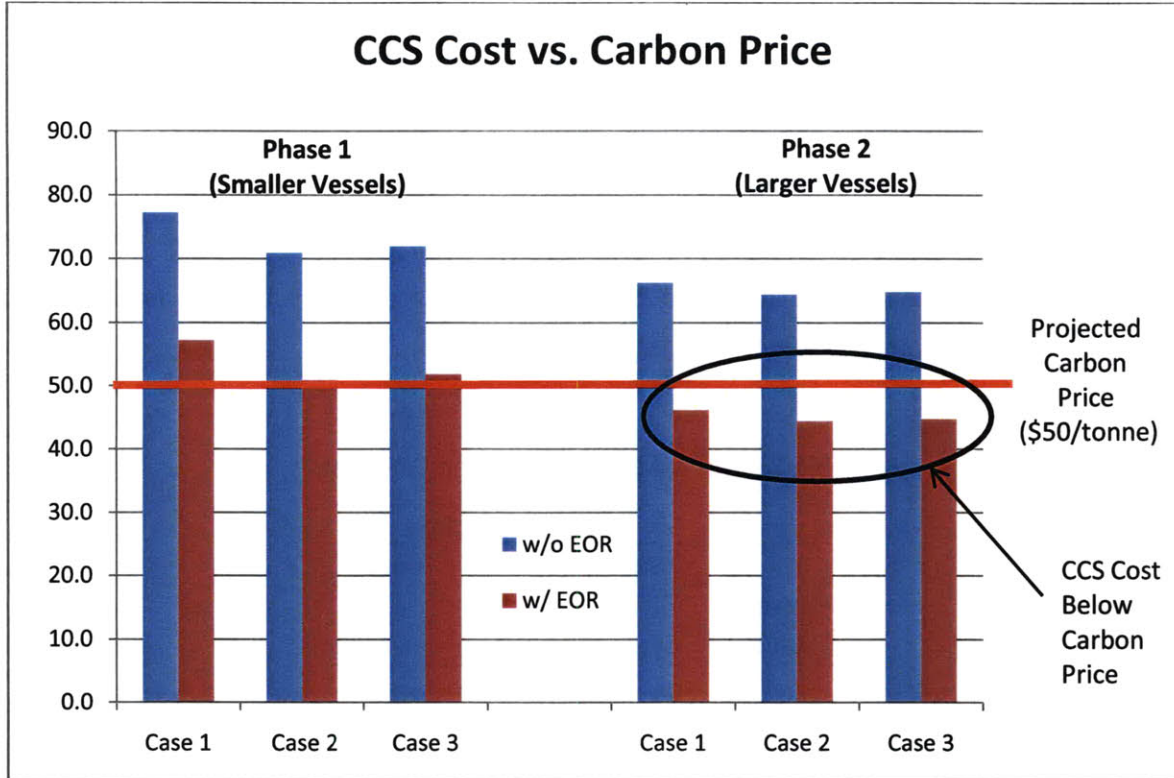


Figure 30: Cost of CCS during Phases 1 and 2, vis-à-vis Projected Carbon Price

The results follow the trends that are expected for Phase 1 and Phase 2 projects. The costs for Phase 1 are well above the carbon price; there is still an economic gap even with additional EOR revenue. Such small projects would require additional financial help, like a subsidy. As Phase 2 arrives, the costs continue to decrease; until, with EOR, all the cases actually cost less (roughly \$5 per tonne) than the projected future carbon price. Regardless of the precise carbon price in the future, these trends are still directionally accurate, matching the predictions from Figure 29.

The backhaul cargo of LNG in Cases 2 and 3 does significantly cut down the transportation costs of CCS. However, it is a small percentage of the overall costs, which include \$60 per tonne for carbon capture and sequestration. Thus, carrying a backhaul cargo does not significantly reduce the overall CCS costs. Instead, a better way to reduce overall costs is to use the carbon dioxide for enhanced oil recovery. In all cases in Phase 2, the presence of EOR revenues reduces the CCS cost per tonne by roughly 30%. Ultimately, EOR is very important to the financial success of CCS projects.

Another cost comparison can be made to validate the model – this time to the prediction of shipping vs. pipeline costs made earlier. Again, this figure is redisplayed below so that conclusions can now be drawn from it.

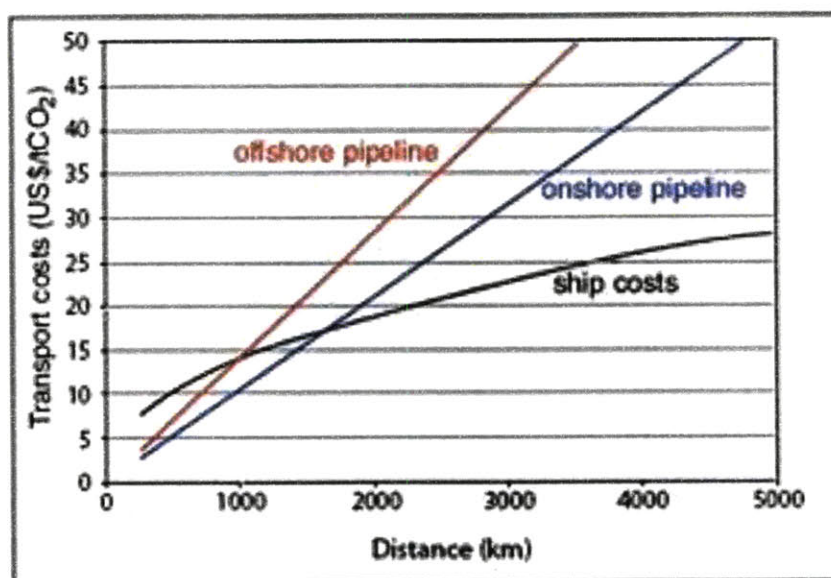


Figure 31: Pipeline vs. Ship Costs (Redisplayed)

The figure predicts that ship transport costs become cheaper than offshore pipeline costs for distances of 1000 kilometers (540 nautical miles), at a cost of roughly \$15 per tonne of CO<sub>2</sub>. Using the model, a scenario was set up with a route distance of 540 nm, an annual CO<sub>2</sub> output of one million tonnes, and a vessel size of 10,000 m<sup>3</sup>. For Case 1, the cost from the model is \$75.3 per tonne, indicating that the transportation cost is \$15.3 per tonne (*i.e.*, \$75.3 minus the constant \$60 for capture and sequestration). Other model data points directionally follow the curve shown in the figure above for ship costs. Thus, the model is an excellent tool to get an idea of CO<sub>2</sub> transportation costs for a various set of inputs, as it has matched up well with the McKinsey model and the ship vs. pipeline model.

