Effect of Government Actions on Technological Innovation for UK’s Carbon Capture and Storage

A Thesis submitted to the University of Manchester for the degree of
Doctor of Philosophy
in the Faculty of Humanities

2018

Yu-Chia Ko

Alliance Manchester Business School
List of Contents

List of Tables ........................................................................................................... 5
List of Figures ............................................................................................................ 6
List of Abbreviations ................................................................................................. 7
Abstract .................................................................................................................... 9
Declaration ................................................................................................................ 10
Copyright Statement ................................................................................................. 11
Acknowledgements ..................................................................................................... 12

Chapter 1. Introduction.............................................................................................. 13
  1.1 Background ....................................................................................................... 13
  1.2 CCS Technologies ......................................................................................... 14
  1.3 Aim of the Research ..................................................................................... 16
  1.4 Research Questions of this Thesis ............................................................... 16
  1.5 Overview of the Thesis ............................................................................... 17

Chapter 2. Literature Review and Analytical Framework ......................................... 19
  2.1 Exploring Technological Innovation Processes ........................................... 19
    2.1.1 Innovation Systems, System Structure and Functions ....................... 20
    2.1.2 System Dynamics and Performance ............................................... 23
    2.1.3 The Analytical Scheme of a Technological Innovation System (TIS) .... 25
    2.1.4 The Dynamics of Functions .............................................................. 29
  2.2 Comparing TIS with Other Innovation System Approaches ...................... 29
    2.2.1 National Innovation System (NIS) ....................................................... 30
    2.2.2 Sectoral Innovation System (SIS) ......................................................... 35
    2.2.3 Social-Technical Systems (ST-Systems) ............................................. 37
    2.2.4 A Framework to Compare TIS with SIS and ST-Systems ................. 39
  2.3 System Interactions of TIS with NIS and SIS .............................................. 46

Chapter 3. Methodology ............................................................................................ 49
  3.1 Introduction ...................................................................................................... 49
  3.2 Research Paradigm ......................................................................................... 49
  3.3 Expert Interview Strategy ............................................................................ 50
  3.4 Interview Questions ....................................................................................... 51
  3.5 Interview Analysis ......................................................................................... 54
3.6 Ethical Concerns ........................................................................................................... 56
3.7 List of Conducted Expert Interviews ........................................................................... 57
3.8 Sources of Secondary Literature ................................................................................. 59
3.9 Patent Analysis ............................................................................................................. 60

Chapter 4. The Performance of the UK CCS Innovation System .................. 61

4.1 Evolution of the UK’s CCS Innovation System .......................................................... 61
  4.1.1 Period: 1990s ....................................................................................................... 62
  4.1.2 Period: 2000 to 2011 ......................................................................................... 63
  4.1.3 Period: After 2011 ............................................................................................ 68
4.2 The Structure of the UK’s CCS Innovation System .................................................. 69
4.3 The UK’s CCS System Functions .............................................................................. 77
  4.3.1 The Function of Entrepreneurial Activity .......................................................... 77
  4.3.2 The Function of Knowledge Development ....................................................... 80
  4.3.3 The Function of Knowledge Diffusion .............................................................. 83
  4.3.4 The Function of Guidance ................................................................................ 86
  4.3.5 The Function of Market Formation ................................................................... 93
  4.3.6 The Function of Resource Mobilisation ............................................................ 95
  4.3.7 The Function of Creation of Legitimacy ............................................................ 96
4.4 Interactions with other Innovation Systems ............................................................... 101
  4.4.1 Interaction with the EU’s Innovation System ..................................................... 102
  4.4.2 Interaction with Norway’s National Innovation System .................................... 107
  4.4.3 Interactions with Sectoral Innovation Systems ................................................ 110
4.5 Dynamics of the UK’s CCS Innovation System ....................................................... 114

Chapter 5. Conclusions ............................................................................................... 119

5.1 Introduction ................................................................................................................. 119
5.2 Key Findings and Policy Recommendations .......................................................... 119
5.3 Contributions to TIS Literature ................................................................................ 127
5.4 Limitations of This Research ..................................................................................... 132
5.5 Areas for Further Research ....................................................................................... 132

Appendix A: Indicative Questions for the 7 system functions ................................. 134
Appendix B: Patent Analysis .......................................................................................... 135
Appendix C: The Approaching Letter for Expert Interview ....................................... 139
Appendix D: Interview Consent Form .......................................................................... 140
Appendix E: CCS Projects of EU’s 5th and 6th Framework Programmes .......... 141
List of Tables

Table 2-1: Description, assessment and interaction of the seven functions of innovation systems ............................................................................................................. 26
Table 3-1: Example of Interview Transcripts with Functional Labels............. 55
Table 3-2: List of Interviewed Capture Experts ............................................. 57
Table 3-3: List of Interviewed Transport Experts ......................................... 58
Table 3-4: List of Interviewed Storage Experts ............................................. 58
Table 3-5: List of Interviewed Other Experts ................................................ 58
Table 4-1: PACT Facilities Sites and Capability ........................................... 79
Table 4-2: CCS Cost Reduction Task Groups and Aims ............................. 91
Table 4-3: System Function Interactions of the UK’s CCS TIS & EUIS ....... 106
Table 4-4: System Function Interactions of the UK’s CCS TIS & Norway’s NIS 109
Table 4-5: System Function Interactions of the UK’s CCS TIS & SISs ......... 112
List of Figures

Figure 2-1: A reproduction of a positive feedback loop of system functions...... 24
Figure 2-2: The Scheme of Analysis for Technological Innovation Systems...... 28
Figure 2-3: National Innovation System’s building blocks.............................. 31
Figure 2-4: National Innovation System ............................................................ 32
Figure 2-5: National, Sectoral and Technological Innovation Systems .......... 47
Figure 4-1: Structure of the innovation system.............................................. 70
Figure 4-2: Interactions of the UK’s CCS TIS with other innovation systems 101
Figure 4-3: Carbon Price Floor Illustration (in real 2009 prices & calendar years) .......................................................................................................................... 104
Figure 4-4: The Functional Dynamics of the UK’s CCS TIS in Period 1990s.. 114
Figure 4-5: The Functional Dynamics of the UK’s CCS TIS in the Period 2000 to 2011 .................................................................................................................. 115
Figure 4-6: The Functional Dynamics of the UK’s CCS TIS in the Period After 2011...................................................................................................................... 117
**List of Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGS</td>
<td>British Geological Survey</td>
</tr>
<tr>
<td>CCS</td>
<td>carbon dioxide capture and storage</td>
</tr>
<tr>
<td>CCSA</td>
<td>Carbon Capture &amp; Storage Association</td>
</tr>
<tr>
<td>CO₂</td>
<td>carbon dioxide</td>
</tr>
<tr>
<td>DBEIS</td>
<td>Department for Business, Energy &amp; Industrial Strategy</td>
</tr>
<tr>
<td>DBIS</td>
<td>Department for Business, Innovation &amp; Skills</td>
</tr>
<tr>
<td>DECC</td>
<td>Department of Energy and Climate Change (UK)</td>
</tr>
<tr>
<td>DEFRA</td>
<td>Department of Environmental, Food and Rural Affairs (UK)</td>
</tr>
<tr>
<td>DTI</td>
<td>Department of Trade and Industry</td>
</tr>
<tr>
<td>EC</td>
<td>European Commission</td>
</tr>
<tr>
<td>EHR</td>
<td>enhanced hydrocarbon recovery</td>
</tr>
<tr>
<td>EMR</td>
<td>Electricity Market Reform</td>
</tr>
<tr>
<td>EOR</td>
<td>enhanced oil recovery</td>
</tr>
<tr>
<td>EPSRC</td>
<td>Engineering and Physical Sciences Research Council</td>
</tr>
<tr>
<td>ETI</td>
<td>Energy Technologies Institute</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>EU ETS</td>
<td>EU Emissions Trading System</td>
</tr>
<tr>
<td>FITs CfD</td>
<td>Feed-in Tariff Contracts for Difference</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IGCC</td>
<td>integrated gasification combined cycle</td>
</tr>
<tr>
<td>IMO</td>
<td>International Maritime Organization</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>Mt CO₂</td>
<td>million tonnes of carbon dioxide</td>
</tr>
<tr>
<td>MW</td>
<td>megawatt (10⁶)</td>
</tr>
<tr>
<td>MWh</td>
<td>megawatt hour</td>
</tr>
<tr>
<td>NGO</td>
<td>non-governmental organisation</td>
</tr>
<tr>
<td>NIS</td>
<td>National Innovation System</td>
</tr>
<tr>
<td>OECD</td>
<td>Organisation for Economic Co-operation and Development</td>
</tr>
<tr>
<td>PML</td>
<td>Plymouth Marine Laboratory</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>research and development</td>
</tr>
<tr>
<td>RCEP</td>
<td>Royal Commission on Environmental Pollution</td>
</tr>
<tr>
<td>SIS</td>
<td>Sectoral Innovation System</td>
</tr>
<tr>
<td>TIS</td>
<td>Technological Innovation System</td>
</tr>
<tr>
<td>TSB</td>
<td>Technology Strategy Board</td>
</tr>
<tr>
<td>UKCCSRC</td>
<td>UK CCS Research Centre</td>
</tr>
<tr>
<td>UKCS</td>
<td>UK Continental Shelf</td>
</tr>
<tr>
<td>UKERC</td>
<td>UK Energy Research Centre</td>
</tr>
<tr>
<td>UKTI</td>
<td>UK Trade and Investment</td>
</tr>
<tr>
<td>UNIDO</td>
<td>United Nations Industrial Development Organisation</td>
</tr>
<tr>
<td>ZEP</td>
<td>European Technology Platform for Zero Emission Fossil Fuel Power Plants</td>
</tr>
</tbody>
</table>
Abstract
The University of Manchester
Yu-Chia Ko
Doctor of Philosophy

Effect of Government Actions on Technological Innovation for UK’s Carbon Capture and Storage

18th February 2018

For emerging technologies with high uncertainty, such as carbon capture and storage (CCS), various government actions can exert a critical influence on each stage of development. As a mitigation technology essential in combating climate change, CCS captures, transports and stores carbon dioxide (CO₂) emissions from large point sources, such as fossil fuel power plants. Since fossil fuel-generated electricity accounts for more than 50 per cent and continues to play an important role in the UK’s energy mix, the UK Government has considered CCS as a key option to reduce CO₂ emissions. In order to facilitate the development of CCS, the Government has taken actions such as R&D funding, demonstration programmes, corresponding regulatory frameworks and the ongoing establishment of price-based support schemes. This research aims to assess how the Government’s interventions affect the development and diffusion of CCS in the UK.

For a holistic examination of the influence of government intervention in the UK’s CCS development, this research adopts the Technology Innovation System (TIS) approach, introduced by Carlsson and Stankiewicz (1991) and further developed by Bergek et al. (2008), for analysing the functional dynamics of CCS innovation systems in the UK, including the functions of entrepreneurial activities, knowledge development, knowledge diffusion through networks, guidance of search, market formation, resource mobilisation and creation of legitimacy. With the analytical framework of TIS, this research conducted expert interviews and secondary literature reviews to understand CCS development over time in the UK and investigate the strong and weak functions of the UK’s CCS innovation system. In addition, this research seeks to explore the interactions of the UK’s CCS TIS with the EU’s innovation system, Norway’s innovation system and sectoral innovation systems such as power generation and steel.

Through systematic assessment, this study identified the main drivers of the UK’s CCS development, including the external stimuli of Norway’s carbon tax policy and the EU’s CCS research priority in the early stage, and the domestic government’s support of R&D funding and network establishment for knowledge development and diffusion. However, the hesitation and changeable position of the Government were recognised as barriers to the development, especially regarding the capital investment for demonstration and commercialisation programmes. This study uses the findings to draw policy recommendations for further CCS development.
Declaration

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification of this or any other university of other institutes of learning.
Copyright Statement

- The author of this thesis (including any appendices and/or schedules to this thesis) owns certain copyright or related rights in it (the “Copyright”) and she has given The University of Manchester certain rights to use such Copyright, including for administrative purposes.

- Copies of this thesis, either in full or in extracts and whether in hard or electronic copy, may be made only in accordance with the Copyright, Designs and Patents Act 1988 (as amended) and regulations issued under it or, where appropriate, in accordance with licensing agreements which the University has from time to time. This page must form part of any such copies made.

- The ownership of certain Copyright, patents, designs, trade marks and other intellectual property (the “Intellectual Property”) and any reproductions of copyright works in the thesis, for example graphs and tables (“Reproductions”), which may be described in this thesis, may not be owned by the author and may be owned by third parties. Such Intellectual Property and Reproductions cannot and must not be made available for use without the prior written permission of the owner(s) of the relevant Intellectual Property and/or Reproductions.

- Further information on the conditions under which disclosure, publication and commercialisation of this thesis, the Copyright and any Intellectual Property and/or Reproductions described in it may take place is available in the University IP Policy (see http://www.campus.manchester.ac.uk/medialibrary/policies/intellectual-property.pdf), in any relevant Thesis restriction declarations deposited in the University Library, The University Library’s regulations (see http://www.manchester.ac.uk/library/aboutus/regulations) and in The University’s policy on presentation of Theses.
Acknowledgements

I sincerely thank my supervisors, Paul Dewick and Jonathan Aylen, for their patient guidance, support and encouragement throughout my journey as their doctoral student. I have been extremely lucky to have them, and they generously imparted their professional research experience to me and also provided their constructive advice on my work.

I would also like to thank my programme advisor, Ronald Ramlogan, for caring and encouraging me to keep myself on track to complete my thesis. Moreover, I am grateful to my thesis examiners, Simon Shackley and Maria Sharmina, for their insightful comments and suggestions so that I can make a better improvement on my thesis.

I would like to express my gratitude to those experts whom I interviewed, as they generously offered their time and expertise to my research. I very much appreciate their willingness and participation. I am also thankful for the UK’s CCS Research Centre’s holding their biannual meetings so that I can regularly obtain up-to-date information on the development of CCS.

I am grateful to RADMA’s Postgraduate Project Support programme in March 2014 for the generous funding support towards travel and transcription expenses involved in my research. I am also thankful to AMBS’s PGR office for every possible assistance that they provided throughout my doctoral programme. I am also obliged to those colleagues in AMBS, MIoIR in particular, for their warm friendship and professional support.

I must express my ultimate gratitude to my wife, Chin-Mei, my parents and all other family members for their love, understanding and steadfast support so that I could concentrate on my research and completing this thesis. I would also like to thank my pastors and friends at St Peter’s House and KuangYen Church for their thoughts, prayers and support for all these years during my study.
Chapter 1. Introduction

1.1 Background

As the problem of climate change becomes more and more serious, the excessive emissions of carbon dioxide (CO₂), one of the major greenhouse gases (GHGs) causing global warming, are then urged to be mitigated (IPCC, 2014). The increasing anthropogenic emissions of CO₂ into the atmosphere is expected to result in global climate change with potentially severe consequences for ecosystems, such as changing weather patterns, melting glaciers, sea level rise and the extinction of species (IPCC, 2014). The impact of a changing climate for humans can also be severe, as more extreme droughts and floods are expected (IPCC, 2014). Direct relation between natural disasters that may have been caused by climate change and the emission of anthropogenic GHGs is hard to prove due to the complexity of the climate system (IPCC, 2014). Nevertheless, the dominant view in scientific research is that, most probably, global warming observed over the past few decades is, in a substantial part, caused by human activities (Oreskes, 2004; IPCC, 2014).

Reducing CO₂ emissions and stabilising GHGs concentrations in the atmosphere have been recognised as important remedies for climate change (IPCC, 2014). The major producers of CO₂ emissions comprise fossil fuel power stations, oil refineries and heavy industries, accounting for 52 per cent of global emissions (ZEP, 2009). As fossil fuels still supply 80 per cent of global energy and will remain our principle source of energy for decades to come, a key set of carbon capture and storage (CCS) technologies has been introduced to mitigate CO₂ emissions (ZEP, 2009). CCS can be defined as the separation and capture of CO₂ from industrial and energy-related sources, transport of the CO₂ to a (usually underground) storage site and long-term isolation of the CO₂ from the atmosphere (IEA, 2015). The ultimate goal of CCS is to store the otherwise emitted CO₂ for geological times in the deep underground (IEA, 2015).

Since fossil fuel-generated electricity accounts for more than 50 per cent in the UK and continues to play an important role in the energy mix, the UK Government has seen CCS as a necessary means to reduce CO₂ emissions (DECC, 2012a). For the development of CCS, the Government has taken actions such as R&D funding,
demonstration and commercialisation programmes, corresponding regulatory frameworks, and the ongoing establishment of price-based support schemes (DECC, 2012a).

1.2 CCS Technologies

CCS can reduce CO₂ emissions from large industrial sources and power stations using carbonaceous fuels by around 90 per cent (ZEP, 2009). As such, it is a key technology within a suite of low carbon solutions for mitigating climate change. In general, CCS can be seen as a set of technologies that integrates three stages: CO₂ capture at large point sources, transport of CO₂ to a suitable storage location, and injecting the CO₂ deep underground for long-term storage (IEA, 2015). The sections below provide a short overview of each of the stages in the CCS process.

Stage 1: Capture

In the first stage of CCS, CO₂ is isolated and captured. CO₂ capture technologies have long been used by industry to remove CO₂ from gas streams where it is not wanted or to separate CO₂ as a product gas (IEA, 2009). In industrial processes, such as natural gas sweetening, for example, CO₂ is removed from natural gas streams to meet specific natural gas quality standards; similarly in plants that produce ammonia or hydrogen (IPCC, 2005).

