Ning Cheng · Mirjam Fürth · Michael Charles Johnson · Zhi Yung Tay
Authors

The Key to Successful Carbon Capture and Storage

Engaging the Public

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FOREWORD

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

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

pre-university education: through appropriate organisations (but not individual schools), promotes careers in science, engineering and technology to young people, their parents and teachers

university education: provides funding for undergraduate and post-graduate scholarships and awards at selected universities and colleges (does not fund students directly)

vocational training and professional development: supports professional institutions, educational and training establishments working with people of all ages.

research: funds existing or new centres of excellence at institutes and universities.

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

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

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

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

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

Southampton

22 August 2011

PREFACE

This book is written during the LRET Summer Collegium 2011 held in the University of Southampton. In recognition to the need to reduced CO_2 emission from coal or fuel fired power plant, research project on an engineering system for carbon capture and storage (CCS) in ocean space utilisation is proposed in the collegium. This book is written to address the engineering challenges in our proposed CCS engineering system. It is recognised that the public perception is the main key to successful CCS project and an engineering system that involves public engagement in the CCS project in the early stage is proposed. The proposed project is known as the “Green Town” where it comprises of an air scrubbing towers that has the ability to capture CO_2 from the air. The selected site for the case study would then be free of anthropogenic CO_2. The captured CO_2 will then be transported by pipelines and stored in depleted oil/gas field for a geological time scale.

Hamburg in Germany is selected as the case study city since it is a port city and is close to available geological formations for CO_2 storage. The K12-B gas field has also been identified as the proposed sequestration site. The CO_2 pipelines will tie-in to existing gas pipelines when they are no longer in use in the near future and the CO_2 injection system for the CO_2 will be retrofitted to gas platform when the gas field is no longer in use. The cost, risk and legal issues for the proposed “Green Town” idea are also addressed as well.

This project also designed and conducted specific surveys in Southampton and Hamburg to investigate the public perception towards the “Green Town” idea and CCS. Unique findings are found and presented in this book.

This book makes an important contribution in addressing the need to engage the public at the early stage of the CCS project. The designed surveys successfully proved that the proposed “Green Town” idea could act as an effective ‘door opener’ to future CCS project. We hope that this book would be useful to engineers and scientists working on the areas of CCS and are looking forward to share our views on the unique findings about the public’s perception of CCS.

We would like to thank our colleagues on the LRET collegium who have made this collegium experiences awesome and are grateful to have attended all the lectures conducted in the research collegium. Special thanks are dedicated to Kerstin Johnson and Anna-Lisa Böbs for their help on our surveys in Hamburg. We would also like to express our gratitude to Mr. Michael Franklin who has made the LRET research collegium possible. We would like to thank Aparna Subaiah-Varma for her dedication in arrangement for our accommodation in the University of Southampton. Finally, we would also like to thank our families. Without their support, all this would be impossible.

Southampton 2 September 2011

Ning Cheng, Mirjam Fürth, Michael Charles Johnson and Zhi Yung Tay

EXECUTIVE SUMMARY

Record high levels of the carbon dioxide (CO_2) in the Earth's atmosphere have triggered the desire to reduce the CO_2 content urgently. Increasingly higher concentrations of CO_2 in the atmosphere will result in a global rise of temperature and as a consequence a negative impact on the environment, such as a shift in animal and plant range, thawing of the permafrost, increase of the mean sea level, widespread glacier melting and a loss of snow cover. It is widely accepted that a great deal of this increase in atmospheric CO_2 content is due to mankind since industrialisation.

This situation needs to be stopped before it becomes irreversible. Global CO_2 emissions must be reduced. Emissions could be reduced by switching to renewable energies such as wind, wave and solar power. However, these renewables are not yet ready to cater for the world energy demands. Fossil fuels currently supply almost 80% of the word's energy supply and will continue to be the main energy source for the foreseeable future.

In order to meet the continuous supply of energy and at the same time reducing the CO_2 concentration in the atmosphere, Carbon Capture and Storage (CCS) is proposed which is able to capture CO_2 directly from the emitting source such as coal and fuel fired power plant. The CO_2 is then transported to a suitable site for permanent storage in geological formations.

The Achilles Heel of CCS

Public perception has been recognized as a vital part of the successful deployment of large scale engineering projects, CCS will be no different. Many reports have shown that negative public perception on CCS is the main obstacle in implementing the CCS project. For example, the Shell's CCS project in Barendrecht, Hollands, and Vattenfall's in Germany have attracted heated objections from the public. As a consequence, this results in the delay of implementing the project. Hence, the public perception should be treated as the key criterion in ensuring a successful CCS project.

The public are being asked to accept some risk, however small, to their environment. In gaining the public support for the CCS project, an early engagement of the public in the project is necessary. The project has to be open and transparent such that information regarding the technology, safety, risks and environmental impact of CCS is provided. The public is reported to have difficulties in understanding the reason to have CCS take place in their community. Government support on the project is also essential so that the public does not perceive the CCS as the idea coming from oil and gas companies solely.

Several reports on public awareness have been studied and the following findings are observed:

- Global warming is not seen as a pressing concern by the public compared with other environmental issues.
- Renewable energies are strongly preferred by the public over the nuclear option and CCS is negatively perceived to be associated with fossil fuel power ('clean coal')
- CCS is not well known among the public
- Leakage after CO_2 sequestration is the number one concern among the public.
- Most of the studies predict that pilot projects or industrial-scale demonstration projects on CCS will have a big impact on the public perception on CCS.
- Communication transparency or an increase in educational effort may play a critical role in promoting and realising CCS.

The public perception towards the CCS process (safety, technical, risk, environmental impact etc.) is identified as the key to a successful CCS project. This book presents the idea of a “Green Town” that would involve the engagement of the public in the early stages of a CCS project.

Conceptual Idea and Aim

Figure (a) illustrates the “Green Town” idea. There is an air scrubbing facility to capture CO_2 from the air (I); the captured CO_2 will be transported by pipelines (II) to be stored in depleted oil/gas fields (III). The purpose of the “Green Town” idea is to create a cleaner environment in the local communal or town by capturing CO_2 from the air. The air scrubbing tower hence plays an important role in the public’s daily life and could thereby enhance the public familiarity towards CCS technology. The main aims of the “Green Town” idea are to:

- Enhance public understanding on CCS and its benefits towards the environment.
- Inspire and interest the younger generation regarding CCS technology
- Encourage public acceptance of CCS technology.

It is anticipated that more air scrubbing facilities could be installed once CCS is proven to be beneficial to the public. The public acceptance of the “Green Town” idea could also remove their scepticism towards direct CO_2 capturing from point sources such as coal power plants or cement plants. Hence, the “Green Town” idea is meant to be a ‘gate opener’ to the future implementation of a fully integrated CCS.

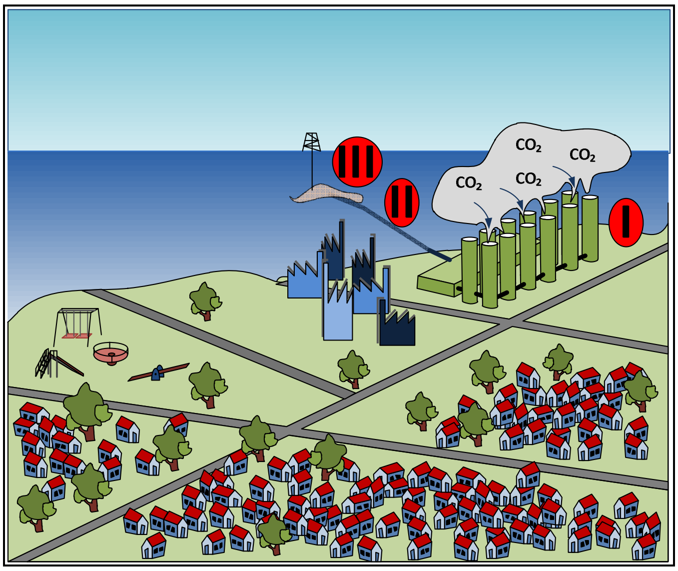

Figure (a): Proposed Concept of “Green Town” Idea

Green Town Case Study

The city of Hamburg in Germany was selected for a case study involving the “Green Town” concept. The total population in Hamburg is approximately 1.8million and it was proposed that 1% of the CO_2 emitted should be captured, transported and stored by the “Green Town” project. It is estimated that an onshore land area of about 16,100m^2 is required for the 1% capture level air scrubbing facility. That level is approximately 200,000 tonnes of CO_2 per year. A site in the industrial area of Hamburg was chosen as a suitable site for the air scrubbing facilities.

The technology being developed by Carbon Engineering Ltd. (CE) of Canada was chosen as the model for the “Green Town” air capture facility. This has the capability to draw in air and remove most of the CO_2. The facility consists of a large ‘slab’ of air contactors (about 20m high) to drive air into the facility, make contact with the CO_2 and absorb it in a fluid and a thermal system to release the collected CO_2 from the fluid before recycling the fluid. CE's air capturing method is a wet-scrubbing technique. The fluid used is an alkaline hydroxide solution. The air scrubbing in the air contactor is shown in Fig. (b) and the chemistry of the wet scrubbing technique is shown in Fig. (c).

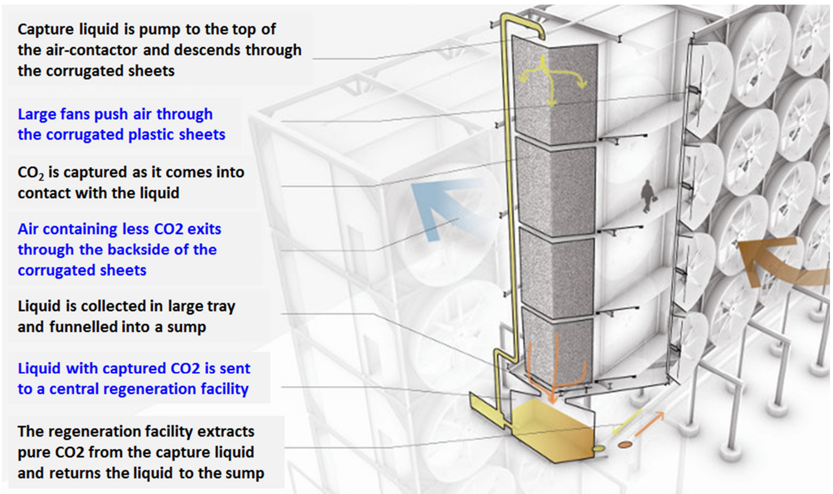

Figure (b): Air Contactor Process
(source:www.carbonengineering.com)

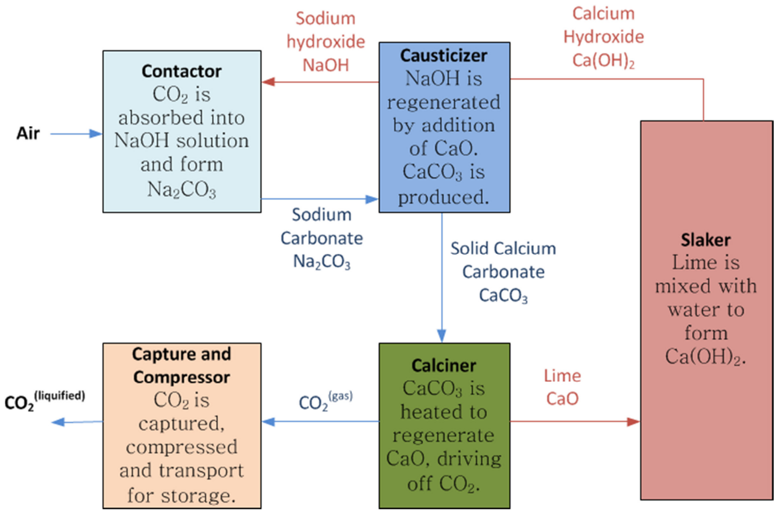

Figure (c): Wet-Scrubbing Process in Air Scrubbing Facility

The facility could be powered by low-carbon fossil fuel such as natural gas or in principle by renewables such as solar or wind power, or as nuclear power.

Fot the case study, the captured CO_2 is envisaged to be transported in liquefied form by using pipelines from Hamburg to Emden (near Groningen) in the Netherlands. Existing subsea trunk pipelines would then be used from close to Emden to the Dutch K12-B platform where the CO_2 would be stored in a depleted gas field.

K12-B platform is on the Dutch continental shelf 150 km North West of Amsterdam. The K12-B is currently a storage site for CO_2 with successful on-going injections. The platform has a possible injection speed of 310,000 to 475,000 tonnes per year and the site has a theoretical storage capacity of 14.4 billion cubic metres.

Surveys on Public Perception

The hypothesis that public perception is crucial to the acceptance of CCS technology was tested by making using questionnaire surveys. Surveys were conducted with the public in Southampton and Hamburg to obtain their opinion on the "Green Town" idea and CCS in general. The objectives of the surveys were to:

- investigate the public awareness on climate change.
- obtain public opinion on the "Green Town" idea and its technology background
- demonstrate public acceptance on "Green Town" idea
- examine the correlation between public perception and their standard demographic variables (age, income, gender, education, etc.)
- measure the degree of public acceptance on the "Green Town" idea
- examine the relationship between acceptance of "Green Town" idea and acceptance of fossil fuel CCS
- measure the financial commitment "Green Town" that might be expected from the public
- compare the public perception on the "Green Town" idea in Southampton and Hamburg

A trial survey was conducted in the Southampton and then a slightly modified version of the survey form (in German) was made for a larger trial in Hamburg.

In general, the public responses towards the "Green Town" idea and CCS in Southampton and Hamburg were similar in many respects. It was found that the public in both Southampton and Hamburg -

i. were concerned with the environment. The people in Hamburg were more environmentally conscious.

ii. liked the idea of the "Green Town" and CCS. It was less well received in Southampton.

iii. are willing to pay around 4 to 5 Pound/month and Euro/month, respectively. It was also shows that the additional energy prices/month that the public are willing to pay to support the "Green Town" idea is independent on their personal income. Reasonable cost estimation could be draw from this basis.

iv. those with a higher educational level have a greater positive response towards the "Green Town" idea. This indicates that school or university could function as a platform to effectively educate the public on the "Green Town" idea. It could also indicate that the opinion of the public could be altered if adequate information on a new technology is provided.

v. those who did not like the "Green Town" idea generally felt negative about having the air scrubbing facility in town and vice versa. This indicates that the public should be engaged at an early stage of CCS projects.

vi. those who liked the "Green Town" idea generally liked CCS. The "Green Town" idea could therefore play an important role in laying a strong foundation for public support of CCS projects.

The public opinion could be altered if more information on the proposed technology is given and if the whole project involves the public engagement in the early stage. The "Green Town" idea plays an important role in laying a strong foundation to incur public interest in CCS project.With regards to most effective means of communication on CCS, television and newspaper were found to be the most effective means in UK whereas newspaper and internet are the two most cited methods in Germany.

Financial

The estimated cost of air capture is around five times higher than ‘conventional’ CCS for thermal power plants. Leakage is the biggest risk associated with these project; it could permanently turn people away from CCS because of its effects to the local environment and population. Therefore safety should have the highest priority. The CO_2 storage method used in this project, i.e. the geological storage in seismically inactive areas is considered to be the safest form of storing CO_2 from the view point of risk and legal aspects. Leakage monitoring systems will also need to be installed to detect any CO_2 leakage during the CO_2 capturing, transportation and storing processes.

Summary

Existing failures with CCS due to public objections have been identified. Engaging the public at an early stage is seen as key to successful large scale CCS projects in the future. The “Green Town” idea was suggested as such a route to engaging the public. The empirical data from questionnaire surveys vindicates the suitability of this approach

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1 INTRODUCTION

This book forms the report of Team CATSS to the LRET Collegium on Carbon Capture and Sequestration (CCS) held at the University of Southampton in summer 2011. Each team in the Collegium has reviewed the background of CCS with the idea of finding an area where there is some kind of deficiency in the knowledge, exploring this area and submitting a report presenting a novel engineering system which deals with the problems that they identified and hopefully makes a strong positive contribution to the canon of work on CCS.

The book begins by reviewing the state of the Earth's environment as reported by the scholarly literature. The idea of climate change has entered the international conscience particularly following coverage of the 1992 Rio 'Earth Summit' and the 1997 Kyoto Agreement. Clearly this is an emotive subject for many people so the review has been made from an impartial point of view. Arguments for and against the importance of the role of anthropogenic CO_2 emissions and the possible link with climate change are reviewed here.

Accepting that mankind's accumulated production of CO_2 from all sources is significant, the idea of mitigation then becomes important. CCS – the capture of CO_2 and the transportation to a site for permanent storage - is seen as one of many mechanisms that might be employed to reduce emissions of CO_2. The proposed methods for CCS are reviewed as well as the magnitude of the contribution CCS might sensibly make to emission targets alongside other mitigation options.

As the book describes, a handful of CCS projects are already in operation. However it will be seen that CCS is becoming more controversial as it becomes better known. CO_2 is a potentially hazardous gas, so there are questions of public safety in the capture and transport phases for example, and questions of the long term viability of sequestration in deep geological formations. Public objections have actually led to the cancellation of trial projects in some instances and these cases are reviewed. Public support is therefore crucial for the successful implementation of CCS at large scale irrespective of the engineering excellence of the approaches adopted.

Taking the city of Hamburg as an example, the concept of a "Green Town" CCS engineering system is introduced. This incorporates the technology of capture of CO_2 from the air. Sites for the plant are identified as well as transportation routes, and a site for sequestration is identified. The financial, political and legal aspects of the solution are briefly discussed. Whilst these are of importance, the focus of the project remains the understanding of the interaction between the engineering community proposing CCS techniques and the public who must accept some degree of risk in their environment.
Team CATSS did not set out to design an engineering system capable of capturing vast quantities of CO_2 but rather set itself the task of exploring the nature of the public objections and substantiating the hypothesis that there is a strong correlation between the public knowledge of CCS and public support. This has been achieved in part by the conduct of two separate questionnaire surveys on the streets of different European countries where it was thought that there could be contrasting attitudes; a pilot survey was made in Southampton with 158 respondents, and a larger scale survey in Hamburg with 366 respondents. The questionnaires presented the "Green Town" idea where air capture of CO_2 and subsequent subsea sequestration is introduced to the public. The questionnaire results are analysed and discussed in detail and presented graphically. The implications for future implementations of CCS are discussed.

2 LITERATURE REVIEW

2.1 Carbon Dioxide (CO_2)

Carbon dioxide (CO_2) exists naturally in the environment and it is the fourth most common gas in the atmosphere (Solomon *et al.*, 1985). It is naturally emitted into the atmosphere through animals' respiration, the decay of plants and from heated sea water. However there are also man-made emissions from combustion, cement production and transport.

2.2 Carbon Cycle

The carbon cycle is the way carbon transforms through different stages. Some of the stages last only for seconds while others last for millennia. CO_2 from the atmosphere is transformed to carbon in leafs, stems and roots through photosynthesis. Parts of the carbon are taken up by plant eating animals but most of it is breathed back into the atmosphere by plants and animals. In some cases, the plants are buried in soil or sediment; hence the CO_2 is unlikely to be recycled back into the atmosphere over geological time spans. The carbon cycle comprises of four important processes, i.e. photosynthesis, respiration, ocean atmosphere exchange and fossil fuels transformation

2.2.1 Photosynthesis

Photosynthesis is the process when plants, algae and bacteria produce organic material (usually in the form of sugar) from the sunlight. Photosynthesis takes place when light comes into contact with chlorophyll in the plants with the help of water. The energy from the light is then used to remove electrons from water where these electrons are then used to transform CO_2 into sugar. This process is called carbon fixation. The sugar is then used as food for the plants.

2.2.2 Respiration

The CO_2 cycle in this process involves the exchange of CO_2 and oxygen (O_2) in the air through respiration by plants and animals. Both plants and animals take in O_2 and breathe out CO_2 into the atmosphere to create the energy they need to survive (McPherson and Sundquist, 2009).

2.2.3 Ocean Atmosphere Exchange

The oceans contain about 50 times the amount of CO_2 currently in the atmosphere (Baes Jr *et al.*, 1985). About three quarters of the earth is covered in water and the average depth is 4000 m (Baes Jr *et al.*, 1985).

From the water surface and down to about 75 m is a well-mixed water layer (Baes Jr *et al.*, 1985). This mixed layer is shallower at the equator and deeper at the poles (Baes Jr *et al.*, 1985). It also has the same CO_2 concentration as the atmosphere (Solomon *et al.*, 1985). The CO_2 needed in the ocean's flora for photosynthesis is obtained from the CO_2 dissolved from the atmosphere into the water surface and oceans (McPherson and Sundquist, 2009).

There is an exchange of CO_2 between the air and sea due to partial pressure (Rackley, 2010). The partial pressure is determined by the concentration of gas and the ambient temperature. For example partial pressure of O_2 in air surface is about 0.21 atm, where the concentration on O_2 in air is about 21% and ambient pressure is 1 atm. Approximately 90 Giga tonnes of carbon (GtC) is exchanged annually (Rackley, 2010) and the increase of CO_2 in the atmosphere have resulted in the oceans absorbing more CO_2 (Rackley, 2010). From 1990 to 2005, the oceans have absorbed a third of the man-made CO_2 emissions, thus increasing the acidity of the surface water. As a result, this would limit the ability of the oceans to increase the CO_2 uptake in the future (Rackley, 2010).

2.2.4 Fossil Fuels Transformation

Organic material that is covered in soil or maritime sediments will turn into oil, gas or coal after a long time provided that the organic material is deprived of oxygen. Fossil fuels were laid down at a time when the atmosphere contained much more CO_2, i.e. 1,500 ppm at the beginning of the Carboniferous Age (Rackley, 2010). It is estimated that the planet holds 4,000 – 6,000 GtC of fossil fuels (Rackley, 2010). The carbon inside these substances will only be released into the atmosphere through combustion process and the use of organic material (oil, gas coal) as a form of energy resources has a history of only a few centuries.

2.3 Greenhouse Gases

When light reaches the atmosphere, sunlight is let through the atmosphere with longer infra-red wavelengths reflected back out into the space (Solomon *et al.*, 1985). The greenhouse effect occurs when some of these infra-red wavelengths are absorbed by CO_2 and are then reflected into the earth (Solomon *et al.*, 1985). There are several greenhouse gases such as chlorofluorocarbons, methane, nitrous oxide and water vapour but CO_2 appears to be the major cause of climate effects among the greenhouse gases (Solomon *et al.*, 1985). Since 1750, it is estimated that 280 GtC has been released back into the atmosphere due to the combustion of fossil fuels. Another 150 GtC has been released to the atmosphere due to the land use changes, such as forestry (Rackley, 2010).

2.4 Current Status of Atmosphere

Humans started to release CO_2 into the atmosphere thousands of years ago with its conversions of forests and grassland for agriculture purpose (Ruddiman, 2007). The burning of fossil fuels has dramatically increased the CO_2 concentration in the atmosphere (McPherson and Sundquist, 2009). The rapid increase of CO_2 levels over past centuries is thought to be due to the burning of fossil fuels and the change of land use (which increase oxidation of plants and humus carbon) (Olson *et al.*, 1985). The Inter-governmental Panel on Climate Change (IPCC) shows that a volume fraction of CO_2 in the atmosphere increased by 1.5% each year. At this rate, the amount of CO_2 in the atmosphere would have doubled by 2100 (Gale, 2004).

The level of CO_2 in the atmosphere is currently 388.5 ppm (Blasing, February, 2011). This CO_2 concentration is the highest for 420,000 years and van Aalst *et al*. (2006) reported that the CO_2 concentration could be the highest in the past 20 million years (van Aalst and Maarten, 2006). The atmospheric CO_2 is at present 1/3 higher than during the eighteen century and much higher than during the last hundred thousand years (McPherson and Sundquist, 2009). It is to be noted that the CO_2 concentration was 342 ppm (Solomon *et al.*, 1985) in 1985 and was only 260-285 ppm in the several centuries before 1800 (Olson *et al.*, 1985).

The annual anthropogenic carbon emission in the 1990s was estimated to be 7.4 GtC, mostly released due to fossil fuels combustion (Grimston *et al.*, 2001). It is estimated that 2.2 GtC was absorbed by the oceans, 1.7 GtC by photosynthesis and 3.5 GtC was retained by to the atmosphere in the form of CO_2 (Grimston *et al.*, 2001). The amount of carbon released from fossil fuels burning increased by 21%

between 1980-1990 (Grimston *et al.*, 2001). It is estimated that emissions of carbon are going to grow with 2.2% world wide and 3.3% in the developing countries (Grimston *et al.*, 2001). In 1990, it was estimated that the emissions of CO_2 would be around 2,000 Gt CO_2 in 2050 (Gale, 2004).

2.5 Future Scenario

The biggest fears regarding climate change is due to the difficulty in detecting the climate change at early stage and the difficulty in stopping it when it is well developed. The level of CO_2 in the atmosphere has varied over the history of humanity and has correspondingly resulted in the change of the climate (McPherson and Sundquist, 2009). Success in projecting the climate change is found to be closely connected to the improvement in projecting the carbon cycle (McPherson and Sundquist, 2009).

2.5.1 Environmental Scenarios

The global mean surface temperature has risen by approximately 0.6°C, with a higher increase on the land than at the sea (van Aalst and Maarten, 2006). On average globally, the 1990's was likely the warmest decade in the past thousand years (van Aalst and Maarten, 2006). The temperature has a big effect on the environment, such as a shift in animal and plant range, thawing of the permafrost, increase of the mean sea level, widespread glacier melting and a loss of snow cover (van Aalst and Maarten, 2006). Depending on the future regulations of CO_2 emissions, the global temperature is expected to rise by 1.4 to 5.8°C (van Aalst and Maarten, 2006). This could cause the sea level to rise between 4cm and 88 cm (van Aalst and Maarten, 2006).

The Taiga and Northern Peatlands (which contain hundreds billions tonnes of terrestrial carbon storage) are experiencing a significant climate warming and result in the thawing of permafrost as well as a dramatic changes in the water and forest ecosystems (McPherson and Sundquist, 2009). The warming increases the vulnerability of these areas to carbon releases due to fire and decomposition (McPherson and Sundquist, 2009). Climate changes have also increased the danger of fire in Australia (Williams *et al.*, 2001).

It is known from plants in greenhouses that when there is no restriction on water, nutrients, light and temperature, plants transform CO_2 faster through the photosynthesis if the level of CO_2 in the air is higher. This produces a longer growing season and a faster vegetation growth (Solomon *et al.*, 1985). However it is hard to determine if this would be the case outside the controlled environment of a greenhouse. This is because a temperature rise would then increase the return of carbon to the atmosphere due to respiration taking place both day and night unlike photosynthesis (Solomon *et al.*, 1985). In such case, the concentration of CO_2 and O_2 would be in equilibrium.

Global warming appears to have local benefits such as boosting agriculture and decreasing demand for heating. However, global warming would also result in many negative phenomena such as losses of ecosystem (van Aalst and Maarten, 2006). The mid-continental areas will become dryer which is likely to increase droughts and wild fires (van Aalst and Maarten, 2006). The developing countries will have harder time adapting to a changing environment as compare to the developed countries (van Aalst and Maarten, 2006)**.**

2.5.2 Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations to provide the governments of the world a clear scientific view of current world's climate situation. The IPCC's First Assessment Report states that: "We are certain of the following:

- There is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be.

- Emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapour, will increase in response to global warming and further enhance it." (IPCC, 1990)

The most famous future scenario is the business as usual (BAU) scenario from IPCC in which nothing is done to limit the CO_2 emission. In this scenario, the equivalent CO_2 concentrations will double from preindustrial levels to 2025 (IPCC, 1990). Under this scenario it is predicted that the temperature will rise by 0.3°C per decade which is the highest over the last 10,000 years (IPCC, 1990). The sea level is expected to rise by 6 cm per decade for the next century (IPCC, 1990). The IPCC divided the future scenarios into four categories:

- Category A1: a more integrated world
- Category A2: a more divided world
- Category B1: a more integrated and environmentally friendly world
- Category B2: a more divided and environmentally friendly world (IPCC, 2000)

2.6 Future of Fossil Fuel and Renewable Energies

As the population grows towards nine billion people in the next 50 years (United Nations, 2004), the world's energy demands will increase proportionately. The total world energy demand is about 400 quadrillion (1×10^{15}) British Thermal Units (BTUs) each year (IEA, 2010). Fossil fuels, including oil, coal and natural gas supplies make up of nearly 88 % of the world's energy needs. This situation will not change in the near future (IEA, 2010).

The International Energy Agency has projected that the CO_2 emissions from the energy sector will increase by 130% from 2005 to 2050, if there is no policy or supply constraint to reduce the fossil fuel consumption(IEA, 2008a). To address this, an energy technology revolution that involves a portfolio of solutions such as increase energy efficiency, CCS, renewable energies, and nuclear power, will be important.

There is an increasing enthusiasm in expanding the needs of advanced clean energy technologies. The growth of renewable energy is promising. Only around 7% of the world's total energy is supplied via renewable energy(IEA, 2009).Moreover, nuclear energy represents merely around 6% of the world's energy supply(IEA, 2009).Radical growth in nuclear energy is not expected in the near future due to the high risks.

According to the IPCC report, CCS is the only technology available today to mitigate greenhouse gas emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation. The IPCC's CCS special report reported that CCS could provide 15% to 55% of the cumulative mitigation effort up to year 2100(IPCC Working Group III, 2005).

2.7 *Carbon Capture and Storage (CCS)*

With the current atmosphere CO_2 concentration achieving a record high of 388.5 ppm (Blasing, February, 2011), there is an urgent need to reduce the current CO_2 concentration to a safer level of 350ppm by 2050 (Inforse-Europe, December, 2008). Carbon Capture and Storage (CCS) offers mitigation technology which would be essential in tackling global climate change as well as ensuring continuous supply of energy. The Intergovernmental Panel on Climate Change (IPCC) defines CCS as a process comprises of three major disciplines (IPCC Working Group III, 2005), i.e.

i. Separation of CO_2 from industrial and energy-related sources
ii. Transportation of CO_2
iii. Storage of CO_2 for long-term isolation from the atmosphere

The CCS technology captures CO_2 from fuel- or coal-powered power plant via pre-combustion, post-combustion or oxyfuel process. The captured CO_2 is then transported for storage by pipelines or liquefied in CO_2 ship. Storage of CO_2 can be in the form of geological storage, ocean storage or mineral carbonation. The detail process of these three disciplines with other alternatives will be presented in Chapter 2.8.

2.7.1 Environmental Impact of CCS

<u>Human and Animal Life</u>

CO_2 is a potentially hazardous gas and causes suffocation at concentration of 30%. CO_2 at the atmospheric level are far below this, of the order of 0.03%. Table 2.1 shows the CO_2 concentration (in parts per million or ppm) and its effects associated to human health (Wisconsin Poison Control Centre, 2011).

TABLE 2.1
EFFECTS OF CO_2 CONCENTRATION TO HUMAN LIFE

CO_2 ppm	**Effects on Human**
250-350	Does not cause harmful effect (normal outdoor condition)
350-1,000	Does not cause harmful effect (Typical level found in occupied spaces with good air exchange)
1,000-2,000	Complaints of drowsiness and poor air
2000-5000	Headaches, sleepiness, and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present.
>5,000	Exposure may lead to serious oxygen deprivation resulting in permanent brain damage, coma and even death.

There are three known (volcanic) lakes where CO_2 has been released suddenly and naturally in large quantities; Lake Monoun and the Lake Nyos in Cameroon and Lake Kivu in East Africa. An incident in 1984 at Lake Monoun resulted in a death of 37 people living nearby. A second deadlier incident occurred in 1986 where an estimated 80 million m^3 CO_2 was out-gassed and resulted in 1,700 deaths and loss of livestock up to a distance of 25km from Lake Nyos (Kling *et al.*, 1994, Clarke, 2001). Lake Kivu has not caused losses of human life but the large CO_2 concentration in the lake is reported to have caused extinction of living creatures for thousands of years. It also caused nearby vegetation to be swept back into the lake. These findings are reported by Professor Robert Hecky from the University of Michigan who tested sediment samples in Lake Kivu (Reitan, 2011)

The reduction of marine pH values over a wide area is likely to have a significant impact on the marine organisms in deep ocean habitats (Johnston and Santillo, 2002). CO_2 causes acidification not only in the water, but also in organism tissues and body fluids. Acidification would also affect groups of marine mammals that have calcium carbonate shells or skeletal structures. Their shells or skeletal structures would dissolve when react with CO_2 in water. Deep water corals and bivalve molluscs, are also vulnerable to this acidification process (Johnston and Santillo, 2002, The Royal Society, 2005).

Ocean Acidification

The deadly consequences of CO_2 release into the lakes due to volcanic and limnic activity is of relevance when considering the effect of ocean acidification as a result of possible failures in the engineering process, transportation and storage system. Ocean acidification is a term that is used to describe the on-going decrease in the pH of the Earth's oceans, caused by their uptake of anthropogenic CO_2 from the atmosphere. It is reported that the surface ocean pH has decreased from approximately 8.25 to 8.14 between 1751 and 1994. This decrease amounts to a 30% increase in acidity of the world's ocean (Caldeira and Wickett, 2003). With that in mind, any leakages from large scale activity could accelerate the ocean acidification process. The properties of Co2 in ocean water and the influence of depth are reported in the paper by Johnston and Santillo (2002).

TABLE 2.2
CHARACTERISTIC OF CO_2 IN VARYING WATER DEPTH

Water Depth	Characteristics of CO_2
< 500m	The introduction of CO_2 will create bubble plume since CO_2 would exist as gas. These bubbles will potentially dissolve in seawater and trapped below the ocean thermocline. However, the retention time of the CO_2 is relatively short, i.e. in the order of 50 years, thus, increasing the risks of CO_2 release back into the atmosphere (GESAMP, 1997).
500m–3000m	CO_2 exists as a buoyant fluid and form a droplet plumes. The droplet flumes might be covered in film of hydrate, and could slow dissolution (Drange *et al.*, 2001).
Intermediate Water Depth	Injection of CO_2 in intermediate water depth would result in a CO_2 enriched plume where diminished pH values are likely to persist for many tens of kilometres down current. Brewer *et al*. (1999) claimed that it is possible that hydrate formation could inhibit the uptake of CO_2 in seawater if the droplet plume rises to the hydrate phase boundary.
> 3000m	CO_2 would form a dense liquid plume which could ultimately form a lake of liquid CO_2 on the sea bottom (Adam *et al.*, 1995, Brewer *et al.*, 1999) bounded by a clathrate surface. The clathrate surface will inhibit the CO_2 dissolution into the overlying waters. Retention times in deep water could be longer than shallower water since deep water exchanges with surface water at a much lower rate as compared to the interactions of surface water with the atmosphere.

There is also a risk of leakage for CO_2 storage in geological form, i.e. by storing CO_2 in depleted oil wells, saline formations or un-mined coal bed. In this case, CO_2 could be released to the environment due to fracture or leaking wells or undetected faults. Hazards would primarily affect groundwater or results in acidification of soils and displacement of oxygen in soils.

Storage Period

One of the main challenges of CCS is to store the captured CO_2 for an indefinite period. This would mean that adequate storage capacity of CO_2 is essential for the CCS to be feasible. Most of the present proposed CO_2 storage methods are in the form of geological storage. Currently, existing industrial-scale CCS projects (projects in the order of 1 Mt CO_2 yr^{-1} or more) are the Sleipner project in the North Sea, the Weyburn project in Canada and the In Salah project in Algeria. Approximately 3-4 $MtCO_2$ that would otherwise be released to the atmosphere, is captured and stored annually in geological formations. Addition projects of CCS are listed in Table T5.5 of the IPCC report (Johnston and Santillo, 2002). It is also estimated that the Utsira aquifer in the North Sea could be used as a CO_2 reservoir for several European countries for at least 20-30 years (FencoEra-NetProject, 2010). In the FENCO ERA-NET project report (FencoEra-NetProject, 2010), it is reported that the Utsira aquifer has the potential capacity to store 2 billion tonnes CO_2 annually to a total cumulative storage capacity of 600 billion tones CO_2. To be cost effective, (Lindeberg *et al.*, 2000) reservoir simulations indicated that only 20 to 60 Gt CO_2 could be stored in the Utsira formation. However, the storage capacity is far greater than the estimated 1.6 Gt CO_2 needed to be captured annually in 2050 in Europe (based on 80% CO_2 emission reduction) (Inforse-Europe, December, 2008). Thus, based on the subsidies established by the government to promote the development of pilot/demonstration plants on CCS, it is also concluded in the report by Inforse-Europe (December, 2008) that the construction of an offshore CO_2 network in the North Sea region for the storage in Utsira aquifer is feasible.

CO_2 could also be sequestered in the form of ocean storage, which involves the direct injection of CO_2 into the ocean through a dissolute plume (for water depth < 3000m shown in Table 2.2) or as an ocean lake (for water depth greater than 3,000m shown in Table 2.2). From the speculation of the characteristic of CO_2 as presented in Table 2.2, storing CO_2 at water depth greater than 3,000m seems to be a more feasible solution since the CO_2 would stay in a more stable condition than at shallower depths (Wong and Hirai, 1997). Wong and Hirai (1997) calculated the size of a CO_2 ocean lake based on a 1GW coal fired power plant operating over 10 years. They concluded that 654,000 m^2 of seafloor and a depth of 80.9m is needed to contain a total of 58 million tonnes of liquefied gas produced from the power plant. The depth of 80.9m would obviously mean that liquid CO_2 might be spread out due to ocean current activities and result in a more widespread impact of CO_2. Even for a depth greater than 3,000m, it is estimated that a lake of CO_2 containing 58.5 Mtonne would dissolve into the deep water over a period of approximately 240 years (Johnston and Santillo, 2002).