Throughout the analysis, the difference in costs between Case 1 and Case 2 is present, indicating that using LNG in the backhaul, or a similar liquid gas, makes the whole operation cheaper. This is one of the biggest advantages a ship has over pipelines: a ship can carry a different cargo back during its return voyage. This advantage should be exploited if possible, if marine transportation is selected. But even though a backhaul of LNG would help lower the

cost of transportation, in reality it would be a very complicated system to enact logistically. First of all, the timing for loading and unloading both cargos at both sites would need to be aligned to ensure quick turn-around times. The volumes of CO<sub>2</sub> and LNG would need to be roughly equivalent, and there would need to be a demand for each cargo as well. Overall, though promising, a liquefied gas backhaul would require a very special set of conditions.

Tug-barges are another option that could potentially reduce the CO<sub>2</sub> transportation cost. For Case 1, a tug-barge does not require the additional loading and unloading times of a tanker, and thus always brings a lower cost than the tanker in Case 1. In Case 2, if the cost to clean a CO<sub>2</sub> tank is not too expensive, the tug-barge system may be less expensive than the associated tanker, especially over longer distances. (However, tankers may be more reliable as the route distance increases.)

As newer technologies are developed for CCS, the costs of capture (here, \$50 per tonne) and sequestration (\$10 per tonne) may also decrease significantly. Such technologies would significantly help the arrival of Phase 2. For instance, if a small-scale Phase 1 project is successful, additional funding would likely be set aside for subsequent research to develop new, cheaper techniques for capture and sequestration. This demonstrates yet another field where successful Phase 1 projects lead to an eventual commercial phase.



## 7 Conclusions and Recommendations

### 7.1 Conclusions

A large number of uncertainties exist as to the future of marine transportation as part of carbon capture and sequestration (CCS) systems. Key issues include:

- National and international environmental policies affecting greenhouse gases in general and CCS in particular.
- Characteristics of specific origin and offshore destination sites for CCS.
- The cost of pipeline versus vessel systems, both today and in the future.
- Future decline in the costs of carbon capture and sequestration.
- Potential future revenue from enhanced oil recovery (EOR) or possibly enhanced gas recovery (EGR).
- Potential for bringing another liquefied gas, such as LNG, back from the destination site to be used as fuel in the power plant creating the carbon dioxide.

While it will take many years to resolve these issues, the current conclusions of this report are:

- All technological challenges to using liquefied CO<sub>2</sub> carriers (and even dual CO<sub>2</sub>/LNG carriers) in a CCS system can be resolved.
- Certain characteristics of origin-destination pairs could make these routes more favorable to vessels than to pipelines.
- In the near future, such liquefied CO<sub>2</sub> carriers must rely on government incentives and/or subsidies in order to operate.
- In the long-term, liquefied CO<sub>2</sub> carrier systems with some combination of larger vessels, EOR, and backhauls of another liquefied gas could make these systems economically viable.

It is helpful to refer to the figure below, not because it predicts the future with precise accuracy, but because it sets out a framework for discussion. The figure considers pipelines as part of the CCS, but the future trends will be the same with vessels. The Demonstration Phase, which is termed Phase 1, will go from the present time until CCS is commercially viable, hopefully by 2020. Until that time, all CCS must rely on government regulations in the form of subsidies, incentives, or carbon taxes in order to operate. In Phase 2, the Commercial Phase, costs for CCS have decreased overall enough to make the system commercially viable.

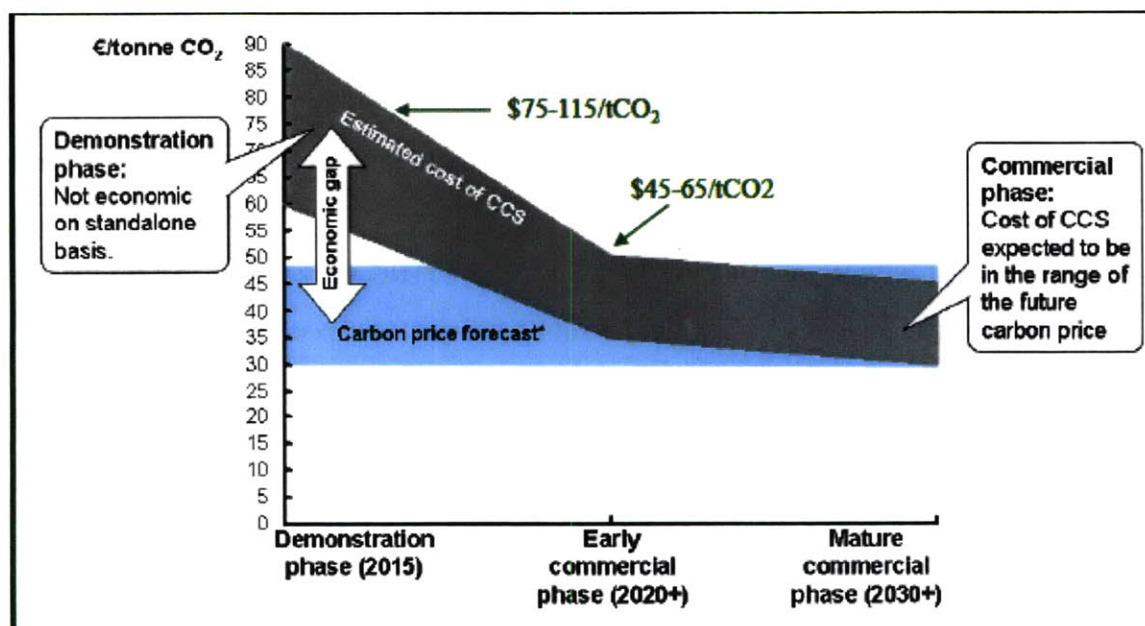


Figure 32: Economic Future of CCS Projects (Redisplayed)