There are three main approaches to capturing CO₂ from fossil fuel power plants: post-combustion, pre-combustion and oxy-fuel combustion (ZEP, 2009; IPCC, 2005). Each of these processes involves the separation of CO₂ from a gas stream by using chemical absorption, physical adsorption, or physical separation (IPCC, 2005). Post-combustion captures CO₂ directly from flue gases exiting the combustion process. Pre-combustion utilises a gasification process to remove CO₂ from the synthetic gas generated from fossil fuels, leaving a hydrogen-rich combustible fuel. Oxy-fuel combustion involves combusting fuel in recycled flue gas enriched with oxygen to produce a CO₂-rich gas. Of these methods, post-combustion CO₂ capture using amine solvent scrubbing is one of the more established methods for CO₂ capture, as this is used to capture significant
flows of CO₂ from flue gas streams in several facilities (IEA, 2009). Oxy-fuel combustion has been demonstrated in the steel manufacturing industry at plants up to 250MW in capacity, and the related oxy-coal combustion method is currently being demonstrated at smaller scales (IEA, 2008). Pre-combustion CO₂ capture from an integrated gasification combined cycle (IGCC) power plant has yet to be demonstrated; however, elements of the pre-combustion capture technology have already been proven in other industrial processes (IPCC, 2005). In other industrial activities, such as steel making and cement plants, processes to capture CO₂ have also been developed (IPCC, 2005). Adaptations to post-combustion, pre-combustion and oxy-fuel combustion processes have been proposed for these types of industrial facilities (GCCSI, 2009).

Stage 2: Transport

The captured CO₂ would then be compressed and transported by high-pressure pipelines to a suitable storage site. The oil and gas industry has been transporting and re-injecting CO₂ into oil fields for over three decades to maintain or increase production. For example, over 30 million tonnes (Mt) CO₂ from natural and anthropogenic sources are transported per year through 6200km of CO₂ pipelines in the USA and Canada (Dooley et al., 2009). Moreover, CO₂ has also been transported by ships, trains and trucks in early demonstration projects (IEA, 2009).

Stage 3: Storage

The final stage of CCS sees the CO₂ injected into, and contained within, suitable underground geological structures, often at depths of one kilometre or more (IPCC, 2005). Appropriate storage sites include depleted oil or gas fields, unmineable coal beds or deep porous saline aquifers, which have impermeable rock (also known as a 'seal') above them (IPCC, 2005). The seal prevents the CO₂ from returning to the surface and forces the CO₂ to slowly permeate through the porous rock, while these sites have securely contained fluids and gases for millions of years, and, with careful selection, they offer confidence in the integrity of storage (IPCC, 2005). Of the three, it is expected that saline formations will provide the opportunity to store the greatest
quantities of CO$_2$, followed by oil and gas reservoirs (IEA, 2008). Once injected, a range of technologies is used to monitor the behaviour of CO$_2$ in the storage location, while this monitoring, as well as the associated reporting and verification processes, provides an additional safeguard to storage activities (IPCC, 2005).

### 1.3 Aim of the Research

For emerging technologies with high uncertainty, like CCS, various government actions can exert a critical influence on each stage of development. In order to study the effect of those government actions on CCS development in the UK, this research adopts the Technology Innovation System (TIS) approach, introduced by Carlsson and Stankiewicz (1991) and further developed by Bergek et al. (2008), for analysing the functional dynamics of CCS innovation system in the UK. With the analytical framework of TIS, this research aims to understand CCS development over time in the UK and investigate the strong and weak functions of the UK’s CCS innovation system.

In addition, this research seeks to explore the interactions of the UK’s CCS TIS with the EU’s innovation system, Norway’s national innovation system and sectoral innovation systems such as power generation and steel. This research particularly identifies the main drivers of and barriers to CCS development and finds their relationship with the UK Government’s actions. This research finally draws policy recommendations for further CCS development and also contributes to the TIS approach with empirical evidence of its interactions with other system levels.

### 1.4 Research Questions of this Thesis

Since CCS has emerged and developed in the UK, and because the Government has taken actions to support and facilitate the development, this research intends to be the first to apply the TIS approach to assess the development in the UK, identify the main drivers and barriers, and provide suggestions for further development. The research questions of this thesis can thus be derived from the above considerations:

How did the technological innovation system of CCS build up over time in the UK and what were/are the main drivers of and barriers to the development?
How did the technological innovation system of the UK’s CCS interact with other innovation systems and how can the investigation into the interactions provide better understanding of the development?

How can the UK’s CCS development be further facilitated with government actions based on the insights into the historical dynamics and current performance?

1.5 Overview of the Thesis

Chapter 2: Literature Review and Analytical Framework

Chapter 2 first looks at the technological innovation system (TIS) literature and explores the application of the TIS approach, including system structure and functions, dynamics and performance. This chapter also compares TIS with other innovation systems, including national innovation system (NIS), sectoral innovation system (SIS) and social-technical systems to justify the TIS approach being most suitable for analysing CCS development in the UK. This chapter finally discusses the literature on system interactions that can contribute to a better understanding of a TIS development.

Chapter 3: Methodology

The third chapter spells out the methodology used in this research. This chapter also details the sources of data collection, including expert interviews and secondary literature review, and methods of data analysis.

Chapter 4: The Performance of the UK’s CCS Innovation System

Chapter 4 contains the empirical analysis of this research to assess the performance of the UK’s CCS innovation system. This chapter firstly explores the dynamics of the development in three periods. In the second and third sections, the analyses of the TIS structure and functions are conducted. Finally, this chapter investigates the interactions of the UK’s CCS TIS with the EU’s innovation system, Norway’s innovation system and sectoral innovation systems.
Chapter 5: Conclusions

Chapter 5 answers the research questions of this research and summarises the contributions this research has made to knowledge. It also provides policy recommendations for future CCS development, and outlines limitations and potential areas for further research.
Chapter 2. Literature Review and Analytical Framework

2.1 Exploring Technological Innovation Processes

Although Carbon Capture and Storage (CCS) has been recognised as a key solution within a portfolio of low carbon technologies for mitigating climate change, it is problematic for CCS to achieve dominance over conventional ways of fossil fuel use (van Alphen et al., 2010). Like other low-carbon energy technologies, CCS has to compete with an incumbent technological system based on fossil fuels that benefits from long periods of experience, leading to high efficiency, low costs, conducive institutional arrangements, and many vested interests (Unruh, 2000). The alignment with CCS’s surrounding structures is weak; hence, its ability to break through and be deployed widely in the UK or even on a global scale is complicated. For example, existing markets do not fully account for the costs of carbon-emitting energy technologies and for the potential benefits of emerging low-carbon technologies. Moreover, developing a capturing facility and a transportation and storage infrastructure for CCS is not only a matter of engineering and the relative price of the technology, but requires, amongst others, companies willing to build, own and invest in such an infrastructure, governments to conduct regional planning exercises and to develop operational standards, as well as local communities living close to pipeline corridors to accept the associated risks (van Alphen et al., 2010).

The development of CCS can therefore be considered as a technological innovation system because it covers the major characteristics of an innovation system, including a specific set of technologies, infrastructure to link the full chain technologies, institutions and actors. Moreover, technological innovations can be understood as the development of a set of interlinked technologies and institutions being shaped and reshaped through the activities of actors. With these technological and institutional structures in place, the innovation process typically gains more direction and speed (Jacobsson & Bergek, 2004). This coincides with the basic idea behind the concept of Innovation Systems, namely that the innovation process is strongly influenced by a network of actors that are developing, advocating or opposing the technology and by an institutional infrastructure that legitimises, regulates and standardises the new technology (Carlsson & Stankiewicz, 1991).
2.1.1 Innovation Systems, System Structure and Functions

Failures in the market and new insights obtained from innovation theories have deepened the general understanding of innovation processes. Scholars such as Nelson and Winter (1977), Lundvall (1992) and Freeman (1995) emphasised that organisations are not innovating in isolation, but in the context of an Innovation System. It has become a well-established heuristic framework in the field of innovation studies, as it presents insights into factors that explain processes of innovation (Lundvall, 1992). The Innovation System approach is a reaction to the linear model of innovation, which starts with basic research, followed by applied R&D and demonstration, ending with production and diffusion of the innovation. The different stages of the linear model of innovation were, in general, considered as separate activities, both in terms of time and in terms of the actors and institutions involved. The Innovation System approach and the evolutionary economics literature from which it stems reject this model (Suurs, 2009). Instead, it stresses that technological innovation involves continued interaction between numerous processes, with R&D, production and market formation all running in parallel and reinforcing each other through positive feedback mechanisms (Smits, 2002).

From the 1980s onwards, Innovation System studies have pointed out the influence of the social system on innovative performance and, indirectly, on long-term economic growth, within nations, sectors or technological fields. Hence, the existence in literature of different Innovation System approaches, such as National Innovation Systems (Freeman, 1987; Lundvall, 1992; Nelson, 1992), Regional Innovation Systems (Cook et al., 1997), Sectoral Innovation Systems (Breschi & Malerba, 1997) and Technological Innovation Systems (Carlsson & Stankiewicz, 1991; Carlsson et al., 2002; Jacobsson & Johnson, 2000). Conceptually, the various Innovation System approaches are comparable since the difference between them is largely a matter of geographical and/or techno-economical delineation. A detailed discussion of those approaches is presented in Section 2.

A number of scholars have adopted the Innovation System framework to study processes of socio-technical change and, in many studies, the focus was on emerging sustainable energy technologies (Jacobsson and Bergek, 2004; Jacobsson and Johnson, 2000; Hekkert et al., 2007; Liu and White, 2001; Negro et al., 2007; Suurs, 2009).
More specifically, these authors have adopted the Technological Innovation System (TIS) approach, as introduced by Carlsson and Stankiewicz (1991), as “A dynamic network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion, and utilisation of technology.” The TIS approach has also been widely applied by policy analysts and international organisations, including the Organisation for Economic Co-operation and Development (OECD) and the European Commission and United Nations Industrial Development Organisation (UNIDO) to assess the structure and functions of innovation systems and to inform how to tailor policy which targets and removes potential barriers to long-term development.

The focus of the TIS approach on the institutions and networks of agents involved in the generation, diffusion and utilisation of a specific technology fits best with the interest of this research: i.e. to understand and analyse technological innovation in terms of the structures and processes that support (or hinder) the development and (commercial) deployment of CCS. In particular, the TIS approach has been used effectively to analyse and deliver explanations for the success or failure of CCS development in various nations, including the United States, Canada, Norway, the Netherlands and Australia (van Alphen et al., 2010), and China (Lai et al., 2012).

Besides being less broad than the National and Sectoral Innovation System approaches, the TIS framework sets itself apart through two main aspects (Suurs, 2009). The first is that the TIS approach emphasises the ability to develop and exploit new business opportunities, as a crucial aspect of technological innovation. Instead of focusing solely on the generation and exchange of knowledge, it stresses the need to exploit this knowledge, or to actively recombine knowledge in order to create new business opportunities. The second feature that distinguishes TIS studies from other IS approaches is a more serious focus on system dynamics. The focus on entrepreneurial action and system dynamics has encouraged scholars to consider a TIS as something to be built-up over time.

Since Carlsson and Stankiewicz introduced the concept of a TIS, an increasing number of scholars have provided insights into the dynamics of this build-up process (Hekkert et al., 2007; Jacobsson & Bergek, 2004; Jacobsson & Johnson, 2000; Negro et al., 2007). This literature stresses that emerging technologies will pass through a so-called
formative stage before they can be subjected to a market environment. This formative stage includes a ‘predevelopment phase’, which is the first phase in the build-up of an Innovation System. The phase ends when a working prototype is available on the market. The subsequent ‘take off phase’ is characterised by a small but increasing demand for the new technology. The formative stage is followed by an acceleration phase, which features strong growth in diffusion of the technology in question and a stabilisation phase, which is characterised by the stabilisation of the demand or the technology.

During this formative stage, actors are drawn in and their networks grow in terms of size and density. Furthermore, institutions are designed and adjusted with the aim of increasingly aligning them to the emerging technology. On the other hand, when a TIS grows, the rate of technological progress generally increases, which, in turn, leads to increased chances of success for the technology in question. A TIS approach may focus on these changes in structure and their effects on technological innovation, but it may also focus on the processes underlying the structural build-up of the system (Jacobsson et al., 2004).

This focus on the process or ‘function’ of a TIS has been developed by a number of scholars, but has not been addressed in a systematic manner in earlier work on Innovation Systems (Hekkert & Negro, 2009). Galli and Teubal (1997) started some thinking in this direction, which was followed up by Jacobsson and Johnson (2000) and Liu and White (2001), and tested and further developed by Hekkert et al. (2007), Hekkert and Negro (2009) and Suurs (2009). They argued that the primary goal of an Innovation System is to contribute to the development and diffusion of innovations. In particular, they reflected on different sub-functions, which are considered to be important for an Innovation System to develop and grow and, thereby, to increase the success chances of the emerging technology.

The sub-functions or system functions are decisive processes that have a direct impact on the development and diffusion of new technologies. The premise is that the structural components of the system – i.e. actors, their networks and institutions–should be successfully arranged to bring about an optimal fulfilment of a set of system functions, each of which covers a particular aspect of technological innovation. Therefore, a well-functioning Innovation System accelerates technological
development and increases the success chances of a new technology, while a poorly performing Innovation System hinders technological innovation (Hekkert & Negro, 2009).

A number of studies have applied the Innovation System Functions approach, which has led to several lists of system functions in the literature (Edquist, 1997; Galli & Teubal, 1997; Jacobsson & Bergek, 2004; Jacobsson & Johnson, 2000; Liu & White, 2001). Recent studies have identified a list of seven system functions to map, describe and explain the dynamics of a number of Technological Innovation Systems for low-carbon technologies (Bergek et al., 2008; Hekkert et al., 2007; Hekkert & Negro, 2009).

2.1.2 System Dynamics and Performance

The system functions are types of processes necessary for a TIS to build-up, while they may also be considered as criteria to be used for evaluating the performance of a TIS in the formative stage (Bergek et al., 2008; Hekkert et al., 2007). This is important since, in the formative stage of technology development, data about output measures, such as market diffusion, and environmental or techno-economic features are usually absent or unformed. The system function approach makes it possible to analyse and evaluate the development of TISs in dynamic terms (Bergek et al., 2008; Hekkert et al., 2007).

Both the individual performance of each system function and the interaction dynamics between them are of importance. Positive interactions between system functions could lead to a reinforcing dynamic within the TIS, setting off virtuous cycles that lead to the diffusion of a new technology (Bergek et al., 2008; Hekkert et al., 2007). An example of a virtuous cycle that can be expected regularly in the field of sustainable technology development is the following, as seen in Figure 2-1. The virtuous cycle starts with F4: Guidance of the Search. In this case, environmental problems are identified and government goals are set to limit or solve the problem. These goals legitimise the mobilisation of resources to finance R&D projects in search of solutions (F6), which, in turn, is likely to lead to Knowledge Development (F2) and increased expectations about technological solutions (F4). Thus, the fulfilment of the individual
functions is strengthened through interaction and, if such positive dynamics between functions were understood better, this could point out how a TIS is to be directed through its formative stage into a stage of market expansion (Jacobsson & Bergek, 2004).

Figure 2-1: A reproduction of a positive feedback loop of system functions

Source: this research

Given the interdependency of the system functions, one can say that a well-developing TIS is characterised by one or more virtuous cycles. However, a system in decline is also characterised by one or more vicious cycles, wherein the system functions interact and reinforce each other in a negative way. For example, Kamp (2004) has shown that the Dutch wind energy Innovation System was well-developed in the 1980s, but collapsed as a result of the absence of knowledge exchange between the emerging turbine industry and users, the latter being mainly energy companies. In this sense, technological innovation is a complex outcome which is determined by its weakest element(s). Evaluative studies, therefore, typically point out the relative strengths and weaknesses of particular TISs.
2.1.3 The Analytical Scheme of a Technological Innovation System (TIS)

To study TIS dynamics, scholars have synthesised the literature on innovation systems to develop a framework for structural and functional analysis (Bergek et al., 2008; Hekkert et al., 2007; Hekkert & Negro, 2009). The structural components include actors, networks (formal and informal) and institutions (Bergek et al., 2008). According to Carlsson and Stankiewicz (1991), the three main components are defined as follows:

- Actors (and their competencies), which may be firms, e.g. users, suppliers or venture capitalists, or other organisations. A particularly important actor is a ‘prime mover’, an actor (or set of actors) which is technically, financially and/or politically so powerful that it can strongly influence the development and diffusion process. Other notable actors are non-commercial organisations acting as proponents of specific technologies.

- Networks constitute important channels for the transfer of both tacit and explicit knowledge. These networks may be built around markets and may, therefore, be conducive to the identification of problems and the development of new technical solutions. They may also be non-market-related and conducive to a more general diffusion of information or to an ability to influence the institutional set-up. Being strongly integrated into a network increases the resource base of individual actors, in terms of gaining access to the information and knowledge of other actors.

- Institutions stipulate various constraints, such as norms and rules, shaping and regulating interactions between actors (Edquist & Johnson, 1997) and the behaviour and value base of various segments in society. The roles of institutions vary; some influence connectivity in the system whilst others influence the incentive structure or the structure of demand. Institutions are important, not only for the specific path a technology takes, but also to the growth of new industrial clusters (Carlsson & Stankiewicz, 1991; Edquist & Johnson, 1997).

A system function captures the contribution towards a system’s performance by a component or set of components (Bergek et al., 2008; Hekkert & Negro, 2009). The functional approach to studying innovation systems can be used to assess the
innovation system and compare it to others (Bergek et al., 2008; Markard & Truffer, 2008). These functions interact with each other, resulting in what Hekkert and Negro (2009) describe as virtuous cycles that transform a system. In a case study analysis, Hekkert and Negro (2009) applied the framework with seven functional assessments of an innovation system and also suggested the interactions of these functions, as described in Table 2-1.