In addition to that, the captured CO_2 in CCS could also be used for mineral carbonation and industrial uses. However, the scale of CO_2 utilization is small compared to total anthropogenic CO_2 emissions. Hence, the contribution of industrial uses of captured CO_2 to the mitigation of climate change is expected to be minimal (IPCC Working Group III, 2005)

2.7.2 Impact of CCS Technology

Effect on Atmosphere

The deployment of CCS could cause significant impact to the environment by reducing the CO_2 concentration in the atmosphere. Stangeland (2007) claims that one-third of the global CO_2 emissions could be reduced through CCS by 2050. A report by CCS info (CCS Info, 2009) claims that the net reduction of CO_2 by CCS technology is 70.5%. This is a drop from 79% CO_2 capture after accounting for the substantial greenhouse gas emissions produced during the CCS process. This process includes the mining of coal, transportation of coal, construction of CCS plant and transportation infrastructure, injection process, control and monitoring of storage facilities as well as the possible leakage at storage point and accidents at pipelines, ships and CO_2 injection facilities.

Industry and Fossil Fuel Power Station

With a projected increase of the world's human population to 8.92 billion by the year 2050 (United Nations, 2004), the world's energy consumption is expected to rise correspondingly (see Chapter 2.6). Currently, the world energy supply is heavily relying on fuel oil (33.5%), coal (26.8%) and gas (20.9%) (Energy State, 2010). The deployment of CCS would definitely ensure a continuous supply of world energy by using fossil fuels while playing a significant role in reducing the CO_2 emission into the atmosphere.

The application of CCS in fuel or coal power plants would increase the capital as well as operational cost. As large commercial scale projects on CCS do not exist, the electricity costs are uncertain. Some recent credible estimates indicate that the US industrial electricity price would increase by twice whereas the residential electricity price would increase by 50%. However, Viebahn *et al*. (2007) made a comparison of the electricity price of renewable energies with coal-powered power plant retrofitted with CCS system and concluded that the former system is more economically viable.

With carbon trading, fossil fuel power stations could benefit from CCS. As part of the European Emissions Trading Scheme (ETS), European Energy commissioner Andris Piebalgs has signalled that the Commission will support proposals to help fund twelve CCS demonstration projects using carbon allowances issued (Murray, 2008). This means that companies that invest in CCS will be able to earn credits for each tonne of carbon they store, in the same way companies currently earn credits for each tonne they prevent from entering the atmosphere.

2.7.3 Safety Issues of CCS

On closer examination of the CCS system, risk of CO_2 leakage might be possible if the CO_2 capture, transport and storage system are not properly design. The most serious impact of CO_2 leakages are likely to arise from the failure of transport pipelines and a large release of CO_2 in gaseous form. The risk of leakage and its environmental impact are reported to be the main concern of the public and this has proven to be an obstacle to the implementation of CCS around the world (Gough *et al.*, 2002, Upham and Roberts, 2010)

Due to the lack of understanding in the storage of CO_2 in geosphere and biosphere sinks, related industrial experience and scientific knowledge could serve as a basis for appropriate risk management. IPCC reported that there are two types of scenarios in which leakage of CO_2 would occur. In the first case, injection well failures and leakage of abandoned wells could create a sudden and rapid release of CO_2. In the second scenario, leakage could occur through undetected faults, fractures or through leaking wells where the CO_2 release to the surface is more gradual and diffuse.

The risk of leakage during transportation and liquefaction process will be discussed in detail in the subsequent section.

Transportations

Transportation of the captured CO_2 in CCS technology could be by CO_2 pipelines or CO_2 ships. Transportation of CO_2 by pipelines is a matured technology in the oil and gas industry whereas transportation of CO_2 by ship at CCS levels is unprecedented.

CO_2 Pipelines

Currently, CO_2 is not regulated as a dangerous fluid under the UK's Pipeline and Safety Regulations (PSR). Moonis and Wilday (2008) have recommended further investigation into the possibility of including CO_2 as a dangerous fluid under PSR. McGillivray and Wilday (2009) have performed a dispersion and risk modelling on the release of CO_2 from pipelines in order to determine the risk associated with. Their findings show that CO_2 captured in the CCS process has sufficient toxicity comparable to natural gas, hence CO_2 has to be regulated as a dangerous fluid under the PSR. Thus, the safety issues related to the transportation of CO_2 by pipelines would somewhat be similar to natural gas pipelines. There are substantial numbers of pipeline accidents over the past few decades. The US Department of Transportation's Research and Special Programs Administration, Office of Pipeline Safety (RSPA/OPS) statistic consolidated a set of 700 natural gas/hazardous liquid pipeline accidents occurred in the period between 2002 and 2003 (Corrosion-Doctor, 2011). It was reported that more than 25% of the transmission pipeline accident cases were due to corrosion whereas over 60% of distribution pipeline accidents were caused by external force damage such as damages from excavation and from natural forces. Other causes of pipeline accidents are the damage due to material/weld failure, equipment failure and explosion. Any failures on a CO_2 pipeline would certainly result in major catastrophic for the environment.

It is however interesting to note that the transportation of dry CO_2 has an advantage because it does not corrode the carbon-manganese steel used generally for pipelines, as long as the humidity is less that 60 % (Johnston and Santillo, 2002). It was reported in the IPCC report (Johnston and Santillo, 2002) that there have been less than one reported incident per year (0.0003 per km-year) and no injuries or fatalities by existing CO_2 pipelines. A list of existing long-distance CO_2 pipelines (Gale and Davidson, 2002) and CO_2 pipelines in North America (Courtesy of Oil and Gas Journal) is presented in Table 4.1 of the IPCC report (Johnston and Santillo, 2002). Barrie *et al* (2004) also claimed that CO_2 can be transported safely by ensuring that adequate risk assessments are carried out, and extra vigilance is used in designing the pipelines and operating the system. However, if CO_2 pipelines are to be constructed in densely populated area, there will be an increased risk to the public. Regular safety reviews must be performed on the operating pipeline, any recorded incidents should be studied carefully, and corrective procedures be established to prevent recurrence. The initial design should also include appropriate procedures for eventual abandonment of the pipelines and prevention of use of damaged equipment and material that are not replaced (Barrie *et al.*, 2004). For the case where free water is present, corrosion rate is much higher and might result in the formation of hydrates (Johnston and Santillo, 2002). Hence, it is not practical to transport wet CO_2 in low-alloy carbon steel pipelines due to the high corrosion rate. Alternatively, the wet CO_2 could be transported in the more expensive corrosion-resistant alloy (stainless steel).

CO_2 Ships

On the other hand, CO_2 transportation by ship has several similarities to the liquefied petroleum gas (LPG) transportation by ship. Current concept design of CO_2 ship is based on existing technology adopted in constructing LPG ship where the CO_2 is stored in a semi-pressurised tank near triple point, i.e. 6.5 bar and -52 ^oC. This triple point condition is important from the economic viewpoint of a large-scale CO_2 ship since CO_2 exists in the highest density under this condition. Storing CO_2 in ship tank under low temperature is a great challenge due to the fact that most metal and alloys appear less ductile (brittle) at low temperature. The tank has to be designed for brittle fracture to prevent spillage of liquid CO_2. Similar to the transportation of CO_2 by pipelines, special care has to be given to the formation of hydrates in CO_2 ship. In the event when CO_2 is loaded and unloaded from the ship, there is a high possibility of CO_2 released to the environment though pipes, pumps and marine loading arms (Barrio *et al.*, 2004). Hence, the marine systems have to be carefully chosen by taking into consideration their resistance to corrosion and low temperature, the need for maintenance, price and availability (Barrio *et al.*, 2004). The IPCC report considered a accident scenario where a liquid CO_2 tanker released liquefied CO_2 onto the surface of the sea. The temperature difference due to the interactions of the leaked CO_2 (low temperature and higher density) with the sea would induce strong currents. If there were little wind and a temperature inversion, clouds of CO_2 gas might lead to asphyxiation.

Alternatively, transportation of CO_2 in ship could also be in the form of CO_2-hydrate. In such cases, CO_2 in hydrate forms would only contain 30%, by weight of CO_2 with the balance (70%) being water (Mitsibishi Heavy Industry Ltd., July 2004). As these hydrates are meta-stable at atmospheric pressure and slightly sub-zero temperature, they could be transported in bulk without pressurisation or deep refrigeration. Transportation of CO_2 by ship has a relatively higher accidental rate as compared to pipelines. As summarised by Lloyds Maritime Information Service, there are 41,086 incidents of varying-degree ship casualties identified in the period between 1978 and 2000, in which 2,129 were classified as serious cases.

There is also proposal for transporting CO_2 and LNG in the same ship. This idea arises due to the need to store CO_2 in depleted gas fields where LNG is produced (Mitsibishi Heavy Industry Ltd., July 2004). However, the need to store LNG at a much lower temperature (-162^{o}C) than CO_2 (-50^{o}C) implies that more energy is required. Furthermore, there could be a risk of CO_2-LNG contamination which would take time in the order of days to purge CO_2 from cargo tanks before loading and unloading of LNG (Mitsibishi Heavy Industry Ltd., July 2004).

Temporary Storage Facilities (Liquefaction Plant)

The temporary storage facilities or the liquefaction plant are used to liquefy and store CO_2 temporarily before the liquefied CO_2 is transported for permanent storage. Similar to transportation of CO_2 by pipelines or ships, CO_2 leakage would be a main concern in the liquefaction plant and a higher risk is anticipated as CO_2 will be released directly to the atmosphere or sediments (affecting the groundwater). The process in the liquefaction plant differs depending on the location of the capture plant (fuel or coal power plant) and the liquefaction plant (usually built near the shore). If the CO2 capture plant is built remotely to the liquefaction plant, the CO_2 will be compressed and transported to the liquefaction plant by high pressure pipeline. If the CO_2 capture plant is built near to the liquefaction plant, the CO_2 will be fed directly to the liquefaction plant where the compression process is carried out in the plant. Hence, the former method has an advantage over the latter one as the CO_2 need not be compressed in the liquefaction plant, hence reducing the power consumption tremendously (Mitsibishi Heavy Industry Ltd., July 2004). However, locating the capture plant further away from the liquefaction plant would indicate an increase in onshore pipelines, hence increasing the risk of CO_2 release to the atmosphere and sediments further.

2.8 CCS Techniques

2.8.1 CO_2 Capture

Capturing CO_2 for CCS could be applied by using different methods. The conventional way is to capture CO_2 from a large point source, for example flue gas release during the combustions of fuel or coal power plant. Alternatively, CO_2 could also be captured directly from the air, by using the air capturing method. There are also other methods such as chemical looping combustions being proposed as a mean to capture CO_2.

Conventional Methods

Pre-Combustion

Removing CO_2 by pre-combustion system involves processing the primary fuel in a reactor with steam and air/oxygen to produce a mixture consisting mainly of carbon monoxide and hydrogen (syngas). The carbon monoxide is then reacted with steam in a second reactor (shift reactor) to produce CO_2 and hydrogen where the CO_2 is then transported for storage. On the other hand, the hydrogen could be used to drive turbine to produce power or alternatively used in the super-critical boiler to increase the efficiency of the power produced. This process is also known as the integrated gasification combined cycle (IGCC) where the additional power produced could be used to offset the energy required in the CO_2 capturing process.

Post-Combustion

The post-combustion system separates the CO_2 from the flue gas that is produced by the combustion of the primary fuel in air. These system normally uses liquid solvent to capture the small fraction of CO_2 (typically 3-15% by volume) present in a flue gas stream (IPCC Working Group III, 2005). For modern pulverised coal (PC) power plant, current post-combustion capture systems would typically employ an organic solvent such as monoethanolamine (MEA).

Oxy-Fuel

The oxyfuel combustion system uses oxygen instead of air for combustion of the primary fuel to produce a flue gas that contains main water vapour and CO_2. This results in a flue gas with a high CO_2 concentration (greater than 80% by volume). The water vapour is then removed by cooling and compressing the gas stream. Further treatment of the flue gas may be needed to remove air pollutants and non-condensed gases (such as nitrogen) from the flue gas before the CO_2 is sent for storage (IPCC).

Air-Capture

The air capturing method involves capturing the CO_2 directly from the atmosphere by using a CO_2 scrubbing towers, artificial tree or quicklime process.

David Keith from the University of Calgary has demonstrated a prototype of air scrubbing tower to remove CO_2 out of the air (see Fig. 2.1). The tower has a base of 4 square feet and a height of 20 feet tall, with a fan at the bottom that sucks air in. The air with reduced CO_2 will be released at the top of the tower. It was reported that such scrubbing tower is able to capture one tonne of CO_2 for less than 100 kWe power. This is equivalent to 10 times as much CO_2 that is released into the atmosphere during the scrubbing process (The Modern Green, 2008). The air scrubbing tower is also able to capture 5,000 times more CO_2 as compared to a tree.

Professor Klaus Lackner from the Columbia's Earth Institute has also designed a synthetic tree that mimics the function of a natural tree where the 'leaves' are able to remove CO_2 out of the air as the CO_2 flows over them. The captured CO_2 could then be stored deep underground. It is estimated that every single synthetic tree would be able to remove 90,000 tonnes of CO_2/year, which is equivalent to the emissions of 20,000 cars (BBC News, 2007, Calabrese, 2008).

Figure 2.1: Prototype of Air Capturing Tower
(source: www.carbonengineering.com)

Quicklime, also known as calcium oxide (CaO) could be used to absorb CO_2 from the atmospheric air by mixing with steam at 400^{o}C and releasing it at 1000^{o}C. This high temperature requirement could be achieved from thermal concentrated solar power (Nikulshina *et al.*, 2006).

The air scrubbing tower has several advantages and disadvantages compared with CO_2 captured from point source as listed in Table 2.3 (Carbon Engineering Ltd., 2011).

TABLE 2.3
ADVANTAGES AND DISADVANTAGES OF AIR CAPTURING METHOD

Advantages	**Disadvantages**
Air scrubbing could be made at any preferred location where geological storage sites are accessible, or where the costs of construction and energy are low	Air capture is a more difficult engineering challenge air capture facilities require more energy and large equipment to capture same quantity of CO_2 as would be captured from a power plant with CCS
Air scrubbing could be used to capture CO_2 from large emitted source such as from power plant or small emitted source such as vehicle	More expensive

<u>Chemical looping combustion</u>

Chemical looping combustion (CLC) is a combustion technology with inherent separation of the greenhouse gas such as CO_2. The technique involves the use of a metal oxide as an oxygen carrier which transfers oxygen from the combustion air to the fuel. The product of the combustion, CO_2 and water, will be kept separate from the rest of the flue gases (Mattison and Lyngfelt, 2001).

2.8.2 *Transport of CO_2*

Pipeline

Commercial-scale transportation of gaseous or liquefied CO_2 uses tanks, pipelines or ships. In order to occupy less volume, CO_2 is often liquefied before transportation. Gas liquefaction is a mature technology and has been used by ship in the LPG (liquefied petroleum gas) and LNG (liquefied natural gas) technology. Similar technology can be applied to CO_2 transportation with limited modification. Apart from that, CO_2 can also be transported in solid and hydrate form. However, solidification of CO_2 requires a lot more energy compared to other options. Furthermore, the hydrate technology is still under development. In view of the large volume involved, pressurised pipelines are considered to be the most practical under today's technology development. In CO_2 pipeline transportation, the volume of CO_2 is reduced by transporting at high pressure and low temperature, where the operating pressures are between 10 to 80 MPa and temperature is generally below 50 ^{o}C.

Although CO_2 may be transported in a solid (dry ice) form in small quantities, the only practical method for distribution of large volumes of CO_2 are:

- transport under refrigerated and/or pressurised conditions
- by engineered pipeline or by ship
- when the CO_2 phase is either a supercritical fluid or fully liquid

Pipelines require a longer lead time and design period to integrate with permanent capture and storage infrastructure. However, pipelines are simple to operate, have high capacity and are economically viable over short to medium distances (up to about 1,500km). (IPCC Working Group III, 2005)

For longer distances, ships can be proved to be more economically viable. Ships offer greater flexibility in which they could operate (conceivably covering several capture and sequestration sites) and be mobilised quickly once built. However, it offers the disadvantage of irregular supply in which liquefaction and temporary storage facilities may be necessary at the capture and/or permanent storage sites.

Pipelines are the most common method for transporting large quantities of CO_2 over long distances. There are currently about 6200km of existing CO_2 pipelines (see Fig. 2.2) globally in the operating with an annual injection of about 50 million metric tonnes CO_2(ETSAP, 2010). Texas, United States, has the oldest long-distance CO_2 pipeline of 225-kilometer, which began its services in 1972 to provide enhance oil recovery (EOR) to the region's oil fields. After which the CO2 pipeline network for EOR has been developed and 13 other large CO_2 pipelines have been constructed, predominantly in the Western United States (Parfomak and Folger, 2007). These pipelines transport CO_2 from places all over the United States-underground reservoirs, natural gas processing facilities, ammonia manufacturing plants, and a large coal gasification project to the oil fields. Additional pipelines may carry CO_2 from other sources to supply a range of industrial applications such as the food industry

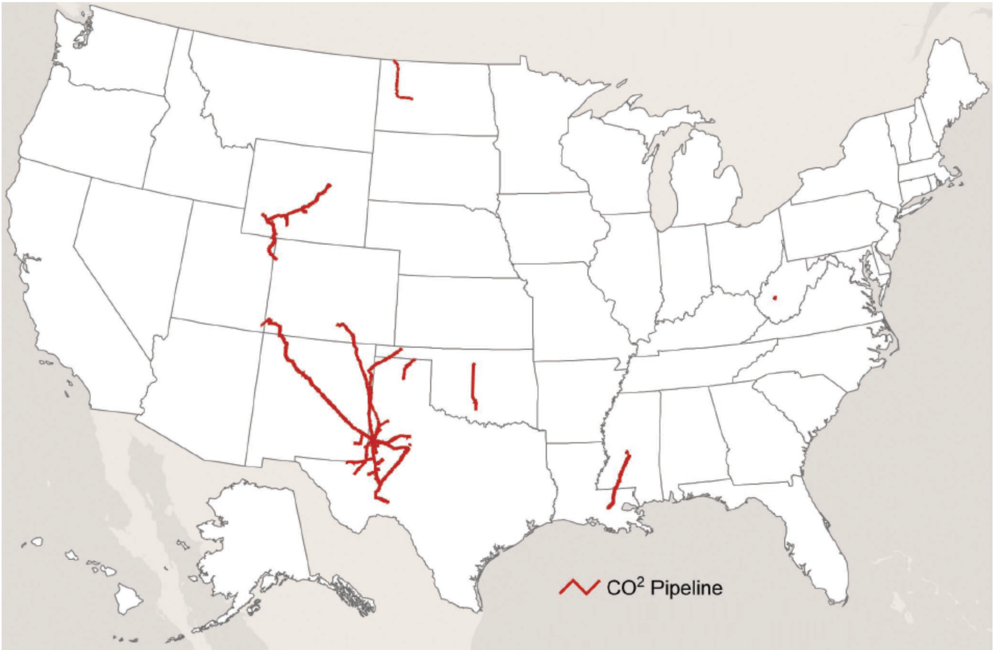

Figure 2.2: Existing CO_2 Pipeline Network in the US
Source: U.S. Dept. of Transportation, National Pipeline Mapping System, (June 2005).
(https://www.npms.phmsa.dot.gov)

The future scenario is still unclear on the size and layout of the pipeline network, although dedicated CO_2 pipelines are required. This uncertainty is due to the uncertainty of suitable geological formation to store the captured CO_2. One recent analysis (Dooley *et al.*, 2004) predicts that 77% of the total annual CO_2 captured from the major North America may be stored in underground reservoirs laying directly under these sources, and that an additional 18% may be stored within 100 miles of additional sources. If this is the case, new CO_2 pipelines would be limited for onsite transportation and only a relatively small number of long-distance pipelines are required.

<u>Ships</u>

In order to maximise the mass of CO_2 to be carried in a fixed volume, solid CO_2 with a density of 1500 kg/m^3 offers the densest state, but on the other hand could also offer difficulties in handling the material. From this point of view, liquid phase transportation offers the best combination of an economic density, and ease in storage and handling (Aspelund *et al.*, 2004).

Figure 2.3 shows the phases of CO_2 under different pressures and temperatures conditions. For large scale transportation, it is desirable to transport the CO_2 in liquid form under low pressure. By referring to Fig. 2.2, this desirable CO_2 phase falls somewhere along the saturation line between the Triple Point and critical point. The density of the liquid CO_2 varies between 1200 kg/m^3 at the Triple Point (5.2vbar, -57°C) and 600 kg/m^3 (73.8 bar, 31°C) at the critical point. Any of these 'semi-pressurised, semi-refrigerated' or 'fully pressurised' options are technically feasible for ships. However, 'fully refrigerated' condition is not feasible as the vapour would condense directly to solid below the Triple Point temperature regardless of the pressure.

Transportation of CO_2 close to the Triple Point becomes the most desirable condition since lower temperatures are easier to achieve than higher pressures. Furthermore, liquid CO_2 has greater density at Triple Point. The rate of change of density around the critical point is also much greater than around the Triple Point. A typical working condition for the CO_2 near the Triple Point with allowance for some tolerances is 6.5bar and-52°C. This is approximately the pressure of a racing bicycle tyre. It is to be noted that these working conditions are very similar to refrigeration and pressurisation technologies of existing LPG carriers that operate at around -50°C /-55°C and 6-7 bar. The largest LNG carrier operates at the atmospheric pressure and at a temperature around -163°C. Note that CO_2 will not liquefy even at this temperature without pressurisation. Conversely, fully pressurised LPG tankers that operate at the ambient temperature but at 18 bar would require careful engineering consideration with typically spherical tanks design.

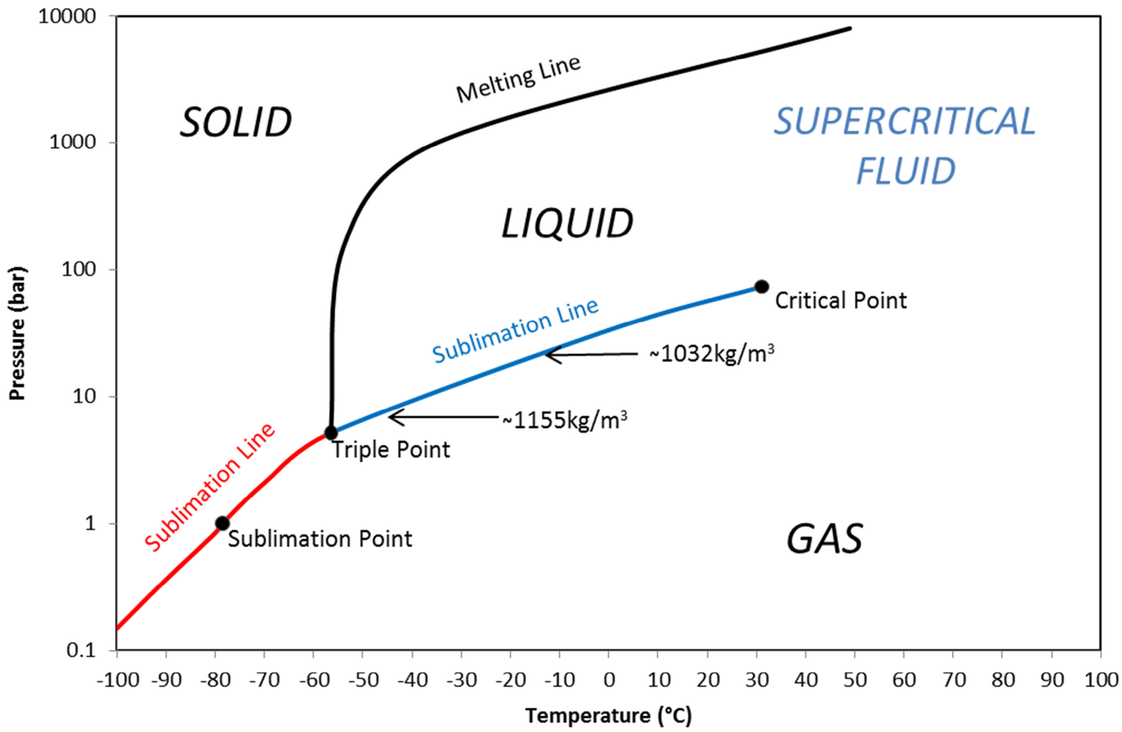

Figure 2.3: Phase Diagram for Carbon Dioxide

A handful of ships has already been designed for transportation of CO_2 in relatively small quantities. The Coral Carbonic built in 1999 for the Dutch gas and liquid transport specialist -- Anthony Veder, operates in the Northern Europe; The ship has 1250m^3 capacity in cylindrical tanks with maximum working pressure around 18-20 bar and temperature down to -40°C (Veder, 2011) The ship provides ultra clean CO_2 to the specialist market for used in the food packaging industry.

Yara, the Norwegian agricultural chemical company, also operates three small CO_2 vessels for distributing liquid CO_2 to terminals in countries around the North Sea area. They serve the demand of CO_2 for the food and beverage industry as well as also for the civil explosive and mining communities. The vessels carry around 1500 m^3 of CO_2 in cylindrical tanks at a pressure of about 14-20 bar.

For CCS purposes, a number of design concepts have been presented to the industry through seminars and conferences. Korean Shipbuilder DSME suggests that existing spherical, cylindrical and bi-lobal design pressure vessels are inappropriate for capacities greater than 50,000 m^3 (Yoo *et al.*, 2010). They have proposed a 100,000 m^3 CO_2 ship design with multiple vertical cylinder tanks. The proposed *DSME ECO2* CO_2 ship uses one hundred cylinders (25-meter tall and 7-meter diameter) and operates at -50°C and 6.8 bar. For short voyages, there would be no refrigeration on board and the pressure could be built up in the cylinders. For longer voyages, a design with a re-liquefaction unit on board was proposed.

Danish shipping giant Maersk, has designed semi-pressurised and semi-refrigerated CO_2 carriers alongside partner Korean shipbuilder HHI (Hyundai) (Klara and Plunkett, 2010). CO_2 could be carried out at a volumes of 15,000 m^3 to 85,000 m^3 but Maersk suggests that a lead time of 2 to 3 years are needed for these ships to be built. Maersk envisages a system where the CO_2 carriers could supply a 'Floating Storage and Injection Unit' (FSIU) along the lines of existing FPSOs, with injection via a turret system.

German gas transport consultancy TGE, in conjunction with the aforementioned Anthony Veder shipping company have proposed a 20,000m^3 CO_2 carrier (Rai *et al.*, 2010). This carrier is equipped with dynamic positioning and turret systems for the discharge of CO_2 at the well head via a floating connector. A similar turret based concept was also proposed by Aspelund *et al.* (2006)

TGE has also tentatively suggested (Munko, 2010) a novel barge carrier concept. This concept comprises of a host ship with a free flooding dock area that is able to carry six large CO_2 tanks. The tanks are designed as free floating barges and could be manoeuvred by tugs to the discharge area.

MHI (Mitsubishi of Japan) (Mitsibishi Heavy Industry Ltd., July 2004) presented their CO_2 ship design which use sphere type tanks. They suggested that 50,000 tonne ship is the largest possible capacity that could be built with current shipbuilding technology.

Ship Design

The design spiral required to bring the CO_2 ship carrier concepts to reality would take several years. A further potential option that would offer immediate capability is the conversion of existing Liquefied Petroleum Gas (LPG) ship. Modifications of the existing LPG ship would require at least two pumps, compression/decompression systems and loading/discharge arrangements for handling the CO_2.

In terms of regulations, the International Maritime Organization's (IMO) International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) is relevant and categorises liquefied CO_2 as 'Type 3G' cargo. The categorisation 'Type 3G' as non-flammable and non-toxic cargo makes it less hazardous than LNG/LPG cargo, hence the ship design should be relatively more straightforward with the current shipbuilding technology.

The properties of the CO_2 have to be considered in design. While dry pure CO_2 presents no problems in contact with steel, wet and impure CO_2 is expected to be quite corrosive for carbon steels. Expensive chromium or high-alloy steels may be required in the steel critical areas.

2.8.3 Storage of CO_2

It is argued that CO2 could be held in geological formations because they already hold gas or liquids for geological timescales. Much work is needed to investigate the geological formations of the confinement used for CO_2 storage, especially on the characteristics of the caps rocks and seals. Such research works is currently underway for the Mount Simon Formation in the USA and the Utsira formation in the North Sea (Gale, 2004).

Not all storage locations are compatible with emissions sources. It will be easier to align CO_2 emissions with storage in densely populated areas as compared to sparsely populated areas. It is projected that 50% of the storage location can be successfully matched with CO_2 emissions (Gale, 2004).

One of the biggest concerns with CO_2 storage is leakage; it is also to some extent unavoidable. However it must be kept at a minimum and below an acceptable level. Therefore, acceptable flux rates have to be determined. The leakage would have to be less than 0.1% of the stored CO_2 in order to ensure that the storage does not turn to an emission source (Gale, 2004). Small seepages would affect the local environment close the storage. The consequence of the seepage depends on the location of the storage. CO_2 could possibly end up pooling at the bottom of buildings or at the basement on the land. This phenomenon has happened naturally due to volcanic activity (Gale, 2004). If CO_2 leaks into the water aquifers, water pollution could occur and would be a great concern if the water is used for drinking. CO_2 leakage into the sea would also change the pH value which could affect the ecosystem (Gale, 2004). However, The effects of CO_2 on underground potable water and on the eco-marine life have not been fully investigated (Gale, 2004).

Large leakages would cause health and safety risks to all humans in close proximity as well as a disturbance to the marine sediments and marine ecosystem (Gale, 2004). The purpose of sequestration is to prevent the CO_2 from reaching the atmosphere. A risk of leakage would negate the prupose of sequestration.

When storing CO_2 it is convenient to store it at its super critical state. There are two major CO_2 sinks, i.e. the geosphere sink and biosphere sink.

<u>Geosphere Sinks</u>

Geosphere sinks are natural basins for carbon dioxide that need to be improved in order to store CO_2 safely (Wong and Bioletti, 2002). Geophere sinks comprise saline aquifers, oil and gas fields and coal seams

Saline Aquifers

Saline aquifers are geological formations of spaces enclosed by rocks. These rocks are saturated with saltwater in which the salty water (brine) is unsuitable for drinking, industry and agriculture purposes. The estimated storage capacity for saline reservoirs is between 400 to 10 000 Gt CO_2. This storage capacity is equivalent to 20-500% of the estimated CO_2 emissions up to year 2050 (Gale, 2004). The best storage condition is found in aquifers with a depth of over 800 m since the CO_2 will appear to be in the supercritical stage (Haimin *et al.*, 2011).

The supercritical state is a state where a substance exists between gas and liquid. Gas exists in high liquidity, with high density and low viscosity. The super critical state occurs when CO_2 is above 31.1°C and the pressure is above 7.38 MPa. The volume of the CO_2 at this state is 1.34 m^3 per tonne (Haimin *et al.*, 2011).

When CO_2 is injected into an aquifer, only a small part of the CO_2 will dissolve whereas the rest will move upwards to the cap rock. The CO_2 will then mix with water when it reaches the cap rock and become less concentrated. As a result, it will be trapped in the aquifer by capillary pressure (Haimin *et al.*, 2011). However, the aquifers are subjected to a larger start-up cost as compared to the gas and oil fields since extensive geological surveys have to be carried out. The world's first carbon capture project is run by Statoil at Sleipner gas field in the North Sea. This project has been operating since 1996 and contained 11 Mt CO_2 in 2008 (Chadwick, 2011).

Oil and Gas Fields

Oil and gas fields have contained oil or gas for a long time and this implies that they could be used to store CO_2 over geological time scales (Grimston *et al.*, 2001). Besides that, they are also geologically stable. The geological structure and physical properties of most formations have been extensively mapped and existing models to predict the displacement and trapping behaviour of the CO_2 for enhanced oil recovery (EOR) are already available (Grimston *et al.*, 2001).

It is estimated that the depleted gas and oil fields are able to store 920 Gt CO_2 or 45% of the estimated CO_2 emissions up to year 2050 (Gale, 2004).

Enhanced oil recovery (EOR) is a technique used to extract fossil fuel by injecting CO_2 into an oil or gas field in order to increase the well pressure. Crude oil recovery is divided into three phases; primary, secondary and tertiary.

- In the primary phase, oil is reclaimed by using the natural pressure of the reservoir with the help of pumping in order to get the oil to the surface. 10 % of the original amount of oil is recovered during the primary phase.

- During the secondary phase water is injected into the field in order to increase the pressure and drive the wellbore. 20% to 40% of the oil is recovered during the secondary phase. However, most of this "easy reachable" oil has already been reclaimed from the U.S. oil fields.

- During the tertiary phase, which is also known as EOR, it is estimated that 30% to 60% (or more) of the original amount of oil in the field can be recovered (Fossil Energy Office of Communications, 2011).

Large scale EOR was first tried in Texas in 1972 and is currently used in about 70 oil fields, most in West Texas. They store an estimated 31 million m^3 CO_2 per day (Grimston *et al.*, 2001). Approximately 80% of the commercially capture CO_2 is used for EOR (Grimston *et al.*, 2001).

Coal Seam

Deep coal seams such as unminable coal mines can be used as CO_2 storage if the pressure and temperature are suitable to store CO_2 (Haimin *et al.*, 2011). CO_2 could be used in methane production, where CO_2 will react with the unused coal. In this process, the CO_2 will bind with the coal and release methane (CH_4). The coal will bind two CO_2 molecules for each methane molecule released. This process is also known as the enhance coal bed methane recovery. In 1996, 5% or 28 million m^3 of the U.S. methane production was extracted this way (Grimston *et al.*, 2001).

Unminable coal seams are estimated to have a capacity to store 20 Gt of CO_2 which corresponds to less than 2% of the estimated total global emissions up to year 2050 (Gale, 2004). The technology for storing CO_2 in coal seams is behind that of other sequestration methods. Even though the overall potential for storing CO_2 in coal seam is low, it must not be discarded since it could have advantages in particular localities.

<u>Biosphere Sinks</u>

Biosphere sinks are natural active basins for CO_2. Biosphere sinks comprises of oceans, soil and standing biomass stocks, wetlands and material sinks.

Ocean

The ocean covers 2/3 of the earth surface and is currently storing over 39,000 billion tonnes of carbon, GtC (Grimston *et al.*, 2001). There are several ways to release CO_2 into the sea. The CO_2 can be released in a liquid form from a pipe towed by a ship where the CO_2 is released at a depth of 1,000 m and will form a rising plume. It can also be injected to the sea by using a manifold lying on the bottom at a depth of 1,000 m (Grimston *et al.*, 2001). At a depth of 4,000 m, CO_2 could be injected into a seabed valley to form a stable "deep lake". If CO_2 is mixed with water to create a dense mix, it can be injected at a depth between 500 to 1,000 m since it will then sink to the bottom. It is also possible to release CO_2 into the sea at the water surface in the form of ice (Grimston *et al.*, 2001).

CO_2 will move through different phases depending on the pressure and therefore the depth. Submerged CO_2 will reach the triple point at a depth of 52 m where the pressure is 5.2 bar (Murray *et al.*, 1996). CO_2 only appears in gaseous form at relatively low pressures and if the pressure increases, it will turn into liquid. The pressure in sea water also increases 1 atm per 10 meters depth and most of the deep sea has a pressure of 200 atm to 600 atm. Therefore, it is most likely that CO_2 will be in a liquid form in the deep sea below 1,800m, where the temperature is between 2°C to 4°C.

Soil and Standing Biomass Stock

The soil and vegetation have already hold 760 GtC (Grimston *et al.*, 2001). However, there is no guarantee that the vegetation will last for geological time scales, especially if there is a change in the climate (Grimston *et al.*, 2001).

Wetlands

Coastal wetlands and sea grass beds capture and store a significant amount of CO_2 naturally. Even though sea grass beds only occupy 2% of the sea bed, it is within these sea beds that 50% of the CO_2 is transferred from the ocean to sediments (Crooks *et al.*, 2010).

Material Sinks

Material sinks are man-made items entrapping CO_2 such as durable wood products, chemicals and plastics (Wong and Bioletti, 2002). However material sinks are not currently recognised as a reduction option (Grimston *et al.*, 2001).

2.9 CCS CONTEXT IN SOCIETY

2.9.1 Public Perception of CCS

Public perception has been recognized as a vital part of the successful deployment of large scale engineering projects. CCS will also be subjected to public scrutiny. Relatively little research has been conducted to date regarding public reactions on CCS, but three scholarly papers and one technical report on this topic have been reviewed in the literature.

David Reiner (Reiner *et al.*, 2006) has conducted a survey study with the aim to compare the public perceptions on the energy and environment in the US, UK, Sweden and Japan. The survey emphasises particularly the public attitudes towards CCS. In the survey, the respondents were asked their opinion on various energy technologies, such as wind energy, nuclear energy, hydrogen power and CCS. The respondents' understanding on the relationship between the energy generation technologies and the environment impacts were also being tested. They found that the public in the studied countries has generally low or very low awareness of CCS technologies. Another important finding is that people tend to have the impression that "greener" energies such as CCS will often lead to higher electricity bills.

Shackley *et al.* (2005) conducted a study on the public perception on CCS in 2004 in the UK. The two major objectives of this report were to firstly explore the public perception on CCS in the UK and to secondly understand the public perceptions on the risk and safety surrounding the CCS. Two citizen panels were formed in 2002 and 2003 to explore the public perception on CCS. Each panel held several meetings where technical experts were invited to give presentations on CCS. In the meantime, 212 face-to-face interviews were also conducted in a UK airport in 2003. After a short introduction to CCS, respondents were asked to describe their opinions on CCS. Although the sample size is relatively small, clear conclusions can still be drawn from this study; the survey results showed that most people were either slightly against or had no opinion when first introduced to CCS. However, moderate support was noted once the purposes of CCS were explained. It is reported that after explanation on CCS, CCS was slightly supported by 43% of the respondents and strongly supported by a further 12%, with 22% against. This indicated that the public support for CCS is somehow conditional, depending on their understanding on CO_2 mitigation purposes and the risks associated with CCS.