After running a number of cases in the model, it is now possible to see where each case fits, vis-à-vis Phase 1 and Phase 2. The Demonstration Phase, Phase 1, will consist of small-scale projects, particularly vessels with smaller capacities and low annual volumes of CO<sub>2</sub>. One such situation could use 5,000-m<sup>3</sup> CO<sub>2</sub> carriers to service a power plant annually outputting one million tonnes of CO<sub>2</sub>, with a route distance of 360 nm. From the model, the resulting cost is \$77.2 per tonne of CO<sub>2</sub>, certainly still at the lower-cost end of Phase 1 in 2015. Revenue from EOR (which on average is about \$20 per tonne CO<sub>2</sub>) would allow the cost to decrease to \$55.2 per tonne.

In contrast, larger ships and larger volumes bring a potential for economic success, and a resulting sustainable Phase 2, the Commercial Phase. Assuming a larger vessel (40,000-m<sup>3</sup>) with the capacity to carry both CO<sub>2</sub> and LNG, and a greater carbon dioxide output (10 million tonnes annually) over the same distance, the new cost becomes \$64.4 per tonne of cargo. Now this cost sits at the upper-cost end of Phase 2. And with an assumed \$20 per tonne from EOR revenue, the cost drops even further to \$44.4 per tonne. But before this commercial phase is reached, the demonstration phase with its smaller vessels must be tried and proven worthwhile.

The difference in costs between Case 1 and Case 2 is significant, and indicates that using LNG in the backhaul, or a similar liquid gas, makes the whole operation less expensive. This is one of the biggest advantages a ship has over pipelines: a ship can carry a different cargo back during its return voyage. This advantage should be exploited if at all possible, if marine transportation is selected. However, the difficulties in putting together such an arrangement are formidable. Not only must the appropriate gas be available at the destination in the appropriate volume, but the origin must be able to use the backhaul cargo in its power plant. The timing of all these factors during the life of the project is extremely challenging.

Furthermore, the presence of a backhaul cargo (in Cases 2 and 3) does save a considerable amount of money in the transportation costs; but overall, when included with much higher costs of carbon capture and sequestration (\$60 per tonne of CO<sub>2</sub>), this advantage is not nearly as significant. Instead, the revenue from EOR is much more beneficial for lowering CCS costs, reducing the CCS cost per tonne roughly 30% in each Case in Phase 2. EOR is a very attractive option for CCS projects to realize commercial success.

The issues of regulation, market sizing, vessel technology, and overall economics together determine where CCS stands; all four are strongly interrelated. For instance, choosing a power plant with the highest CO<sub>2</sub> emissions (a market sizing issue) may address the greenhouse gas issue, but it may not be possible if the existing CO<sub>2</sub> tankers are not large enough (a vessel technology issue). Likewise, a small project with a short distance and favorable capture and sequestration costs (an overall economics issue) may not qualify for a

subsidy because it does not have a large-enough scope (a market sizing issue *and* a regulation issue).

CCS is simply not economically competitive yet, and probably will not be for years to come. But if small-scale, demonstration projects are enacted now and can find success, it is probable that CCS will eventually see a commercial phase with larger vessels, larger volumes, and hopefully a larger effect overall on the reduction of CO<sub>2</sub> emissions.

## 7.2 Recommendations

For a potential stakeholder in a CO<sub>2</sub>-vessel project, the following recommendations are offered in Phase 1:

**Public Policy.** Observe the national level of determination to reduce carbon dioxide emissions. Consider whether CCS is generally accepted as being equivalent to alternative energy sources that do not create carbon dioxide.

**Policy/Regulatory Implementation.** Observe the current and projected levels of carbon tax to be paid by power plants as well as the potential subsidies and incentives for CCS. Consider whether all regulatory and liability hurdles have been removed.

**Origin-Destination Pair.** Determine the best origin-destination pair. Ideally, no new docking facilities will be needed at the origin and no new unloading facilities will be required at the destination. In the best case, the CO<sub>2</sub> can be sold to implement enhanced oil recovery. The origin-destination pair should be one that cannot be easily served by a pipeline, at least in the foreseeable future.

**Vessel Construction and Operation.** Analyze the best alternatives for shipyards and sources of crew. Experience with liquefied gas projects is greatly preferred.

In Phase 2, the potential stakeholder must not only deal with the above factors, but also consider how to take advantage of economies of scale with larger vessels. Long-term contracts for the use of the vessel and vessel financing as part of the overall project are prerequisites. One should also consider whether the unique characteristics allowing for a backhaul of another liquefied gas exist, so that a liquefied gas, such as LNG can be returned to the origin to be used

in the power plant creating the carbon dioxide. Another recommendation here for CCS planners is to pay attention to new technologies in the CO<sub>2</sub>-treatment sector: as new methods are perfected for the capture and sequestration of carbon (currently at \$50 and \$10/tonne CO<sub>2</sub>), these costs will become cheaper. Also, keep a watch on oil prices; as the revenue from enhanced oil recovery increases, CCS becomes increasingly economically viable.

Potential CO<sub>2</sub> vessel projects as part of CCS systems involve many factors with significant uncertainties. However, if one carefully follows developments in this area, opportunities may present themselves.



## **Appendix A: Model User Manual**

The following provides instructions for use of the model as well as a description of each spreadsheet tab.