Table 2-1: Description, assessment and interaction of the seven functions of innovation systems

<table>
<thead>
<tr>
<th>System function</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Function 1: Entrepreneurial Activity</td>
<td>Entrepreneurs are at the core of any innovation system. They are risk takers performing the innovative (pre-) commercial experiments, seeing and exploiting business opportunities. The function assesses the level and nature of activity by entrepreneurs attempting to take advantage of new knowledge (Function 2), efforts of networks or associations (Function 7) and new markets (Function 5) with concrete business attempts.</td>
</tr>
<tr>
<td>Function 2: Knowledge Development</td>
<td>Technology R&amp;D is a prerequisite for innovations, creating variety in technological options and breakthrough technologies. Hekkert and Negro (2009) describe this function as ‘learning by searching’ and ‘learning by doing’. The function assesses the level of R&amp;D and working knowledge regarding a technology or innovation being produced and built on. This function is evidence of entrepreneurial activity (Function 1) in addition to formal R&amp;D.</td>
</tr>
<tr>
<td>Function 3: Knowledge Diffusion through Networks</td>
<td>This is important in a strict R&amp;D setting, but especially in a heterogeneous context where R&amp;D meets government and market. Hekkert and Negro (2009) describe this as “a precondition to ‘learning by interacting’. When user producer networks are concerned, it can also be regarded as ‘learning by using’.” This function differs from the previous function in that it assesses the level and nature of knowledge exchange between actors and networks by assessing the level of integration of this knowledge into other system mechanics, such as policy making and programme design (Function 4).</td>
</tr>
<tr>
<td>Function 4: Guidance of the Search</td>
<td>This function represents the selection process that is necessary to facilitate a convergence in technology development, involving policy targets and expectations about technological options. This function assesses articulation of the demand for a technology or system capabilities in terms of visibility and clarity. The manifestation of this articulated demand is itself indicative of a degree of legitimacy (Function 7) to the development of the technologies and, in turn, stimulates the mobilisation of resources (Function 6) towards further knowledge development (Function 2) and often entrepreneurial experimentation (Function 1). The assessment of this function also includes less formal indicators, such as expectations from various stakeholders.</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Function 5: Market Formation</td>
<td>This function comprehends formation of a new (niche) market by creating temporary competitive advantage through favourable tax regimes, consumption quotas, or other public policy activities. This function assesses the creation of protected spaces for new technologies. This can take into account demand stimulated by subsidies and other incentive programmes, but also incentives set up by agents outside of government. It also assesses the maturity and capability of a market to absorb new technology. Increased functionality of market formation encourages entrepreneurial experimentation (Function 1) and in establishing the legitimacy of an alternative technology for the existing system (Function 7).</td>
</tr>
<tr>
<td>Function 6: Resource Mobilisation</td>
<td>Financial and human resources are necessary inputs for all innovative activities, and can be enacted through, for example, investments by venture capitalists or through governmental support. This function assesses the availability of financial and human capital to support knowledge development (Function 2) and entrepreneurial activity (Function 1). This function also considers the accessibility of existing infrastructure and capabilities of the entrepreneurs or development of the new technologies in general.</td>
</tr>
<tr>
<td>Function 7: Creation of Legitimacy</td>
<td>The introduction of new technologies often leads to resistance from established actors, or society. Advocacy coalitions can counteract this inertia and lobby for compliance with legislation or institutions. This function assesses the receptiveness of stakeholders (incumbents, government policy, the public, etc.) to a particular</td>
</tr>
</tbody>
</table>
technology or innovation. It also considers the actions of advocacy coalitions and supporters of the technology or innovation. The receptiveness has an influence on the resource availability (Function 6), market formation (Function 5) and the development of policies and programmes to support the development and diffusion of a technology (Function 4).

Source: Hekkert and Negro (2009)

Bergek et al. (2008) formalised a method for analysing TIS through following a 6-stage procedure, as shown in Figure 2-2. The first step involves setting the starting point for the analysis, i.e. defining the technological innovation system in focus. In the second step, the structural components of the system should be identified, including actors, networks and institutions. The third step is to move from structure to functions.

![Figure 2-2: The Scheme of Analysis for Technological Innovation Systems](image)

Source: Figure adapted from Bergek et al. (2008)

The analysis of functions starts with what is actually going on in the system with respect to the seven key processes (functions) whereby a picture of an ‘achieved’ functional pattern comes up, i.e. a description of how each function is currently filled.
in the system. The subsequent fourth (normative) step is to assess how well the functions are fulfilled and set process goals in terms of a ‘desired’ functional pattern. The fifth step is to identify mechanisms that either induce (drive) or block a development towards the desirable functional pattern. In the sixth step, key policy issues are specified with relation to these inducement and blocking mechanisms.

2.1.4 The Dynamics of Functions

The TIS approach has been widely applied to appraise a system’s performance, including structural and functional, at a static moment and to identify the system problems. However, the approach encountered some criticisms in that it focuses more on the functioning of systems, such as the element weaknesses, rather than system dynamics and changes, and that it gives little attention to the reasons behind the system weaknesses (Lachman, 2013). For a better understanding of system dynamics and changes, this research conducts the TIS analysis in three periods of the UK’s CCS development to explore the system dynamics in each period and the system changes among these periods. Although seven functions have been identified by TIS scholars to assess a system performance, it appears impossible that the identified seven functions of a TIS can be well-developed simultaneously. Moreover, to facilitate the development of a TIS such as CCS, the government might not only develop a set of supportive policies, but also need to prioritise its actions with restricted resources and situation. Accordingly, within the context of the UK’s CCS development, this research investigates critical functions of the system in each period and explores their interactions and dynamics, such as virtuous and vicious cycles.

2.2 Comparing TIS with Other Innovation System Approaches

This section presents the basic notions of National Innovation System (NIS), Sectoral Innovation System (SIS) and Social-Technical Systems (ST-Systems), compares TIS with these system approaches, and explains why TIS is the most suitable one for this research, whereby some useful points from these approaches can be integrated into the TIS approach.
2.2.1 National Innovation System (NIS)

The concept of a National Innovation System (NIS) was developed in the 1980s and is mainly linked to three scholars: Freeman (1987), Lundvall (1992) and Nelson (1993). In comparison to the neoclassical economics approaches, the concept of NIS provided a new approach to innovation and its governance and stimulation (Soete et al., 2010). Adopting a holistic view of innovation rather than focusing on isolated aspects of the process, the concept of NIS highlights the interaction of actors involved in innovation and investigates how these interactions can be influenced by social, institutional and political factors (Fagerberg & Verspagen, 2009). The approach was remarkably successful in a short period of time and has been used in academia and policy contexts (Teixeira, 2013). It is often used as an analytical framework (Sun & Liu, 2010) for assessing the differences between countries in terms of their production and innovation systems (Álvarez & Marín, 2010).

Freeman (1987) utilised the concept of NIS to describe and explain Japan’s innovation performance. He focused on the interaction between technology, social embeddedness, economic growth and system-enforcing feedback loops (Soete et al., 2010). The emphasis in his work was placed on four elements of the Japanese NIS:

- the role of policy (in particular, the role of the Ministry of International Trade and Industry),
- the role of corporate R&D in accumulating knowledge and developing advantages from it,
- the role of human capital, the organisation of work and the development of related capabilities,
- the role of industrial conglomerates in being able to profit from innovations emerging from developments along the business value chain.

Lundvall (1992) highlights the role of interaction for the production and the diffusion of new knowledge, shifting away from a sectoral view towards a broader view of the national institutional environment. Emphasising the role of the nation state, Lundvall outlines three major building blocks of an NIS (see Figure 2-3).
The first building block probes into the sources of innovation and the actions of actors that lead to innovation, including exploration and learning, while the second building block distinguishes between two types of innovation, namely radical and incremental innovation (Lundvall, 1992). The third building block deals with non-market institutions, while Lundvall (1992) distinguishes between institutions and user-producer interaction as an important form of knowledge exchange.

However, Nelson (1993) focuses on the set-up of actors and how and why they collaborate. He probes into the institutions working in the science and technology sector or supporting it, especially universities conducting R&D.

Based on these three major contributions, the NIS approach has been developed further over the past 20 years, and now the importance of the NIS concept and approach has been recognised in the field of innovation studies (Martin & Bell, 2011). The concept of NIS is widely employed in developing national strategies for science, technology and innovation. As Lundvall’s focus is on knowledge creation and learning, the learning society, which generates knowledge, is recognised as the most important resource of an innovation system while learning is its essential mechanism. From this
starting point, the notion of the knowledge economy was developed (Godin, 2006). Looking at both streams, five main elements of the concept emerged following the comprehensive overview of the NIS concept by Soete (2010), as shown in Figure 2-4.

![Figure 2-4: National Innovation System](source)

Source: Figure adapted from Soete et al. (2010)

Firstly, the sources of innovation are of great importance in NIS. Although traditional economics approaches to innovation mainly rely on an analysis of R&D, while it is not only R&D that is crucial in innovation. Producer-consumer relationships provide a source of innovation, as do the purchase and availability of equipment and the training of workers (Lundvall, 1992). Thus, innovation occurs in production, distribution and consumption (Godin, 2006).

It is also important to probe into institutions and how they affect the interactions between actors within an NIS, while the NIS approach, including market and non-market institutions, provides the framework for governments to implement policies in order to influence the process of innovation (Metcalf, 1995). Institutions are thus considered a preferred target of policy intervention at the national level.
Interactive learning is the third element, while the importance of continuous learning is highlighted in order to adapt to changes. Other concepts can thus be connected to the NIS, including human resource management, labour market institutions and learning capacities of firms (Arundel et al., 2007), as well as to absorptive capacities (Nootenboom, 2000) of firms and the economy as a whole.

Interactive learning is also closely connected to the fourth element, which is interaction. Because innovation is considered to occur mainly within interaction, a successful innovation system can thus create an environment of continuous knowledge production, knowledge use and innovation. However, an institutional environment without efficient and effective coordination of interactions can impede the development of an innovation system as the interaction is mainly affected by institutions.

Finally, social capital is considered to be an important element in the NIS approach, while more advanced institutions in a system can establish a higher stock of social capital (Soete et al., 2010). Trust, a form of social capital, can thus influence the innovation process, because trust can reduce the risk associated with innovation and especially the risk of financing innovation (Soete et al., 2010).

The NIS approach has found acceptance amongst policymakers, as it provides more opportunities for input, in comparison to the traditional market failure approach, which includes correction through policy intervention. Thus, the NIS approach was used on a national level, such as in Sweden and Finland, and on a supra-national level, for instance at the OECD (OECD, 1997; OECD, 1999).

The more comprehensive nature of the NIS approach has two advantages in policy intervention. The NIS approach can expand the use of policy instruments, such as the focuses on accelerating the diffusion of knowledge and increasing the capabilities of firms in the case of facilitating university-industry collaborations, while the traditional approach would just increase public investment for the market failure. Moreover, in comparison to the traditional top-down approach, the NIS approach is considered to increase more evenly-based interactions and communications for better policy making (Soete et al., 2010).
However, there are a number of shortcomings of the NIS approach. Since the NIS approach is not a formal one, there is no agreement on what has to be taken into account and what needs to be analysed when assessing a national innovation system. Furthermore, the NIS approach, despite having been worked on for more than two decades, still remains ‘under-theorised’ in terms of a lack of common definitions and terminologies. Based on the fact that the concept evolved around empirical studies of well-developed systems, the NIS approach is criticised as mainly an ex-post analysis framework, while it lacks the possibility of ex-ante system building (Johnson et al., 2003).

In sum, according to Freeman (1987), a “National innovation system is the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies.” The national innovation system (NIS) is limited by national borders and focuses on domestic factors that influence the level of technological and organisational development in both private and public sector. Relevant actors in NIS are characteristically enterprises, universities, government research institutes, politicians and policymakers. For an NIS, Freeman and Perez (1988) stressed the positive role of government, working closely with industry and the science base, to provide:

- direction and support for development and marketing of advanced technologies;
- an integrated approach to R&D, design, procurement, production and marketing within large firms;
- a high level of education and scientific culture, combined with practical training and frequent up-dating in industry.

In addition, the characteristics of a nation’s innovation system are important for the performance of technology development. Hence, a country’s distinctive industrial and political pattern can be used as explanatory factors for the diffusion of certain technologies. Although this research focuses solely on the technological development of CCS in the UK rather than the whole of the UK’s NIS, the technological innovation system of the UK’s CCS would inevitably be influenced by the NIS. This research, thus, explores how the UK’s NIS supports the development of CCS with related policies and institutions.
2.2.2 Sectoral Innovation System (SIS)

Based on the concepts of evolutionary theory and key aspects of innovation system studies, Breschi and Malerba (1997) introduced the notion of SIS and defined an SIS as “a set of new and established products for specific uses and the set of agents carrying out market and non-market interactions for the creation, production and sale of those products” (Malerba 2002). A sectoral system consists of basic elements, including:

- Products.
- Agents:
  - Firms: Users, producers and input suppliers.
  - Non-firm organisations: Universities, financial institutions, government agencies, trade-unions, technical associations.
  - Sub-units of larger organisations: R&D or production departments.
  - Groups of organisations: Industry associations.
  - Individuals: Consumers, entrepreneurs, scientists.
- Knowledge and learning processes.
- Basic technologies, inputs, demand, and the related links and complementarities.
- Mechanisms of interactions both within firms and outside firms.
- Processes of competition and selection.
- Institutions: Standards, regulations, labour markets.

The notion of SIS extends the traditional concept of sector used in industrial economics only focusing on firms and their activities in markets. It also studies other agents in addition to firms and both market and non-market interactions. In a sectoral system, agents interact through processes of communication, cooperation, competition and command, and their interactions are shaped by institutions. The notion puts emphasis on the structure of the system in terms of products, agents and networks, knowledge and technologies, as well as institutions, and on its dynamics and transformation. Over time, a sectoral system would change and transform through the interactions and coevolution of its various elements (Malerba, 2002).

The SIS approach adopts the sector in which it is used (including various technologies) as their system boundary, rather than a spatial dimension to define its boundaries, while Pavitt (1984) first suggested that particular sectors have different technological
Pavitt (1984) developed a taxonomy according to the sources of technology, the requirements of users and the appropriability regime. The taxonomy was fourfold:

- **Supplier-dominated sectors** – mostly traditional manufactures such as textiles and agriculture, which rely on outside sources for innovation
- **Scale-intensive** large firms producing basic material and consumer durables such as autos, white goods; sources of innovation are both internal and external to the firm
- **Specialised suppliers** – producing technology to be sold to other firms
- **Science-based** ‘high tech’ goods which rely on in-house and publicly-funded research, e.g. pharmaceuticals

As agents in a sectoral system, governments have great influence on the establishment of most institutions. Institutions encompass norms, routines, shared habits practices, rules, laws, standards, etc., and configure the environment within which agents deploy their activities. Malerba (2002) took the example of a patent system to illustrate that national institutions play an important role in affecting the sectoral patterns of innovation.

There are implications for policymakers from the SIS approach. Exploring the co-evolutionary processes within any technology sector can help to identify the factors that result in successful or failed policy intervention. Moreover, policy measures may not work if they are not specific enough, or do not match sectors’ conditions. Therefore, a comparative analysis of the sectors can be conducted to identify the factors that influence the development of the institutional configuration in relation to the policy intervention.

Although the SIS approach uses some elements which are similar to the TIS approach, such as agents, institutions and mechanisms of interactions, the main reasons that it is not suitable for this research are: the SIS approach defines the system’s boundary with a set of products, and places substantial emphasis on the processes of transformation of the existing system (Malerba, 2002). However, the TIS approach establishes system boundary by technological domain and can focus on new, emerging systems with the ability to develop new business opportunities.
2.2.3 Social-Technical Systems (ST-Systems)

Building on the approach of large technical systems, Geels (2004) considered systems at the sectoral level as socio-technical systems, made up by a cluster of elements, including technology, science, regulation, user practices, markets, cultural meaning, infrastructure, production and supply networks. The elements of socio-technical systems are created, maintained and refined by supply-side actors (firms, research institutes, universities, policymakers) and demand-side actors (users, special-interest groups, media). The linkages between elements are necessary to fulfil societal functions, such as transport, communication and nutrition. The functioning of socio-technical systems involves those social actors or groups interacting and forming networks with mutual dependencies. The inter-group coordination is represented with the concept of socio-technical regimes (Geels, 2007).

In order to observe the change or transition of socio-technical systems, Geels (2004) proposed three interrelated analytical dimensions: (a) socio-technical systems, the tangible elements (artefacts, devices, and infrastructures) needed to fulfil societal functions; (b) actors and social groups who maintain and refine the elements of socio-technical systems, and (c) rules (regimes) that guide perceptions and activities of actors and social groups.

Geels (2004) distinguished formal, normative and cognitive rules. Formal rules are standards, government regulations and so on. Normative rules include identity, behavioural norms, role expectations and so on. Cognitive rules are guiding principles, goals, search heuristics, problem agendas, and rules of thumb. The different rules do not exist individually, but are linked together in semi-coherent sets of rules, called regimes.

The transition theory uses three general levels or perspectives within a system or sector to explain the endogenous and exogenous dynamics of transition: landscape, regime and niche (Geels, 2002). The landscape level (macro-level) describes the pressures on a sector such as legislation, public opinion, the price of inputs and so on. The regime level is the most tangible and identifiable level of the system, which includes the incumbent actors and networks, infrastructure and technology. The socio-technical regime is seen as a coherent, highly interrelated and stable structure at the meso-level. From the evolutionary perspective, a regime represents the selection environment for
technological development in a certain field or sector, thus exerting a significant barrier for radical innovations to diffuse. Radical innovations may still occur, if they are protected by niches from the prevailing selection pressures. The niche level (micro-level) includes radical or disruptive innovations pioneered by actors and networks often characterised as entrepreneurs and small business acting within protected spaces (often called niche markets).