The survey also indicated that leakage appears to be the number one concern among respondents (49% expressed concern) with the effect on ecosystems ranked second (31%). The third and fourth ranked concerns were, respectively, the new and untested nature of the technology and the possible impacts on human health. It was also noted that more certainty about the risks of CCS in the long-term would help people form a clear decision about the desirability of CCS. The end of the study also suggested that a transparent, inclusive and open decision-making process could be very helpful to increase the public acceptability.

In 2007, Morris (2007) conducted a worldwide assessment study in a paper entitled "carbon capture and storage public perception of CCS". A number of aspects of CCS were covered in this study. For example, cost of deployment, scale of deployment, perceived risks, information accessibility and policy issues. With regards to the cost of deployment, the paper concluded that the public often have the impression that CCS projects are large as compared to some other "green" options and required high capital investments.

The public generally has little understanding on the feasibility of the deployment and the effects of CCS on the energy system. There is relatively little information gathered, neither in the journalistic media nor in the public forum, which results in little material for the formation of initial public perception on the risks of CCS.

Reiner (2006) conducted a survey study on the public attitudes towards the energy and environmental concerns in 2003. Over 1,200 people representing a general population sample of the United States participated in the survey. The goal of this study was to try and understand people's attitudes towards global warming and climate change mitigation technologies. The public could generally correctly identify that automobiles, coal burning power plants and factories are the main sources of CO_2 emission, but when they are asked on their concern on global warming, global warming only ranked ninth on a list of 10 comparable environmental problems.

An interesting part of this study was that the survey included questions asking about the respondents' willingness to pay extra on their electricity bill to cut CO_2 emission. Based on the responses, the average financial willingness of the public to pay for the CO_2 bill was around US$6.5 per month. This sensitivity figure could be a good indicator on the level of surcharge that would be sustainable when calculating the "green energy" cost recovery that involves CCS. Further study of the cost showed that CCS could potentially double the electricity price which was cited as almost the same cost as 100% nuclear power. However, it was suggested that renewable energy (solar and wind power) would increase the unit electricity cost up to 1.6 times compare to CCS or nuclear power price. The authors expressed doubt that the public would maintain their support for renewable energy if such additional costs were associated with them.

Apart from scholarly studies, the views of some environmental pressure groups can be seen from their public literature. For example Greenpeace (2008) holds a strong negative view on CCS. They argued that CCS will not be ready in time to make a strong impact on reducing the atmospheric CO_2 levels as they see CCS as being years away from being market-ready. Furthermore, they suggested that CCS requires around 10% to 40% extra energy. Similar to the general public's concerns noted above, Greenpeace believed that storing CO_2 underground is risky.

Summarising the main points from the articles on public perception:

- Global warming is not seen as a pressing concern compared to other environmental issues.
- CCS is not well known among the public in a wide range of regions surveyed including EU, UK, Australia and the US.
- Most of the studies predicted that the pilot projects or industrial-scale demonstration projects have the potential of having a big impact on the public perception on CCS.
- Communicating transparently or increased educational efforts may play a critical role in promoting and realising CCS.
- Renewable energies are strongly preferred by the public over the nuclear option and CCS is negatively associated with fossil fuel power.
- Regarding CCS itself, leakage after sequestration is the number one concern among the public.

2.9.2 Real Life Perception Experiences

In Holland, Royal Dutch Shell eventually failed in an attempt to begin sequestering CO_2 in near-depleted gas fields near the town of Barendrecht, despite initial government backing. They planned a 10 million tonne sequestration over 25 years. Despite following common practice, including the opening of a public information centre, public unrest ensued including stormy public meetings with Shell amid fears of eruption of CO_2 from beneath the ground, suffocation by released gas, water acidification, the effect on land values, the effect on tourism and so on (Feenstra *et al.*, 2010a). Local politicians also opposed the project. Shell itself conceded that their public relations material could have been much better, in particular they produced diagrams that failed to show to scale how deeply underground the storage was (Voosen, 2010b). The Dutch government eventually cancelled the project in November 2010 citing the lack of public support and also claimed that other projects outside the Netherlands provide demonstration of CCS technology.

Land based sequestration projects have also hit problems from public concern in Germany. In the town of Beeskow, in the Brandenburg area south west of Berlin, the German arm of Swedish power company Vattenfall aimed to sequester CO_2 from its Schwarze Pumpe oxyfuel demonstrator (Voosen, 2010a). Vattenfall also set up an information centre in the town, but the public formed action groups to put pressure on politicians (Fischer, 2010). Brandenburg is a major coal producing area, so may face increased pressure from the German Federal government to adopt CCS in coming years.

German power company RWE also faced public opposition resulting in the suspension of a power plant capture project in Hürth and the halting of exploration of potential storage sites in Schleswig Holstein.

Similar fears surfaced as in Barendrecht, German objectors also cited the case in 2008 in Mönchengladbach where there was a CO_2 leak from a factory's fire-suppressant system. The gas pooled in the town and several residents passed out due to lack of air. The cloud was finally dispersed by helicopters. Twenty people required hospital attention. They also cited the 1986 Lake Nyos incident (see Chapter 2.7.1)

The proposed Longannet sequestration project in Scotland, including a pipeline extension, does not appear to have received strong objection. The area is already heavily involved in offshore engineering, and the Scottish Parliament has suggested that 5000 jobs could be created by the project (Government, 2011).

Whilst several injection projects are in action, including the subsea project at Sleipner in Norwegian waters, these cases clearly demonstrate that the public have the power to prevent even CCS demonstration projects from happening, let alone full scale projects. The challenge of creating a positive public perception about CCS and gaining public acceptance should be major considerations for any CCS project alongside the technical challenge.

2.9.3 Motivation for Adopting CCS

CCS is being motivated by public concern about climate change upwards through national and international political arenas. At international level, the focus for climate change is the United Nations, through the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. The 'Annex I' or developed countries accepted greenhouse gas (GHG) emissions targets which in general they have taken seriously. The US did not sign the Kyoto Protocol but manages its own emissions targets.

The 1992 'Earth Summit' and Rio Convention established international desire to reduce GHG emissions but failed to establish targets and mechanisms for doing so; the 1997 Kyoto Protocol attempted to address these drawbacks and did succeed in gaining commitments from many nations.

The Kyoto Protocol is a convention to the UNFCCC aimed at tackling global warming by achieving "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." (Article 2), and specifically mentions "Carbon sequestration technologies" at Article 2.1.

The protocol came into force in 2005. Only the United States has not ratified the protocol; President George W. Bush on his election in 2000 stated that he took climate change "very seriously," but "I oppose the Kyoto Protocol because it exempts 80% of the world, including major population centres such as China and India, from compliance, and would cause serious harm to the U.S. economy" (Dessai, 2001)

Thirty seven developed countries, the 'Annex I' countries, committed themselves to a reduction of collective GHG emissions, including CO_2. As a first stage target, a reduction of 5.2% from the 1990 levels by 2012 is required. Several 'flexible mechanisms' are included such as carbon trading, the Clean Development Mechanism (CDM) and Joint Implementation (JI) to allow emission 'credits' countries either by financial transaction with other countries or contribution to emission reduction projects. China and India were not Annex I countries.

Each Annex I country meets annually at the 'Conference of Parties' (COP) to confirm progress through an annual report on its anthropogenic greenhouse gas emission, and details of projects they wish to be considered for accreditation under the 'CDM' process. However, UNFCCC recognizes that even if the Annex I countries meet the first round commitments, much greater reductions will be required in future to meet the long term objective of stabilising global GHG levels.

Long term motivation for climate change management and the implications for CCS will be once again in focus in 2012 as the Kyoto first round deadline for the Annex I countries approaches. Already many commentators suggest that with the rapid growth of China and India, and the non-participation of the US, that the Kyoto Protocol has become increasingly meaningless. Yvo de Boer, Secretary General of the UNFCCC 2006-2010, has stated (on future prospects) “The spirit of the Kyoto Protocol has disappeared. Its body is being artificially kept alive and perhaps some of the organs may get transplanted. But we have to admit that the Kyoto Protocol is dead” (PÖtter, 2011).

Mandatory GHG reduction in a post-Kyoto world therefore is rather unclear at this stage, although world leaders at the 33^{rd} G8 summit in 2007 said they would "aim to at least halve global CO_2 emissions by 2050" within the UNFCCC framework and want to include the emerging economies.

Financial Incentives

Generally speaking, policies that could encourage CCS implementation include:

- creating a value for CO_2 emission reductions (for example in an Emissions Trading Scheme)
- providing public funds, tax incentives or subsidies;
- establish mechanisms to reduce uncertainties, including a long term liability regime
- make CCS technologies compulsory

The trading schemes have received mixed reactions but generally seem to have been the most powerful way that large scale CCS projects have been supported by governments. Nevertheless, Carbon Trading has increased substantially in recent years as seen in Fig. 2.4.

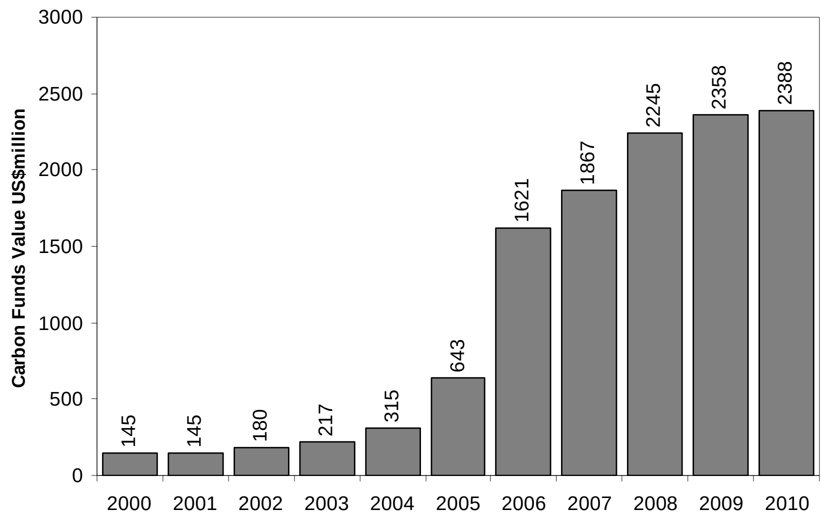

Figure 2.4: Growth of Carbon Funds and Facilities at theWorld Bank
(Data source:World Bank Carbon Trading Unit)

The European Commission is attempting to support the construction of 10-12 CCS demonstration projects across Europe by 2015. These would be supported by 300 million credits in the EU ETS carbon trading programme (O'Brien, 2009) whose value is highly variable but were about €11/tonne in August 2011. The peak was about €20/tonne reached in late 2010. Additionally €1.05 billion is available to CCS projects who may apply for funding as part of the European Economic Recovery Programme. As an example of the distribution of this fund, the UK government has held a competition for its €180 million share and is yet to confirm the sole remaining candidate, the Longannet project in Scotland as its choice.

Carbon Taxes

A number of nations have already introduced Carbon Taxes as a mean to provide for environmental projects including CCS.

Since 1991, Norway has employed a carbon tax (at approximately US$55 per tonne of CO_2) on carbon emissions from offshore oil and gas activities. This has encouraged CO_2 sequestration at the Sleipner field for example. The other Scandivian countries: Finland, Sweden and Denmark have also brought Carbon Taxes into force.

India introduced a carbon tax in July 2010 of approximately US$1 per tonne of coal produced or imported by/to the country. The tax should raise around $535 million that may be used to help fund a 'National Clean Energy Fund' (Natalie Obiko Pearson, 2011) - likely to be used to increase the power network to better encompass renewable energy sites.

Australia is close to implementing a general Carbon Tax and in July 2011 announced publicly that the 500 largest polluters in Australia would be taxed at a rate $23/tonne of carbon dioxide emitted from July 2012.

Other nations with operating Carbon Tax schemes include the Netherlands, Ireland and Switzerland, Costa Rica, also some provinces of Canada, also Colorado, California and Maryland states of the US.

Many more nations have announced their intention to implement Carbon Tax legislation

2.9.4 Government's Roles in CCS

International

The international governmental community's views on CCS must be seen in context of Kyoto commitments (see 2.9.3). The sources of motivation for adopting CCS vary from country to country, but generally speaking the international community has embraced the objectives of the 1992 Rio Convention and the 1997 Kyoto protocol which recognises CCS as a valid approach to GHG emission reduction. Naturally some nations see the technology development as an opportunity to develop expertise that may be sold, licensed or exported in other nations.

Considering the G7 countries plus India and China gives a cross section of the capabilities of the major GHG emitters:

CANADA The federal government in the 2008 and 2009 budgets invested approximately $1.4 billion in Carbon Capture and Storage development. In July 2008, Alberta province announced a $2 billion investment in four large-scale carbon capture and storage projects

FRANCE has little interest in CCS as it is a high nuclear power user, but is funding an oxyfuel demonstrator system.

GERMANY generates a high proportion of its energy from coal and has allowed commercial development of an oxyfuel project in Schwarze-Pumpe, and a pilot scrubber at Niederaußem.

ITALY has cancelled a post-combustion demonstration at Porto Tolle.

JAPAN has one geological deposition demonstrator at Nagaaka.

UNITED KINGDOM has an oxyfuel demonstrator in Scotland and also a CCS demonstrator awaiting approval - including piping captured CO_2 to a subsea storage site.

UNITED STATES has more than a dozen CCS projects running with land based sequestration, used for EOR or gas recovery in each case. President Obama has stated that America will lead the fight against climate change and has put forward proposals to cut greenhouse gas emissions by 80% compared to 1990 levels by 2050.

INDIA is appears to have little interest in CCS. It generates power mainly from coal and is currently building a series of coal fired 'Ultra Mega Power Plants' that will not use CCS at start-up

CHINA is also Kyoto I exempt and does not have meaningful CCS capability yet.

Also NORWAY and AUSTRALIA have demonstrated commitment to CCS through large CCS projects.

UK

CCS could have a major impact on the global CO_2 emissions if it is economically and technically feasible on the large scale. In UK, one third of the electricity demand [ref] is being met by the coal fired power plant during normal operations. The UK government is in support of CCS demonstration projects, which include both pre- and post-combustion coal projects. The Government also intended to provide up to £90 million public funds for detailed design and development work (front end engineering design studies) (Environmental Audit Committee, August 2009). David Hughes from the IOR views (IOR Views, 2006) summarised the following European Government actions in support of CCS:

- The Energy Review reported that the UK government is seeking to amend the London Convention which protects the marine environment worldwide to allow CO_2 storage beneath the seabed. It is also seeking changes to the OSPAR convention which provides further protection to the environment in the North East Atlantic.

- On the regulatory side, the UK government, in collaboration with Norway, is looking at arrangements for the licensing of CO_2 storage sites, and the issues surrounding the decommissioning of such sites and the associated long-term liabilities.

- The government sees the requirements for the CCS infrastructure as a major challenge which would benefit from coordinated international action. Hence, the UK and Norway announced in June 2006 a CCS joint project in the North Sea which will examine the likely future need for a pipeline network and the cost effective ways of realising the benefits of CCS.

- On the legal and regulatory framework, the government is examining how existing tax rules impact the change of use of oil and gas infrastructure to CCS. A crucial step is to ensure that the environmental benefits of CCS are rewarded under schemes and policies designed to encourage CO_2 emissions reductions in such a way that they can influence investment decisions.

- CCS is now recognised under Kyoto, and the government is working with EU partners to ensure that it is recognised as a Clean Development Mechanism (CDM) by the UN. The government is also pushing for CCS to be recognised within the EU Emissions Trading Scheme (ETS).

- The next step is a commercial demonstration of CCS. The Treasury is examining the costs of such demonstration projects and a statement will be made in November/December 2006 in the Pre-Budget Report.

Up to £1 billion fund has been made available for the first CCS demonstration project in UK, which is to date the largest public funding contribution in the world for a single CCS project (Department of Energy and Climate Change, 2010). The European Commissions also intent to stimulate the construction and operation of a set of CCS demonstration projects by 2015 (European Commission Energy, 2010, CCS Network, 2011) and had presented a strategy to support the development of these CCS projects, which include the launching of a European Industrial Initiation on CCS. A proposal to allocate an amount of €4 billion funding to cutting-edge climate technologies such as renewables and CCS has been proposed by the Commission on 3 November 2010. The so-called 'New Entrant Reserve 300' fund was agreed in 2008 by EU heads of state to support CCS technology – a method of burying harmful greenhouse gases spewed by industrial activity (EurActiv, 2010).

2.9.5 National and International Legal Landscapes

The 2005 IPCC report (Metz *et al.*, 2005) suggests that with regard to legal issues surrounding CCS, many nations have some petroleum, mining or drinking water related legislation of relevance to CCS. The issue of long term liabilities for injection sites and responsibilities for the environmental impact of unintentional CO_2 release remains undeveloped. This is particularly important because of the intention that sequestered CO_2 should remain in place for an indefinite period.

According to customary international law, states have the right to conduct activities such as CCS in the areas under their jurisdiction. When there is a trans-boundary effect, the ‘polluter pays’ principle applies. In disputes, decisions will be made by the ‘World Court’, the International Court of Justice in The Hague.

The major international instruments of relevance for CCS, in particular marine sequestration, are *the United Nations Convention on the Law of the Sea (UNCLOS)* of 1982 which is a framework agreement which provides protection to all marine areas; and the *UN’s International Maritime Organization Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972*, also known as the *London Convention*. This was amended in 1996 and came into force in 2006 specifically to allow transboundary CO_2 transportation and sequestration activities in subsea geological formations. Deep subsea CO_2 liquid ‘lakes’ would not be permitted by the convention as they would both pollute the ocean and cause mortality to bottom living organisms.

The *Oslo-Paris Convention for the Protection of the Marine Environment of the North-East Atlantic* controls waste and pollution includes the North Sea.

National policies and regulation apply. EU, US, Australian and Canadian policy are summarised by Odeh and Haydock (2010) also with particular reference to UK and China. For the US, Wilson and Bergan (2011) gives a list of relevant policies on a state by state basis. For example, Kansas, Montana and North Dakota have passed legislation that the state accepts long term liability for geological CO_2 storage sites. Many nations have existing laws for their mining or fossil fuel extraction industries with some applications to CCS.

The EU directive on geological storage should have been adopted by member states in their national laws by June 2011, opening the way for CCS projects by removing CO_2 as a pollutant in waste and water laws.

The main challenges for CCS from the legal perspective seems to be the decision on whether CCS should attract its own dedicated legal framework, or if it can be successfully managed by amendment to existing conventions. There are currently no overarching international agreement or regulatory frameworks governing the 'full-chain' of CCS activities, either onshore or offshore.

Economic Outlook

CCS is clearly economically viable where the costs can be offset by the benefit of improved recovery rates in EOR processes, for example at the Weyburn EOR site in the USA and K12-B Dutch enhanced gas recovery project.

Dedicated CCS projects with the aim of sequestration alone will probably never be self-financing without any stimulus from carbon trading, carbon taxes or other routes. For example, the latest report by the zero emission platform (ZEP) group (ZEP, 2011) shows the cost of new build coal, lignite and natural gas power stations with and without CCS, and indicates the levels of funding via ETS carbon credits required. Only in the mid- and high-level ETS scenarios is CCS considered viable.

However, there are only a handful of demonstrator projects currently running worldwide so at the time of writing it is difficult to judge with any accuracy the capital expenditure, operational and on-going costs of CCS. For example, it may be that one of the three capture processes (pre- or post-combustion or oxy-fuel) eventually emerges as a clear winner, or that particular sequestration super-sites take the lion's share of CO_2 deposition, with associated economies of scale and network costs, rather than a large number of smaller sites. For example Norwegian Statoil are already injecting CO_2 into the Utsira geological formation via the Sleipner platform and it is estimated that this formation could be 20-60GT and satisfy all the EU's CO_2 requirements for 100 years.

Initial high costs for development of CCS are being helped in the EU by subsidies of €4bn and by the emissions trades scheme, with CO_2 currently priced at around 24 $/tonne is expected to rise to 50 $/tonne by 2020. Some commentators suggest that CCS projects will become viable at 45 – 64 $/tonne (Naucler *et al.*, 2008). CCS projects are under development by all the major international energy players, including Shell, BP, Vattenfall, RWE of Germany and Italian multinational ENI, for example.

3 A GREEN TOWN DESIGN SOLUTION

In 2007, a plan to establish an onshore CCS demonstration project was been initiated by Shell in the Dutch Town Barendrecht. This project involved a group of experienced engineers and scientist and if successful, this project could have layed a foundation for the replication of a fully integrated CCS system in the Netherlands. The plans however caused debate between proponent and opponents towards the project, and had ultimately led to concellation of the project. The communication between the proponent and opponents are reported in Feenstra *et. al*. (2010b) and three main lessons to be learnt from the incident are as follows:

- **Shortcoming in public understanding on CCS**
  This is identified as the main obstacle in implementing the project. The public was reported to have difficulties in understanding the reason to have this project taking place in their community.

- **Openness and transparency of the project process**
  The public required more information on the project process such as concerns regarding technical details and safety of the project. The initial presentation and procedures of the project were reported to be too complicated for the public to understand.

- **National government involvement**
  The government was perceived to have little involvement. This project was perceived as an idea from Shell. If more attention were given to this project by the government at the initial phase, the public might have interpreted the project differently and accepted it better.

With regards to these main lessons learnt, it can be summarised that the public perception and their engagement in CCS in the early stage are the most important aspects in ensuring a successful CCS project. It is usually the lack of understanding of the public in the CCS process that results in the public's disagreement of the project. It is also presented in Chapter 2.9.1 that the public perception towards the CCS process (safety, technical, risk, environmental impact etc.) is identified as the key to a successful CCS project. Hence, the "Green Town" idea that would involve public in the initial stage of the CCS project is proposed.

3.1 The Green Town Concept

Figure 3.1 shows a pictorial representation of the "Green Town" idea with community and playgrounds, where this "Green Town" is to be free of anthropogenic CO_2 emission. The zero anthropogenic CO_2 emission could be achieved by having an air scrubbing facility installed in the community. This slabs air capturing facility (see Fig. 3.2) is developed by Carbon Engineering Ltd. and has the capability to draw in air and remove most of the CO_2 (see label I in Fig. 3.1). The captured CO_2 will then be transported by pipelines (see label II in Fig. 3.1) and stored in depleted oil/gas field offshore (see label III in Fig. 3.1). The details of the site selection, air capturing facility, transportation and storage are given in the subsequent chapters.

The aims of the air capturing facility are:

- Enhance public understanding on CCS and its benefits towards the environment.
- Gain interest of younger generation towards CCS technology
- Encourage public acceptance of CCS technology.

These aims could be achieved by having the involvement of CCS in the public's daily life by installing the air scrubbing facility in their local community, thus enhancing their familiarity towards CCS technology. A meter displaying the captured CO_2 by the scrubbing facility could also be installed in public such as in the playground, shopping centre, etc. This meter would also help in keeping the public informed on the air condition or amount of CO_2 concentration in the air. Having proven the benefit of CCS to the public, it is anticipated that more air scrubbing facilities could be installed. The public understanding on the CCS process could also remove their scepticism towards direct CO_2 capturing from point sources such as coal power plant or cement plant. This would certainly help in further reducing the CO_2 concentration in the air and at the same time assuring a continuous supply of energy and economic stability.

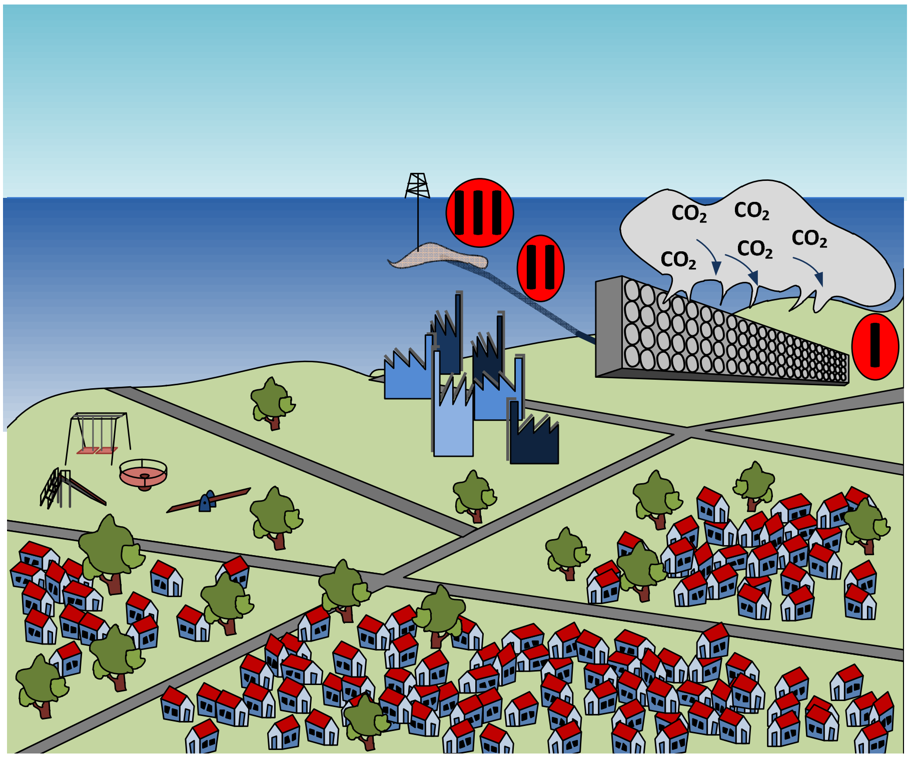

Figure 3.1: Proposed Concept of "Green Town" Idea

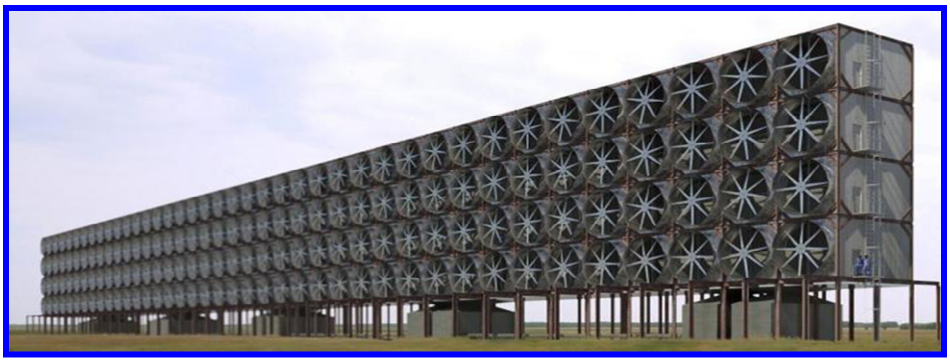

Figure 3.2: Artist Impression of Air Contactor

3.2 Site Selection

A city will be selected for the case study for the "Green Town" project. A city where CCS has a good chance of success will be considered. The selected city must be in a country whose government is in support and values the importance of CO_2 reduction. The selected city/country should also have substantial amount of funding for CCS project. Four countries are considered for the case study, i.e. Australia, UK, Germany and Norway. The CCS current statuses in these four countries are summarised as follows:

- **Australia**
  Australia has introduced CCS legislation early and is currently implementing a carbon tax. Both industry and government has pledged funding.

- **UK**
  UK has several on-going CCS projects. The government is currently funding several projects.

- **Germany**
  Germany is facing out nuclear due to their environmental concerns. The Green Party gained control over several states in the local elections in May 2011 (Evans, 2011). The industry is also heavily investing in CCS.

- **Norway**
  Norway has a carbon tax and has launched the world's first CCS project (Sleipner). The government are also sponsoring the CCS projects.

The government and industrial funding for the CCS, storage site, Green Index Ranking, Pollution Index Ranking and GDP per Capita Ranking of these countries are given in Table 3.1. The Green Index Ranking ranks number 1 for the greenest country, Pollution Index Ranking ranks number 1 for the worst polluted country and GDP per capita ranks number 1 for the richest country. (the references are correct at time of printing)

By considering all the factors listed in Table 3.1, Germany was selected for the case study for the "Green Town" idea. This is further supported by the fact that CCS in Germany has a broad support by the industry and Green politic is powerful in Germany. In addition to that, Germany is also the richest country in Europe which would enable it to provide the funding needed for the project. Besides that, Germany is also very much committed to the reduction of greenhouse gases based on the Kyoto protocol and the European burden sharing.

On top of this, the EU has agreed to set aside 300 million emission unit allowances (EUAs) from the New Entrance Reserve (NER 300) to demonstrate CCS and innovative renewable energy technologies – including funding for up to 12 large-scale CCS demonstration projects. This is currently valued by the European Commission at €4-5 billion for CCS demonstration. The EU also launched an EU Energy Programme for Recovery (EEPR) in which €1 billion was set aside for CCS demonstration projects in Poland, Germany, the Netherlands, Spain, Italy and the UK. (NER300.com, 2010)

Having determined the country for the case study, a city in the selected country has to be determined. The team wished to select a city within easy reach of marine sequestration sites in the North Sea, so the northen cities of Blumensand, Cuxhaven, Hamburg and Lübeck and Hannover were considered. Hamburg was selected as the preferred site. It is a large city with an active port and several industries considered to be CO_2 emitters,

This city must be within easy reach to the North Sea, the German North Sea coast, the East Frisian and North Frisian area. It has to be a city and not a town or village since the project aims to influence as many people as possible. Based on these criteria, Hamburg is selected as it is the largest port city, and is situated on the River Elbe which is 110 km from the coast closest to the North Sea.

TABLE 3.1
GOVERNMENT AND INDUSTRIAL FUNDINGS FOR CCS, STORAGE SITE, GREEN INDEX RANKING, POLLUTION INDEX RANKING AND GDP FOR AUSTRLIA, UK, GERMANY AND NORWAY

	Australia	**UK**	**Germany**	**Norway**
Government funding	$2 billion CCS Flagships Program. $2 billion of State Government funding. (source:www.ret.gov.au)	Up to £1bn of capital funding for the first CCS demonstration project (http://www.decc.gov.uk/en/content/cms/emissions/ccs/ccs.aspx)		$1bn funding (source:www.ccstlm.com)
Industry funding	$2 billion of industry funding (source:www.ret.gov.au)		Janschwalde €1.5 billion, Vattenfall Schwarze Pumpe: 70 M€, Vattenfall Goldenbergwerk – currently on hold due to legal issue: €2 billion, RWE (http://sequestration.mit.edu/tools/projects/map_projects.html)	
Storage-site	Gorgon site	North Sea	North Sea	North Sea
Green Index Ranking Environmental Performance Index (EPI) ranks http://epi.yale.edu/	51	14	17	5
Pollution Index Ranking GHG emission (http://www.guardian.co.uk/news/datablog/2011/jan/31/world-carbon-dioxide-emissions-country-data-co2)	15	10	6	68
GDP per Capita Ranking (Source: International Monetary Fund 2010)	10	21	19	4

Hamburg

Germany is divided into a system of sixteen federal states of which a small number, including Hamburg, are city states. The 'Free and Hanseatic State' of Hamburg has approximately 1.8 million inhabitants (Hamburg official state website www.hamburg.de).

Hamburg is split by the River Elbe which runs approximately East-West through the city; to the North are the main residential, administrative and historic areas whereas to the south the dockland dominates, together with heavy industrial areas, before giving way to agricultural land. Hamburg's major industries including the container port, Airbus Industrie, Blohm+Voss (shipbuilder) and Aurubis (Copper specialist) are all located in this area.

The northern districts (Altona, Eimsbüttel, Nord and Wandsbek) are very well developed with extensive transport networks integrated with the residential and business areas, offering little scope for development of air capture facilities. The southern districts of Hamburg and Bergedorf have residential settlements but are mainly agricultural; whilst 'green field' sites could be available, placement of air capture facilities there was seen as undesirable.

The central district Mitte, covering the port and industrial areas, was seen as the most suitable location for new industrial facilities. A search of this area for 'brown field' sites was therefore made using the satellite imagery available in Google Maps.

A number of sites were identified and their approximate areas estimated, as shown by the blue flags in Fig. 3.3.

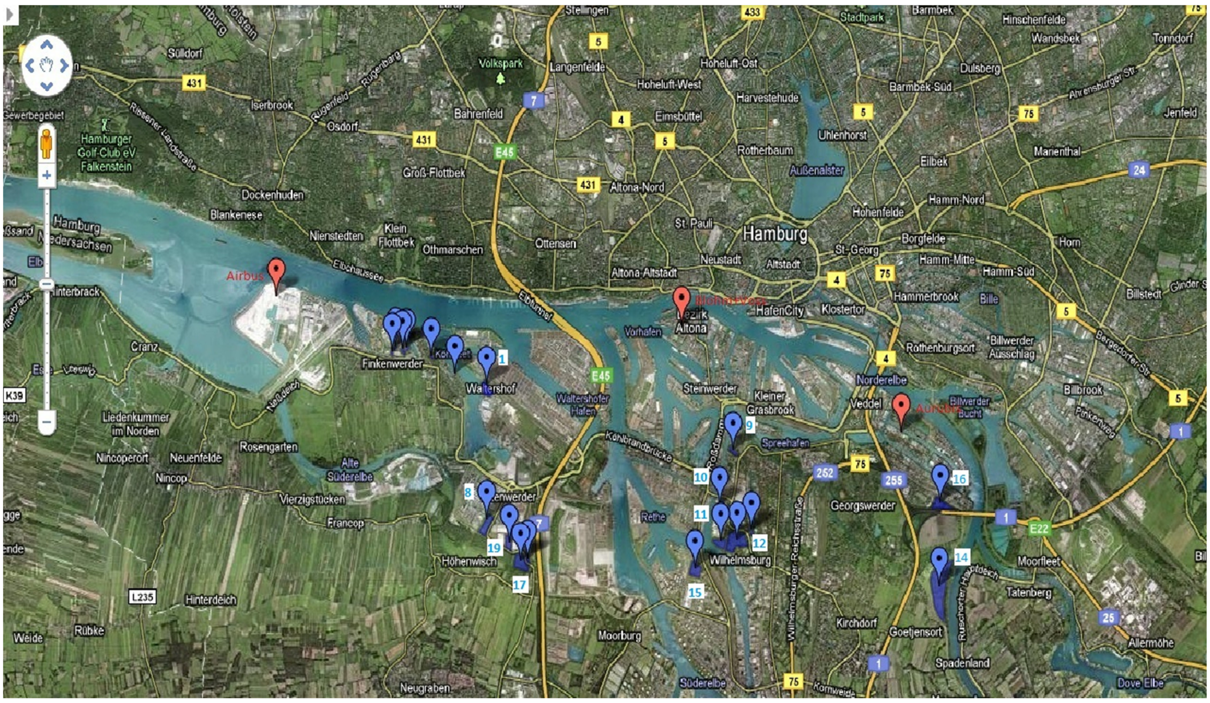

Figure 3.3: Location Of 'Brown Field' Sites in Hamburg (Acknowledgement: Google – Imagery 2011)

The estimated areas and zones of these sites are given in Table 3.2. The largest ten sites have also been labelled in Figure 3.3. Identification of potential sites has not been exhaustive nor in great depth. It could be that many suitable sites exist that are not identified, or that some of the sites selected are unsuitable due to already planned development. Nevertheless, Table 3.2 shows that a sizable number of potential sites do exist in Hamburg. The sites identified tend to cluster in the industrial areas of Altenwerder, Georgswerder, Wilhelmsburg and Finkenwerder.

An area of about 16,100m^2 is necessary to capture approximately 1% of the city's annual CO_2 emission with the proposed air capture system (based on the German national average per head of population, i.e. 10.16 tCO_2 emitted per person per year (World Resources Institute, 2003). The CO_2 emitted by 1% population is approximately 180,000tCO_2 per year. It can be seen that - before taking into account the area required for access, services etc.

TABLE 3.2
ESTIMATED AREAS AND ADDRESSES OF POTENTIAL SITES FOR
AIR SCRUBBING FACILITY

Site	Location	Zone	Approx. Length (m)	Approx. Width (m)	Area (m^2)	Rank by Size
1	Antwerpenstrasse (within Eurogate)	Waltershof	250	120	30,000	9
2	Hein-Saß-Stieg	Finkenwerder	75	70	5,250	16
3	Hein-Saß-Weg 10 (east of Goodrich Aerospace Europe GmbH premises)	Finkenwerder	75	70	5,250	16
4	Hein-Saß-Weg (North of junction with Hein-Saß-Stieg)	Finkenwerder	125	50	6,250	15
5	Hein-Saß-Stieg	Finkenwerder	120	53	6,360	14
6	Fochsweg	Finkenwerder	102	42	4,284	18
7	Koehlfleet-Hauptdeich	Finkenwerder	50	22	1,100	19
8	West corner of Vollhoefner Weiden	Altenwerder	140	400	56,000	4
9	North-east of Fährstieg	Wilhelmsburg	220	100	22,000	10
10	Neuhoefer Str	Wilhelmsburg	255	120	30,600	8
11	Alte Schleuse / Reiherstieg-Hauptdeich	Wilhelmsburg	250	150	37,500	6
12	Bei der Wolkammerei/Relherstieg-Hauptdeich	Wilhelmsburg	500	250	125,000	2
13	Industrielstrasse/Bei der Volkämmerei junction	Wilhelmsburg	150	60	9,000	13
14	East side of Kreetsander Hauptdeich	Georgswerder	800	400	320,000	1
15	Blumensand	Willhelmsburg	240	210	50,400	5
16	South East end of Müggenburger Hauptdeich	Georgswerder	250	60	15,000	11
17	Vollhöfner Weiden	Altenwerder	320	200	64,000	3
18	Vollhöfner Weiden	Altenwerder	150	70	10,500	12
19	Vollhöfner Weiden	Altenwerder	260	120	31,200	7
				Total Area	**829,694**	

The Google Maps satellite imagery may not be freshly created, so the opportunity was taken whilst in Hamburg in August 2011 to make questionnaire surveys (Chapter 4) to visit a small number of sites in the Wilhelmsburg area and to check their status. Site 9 had been partially built upon but approximately 75% remained exploitable. Site 12 was inaccessible as the 'Dockville' music festival was being held there, but presumably remains undeveloped.

Site 15 is chosen for the proposed site for the air scrubbing facility. Site 15 was visited and it remained undeveloped. The middle ground of site is shown in the photograph in Figure 3.4.