### **A.1 Opening the Model**

The model was created using Microsoft Excel. To preserve the original model file, open the model and save a copy named “Original Model” or another name that identifies the original copy. (A CD with a copy of the original model will be provided with the final report to ensure that an original copy is retained.) Every time the model is run, choose to “Save As” under a different name, such as “Model – May 1” or “Model – Varying Ship Capacities,” to identify changes made to the model.

### **A.2 Entering User Inputs**

The tab entitled User Inputs is used to update the model for various cases; here the user can alter distances between origin and destination, the amount of CO<sub>2</sub> to be transported annually, the current fuel cost, and the ship capacity in cubic meters. If there are only two points on the route (*i.e.* one origin and one destination, as in Case 1 and Case 2), the user should input ‘0 nautical miles’ for the third leg. Once all inputs are entered correctly, the user can then look immediately below at the “Costs” displayed in light blue to see the cost per tonne of cargo moved. To view a more complete cost breakdown, the user should look at the Costs spreadsheet.

### **A.3 Viewing Model Results**

The Costs spreadsheet shows the results of the analysis calculations, ultimately giving a final value for the cost for shipping a single tonne of carbon dioxide. The first three columns represent Cases 1, 2, and 3 using a conventional tanker. The second two columns calculate the cost for a tug-barge to operate along Cases 1 and 2.

### **A.4 Viewing Route Logistics**

The Route Logistics tab calculates the time involved during each step of the marine transportation of the CO<sub>2</sub>. Using the amount of CO<sub>2</sub> to be annually transported, this

spreadsheet calculates the number of vessels necessary to carry out the desired route (which directly affects the costs). The prominent information displayed here is the number of vessels necessary and annual number of voyages. Again, there are 5 columns of calculations, one for each scenario.

#### **A.5 Viewing Model Data**

The Model Data tab contains a large bank of information that has been collected regarding costs for capital expenses, operating expenses, and voyage expenses. This data has been carefully reviewed and considered in order to provide realistic costs that are shown in the Costs spreadsheet. Cost data not listed here (for example, the cost of retrofitting a shore-based power plant to capture CO<sub>2</sub>) has been collected from other sources that are listed in the Selected References that follow. Some values ultimately used within the Costs spreadsheet (for example, fuel cost of a ship based on capacity) are based on trendlines developed within this “Model Data” page.

#### **A.6 Viewing Sensitivity Analyses**

The next six tabs contain data from various sensitivity analyses conducted using the model; each is discussed in detail in section 7 above. The first outlines a basic scenario with a relatively low yearly CO<sub>2</sub> output and a small vessel, indicative of today’s small CO<sub>2</sub> transportation industry in the midst of Phase 1. The other 5 tabs investigate hypothetical scenarios, varying (1) ship capacity, (2) annual CO<sub>2</sub> output, (3) route distance, (4) fuel cost, and (5) tug-barge vs. tanker.