The mechanics of change on the regime are brought about by the combination of actions and pressures from the landscape and niche levels. Landscape level factors can and do change. They may, therefore, exert pressure on the regime. Such forces may weaken and destabilise a regime as they disturb the coherence of its elements. While, under a strong and stable socio-technical regime, radical innovations have a hard time to diffuse beyond the niche-level, they may eventually break through when the regime is weak. Such a transition process, or regime shift, involves changes in technologies and technical artefacts as well as in user practices, policies, markets, industrial structures and supporting infrastructures (Geels, 2002). Through those perspectives, the observed transition pathways of large technical systems have been categorised into four types (Verbong & Geels, 2010), as briefly summarised below.

1. Transformation: external pressure from the landscape is exerted on the regime causing a search for alternatives; however, niche innovations are not developed enough to move beyond formative stages of development. Thus, the regime retains control but they change their trajectory. Radical innovations stay within niches.
2. Reconfiguration: niche-innovations are more developed, regimes struggle under external landscape pressures (perhaps input prices), and begin to adopt certain niche-innovations.
3. Technological substitution: landscape pressures create windows of opportunity for niches. Their accumulation and clustering eventually take over and replace the existing regime.
4. De-alignment and re-alignment: landscape pressures create major problems for regimes that collapse and de-align. There is a period of searching for dominant design with multiple niche experiments, but eventually the whole system is restructured.
The transitions theory tends to emphasise new technology invented and developed in protected spaces on the margin of existing, dominating technical regimes. The new technology may later grow to challenge established practices. However, CCS has emerged from within the existing fossil fuel regime and is promoted, developed and planned for mostly by the incumbents in the electricity generating sector and from the companies that develop and manage oil and gas fields. According to Winskel (2012), as a large-scale technology, drawing partly on components developed from other sectors, fostered largely by regime incumbents, and aimed at adapting rather than replacing existing systems, CCS evidently cannot qualify as a system innovation. CCS has also been considered as an essentially defensive response to the decarbonisation imperative and, therefore, unlikely to be capable of bringing about system change on the scale required (Winskel, 2012).

According to Winskel (2012), constructivist-based system innovation theories, such as transition theory, highlight essential elements for characterising major change in social-technical systems, including radical niche technologies and practices as the source of system-changing innovations, learning processes focusing on interaction among distributed actors over long time periods, the breakdown and replacement of existing organisations and institutions to allow for the diffusion of niche innovations, and moderate policy intervention. These theories generate insights into the interplay of multi-level structures and agents, and the value of diversity and experimentation in early stage innovation. They also provide important lessons on the risks and pitfalls of policymaking for accelerated change. However, Winskel (2012) argues that these theories have put too much emphasis on niche-led disruptive innovation as a primary driver of social-technical system change, whilst having paid insufficient attention to regimes as loci of system change and innovation. The emergence of regime-led innovations such as CCS can facilitate these system innovation approaches to consider their greater involvement in system change given stronger change imperatives and raised policy expectations (Winskel, 2012).

### 2.2.4 A Framework to Compare TIS with SIS and ST-Systems

For the development of technological systems, TIS, SIS and ST-Systems share an emphasis on inter-linkages or interactions between elements, and they all see
innovation as a co-evolutionary process. Comparing the three systems' approaches to innovation and technological change, Coenen and Díaz López (2010) suggest that the common understanding of innovation can be considered a repeatedly interactive learning process within certain social networks (Coenen & Díaz López, 2010). They propose an analytical framework which might be used to compare and contrast any conceptual framework for understanding the innovation process in terms of the assumptions made about: system boundaries, actors and networks, institutions, knowledge, dynamics, and policy approach (Coenen & Díaz López, 2010).

**System Boundaries**

It is important for any analysis seeking to understand a given innovation process or set of processes to draw boundaries around the system under examination. Drawing appropriate boundaries of systems can avoid not only an explosion of possible factors and drivers for innovation, but also isolating systems from their environments (Asheim & Coenen, 2005; Coenen & Díaz López, 2010). Boundaries are drawn in different ways by different authors. Edquist (2005) provides a useful distinction between boundaries drawn on the basis of geography, technological fields, product areas and activities. Coenen and Díaz López (2010) recognise that any such boundary should not be conceptualised in too rigid a way, as every system of innovation will be set within a certain context.

The SIS approach to system boundaries emphasises on products or product-groups so that such systems can involve multiple technologies and are not geographically bounded. However, this framework is only suitable for those systems with ‘given and relatively stable’ components, including firms and institutions, because it sets boundaries on the basis of existing products (Coenen & Díaz López, 2010). The TIS framework is based on technological domains so that such systems may involve different sectors and transcend geographical boundaries. ST-Systems are based on societal functions, often geographically bounded, and may involve various sectors and technologies. Coenen and Díaz López (2010) conclude that the TIS and ST-Systems frameworks are more appropriate for emerging demand and products, as is the case of CCS in this research. System boundaries for this research are set on the basis of the technological domain of CCS and the geography of the UK.
Actors and Networks

Drawing on Edquist (1997), Coenen and Díaz López (2010) then consider the ‘components’ of the system and the relations between them. ‘Components’ refer to the kinds of organisations and institutions within a given innovation system. Based on Liu and White (2001), they add a distinction between primary and secondary actors, where primary actors are directly engaged in innovation activities, while secondary actors such as governmental entities can affect primary actors’ actions and networks. Both the SIS and the TIS approaches tend to provide a firm-centred analysis, while the scope of the ST-Systems approach is much wider. Although the three frameworks adopt similar categorisations of the kinds of actors in the system (universities, public authorities, consumers, suppliers, banks, etc.), they depart from different micro-foundations for organisational behaviour: the SIS and TIS frameworks are more rooted in economics, while the ST-Systems framework is more rooted in sociology. This also influences the way they conceive of change, or the dynamics of innovation systems.

For actors within the CCS system, this research focuses on not only firms, but also other important actors, such as governments, universities, research institutes and industrial associations. However, this research adopts the network concept of SIS and TIS because they focus on the wide range of interaction and cooperation among actors and emphasise the importance of networks for economic exchange and knowledge integration (Coenen & Díaz López, 2010).

Institutions

Systems approaches to innovation attribute an important role to ‘institutions’ of different kinds. They recognise that through actors’ actions (e.g., behaviour and strategy), they can recognise the influences of different institutional patterns, which comprise various laws, rules, norms and routines (Coenen & Díaz López, 2010). According to Coenen and Díaz López (2010), some of the common distinctions made between types of institutions in the literature are between ‘formal’ and ‘informal’ institutions (Edquist & Johnson, 1997), regulatory, normative and cultural-cognitive types of institutions (Scott, 1995), and different levels of institutional structures (Hollingworth, 2000).
For institutional analysis, the ST-Systems approach might be appropriate for the case of CCS system as it has been developed to assess transition to a new system with emphases on social learning and institutional change. This approach elaborates regulative, normative and cognitive institutions, respectively, in different regimes of socio-technical systems, including science, technology, infrastructure, policy, culture and market (Geels, 2004). This approach also points out institutional challenges for transitions such as the development of CCS: path-dependence and lock-in that are created into existing systems, and less articulated and clear-cut rules in technological niches (Geels, 2004). As to the SIS and TIS approaches, they both first determine all relevant institutional elements, and subsequently identify institutional problems that may hinder innovation.

**Knowledge**

For systems approaches to innovation, knowledge and learning are both strategic and fundamental for innovation systems because knowledge evolving through the processes of learning is embodied in actors and their routines. Coenen and Díaz López (2010) distinguish between systems approaches that treat knowledge as a commodity, susceptible to economic exchange (for the SIS and TIS frameworks) and those that pay more attention to knowledge in practice, an ability to act, rather than a good (for the ST-Systems framework). However, knowledge regards the concepts of commodity and learning in this research because knowledge can be packed in patents or business confidentiality with commercial value, while learning through networks or collaborations also generates knowledge.

**Dynamics**

Systems perspectives on innovation offer rich conceptualisations of dynamics, but appear to have quite distinct concerns. The SIS approach sees dynamics in sectoral systems as mainly incremental and step-wise, in the result of the “co-evolutionary processes of their various elements, involving knowledge, technology, actors and institutions” (Coenen & Díaz López, 2010). Innovation processes are considered as
“often path-dependent and, through increasing returns and irreversibilities, susceptible to lock-in” (Coenen & Díaz López, 2010; Malerba, 2002).

The TIS framework is mainly interested in particular emergent technologies that have not yet achieved breakthroughs. Drawing mostly on Hekkert et al. (2007), this approach is concerned with mapping the “various functions and activities” that take place in a given innovation system. The approach offers a taxonomy of functions: entrepreneurial activities, knowledge development, knowledge diffusion through networks, guidance of search, market formation, resource mobilisation and creation of legitimacy, counteracting resistance to change. The idea of functions can be used to describe and explain shifts in technology-specific innovation systems, but also provide a basis for policy intervention correcting weak functions. Hekkert et al. (2007) argue that, since functions influence each other, a virtuous cycle can be created within an innovation system, which, in turn, can create sufficient momentum for discontinuous change.

The ST-systems framework is designed to focus on major technological transitions that involve changes in societal functions such as communication and transportation; to this end, the approach comprises a multi-level analysis (e.g., technological niches, socio-technological regimes, and landscape developments) with seven dimensions in the socio-technical regime (technology, user practices, symbolic meaning of technology, infrastructure, industry structure, policy and techno-scientific knowledge). As a result, this framework requires considerable historical data for proper analysis, and most previous studies tend to apply this approach to transition cases in which the technologies had already been well-developed, commercialised or changed, such as the transition from sailing ships to steamships, 1780-1900 (Geels, 2002), biogas development in Denmark and the Netherlands, 1973-2004 (Raven & Geels, 2010) and a case study of Dutch nuclear energy, 1945-1986 (Geels & Verhees, 2011).

According to Coenen and Díaz López (2010), the ST-Systems framework is primarily geared towards analysing technological transitions while the other frameworks have difficulties in doing so because of “their focus on intra-system drivers, interactions and dynamics”. They also argue that through its distinct use of the niche and regime concepts, the approach has proven a “highly appropriate framework to understand and
explain large-scale and discontinuous changes in socio-technical systems” (Coenen & Díaz López, 2010).

**Policy Approach**

Systems approaches to innovation can contribute to public policy, as they can help correct the classic market failures relating to innovation, but also certain systemic failures (Foxon & Pearson, 2008). Coenen and Díaz López (2010) cite a number of authors who have made a contribution to the identification and removal of systemic failures. Despite differences in intellectual tradition and empirical focus, the three different frameworks provide a complementary mix of policy interventions. The SIS perspective is most concerned with analysing the conditions and the behaviour shaping innovation performance in a sector and the firm is seen as the basic unit responsible for innovation. Public policy is, thus, developed to influence the transformation of sectoral systems, the innovation and diffusion processes, and the competitiveness of firms and countries. Benchmarks are developed as indicators of systemic problems within sectors over time or across different regions or countries. The role of the policymaker is as a facilitator engaging problem solving activities within the relevant policy domain, while the aim is to strengthen sectoral innovation performance. Policymakers actively monitor and intervene in the sector with specific policies for the creation of knowledge, provision of R&D financing, enabling extensive and effective cooperation and networks, improving IPR regimes, facilitating technology transfer, supporting skill formation and public procurement (Coenen & Díaz López, 2010).

The TIS literature, such as Hekkert *et al.* (2007) and Bergek *et al.* (2008), is particularly interested in explaining how intervention can foster and diffuse emerging technologies. Policy is prescribed to address systemic failures based on analysis of the key functions and the identification of weak points. Policy interventions are, thus, justified with reference to a wider set of considerations than is the case in the context of the SIS approach. Interventions are aimed at strengthening weak functions with respect to the phase of the technology life cycle, such as emerging, formative or growth. Policy recommendations are, then, developed on the basis of the identification of inducing and blocking mechanisms, and with reference to the functions of an innovation system. For the TIS approach, government intervention can be categorised
by the system functions: R&D funding and subsidies (for resource mobilisation, entrepreneurial activity, knowledge development and diffusion), demonstration projects (for knowledge development), setting up of non-product related products and process methods and standards (for market formation and guidance), favourable tax regimes (for guidance), or minimal consumption quotas (for market formation), and information campaigns (for the creation of legitimacy) (Coenen & Díaz López, 2010).

The scope of the ST-Systems perspective extends somewhat beyond the traditional territory of innovation, competitiveness, industrial and environmental policy domains. Based on Kemp et al.’s (1998) notion of strategic niche management, the policy approach of the ST-Systems is to set up transition experiments to “enable spaces for learning, institutional adaptation and constituency building” (Coenen & Díaz López, 2010), thus allowing for disruptive innovation that break the lock-in effect. However, authors informed by the ST-Systems perspective also envision other forms of public policy intervention, such as the articulation of expectations and visions, network formation, resource allocation, the facilitation of open-ended leaning processes, as well as support for technology diffusion (Coenen & Díaz López, 2010). Consistent with the much wider vision of the ST-Systems framework, a much wider range of actors is also envisioned and can include wider social movements.

These systems approaches to innovation develop their notions of policy intervention on the basis of their respective emphases: “innovation performance of firms in a sector” (for SIS), “co-evolution and diffusion of emerging technologies” (for TIS) and “fostering a sustainability transition” (for ST-Systems) (Coenen & Díaz López, 2010). Although what each of them stresses for analysing an innovation system might be different, they are all influenced by evolutionary theory with the understanding that a system undergoes change and transformation through the co-evolution of its various elements towards the new technology becoming dominate. The concept of sustainability can be found in the three approaches, as a system requires long-term stable environmental quality and resource availability for its growth, while the ST-systems approach elaborates ‘sustainability transitions’ more explicitly, such as exploring sustainability transitions in the electricity sector with socio-technical pathways (Verbong & Geels, 2010). However, in spite of overlap, the three approaches to policy intervention can be integrated for the analysis of government actions on CCS systems in this research.
Conclusion

For the focuses of the UK Government’s actions on CCS and their effects on CCS innovation, the TIS framework well suits this research mainly because it has suitable advantages with regard to system boundary, actors and networks, knowledge, and policy approach. Moreover, this framework is particularly interested in how government actions influence the development of emerging technologies and provides more consideration to policy interventions than the SIS framework (Coenen & Díaz López, 2010). Through the analyses of system components and functions, the TIS approach can identify emerging uncertainties within an innovation system and can also identify public policies that focus on mitigating the weaknesses of the innovation system to promote the effectiveness and efficiency of innovation diffusion (Lai et al., 2012; van Alphen et al., 2010).

Although the ST-Systems framework provides the most comprehensive understanding of a technological transition and better analysis with regard to institutions and dynamics, the development of CCS in the UK is still in the formative stage and has not existed long enough for the analysis of this framework. Furthermore, the ST-Systems approach focuses on the technological niche, while the UK’s CCS is considered to lack of niche at the current stage because of insufficient market incentive in terms of the niche for carbon storage from CO₂ enhanced oil recovery (Rai et al., 2010).

2.3 System Interactions of TIS with NIS and SIS

Although the TIS theory and its seven function approach have been successfully applied to analyse the development of manifold technologies and to identify system weaknesses for policy improvement, some areas have been suggested for further research to improve the usefulness of the TIS framework for policy in the field of environmental innovations (Jacobsson & Bergek, 2011), including measuring functionality, interaction of TIS with higher system levels, and competence, organisation and politics of policy. Some studies have developed useful methods for measuring functionality, but only a few discuss the interaction of TIS with other
system levels, the effectiveness of governmental action and policy, especially lack of empirical studies in the field of environmental innovations like CCS.

For this research, due to the complexity and wide scope of CCS technologies, the sole, specific focus on CCS TIS might miss important observations from the higher system levels, such as national innovation system (NIS) and sectoral innovation system (SIS). According to Markard and Truffer (2008), the relation among national (NIS), sectoral (SIS) and technological (TIS) systems of innovation can be depicted as in Figure 2-5.

![Figure 2-5: National, Sectoral and Technological Innovation Systems](image)

**Figure 2-5: National, Sectoral and Technological Innovation Systems**

Source: Figure adapted from Markard and Truffer (2008)

The development of CCS in the UK must be affected by the UK’s NIS and the characteristics of the UK’s NIS are important for the performance of CCS development, such as industrial and political patterns. Moreover, CCS originates from several sectors, including fossil fuel power generation, heavy industries, pipeline, and oil and gas industries. The innovation systems of those sectors also affect the development of CCS, such as their original collaborative patterns or networks. Hence, by studying the UK’s CCS TIS and its interactions with the UK’s NIS and those related SISs, including
electricity generation, oil and gas, and steel-making sectors, this research expects to contribute more thorough understanding of TIS formation and development.

Another theoretical contribution this research can make for the TIS approach is to provide a more in-depth analysis on system dynamics, changes and evolution, since the approach encountered criticism that it focuses more on a specific, static moment to identify the system problems, and more on the functioning of systems, such as the element weaknesses, while paying less attention to system changes (Smith et al., 2010). This research, thus, conducts analysis in three periods of the UK’s CCS development, including the virtuous and vicious cycles of system functions in each period, to study the system changes and evolution. Apart from identifying critical functions, this research proposes to prioritise the system functions in each period for government action and policy.
Chapter 3. Methodology

3.1 Introduction

In this research, analysis of the UK’s CCS Industry as a TIS is undertaken by making use of the TIS approach with certain analytical frameworks, including structural and functional analyses. The methods of data collection in this research are expert interview and secondary literature review with aims to analyse the state of development of the UK CCS industry and explore how the innovation system around CCS technologies evolved over time in the UK, including analysis of its interactions with other innovation systems. In addition to expert interviews, the sources of secondary literature review mainly include government documents, trade journals and media. This systems analysis is performed to investigate in more depth where the strengths and weaknesses lie in the UK’s CCS innovation system, including the main drivers of and barriers to the growth, and, particularly, what government actions have affected the development of the UK’s CCS innovation system.