Figure 3.4: Photograph of Site 15

With the exception of the Altenwerder sites, most of the sites lie directly next to dock areas or near to the River Elbe itself.

3.3 Air Scrubbing Facility

The air scrubbing facility consists of a system of air contactors to drive air into the facility and a regeneration system to regenerate the water-based solution that is used in capturing CO_2 from the air. The air contactor system might take the form of a slab shapres matrix of 4 x 80 air contactor. This layout is proposed by Prof. David Keith of the University of Calgary and his company Carbon Engineering (CE) Ltd. is shown in Fig. 3.2. In the subsequent chapters, the air contactor and air regeneration system as patented by Carbon Engineering Ltd. are presented. The design of the air scrubbing facility in the "Green Town" will be based on this patented design. The CE's air capturing method is based on the wet-scrubbing techniques, where air is driven into the device to come into contact with an alkaline hydroxide solution. It is to be noted that the technology development of the air scrubbing facility is under process and will be completed in 2013. A pilot plant would then be built from 2013 to 2016 and the commercial deployment of the facility will only be available after 2016 (Carbon Engineering Ltd., 2011). The information on the air scrubbing facility in the subsequent chapters is retrieved from the CE website (www.carbonengineering.com).

The selected air scrubbing facility should be subjected to the following design specification:

- Ability to capture specific amount of CO_2
- Does not use up large spaces
- Low energy consumption
- Zero or near-zero CO_2 emission
- Water-based solution used in wet scrubbing technique should be cheap
- Powered by renewables if possible
- Low noise

3.3.1 Air Contactor System

The air contactor system is shown in Fig. 3.5 and comprises powered fans that are used to drive air into the facility. Each fan has a diameter of 5.5m and an inlet velocity of 1.5m/s. The fans are arranged in cross-flow slab geometry arrangement in order to minimise the use of land. It is to be noted that the counter-flow slab geometry arrangement would use 4 times more spaces as compared to the cross-flow slab.

The air will be driven in to come into contact with the hydroxide solution through corrugated sheets located inside of the air contactor. The air with reduced CO_2 will exit through the backside of the corrugated sheet whereas the liquid with captured CO_2 will be sent to a central regeneration facility (process shown in the Chapter 3.3.2) to remove CO_2. The liquid will then be circulated in the regeneration facility and be reused.

It is also able to reduce pumping work by having an intermittent flow with 10kg-air/kg-solution mass flow ratios, hence reducing the power consumption. The noise produced by the air contactor is lesser than a forced draft cooling tower. Each of the air contactor as shown in Fig. 3.5 is able to capture at least 58,000 tonnes-CO_2/year.

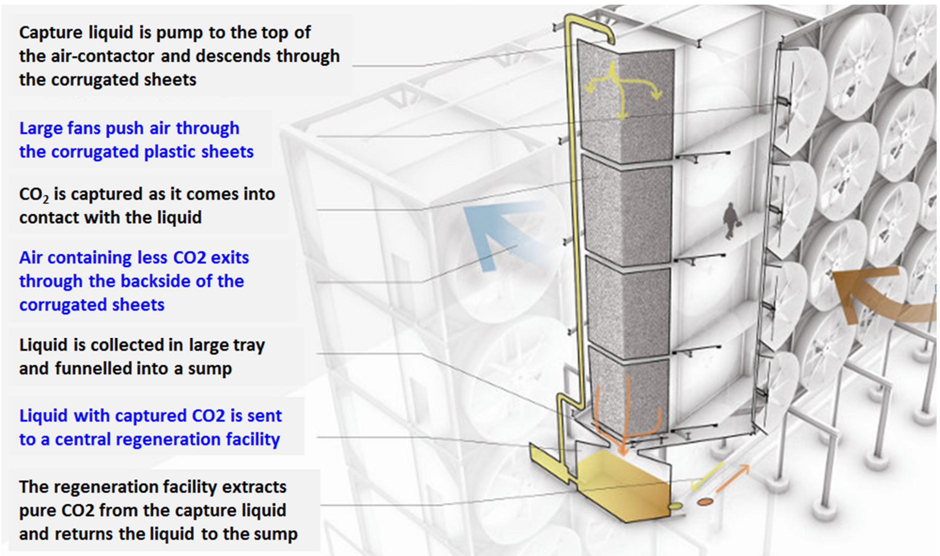

Figure 3.5: Air Contactor Process (source:www.carbonengineering.com)

3.3.2 CO_2 Capturing System (Wet Scrubbing Technique)

The wet-scrubbing technique uses water-based solution such as alkali hydroxide solution to absorb CO_2 out of the air as it passes through the air contactor. The hydroxide solution is circulated in a regeneration cycle for continuous capture of atmospheric CO_2 and production of pure CO_2.

The schematic diagram of the generation cycle is shown in Fig 3.6. In the process of heating the solid calcium carbonate in the calciner, the heat could also be used to drive a turbine to generate electricity for powering the air scrubbing facility.

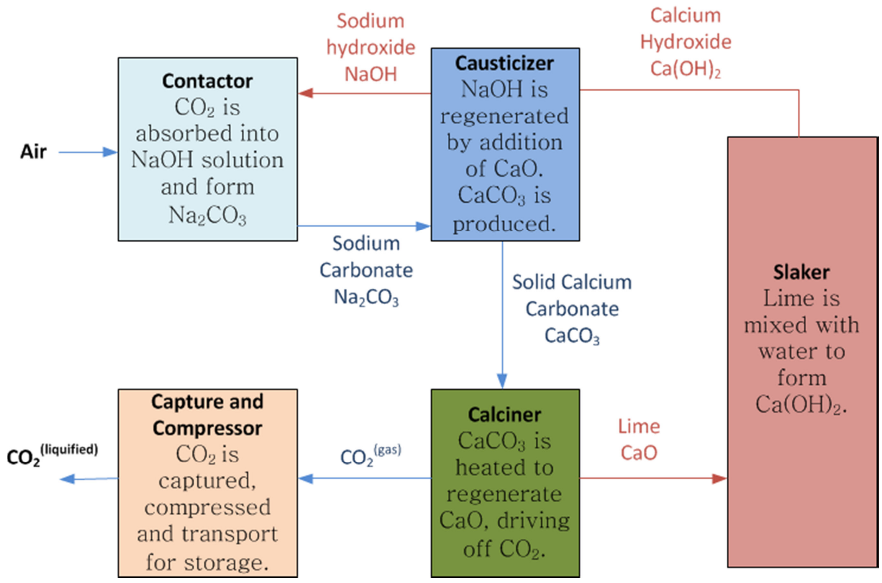

Figure 3.6: Wet-Scrubbing Process in Air Scrubbing Facility

The wet-scrubbing method has several advantages as follows:

- The air contactors must be huge in order to capture meaningful amounts of CO_2. A liquid-based system allows the captured CO_2 to be collected into a single location with simple and inexpensive pumps and pipes.

- The absorbing surface of the wet scrubbing system is continually replenished and is less prone to small scale fouling and clogging due to atmospheric dust particles.

- The wet scrubbing is well-proven to be both robust and cost-effective at large industrial scales, and it significantly reduces the "scale-up risk" associated with CE's design. It avoids the reliance on specialized and/or expensive materials and processes that have not yet been proven at industrial scale.

- The wet scrubbing air capture design by CE uses a well-understood chemical-regeneration cycle, to regenerate the sodium hydroxide solution that is returned to the contactor and enables continuous capture of CO_2. A variation of this regeneration cycle, called the Kraft Recovery Process, has been commercially used at an industrial scale for more than a century to produce kraft pulp.

3.3.3 Power

A good deal of thermal power is required by the calciner and electivity by the plant equipment plus contactor fans. The demonstrator is powered by gas. However, the facility could be also powered by low-carbon fossil fuel such as natural gas, or renewable such as solar and wind powers as well as nuclear power. For natural gas powered facility, 0.5 tonnes of CO_2 are produced for each tonne that is captured from the air, but both CO_2 streams would then merge within the plant and be transported for storage. Hence, it is possible to achieve a zero-carbon emission by the air scrubbing facility. Alternatively, the air scrubbing facility could also be constructed near shore or offshore so that air could conceivably be drove into the system by using natural air flow. This could reduce the energy consumption for the air contactors fans.

3.3.4 Sizing

The sizing of the air scrubbing facility would depend on the following criteria:

i. Amount of CO_2 to be captured
ii. Space of construction available

Based on the CO_2 emitted by 1% the total population in Hamburg i.e. 200,000 tonnes-CO_2 per year (see Chapter 3.2), at least eighty 5.5-m diameter fans are required. To accommodate the air capturing facility by taking into consideration spaces needed for offices, power generator, cooling system etc., an area of at least of (16,100 m^2) is required. The area required for the air scrubbing facility with respect to the percentage targeted population in Hamburg is shown in Table 3.3. The site selection for Hamburg will be shown in the previous chapter.

TABLE 3.3
AREA REQUIRED FOR THE AIR SCRUBBING FACILITY WITH RESPECT TO THE PERCENTAGE TARGETED POPULATION IN HAMBURG

Percentage Targeted Population (%)	Population	CO_2 Emitted (tonnes)	No. of Tower Needed	Area Occupied (m2)
1	18000	182880	9144	16158.78181
2	36000	365760	18288	32317.56363
3	54000	548640	27432	48476.34544
4	72000	731520	36576	64635.12725
5	90000	914400	45720	80793.90907

3.4 CO_2 Pipeline Routing and Design

The captured CO_2 from the air scrubbing facility is transported in liquefied form by using pipelines. The benefits of transporting CO_2 in liquefied form by using pipelines have been described in the Literature Review in Chapter 2.

3.4.1 CO_2 Pipeline Design Challenges

Pipelines are by far the most economical mean of large scale overland transportation for crude oil, natural gas and their processed products. The onshore CO_2 pipeline transportation is most likely to be implemented through a CO_2 transportation cluster in order to ensure a continuous mass flow.

It is noteworthy that North America has operated more than 6,200km long CO_2 pipeline for over 30 years mainly for the purpose of EOR. However, those CO_2 pipelines are primarily restricted to low population density areas and operated below supercritical conditions. Safety issues will become more complex in populated areas where most power plants are located. Apart from this, it is not possible to draw a statically credible conclusion due to the small number of CO_2 pipelines.

In the pipeline design, it is important to include geotechnical design consideration which is a significant aspect in the offshore pipelines design due to the harsh operating environment. Apparently, there are not many design codes available for CO_2 pipeline designs. By far, DNV-RP-J202 and DNV-RP-J202 are the only published code of practice.

CO_2 capture and transport is also costly and a regulatory framework is therefore needed to provide guidance for future investment decisions.

3.4.2 Design Code Selection

There are several different existing codes and standards for the design and operation of submarine pipeline and risers. The main design codes and standards that are commonly used in offshore industry are listed as follows:

- ANSI/AMSE B31.4 (1992) – Liquid Transportation Systems for Hydrocarbons, Liquid Petroleum Gas, Anhydrous Ammonia and Alcohols
- ANSI/AMSE B31.8 (1992) – Gas Transmission and Distribution Piping Systems
- DNV OS-F101 (2000)-Rules for Submarine Pipeline Systems
    - DNV RP F105 (2002)-Free Spanning Pipelines
    - DNV RP F107 (2001)-Risk Assessment of Pipeline Protection
    - DNV RP E305 (1988)-On-bottom Stability Design of Submarine Pipelines
    - DNV Guideline No. 13 (1999)-Interference between Trawl Gear and Pipelines
    - DNV Classification Note No.30.5 (2000)-Environmental Conditions and Environmental Loads
- API Recommended Practice 1111 (1999)-Design, Construction, Operation and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design)
- API RP2RD (1998)-Recommended Practice for Design of Risers for Floating Production Systems and TLP's
- ISO 13623 (2000)
- BS8010-(1993)-Code of Practice for Pipelines. Part 3-Pipelines Subsea: Design, Construction and Installation
- ABS (2001)-Guide for Building and Classing Subsea Pipeline Systems and Risers
- NPD (1990)-Regulations Concerning Pipeline Systems in the Petroleum Activities
- AS 2885 (1997) Pipelines- Gas and Liquid Petroleum
- AGA (1993)-Submarine Pipeline On-Bottom Stability-Analysis and Guidelines

This study reviewed and considered all the above latest international industry codes. Four out of them have been selected for further comparison:

- ASME B31.8 Gas Transmission and Distribution Piping Systems, 1999
- EN 14161 Petroleum and Natural Gas Industries-Pipeline Transportation Systems, 2003
- API RP1111 Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines (Limit State Design), 1999
- DNV OS-F101 Submarine Pipeline Systems, 2000

For the overall pipeline design, wall thickness and material selection are deemed to be the first principal consideration as this aspect influences other design aspect. ASME B31.8 was first excluded as it is mainly for gas transmission designs. EN 14161 was also excluded due to the fact that not all the capabilities of the pipeline are fully explained. API RP1111 was not chosen because the bending safety factor is not defined clearly. DNV OS-F101 was finally selected for its ability to incorporate technology development through various resistance factors such as collapse testing and thermal ageing.

3.4.3 CO_2 Pipeline Design Principals

The CO_2 pipeline design requires the determination of the source and sinks location. The source location is Hamburg whereas the sink location is the K12-B gas field in the Dutch Continental Shelf (see Chapter 3.5). Once the source and sink locations have been identified, the length of the pipeline connections network could be estimated.

The design of the pipeline takes into consideration the physical characteristics of the product mixture to be transported, the pipe sizing, the pressures for the pipeline, and the mechanical design (operating, valves, pumps, compressors, seals, etc). Both onshore and offshore pipelines have to be optimized with following factors: diameter, wall-thickness, pressure variations, flow rates and operational period. Typical, offshore pipeline is constructed from steel pipeline with multiple protection coatings, and is often coated with high density concrete to both protect the pipeline and provides sufficient weight to remain on seabed stably (see Fig. 3.7).

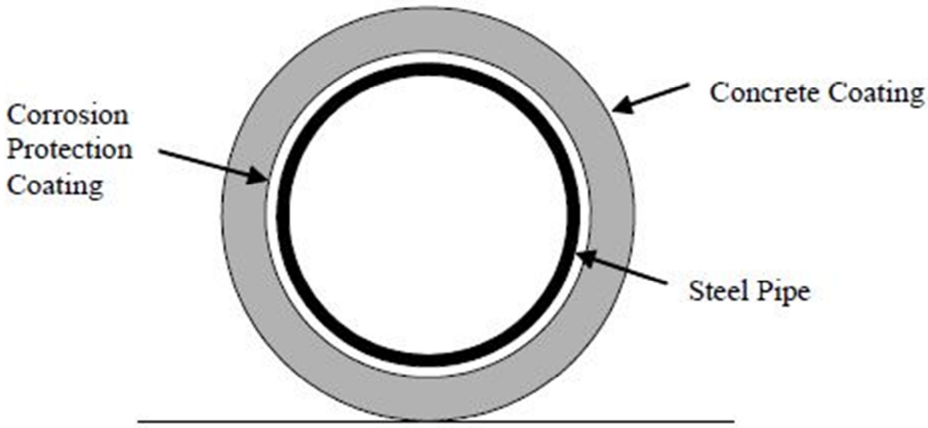

Figure 3.7: Typical Cross-Section of a Conventional Offshore Pipeline.

The pipeline design process follows the same general principle as any engineering project. There are generally three phases in the pipeline design, i.e. the conceptual, preliminary and detailed design. When designing a pipeline, the engineering environmental conditions along with the social factors have to be considered in the initial conceptual design loop.

The design of the pipeline for transportation of CO_2 from the “Green Town” to the sequestration site in this book will be at the conceptual design stage. The potential difficulties and areas that may be needed in the preliminary and detailed design stages will be addressed and highlighted.

The conceptual design of the offshore and onshore pipelines involves the following objectives:

- Propose technical solution
- Assess the technical solution feasibility for a range of different system concepts.
- Identify the data and other information needed for the design and construction of the project
- Perform basic cost/benefit analysis and scheduling exercise.
- Assess if tie-in of a pipeline to an existing pipeline infrastructure is feasible and cost beneficial.

The design of the CO_2 pipelines involves the following aspects:

i. Determine source and sink locations

ii. Routing of pipelines based on geographical data, cost and existing or provision pipeline project

iii. Site survey to obtain specific information such as soil properties, seabed obstruction, wave, current, water depth etc.

iv. Hydraulic design
The hydraulic design would take into consideration the liquefied CO_2 characteristic behaviour, flow pressure, flow velocity and pressure losses in the pipes. This would help in sizing the pumps and determining the inlet/outlet pressure needed in driving the liquefied CO_2. The hydraulic design also involves the operating modes of the flow, i.e. steady state of transient. The pipeline should be able to perform satisfactorily under both conditions.

v. Pipeline design
The pipeline design would involve the selection of pipe thickness, pipe diameter as well as pipe material. The designed pipeline shall be able to withstand the high pressure and low temperature condition of the liquified CO_2. The pipe material is a vital part in determining the overall cost, lifetime and maintenance requirement of a pipeline.

vi. Stability analysis
A paramount part of the pipeline design is to evaluate the on-bottom stability under the influence of extreme environmental conditions. The stability of the pipeline must to be assessed according to the hydrodynamic loading from steady currents and wave induced water particle motions. Pipeline instability involves a very complex interaction between pipe, water and soil. There are other methods that could be considered during pipeline design in order to achieve pipeline stability. For instant, external forces are balanced by seabed reactions by providing sufficient weight. One of the most common and well proven design approaches is to establish the minimum amount of concrete weight coating required to keep the pipeline in place.

vii. Cost estimation
Cost estimation of the pipeline would involve the operating expenditure (OPEX) and capital expenditure (CAPEX) of the pipeline. Larger diameter pipeline generally leads to larger capital expenditure but will have much lower operating cost than a small diameter pipe. Besides that, it also depends on the length of the pipe to be constructed, material, construction difficulty as well as the maintenance cost. It is proposed that the X60 steel is used for the CO_2 pipeline.

viii. Pipeline Installation
In general, there are two kinds of installation methods for the offshore pipeline:

- Offshore fabrication and installation
- Pre-fabrication and testing onshore, followed by transportation to site for installation

Offshore installation may be carried out by using an anchored lay barge or dynamically positioned laying vessel. The “S” lay and “J” lay are two configurations that are commonly used.

The selection of the pipeline installation method depends upon the required length and diameter of the pipeline, the water depth and the relative cost. In this project, the offshore pipeline is of limited length, thus it is proposed that the pipeline will be fabricated onshore and transported to offshore for installation.

ix. Integrity Monitoring and Communication System

x. Corrosion Monitoring

xi. Pigging/maintenance/repair

xii. CO_2 pipeline risk mitigation

xiii. Decommissioning

Aspects x, xi, xii and xii are explained in detail in Chapter 5.

3.4.4 Route Selection

The most direct route is generally preferred for an offshore pipeline, as at this point of time site-specific information from surveys and pipeline design are not available. This line was designed close to the future CO_2 pipeline proposed by Europipe (Neele *et al.*, 2009) thus minimise the expense of constructing new pipelines.

A pipeline network consists of the manifold, the trunk lines and the distribution system. Major trunk lines could be used for CO_2 transportation once all the fields along the trunk line are depleted. A lot of money could be saved by tapping into existing trunk lines, hence, for our pipeline system, a new pipeline will be connected from the source in Hamburg to tap into the NTG Noordwest/Oost trunk line (one of the proposed CO_2 pipeline). The NTG Noordwest/Oost trunk line is connected to Groningen which is the access point to Hamburg. The distance from the west of Hamburg to the K12-B gas field is about 410km as shown in Figure 3.8.

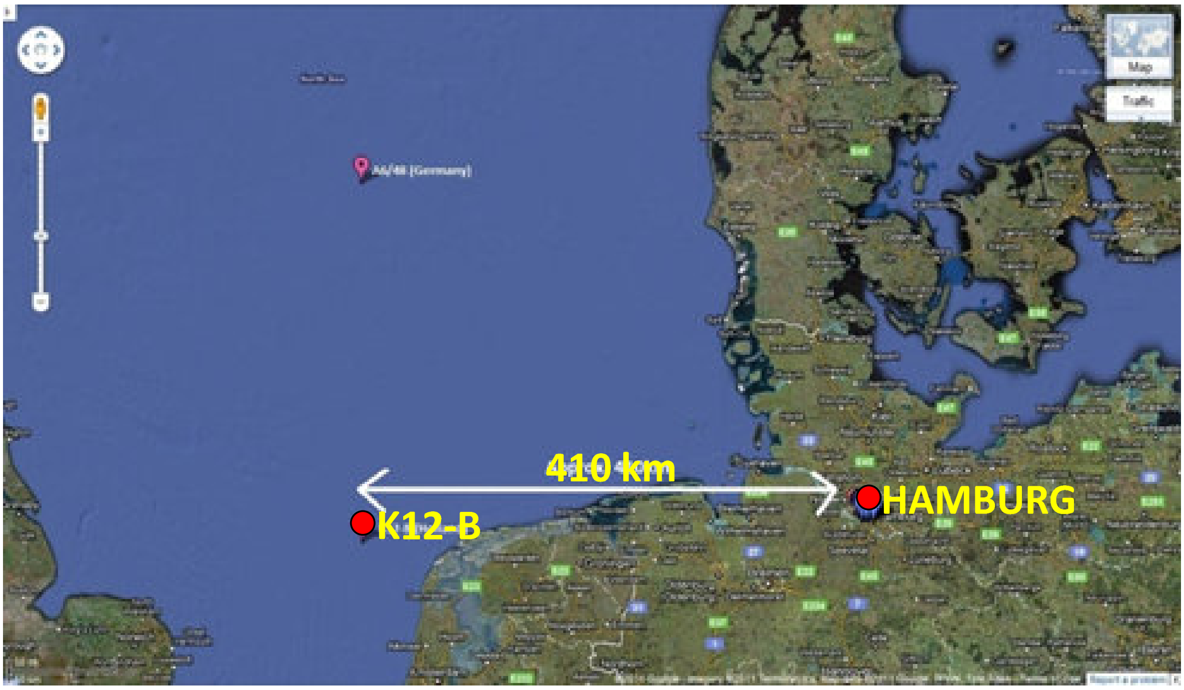

Figure 3.8: Map of Germany/Netherlands area (acknowledgement: Google Maps)

The following factors will also be considered in the preliminary/detailed design:

- **End point of the pipeline**
  The choice of end point, for example at a platform, location of risers and J-tube or a shore crossing is very important to pipeline route selection.

- **Intermediate point of the pipeline.**
  It is advantageous to include additional tie-ins from other facilities.

- **Seabed characteristics.**
  Site investigation is desired to avoid running the pipeline on irregular seabed, unstable ground or man-made obstructions. Pipelines are expected to run perpendicular to the contours. Severe slopes may need to be traversed.

- **Pipeline crossing.**
  This should be avoided if possible as they are costly and may require extra future inspection and maintenance.

- **Tie-in method.**
  Flexibility using spools deflect-to-connect methods would require different pipeline routing

- **Installation method.**
  Different installation methods require different alignment which can be determined from the allowable curvature of the pipeline.

The transportation of CO_2 via pipelines from our proposed "Green Town" at Hamburg to the K12-B site is divided into two scenarios:

Scenario 1:

- **Section 1 – From air scrubbing facility to Winsen**

The pipeline has to be connected from the industrial areas (location of air scrubbing facility) in the south of Hamburg to Winsen, a distance of approximately 32km estimated based on the existing road system. The pipe has to be lay across the Elbe River. The provision route would likely be the E22 route road bridge near Neuland at 53.474702 N, 10.022728 E.

- **Section 2 – From Winsen to the Emden/Groningen**
  The pipeline will be connected from Winsen to the sea (Emden in the Netherlands) by tapping into the Travemünde-Groningen Gas pipeline owned by the Dutch company Gasunie (see Fig. 3.9). The travemünde-Groningen Gas pipeline is an entrenched pipeline passing through the south of Hamburg (Winsen). Note that the section from Winsen to Emden in the Netherland is approximately 220km. It is also to be noted that Gasunie is currently constructing a 440-km pipeline in Germany as part of the North Eastern Line (NEL) to transport gas from Russia to North Western Europe. Most of the construction is in the region just south of Hamburg.

- **Section 3 – from Emden to Krummhorn**
  Pipeline could be connected from Emden/Groningen to the landfall near Krummhorn (see Fig. 3.10). This route offers the most cost effective option for the pipeline system.

Figure 3.9: Route of the E43 Travemünde-Groningen Gas Pipeline

- **Section 4 From Krummhorn to K12-B**
  Pipeline is run from krummhorn to K12-b directly. The total length is 212 km.

Scenario 2:
An alternatively route could be connected from Emden to the K12-B site as follows: There is an existing gas pipeline running east from K12-B to the nearby Fresian island of Zuiderstrand is due to cease operation in 2023 (Cronenberg *et al.*, 2009). Considerable infrastructure cost

savings could be achieved if these pipeline routes could be converted to the use for CO_2 transport. Pipeline is run from Krummhorn to Fresian Island of Zuiderstrand via existing pipelines. The pipeline length from Krummhorn to Fresian Island of Zuiderstrand is only 28 km whereas the submerged pipeline length from Fresian Island of Zuiderstrand to K12-B site is 205 km.

In this case only a short new section of pipeline would be required between Krummhon and Zuiderstrand.

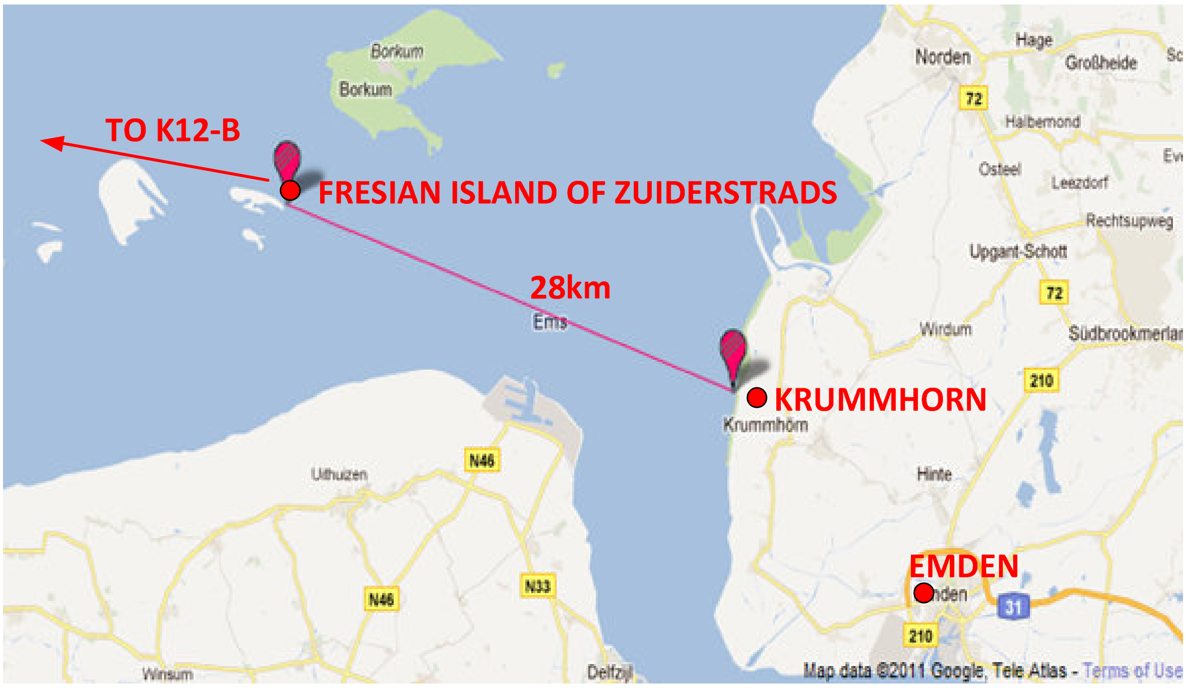

Figure 3.10: Fresian Islands Area Near Emden

3.4.5 Selection of Pipeline Diameter and Wall Thickness

It is necessary to consider both the pressure drop and velocity flow when choosing a pipeline diameter. The line needs to be large enough so that the pressure available can drive the liquefied CO_2. In this study, the proposed pipeline diameter was selected to be 36” which is the same as the existing infrastructures at K12-B NTG line. This is mainly due to two reasons:

i. From the principle of continuity, the velocity will change when the fluid flow passes through a pipe with changing cross section. This change of velocity will result in a net energy loss, which is seen as a drop in pressure. Therefore a uniform pipeline is generally preferred.

ii. Large diameter pipeline will have a large capital expenditure associated with it but generally has a much lower operating cost. The future plan for the proposed CCS system will ideally emerge into a large CCS network. Hence, large diameter pipeline is preferred from a long term cost saving perspective.A 36” pipeline would be over spec for the “Green Town” project alone but offers longterm flexibility.

The pipeline wall thickness will be designed according to the selected 36” diameter pipeline according to the DNV OS-F101 (2000)(DNV, 2000) and working stress design principal. It is assumed that the X60 steel is used for the design and the in-situ design condition for an internal pressure is 8.5 MPa. The pipe is to be laid in a water depth of 50m. By checking the API Spec-5L(API, 1987) , it is known that the specified minimum yield stress (SMYS) is 413 MPa on X60 steel (see Table 3.4).

TABLE 3.4
SPECIFIED MINIMUM YIELD STRESS AND TENSILE STRENGTH
WITH RESPECT TO API GRADE

API Grade	Specified Minimum Yield Stress		Specified Minimum Tensile Strength	
	Ksi	Mpa	Ksi	Mpa
X42	42	289	60	413
X46	46	317	63	434
X52	52	358	66	455
X56	56	386	71	489
X60	60	413	75	517
X65	65	448	77	530
X70	70	482	82	565
X80	80	551	90	620

Water density, ρ_{water}=1027kg/m^3
Hydrostatic pressure, P_o= ρ_{water}×Depth×g
=1027×50m× 9.81
=0.503MPa
Inner pressure, P_i=8.5 MPa

Based on DNV OS-F101 (2000), the safety factor μ_s is 0.77. Pipeline outer-diameter D_o=914mm, and SMYS = 413 MPa.

For a 1-m diameter cross-section pipe, we have

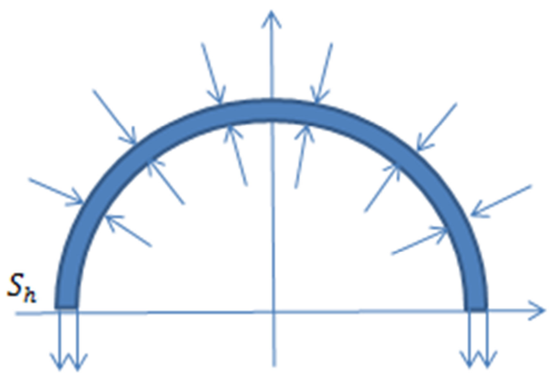

Figure 3.11: Free Body Diagram of an Internally Pressurised Cylinder (Pipe)

Figure 3.11 shows the free body diagram of an internally pressurised cylinder (pipe). Integrating over the circumference gives the equilibrium equation:

$$S_h=\frac{P_iD_i-P_oD_o}{2t}$$

To ensure the pipeline is safe:

$$S_h \leq \mu_s \times \delta_y$$
$$\frac{P_i(D_o-2t)-P_oD_o}{2t} \leq \mu_s \times \delta_y$$

where:

S_h is the "hoop stress" in pipe
P_i is the inner pressure
P_o is the outer pressure
t is the pipeline thickness

Furthermore,

$$\delta_y = 413 \text{ Mpa}$$
$$S_h \leq \mu_s \times \delta_y$$
$$S_h \leq 318.07 \text{Mpa}$$

Therefore:

$$t \geq \frac{P_iD_o-P_oD_o}{2(\mu_s \times \delta_y + P_i)}$$
$$t \geq 11.19\text{mm}$$

Therefore, the designed pipeline wall thickness must be bigger than 11.19mm . The cost estimation will be based on the parameters provided above.

Decommissioning

Decommissioning and abandonment plans need to be included in the design phase. Common methods considered are:

- Leaving in-place (either buried or unburied)
- Removal

Removal of the pipeline is expensive. It is therefore proposed that the designed CO_2 pipeline shall be abandoned after decommissioning. The pipeline may eventually fully corrode and marine growth may completely cover the pipeline.

3.5 CO_2 Storage Site Selection

The storage is of great importance since it must last for geological timescales. Many questions were asked about the storage by the participants in the survey. This shows that the storage needs to be safe and appear safe in order to get people on-board with CCS.

3.5.1 Selection Criteria

A set of criteria were constructed to select the best storage site. The CO_2 storage site for the captured CO_2 from the "Green Town" must fulfil the following criteria:

- In a reasonable proximity to Hamburg
- Ability to store 200,000 tonnes CO_2 per year and having a possibility to expand
- Must be Safe
- Has an existing facility

Close Proximity to Hamburg

The cost of transportation and the CO_2 emissions increase with the distance, hence the considered storage site has to be close to the "Green Town". The closest offshore locations for CO_2 storage are in the North Sea.

Hamburg is connected to North Sea via a 110 km passage of the River Elbe. The North Sea covers an area of 570,000 km^2 (Encyclopædia Britannica, 2011). It is a marginal sea in the Atlantic Ocean and is bounded by the United Kingdom to the west, Scandinavia to the east, and Germany, Belgium and the Netherland to the south. The north boundary line starts from the Shetland Islands to Norway where the north of the North Sea is the Norwegian Sea. Offshore activities such as oil and gas productions are active in the North Sea and the captured CO_2 could be used for EOR.

Storage Capacity

The storage site must be able to contain the CO_2 from the "Green Town" project in Hamburg. The "Green Town" project would act as the "door opener" to future CCS projects, hence it is expected that large scale CCS project would take place in the future. With regard to this, provision is also made such that the selected storage site could be used for future CCS projects.

Safety Aspects

The storage has to be safe and must be able to hold the injected CO_2 for geological time scales. However, it is possible that the injected CO_2 could be emitted back into the atmosphere if fossil fuels from the depleted oil/gas fields are retrieved by the future generation. It would be undesirable, both for the environment and for CCS technology, if the storage site starts to leak and turn into a CO_2 emitter (Gale, 2004).

CO_2 lakes are discarded since they are not able to store CO_2 for millennia and they contravene London Protocol. A simulation model by Enstad *et al*. (2008) shows that a 50-meter CO_2 lake located at a flat bottom at a depth of 3,000 m will dissolute in 4 to 67 years.

In the long term, onshore CO_2 storage is unavoidable since onshore CO_2 storage has a much larger capacity as compared to offshore storage (Neele *et al.*, 2010). However, storing CO_2 closer to populated areas is not popular; nevertheless most of the CO_2 emissions sources are located in these highly populated areas. Hitherto, the resistance toward onshore storage has been high due to the uncertainty in the risk associated with it (Odenberger *et al.*, 2008).

The characteristic of the selected CO_2 storage site must be well understood for security purposes. The depleted oil or gas field, which is the most mature type of storage formation, would provide this security aspect since they have been holding fossil fuels for millennia. They are also geologically stable. Besides that, extensive data on the geological structure and physical properties of the formations are already available. It is to be noted that the natural gas industry has already been using depleted gas fields for storing CO_2 (Christensen and Holloway, 2004).

Existing Facility

The injection process would be much simpler if an existing oil/gas structure is used as a platform for the CO_2 injection system. Furthermore, a field that is in use is also more likely to be better surveyed as compared to an already depleted field. Some of the structures may be reused after retrofitting has taken place (Christensen and Holloway, 2004). However there is a relative short window for retrofitting the CO_2 injection system to the platform since the OSPAR conventions states that existing structure has to be removed within two years after the oil/gas production ceased (van der Velde *et al.*, 2008). Therefore, the location has to be a field with existing facility that is still in operation but that are about to become inactive because it might be too expensive to introduce the injection system once the structure is removed (Christensen and Holloway, 2004).

The oil/gas operators do not foresee major technical objects to retrofit the platforms for CO_2 sequestration (van der Velde *et al.*, 2008). Drilling new wells in a depleted field is complicated and expensive due to the lack of back pressure. Thus, the use of existing drill shafts is therefore preferred (van der Velde *et al.*, 2008).

3.5.2 Storage Site Selection

For Hamburg case, there is obvious legal benefit to store the CO_2 within the German sector. The recommended storage sites for Germany are either offshore aquifers or an onshore depleted gas fields (Vangkilde-Pedersen, 2009). However, storing CO_2 on onshore depleted gas field is not preferable based on the arguments given in the previous chapter (Chapter 3.5.1).

The biggest German oil field is the Mittelplate which is 7km offshore and accounts for half of the German production. However, the Mittelplate will be in operation until 2041, hence, will not be ready for CO_2 storage in the near future.

The Dutch Continental Shelf is another potential site for CO_2 storage. It is within the easy reach of Germany and the theoretical storage potential of the Dutch Continental Shelf (DCS) is approximately 1,566 Mt (van der Velde *et al.*, 2008). This volume is spread over 153 fields where the largest 21 fields make up of half of the storage capacity (van der Velde *et al.*, 2008). However, fields with a storage capacity of less than 2.5 Mt might be too small to be efficient (van der Velde *et al.*, 2008). Half of these 153 fields have a fair to good injectivity. It is to be noted that the injectivity depends on the permeability and the thickness of the formation (van der Velde *et al.*, 2008). There are 55 fields with a total storage capacity of 918Mt still in operation based on a cut-off point below 2.5 Mt and 0.25 Dm (injectivity) (van der Velde *et al.*, 2008).(The field also has to be deeper than 800m in order to store the CO_2 at the dense-supercritical form.) The K12-B gas field is located at the Dutch Continental Shelf and is selected as the storage site for the captured CO_2 from the “Green Town”

K12-B Gas Field

K12-B is originally a gas platform operated by Gaz de France Production Netherlands B.V. (GPN) (van der Meer *et al.*, 2006). The platform has been in use since 1985 and is located 150 km north west of Amsterdam. The K12-B reservoir is at a depth of 3,800 m and has a formation temperature of 132°C (van der Meer *et al.*, 2006). Four wells, i.e. K12-B1, K12-B2, K12-B5 and K12–B7 started operation in January 2006 to produce gas. The theoretical storage space for K12-B is 14.4 BCM (K12-B CO_2 Injection Project). A test facility for CO_2 injection is installed on K12-B and it does not require CO_2 pipelines since the injected CO_2 is separated from the reclaimed gas.
The CO_2 injection at K12-B is planned in three test stages.