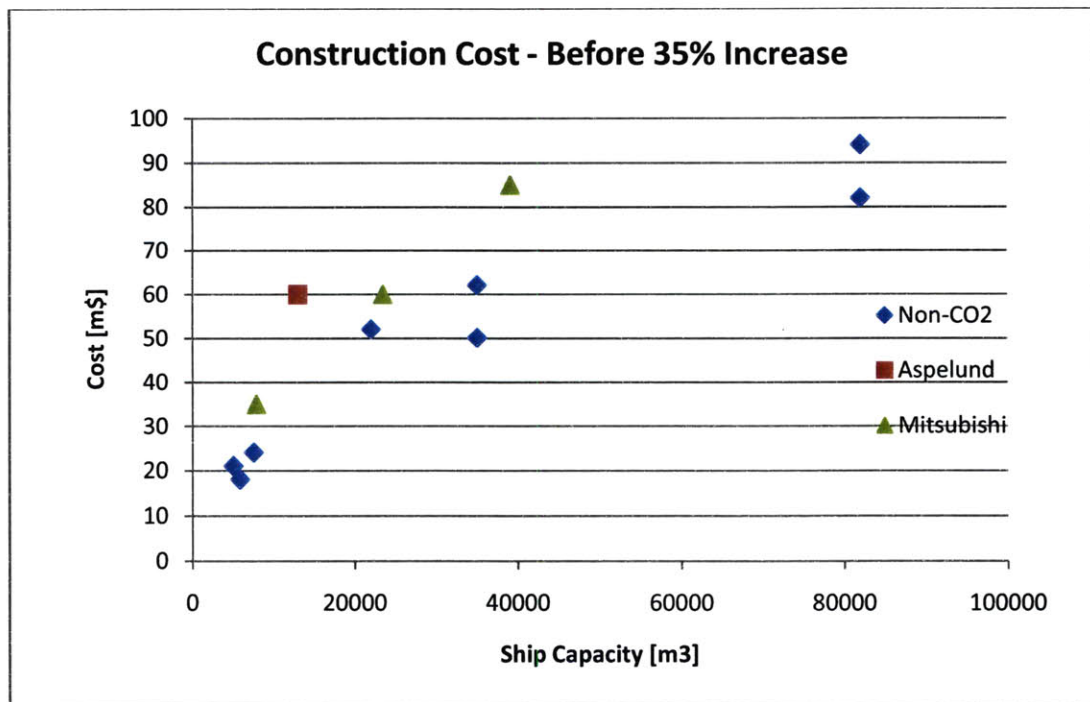


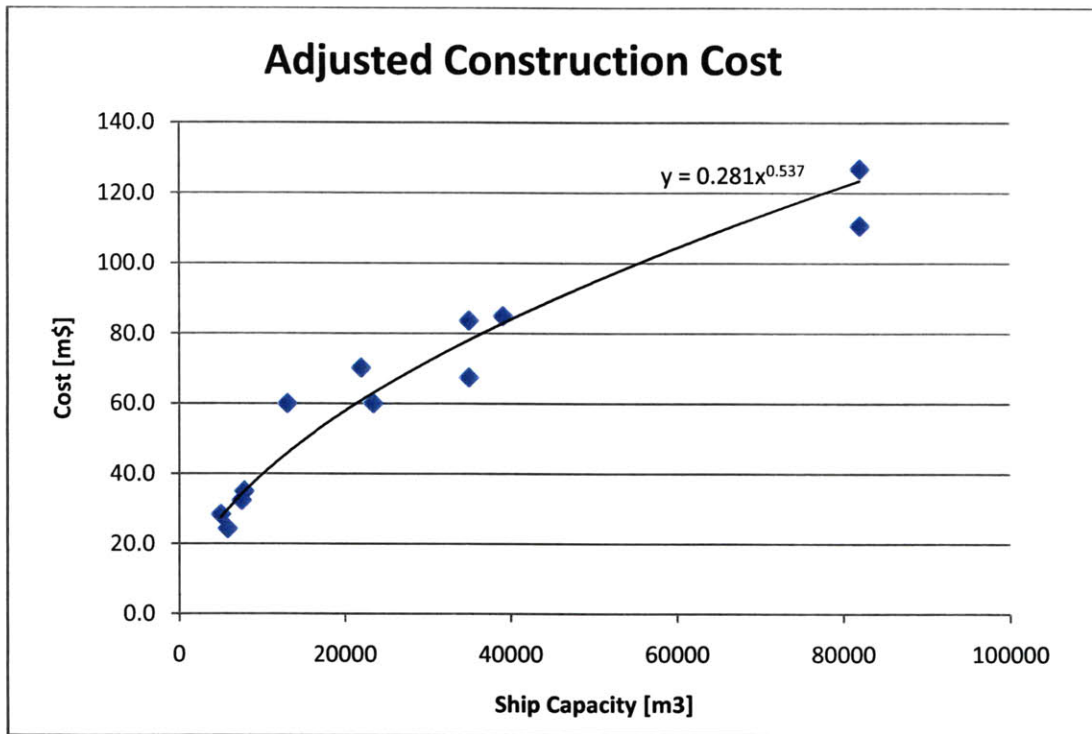
## Appendix B: Model Source Data

### B.1 Construction Cost

Ship Capacity	Price	Source	Type	Year	With 35% Inc. For CO2 Tanker
[m3]	[mil \$]				
5000	21	LPG Carrier	*LPG	2009	28.4
7500	24				32.4
35000	50				67.5
82000	82				110.7
13000	60	Aspelund	LCO2	2008	60.0
7821	35	Mitsubishi	LCO2	2004	35.0
23460	60				60.0
39100	85				85.0
35000	62	Shipbuilding History.com	*LPG	2009	83.7
22000	52				70.2
82000	94				126.9
5820	18	Clarkson's	*Ethyl/LPG	2010	24.3

*\*Note: An additional 35% has been added to all non-CO2 vessel costs for use in the model.*

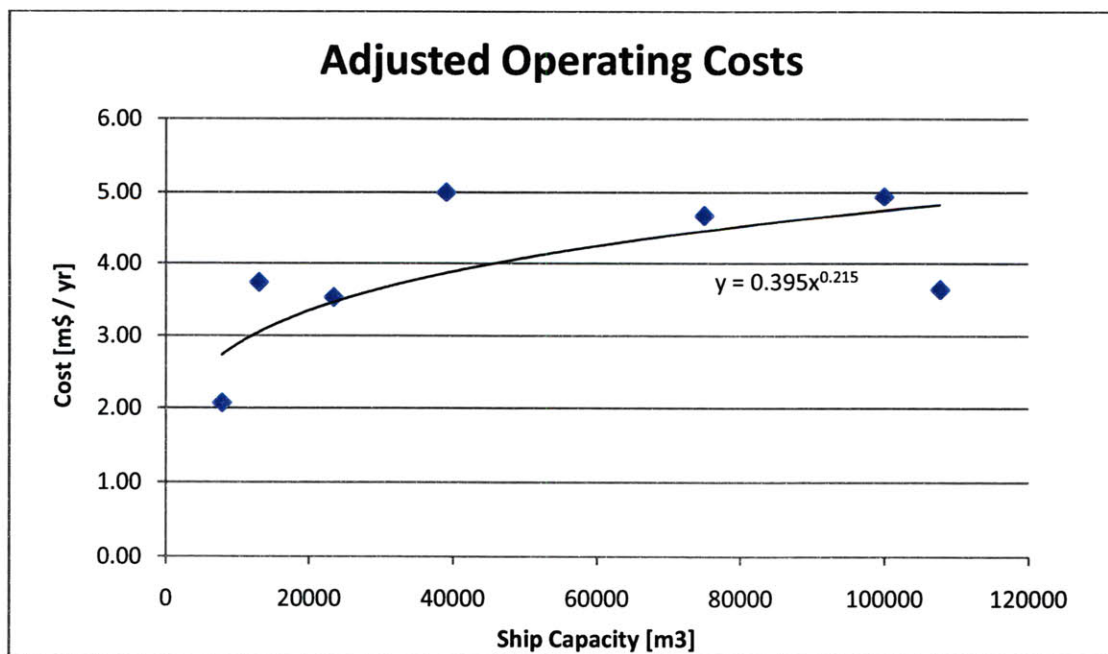
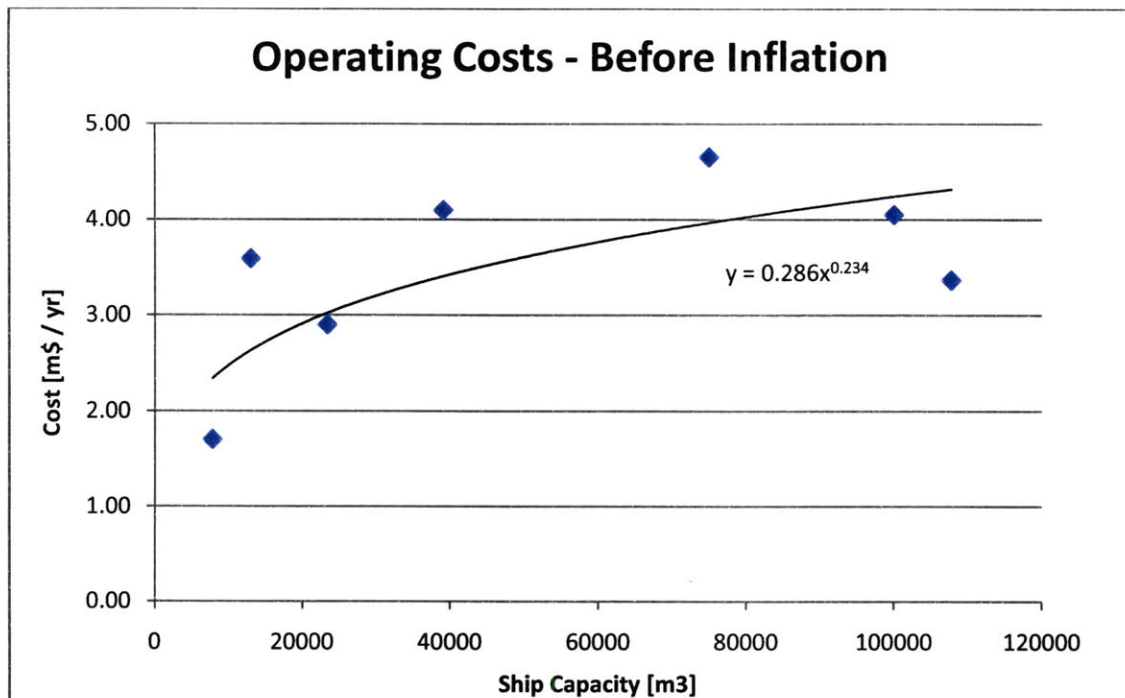