In this chapter, the following Research Paradigm section provides the assumptions of this research regarding ontology and epistemology that resulted in the adopted methodology. The section of Expert Interview Strategy indicates the main source whereby this research obtained the list of candidates for expert interviews, while the next three sections detail the interview questions, the interview analysis and the ethical concerns. Finally, the list of conducted expert interview is provided in Section 3.7, sources of secondary literature are listed in Section 3.8, and a trial patent analysis on CCS is explained in Section 3.9.

3.2 Research Paradigm

Any research involves the adoption of a research paradigm with researchers’ assumptions about how the world is and how to know it, and, thus, the choice of methodology. Denzin and Lincoln (2008) described research paradigm as, “The net that contains the researcher’s epistemological, ontological, and methodological premises may be termed a paradigm [...] All research is interpretive; it is guided by the researcher’s set of beliefs and feelings about the world and how it should be understood
and studied.” In the social world, ontology pertains to the nature and form of social reality, while epistemology refers to the theory of knowledge with focus on the knowledge-gathering process (Blaikie, 2000; Grix, 2002). Methodology is linked to the logical guidance on the process of inquiry with principles and procedures to be followed (Creswell, 1998; Denzin & Lincoln, 1998).

Among post-positivism paradigms, this research adopts the position of critical realism with key assumptions that the real world exists with natural and social objects, while researchers’ knowledge of reality is fallible and the reality cannot be fully captured. Researchers must be critical of the objects being studied in order to explain and understand the social phenomena (Sayer, 1992). Critical realist researchers also tend to explore the mechanisms underlying the social phenomena for better theoretical explanations (Easton, 2010; Lawson, 1997). Adopting a critical realist’s perspective, this research investigated the development of the UK’s CCS innovation system in relation to the Government’s actions with the approach of Technological Innovation System, as the approach provides various angles to assess the development with structural and functional analyses. Moreover, this research collected evidence with expert interviews plus secondary data, including government documents, industrial and academic reports, and news, for more thorough understanding and explanation of the development.

3.3 Expert Interview Strategy

The innovation literature has recognised the importance of using interviews or surveys to understand what experts consider to be significant innovations in a technology area (Archibugi & Pianta, 1996; Cohen & Levin, 1989; Hansen, 1992). For emerging technologies like CCS, expert interviews are often considered an important method of data collection since there are still insufficient secondary data in the fields, such as patent, financial or market data. In this research, expert interviews are conducted to obtain information on the evolution of the UK’s CCS innovation system and, in particular, to identify critical innovations and their relationship with the Government’s actions. In addition, expert interviews are sought in order to obtain insight into the validity of some of the data sources analysed with the other research methods.
In order to gain the most useful expert opinions from the interview process, this research mainly selected potential interviewees from the community network of the UKCCSRC according to their activeness, such as the length of their participation and the frequency with which they presented papers at a conference held by the network. The establishment of the UKCCSRC community network is supported by the UK Government through a £1 million grant from the Research Council’s UK Energy Programme. The UKCCSRC comprises around 400 academic members with CCS interests from various disciplines, including engineering, technology, environment, sociology and economics. There are also over 350 industry, governmental and non-governmental organisation (NGO) stakeholders contributing to this network. UKCCSRC provides an open forum for sharing information and ideas in this emerging field to advance innovation collaboration and rapidly expand CCS R&D in the UK. Thus, the list and contact details of experts were obtained from the office of the UKCCSRC and this research then conducted interviews with 29 experts representing a number of different organisational affiliations, including the government bodies, electricity utilities, fossil fuel companies, equipment suppliers, heavy industries, small/start-up companies, NGOs, industrial lobbies and academic groups.

3.4 Interview Questions

According to the studies of van Alphen et al. (2010) and Lai et al. (2012), in order to identify to what extent the seven functions of innovation systems have been fulfilled through the structure of the systems, semi-structured interviews or a survey of CCS experts can be conducted with a number of indicative questions that provide insight in the fulfilment of the functions as they relate to CCS development. The indicative questions, as shown in Appendix A, were developed by van Alphen et al. (2010), based on the study of Bergek et al. (2008). To further assess the system’s performance, the interviewees were asked to rate their level of satisfaction with the fulfilment of a particular system function on a 5-point Likert scale where 1 = very weak, 2 = weak, 3 = sufficient, 4 = good and 5 = very good. The respondents provided their view on what should be done to improve the fulfilment of those system functions that were seen as impeding a higher performance of the entire CCS innovation system. This provides the basis for advice on policy strategies to enhance the development of CCS (van
Alphen et al., 2010). Based on the analytical scheme of Bergek et al. (2008) and the indicative questions from van Alphen et al. (2010) and Lai et al. (2012), this research developed two sets of interview questions, as described in Section 3.2.

This research conducted expert interviews on a semi-structured basis by asking two sets of open-ended questions with several corresponding prompts. Each expert interview was conducted face-to-face and lasted no longer than one hour. Based on the seven functions of TIS framework, the interview questions were developed and rearranged into two groups. The first group of questions explore how experts and their organisation got involved with CCS. The second set of questions investigates experts’ views on CCS development over time in the UK in terms of technological innovations, supportive resources, and government policy and regulation. The detailed interview questions with prompts are listed below.

Q1. When/How did you or [your company/organisation] get involved in CCS in the first instance? [F4: Guidance; F5: Market formation; F7: Legitimacy]

- What drivers, incentives or pressures, are there for [your company/organisation] to get involved in CCS?
  - Incentives: e.g. public funding, expectations on Feed-in Tariff Contracts for Difference for low carbon electricity or carbon price, enhanced oil recovery.
  - Pressures: e.g. government policy and regulation, competitors, customer interest.

- What is your understanding about the market for CCS in terms of low carbon electricity? What steps need to be taken by the Government for the improvement of the market?

- Are the positions on CCS of you and [your company/organisation] changing over time? How? Do you think any governmental action is related to the changes?

- What is your understanding about the public perception of CCS? Does it affect the positions on CCS of you and [your company/organisation]?
Q2-1. How does [your company/organisation] develop CCS? Do you do your own R&D or collaborate with others? [F2: Knowledge development; F3: Knowledge diffusion through networks]

- What organisations do you or [your company/organisation] work with on CCS? (e.g. universities, research institutes, other companies) On what specific aspect of CCS? With others? How long have you been working together (had you worked together before in another capacity)? How important is the relationship to the development of CCS?
- How does [your company/organisation] deal with the outputs of CCS R&D? Does [your company/organisation] patent R&D outputs?
- How do you or [your company/organisation] link with the wider technical community in CCS? (e.g. government-sponsored network, trade association, academic workshop or conference)
- Do you think the Government-supported technical network - the UK CCS Research Centre Community Network (UKCCSRC) - is useful for you and for technological innovation in CCS? In what way(s)?
- Overall in the UK, do you think there has been progress on CCS over the last 10 years? Which specific aspect of CCS? Which firms have been crucial? Has this progress been facilitated by the Government? Do you think any government actions hindered CCS progress? How and in what aspect?

Q2-2. What is your understanding about CCS pilot or demonstration projects in the UK? [F1: Entrepreneurial activity]

- Do you or [your company/organisation] take part in any of the projects? How? Who with? How long? To what end?
- Do you think the CCS demonstration and commercialisation competition programmes launched by the UK Government are helpful for you and [your company/organisation]? How? (e.g. Front-End Engineering and Design reports from the first competition, sufficient capital investment, supply chain establishment)
• Do you see new firms entering the CCS industry? Which areas of the sector or along the supply chain? Which firms? Which industrial sector are they from?

Q2-3. What is your understanding of supportive resources for CCS in the UK in terms of finance, human and complementary assets? [F6: Resources mobilisation]

• From where do you or [your company/organisation] access financial resources for CCS R&D? (e.g. government funding)
• From where do you or [your company/organisation] obtain financial resources for pilot or demonstration projects? From government or private venture capital or internally funded?
• From where do you or [your company/organisation] find human resources for CCS? (e.g. engineer, manager) Are they sufficient in the UK?
• From where do you or [your company] find complementary products or services for CCS? (e.g. supply chain)
• How could the availability of these supportive resources be improved?

3.5 Interview Analysis

As being developed based on the seven functions of TIS framework, the interview questions cover a wide range of subjects, including technology, innovation, market, industry, network, resources, policy and regulation, as shown in Section 3.4. The questions were designed into two groups: the first group mainly investigates how experts and their companies or organisations got involved with CCS, while the second group probes into how they conduct their R&D on CCS and what their views are on CCS development over time in the UK. In order to conduct the functional analysis more efficiently and effectively, the sub-questions in each group are labelled with corresponding functions of TIS framework. When the interview transcripts were analysed, the answers from the expert interviews for each sub-questions were coded and categorised with corresponding functions. An example of a sub-question in the first group is demonstrated as Table 3-1.
Table 3-1: Example of Interview Transcripts with Functional Labels

<table>
<thead>
<tr>
<th>Expert</th>
<th>Answer</th>
<th>Functional label</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>CO₂ started to come onto our horizon as a company in about 2002, 2003, where it started to become a research priority for the European Commission. [...] The thing that focused our mind most at that time was the research agenda of the European Commission, and at the time they I think were more forward looking on CO₂ than the UK Government were. So one of their research areas at that time was innovative technologies for cost reduction in CO₂ capture, transport and storage. And the first project that we did in that area was funded by a fund called the Research Fund for Coal and Steel, which is a predecessor of the European Union.</td>
<td>F4: Guidance</td>
</tr>
<tr>
<td>S2</td>
<td>BGS has actually been involved in CCS since the early 1990s, we were one of the very first organisations to realise its potential. BGS was the coordinator of the Joule 2 project which was a very famous, ground breaking project for CCS in the mid-1990s, and funded by the Commission of the European Communities and the UK Department of Trade and Industry. Then Statoil started to inject CO₂ at Sleipner in 1996. And from then a whole series of research projects, partly funded by the European Union, partly funded by the industry, were kind of associated with Sleipner.</td>
<td>F4: Guidance</td>
</tr>
</tbody>
</table>

Source: this research

However, in practice, a CCS expert with a certain area of expertise usually cannot answer the whole set of the interview questions comprised of all the functions of the TIS. From the interview experience of this research, some experts tended to answer only those questions that were related to their expertise and talked only about what they were familiar with or had relevant experiences on. However, some experts tended to answer all the questions even though some questions were not related to their expertise or experiences. As a result, some answers would cause biases with the functional analysis. This research thus verified the answers with other literature, such as government documents, industrial reports and news articles, as well as other experts’
opinions. Additionally, in order to reduce the potential biased answers, this research tailored the interview questions to fit each expert’s background and expertise after learning from the first few interviews. For example, some questions that were irrelevant to an expert’s expertise or experience would be eliminated for his/her interview, while the interview questions might also be prioritised with relevance so that the question that was closest to the expert’s expertise would be asked first. Therefore, this research can conduct more effective and less bias analysis with the calibrated questions and the verified answers.

3.6 Ethical Concerns

Ethical issues concerning the interviews were first informed in the approaching letters, as shown in Appendix C, and were mentioned again before the interviews began for obtaining the interviewees’ consent. The expert interviews in this research were conducted under the normal ethical protocols governing university research activities. The identities and responses of the interviewees remain anonymous in any analysis and reporting of this research. The interviews were audio-recorded, and the data are lawfully processed, secured and not kept longer than necessary. In order to collect high quality data, it is important to be as transparent as possible to gain the trust of the interviewees, and to build a rapport with them from the first contacting to the interview and beyond the interview (Ostrander, 1993).

At the beginning of the interview, I reprised the ethical protocols concerning confidentiality and voluntary participation, and had interviewees sign a consent form, as shown in Appendix D. I also informed each interviewee that interview would be analysed along with other interviews of expert stakeholders involved with the UK’s CCS. The analysis would be written up as part of my doctoral thesis and I would also look to use the evidence in forthcoming academic journal articles.

At the end of interview, in addition to expressing my appreciation, I asked each interviewee to recommend any other suitable experts on CCS for my research. I also emailed each interviewee a write-up of the interview and asked them to check whether I had misunderstood or misinterpreted or if they wanted to clarify their positions.
3.7 List of Conducted Expert Interviews

This research approached 52 experts from academia, industry, government and other organisations; eventually, 23 interviews were conducted during March 2013 to August 2014, as shown in Table 3-2, Table 3-3, Table 3-4 and Table 3-5. The contact information was mainly obtained from the UKCCSRC and several industrial collaborative organisations, such as CCSA and APGTF. Snowballing strategy was also used to obtain additional contact information on potential experts. Moreover, this research conducted additional 6 interviews during September 2016 to May 2017 to obtain experts’ opinions from small or start-up companies and environmental NGOs. For the 29 total interviews, 11 experts are from industry (38%), 12 experts are from academia (41%), 4 experts are from government (14%), and 2 are from NGOs (7%).

Table 3-2: List of Interviewed Capture Experts

<table>
<thead>
<tr>
<th>Code</th>
<th>Affiliation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>E.ON New Build &amp; Technology Ltd</td>
<td>Technical Head, Zero Emission Power Plant</td>
</tr>
<tr>
<td>C2</td>
<td>PACT, UKCCSRC</td>
<td>Business Development Manager</td>
</tr>
<tr>
<td>C3</td>
<td>Tata Steel</td>
<td>Head of Climate Change</td>
</tr>
<tr>
<td>C4</td>
<td>International Committee for Non-Destructive Testing</td>
<td>Chairman (Former Director of Technology, Policy Liaison at Doosan Babcock)</td>
</tr>
<tr>
<td>C5</td>
<td>University of Leeds</td>
<td>Professor of High Temperature Combustion Technology, Head of School, Director of PACT</td>
</tr>
<tr>
<td>C6</td>
<td>University of Hull</td>
<td>Senior Lecturer for CCS</td>
</tr>
<tr>
<td>C7</td>
<td>University of Edinburgh</td>
<td>Professor of Power Plant Engineering and Carbon Capture</td>
</tr>
<tr>
<td>C8</td>
<td>Cambridge Carbon Capture</td>
<td>Chief Executive Officer</td>
</tr>
<tr>
<td>C9</td>
<td>WRK Design &amp; Services</td>
<td>Founder and Owner</td>
</tr>
</tbody>
</table>

Source: this research
Table 3-3: List of Interviewed Transport Experts

<table>
<thead>
<tr>
<th>Code</th>
<th>Affiliation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>National Grid</td>
<td>CCS Technical Lead</td>
</tr>
<tr>
<td>T2</td>
<td>Newcastle University</td>
<td>Senior Lecturer for CCS</td>
</tr>
<tr>
<td>T3</td>
<td>Progressive Energy</td>
<td>Engineering Director</td>
</tr>
</tbody>
</table>

Source: this research

Table 3-4: List of Interviewed Storage Experts

<table>
<thead>
<tr>
<th>Code</th>
<th>Affiliation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Durham University</td>
<td>Professor in CCS &amp; Geo-Energy</td>
</tr>
<tr>
<td>S2</td>
<td>British Geological Survey</td>
<td>CCS Team Leader</td>
</tr>
<tr>
<td>S3</td>
<td>Plymouth Marine Laboratory</td>
<td>Marine System Researcher</td>
</tr>
<tr>
<td>S4</td>
<td>University of Edinburgh</td>
<td>Professor of CCS</td>
</tr>
<tr>
<td>S5</td>
<td>Senior CCS Solutions Ltd</td>
<td>Consultant</td>
</tr>
<tr>
<td>S6</td>
<td>Ocean Resource</td>
<td>Chief Executive Officer</td>
</tr>
</tbody>
</table>

Source: this research

Table 3-5: List of Interviewed Other Experts

<table>
<thead>
<tr>
<th>Code</th>
<th>Affiliation</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>O1</td>
<td>Tyndall Centre Manchester</td>
<td>Research Fellow</td>
</tr>
<tr>
<td>O2</td>
<td>North east of England Process Industry Cluster</td>
<td>Technical Manager</td>
</tr>
<tr>
<td>O3</td>
<td>CO₂Chem</td>
<td>Director</td>
</tr>
<tr>
<td>O4</td>
<td>Health and Safety Laboratory</td>
<td>Principal Consultant</td>
</tr>
</tbody>
</table>
3.8 Sources of Secondary Literature

Apart from expert interviews, this research also collects secondary literature for analysis, the main sources of which are listed below.

Research papers:

- Google Scholar

Government reports:

- Gov.uk
- The National Archives
- House of Commons Library
- The UK’s CCS Research Centre
- The Scottish Carbon Capture & Storage
- The Committee on Climate Change
- The UK Energy Research Centre

Industrial journals and reports:

- Carbon Capture & Storage Association
- Advanced Power Generation Technology Forum
- Carbon Capture Journal
3.9 Patent Analysis

In addition to interviews, quantitative methods can complement more information on certain functions, such as patent analysis (Bergek et al., 2008; van Alphen et al., 2010). A patent analysis can determine the development of the CCS knowledge field and identify interrelationships between scientists and inventors from different organisations (F1: Entrepreneurial activity; F2: Knowledge development). The analysis of patent data can be used to identify trends in R&D and the potential for knowledge exchange (F2: Knowledge development; F3: Knowledge diffusion).

For the investigation into knowledge development and diffusion, this research conducted a pilot project of patent analysis of the UK’s CCS and the initial result is shown in Appendix B. However, the result cannot show the exact trend for the technological development because there had not been sufficient patents yet. Moreover, it is common in the UK’s CCS industry that some knowledge is kept as business confidentiality. Although granting a patent ensures exclusive rights to commercialise an invention, patents require full disclosure of technological and design details. Firms thus choose to licence their intellectual properties that are not to be disclosed as business confidentiality or trade secrets by the use of legally binding agreements. Because of those constraints, this research chose not proceed with patent analysis.
Chapter 4. The Performance of the UK CCS Innovation System

For better understanding of the performance of the UK’s CCS innovation system, especially in relation to the influence of the Government actions, this research first lists important actions in three periods, 1990s, 2000 to 2011 and after 2011. Secondly, the structural components of the TIS are identified in terms of its actors, networks and institutions. The analysis of the TIS functions then proceeds with the current status in the system in terms of the seven key aspects and to assess how well the functions work from experts’ perspectives. This research intends to identify mechanisms that drive or impede the development with regard to each function in the TIS and also explore their relationships or interactions with other system levels, such as national innovation system or sectoral innovation system. To this end, key policy issues can be specified in relation to these inducement and blocking mechanisms.