- Phase 1 was a desktop study to assess the feasibility of the project. It investigated the underground injection, existing techniques, equipment and facilities.

- Phase 2 was a demonstration phase from February 2005 to December 2005 and comprised two tests. The total injection in Test 1 was 9,000 tonnes (van der Meer *et al.*, 2006) whereas the average injection rate was 2,350 kg per hour which is equivalent to 29,200 Nm^3 per day. It had an average injection speed of 26,000 Nm^3 per day (van der Meer *et al.*, 2006). Traced substances were also injected in this phase and the monitoring and measurements shows a good comparison of the results with the theoretical models (van der Meer *et al.*, 2006).

- Phase 3 is a full-scale CO_2 injection at a rate of 20,000 to 30,000 Nm^3 CO_2 per hour, which is equivalent to 310,000 to 475,000 tonnes per year (van der Meer *et al.*, 2006). This is well above the 200,000 needed for the "Green Town" solution.

At January 2009, the injection of CO_2 was still on-going and 60 ktCO_2 has been injected (K12-B CO_2 Injection Project).

For future development, it is preferable if the field is situated in a cluster system to cater for the further increase in CO_2 capture capacity. It is noted that a cluster of 200 Mt is needed to store the CO_2 from one power plant (40 years life span and 5Mt annual emissions). This capacity is only found in the Dutch Sectors K and L (van der Velde *et al.*, 2008).

3.6 Future Possibilities

There are several platforms in the K sector and all of the NGT Noordwest/Oost pipeline serving K12-B will be available in 2023 (van der Velde *et al.*, 2008). The last trunk line to be depleted is the WGT and it will be available for CO_2 transportation in 2028 (Christensen and Holloway, 2004). Overall the Netherland fields have a potential of 918 Mt, when the cut-off factors are considered. There is therefore potential to store the CO2 emissions from four power plant that emits 5 Mt per year and are in operation for 40 years(Christensen and Holloway, 2004) .

Cost estimations and more detailed transport scenarios for larger CO_2 storage have been investigated by Cronenberg *et al.* (2009), Jansen *et al.* (2011) and Neele *et al.* (2011).

4 SURVEY RESULTS AND ANALYSES

Following the argument that the public perception is the key to a successful CCS project, surveys were conducted in the City of Southampton and Hamburg to obtain the public opinion of the "Green Town" idea. The objectives of the surveys are to:

- investigate the public awareness on climate change
- obtain public opinion on "Green Town" idea and its technology background
- obtain public acceptance on "Green Town" idea
- obtain the correlation between public perception and their standard demographic variables (age, income, gender, education, etc.)
- obtain the correlation between public opinion and public acceptance on the "Green Town" idea
- obtain the correlation between public opinion on the "Green Town" idea and CCS
- study the sensitivity of additional energy prices
- compare the public perception on the "Green Town" idea in Southampton and Hamburg

The first survey was conducted in the City of Southampton to obtain the public responses and opinions towards the surveys. A sample of the survey form is given in Appendix A. A modified version on the survey form is further made for the surveys conducted in German. It was translated to German (Appendix B) and the English version of the sample is shown in Appendix C.

Both the survey forms for Southampton and Hamburg consists of four parts:

- **First part**
  This section is to obtain the level of public awareness of global warming and greenhouse gases.

- **Second part**
  In this section, a description of the proposed "Green Town" idea is given in a pictorial figure. The information of air capturing facility, means of CO_2 transportation and storage are also described. In addition to that, more detail information on CO_2 leakage and CO_2 storage in depleted oil/gas field are also given. The description of the "Green Town" idea is designed in a way that information given is of neutral viewpoint and issue regarding CO_2 leakage (safety and risk) is provided as well.

  The public opinion and their acceptance on the "Green Town" idea are then sought. The additional energy price per month that the public is willing to pay to support the "Green Town" idea is also included in the survey.

- **Third part**
  This section is to obtain the demographic variables of the public such as sex, age, educational level, income and occupation.

- **Forth part**
  In this section, the public opinion on CO_2 capturing directly at point source such as at the chimney at the power plant is obtained. The purpose is to study the knowledge of the public on CCS and the means of information/media the public awareness on CCS.

4.1 Strategy for Survey

Figure 4.1 shows the sample size required to be collected in the surveys to obtain specific confidence levels or confidence interval. The Creative Research System website (www.surveysystem.com) defines confidence levels and confidence interval as follows:

- The **confidence level** tells you how sure you can be. It is expressed as a percentage and represents how often the true percentage of the population who would pick an answer lies within the confidence interval. The 95% confidence level means you can be 95% certain; the 99% confidence level means you can be 99% certain. Most researchers use the 95% confidence level.

- The **confidence interval** (also called margin of error) is the plus-or-minus figure usually reported in newspaper or television opinion poll results. For example, if you use a confidence interval of 4 and 47% percept of your sample picks an answer you can be "sure" that if you had asked the question of the entire relevant population between 43% (47-4) and 51% (47+4) would have picked that answer.

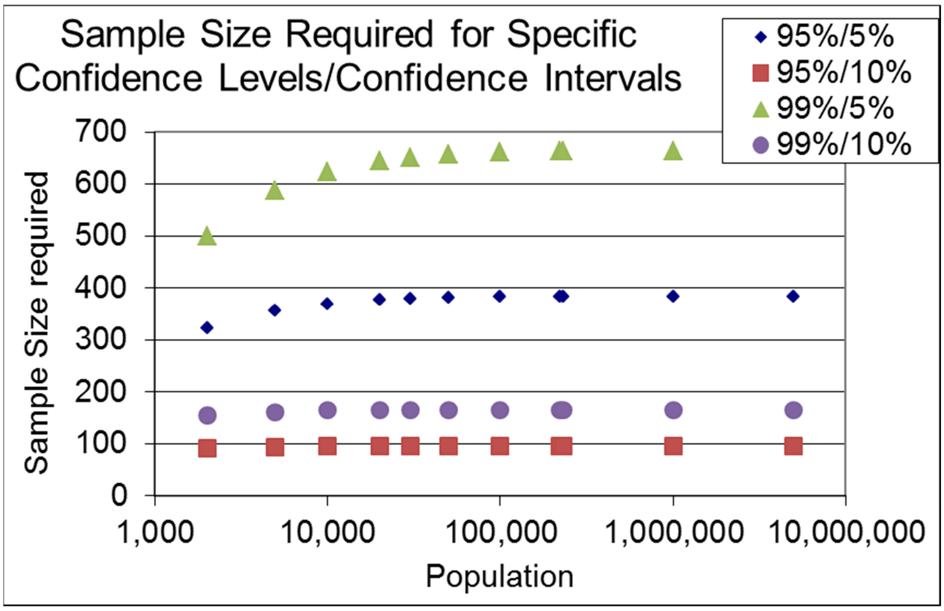

Figure 4.1: Sample Size Required for Specific Confidence Level/Confidence Intervals

The 95% confidence level is used in the surveys conducted in Southampton and Hamburg, with 9.8% confidence intervals for the surveys in Southampton and 6.3% confidence interval for the surveys in Hamburg. The sample size collected in both cities are given in Table 4.1

TABLE 4.1
SAMPLES COLLECTED IN SOUTHAMPTON AND HAMBURG

	Total samples	Locals	Confidence level	Confidence intervals
Southampton	366	248	95%	6.3%
Hamburg	158	100	95%	9.8%

The results and discussions for the surveys conducted in Southampton and Hamburg are presented in the subsequent chapters.

4.2 Survey Results from Southampton

4.2.1 Samples Information with respect to Demographic Variables

The surveys were conducted in the Southampton Airport, Central train station, University of Southampton, Highfield campus, Central bus station, bus. The total population in Southampton is approximately 239,700 with 50.43% male and 49.26% female (Southampton City Council, 2007). Out of the 100 samples on locals, 57% are male and 42% are female. There is a higher percentage of male respondents than the female in the samples. Figure 4.2 shows the percentage of the public in accordance to the age range. Most of the samples fall in the age range between 18-25 and 26-35 years old and about 38% of the samples falls in the age range of 35 and above.

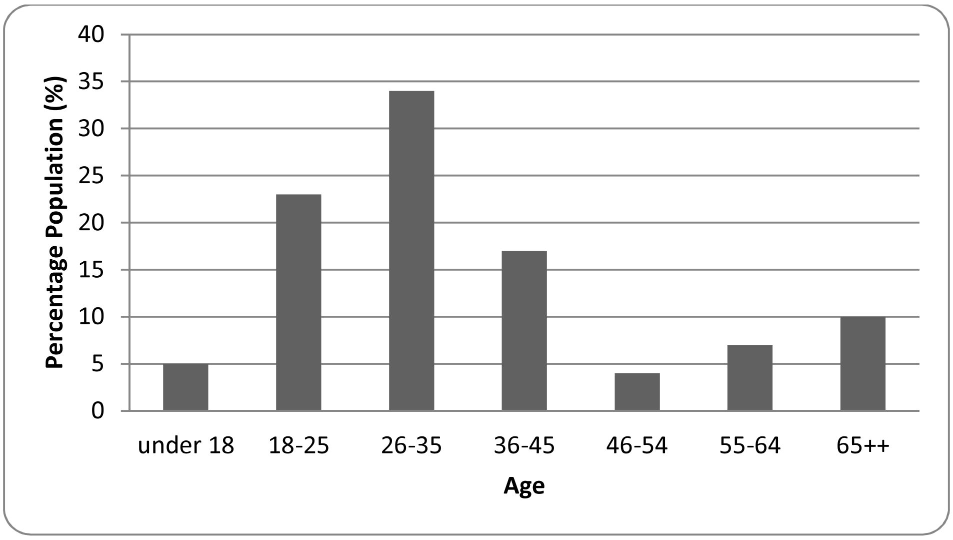

Figure 4.2: Population vs Age

The educational level of the public were also obtained where four different qualifications are listed in the surveys for selection, i.e. GCSEs, A level or equivalent, university degree or equivalent and others. 37.04% obtained college vocational degree and 48.97% university academic degree. Figure 4.3 shows the educational level of the samples collected in percentage in each of the age group. It can be seen that except age group “under 18” and “above 65”, most of the public are highly educated across all the other age groups.

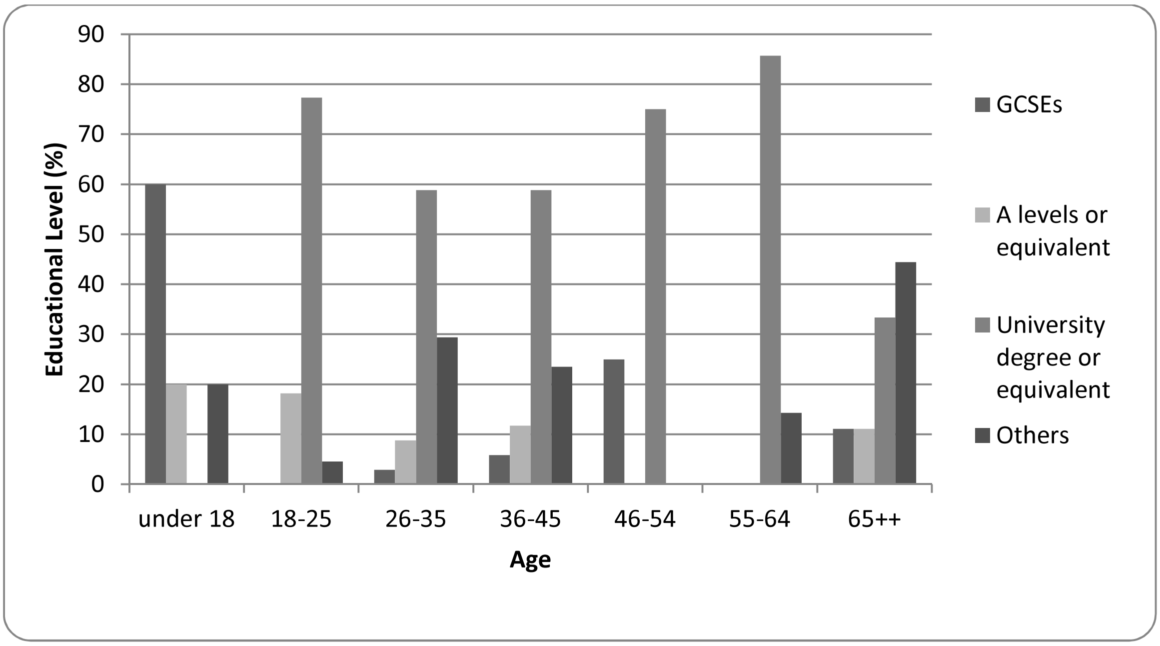

Figure 4.3: Educational Level vs Age

Out of the 100 local samples, 42% is student, 45% non-student and 13% retiree. The non-students samples consist of teachers, professionals (engineers, lawyers, doctors etc.), and employees.

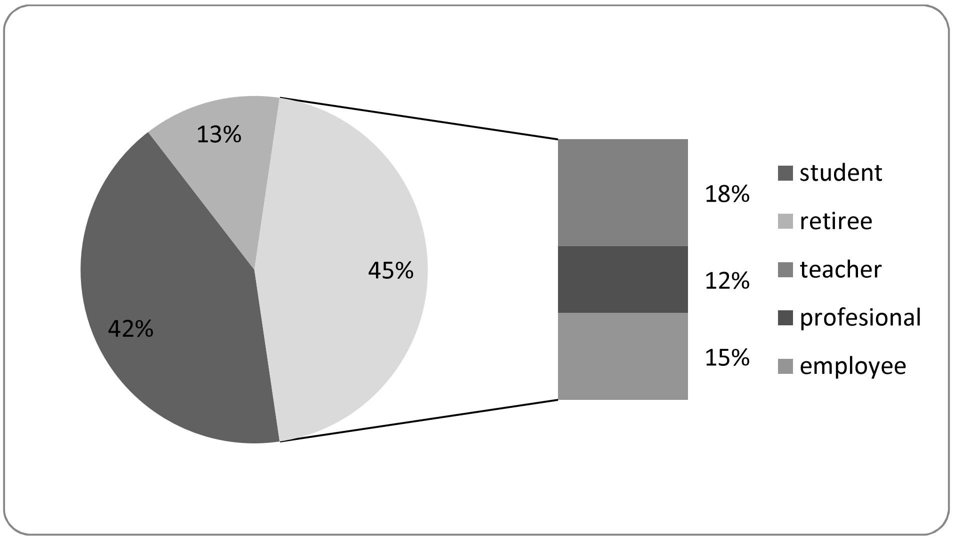

Figure 4.4: Occupations of Public

In general, nearly 96% of the public interviewed in Southampton are aware of global warming and are environmentally conscious. It is also noted that more than 95.9% of the public do have a habit of recycling. On a 0-5 scale, with 5 denotes *very concern on global warming* and 0 *not concern*, 28.1% rated 5 whereas no one rated 0 (see Fig 4.5). 87.3% of the public rated 3 and above and this would indicate that the public would generally be more supportive on the means to create a greener environment.

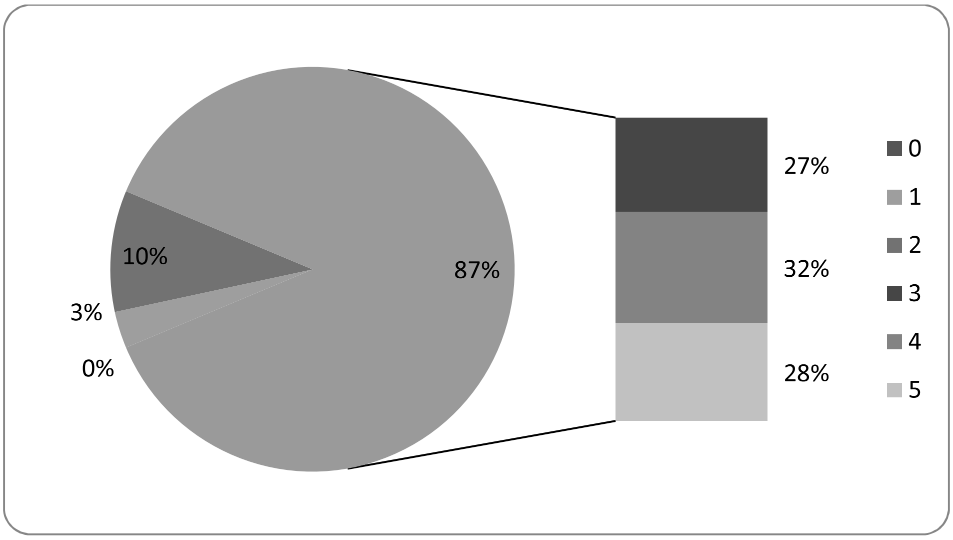

Figure 4.5: Public Concern on Global Warming
(0 denotes *not concern* and 5 *very concern*)

4.2.2 Public Opinion on Green Town Idea

In Part 2 of the survey, the public was asked on their opinion on the "Green Town" Idea. The results are given in Fig. 4.6. They were asked to select their preferences on the idea out of six choices: *don't like it at all*, *don't like it*, *neither like nor dislike it*, *like it*, *really like it* and *don't know*. The public in general (56.56%, percentage summation of *like it* and *really like it*) has positive response towards the idea whereas only 8.08% (percentage summation of *don't like it at all* and *don't like it*) of the public dislike the idea of the Green Tower. 28.28% stays neutral.

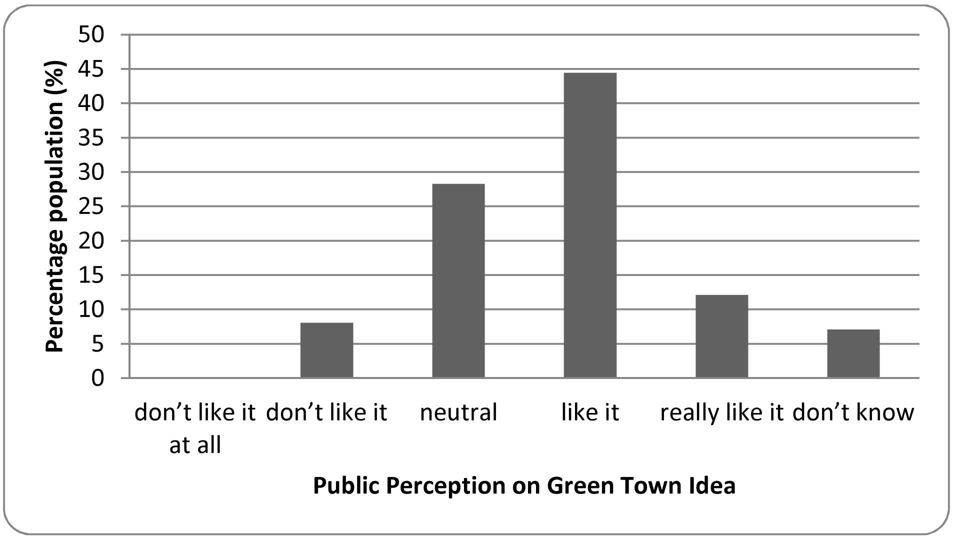

Figure 4.6: Percentage Population vs Public Opinion on "Green Town" Idea

On the next question, the public is asked to rate their preferences on having the air scrubbing facility in their town. On a scale of 0-5, with 0 denotes *negative response* and 5 *positive response*, more than half of the public (75.5%) is positive towards the idea of installing the air scrubbing facility in their town (see Fig. 4.7).

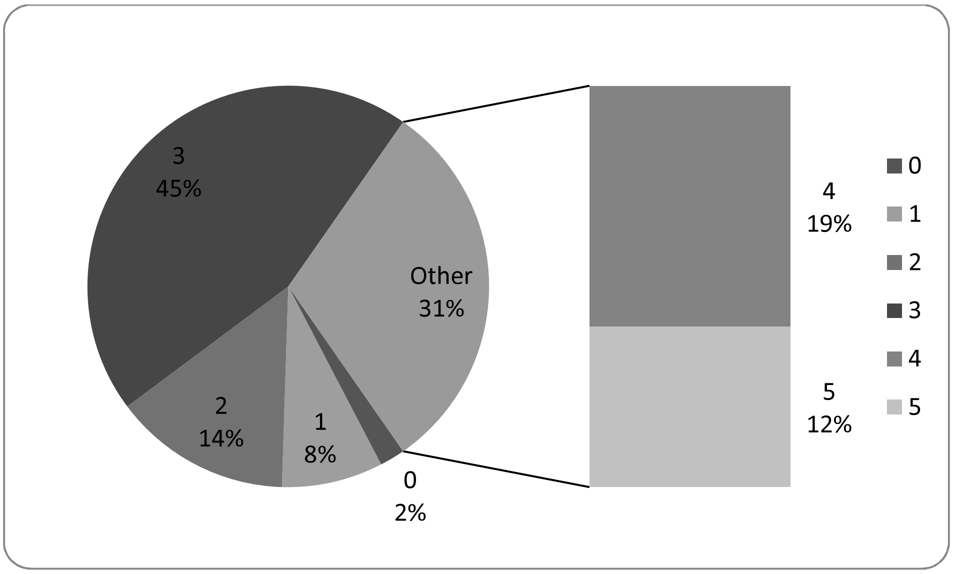

Figure 4.7: Public Acceptance on “Green Town” Idea

However, when asked on the additional energy prices/month that the public would be willing to pay to support the “Green Town” idea, almost 40% would prefer no additional energy price increase whereas over 30% would agree to pay for 5 Pound/month (see Fig. 4.8). This implies that the government support and involvement may be essential in realising a successful CCS project. This fact is further supported in Fig. 4.9 where it shows that the additional energy prices/months that the public is willing to pay to support the “Green Town” idea is independent on their personal income. Based on the 98 valid local samples, the average additional energy price per month that the public is willing to pay is 4.74 Pound/month.

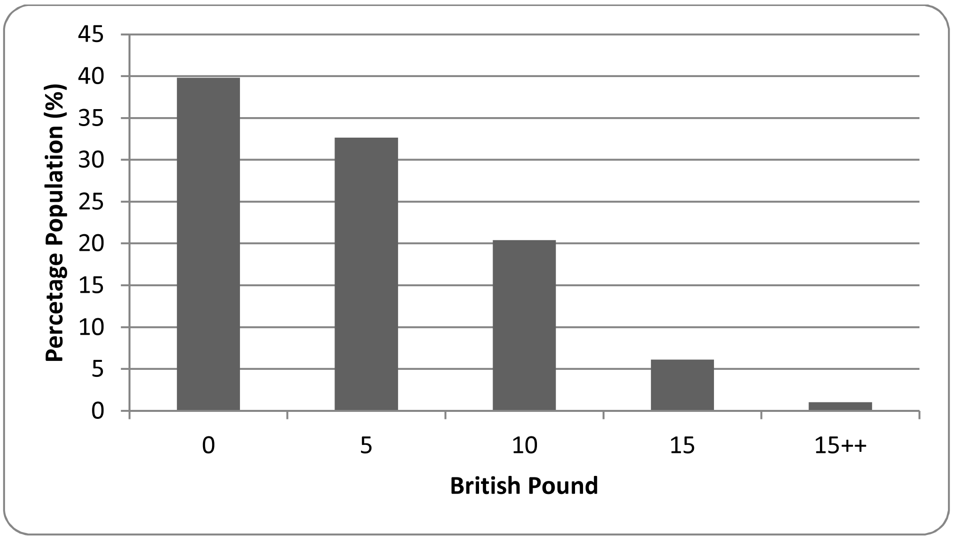

Figure 4.8: Percentage Population vs Price Willing to Pay in British Pound

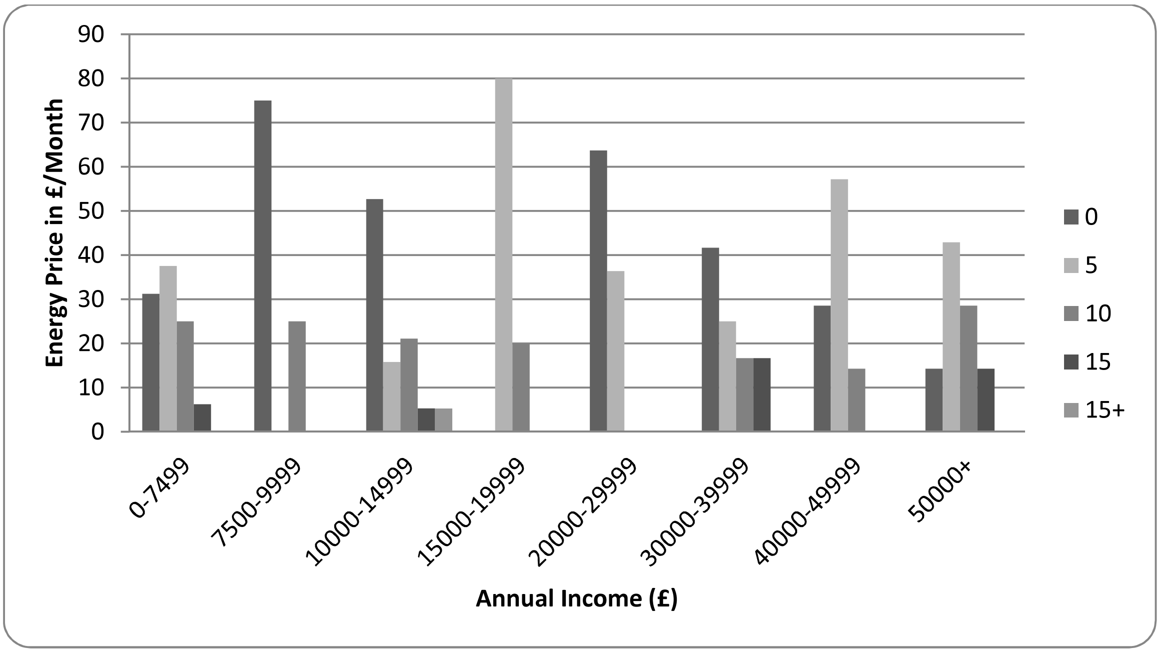

Figure 4.9: Energy Price in Pound/Month vs Annual Income (in Pound)

Figure 4.10 and 4.11 show respectively the public perception and public acceptance on the "Green Town" idea in accordance to their educational level. In general, most of the public that receives education would like the idea of "Green Town" and shows positive response towards the "Green Town" idea. This indicates that school or university could function as a platform to effectively educate the public on the "Green Town" idea. It could also means that the opinion of the public could be altered if adequate information on a new technology is provided.

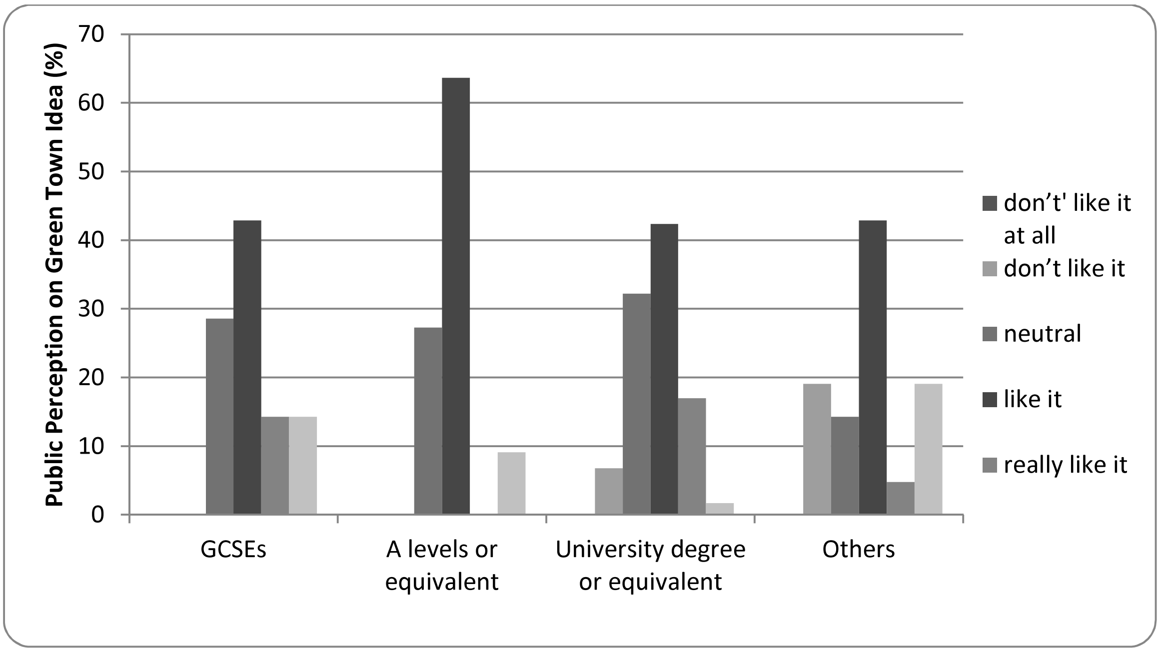

Figure 4.10: Public Perception on "Green Town" Idea vs Educational level

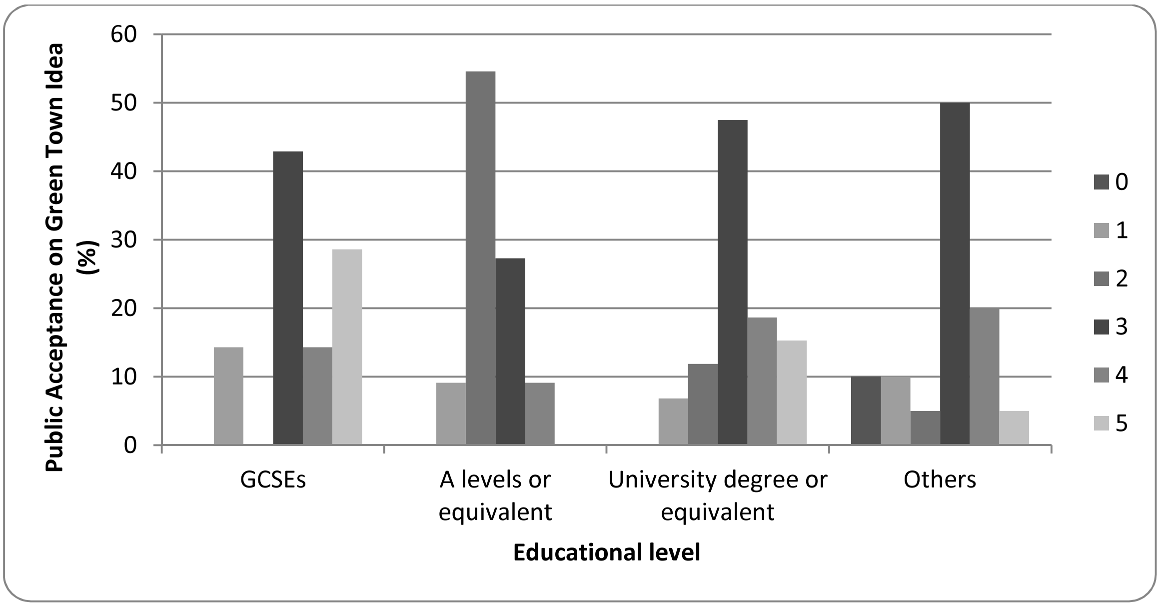

Figure 4.11: Public Acceptance on "Green Town" Idea vs Educational Level

4.2.3 Public Perception on CCS

At the end of the survey form, the public perception on CO_2 capture from point source (i.e. CCS) is also obtained. The results are given in Fig. 4.12 which shows that 42% of the public like the idea of capturing CO_2 from point source such as chimney in coal power plant. This positive response (*like it* or *really like it*) is 14.56% less as compared to the public opinion on the "Green Town" idea. This might probably indicate that the public would prefer the idea of capturing CO_2 directly from the atmosphere rather than from the point source as this method is generally friendlier to public. Out of the 100 locals' samples collected, nearly half (47.4%) of the public have heard of CCS whereas the other half have not. This indicates that more information on CCS has to be provided to the public mass media such television, radio, internet or newspaper in order to keep the public informed on the technology.

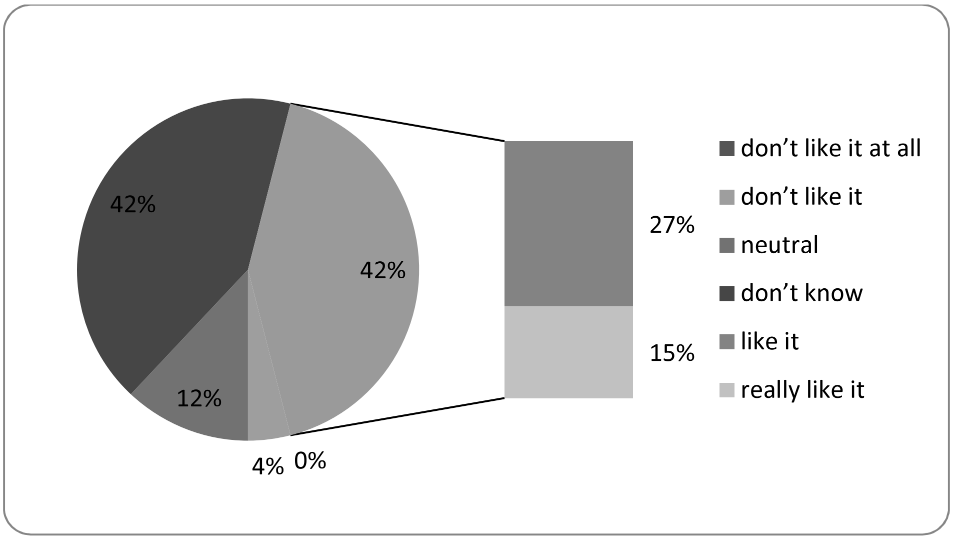

Figure 4.12: Percentage Population and Public Opinion on CCS

An interesting finding on the awareness of the public on CCS with regards to their age group percentage is shown in Fig. 4.13. It shows that the younger generation aged 35 and below have a slightly higher percentage of knowing CCS technology whereas the findings on the older generation aged 35 and above are on the other way round.

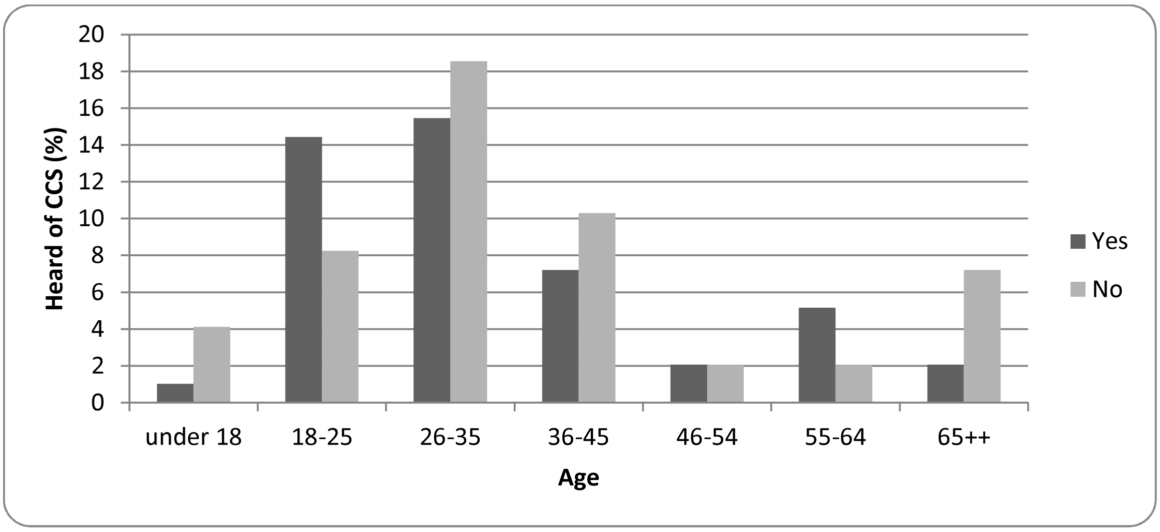

Figure 4.13: Public Awareness on CCS Technology vs Age

Figure 4.14 investigates the public awareness of CCS techology with respect to their educational level. It can be seen that greater percentage of the public who obtained a university academic degree has heard of CCS technology. However, it could be seen that all the public interviewed that do not have a GCSE has never heard of CCS. The percentage of the public feeling positive on the “Green Town” idea is also higher for those having a college vocational degree and university academic degree (see Fig. 4.15). This implies that education could play an important role in educating the public on CCS and information regarding CCS could effectively be delivered to the public through schools and universities.