## B.2 Operating Costs

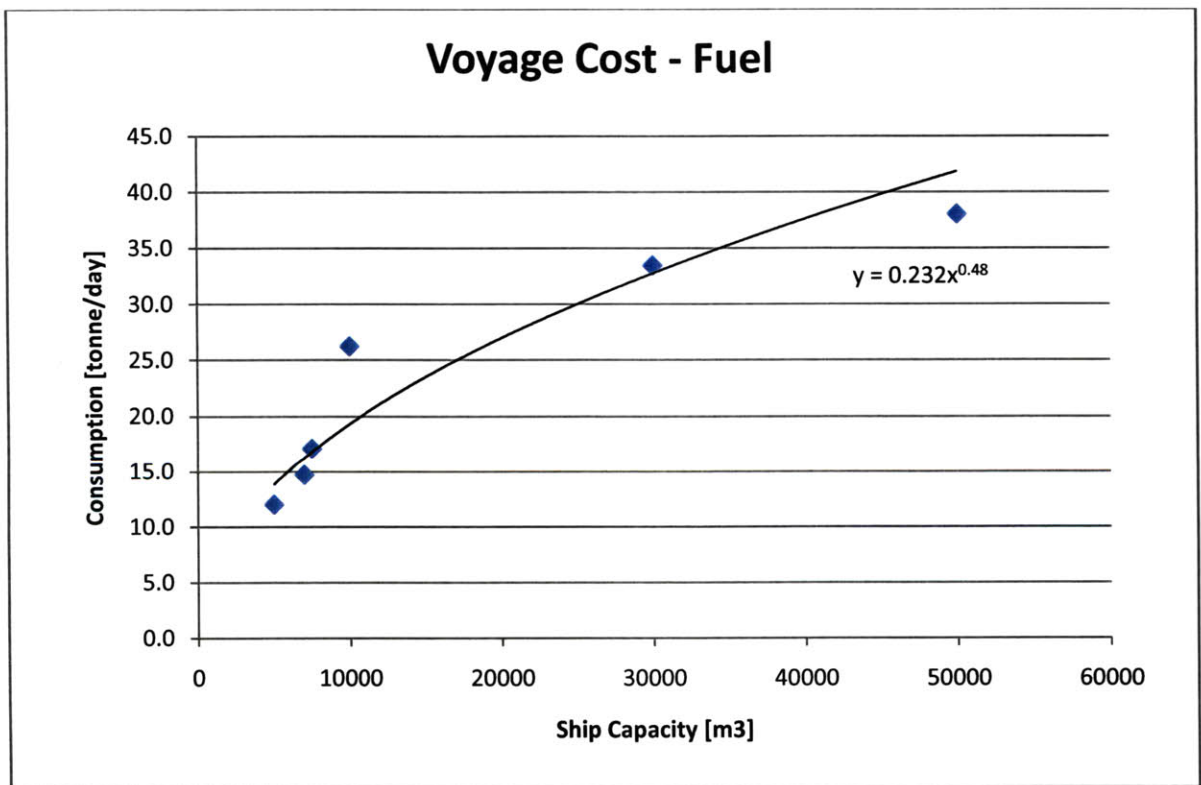
Ship Capacity [m3]	Price [mil \$/yr]	Source	Type	Year	In 2009 \$
75000	4.65	Wood Mackenzie	LNG	2009	4.65
13000	3.59	Aspelund	LCO2	2008*	3.73
107759	3.37	Drewry	LNG	2007*	3.64
7821	1.70	Mitsubishi	LCO2	2004*	2.07
23460	2.90				3.53
39100	4.10				4.99
100000	4.05	Erasmus Uni	LNG	2004*	4.93

*\*Note: All data has been converted to 2009 data using an inflation rate of 4%.*



### B.3 Fuel Costs

Ship Capacity	Consumption	Source	Type	Year
[m3]	[tonne/day]			
10000	26.2	Mitsubishi	LCO2	2004
30000	33.4			
50000	38.0			
7000	14.7	LPG Carrier	LPG	2008
7500	17.1			
5000	12.0			



## Appendix C: Selected Model Sheets

The following set of data, taken from the model, shows all individual results of the model for a few selected scenarios described above.