4.1 Evolution of the UK’s CCS Innovation System

This research investigates the evolution of the UK’s CCS innovation system through important actions or events that affect or contribute to its development. These actions or events are chronologically organised into three periods, 1990s, 2000 to 2011 and after 2011. In the 1990s, the UK Government had a less clear position or policy on CCS, but the initial domestic CCS R&D activities were stimulated by forces from outside of the UK. The second period of 2000 to 2011 started with the Government first suggesting CCS to address the problem of climate change, and ended with the failure of the UK’s first CCS demonstration competition. After 2011, the Government reinforced CCS policy with a clearer development roadmap and took further substantial actions, such as the R&D funding programme and the second demonstration and commercialisation competition. When addressing the evolution of UK domestic CCS policy, Littlecott (2012) divided the period of 2004-2012 into three phases: the first phase of 2004-2008 starts with the UK’s initial CCS policy developing within the coal policy of the then Department of Trade and Industry, which was influenced by G8 and EU agreements on requirements for future new coal power plants; the second phase of 2008-2010 represents the era of Ed Miliband, the then Secretary of State for Energy and Climate Change, with a more positive policy context, including
a CCS levy and the first CCS demonstration programme; the third phase of 2010-2012 highlights the new Coalition Government’s austerity and hesitation with CCS, including the ultimate failure of the first demonstration competition and the delay of the CCS roadmap (Littlecott, 2012). These three phases can be considered as the changes of government authorities with respective policy actions and impact; however, the three periods in this research were set with longer time for better observations on the development of TIS, while also being divided with the critical time points for the TIS: CCS’s first appearance in the Government’s official document providing the initial domestic guidance; the failure of the first demonstration programme and the announcement of reinforced CCS policy package aiming for a holistic boost to the TIS.

4.1.1 Period: 1990s

In the period of the 1990s, climate change started to be paid attention by the Government, although there was no clear CCS policy in the UK in spite of the adoption of the Kyoto Protocol in 1997 for reducing greenhouse gases. However, some domestic CCS R&D activities and even international collaboration had begun, mainly due to outside stimuli, such as R&D support from the EU’s Framework Programme and Norway’s carbon tax policy. The early R&D on CO₂ storage by the British Geological Survey was greatly facilitated by both those forces, including the projects of Joule 2 and Saline Aquifer CO₂ Storage with Norwegian oil company, Statoil. Also, because of the Kyoto Protocol and the EU’s R&D priority on CCS, companies in the UK initiated related R&D activities during this period.

In the early 1990s, the European Commission first supported CCS research and development (van den Broek et al., 2010). The Third Framework Programme (1990-94) covered the first CCS activities (mainly CO₂ capture research), and in 1993 a funded study was coordinated by the British Geological Survey (BGS) dealing with the possibilities of underground disposal of CO₂ as part of the Joule II Non-nuclear Energy Research Programme (Holloway, 1996b).

In 1996, the world’s first commercial CO₂ storage project at Sleipner started to operate. The Sleipner gas field is located in the Norwegian sector of the North Sea and is operated by Statoil, while the project injected the separated CO₂ from natural gas into
the Utsira Sand/Formation, a deep saline reservoir 800-1,000 metres below the sea floor (Baklid et al., 1996; Chadwick et al., 2008). To collect relevant information about the injection of CO\textsubscript{2} into the Utsira formation at the Sleipner field and similar underground structures around the North Sea, the Saline Aquifer CO\textsubscript{2} Storage (SACS) Project was established in 1998 and supported under the European Commission’s Fourth Framework Programme; the follow-up SACS2 Project (2000-2002) was also funded under the European Commission’s Fifth Framework Programme (IEA, 2003). Through the two projects, BGS has obtained plenty of experience in the storage of CO\textsubscript{2} in underground saline aquifer formations, and, thus, benefited the UK’s CCS development. More details are elaborated in Section 4.4.2.

4.1.2 Period: 2000 to 2011

In the period of 2000 to 2011, CCS development in the UK started to gain momentum with the Government recognising the critical challenge of climate change and suggesting CCS to reach decarbonisation targets in several Energy Reviews and Energy White Papers. In addition to the Climate Change Act 2008, the Government also took action on CCS domestic and international regulations. Most importantly, the first CCS demonstration competition programme was launched with funding support from the Government to facilitate the technological development, although the competition ended in 2011 with no winner. This section presents below important activities, events or actions that influenced the development of CCS TIS in the UK during the period of 2000 to 2011.

The report, Energy: The Changing Climate, published by the Royal Commission on Environmental Pollution in 2000 recognised climate change as a ‘radical challenge’ and considered CCS as one of significant options for a 60 per cent CO\textsubscript{2} emissions reduction by 2050 (RCEP, 2000). In the 2002 Energy Review from the UK Cabinet Office’s Performance and Innovation Unit, CCS was also identified as a significant option for carbon abatement, while it noted that CCS faced major uncertainties regarding cost/investor acceptability, safety/environmental impact and public acceptability (PIU, 2002). Moreover, an energy system modelling study for the UK’s long-term low carbon energy options, undertaken by AEA Technology and Imperial College and presented by the DTI in 2002, suggested the role of CCS in the UK energy
mix, and thus affected later energy planning and policy making, especially for the ‘Carbon Capture Ready’ regulation (DTI, 2003; DTI, 2005).

In 2003, the UK Government’s Energy White Paper accepted the need for long-term targets for CO₂ emissions reductions, while CCS with EOR was mentioned yet seen as only a less important role in UK energy futures compared to renewable energy (DTI, 2003). However, given the “potentially significant strategic role that might be played by CCS in longer-term energy security” here was a promise in this White Paper to “set up an urgent detailed implementation plan … to establish what needs to be done to get a demonstration project off the ground … [using] funding from international sources” (DTI, 2003).

In 2005, the Intergovernmental Panel on Climate Change (IPCC) published an IPCC Special Report on CCS (IPCC, 2005) and judged CCS to be a technically feasible method of securing up to half of all cumulative CO₂ mitigation worldwide until 2100. While acknowledging significant economic and other uncertainties, the Special Report also identified the prospect of substantial cost reductions in CCS costs over the coming decade (IPCC, 2005). The Special Report, including a summary for policymakers and a technical summary, was considered an important assessment for CCS development (DTI, 2005).

The UK Government’s 2005 strategy report on Carbon Abatement Technologies concluded that, on the basis of energy system modelling commissioned by government, CCS was cost competitive with nuclear power and most renewable technologies, other than onshore wind (DTI, 2005). The Department of Trade and Industry (DTI) further launched a Coal Forum in 2006 with a remit to ‘find solutions to secure the long-term future of coal-fired power generation and UK coal production’ (DTI, 2006), and efforts to promote CCS were stepped up.

In 2006, the London Convention and Protocol Contracting Parties adopted amendments to Annex I of the Protocol to regulate carbon capture and sequestration in sub-sea geological formations (CCS-SSGF) (IMO, 2006). These amendments created a legal basis in international environmental law to regulate CCS-SSGF for permanent isolation and, therefore, were included in the EU’s CCS Directive on the geological storage of carbon dioxide (EC, 2009).
In June 2006 The Chancellor and the Norwegian Prime Minister announced a joint project on enabling CCS in the North Sea. This included an examination of the likely need for a physical infrastructure of pipelines, the advantages of and barriers to the development of such a potential network, and ways in which the benefits of CCS could be realised in the most efficient and cost-effective way. The project also examined aspects of the international regulatory regime, including the rules for CCS in the EU Emissions Trading Scheme (DTI, 2006).

While the 2006 Energy Review questioned the economic and commercial feasibility of CCS, the Government considered that ‘CCS has great potential as a means of reducing global carbon emissions’ and that the UK has some natural and commercial advantages in developing CCS, because of the skills to be found within its well-established oil and gas industries, and the role that oil and gas fields in the North Sea might play in CCS storage (DTI, 2006). In addition, a CCS Regulatory Task Force was established with membership from across the Government to develop proposals for new regulation as required in the following areas: the licensing of carbon dioxide storage sites and activities offshore; decommissioning and long-term liabilities associated with storage facilities; and licensing and regulation of onshore facilities, including carbon capture, transport and storage and “capture-ready” plant (DTI, 2006).

In the 2007 Energy White Paper, the Government continued supporting the development of CCS, including the regulatory frameworks, international collaborations, and demonstration programme. However, the Government remained conservative toward the commercial viability of CCS in the UK by judging that for the UK up to 2030, nuclear and renewables would be more likely to come forward unless the cost of CCS fell substantially (DTI, 2007).

In November 2007, the then Department for Business, Enterprise and Regulatory Reform launched the first competition programme for industry to run a project to design, construct and operate the UK’s first commercial-scale CCS demonstration project at a coal-fired power station, by 2014, with government funding (NAO, 2012). The key actions regarding the first demonstration programme are highlighted below.

- In March 2008 nine bidders came forward for pre-qualification for the first CCS demonstration competition programme.


In November 2009, two bidders (E.ON and ScottishPower) submitted outline solutions while the Peel Consortium withdrew from the competition.

On 12th March, 2010, the front-end engineering and design (FEED) contracts were awarded to E.ON for £12 million and the ScottishPower consortium for £30 million to carry out detailed technical studies to reduce uncertainties in proposed solutions (NAO, 2012).

On 20th October, 2010, E.ON withdrew from the competition as its proposed Kingsnorth project cannot meet the competition timescales (NAO, 2012).

In October 2010, the Government reached a decision on affordability for the first demonstration project in the Spending Review. It decided that the project would be funded with up to £1 billion of capital investment from direct taxation and not through a levy (NAO, 2012).

11th February, 2011 – 19th October, 2011, the last remaining bidder in the first competition, the ScottishPower consortium, submitted the detailed solution and negotiated the contract with the Government.

On 19th October, 2011, the Government terminated negotiations with the ScottishPower consortium as the Government considered it could not agree a deal that would represent value for money (NAO, 2012). The first CCS competition ended without any winner.
On 26th November, 2008, the Climate Change Act 2008 became law. The Act makes it the duty of the Secretary of State to ensure that the net UK carbon account for all six Kyoto greenhouse gases for the year 2050 is at least 80 per cent lower than the 1990 baseline, toward avoiding dangerous climate change. The Act aims to enable the UK to become a low-carbon economy and gives ministers powers to introduce the measures necessary to achieve a range of greenhouse gas reduction targets. An independent Committee on Climate Change has been created under the Act to provide advice to the UK Government on these targets and related policies.

The EU’s CCS Directive (Directive 2009/31/EC), which came into force on 25th June, 2009, builds a legal framework for the environmentally safe geological storage of carbon dioxide with requirements for storage covering the entire lifetime of a storage site with focus on selection of storage sites, exploration permits, storage permits with operation, closure and post-closure obligations and provision for transfer of responsibility (EC, 2009). The UK implements the CCS Directive mainly through the Energy Act 2008 (Chapter 3), which introduces a regulatory framework to facilitate the offshore storage of carbon dioxide (UK HC, 2008).

In November 2009, the UK Government set out its decision on what ‘Carbon Capture Ready’ is to mean in the UK (DECC, 2009). The criteria include demonstration of the technical feasibility of CO2 transport and retrofitting capture technology, the economic feasibility of future full chain CCS operations, the identification of suitable area for storage, and the availability of space on site for capture equipment. Consented plants will be required to retain the space on site as well as to report regularly to the regulator on the technical feasibility of retrofitting capture technology.

In the UK Energy Act 2010, the Government introduced a levy on electricity suppliers which would be managed by the Office of Gas and Electricity Markets to provide a financial incentive to support CCS demonstration projects at coal-fired power stations (HM Government, 2010a). However, in March 2011, the new Coalition Government announced that it would not proceed with the levy as a method of funding the demonstration plants, and would instead fund the demonstrations from general taxation (HM Treasury, 2011).
4.1.3 **Period: After 2011**

Although the failure of the first CCS demonstration competition resulted in the vacillation of the UK’s CCS development, the Government promptly assured the clear position on CCS in 2012 and reinforced CCS policy with the announcement of the UK’s CCS Roadmap, including the second commercialisation competition and a £125m R&D funding programme. Two preferred bidders, the Peterhead CCS Project and the White Rose CCS Project, were selected and funded for FEED studies in the second competition whilst the £125m funding programme has supported around 100 CCS R&D projects, including the establishment of the UK CCS Research Centre to coordinate the knowledge sharing and diffusing network. However, the sudden turn of CCS policy with the cancellation of the £1billion capital investment for the two commercialisation project on 25th November, 2015 has again damaged CCS development in the UK.

The Government published the CCS Roadmap in April 2012 along with a policy package setting out how to achieve the goal of seeing commercial deployment of CCS in the UK in the 2020s, including five key government actions (DECC, 2012):

- A CCS Commercialisation Programme with £1 billion in capital funding
- A £125m, 4-year, co-ordinated R&D and innovation programme and establishing a new UK CCS Research Centre
- Development of a market for low carbon electricity through Electricity Market Reform (EMR), including availability of Feed-in Tariff Contracts for Difference for CCS low carbon electricity
- Intervention to address key barriers to the deployment of CCS
- International engagement focused on sharing the knowledge to help accelerate cost reduction

In April 2012, the Government opened the second CCS commercialisation competition. The competition closed to bids in July 2012 and four full chain projects were shortlisted in October 2012, including the Peterhead CCS Project, the White Rose CCS Project, the Captain Clean Energy Project and the Teesside Low Carbon Project. The follow-up actions regarding the second competition programme are highlighted below (NAO, 2017).

On 9th December, 2013, the Government announced that it intends to award a multi-million pound contract for detailed design and planning, known as a FEED study, to Capture Power Limited for the White Rose CCS Project, which includes the Yorkshire-Humber CCS Trunkline, a CO\(_2\) transportation and storage solution to be undertaken by National Grid Carbon Limited.

On 24th February, 2014, the Government announced FEED study funding for the Peterhead CCS Project (Shell and SSE), as part of the CCS Commercialisation Competition.

On 25th September, 2015, Drax announced that it would withdraw as a partner of Capture Power Ltd, the developer of the White Rose CCS Project, and would not continue to invest once its current CCS FEED project is completed.

On 25th November, 2015, the UK Government cancelled the £1billion capital fund for the two CCS commercialisation projects from the second competition programme.

4.2 The Structure of the UK’s CCS Innovation System

The structure of the innovation system consists of innovation system components, including actors, institutions, networks and technological factors (Hekkert et al., 2011), as shown in Figure 4-1. Actors involve knowledge institutes (research), educational organisations, industry (supply), market actors (demand), government bodies and supportive organisations. It is the actors of a TIS that contribute to the generation, diffusion and utilisation of the technology. The development of a TIS also depends on the interrelations and interactions among all actors, resulting in networks. Institutions include formal institutions such as rules that are codified and enforced by authorities,
and informal institutions that are more tacit and organically shaped by the collective interaction of actors. Technological factors consist of artefacts and the technological infrastructures in which they are integrated.

**Figure 4-1: Structure of the innovation system**

Source: Figure adapted from Hekkert *et al.* (2011)

**Actors**

In the UK’s CCS TIS, universities usually provide both research and education, including important participants such as Cambridge, Cranfield, Durham, Edinburgh, Imperial College, Leeds, Newcastle, Nottingham and Sheffield. Research institutes include The British Geological Survey (BGS), Energy Technologies Institute (ETI), Plymouth Marine Laboratory (PML), UK CCS Research Centre (UKCCSRC), UK Energy Research Centre (UKERC) and Scottish Carbon Capture and Storage (SCCS). Government bodies involve in CCS include Department of Energy and Climate Change (DECC), Department for Business, Innovation & Skills (DBIS), Engineering and Physical Sciences Research Council (EPSRC), Technology Strategy Board (TSB), Department for Environment, Food and Rural Affairs (DEFRA), Environmental
Agency, Department of Treasury, National Audit Office, Health and Safety Laboratory and UK Trade and Investment (UKTI). Non-department government entities, including The Crown Estate and Scottish Enterprise also participate in the CCS development.

- **DECC**: the main government body developing CCS policy, such as CCS roadmap, R&D funding, demonstration and commercialisation programme, and Electricity Market Reform (EMR).
- **BIS**: supports the development of emerging technologies like CCS for the UK to gain competitive advantage, such as industrial CCS policy development.
- **EPSRC**: funds the research and development of CCS, doctoral training programmes and UKCCSRC.
- **TSB**: supports and invests in the UK’s energy sector for CCS innovation.
- **DEFRA**: assess the environmental impact or risks of CCS deployment.
- **Environmental Agency**: regulates the environment impact of CCS, issues an EU Emissions Trading Scheme (EU ETS) permit to power stations and energy intensive industrial installations that emit CO₂ and advises the Government on new applications to build power stations to ensure that they are ‘Carbon Capture Ready’ and could install CCS at a later date.
- **Department of Treasury**: assess the costs of CCS development, especially for infrastructure and capital investment for the demonstration and commercialisation competition programme, and draws up a budget for public spending on CCS.
- **National Audit Office**: scrutinises public spending on CCS and especially reported on the competition, cancelled in October 2011, to design, construct and operate the UK’s first commercial-scale CCS project.
- **Health and Safety Laboratory**: investigates health and safety issues of CCS working environment, especially for the transport and storage of high pressure CO₂.
- **UKTI**: seeks business opportunities for the UK’s CCS industry to transfer knowledge and experience such as the collaboration with China.
- **The Crown Estate**: holds the rights for CO₂ storage on the UK continental shelf, and investigates the ways that competitive access to offshore storage
sites/rights can be provided to deliver optimal outcomes for the CCS sector and deployment of infrastructure.