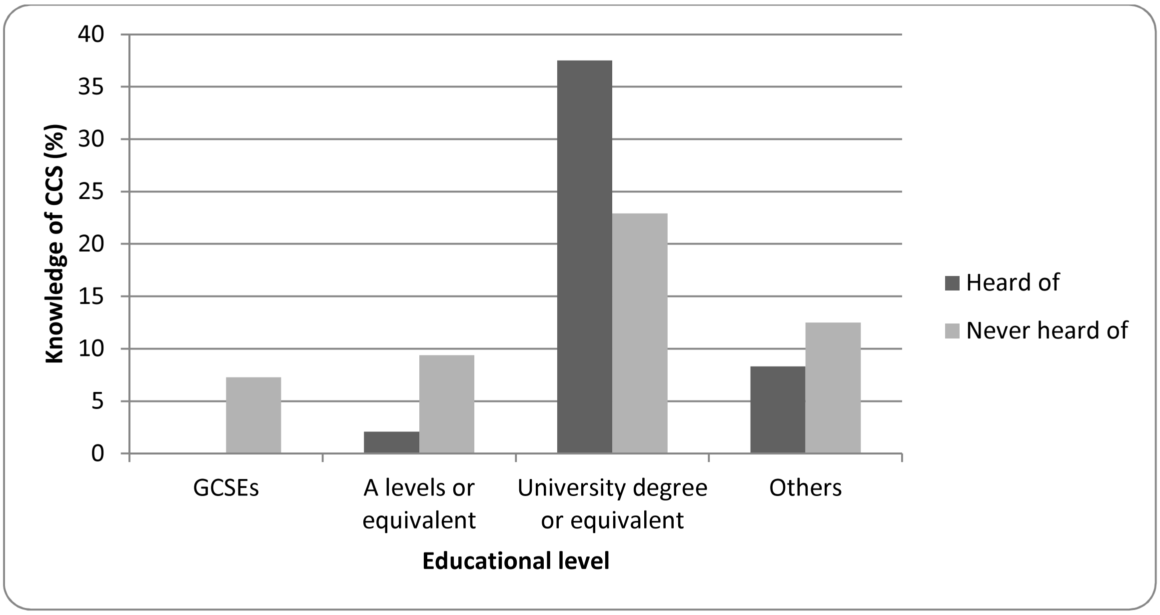

Figure 4.14: Public Awareness on CCS Technology vs Educational Level

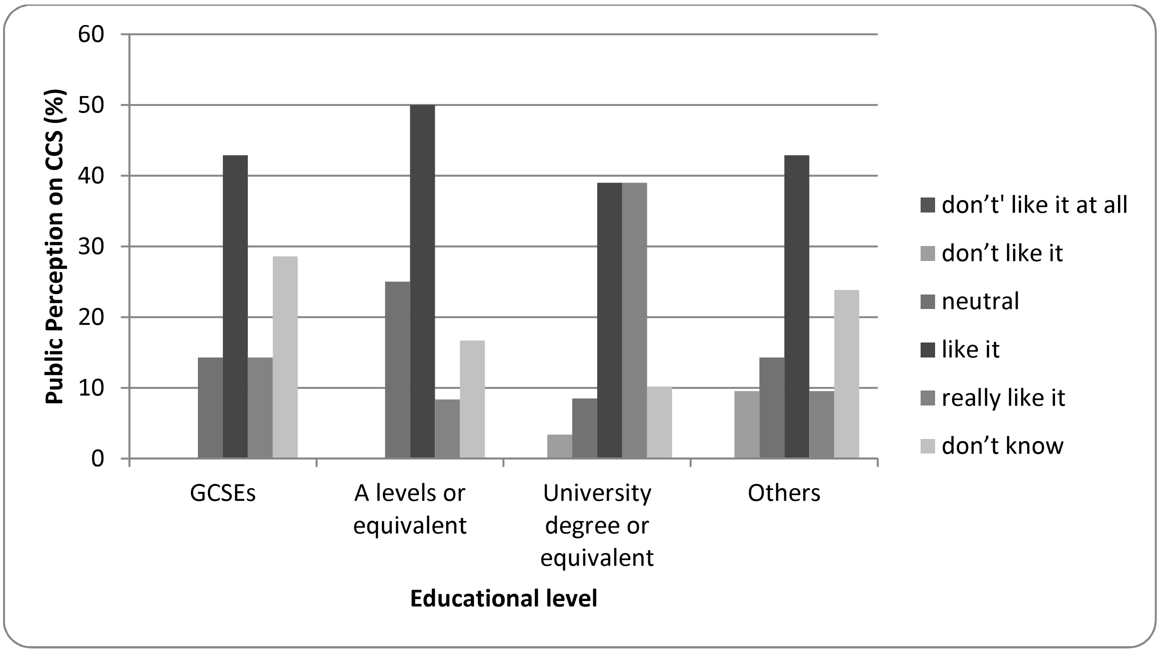

Figure 4.15: Public Perception on CCS vs Education Level

4.2.4 Correlation between Public Perception and Public Acceptance on "Green Town" Idea

Figure 4.16 shows the correlation between the public perceptions on the "Green Town" idea vs their acceptance on having the air scrubbing facility in their town. It shows that there is a direct correlation between the public perception and acceptance. It is fair to say that those who do not like the "Green Town" idea would generally feel negative on having the air scrubbing facility in town and vice versa. This indicates that the interest of the public on the "Green Town" idea should be inculcated in the early stage and the engagement and opinion of the public is important to enhance public acceptance on the "Green Town" idea. The same would apply in ensuring a successful CCS project.

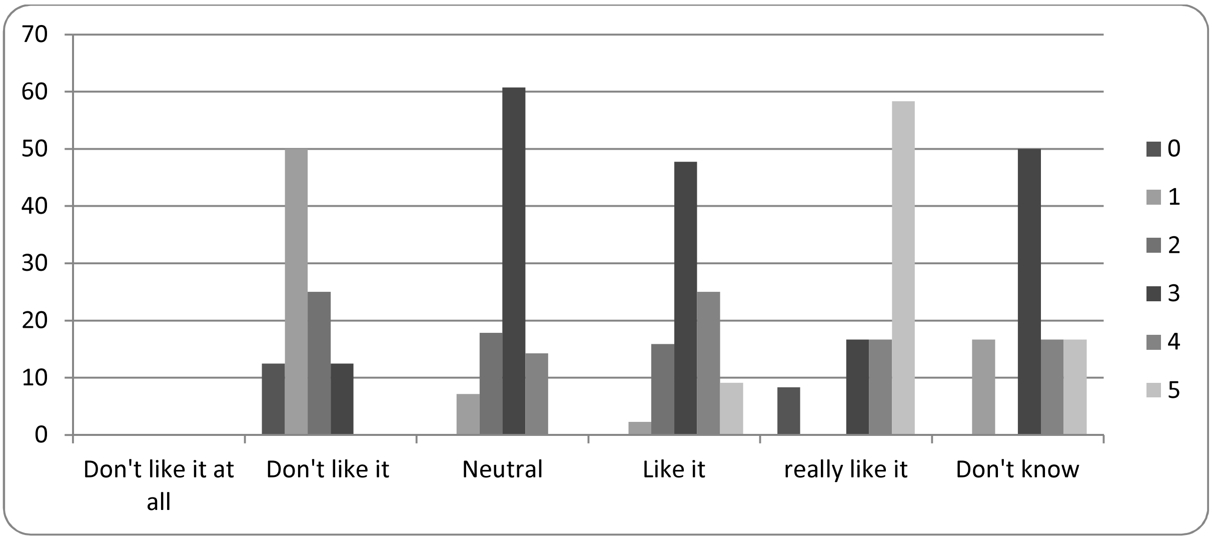

Figure 4.16: Public Perception on "Green Town" Idea vs Public Acceptance on "Green Town" Idea

4.2.5 Correlation between Public Perception on “Green Town” Idea and CCS

Figure 4.17 shows the correlation between public perceptions on the “Green Town” idea vs the public perception on CCS. The figure shows that public who like the idea of “Green Town” would generally appear to like CCS. However, those who appear neutral on the “Green Town” idea do not like CCS. This implies that the “Green Town” idea plays an important role in laying a strong foundation to incur public interest in CCS project.

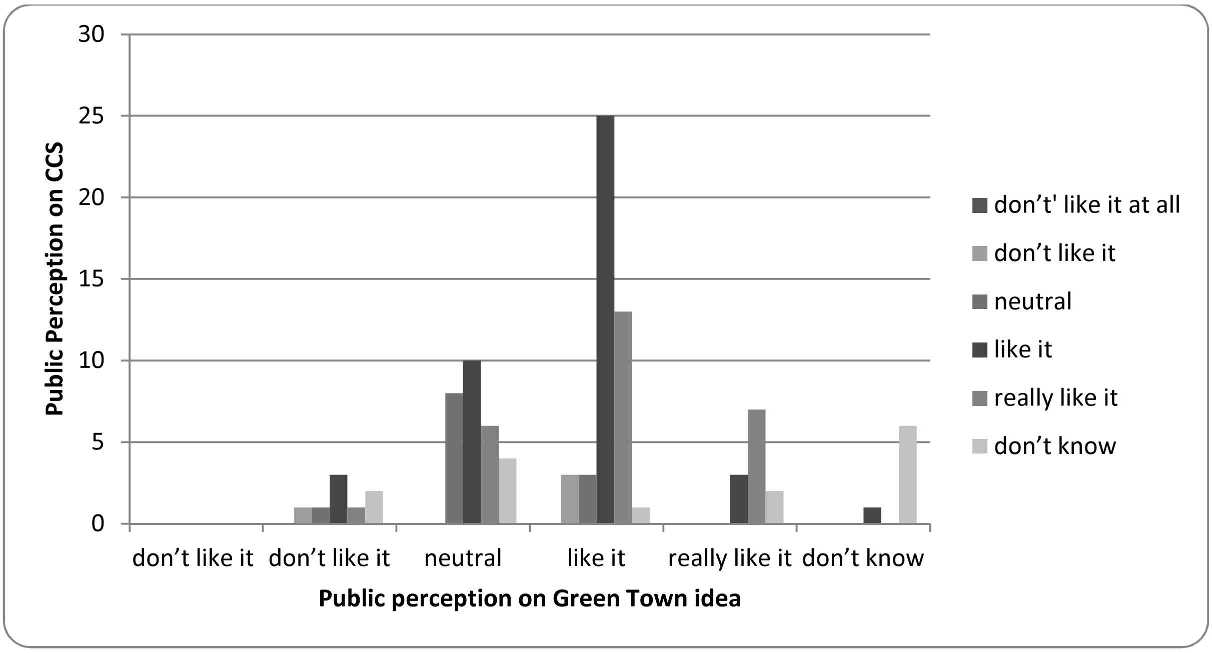

Figure 4.17: Public Perception on “Green Town” Idea vs Public Perception on CCS

4.2.6 Media

Figure 4.18 shows the types of sources the public heard of CCS. It can be seen that the newspaper and TV are the main sources used by the public to obtain information regarding CCS. This two sources made up 55% of the total source. The public also receive information on CCS through internet (19%) and journals/conference (21%). Other sources are such as magazine (3.5%) and radio (1.7%).

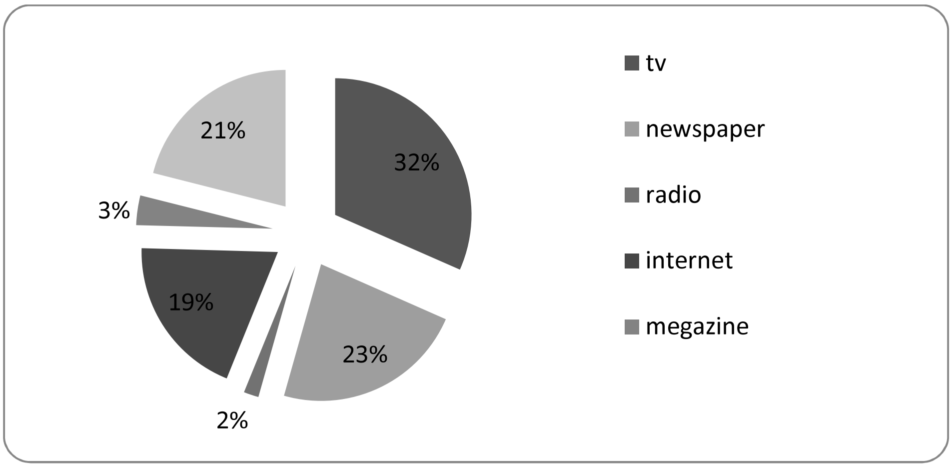

Figure 4.18: Means of Media/Sources

4.3 Survey Results from Hamburg

4.3.1 Samples Information with respect to Demographic Variables

The surveys were conducted in the Hauptbahnhof Train Station, Dammtor Train Station, Hamburg University main campus, parks, bus and metro. The total population in Hamburg is approximately 1.8million with 48.81% male and 51.19% female (Statistical office Hamburg and Schleswig-Holstein, 2007). Out of the 248 samples on locals, 49.17% are male and 50.83% female. This gives a good distribution according to the percentage of males and females in Hamburg. Figure 4.19 shows the percentage of the public in accordance to the age range. Most of the samples fall in the age range between 18-25 and 26-35 years old and about 19% of the samples falls in the age range of 35 and above.

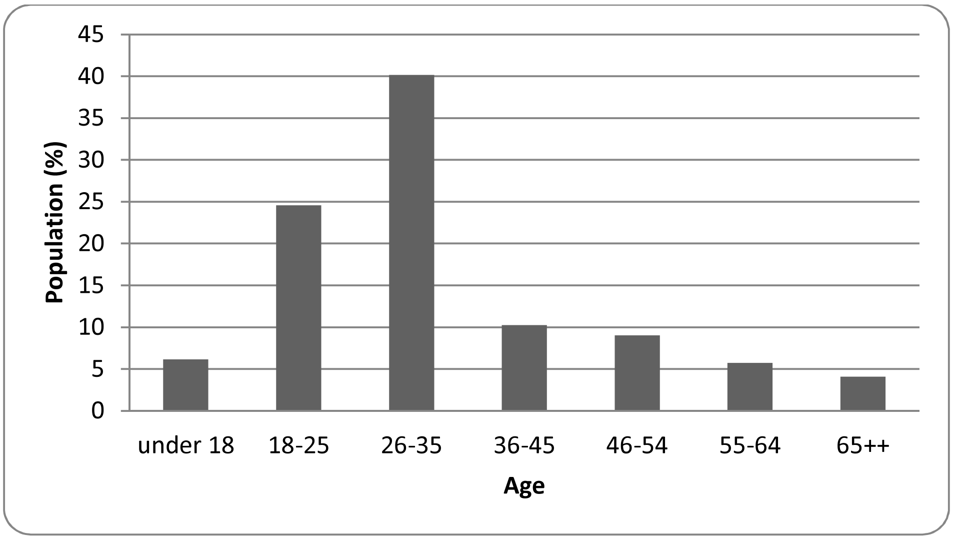

Figure 4.19: Population vs Age

The educational level of the public were also obtained where five different qualifications are listed in the surveys for selection, i.e. without school certificate, school certificate, school leaving certificate, college vocational degree and university academic degree. 37.04% obtained college vocational degree and 48.97% university academic degree. Figure 4.20 shows the educational level of the samples collected in percentage in each of the age group. It can be seen that most of the public are highly educated with age 26 and above received university academic degree.

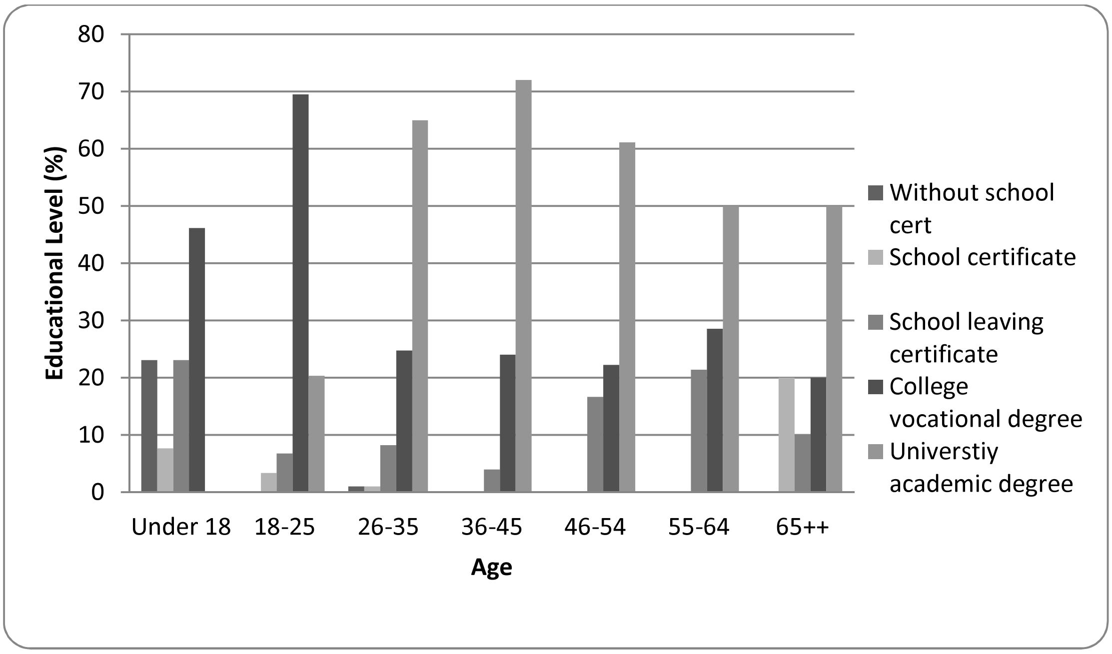

Figure 4.20: Educational Level vs Age

Out of the 238 local samples, 43% is student, 54% non-student and 3% retiree. The non-students samples consist of teachers, professionals (engineers, lawyers, doctors etc.), technicians, employers and employees (see Fig. 4.21).

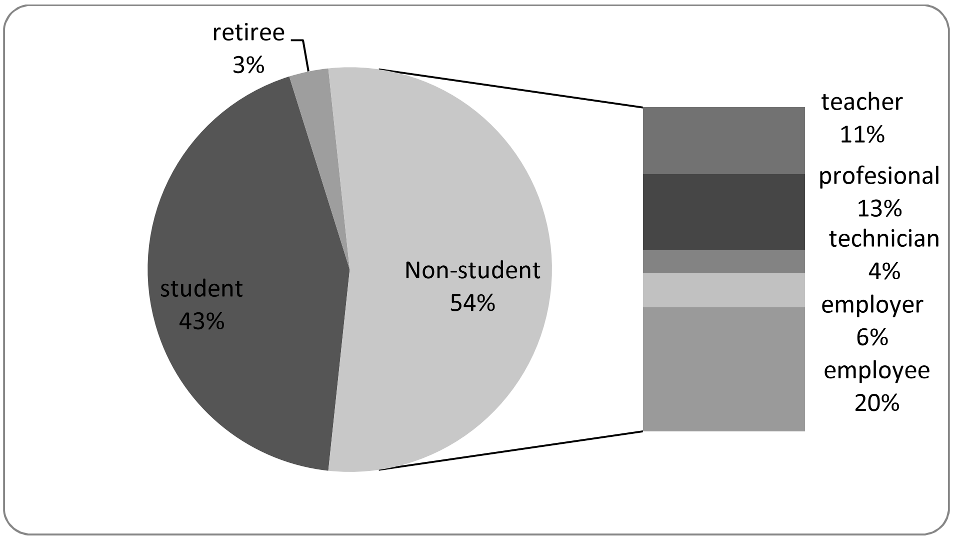

Figure 4.21: Occupations of Public

In general, most of the public in Hamburg are aware of global warming (99.19% heard of global warming and 97.5% heard of greenhouse gases) and are environmentally conscious. It is also noted that more than 80% of the public do have a habit of recycling. On a 0-5 scale, with 5 denotes *very concern on global warming* and 0 *not concern*, 40% rated 5 whereas only 2.39% rated 0 (see Fig 4.22). 88% of the public rated 3 and above and similarly to the surveys conducted in Southampton; this indicates that the public would generally be more supportive on the means to create a greener environment.

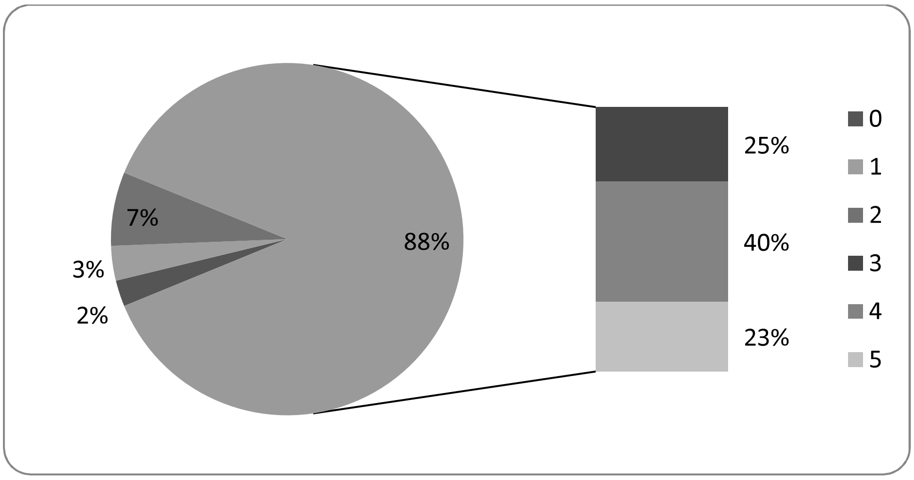

Figure 4.22: Public Concern on Global Warming
(0 denotes *not concern* and 5 *very concern*)

4.3.2 Public Opinion on "Green Town" Idea

In Part 2 of the survey, the public is asked on their opinion of the "Green Town" Idea. The results are presented in Fig. 4.23. They are asked to select their preferences on the idea out of six choices: *don't like it at all*, *don't like it*, *neither like nor dislike it*, *like it*, *really like it* and *don't know*. The public in general (44.3%, percentage summation of *like it* and *really like it*) has positive response towards the idea whereas only 20% (percentage summation of *don't like it at all* and *don't like it*) of the public dislike the idea of the Green Tower. 25% stays neutral.

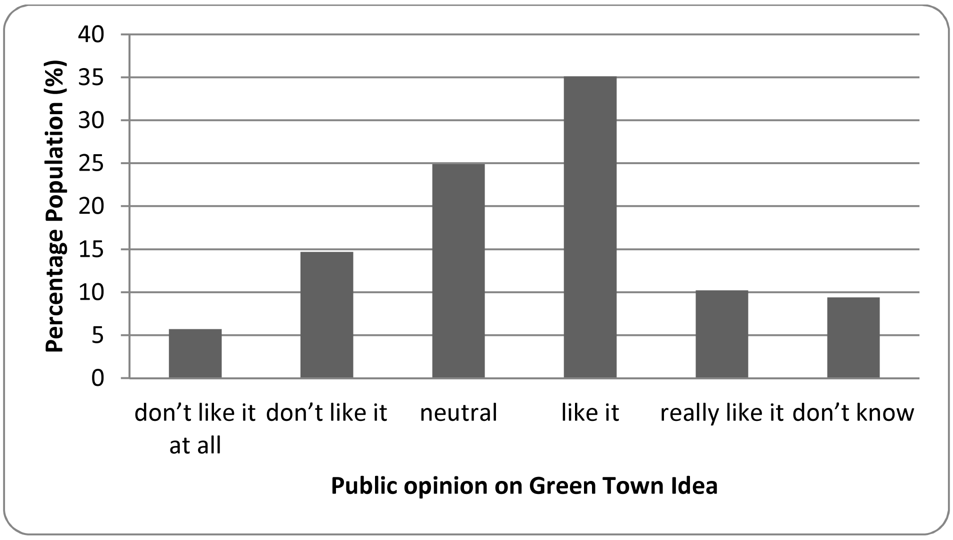

Figure 4.23: Percentage Population vs Public Opinion on "Green Town" Idea

On the next question, the public is asked to rate their preference on having the air scrubbing facility in their town. On a scale of 0-5, with 0 denote *negative response* and 5 *positive response*, more than half of the public (57%) is positive towards the idea of installing the air scrubbing facility in their town (see Fig. 4.24).

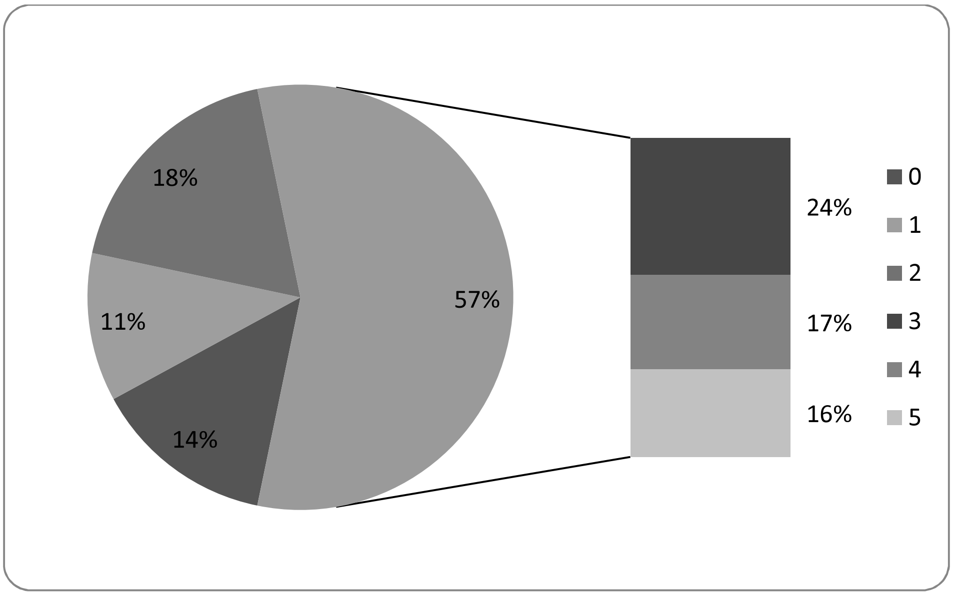

Figure 4.24: Public Acceptance on "Green Town" Idea

However, when asked on the additional energy prices/month that the public would be willing to pay to support the "Green Town" idea, more than 45% would prefer no energy price increase where 27% would agree to pay for 5 Euro/month (see Fig. 4.25).This implies that the government support and involvement may be essential in realising a successful CCS project. This is further supported in Fig. 4.26 where it shows that the additional energy prices/months that the public is willing to pay to support the "Green Town" idea is independent on their personal income. Based on the 238 local samples collected, the average additional energy price per month that the public is willing to pay is Euro 4.72/month.

Figure 4.25: Percentage Population vs Price Willing to Pay in Euro

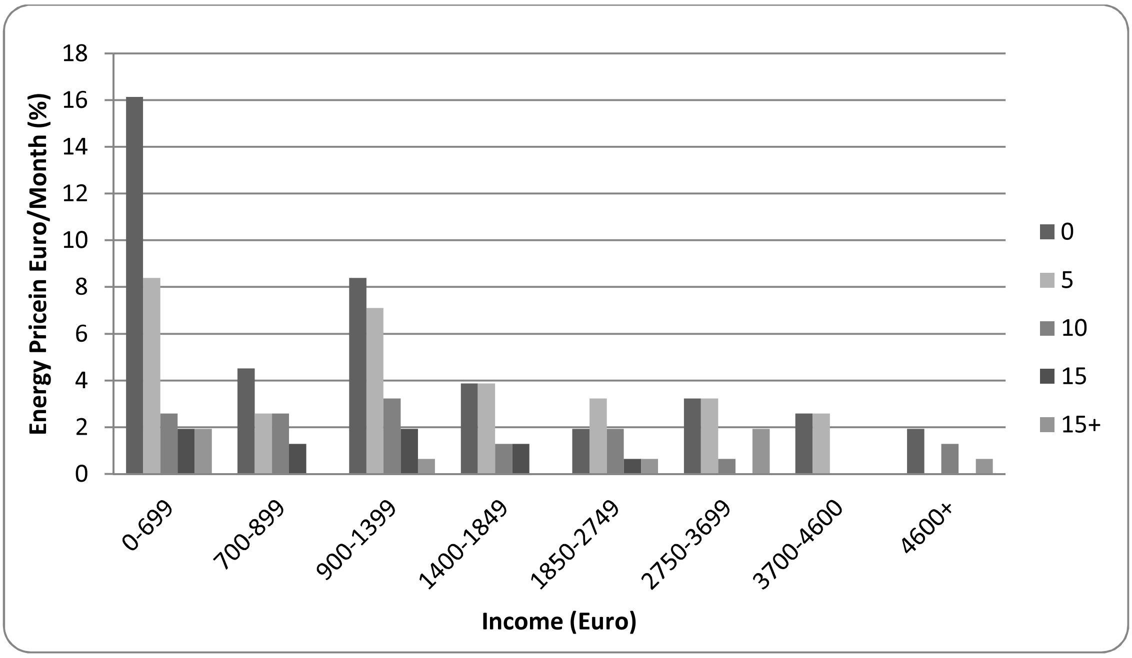

Figure 4.26: Energy Price in Euro/Month vs Monthly Income in Euro

Figure 4.27 and 4.28 show respectively the public perception and public acceptance on the "Green Town" idea in accordance to the educational level of the public. In general, most of the public that receives education would like the idea of "Green Town" and shows positive response towards the "Green Town" idea. This indicates that school or university could function as a platform to effectively educate the public on the "Green Town" idea. It could also indicate that the opinion of the public could be altered if adequate information on a new technology is provided.

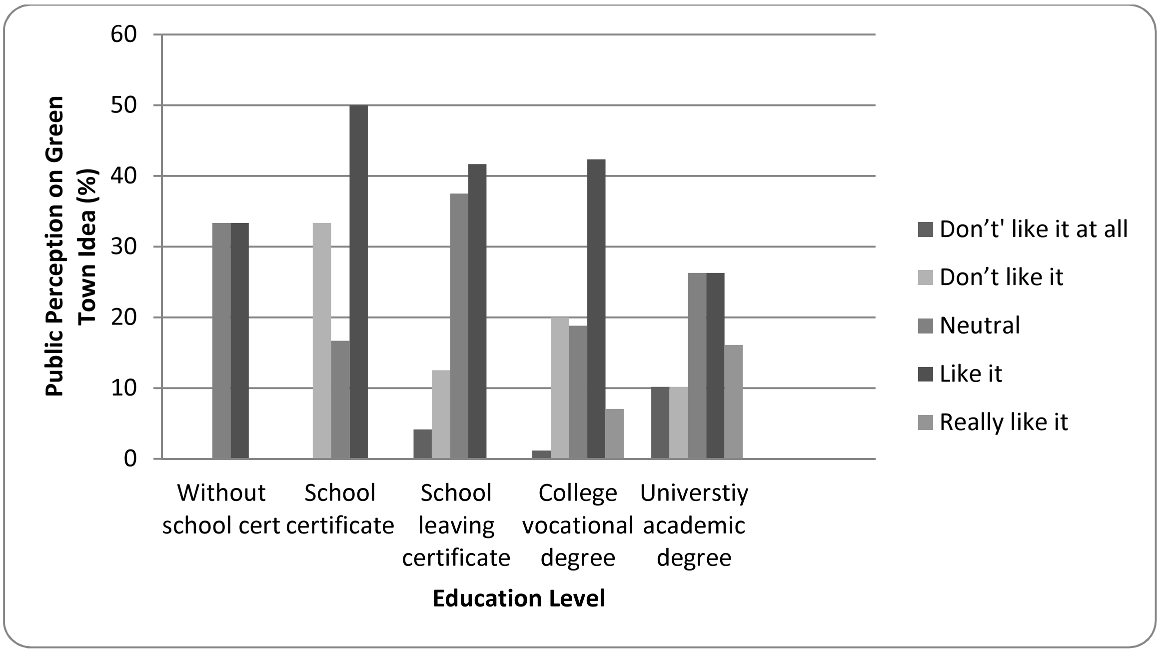

Figure 4.27: Public Perception on "Green Town" Idea vs Educational level

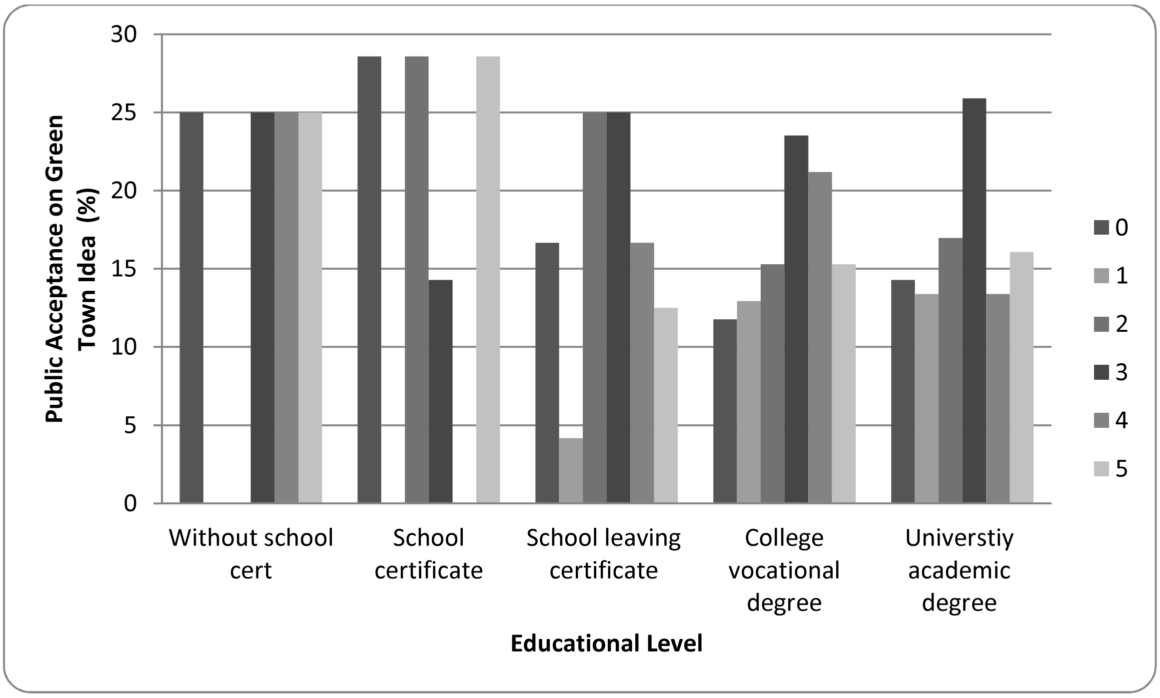

Figure 4.28: Public Acceptance on "Green Town" Idea vs Educational Level

4.3.3 Public Perception on CCS

At the end of the survey form, the public perception on CO_2 capture from point source (i.e. CCS) is also obtained. The results are given in Fig. 4.29 which shows that 64% of the public like the idea of capturing CO_2 from point source such as chimney in coal power plant. This positive response (*like it* or *really like it*) is 20% more as compared to the public opinion on the "Green Town" idea. This might probably show that the public would prefer the idea of capturing CO_2 directly from the point source rather than from the atmosphere as this method is generally more effectively in reducing large amount of CO_2 in the air. On a different argument, by introducing how the "Green Town" idea (which is based on the CCS concept) could benefit the public in providing a cleaner environment, this has successfully resulted in a change in the public opinion to start accepting CCS as a mean to effectively reduce CO_2 emission to the air. This shows that the public opinion could be changed if more information on the proposed technology is given and if the whole project involves the public engagement in the early stage. Out of the 248 locals' samples collected, half of the public have heard of CCS whereas the other half have not. This indicates that more information on CCS has to be provided to the public mass media such television, radio, internet or newspaper in order to keep the public informed on the technology.

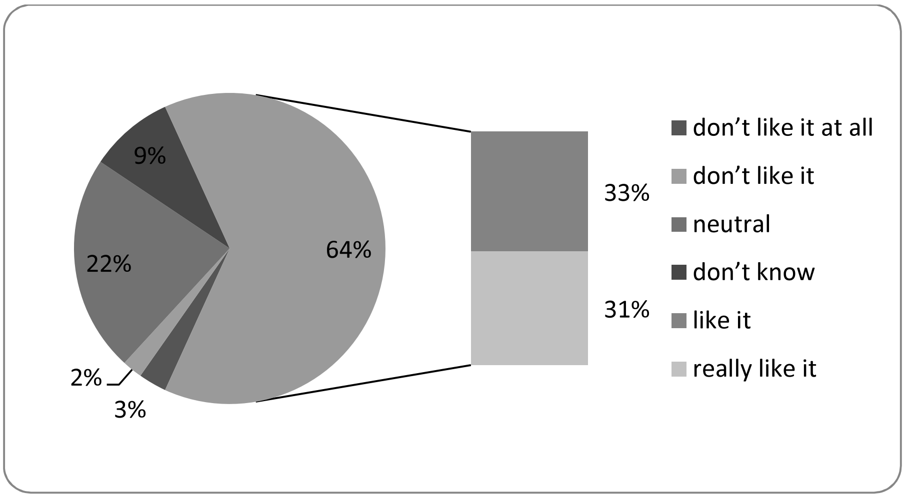

Figure 4.29: Percentage Population and Public Opinion on CCS

Similar to the sample in Southampton, an interesting finding on the public awareness on CCS with regards to their age is shown in Fig. 4.30. It shows that the younger generation aged 35 and below have a slightly higher percentage of not knowing CCS technology whereas the findings on the older generation aged 35 and above are on the other way round. Interestingly, out of 9 people who aged 65 years old and above, 8 of them have heard of CCS.