### INSTRUCTIONS

Input distances, current fuel cost, yearly CO<sub>2</sub> output of plant, and ship size.

Distance, Leg 1	360	nautical miles	
Distance, Leg 2	360	nautical miles	<i>Note: For routes with 1 origin and 1 destination, let distance of Leg 3 be 0.</i>
Distance, Leg 3 (Optional)	120	nautical miles	
Fuel Cost	500	\$/tonne	
Yearly CO <sub>2</sub> Output	6	million tonnes CO <sub>2</sub>	
Ship Size	10000	m <sup>3</sup>	
	11670	tonne CO <sub>2</sub>	

## ROUTE LOGISTICS – Tanker Cases 1, 2, 3

		<b>Case 1</b> (Unload CO2 and Return)	<b>Case 2</b> (Return with LNG)	<b>Case 3</b> (Pick up LNG at Point C)
Production of CO2	tonne/day tonne/yr	16438.4 6000000	16438.4 6000000	16438.4 6000000
<b>Vessel Capacity</b>	<b>tonne</b>	<b>11670</b>	<b>11670</b>	<b>11670</b>
CO2 Capacity	tonne	11670	5835	5835
LNG Capacity	tonne	0	2500	2500
1st Leg Distance	nautical mi	360	360	360
Vessel Speed	knots	15	15	15
Transit Time	hr	24.00	24.00	24.00
2nd Leg Distance	nautical mi	360	360	360
Vessel Speed	knots	15	15	15
Transit Time	hr	24.00	24.00	24.00
3rd Leg Distance	nautical mi	--	--	120
Vessel Speed	knots	--	--	15
Transit Time	hr	0.00	0	8.00
Loading CO2 Rate	m3/hr	1572.2	1572.2	1572.2
Loading CO2 Time	hr	7.36	4.18	4.18
Unloading CO2 Rate	m3/hr	1572.2	1572.2	1572.2
Unloading CO2 Time	hr	7.36	4.18	4.18
Tank Cleaning Rate	m3/hr	--	1000	1000
Tank Cleaning Time	hr	0	0	0
Loading LNG Rate	m3/hr	--	1572.2	1572.2
Loading LNG Time	hr	0.00	3.18	3.18
Unloading LNG Rate	m3/hr	--	1572.2	1572.2
Unloading LNG Time	hr	0.00	3.18	3.18

# **ROUTE LOGISTICS (CONTINUED) – Tanker Cases 1, 2, 3**

<b>Total Time</b>	<b>Hr</b>	62.72	62.72	70.72
	<b>Day</b>	2.61	2.61	2.95
Operating days	day/yr	347	347	347
<b>Number of Voyages</b> (per vessel)	voyage/yr	132.7	132.7	117.7
		132	132	117
Volume moved (per vessel)	tonne/yr	1548415.6	774207.8	686628.6
<b>Number of Vessels</b>	--	3.874929	7.75	8.74
		4	8	9

## SCHEDULE OF COSTS – Tanker Cases 1, 2, 3

	Units	Case 1 (Unload CO2 and Return)	Case 2 (Return with LNG)	Case 3 (Pick up LNG at Point C)
<b>Number of Vessels</b>	--	<b>4</b>	<b>8</b>	<b>9</b>
<b>NON-VESSEL COSTS</b>				
Production of CO2	tonne/day	16438.4	16438.4	16438.4
	tonne/yr	6000000	6000000	6000000
<i>Actual Amount of CO2</i>	<i>tonne/yr</i>	6193662	6193662	6179658
<i>Actual Amount of LNG</i>	<i>tonne/yr</i>	0	2653669	2647668
Capture Cost	\$/tonne	50	50	50
<b>Total Capture Cost</b>	<b>\$/yr</b>	<b>309683121</b>	<b>309683121</b>	<b>308982881</b>
Sequestration Cost	\$/tonne	10	10	10
<b>Total Sequestration Cost</b>	<b>\$/yr</b>	<b>61936624</b>	<b>61936624</b>	<b>61796576</b>
Storage Capacity Needed	--	25000	12500	12500
Storage Cost per Volume	\$/m3	1500	1500	1500
<b>Total Storage Cost</b>	<b>\$</b>	<b>37500000</b>	<b>18750000</b>	<b>18750000</b>
Rate of Loan	%	0.08	0.08	0.08
Length of Loan	yr	25	25	25
<b>Total Tank Storage Cost</b>	<b>\$/yr</b>	<b>3512954</b>	<b>1756477</b>	<b>1756477</b>
Tank Cleaning Rate	\$/m3	0	0	0
Tank Cleaning Cost	\$/ship	0	0	0
Fleet Annual Tank Cleaning Cost	\$/yr	0	0	0
<b>Total Non-Vessel Costs</b>	<b>\$/yr</b>	<b>375132700</b>	<b>373376223</b>	<b>372535935</b>