- Scottish Enterprise: Scotland's main economic development agency, promotes and develops sectors involved in low-carbon technologies including CCS.

In addition, the Committee on Climate Change (CCC) is an independent but statutory body created under the Climate Change Act 2008 to advise the UK Government on greenhouse gas emissions reduction targets and preparation for climate change. The CCC has made recommendations that new coal-fired power stations should be fitted with CCS and gas CCS should be included in the demonstration programme.

Industrial actors cover overall CCS value chain, including fossil fuel power plants and other industrial sources, capture, transport and storage companies, developers and investors, and equipment suppliers.

- Electricity companies: E.ON, SSE, RWE, EDF, Drax Power and Progressive Energy.
- Capture companies: Doosan Babcock, Alstom, BOC, Aker, Siemens and Mitsubishi Heavy Industries.
- Transport companies: National Grid and AMEC.
- Storage companies: Shell, BP, CO₂ DeepStore, Petrofac and Statoil.
- Industrial clusters: Yorkshire and Humber, Teesside.
- Developers and investors: Capture Power (White Rose CCS Project), 2Coenergy (Don Valley CCS Project), Tees Valley Unlimited.

**Networks**

Various networks exist in the UK’s CCS TIS and each has its own feature and specific function. Apart from research institutes like the UK’s CCS Research Centre (UKCCSRC), industry-led networks have also been established, including Advanced Power Generation Technology Forum (APGTF) and Carbon Capture and Storage Association (CCSA). APGTF was formed in 1999 by the power generation sector in the UK with a focus for R&D activities on emissions abatement technologies, especially for CCS, and has held numbers of workshops for knowledge sharing on
CCS innovation. APGTF has also published a range of reports on carbon abatement technology and CCS since 2000, such as the reports of Cleaner Fossil Power Generation in the 21st Century (APGTF, 2009, 2011 & 2014). Launched in 2006, CCSA comprises not only the power generation sector, but the whole value chain of CCS, including companies in manufacturing and processing, engineering and contracting as well as support services to CCS such as law, banking, consultancy and project management. CCSA represents the interests of its members in promoting the business of CCS rather than the technical part, and works closely with the UK Government and European Commission in developing an appropriate regulatory framework for CCS, as well as an incentive framework through the Electricity Market Reform to provide sufficient financial resources for CCS demonstration and commercialisation projects (CCSA, 2012).

In addition to intangible networks, CO₂ transport networks are also crucial for the UK’s CCS development as emitters, including power plants and industrial facilities in certain regions can share pipeline infrastructure, such as Yorkshire/Humber CCS network and Tees Valley industrial CCS network. As part of the White Rose project, the Yorkshire Humber CCS Trunkline project developed by National Grid comprises the construction of a Cross Country Pipeline and sub-sea pipeline for transporting CO₂ captured from power and industrial sectors in the region to a permanent geological storage site beneath the North Sea (National Grid, 2013). The 75km onshore pipeline will be routed from the proposed White Rose CCS Project (Drax, North Yorkshire) via proposed multi-junction at Camblesforth (North Yorkshire) to a landfall point near Barmston (East Riding of Yorkshire). National Grid Carbon Limited also collaborates with 2CO Power Limited on the Don Valley Power Project to provide the pipeline which will transport CO₂ from the plant to the North Sea (National Grid, 2013).

Moreover, according to the report of Yorkshire and Humber CCS Cross Country Pipeline (National Grid, 2013), the region contains some other large CO₂ emitters that can utilise the regional CO₂ transport system, and these emitters are located in two principal clusters: the Aire Valley and the South Humber Bank. The project application was submitted by National Grid in 2014 to the Planning Inspectorate, the government body responsible for assessing major infrastructure applications. However, the Government refused the development consent for this project in January 2017, mainly because the second competition programme was cancelled, while the pipeline was part
of the White Rose Project, one of the preferred bidders for the second competition, and thus the development was weakened (DBEIS, 2017a).

Another pipeline network is the Teesside Low Carbon Project, which was launched in 2012 and proposed to develop CCS infrastructure for key power and industrial emitters of CO₂ in Teesside. The integrated pipeline network was developed by National Grid Carbon for CO₂ transportation to a depleted oil field in the central North Sea where it will be injected for permanent storage (BOC, 2012). This project was led by a consortium formed of BOC, International Power, National Grid, Fairfield Energy, Premier Oil and Progressive Energy (BOC, 2012). The project applied for the UK’s second competition programme, but was not chosen as one of the final two bidders and placed on the reserve list (DECC, 2013a). However, the region’s industry regrouped and launched a new project, Teesside Collective, for CCS development in January 2015. The new project is led by Tees Valley Combined Authority and the Tees Valley Local Enterprise Partnership, working with major companies in the region, including BOC, Lotte Chemical, GrowHow and SSI UK, along with the North East of England Process Industry Cluster (NEPIC), a local existing cluster company created and owned by its member companies to represent the companies and supply chain of the Process Industry in the region. With the Government’s funding support, Teesside Collective published the Blueprint for Industrial Carbon Capture and Storage in the UK, expecting the project to be operational from 2024 (Teeside Collective, 2015a). Although one of the key members, SSI UK, closed down in October 2015, Teesside Collective was determined to proceed with the project with the addition of another major industrial company, Sembcorp Utilities UK (Teeside Collective, 2015b).

In addition, in terms of industrial CCS, Expert C3 stressed the necessity of the Government’s support for the establishment of CCS clusters so that CO₂ transport can be economically feasible, as follows.

“For the steel industry in the UK, at the moment, the most important thing that needs to happen is that clusters come into existence, because […] an individual steel plant can’t consider setting up a pipeline just for itself to another new store in the North Sea, or something. That’s just never going to be economically feasible. So, for the government to encourage the development of clusters around a right sized, oversized, whatever we want to call it, pipeline
that’s capable of taking CO₂ from a number of power stations/industries is really important, because without that sort of infrastructure it’s very, very doubtful that a steel company would be able to implement CO₂ capture.”

(Expert C3)

**Institutions**


**Carbon Capture Ready**

‘Carbon Capture Ready’ (CCR) has been used as a regulatory requirement in the UK since at least 2006, mainly requiring any new fossil-fuelled power station to set suitable space aside for the future retrofit of carbon capture equipment; however, its criterion was not clearly defined and not implemented in a consistent manner (Markusson & Haszeldine, 2010). In order to comply with EU policy on a minimum requirement for CCR, in November 2009 the Government announced its decision on a more detailed definition of CCR, including demonstration of the availability of sufficient space on site for capture equipment in the future, the technical feasibility of CO₂ transport and retrofitting capture technology, the identification of suitable area for storage, and the economic feasibility of future full chain CCS operations (DECC, 2009). However, Markusson and Haszeldine (2010) indicated that the CCR regulation still lacks consideration for ‘core power generation technology, downstream transport and storage, system integration, and future retrofitting requirements’. With serious uncertainties, CCR cannot guarantee the abatability of new-built fossil-fuelled power plants and, hence, is considered as an ineffective regulatory strategy (Markusson & Haszeldine, 2010).
Emissions Performance Standard

In July 2011, the Government proposed a regulation of emissions performance standard (EPS) that set at an annual limit of CO₂ equivalent to 450g/kWh (at baseload) to reinforce the requirement that no new coal-fired power stations are built without CCS (DECC, 2011b). This mandatory EPS was considered as the most straightforward way of introducing CCS and likely to reduce investment uncertainty and stimulate the innovation of CCS technologies with additional complementary support or incentives (Stechow et al., 2011). This kind of command-and-control instrument has been proved as a strong stimulant to some developments of environmentally friendly technologies, such as the FGD technology for SO₂ emission control (Popp, 2003; Taylor et al., 2003). The EPS regulation was officially introduced in the Energy Act 2013 and would be reviewed by the Government on a three yearly basis (DECC, 2015b).

Feed-in Tariff Contracts for Difference

In order to encourage investments in CCS projects, the Government has been developing a scheme of feed-in tariffs (FITs) combined with contract-for-differences (CfD) for low carbon electricity through Electricity Market Reform (EMR), including CCS. This scheme guarantees the price received by the generators if the wholesale electricity price is below an agreed level. The greater revenue certainty provided by the FITs CfD scheme can lead to developers being able to reduce the costs of financing their investments (DECC, 2012; ERF & ETI, 2013).

Carbon Floor Price

In order to drive investment in low-carbon power generation, the UK Government introduced the carbon floor price in April 2013 to levy a top-up carbon price support (CPS) tax for CO₂ emissions from fossil fuels power generators (Sandbag, 2013). The initial top-up rate for 2013-14, announced in 2011, is £4.94/tCO₂. The carbon floor price is made up of the price of CO₂ from the EU Emissions Trading System (EU ETS) and the CPS rate per tCO₂ which is the UK-only additional tCO₂ emitted in the power sector (Sandbag, 2013).
4.3 The UK’s CCS System Functions

Based on key findings from the conducted interviews, four biannual meetings of UKCCSRC, and secondary review of government documents, trade journals and media, this research developed an analysis of seven functions for the UK’s CCS innovation system in this section. The UKCCSRC’s meetings include 19th-20th September, 2012 at Durham University, 8th-9th April, 2013 at the University of Sheffield, 2nd-3rd April, 2014 at the University of Cambridge and 13th-14th April, 2016 at the University of Manchester.

4.3.1 The Function of Entrepreneurial Activity

According to Hekkert and Negro (2011), entrepreneurs are an absolute necessity in the formation of any innovation systems, and are important actors to take potential business opportunities by bringing new knowledge of technology or service into actions. Entrepreneurs are considered “either new entrants that have the vision of business opportunities in new markets, or incumbent companies who diversify their business strategy to take advantage of new developments (Hekkert & Negro, 2011).” Bergek et al. (2008) also stress that the notion of entrepreneurial function does not refer only to new or small firms, but also to large, established companies that diversify into new technologies as long as they make new combinations of existing elements or resources, including a new quality or use of a good, a new production method, a new market and a new form of organisation, according to Schumpeter’s formulation (Schumpeter, 1934). Entrepreneurial activities that engage in new technologies and applications can reduce the uncertainties impeding the development of a technological innovation system. They can be observed as a social learning process in which some survive whilst many are eliminated (Kemp et al., 1998). This research investigates the functional performance by probing into the status of the entrepreneurial activity emerging in the TIS of CCS.

According to interviewed experts C1, C3, C4, C5, T1, T3 and S2, many CCS entrepreneurs come from the original sectors or industries such as fossil fuel power plants, electricity companies, oil and gas companies, as well as other heavy industrial firms. They commonly started their own R&D in the early stage, then sought
collaborations or participated in demonstration and commercialisation projects. As Expert C4 mentioned,

“We both did it [R&D] ourselves, where the work was going to be confidential or sometimes where it was early work before you could really find any partners. And, we collaborated whenever it was beneficial. It could be beneficial because sharing technical knowledge with another expert company, or sometimes collaboration, is a condition to gain funding. So sometimes, quite cynically, if we want funding we have to collaborate. If you find somebody else who wants funding, they have to collaborate and you work together.”

(Expert C4)

According to Expert C4, entrepreneurial activities on CO₂ capture technology started from early 1990s in the UK as CO₂ emissions agenda became a risk to the main business of coal power plant companies such as Doosan Babcock. Doosan Babcock started its own CCS R&D on oxy-fuel and gradually with post-combustion as well. After the early stage, the company sought beneficial collaborations for funding and knowledge sharing. For small-scale pilots, including 5, 10 and even 40 megawatts (MW), Doosan Babcock had two projects: the CCPilot100+ Project at SSE’s Ferrybridge power station in West Yorkshire and the Oxycoal 2 Project at Doosan Power System’s Clean Combustion Test Facility in Renfrew, Scotland. For larger scale demonstration projects such as 250 or 400 MW, Doosan Babcock has tried to take part in many and was pre-selected to bid for numerous projects, such as Kingsnorth, Hunterston and Peterhead.

Expert C1, the technical head of a coal-fired power plant, also recalled that their company started their own CCS R&D with a small scale oxy-fuel CO₂ capture combustion project in 2003 when CCS became a research priority for the European Commission. As the power plant was operated by an international energy company, the number of their CCS projects later increased to three, including one for pre-combustion capture and two for post-combustion capture, while the projects were internationally coordinated and managed by an international team within the company.

Apart from entrepreneurial activities in existing large companies, new start-up or small firms also engage in the TIS with financial support from the public sector, such as
Innovate UK (formerly Technology Strategy Board), as well as the private sector, such as the Carbon Trust and Shell’s Springboard programme for low-carbon innovation. For example, Expert C9, a founder and owner of a small chemical engineering design and services company, started their CO$_2$ capture R&D with funding from the Technology Strategy Board in 2011. The small company was established in 2002 with their core technology, the Downflow Gas Contactor Reactor, an efficient mass-transfer device for the process industries while they intended to expand the proprietary technology to CO$_2$ capture through the TSB-funded project, Entrapment of Carbon Dioxide for Reuse.

In order to catalyse industrial and academic R&D, the government has supported the establishment of the Pilot-Scale Advanced Capture Technology (PACT) facilities since 2012. The Core Facilities of PACT at Beighton, Sheffield are jointly established and operated by the Universities of Leeds and Sheffield, with three other satellite facilities established and operated by the University of Nottingham, the University of Edinburgh and Cranfield University respectively at their locations. The R&D capabilities of each PACT site are outlined in Table 4-1. According to Expert C2, both academia and industry have utilised the PACT facilities for small-scale CCS R&D including combustion research, chemical looping, industrial carbon capture and CO$_2$ transport.

**Table 4-1: PACT Facilities Sites and Capability**

<table>
<thead>
<tr>
<th>PACT sites</th>
<th>Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Facilities at Beighton, Sheffield</td>
<td>• 1 tCO$_2$/day Solvent-Based Capture Plant</td>
</tr>
<tr>
<td></td>
<td>• 250 kW air/oxy combustion rig for coal/biomass</td>
</tr>
<tr>
<td></td>
<td>• 330 kW Gas CHP Turbines</td>
</tr>
<tr>
<td></td>
<td>• Gas Mixing Facility: synthetic/modulated flue/industrial process gas</td>
</tr>
<tr>
<td></td>
<td>• Online Monitoring and analytical facilities</td>
</tr>
<tr>
<td>Nottingham Facilities</td>
<td>• Solvent analysis</td>
</tr>
<tr>
<td></td>
<td>• Thermal analysis</td>
</tr>
<tr>
<td></td>
<td>• Spectrometry and spectroscopy</td>
</tr>
<tr>
<td></td>
<td>• Modular 800C, 100bar flow reactor</td>
</tr>
<tr>
<td></td>
<td>• Milling equipment with powders analysis</td>
</tr>
<tr>
<td>Edinburgh Facilities</td>
<td>● Transportable Mini-Lab for onsite, long-term capture media testing under real operating conditions</td>
</tr>
<tr>
<td>----------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Cranfield Facilities | ● 150kW PF Air/Oxy Rig  
               ● CO₂ Transport Flow Rig  
               ● 50kW Chemical Looping Facility  
               ● 750kW Gas Turbine Burner with deposition probes  
               ● 300kW Circulating Fluidised Bed Combustor/Gasifier |

Source: the PACT’s website and Expert C2

Nevertheless, several respondents from the expert interviews of this research, including Expert C1, C4 and T3 from large firms, Expert C8 and C9 from small or start-up firms, as well as Expert C5, C6 and S1 from academia, argued that CCS entrepreneurial activities in the UK are still insufficient, especially for lack of test at a meaningful and full chain scale. The unsuccessful first demonstration competition, the delay of the competition programme and the reduced number of demonstration and commercialisation projects all weakened the function of entrepreneurial activity.

4.3.2 The Function of Knowledge Development

Knowledge development through mechanisms of learning is at the core of any innovation systems and encompasses ‘learning by searching’ and ‘learning by doing’ (Hekkert & Negro, 2011). Bergek et al., (2008) suggest that the types of knowledge range from scientific, technological, production and market to design knowledge, while the sources of knowledge include R&D, learning from new production or applications, and imitation. The performance of this function can thus be measured by a range of indicators, such as number, size and orientation of R&D projects; number of patents; assessments by experts (Bergek et al., 2008).

Knowledge development of CCS technology has grown and accumulated since the entrepreneurial activities emerged and the basic research continued. As mentioned in the function of Entrepreneurial Activity, knowledge and experience can be produced
from in-house R&D projects, as well as collaborative R&D projects. Regarding the R&D output, Expert C3 from a steel company explained,

“We would write the internal reports for use within the company, and with our partners, especially in Europe, reports that are available, because they’ve been European funded, so they have to be available, we also write research papers for academic journals. Then we will make patent decisions as we go along. And in terms of CCS, at the moment, we haven’t done any patenting. The patenting has really been around the new iron making technologies that CCS would be applied to. We make the decision about patenting with CCS as we do more pilot, and demonstration work […]”

(Expert C3)

In addition, the Government’s £125m 4-year CCS R&D and innovation programme was considered as one of major drives to the knowledge development, including £55 million to support fundamental research and understanding, £27 million to support the development and demonstration of CCS components and next generation technologies (such as turbines or new solvents to capture the carbon dioxide) and £43 million for pilot scale projects to bridge the gap between research and commercial scale deployment. In total, around 100 separate projects are funded through this programme. The government funded CCS R&D programme has benefited the knowledge development of CCS due to its wide coverage of a full CCS system (DECC, 2013b).

In order to test the technology and obtain further practical knowledge, several CCS pilot, demonstration or commercialisation projects were created in the UK. According to Expert C4, CCS pilot projects are considered as power plants with CCS capacity below 40 MW and important projects in the UK include Aberthaw Pilot Plant, Ferrybridge CCPilot100+ and Renfrew Oxycoal2. The details of these pilot projects are shown in Appendix F.