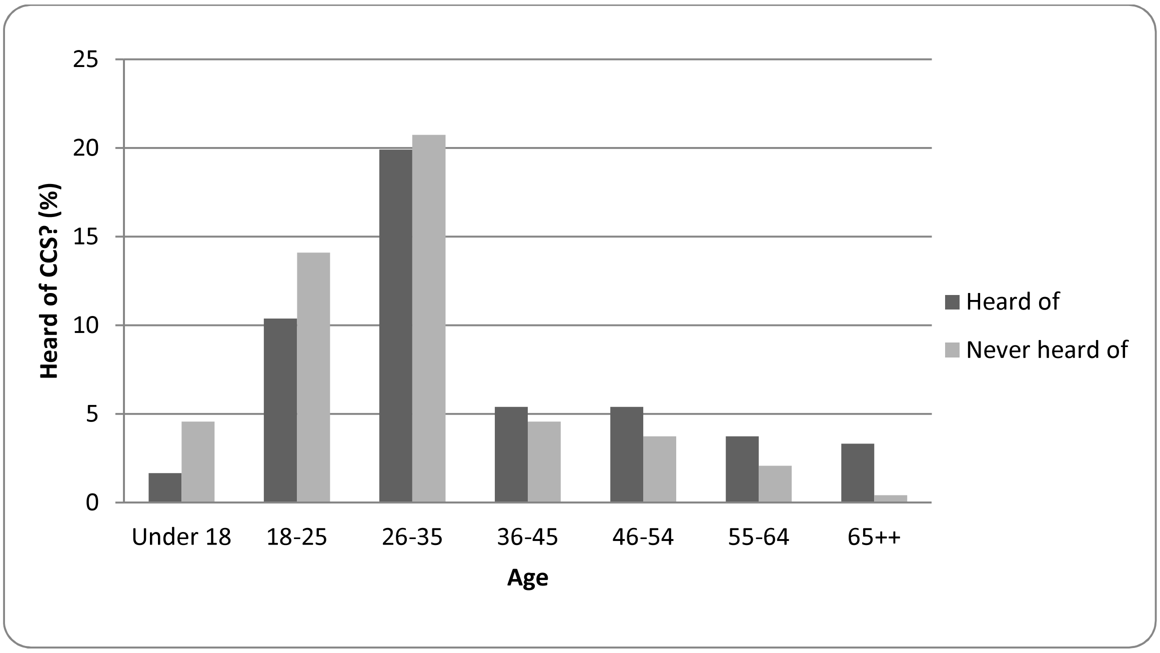

Figure 4.30: Public Awareness on CCS Technology vs Age

Figure 4.31 investigates the public awareness of CCS techology with respect to their educational level. It can be seen that greater percentage of the public who obtained a university academic degree has heard of CCS technology but the percentage is only slightly higher as compare to those that have never heard of CCS. However, it could be seen that a large percentage of the public that do not have a school cert (75%) has never heard of CCS. The percentage of the public feeling positive on the “Green Town” Idea is also higher for those having a college vocational degree and university academic degree (see Fig. 4.32). This implies that education could play an important role in educating the public on CCS and information regarding CCS could effectively be delivered to the public through schools and universities.

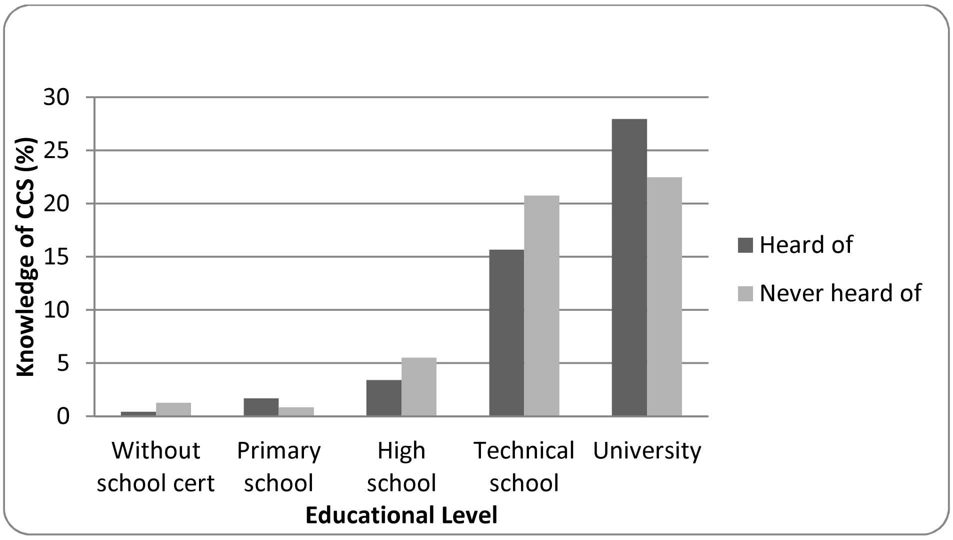

Figure 4.31: Public Awareness on CCS Technology vs Educational Level

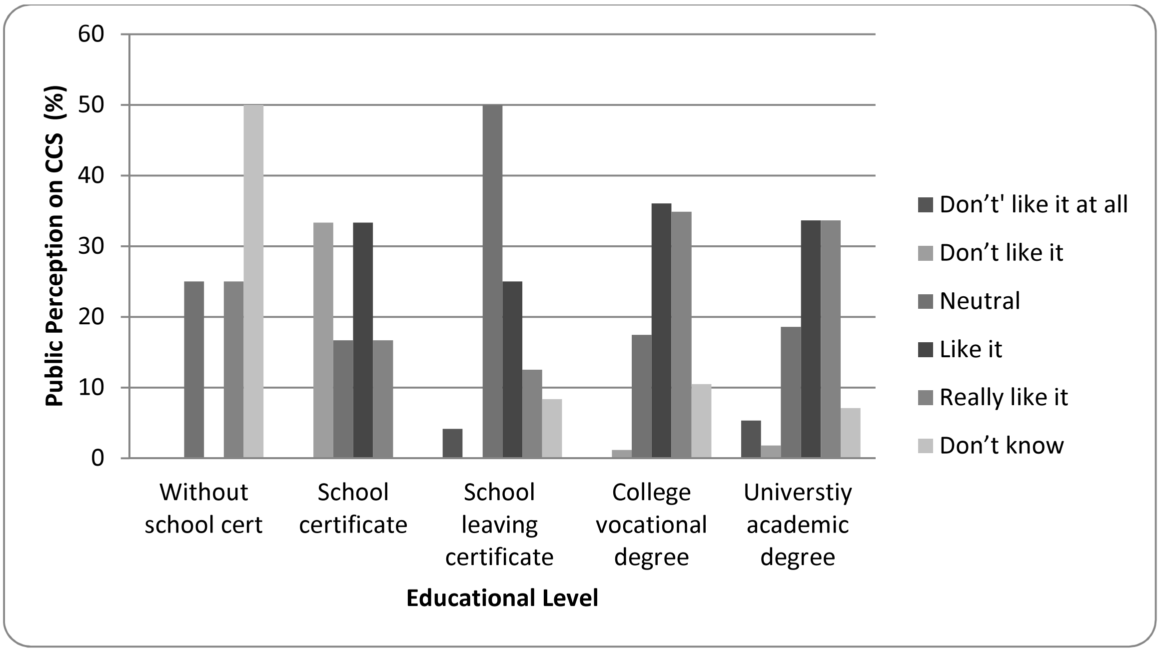

Figure 4.32: Public Perception on CCS vs Education Level

4.3.4 Correlation between Public Perception and Public Acceptance on "Green Town" Idea

Figure 4.33 shows the correlation between the public perceptions on "Green Town" idea vs their acceptance on having the air scrubbing facility in their town. It shows that there is a direct correlation between the public perception and acceptance. This is to say that those who do not like the "Green Town" idea would generally feel negative on having the air scrubbing facility in town and vice versa. This indicates that the interest of the public on "Green Town" idea should be inculcated in the early stage and the engagement and opinion of the public is important to enhance public acceptance on the "Green Town" idea. The same would apply in ensuring a successful CCS project.

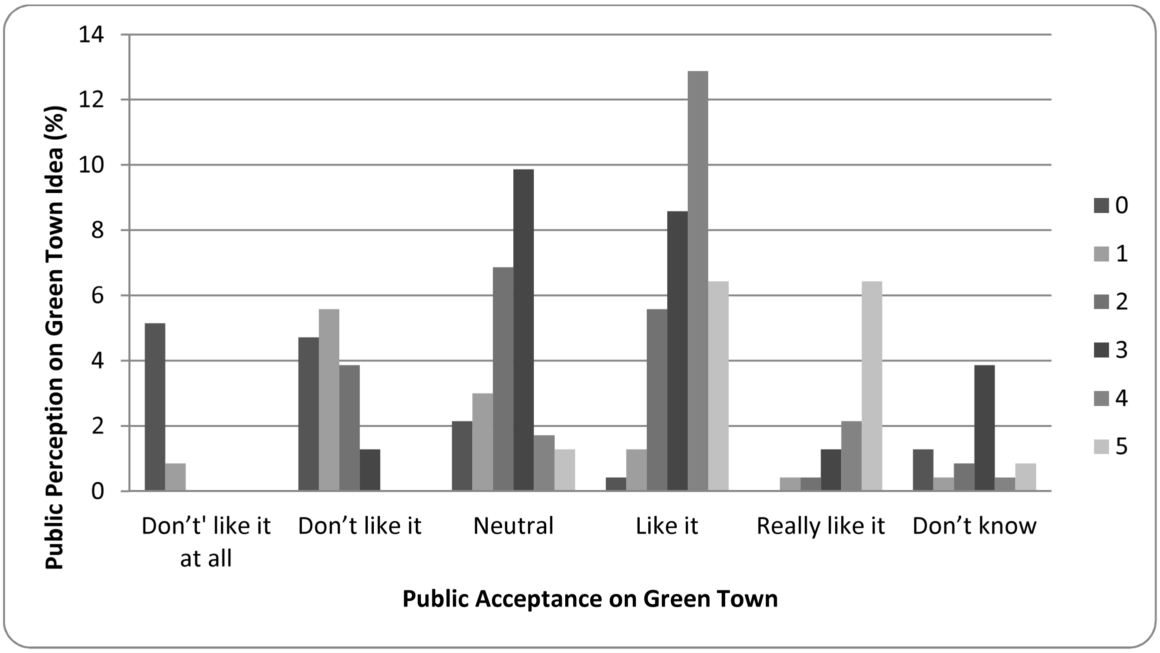

Figure 4.33: Public Perception on “Green Town” Idea vs Public Acceptance on “Green Town” Idea

4.3.5 Correlation between Public Perception on “Green Town” Idea and CCS

Figure 4.34 shows the correlation between public perceptions on “Green Town” idea vs public perception on CCS. The figure shows that public who like the idea of “Green Town” would generally appear to like CCS. However, those who appear neutral on the “Green Town” idea do not like CCS. This implies again that the “Green Town” idea plays an important role in laying a strong foundation to incur public interest in CCS project.

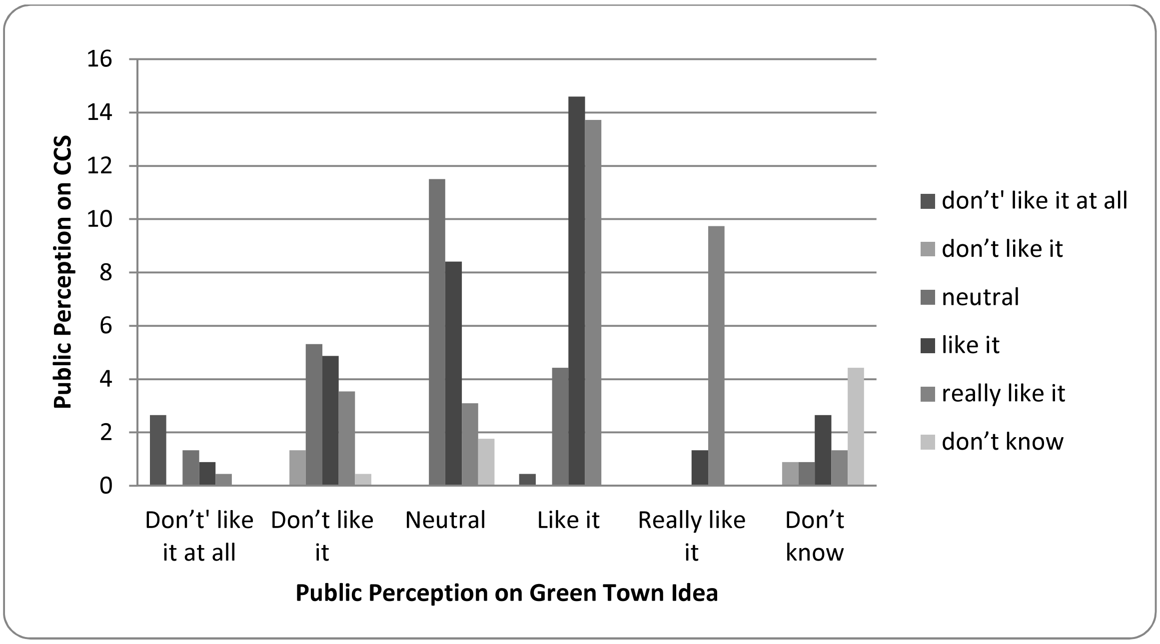

Figure 4.34: Public Perception on “Green Town” Idea vs Public Perception on CCS

4.3.6 Media

Figure 4.35 shows the types of sources the public heard of CCS. It can be seen that newspaper and internet are the main sources used by the public to obtain information regarding CCS. This two sources made up 62% of the total source. The public also receive information on CCS through newspaper (14%) and radio (12%). Other sources are such as magazine (9%) and journal (9%).

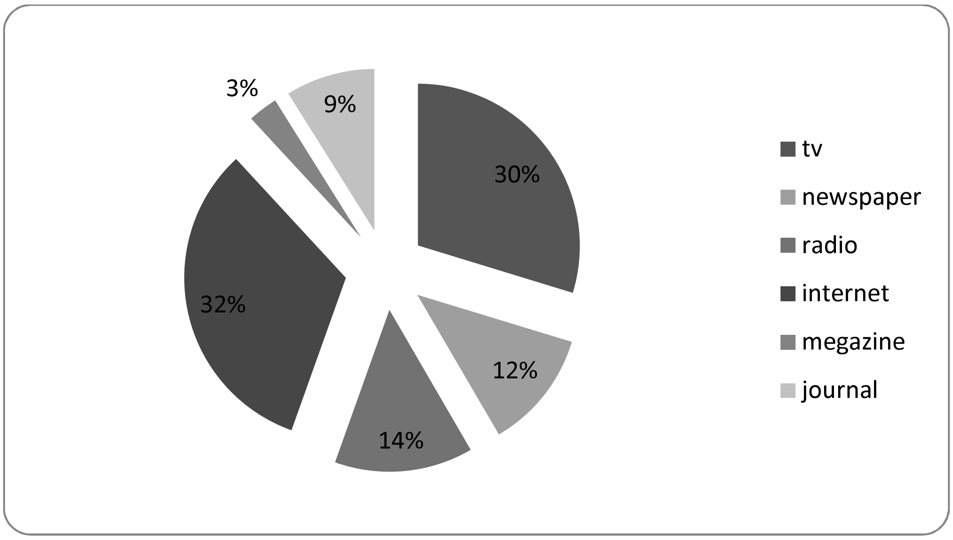

Figure 4.35: Means of Media/Sources

4.4 Survey Results Comparison

To explore the diversity of public perception on CCS between Southampton and Hamburg, a data comparison analysis is conducted. The key findings of this comparison are listed below:

i. Figure 4.36 shows a direct population-age comparison between interviewees in Southampton and Hamburg. It can be seen that the age distribution is very much similar between two cities. This provides a good basis for comparison. Hamburg has a slightly higher percentage of young people across all age groups below 35 years old. In contrast, Southampton has a higher percentage of people in the age groups 36 and above except for age group between 46 to 54. This could possibly imply that the average age of the Hamburg residences is younger than Southampton.

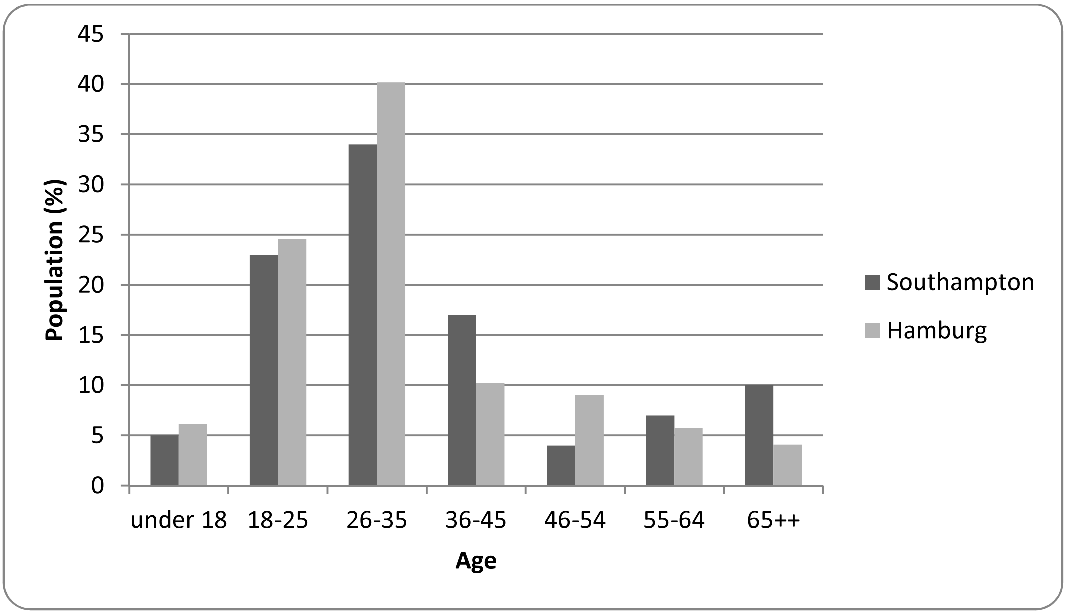

Figure 4.36: Population VS Age

ii. It is notable that a large portion (around 40%) of the interviewees are students, this applies to both samples collected from Southampton and Hamburg. This is possibly due to the fact that higher response rate was received from the university campus as compared to other public venues, for example airport, train station, etc.

iii. Although the educational system is different between UK and Germany, it can still be noticed that majority of the interviewee group (18-35) have received higher education qualifications.

iv. Figure 4.37 shows the comparison of environmental concerns between Southampton and Hamburg. It can be seen from the public's responses to the questions on *global warming awareness* and *concerns of global warming* that Hamburg has a slightly higher population percentages responses (see Fig. 4.37). This indicates that Hamburg people are more environmentally conscious.

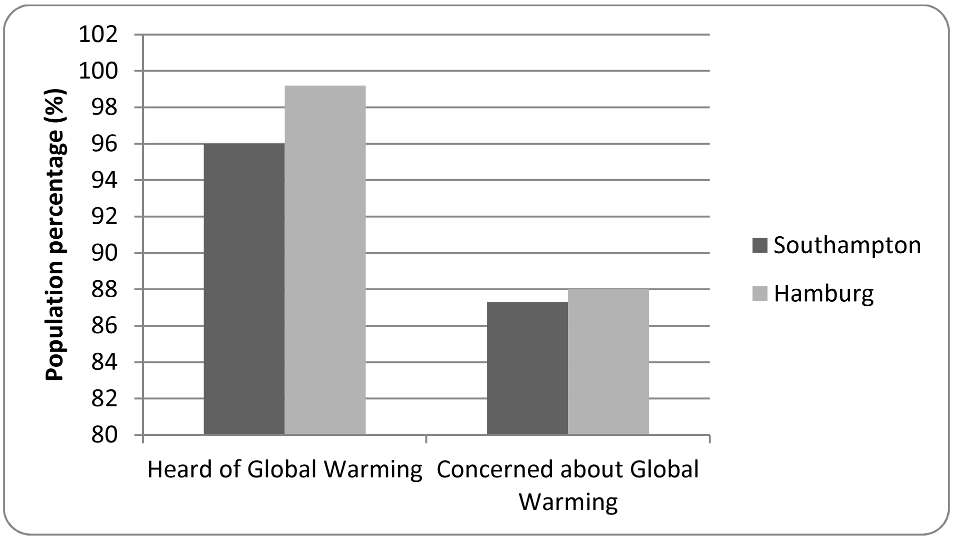

Figure 4.37: Comparison of Environmental Concerns

v. Figure 4.38 shows the preference differences between Southampton and Hamburg. It can be seen that "Green Town" idea is less prefered in Hamburg than in Southampton. However, consistent data trend has been observed in both cites.

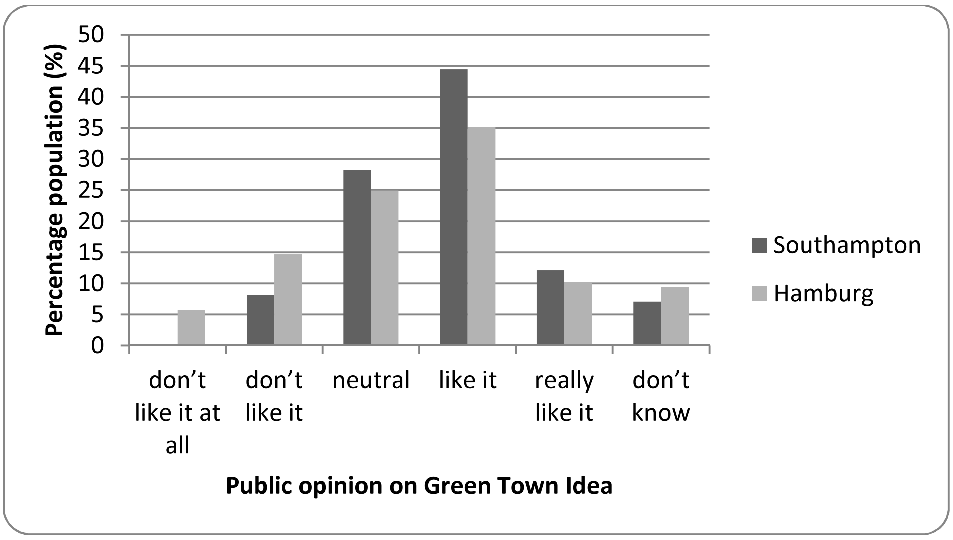

Figure 4.38: "Green Town" Idea Preference Comparison

vi. In terms of extra money payable to support the "Green Town" idea, the average addition energy price per month that the public is willing to pay in Southampton and Hamburg is, respectively, around 4 to 5 Pound/month and Euro/month. Reasonable cost estimation could be drawn from this basis. The study also indicates that the additional energy prices/month that the public is willing to pay to support for the "Green Town" idea is independent on their personal income.

vii. Consistent findings are observed on the public perception and public acceptance on the "Green Town" idea in accordance to the educational level of the public. In general, most of the public that receives education would like the idea of "Green Town" and shows positive response towards the "Green Town" idea. This indicates that school or university could function as a platform to effectively educate the public on the "Green Town" idea. It could also indicate that the opinion of the public could be altered if adequate information on a new technology is provided.

viii. Figure 4.39 shows the comparison of the public opinion on CCS between Southampton and Hamburg. It can be seen that CCS is more prefered in Hamburg as compared to Southampton.

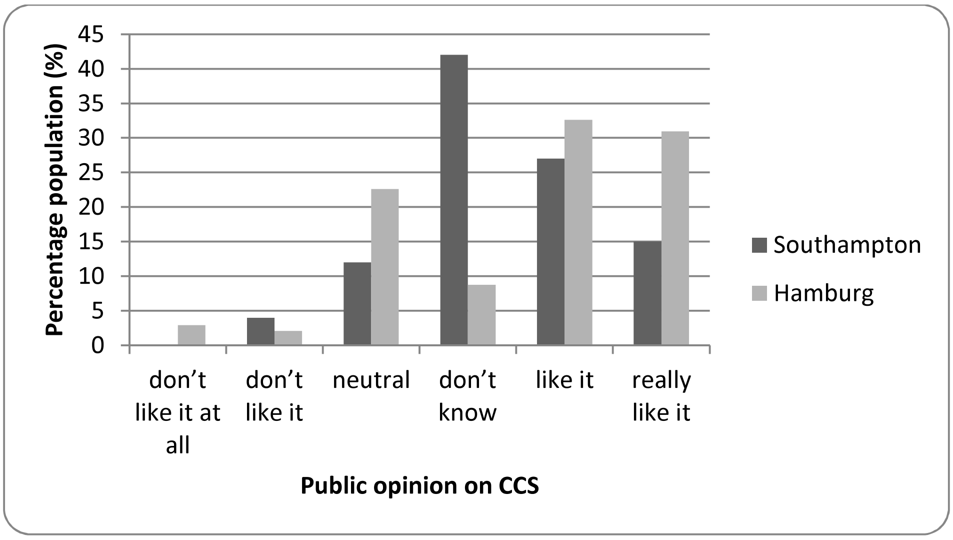

Figure 4.39 Comparison of public opinion on CCS

ix. It has been observed in both cities that there is a direct correlation between the public perception and public acceptance. It shows that those who do not like the "Green Town" idea would generally feel negative on having the air scrubbing facility in town and vice versa. This indicates that the interest of the public on "Green Town" idea should be inculcated in the early stage and the engagement and opinion of the public is important to enhance public acceptance on the "Green Town" idea. The same would apply in ensuring a successful CCS project.

x. It is observed in both cities that the public who like the "Green Town" idea would generally appear to like CCS. However, those who appear neutral on the "Green Town" idea do not like CCS. This implies again that the "Green Town" idea plays an important role in laying a strong foundation to incur public interest in CCS project.

xi. With regards to most effectiveness means of communicating methods on CCS, TV and newspaper are most effective in UK while newspaper and internet are the two most effective methods in Germany.

5 ECONOMIC AND LOGISTIC ASPECTS OF THE DESIGN SOLUTION

5.1 Economic Aspect

The focus of the “Green Town” concept proposed in this project has been on the public engagement aspect rather than on financial or commercial viability of the proposal. Nevertheless, cost estimates for the various options suggested that such factors must form part of the exercise since a vastly expensive engineering system compared with the alternatives would be detrimental to the arguments in favour of the concept.

Estimation for project Capital Expenditures (CAPEX) and Operating Expenditures (OPEX) are presented. A fuller analysis, in addition to much greater detail of component costs, would also need to include Internal Rate of Return and depreciation of the assests (Net Present Value). For commercial projects the Payback Period (PP); depending on the project, viability might be deemed to be below a 5-10 year threshold.

Furthermore, detailed analysis would include the effect of variation in operational factors including downtime and financial factors including bank interest rates, the rate of inflation, the price of oil and gas and the variability of the appropriate carbon tax in the region of operation. An example of this is the EU-ETS introduced in Chapter 2. The EU-ETS has seen a huge variation in the valuation of CO_2.

The cost figures given may only be regarded as a rudimentary cost analysis of the components of “Green Town”. The approach is to make reference to comparative technology in the engineering sector, rather than attempt detailed costing from the bottom upwards. Inevitably, this will lead to a considerable range of uncertainty in the figures presented. Nevertheless, the level of detail is felt to be the most appropriate at this stage.

5.1.1 Capture

Land costs

The case study presented in this project is on the implementation of the concept in the city of Hamburg in Germany. Table 5.1 presented several specific candidate sites in the industrial areas of Hamburg. A considerable land area is required for the air contactor system which is the interface between the air and the liquid scrubbing medium employed in the air capture technique reviewed in this study.

The price of land in Germany has risen considerably over the last 15 years, from about €65/m^2 in 1997 to around €120/m^2 in 2009. There are local variations, with land in Berlin at a premium (€400/m^2 in 2009) and land in eastern Germany around €50/m^2 (AllGrund, 2008)For the purposes of an estimate for this project, ‘Low, ‘Medium’, and ‘High’ values have been set at 90, 120 and 150 Euros per square metre respectively.

TABLE 5.1
COST ESTIMATE FOR LAND IN HAMBURG

		Land Price (€Million)			Land Price (US$Million)		
		Low €90/m^2	Mid €120/m^2	High €150/m^2	Low	Medium	High
Site	Area [m^2]	90	120	150	126	168	210
"1% AREA"	16158	1.5	1.9	2.4	2.0	2.7	3.4
SITE 15 (3%)	50400	4.5	6.0	7.6	6.4	8.5	10.6
SITE 12 (8%)	150000	14	18	23	19	25	32
SITE 14 (20%)	320000	29	38	48	40	54	67

Table 5.1 shows an estimate of these prices applied to the Hamburg sites. The "1% area" refers to a land area sufficient to capture 1% of Hamburg's emitted CO_2 per annum. The subsequent rows refer to specific sites identified in Table 3.2. The "1% area" is expected to cost around US$3M, whereas the largest site identified might cost around US$54.

Plant Costs

It is extremely difficult to make an accurate estimate of the CAPEX needed for the chemical engineering plant required for the "Green Town" project. Whilst the kiln and calcium cycle components may be regarded as having parallels in regular industry, the air contactor systems proposed are nascent technologies and, due to the size required, make a huge contribution to the costs. It is not clear how demonstrator costs might scale up to a grand scale system. Furthermore, the cost details are difficult to obtain because of the commercial sensitivities.

The American Physical Society produced a report on the potential of air capture methods (Socolow, 2011) which did attempt to estimate the capital costs. For a system capable of air capturing 1 Million tonnes of CO_2 per annum, they estimated the cost of the Air contactor system to be $290M. The calcium carbonate cycle equipment was emitted at $120M giving a total of $480M. They then applied a standard multiplication factor of 4.5 was applied to reflect other costs (a wide range covering engineering, piping, tanks, connections, infrastructure, buildings etc. excluding land) to give a grand capital cost of about $2.2billion. The multiplier of 4.5 was actually considered to be optimistic, a multiplier of 6.0 was felt to be appropriate for new technologies.

The APS figures are disputed by the Carbon Engineering company (Keith 2011), in particular it is suggested the cost of the Calciner, a major component of the calcium carbonate cycle, could be reduced from $120M to $60M. The costs of the contactors are disputed since the APS calculations are said to overestimate the performance in some respects and underestimate in others. Furthermore it is pointed out that the APS report changed the specification of gauze 'packing' materials to a specification that might be half as expensive, in different versions of the report without altering the costs. The plant cost might then be as low as $280M for the APS system, with a grand capital cost of $1.26billion after applying the infrastructure factor of 4.5.

The APS system was designed for a performance of 1 Million Tonnes CO_2 per annum. Assuming linear scaling of these costs, for the sites identified in Hamburg are given in Table 5.2.

TABLE 5.2
CAPITAL COSTS OF AIR CAPTURE PLANT

Site	Site Area [m^2]	Thousand Tonnes of CO_2 Captured per Year	Basic Capital Cost (US$ Million)		Capital Cost including x4.5 factor to Include Infrastructure (US$ Million)	
			LOW	HIGH	LOW	HIGH
"1% AREA"	16158	180	50	86	227	389
SITE 15 (3%)	50400	561	157	269	707	1213
SITE 12 (8%)	150000	1671	468	802	2105	3609
SITE 14 (20%)	320000	3565	998	1711	4492	7700

Running Costs

The APS report (Socolow, 2011) also estimates annual running costs, in the US, for their 1 million tonne CO_2 design. They estimate annual maintenance costs of $70M, Labour costs of $20M and $4M for consumables such as additional chemicals. Additionally gas fuel costs for the kiln are included at $46M and electrical power at $35M. The total running cost is therefore $175M per annum.

The Carbon Engineering system is currently using gas to generate electricity as well as to heat the kiln. The electrical power costs might then be discounted to give a ‘Low’ running cost of $140M per annum. Using the $175M figure quoted above as a ‘high’ value leads to the operating costs given in Table 5.3.

TABLE 5.3
RUNNING COSTS OF AIR CAPTURE PLANT

Site	Site Area [m^2]	Thousand Tonnes of CO_2 Captured per Year	Operating Cost per Annum (US$ Million)	
			LOW	HIGH
"1% AREA"	16158	180	25	32
SITE 15 (3%)	50400	561	79	98
SITE 12 (8%)	150000	1671	234	292
SITE 14 (20%)	320000	3565	499	624

Cost per Tonne of CO_2

Plant costs for CCS devices are typically converted to a cost per tonne of CO_2 captured in order to facilitate comparison between different systems.

The APS report (Socolow, 2011) goes on to make this calculation for its 1 Million Tonne CO_2 capture example and compares this with the cost of Post Combustion capture at a thermal power plant. Table 5.4 reproduces the costs reported; the installed cost multiplier value 4.5 is used for the Air Capture system and Capital Costs are recovered over a 20 year period.

TABLE 5.4
RUNNING COSTS PER TONNE OF CO_2 CAPTURED AIR CAPTURE PLANT (Socolow, 2011)

Cost per Tonne Captured $/tonne	Post Combustion Capture	Air Capture
Capital Costs	22	260
Operating Costs	40	170
Total Cost	62	430

Air capture is therefore about seven times more expensive than post combustion capture using these figures. Tables 5.2 and 5.3 suggest that the air capture costs might be somewhat lower, about 40% lower and 20% lower for capital and operating costs respectively; these would lead to a revised total cost of about $300 per tonne of CO_2, which is still five times higher than for post combustion capture.

The APS report goes on to calculate the 'avoided cost' of per tonne of CO_2 entering the atmosphere, i.e. including the CO_2 produced by the capture process itself. These costs are still around 40% higher. Again, this might reduce to nil if it renewable power could be employed for the air capture system.

Air capture is therefore an apparently expensive technology at this time even when allowing for considerable error in cost estimates. This state of affairs should be seen in the context of the value of Carbon Dioxide in trading systems however; The European ETS mentioned in Chapter 3 has previously peaked at an equivalent dollar value around $30 per tonne and has been highly variable. This value could conceivably increase many fold in the coming years as pressure is put on the global community to deal with GHG emissions, and in this scenario the technologies would look much more attractive. Simultaneously, researchers are working to reduce the cost of air capture; Professor Keith is reported as hoping he might reduce the cost of his system to $100 per tonne and other researchers suggesting a $40 per tonne target.

5.1.2 Pipeline

The geographic distance for pipeline layout Scenario 1 (see Chapter 3), i.e. to run pipeline directly across the sea from Hamburg to K12-B sequestration site, is about 420KM (see Table 5.5).

TABLE 5.5
LENGTH OF PROPOSED PIPELINE WITH RESPECT TO LOCATION FOR FIRST OPTION

Length		**Location**
32	km	Pipeline Hamburg →Winsen
220	km	Winsen →Emden
17	km	Emden →Krummhorn
212	km	Submerged pipeline Krummhorn →K12-B

The costs of the pipelines are as follows:

- Length of onshore pipeline: 269km, total capital expenditure is $134.5 million US dollars
- Length of offshore pipeline: 212km, total capital expenditure is $626.5 million US dollars

Therefore, total capital cost is $761 million US dollars. This expenditure on capital cost projection is based on the Dutch report by Croneberg (Cronenberg *et al.*, 2009) and IPCC special report on carbon capture and sequestration 2005 (IPCC Working Group III, 2005)

For Pipeline Scenario 2 (see Chapter 3), the pipelines system use the existing gas pipeline running east from K12-B to the nearby Fresian Island of Zuiderstrand. The length of the pipeline with respect to its location is presented in Table 5.6.

TABLE 5.6
LENGTH OF PROPOSED PIPELINE WITH RESPECT TO LOCATION FOR SECOND OPTION

Length		Location
32	km	Pipeline Hamburg →Winsen
220	km	Winsen →Emden
17	km	Emden →Krummhorn
28	km	Submerged pipeline Krummhorn →Zuiderstrand

The costs of the pipelines are as follows:

- Length of onshore pipeline: 269km, total capital expenditure is $134.5 million US dollars
- Length of offshore pipeline: 28km, total capital expenditure is $82.75 million US dollars

Therefore, total capital cost is $217.25 million US dollars. This cost estimation is based on the Dutch report by Cronenberg *et al.* (2009) and IPCC special report on carbon capture and sequestration 2005(IPCC Working Group III, 2005).

With a 30% plus-minus marginal principal, total cost for the first scenario is between $532.7 to $989.3 million dollars whereas the total cost for the second scenario is between $152.1 to $282.4 million dollars.

5.1.3 Storage

During the feasibility study (Phase 1 of K12-B), the cost for full scale CO_2 injection was estimated to be between € 5-10 per ton of CO_2. The cost consists of CAPEX and OPEX. The estimated costs of storing CO_2 at K12-B are shown in Table 5.6 (Van der Meer *et al.*, 2005).

TABLE 5.7
THE COST OF CO_2 STORAGE AT K12-B, INTEREST RATE 9%; 10 YEARS OF OPERATION

Cost of full-scale operations	
CAPEX	€ 10.000,000
OPEX	€ 1.400,000
Other cost/revenues	unknown
Amount of stored CO_2 t/y	480,000
Costs per stored CO_2/tonne	€ 5-10

The cost for storing CO_2 in a depleted hydrocarbon field (for a field of capacity of 500-2,000 $GtCO_2$) is estimated to “a few euros” per tonne (Saysset *et al.*, 2006). This indicates that € 5-10 is a reasonable value.

5.2 Legal Issues

Novel technology legislation is a major concern in implementing large projects. For the "Green Town" project that involves the laying of pipelines across two countries, i.e. German and the Netherlands, the implementation of the projects has to be subjected to both the German and Dutch legislations as well as the European and International Law. It is difficult to interpret the exact meaning or consequences of the legislation before it has been tested in a court of law.

The CO_2 air scrubbing facility as well as the transportation and storage of CO_2 have to comply with all the specific legislation that regulates CCS. However, all the specific legislation regulating CCS is brand new. As late as 2005, there was no legislation specifically regulating CCS, either in the international or European levels (Purdy and Macrory, 2005). In January 2007, the European Union launched the first CCS legislation (Kerr *et al.*, 2009). However, earlier laws were said to be applied to CCS but these laws were not for CCS purpose (Purdy and Macrory, 2005). Clues to which legislation the courts might take with regards to the storage of CO_2 in sea can be referred to their counterparts on other materials that are stored under the seabed (Purdy and Macrory, 2005). Most of the specific CCS regulation regulates the geological storage. It is noted that the regulations of CO_2 pipeline transport is mainly regulated by law of national gas network.

5.2.1 Capture

Within the European Union (EU) [1], the CO_2 capture process by the air scrubbing facility shall be largely regulated by the EU's *Integrand Pollution Prevention and Control (IPPC) Directive (Art 37)* (Faculty of Laws University College London, 2007-2011b). The IPPC controls the release of pollution into the air, water and onto the land (Faculty of Laws University College London, 2007-2011b). All operators of capture facilities will have to obtain an IPPC permit, which requires the use of the "best available techniques" (BAT) (Faculty of Laws University College London, 2007-2011b). Operators also have to make assessments on the impact on the environment by any capture procedure in agreement with the *Environmental Impact Assessment (EIA) Directive (Art 31)* (Faculty of Laws University College London, 2007-2011b).