### SCHEDULE OF COSTS (CONTINUED) – Tanker Cases 1, 2, 3

<b>CAPITAL COSTS</b>				
Overall Vessel Capacity	tonne	11670	11670	11670
	m3	10000	10000	10000
CO2 Capacity	tonne	11670	5835	5835
LNG Capacity	tonne	0	2500	2500
Vessel Cost, One-time	\$	39867162	39867162	39867162
Fleet Cost, One-time	\$	159468646	318937293	358804454
Rate of Loan	%	0.08	0.08	0.08
Length of Loan	yr	25	25	25
Vessel Cost, Annual	\$/yr	3734707	3734707	3734707
Fleet Cost, Annual	\$/yr	<b>14938828</b>	<b>29877656</b>	<b>33612363</b>
<b>OPERATING COSTS</b>				
Vessel Operating Cost	\$/day	7894	7894	7894
	\$/yr	2881489	2881489	2881489
Fleet Operating Cost	\$/yr	<b>11525955</b>	<b>23051910</b>	<b>25933399</b>
<b>VOYAGE COSTS</b>				
Fuel	tonne/day	19.3	19.3	19.3
	tonne/voyage	38.7	38.7	45.1
	\$/tonne	500	500	500
	\$/voyage	19330	19330	22552
Harbor Fees	\$/voyage	45000	45000	45000
Single Voyage Cost	\$/voyage	64330	64330	67552
Number of Voyages	--	132	132	117
Single Vessel Voyage Cost, Annual	\$/yr	8491585	8491585	7903571
Fleet Voyage Cost	\$/yr	<b>33966340</b>	<b>67932681</b>	<b>71132138</b>
<b>OVERALL COSTS</b>				
Annual Cost, CCS Project	\$/yr	435563823	494238470	503213836
Cost per tonne	\$/tonne	<b>70.3</b>	<b>70.0</b>	<b>70.9</b>

## ROUTE LOGISTICS – Tug/Barge Cases 1,2

	Units	Tug and Barge (Case 1)	Tug and Barge (Case 2)
Production of CO2	tonne/day tonne/yr	16438.4 6000000	16438.4 6000000
<b>Vessel Capacity</b>	<b>tonne</b>	<b>11670</b>	<b>11670</b>
CO2 Capacity	tonne	11670	11670
LNG Capacity	tonne	0	5000
1st Leg Distance	nautical mi	360	360
Vessel Speed	knots	15	15
Transit Time	hr	24.00	24.00
2nd Leg Distance	nautical mi	360	360
Vessel Speed	knots	15	15
Transit Time	hr	24.00	24.00
3rd Leg Distance	nautical mi	--	--
Vessel Speed	knots	--	--
Transit Time	hr	0	0
Loading CO2 Rate	m3/hr	--	--
Loading CO2 Time	hr	0	0
Unloading CO2 Rate	m3/hr	--	--
Unloading CO2 Time	hr	0	0
Tank Cleaning Rate	m3/hr	--	--
Tank Cleaning Time	hr	0	0
Loading LNG Rate	m3/hr	--	--
Loading LNG Time	hr	0	0
Unloading LNG Rate	m3/hr	--	--
Unloading LNG Time	hr	0	0

# **ROUTE LOGISTICS (CONTINUED) – Tug/Barge Cases 1,2**

<b>Total Time</b>	<b>hr</b>	48.00	48.00
	<b>day</b>	2.00	2.00
Operating days	day/yr	347	347
<b>Number of Voyages</b> (per vessel)	voyage/yr	173.4	173.4
		173	173
Volume moved (per vessel)	tonne/yr	2023286.3	2023286.3
<b>Number of Vessels</b>	--	2.97	2.97
		3	3

## SCHEDULE OF COSTS – Tug/Barge Cases 1,2

	Units	Tug and Barge (Case 1)	Tug and Barge (Case 2)
Number of Vessels	--	3	3
<b>NON-VESSEL COSTS</b>			
Production of CO2	tonne/day	16438.4	16438.4
	tonne/yr	6000000	6000000
<i>Actual Amount of CO2</i>	<i>tonne/yr</i>	6069859	6069859
<i>Actual Amount of LNG</i>	<i>tonne/yr</i>	0	2600625
Capture Cost	\$/tonne	50	50
<b>Total Capture Cost</b>	<b>\$/yr</b>	<b>303492938</b>	<b>303492938</b>
Sequestration Cost	\$/tonne	10	10
<b>Total Sequestration Cost</b>	<b>\$/yr</b>	<b>60698588</b>	<b>60698588</b>
Storage Capacity Needed	--	15000	15000
Storage Cost per Volume	\$/m3	1500	1500
Total Storage Cost	\$	22500000	22500000
Rate of Loan	%	0.08	0.08
Length of Loan	yr	25	25
<b>Total Tank Storage Cost</b>	<b>\$/yr</b>	<b>2107773</b>	<b>2107773</b>
Tank Cleaning Rate	\$/m3	0	2.5
Tank Cleaning Cost	\$/ship	0	25000
Fleet Annual Tank Cleaning Cost	\$/yr	0	12975000
<b>Total Non-Vessel Costs</b>	<b>\$/yr</b>	<b>366299298</b>	<b>379274298</b>

## SCHEDULE OF COSTS (CONTINUED) – Tug/Barge Cases 1,2

<b>CAPITAL COSTS</b>			
Overall Vessel Capacity	tonne	11670	11670
	m3	10000	10000
CO2 Capacity	tonne	11670	11670
LNG Capacity	tonne	0	5000
Vessel Cost, One-time	\$	33887087	33887087
Fleet Cost, One-time	\$	121993514	121993514
Rate of Loan	%	0.08	0.08
Length of Loan	yr	25	25
Vessel Cost, Annual	\$/yr	3809401	3809401
Fleet Cost, Annual	\$/yr	<b>11428203</b>	<b>11428203</b>
<b>OPERATING COSTS</b>			
Vessel Operating Cost	\$/day	7894	7894
	\$/yr	2881489	2881489
Fleet Operating Cost	\$/yr	<b>8644466</b>	<b>8644466</b>
<b>VOYAGE COSTS</b>			
Fuel	tonne/day	19.3	19.3
	tonne/voyage	38.7	38.7
	\$/tonne	500	500
	\$/voyage	19330	19330
Harbor Fees	\$/voyage	45000	45000
Single Voyage Cost	\$/voyage	64330	64330
Number of Voyages	--	173	173
Single Vessel Voyage Cost, Annual	\$/yr	11129123	11129123
Fleet Voyage Cost	\$/yr	<b>33387369</b>	<b>33387369</b>
<b>OVERALL COSTS</b>			
Annual Cost, CCS Project	\$/yr	419759336	432734336
Cost per tonne	\$/tonne	<b>69.2</b>	<b>66.9</b>



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