5.2.2 Transport

CO_2 transport can be regulated by different types of law. However, it is still unclear whether the CO_2 shall be legally defined as a waste or a commodity (Faculty of Laws University College London, 2007-2011a). If CO_2 is classed as a waste, it would be regulated by the *1989 Convention on the Control of Trans-boundary Movements of Hazardous Wastes and Their Disposal* (Basel Convention) as well as the *1991 Convention on the Ban of the Import into Africa and the Control of Trans-boundary Movement and Management of Hazardous Wastes within Africa* (Bamako Convention) (Faculty of Laws University College London, 2007-2011a). On the other hand, if CO_2 is classed as a commodity, the regulatory framework would be regulated by the *International Agreements on the Transport of Goods* (Faculty of Laws University College London, 2007-2011a). It is not impossible that the definition of CO_2 will differ between countries.

The EU directive on the geological storage of CO_2 regulates the third party access (Faculty of Laws University College London, 2007-2011b). The EU is looking for individual member states of the EU to legislate the use of pipelines for CO_2 transport, even though they will be subjected to regulations of the International Energy Agency (IEA)[2] (Faculty of Laws University College London, 2007-2011b).

[1] The EU is an economic and political union of 27 member states which are located primarily in Europe
[2] IEA is an worldwide intergovernmental organisation established to meet the industrial countries' energy demands

Current regulation regarding the transport of natural gas can give an indication as to what future CO_2 transport regulation might look like. However, there are still conflicting legislations regarding cross border pipelines (Faculty of Laws University College London, 2007-2011a).

The pipeline transportation of CO_2 from the "Green Town" from Hamburg to the K12-B sequestration site via the Netherlands would subject to the German Natural Gas Pipeline Regulations and the Dutch Natural Gas Pipeline Regulations.

German Natural Gas Pipeline Regulations

German pipeline grid operators would require permission to work under the German Energy Act. However, authorisation can only be refused if legal requirements are not met (Global Legal Group Ltd, 2008a). It is possible, under special circumstances to acquire land for pipelines through expropriation. This regulation is only applied if an agreement could not be made through general contract law (Global Legal Group Ltd, 2008a). Connection to the network must be made on a non-discriminatory basis and can only be refused if connections are technically or economically unreasonable (Global Legal Group Ltd, 2008a). The operators are free to determine the terms of operation as long as they are market orientated (Global Legal Group Ltd, 2008a).

Dutch Natural Gas Pipeline Regulations

Downstream pipelines in the Netherlands are regulated by the Dutch Gas Act 2000 (Global Legal Group Ltd, 2008b). The owner of a downstream pipeline network has to appoint a network company which has to be approved by the Minister pursuant to the Gas act (Global Legal Group Ltd, 2008b). Network companies are supervised by the Office for Energy Regulations (Global Legal Group Ltd, 2008b). There are various possibilities to acquire land to build pipelines on ownership, either by a right of superficies (*recht van postal*-law of building) or by a separate agreement with the owner of the land (Global Legal Group Ltd, 2008b). It is not possible to create ownership of buildings or works by contract but a lease can be used (Global Legal Group Ltd, 2008b). Third party access (TPA) to downstream pipelines is regulated by regulated TPA (rTPA) which is a part of TPA. Note that TPA is based on the European Gas directive (Global Legal Group Ltd, 2008b). Cross border connections are regulated by the Gas Act as well as its associated regulations (Global Legal Group Ltd, 2008b). The terms for accessing the downstream pipelines are regulated centrally and are thus not up to the owner (Global Legal Group Ltd, 2008b). The Dutch Energy (DTe) sets tariff structures for access and determines the maximum price. The terms and condition that a network company sets must be reasonable, transparent and non-discriminatory (Global Legal Group Ltd, 2008b).

5.2.3 Storage

The main bulk of all the CCS regulation is regarding the CO_2 storage. It is also where most of the interpretation of existing non CCS specific laws are made.

United Nations Convention on the Law of the Seas (UNCLOS)

The use and protection of the seas is regulated by the UNCLOS. UNCLOS does not prohibit or control CO_2 storage or dumping, but it demands all states to take all measures necessary to prevent, reduce and control pollution of the marine environment (Purdy, 2006). In specific CO_2 legislations, the term 'storage' is often used, but the term 'dumping' that regulates CO_2 storage was used in the earlier legislation. However, the term 'dumping' is used for CO_2 lakes and storage in geological formations in some contexts.

The London Convention and 1996 Protocol

The London Convention and its 1996 Protocol are global laws that legislate the deliberate dumping of waste at sea (Purdy, 2006). The 1996 Protocol came into force in 2006 with the aims to reduce pollution (and when possible eliminate it) (Purdy, 2006). Both the Netherlands and Germany are parties of the London Convention and the 1996 Protocol (IMO, 2010, IMO, 2011). Article XII of the London Convention states that members should "within the competent specialized agencies and other international bodies, measures to protect the marine environment against pollution caused by (a) hydrocarbons including their wastes…" (Mace *et al.*, 2007).

There are four major issues in determining the legality of CO_2 storage under the London Convention and 1996 Protocol (Purdy, 2006):

- Firstly, the geological formations under the seabed probably do not fall within the London Convention since it only aims to regulate dumping at sea (it is arguable whether shall geological formations be considered as 'sea') (Purdy, 2006). The Protocol goes beyond this and regulates dumping in the "sea, seabed and subsoil" (Purdy, 2006). It is arguable regarding the definition of seabed and subsoil. It could be defined as either 'rock immediately under the seabed' or 'the entire earth column below it' (Purdy, 2006).

- Secondly, it is uncertain whether CO_2 should be considered as a waste material (Purdy, 2006). CO_2 is not on the list of waste materials listed in the *London Convention Annex 1*. However it would "probably" fall under the "industrial waste" category if it was captured directly from a manufacturing or processing operation (Purdy, 2006). The Protocol is simpler in that it prohibits dumping of all wastes that are not on the list in Annex 1 (Purdy, 2006). It is regarded as "most unlikely" that CO_2 will be included on the list of approved wastes (for dumping) (Purdy, 2006). It is therefore concluded that CO_2 would fall under the definition of waste, especially since the definition of "dumping" refers to "wastes or other matter." (Purdy, 2006).

- Thirdly, the convention and the protocol defines dumping as "any deliberate disposals at sea as wastes or other matter from vessels, aircrafts, platforms or other man-made structures at sea" (Purdy, 2006). This would make it illegal to deposit CO_2 with the use of platforms or ships, however not with pipelines (Purdy, 2006). There is also a part in the Protocol which further supports this by saying that it does not legislate subsea structures only accessibly from land (Purdy, 2006).

- The forth issue is on the availability of any exceptions in the Convention and the Protocol that allows for CO_2 storage (Purdy, 2006). Both the Convention and Protocol excluded "dumping" from "the disposal or storage of wastes or other matter directly arising from, or related to the exploration, exploitation, and associated off-shore processing of seabed mineral resources" (Purdy, 2006). This "would suggest" that CO_2 from EOR or enhanced gas recovery (EGR) can be legally stored (Purdy, 2006). The second possible exception is that the Convention and the Protocol defines "dumping" as the "placement of matter for a purpose other than mere disposal" (Purdy, 2006). It could be argued that CO_2 is temporally stored until the environment permits a release. This is not very likely since there are currently no plans to retrieve the stored CO_2 (Purdy, 2006).

European Union Legislation

In January 2007, the European Union introduced its CCS directive. The directive states that the Commission would review and provide comments on any draft storage permits. This is not binding but the Member State would be required to "provide reasons" for not involving the commission (Kerr *et al.*, 2009). The directive includes obligations for operational conditions, closure and post-closure, monitoring, reporting requirements and the immediate remediation of any irregularities or leakage (Kerr *et al.*, 2009). The directive also proposes the transfer of CCS facilities to the authorities when it is clear that the storage will be completely contained for the indefinite future. However, the timescale and exact wording is yet to be determined (Kerr *et al.*, 2009).

The EU directive on the geological storage of carbon dioxide was adopted on 6 April 2009, member states have until the 25th June 2011 to implement it into their legislation (The European Parliament and the Council of the European Union, 2009). The directive focuses more on storage than capture and transport. It removes CO_2 from previous water and waste laws and introduces specific CO_2 legislation. The legislation is described as "enabling" rather than making CCS mandatory (Faculty of Laws University College London, 2007-2011b).

<u>OSPAR</u>

The OSPAR Convention is a regional agreement that regulates the North-East Atlantic Ocean Maritime area (Mace *et al.*, 2007). The "Maritime area" includes the internal waters, the territorial seas of the parties, the sea beyond and adjacent to the territorial sea, and the high seas. It also includes the seabed and the subsoil (Art 1(a)) (Mace *et al.*, 2007). The Convention was adopted in 1992 and came into force in 1998 (Faculty of Laws University College London, 2007-2011c). It is signed by among others the Netherlands, Germany and the United Kingdom (OSPAR Commission, 2011) . Parties are obliged to "take all possible steps to prevent and eliminate pollution" (Mace *et al.*, 2007). The convention allows CO_2 storage if it is associated with offshore activities, but prohibits it if it dumped through vessels and man-made structures (Annex I and II) (Mace *et al.*, 2007).

In June 2007, the OSPAR Commission adopted amendments which allowed for the storage of CO_2 under the seabed (Faculty of Laws University College London, 2007-2011c). These amendments have been ratified by the UK, Norway, and Germany as well as the EU. The Netherlands has declared that they will ratify the amendments sometime after the 25th June 2011 (the introduction of EU directive mentioned above) (Faculty of Laws University College London, 2007-2011c). The amendment specifically prohibits the storage of CO_2 in the water column or on the sea bed due to "potential negative effects" (OSPAR Commision, 2007a). The amendment states that CO_2 can be stored if it is done within geological formations, the proportion of the storing matter that is pure CO_2 is overwhelming and if the CO_2 is stored permanently and regarded as causing no consequences for the environment (OSPAR Commision, 2007b).

5.3 Risk and Monitoring System

When considering the risks of implementing CCS it has to be compared against the risk of not implementing it (de Coninck *et al.*, 2009). The introduction of CO_2 storage could not wait until the risk of leakage is "almost eliminated" because continuing emitting CO_2 into the atmosphere is much worse (Bachu, 2008). Locally, it is important with monitoring and assessing leakage, but it is more important to reduce CO_2 emissions globally (Bachu, 2008). This is to say that CO_2 leakage could have a deadly outcome locally but not storing CO_2 could severely effect globally.

It is technically difficult to determine the risks associated with CCS, but the biggest challenge lies is the way different people and organisations define and interpret the risks. Risk is the combined product of how an event is likely to occur and how severe the consequence of the incident is (de Coninck *et al.*, 2009). The interpretations of risks are generally different on the personal and corporative levels. The public tends to look at the consequences (that is why more people fear airplanes than cars); whereas the likeliness of accident is more importance in a business.

The management of the process is as important (or may be more important than) as the physical risks (de Coninck *et al.*, 2009). There are often an over confidence in procedures even though people fail to follow the procedures all the time. People often take shortcuts when doing repetitive assignments especially if they fail to see the consequences of their actions.

Determining risks in either a qualitative or quantitative term are difficult for new and unproven technologies like CCS (de Coninck *et al.*, 2009). This is because the risks are usually determined from data of previous accidents, which is often scarce for a new technology. This is why there are more risks estimations for CCS which is in operation, where data can be found in similar operations such as in natural gas transport or the industry handling of CO_2. The risk in the storage formation where the CO_2 is left in the storage that is subjected to nature forces is harder to quantify (Herzog and Golomb, 2004).

The major risks regarding "Green Town" are similar to those of other CCS systems since most major risks are associated with leakage.

5.3.1 Green Town

During permit applications most the consequences of accidents has to be considered (Zakkour and Haines, 2007). Even though CO_2 is routinely handled by the industry, the handling has not been presented in highly populated areas before (Zakkour and Haines, 2007).

The technology risks of the air scrubbing tower as given by Carbon Engineering Ltd. (Carbon Engineering Ltd., 2011) are:

- No direct scale-up experience
- Drift loses from an open gas scrubber (air contactor)
- Physical fouling of packing media
- Interaction of solution with non-process elements
- Process interaction with environmental conditions

5.3.2 Transporting and Injecting CO_2

Extensive CO_2 pipelines are currently in operation and the safety record has been good (Zakkour and Haines, 2007). However, before starting any operation, dispersion modelling of transportation leakages has to be done (Mazzoldi *et al.*, 2008). The risk increases when pipelines are routed through densely populated areas, since the consequences of failure are greater (Bachu, 2008).

5.3.3 Storage Leakage

One of the biggest concerns regarding leakage is from the final storage. This is obviously connected to the fact that storage is supposed to last for geological timescales.

A critical element of risk regarding accidents and leakages is the handing of supercritical CO_2, the practices of which is not fully developed (Zakkour and Haines, 2007). Injection into the storage site is the most risky part of the CCS, the pressure difference is highest at the injection well and then decreases with the radial distance from the injection point. This could cause opening of pre-existing fractures, rock fracturing , fault activation and even minor earthquakes (Bachu, 2008).

Among the Dutch stakeholders, the industry has the most confidence in the control of leakage. The government is also positive but stresses the need for more research. The environmental NGOs are more concerned about leakage where they are concern on the uncertainties in possible leakage pathways, the behaviour of CO_2 in the reservoir and the material used for sealing abandoned wells (van Alphen *et al.*, 2007).

Generally, depleted gas field are regarded as safe since it has held gas for millennia and leakage through the cap rock would happen over tens of thousands or years or longer. There are no guarantees that leakage would not occur as there have been a few leakages from gas reservoirs. However, this number is only a few as compared to the number of reservoirs (Bachu, 2008) in operations. Therefore, the K12-B site is proposed for this project.

5.3.4 Monitoring

Pipeline Monitoring

Enormous amounts of CO_2 contained in the pipelines (typically several thousand tonnes), hence pipeline that could operate safely is of paramount importance.

External safety is a key factor that should be assessed in prior and during the operational phase of CO_2 transportation. Several risk assessments for CO_2 transport pipelines have been proposed, for instance see paper by Golomb (1997). The review of these risk assessments is important as it allows the identification of the important knowledge gaps. To date, several uncertainties and knowledge gaps exist with regard to the dispersion behaviour and the modelling of the supercritical-CO_2 released into the atmosphere, CO_2 threshold values and the possible effects of CO_2 leakages at different distances from the pipeline. Furthermore, existing literature shows significant differences with respect to the outflow and dispersion (Cumber, 2007)

Quantitative risk assessment (QRA) is a common method used to quantify the risk of the CO_2 pipelines. The whole process of performing a QRA involves several methodological choices and assumptions as input parameters. Selection of input parameters and methodological potentially have large impacts on the results of the QRA. The QRA method is preferable for the preliminary detailed design.

Pipeline leakage and corrosion monitoring are necessary to detect any leakages from the pipe. Maintenance has to be carried out to ensure that the pipelines are safe for usage.

Integrity Monitoring and Communicating System

A monitoring program has to be developed throughout the pipeline's life time to ensure that corrosion failure does not occur. Therefore, part of the design loop shall include a recommendation for corrosion management plan. Pipeline working condition and its material will determine the level of monitoring plan. Combined monitoring plan may be applied to achieve a higher level of confidence in the pipeline condition.

Corrosion Monitoring

A range of corrosion monitoring methods can be used for pipeline. These include both the non-destructive test (NDT) measurement method and the computational simulation methods. Corrosion process and expected corrosion rates must be both taken into account when specifying a corrosion monitoring plan.

Pigging/ Maintenance /Repair

Pig is device that can be driven inside the pipeline by using the pressure differential. It is used for the purposes of:

- Cleaning
  Cleaning is a useful tool, not only to ensure that the cleanness of the pipeline is maintained, but also to prevent pipeline corrosion as it improves the efficiency of the corrosion inhibitors.

- Dewatering
  Dewatering pig is used to clear the pipeline to ensure that water is not present.

- Calipering

- Corrosion and crack monitoring

- Leak detection

5.3.5 Abandoned Wells Monitoring

EOR operators states that all wells would leak but only to some extent. However, there has been no demonstrable or substantial leakage from long-lives EOR fields. In 1982, the Sheep Mountain CO_2 Dome in Southern Colorado (where CO_2 is stored to be used in EOR) experienced a failure of a production well. The broken well remained uncontrolled for 17 days and five attempts were needed before it could be closed, there was a total leakage of around 200,000 tonnes of CO_2. The CO_2 did not only emit from the well but also from the rock fractures and soil nearby. No loss of life or serious injuries were found in this incident. Wilson *et al*. (2007) claimed that a leakage of 7,000 to 11,000 t of CO_2 per day (as in this case) could be considered a safe upper limit for allowable risks. It is noted that the CO_2 to be injected from the "Green Town" project is much smaller as compared to this allowable value.

The biggest risk of leakage comes from the design failures in the well cap (Damen *et al.*, 2006). The well head and pipeline failures will cause a rapid leakage of CO_2 but these period are relative short. The frequency of occurrence is also very low by referring to the statistics for underground natural gas storage (Bachu, 2008).

Monitoring the CO_2 at the storage site can be done using intrusive or non-intrusive methods (Bachu, 2008). Intrusive methods are based on pressure measurements and subsurface sampling. This is done by using observations or pressure measurements at the well or by injecting tracers. Non-intrusive methods are based on geophysical techniques such as time-lapse three-dimensional seismic imaging and vertical seismic profiling which detects and traces the movement of the CO_2 plume. These are all proven technologies used by the oil and gas industry (Bachu, 2008).

6 CONCLUSIONS

The cancellation of CCS projects in Holland and Germany has shown that public support is a major factor in the success of large engineering projects.

Those cases demonstrate that in order to realise CCS projects, public understanding of the CCS project as well as the transparency in the implementation are very important. The involvement of the national government in CCS is also significant as the public usually do not trust commercial companies so much as the government. National government involvement is recommended since the impact of CCS in environmental and financial terms is huge – this is large scale 'geo-engineering'. Public engagement in CCS projects from the early stages is also seen as very important.

With these points in mind, this work introduces the concept of a "Green Town" that involves the public in the understanding of climate change and pilots the idea of mitigation by CCS techniques. Ideally, the "Green Town" would be able to sequester all of its CO_2 emissions. It was proposed that 'air capture' technology be used for this purpose. The wet scrubbing air capture model proposed by the Canadian company Carbon Engineering Ltd. was adopted. This consists of a series of fan driven air contactors extracting CO_2 directly from the air to a fluid medium; the fluid from all the contactors is pooled so that the collected CO_2 can be extracted in a thermal process. The collected CO_2 would then be transported offshore by pipeline to be stored permanently in suitable subsea geological formations.

Hamburg in Germany was selected as the site for a case study for the "Green Town" model based on the arguments that:

- The government of Germany is supportive towards CCS
- Substantial funding has been allocated for CCS
- Germany is generally regarded as being environmentally aware
- Germany is populated and highly industrial so that Germany ranks poorly on international pollution measures
- Germany is a first world country and receptive to advanced technology
- Hamburg's proximity to the North Sea where CO_2 sequestration sites are located
- Hamburg as a major port city also offers flexibility with transportation methods

For the "Green Town" concept applied to Hamburg, a minimum capture level was set at 1% of the expected city wide CO_2 emissions. This was considered the minimum capture level that would still be regarded as meaningful given that the primary objective of this project was to introduces CCS and create a strong positive public perception of CCS; the volume of CO_2 to be captured was of secondary importance. Brownfield sites in the industrial south-central part of the city were identified as suitable for the construction of the air scrubbing facilities. Considerable land area is required. The existing Travemünde-Groningen gas pipeline was identified as providing a suitable route to follow to the sequestration site, via a short new overland pipeline from the capture site. The sequestration site selected is a platform in the Dutch sector of the North Sea, the K12-B platform, which has already been engaged in CO_2 injection activities since 1985. K12-B also has an existing gas pipeline connection to the mainland that is expected to fall into disuse within 12 years and could provide substantial amount of saving of the pipeline cost if converted for CO_2 transport. Other gas fields in the area will be depleted within a few years and so the area offers the chance for additional CO_2 sequestration by retrofitting CO_2 injection equipment onto the existing gas platform. Subsea geological formations are proposed for the storage of CO_2 as they are least risky form of storage – if oil and gas can be held there for millennia, then it should be that CO_2 should also storable there for millennia. The design considerations for the pipeline and sequestration sites, and long term monitoring system were identified as well as the risks to be considered.

A major part of this study was the gathering of data on public perception of CCS using questionnaire surveys. A trial survey was carried out in Southampton before a larger survey was conducted in the City of Hamburg. Comparisons of the survey results are made between Hamburg and Southampton. Several similarities were identified where it was found that the public in both cities are generally environmental conscious and are very supportive towards the “Green Town” project and CCS. The public perception and acceptance on the “Green Town” idea and CCS were also successfully investigated. The correlation between the public perception on the “Green Town” and CCS with the demographic variables such as education level and age were also studied. It was found that the public perception on “Green Town”/CCS could be altered if proper and adequate information on the CCS project is provided. Hence, the engagement of the public in the early stage of the CCS project is significant. The “Green Town” idea plays an important role in laying a strong foundation to incur public interest in CCS project. Information regarding CCS could also be delivered to the public through schools or university and mass media such as television, radio and internet. The survey also asked how much money the public might be willing to pay to support the “Green Town” idea, on average about €5 per month was volunteered, so this reaction was deemed positive. Air capture is currently about 5 times more expensive than post capture combustion at coal fired power stations. At €5 per person per month this would be enough to fund air capturing facilities in Hamburg at the capacities suggested.

In summary, existing failures with CCS due to public objections have been identified. Engaging the public at an early stage is seen as key to successful large scale CCS projects in the future. The “Green Town” idea was suggested as such a route to engaging the public. The empirical data from questionnaire surveys vindicates the suitability of this approach.

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APPENDIX A SOUTHAMPTON SURVEY

We are conducting a survey on behalf of the University of Southampton, UK.
This will help to form some future government policies. You don't need to have any specialised knowledge, it is your opinion as a member of the general public that we are interested in.

1. DO YOU LIVE LOCALLY?	YES	NO
2. HAVE YOU HEARD OF GLOBAL CLIMATE CHANGE?	YES	NO
3. HAVE YOU HEARD OF GREEN HOUSE GASES?	YES	NO

4. PLEASE RATE THE LEVEL OF YOUR CONCERN ON CLIMATE CHANGE?

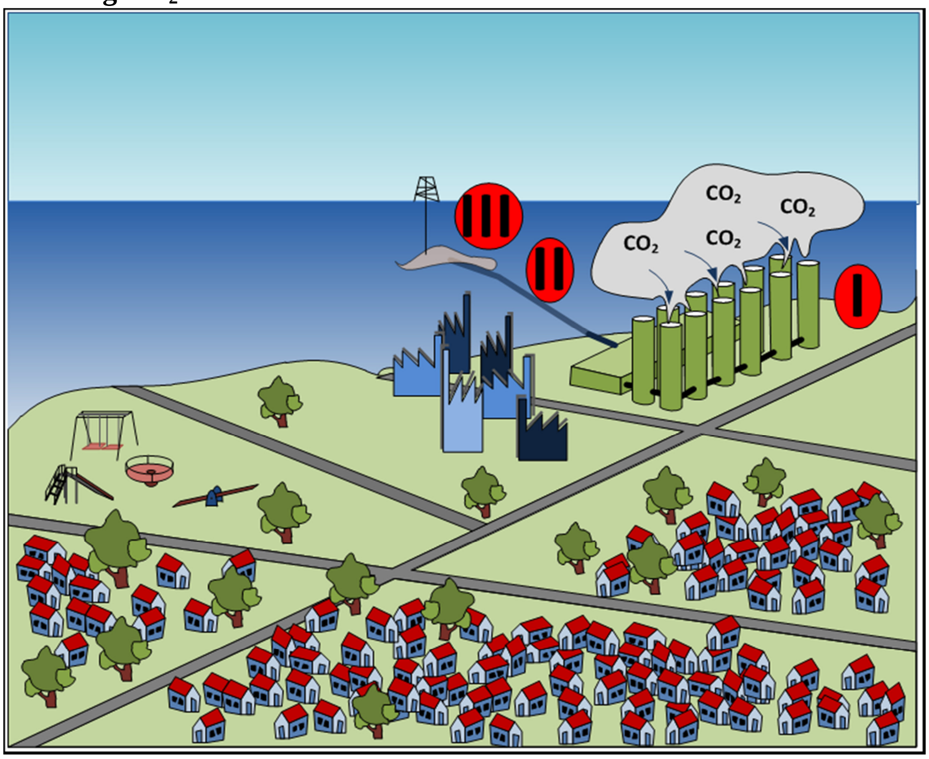
NOT CONCERNED — VERY CONCERNED

0	1	2	3	4	5

Please read the following description of the technology

The government is considering implementing a new technology in some cities and your opinion is highly valued. A major source of climate change is carbon dioxide (CO2) emission. A CO2 capturing device that removes CO2 from the air is proposed.

Removing CO_2 from the air



I. CO2 is captured from the 'Green Tower'.

II. Captured CO2 is transported by offshore pipelines.

III. Transported CO2 is stored in geological formation for a long period. Leakage is highly unlikely.

5. DO YOU LIKE THE IDEA OF "GREEN TOWER" ?

DON'T LIKE IT AT ALL	DON'T LIKE IT	NEITHER LIKE NOR DISLIKE IT	LIKE IT	REALLY LIKE IT	DON'T KNOW

6. HOW DO YOU FEEL ABOUT "GREEN TOWER" IDEA IN YOUR TOWN?

NEGATIVE POSITIVE

0	1	2	3	4	5

7. HOW MUCH WOULD YOU BE PREPARED TO PAY PER MONTH TO SUPPORT "GREEN TOWER" ?

£	0	5	10	15	MORE

ABOUT YOURSELF

8. ARE YOU Male Female

9. COULD YOU PLEASE TELL ME WHICH AGE GROUP YOU FALL UNDER?

A	Under 18
B	18-25
C	26-35
D	36-45
E	46-54
F	55-64
G	65+

10.QUALIFICATIONS

A	GCSEs
B	A levels or equivalent
C	University degree or equivalent
D	Other(s) (please specify) ______________________

11. TOTAL PERSONAL INCOME (before tax)

	Yearly (£)	Weekly (£)
A	0-7499	0-144
B	7500-9999	145-192
C	10000-14999	193-288
D	15000-19999	289-385
E	20000-29999	386-577
F	30000-39999	578-769
G	40000-49999	770-962
H	50000+	963+

12. COULD YOU PLEASE TELL ME WHAT YOUR OCCUPATION IS

13. DO YOU RECYCLE PAPER/GLASS/PLASTICS ETC.? YES NO

14. IN THE LONG TERM, HOW DO YOU FEEL ABOUT CO2 CAPTURING DIRECTLY AT THE CHIMNEY AT POWER PLANTS?

DON'T LIKE IT AT ALL	DON'T LIKE IT	NEITHER LIKE NOR DISLIKE IT	LIKE IT	REALLY LIKE IT	DON'T KNOW

15. HAVE YOU HEARD OF CARBON CAPTURE AND STORAGE BEFORE? YES NO

16.IF YES, WHERE HAVE YOU HEARD OF IT ? ______________________

APPENDIX B HAMBURG SURVEY

Lloyd's Register Educational Trust — University of Southampton

Wir machen eine Untersuchung zu einer neuartigen Möglichkeit, Kohlendioxid (CO2) in der Luft zu reduzieren. Diese Untersuchung wird im Namen der University of Southampton, Großbritannien durchgeführt. Sie brauchen kein spezielles Vorwissen, wir sind an Ihrer Meinung als Mitglied der allgemeinen Öffentlichkeit in Deutschland interessiert. Kreuzen Sie bitte die Aussagen an, die am ehesten auf Sie zutreffen.

1. Wohnen Sie In Hamburg?

JA	NEIN

2. Haben Sie von globalem Klimawandel gehört?

JA	NEIN

3. Wenn ja, wie Besorgnis erregend finden Sie den Klimawandel

Nicht Besorgnis erregend — sehr Besorgnis erregend

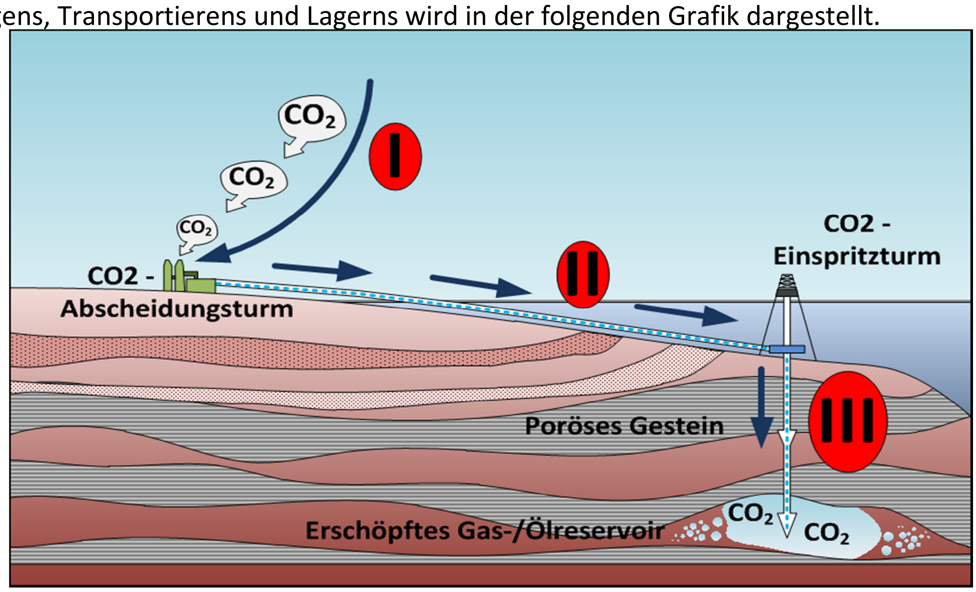
0	1	2	3	4	5

4. Haben Sie von Treibhausgasen gehört?

JA	NEIN

Bitte lesen Sie die folgende Beschreibung des vorgeschlagenen Ansatzes

Eine Hauptquelle für den Klimawandel ist der Kohlendioxid- (CO2-) Ausstoß. Es ist möglich, CO2 mit Hilfe einer neuartigen Technologie, dem CO2-Auffangturm, aus der Luft zu entfernen. Diese Türme werden in Städten installiert, und das gesammelte CO2 wird zu einer Lagerstelle transportiert. Der Prozess des Auffangens, Transportierens und Lagerns wird in der folgenden Grafik dargestellt.



I. CO2 wird vom Turm aufgefangen.
II. Das aufgefangene CO2 wird mit Offshore-Pipelines transportiert.
III. Das transportierte CO2 wird in einem entleerten Öl-/Gas-Reservoir gelagert. Dieses Reservoir liegt über 1500m unter dem Meeresboden und ist von dicken, porösen Felsen umschlossen. Daher ist ein Leck höchst unwahrscheinlich. Ein CO2-Kontrollsystem wird zusätzlich installiert, um undichte Stellen im Reservoir entdecken zu können. Seit 1996 werden bereits einige entleerte Reservoirs zur CO2-Lagerung benutzt, und undichte Stellen sind bisher noch nicht festgestellt worden.

5. Gefällt Ihnen das Konzept des „CO2-Auffangturms“

sagt mir überhaupt nicht zu	sagt mir nicht zu	neutral	sagt mir zu	sagt mir sehr zu	ich weiß nicht

bitte wenden →

6. Was würden Sie von einem CO2-Auffangturm in Ihrer Stadt halten?

NEGATIV POSITIV

0	1	2	3	4	5

7. Wie viel Geld würden Sie bereit sein monatlich zu zahlen, um den CO2-Auffangturm zu unterstützen?

€	0	5	10	15	mehr als 15

Zu Ihrer Person

8. Sind Sie

männlich	weiblich

9. Wie alt sind Sie?

	Alter
A	Unter 18
B	18-25
C	26-35
D	36-45

	Alter
E	46-54
F	55-64
G	65+

10. Bildung

A	Ohne Schulabschluss
B	Hauptschulabschluss
C	Realschulabschluss
D	Abitur / Fachabitur
E	Hochschul- oder Fachhochschulabschluss

11. Persönliches monatliches Einkommen (brutto) [nicht unbedingt erforderlich]

A	0-699
B	700-899
C	900-1399
D	1400-1849
E	1850-2749
F	2750-3699
G	3699-4600
H	4600+

12. Beruf ______________________

13. Denken Sie, dass Sie umweltbewusst leben?

JA	NEIN

14. Was halten Sie davon, CO2 direkt an den Schornsteinen von Kraftwerken aufzufangen?

sagt mir überhaupt nicht zu	sagt mir nicht zu	neutral	sagt mir zu	sagt mir sehr zu	ich weiß nicht

15. Haben Sie von CO2-Abscheidung und –Speicherung (CCS) gehört?

JA	NEIN

16.Wenn ja, wo? (z. B. Fernsehen, Radio, Internet etc.) ______________________

Danke und ein schönes Wochenende!

APPENDIX C HAMBURG SURVEY TRANSLATED INTO ENGLISH

Lloyd's Register Educational Trust

UNIVERSITY OF Southampton

We are conducting a survey on a novel idea to reduce CO2 in the air. This survey is conducted on behalf of the University of Southampton, UK. You do not need to have any specialised knowledge, it is your opinion as a member of the general public that we are interested in. Your opinion will help to form some of the future government policies with regards to the environment. Please kindly tick your answer in the box provided.

1. Do you live in Hamburg?	YES	NO
2. Have you heard of global climate change?	YES	NO

3. If yes, please rate the level of your concern on climate change?

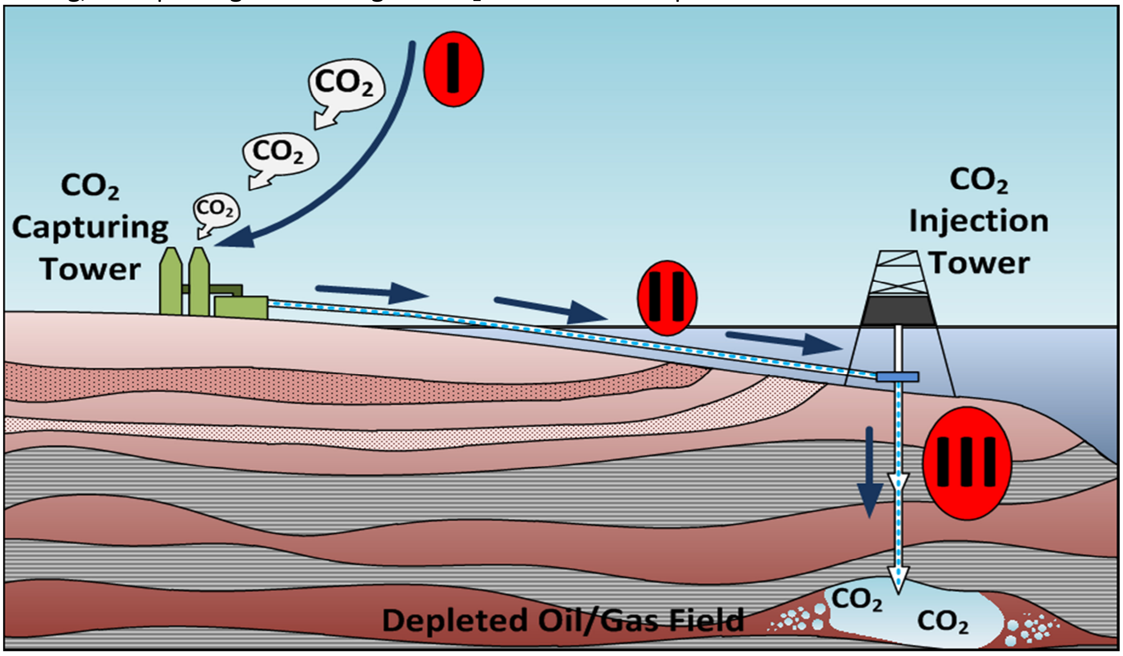
not concerned — very concerned

0	1	2	3	4	5

4. Have you heard of greenhouse gases?	YES	NO

Please read the following description on the proposed idea

A major source of climate change is carbon dioxide (CO_2) emission. The government is considering removing CO_2 from the air by using a new technology known as the 'CO_2 Capturing Tower'. This tower will be installed in the town and the captured CO_2 will then be transported for storage. The process of capturing, transporting and storing the CO_2 is shown in the picture below.



I. CO_2 from the air is captured by the CO_2 capturing tower.

II. The captured CO_2 is transported by offshore pipelines.

III. The transported CO_2 is stored in depleted oil/gas reservoir. This reservoir is more than 1500m deep underneath the seabed and is enclosed by thick porous rocks. Hence, leakage is highly unlikely. CO_2 monitoring system will also be installed to detect any leakages from the reservoir. Since 1996, a few depleted reservoirs were already used to store CO_2 and leakage has not been detected so far.

5. Do you like the idea of "co_2 capturing tower"?

don't like it at all	don't like it	neither like nor dislike it	like it	really like it	don't know

Please Turn Over →

6. How do you feel about the "CO2 capturing tower" idea in your town?

NEGATIVE POSITIVE

0	1	2	3	4	5

7. How much would you be prepared to pay per month to support the CO2 capturing tower?

£	0	5	10	15	More than 15

About yourself

8. Are you   Male   Female

9. How old are you?

	Age
A	Under 18
B	18-25
C	26-35
D	36-45

	Age
E	46-54
F	55-64
G	65+

10. Education

A	“Without qualifications”
B	“Secondary school”
C	“GCSE”
D	“A levels”
E	“College or University “

11. Personal income (€ before tax) [optional]

A	0-699
B	700-899
C	900-1399
D	1400-1849
E	1850-2749
F	2750-3699
G	3699-4600
H	4600+

12. Occupation ______________________________

13. Do you consider yours self to be environmental friendly?   YES   NO

14. In the long term, how do you feel about co_2 capturing directly at the chimney at power plants?

don't like it at all	don’t like it	neither like nor dislike it	like it	really like it	don't know

15. Have you heard of carbon capture and storage (CCS) before?   YES   NO

16. IF YES, WHERE HAVE YOU HEARD OF IT? (e.g. TV, website, radio, etc.) ____________________

Thank You and Have A Nice Weekend!