The demonstration and commercialisation projects from the first and second competition programmes were considered another important drive to knowledge development, which began with Front-End Engineering and Design (FEED) studies. The FEED study includes knowledge areas such as project design, technical design, health and safety, environment, consents and project management. The Government
funded the preferred bidders from the first and second competition programmes to undertake FEED studies so that the produced knowledge can be learnt and help to reduce the costs of future engineering and design work. For the first competition programme, two FEED studies were completed in 2011 respectively by the Kingsnorth CCS project and the Longannet CCS project. For the second competition, the White Rose CCS Project and the Peterhead CCS Project also completed the FEED reports as Key Knowledge Deliverables, which have been published by the Government in June 2016 (DECC, 2016a).

Although the FEED reports should have been helpful, Expert C1 who took part in one of the FEED studies from the first competition indicated that the result might not be as much as expected by the Government because some areas were still kept as business secrets by technology suppliers. For example, in the FEED report of the Kingsnorth CCS project, the section of CO\(_2\) Capture Unit - Major Component Equipment List for CO\(_2\) Recovery Plant presents several grey areas as Mitsubishi Heavy Industries’ confidential information, such as the material of construction, the pressure and temperature conditions for the CO\(_2\) absorber (DECC, 2011a). The problem of developed but closed knowledge would be further discussed in Section 4.3.3 as it relates to knowledge diffusion.

The increase of patent numbers is seen as an important indicator for the growth of technological development. Expert C5, a professor with CO\(_2\) capture expertise, indicated that the number of CCS patents has been trending up, especially for the field of CO\(_2\) capture, but most of the patents are of improving efficiency, yet not of significant change in the technology. From an industrial perspective, Expert C1, a technical leader of a power plant operator, mentioned that patenting is not the utility’s mindset while it is pursued by the OEMs such as boiler manufacturers, flue gas treatment plants and air separation units. However, Expert C4, a former technological director of a power sector OEM company, stressed:

“Obviously we’re spending money, so we want to try to protect. So we did seek patents wherever possible, but I think it’s not huge. Personally I think the patent system is very flawed. You will find two patents for the same thing; you’ll find patents that overlap; you’ll find patents for things that we already do. We had some, but never did patents stop us doing anything, and never did
patents prevent other people doing anything. [...] It [patent] wasn’t a huge thing for us, more that we just controlled the content of anything we published. We would just avoid publishing confidential information.”

(Expert C4)

From the perspective of small companies focusing on CO₂ capture and utilisation, Expert C8 and C9, both indicated the importance of patenting their technologies, including not only the protection but also the increase of credits to their companies, which can benefit their applications for funding.

4.3.3 The Function of Knowledge Diffusion

Knowledge diffusion is essential to the development of any innovation systems, especially through networks, as the exchange of information in terms of scientific, technological or design knowledge can facilitate R&D of a TIS, while knowledge sharing among heterogeneous actors, such as academic, industrial and government entities, can also help policy and regulation making to be in line with the latest technological insights (Hekkert & Negro, 2011). This research thus investigates networks and mechanisms that were highlighted by interviewed experts for the performance of this function.

It is notable that experts from industries indicated that most of their CCS collaborative projects are from original collaborators or sectoral networks, such as UK Advanced Power Generation Technology Forum. The APGTF is an industry-led stakeholder group and was formed in 1999 to provide the focus for the Power Generation Sector in the UK for research, development and demonstration activities on near-to-zero and zero emission technologies from fossil fuel, biomass, and associated technologies. Since 2005, its main focus has been on carbon abatement technologies, especially carbon capture and storage. Respondents from power sectors considered that the APGTF plays an important role for CCS knowledge sharing and diffusion in the UK as the forum holds workshops every year to provide updated information on CCS development in terms of technology and policy.
The government-supported UKCCSRC is considered as another platform for knowledge sharing and networking. However, Expert C1, C3, C4, T1, T3 and O2 from industries believe the current main functions of the centre are knowledge sharing and R&D project coordinating among academic entities, even though the centre has made industrial involvement. Moreover, the knowledge shared on the platform is of fundamental R&D and less ready for practical applications. Nevertheless, an industrial respondent, Expert T3, specialising in pipeline and CO₂ transport, indicated that the centre’s biannual meetings provide valuable opportunities for industrial participants to discuss practical and technical problems with academic researchers to find feasible solutions and even establish collaborations.

However, with the experience in the first competition and the Front End Engineering Design (FEED) report, Expert C1 indicated that the protection of Intellectual Property (IP) might have been a barrier to the knowledge diffusion, as follows.

“I partially wrote the one [FEED report] that we did. If you look at the design for Kingsnorth you have a full process description, a full heat and mass balance for the process, except for two or three key elements in the process. […] I think two zones in the design with a process flow sheet just as a grey box and where there are no descriptions of the process streams going in or out. And those were areas where the technology supplier felt that they had a key innovator solution that was of significant advantage to them and where they had IP to protect.”

(Expert C1)

Expert C1 also explained that the different positions on this problem between the Government and technology suppliers. The Government provided funding for the demonstration projects, along with their FEED studies, in order to facilitate the knowledge development and diffusion through disclosing as much knowledge obtained from the projects as possible. However, for technology suppliers, the funding they received from the Government was insufficient to compensate their own investments in the technology. As Expert C1 explained,

“The technology suppliers who were involved typically maybe spend £100m, £200m of development money to come up with their own design. The actual cost to construct the hardware and so forth on the ground maybe £900m of the
£1,000m. [...] They would be paid maybe £40m for that design for which they have spent £200m to develop the technology, to develop the expertise. So from their point of view a situation where the Government requires IP to be shared around the world is disastrous because they immediately lose any privilege that they have in the market, any pre-existing know how, because the Government view, certainly at that time was that the IP, all the design information, all the underlying information would be made public and that was simply not acceptable to the suppliers. So there may have been issues of contract negotiation like that as well which broke down.”

(Expert C1)

The UK CCS Cost Reduction Task Force also indicated that several problems regarding design optimisation were addressed by technology suppliers and project developers as part of FEED studies, including trade-off between design constraints, availability and integration; however, the knowledge/information has not been made public due to the confidentiality concerns (CCS Cost Reduction Task Force, 2013). The Task Force considered the possibility for revealing and sharing the confidential knowledge in terms of design optimisation because it can benefit the CCS industry as a whole (CCS Cost Reduction Task Force, 2013).

In addition to the domestic knowledge diffusion, the UK Government also supports international CCS deployment with the aim of mutual knowledge sharing. In 2012, £60m was provided by the Government from the International Climate Fund (ICF) to trust funds operated by the World Bank and Asian Development Bank for the International CCS Capacity Building Programme to finance CCS pilot and demonstration projects in developing countries, especially focusing on China, Indonesia, South Africa and Mexico (DECC, 2012c).

According to the latest review report in 2015, four CCS pilot projects have been developed on track in those countries, respectively, and also “delivered a strong result in terms of developing effective relationships between donors (UK, Norway and Global CCS Institute) and recipient countries to share knowledge and expertise in development and deployment of CCS (DECC, 2015a).” As Expert O9, a CCS programme leader of an international environmental non-governmental organisation, mentioned,
“Just take China as an example. With UK’s support, China has established a pilot-scale full chain CCS demonstration project in Tianjin and also set up two CCS centres. One of these will be led by the UK-China CCS Centre supported by the UKCCSRC. The UK has also been proactively supporting the development of the Guandong regional CCS initiative, with expert input from UK academia and strategic guidance from the Foreign and Commonwealth Office.”

(Expert O9)

4.3.4 The Function of Guidance

Guidance can be regarded as incentives and/or pressures for firms and other organisations to be influenced to enter a TIS and take part in its development, including beliefs and expectations in growth potential; policy and regulations; assessments of technological opportunities; technical bottlenecks; and crises in current business (Bergek et al., 2008). Hekkert and Negro (2011) indicate that the function of guidance also comprises the process of technological selection that can be fulfilled by not only the industry but also the government and/or the market. This research assesses the performance of this function in two stages with 2011 as a watershed because a strong CCS policy was introduced in 2012 after the first demonstration programme failed in 2011, while there was no holistic CCS policy in the UK prior to 2011.

Guidance in the early stage

Sixty-two per cent of interviewed experts point out that their initial involvement with CCS were prior to UK Government’s substantial actions. Although CCS had been mentioned in the Royal Commission on Environmental Pollution’s 2000 report on Energy: The Changing Climate (RCEP, 2000), and the 2002 Energy Review from the UK’s Cabinet Office’s Performance and Innovation Unit (PIU, 2002), the Department of Trade and Industry first discussed CCS in its Energy White Paper: Our Energy Future – the first comprehensive contribution to UK energy policy for 15 years (DTI, 2003; Winskel, 2012). However, CCS did not become established as an important
prospect in UK energy policy until the late 2000s. Despite the Government’s unclear attitude towards CCS in the early stage, industry, along with academia, had started CCS research and development.

According to a CCS expert at The British Geological Survey (BGS), BGS was one of the very first organisations to realise CCS potential and has been involved in CCS since the early 1990s, although he started working on CCS in 1997. With the involvement in monitoring and modelling the distribution of injected CO$_2$, BGS participated in the Sleipner project, the world’s first demonstration and commercialisation of carbon dioxide capture and underground storage. In order to increase the quality of natural gas and evade the 1991 Norwegian CO$_2$ tax, in 1996, Statoil started to capture CO$_2$ from produced gas, inject it back and store it in a subsea aquifer in the Sleipner area of the North Sea.

Expert S1, specialising in the technology of enhanced oil recovery (EOR), had worked for the oil industry for 28 years before entering academia and, since the early 1990s, he has worked on redeveloping dead or dying fields such as EOR. EOR was developed in the first instance to increase the amount of crude oil that can be extracted from an oil field; however, EOR has subsequently been seen as a valuable option for CO$_2$ storage and, therefore, an incentive to develop CCS (DECC, 2012a). However, Expert S1 also pointed out the problem with the UK’s EOR development and suggested a tax policy might trigger the development.

“It’s a problem with both cost and supply, and at the moment there’s no CO$_2$ supply. I think it requires big thinking, big thinking from Government. The way in which CO$_2$ EOR began in Texas was with a tax system which made it favourable to get CO$_2$ EOR going and because of that a billion barrels of extra oil has been won. I think if you got it going in Britain, although the percentage of tax might be smaller, the overall amount of tax would be much larger. And once the first project is running then many projects will follow on.”

(Expert S1)

“From 2005, it was quite clear that CCS will have an impact, will be a major technology that will keep the industry interested, and therefore, we, as academic people, thought we should try to contribute to that,” Expert C5 with expertise in CO$_2$
capture from academia, remarked. Since 2005, he and his research group have started to work on CCS with the coal-fired power industry such as E.ON and Doosan Babcock. At that early stage, those companies anticipated the potential for CCS in the UK, therefore, started investing in its R&D and also seeking collaboration with universities.

Expert C1, with 26 years of experience in the power industry, recalled that E.ON started to develop CO₂ abatement technology in the early 2000s as it became a research priority funded through the European Commission’s Framework Programme for Research. At that time, the attitude of the European Commission towards CCS was more certain than that of the UK Government. The European Commission created a research interest in the area of innovative technologies for cost reduction in CO₂ capture, transport and storage. This action did catch the attention of the power sector, technology suppliers and universities, regardless of whether it might be seen as a threat or an opportunity. E.ON anticipated the future regulations and started its first CCS project with funding from the European Coal and Steel Community, which was one of the predecessors of the European Union. However, in contrast with the UK, Expert C1 considered that Norway’s Government provided clearer guidance for the technological development of CO₂ emissions reduction, such as CCS with the carbon tax policy.

“The longest established and probably most effective is the scheme in Norway, where there is a carbon tax. And so that has driven carbon capture being fitted to things like the gas clean up plants on gas production wells. Well, rather than once you've cleaned the CO₂ to go to the atmosphere, they have a tax of something like €50 a ton I think, and so they are separating it and re-injecting it back into the ground […]”

(Expert C1)

Expert C4, who previously worked at Babcock Energy Ltd (the company was renamed Mitsui Babcock Ltd in 1995 and renamed again Doosan Babcock Energy Ltd in 2006), indicated that, since the early 1990s, the company has started to develop CO₂ capture technologies because the company perceived the carbon emissions agenda as being a risk to its main business, which was coal power stations. The company obtained R&D funding from the European Union for its early CO₂ capture projects, including oxy-fuel and post-combustion.
Expert T1 responded that, in 2009, National Grid started to get involved with CCS shortly before the first demonstration project, which was for transporting CO$_2$ from Longannet Power Station in Scotland up to the Goldeneye field. National Grid participated in this project and started to consider re-using existing gas pipelines to make best use of assets that would otherwise be redundant in the near future.

According to the above experts, at the early stage of CCS development in the UK, the Government did not see CCS as a mainstream strand of energy policy and provided little guidance for further development. However, the EU’s CCS research priority through the Framework Programme for Research did prompt the UK’s CCS development, especially for the coal-fired power industry and the steelmaking industry. Once industries started developing CCS, they sought collaboration with academia. In addition, the advanced CO$_2$ tax policy in Norway had certain indirect influence on the UK’s CCS through the international collaboration between Statoil and BGS, while EOR also provided incentive for the development. According to Evar (2014)’s social network analysis of Sleipner publications, BGS has close connections with industry actors, including Norway’s Statoil, and also has a relatively high number of productive individuals within a network dominated by various national research institutes from across Europe.

Although the UK Government mentioned CCS in the 2003 Energy White Paper (DTI, 2003), by the mid-2000s the role of CCS in energy system futures was still being questioned. The 2006 Energy Review downplayed the prospect of a major role for CCS in UK energy futures, and questioned its economic and commercial feasibility (DTI, 2006). In the 2007 White Paper, the Government remained unenthusiastic about CCS, indicating for the UK ‘up to 2030, nuclear … and renewables would be more likely to come forward than CCS’ (DTI, 2007). Although the Government announced the first CCS demonstration competition programme in November 2007, which was expected to provide a better understanding of the likely costs and timing of the wider deployment of this technology, the announcement and the funding schedule had been considered being delayed (Carbon Capture Journal, 2007; Hotten, 2007). According to Scrase and Watson (2009), BP transferred its project at the Miller field to Abu Dhabi because the Government hesitated to support it and had delayed the funding programme. BP described the delay of the first competition as “an extension too far,” for it had already spent £30m on the project by May 2007; therefore, the oil company
decided not to proceed with its original plan to join the competition programme due to
the uncertainty about funding (Hotten, 2007). Moreover, after withdrawing the
Kingsnorth CCS project from the first competition, E.ON transferred their internal
CCS R&D resources to the Maasvlakte project in the Netherlands, for the project has
the company’s second logical power plant to fit carbon capture (Expert C1; Carbon
Capture Journal, 2010).

The Longannet CCS Project, led by the consortium of ScottishPower, National Grid
and Shell, participated in the UK’s first CCS competition programme, and was one of
the two remaining bidders awarded with FEED contracts (NAO, 2012). In May 2009,
ScottishPower began a small 1 MW demo capture project, which successfully captured
over 90% CO₂ while the CO₂ was planned to be piped offshore to Shell's Goldeneye
Gas Platform (DECC, 2011c). The consortium’s engineering and design study
confirmed that its capital cost estimate for the project potentially rose to £1.5 billion
because of estimating uncertainty, which was well above the £1 billion Treasury limit
(DECC, 2011c). After negotiations, the Government cancelled the programme on 19
October 2011 to protect value for money and announced “a decision [was] made not
to proceed with Longannet but to pursue other projects with the £1 billion funding
made available by the government” (NAO, 2012).

**Guidance after 2011**

The UK’s first CCS competition programme lasting from November 2007 till October
2011 with no substantial result which had impeded the CCS development in the UK.
Respondents revealed that some companies had, thus, moved their resources from the
UK to other countries because of the Government’s weak commitment and low
ambition towards CCS development. As, in 2012 the Government published the CCS
Roadmap, announced the £125m, 4-year R&D funding programme and opened the
second CCS competition programme, doubt about the Government’s resolution on
CCS still remained among industries. However, in March 2013, the Government’s
announcement of the two preferred bidders for the second CCS competition was seen
as a breakthrough for the UK’s CCS development, because the £1 billion in capital
funding was vital for the early phase commercialisation projects.
A further clear guidance was made by the CCS Cost Reduction Task Force, established by DECC, in the report of the Potential for Reducing the Costs of CCS in the UK (CCS Cost Reduction Task Force, 2013). The report identified seven key steps to support the large-scale development of power and industrial CCS in the UK, as follows:

1. Ensure optimal UK CCS transport and storage network configuration.
2. Incentivise CO\(_2\) EOR to limit emissions and maximise UK hydrocarbon production.
3. Ensure funding mechanisms are fit-for-purpose.
4. Create bankable contracts.
5. Create a vision for development of CCS Projects in the UK from follow-on projects through to widespread adoption.
6. Promote characterisation of CO\(_2\) storage locations to create maximum benefit from the UK storage resource.
7. Create policy and financing regimes for CCS from industrial CO\(_2\).

To ensure the actions will be delivered, the Task Force also recommended three national leadership groups should be created to take forward the recommendations, as shown in Table 4-2.

<table>
<thead>
<tr>
<th>Groups</th>
<th>Aims</th>
</tr>
</thead>
<tbody>
<tr>
<td>The UK CO(_2) Storage Development Group</td>
<td>This group will be led and co-ordinated by The Crown Estate. The aim of the group will be to unlock cost reductions through the benefits of scale and to reduce risks in the CO(_2) storage and transport sector.</td>
</tr>
<tr>
<td>The UK CCS Commercial Development Group</td>
<td>This group will involve active banking and insurance industry participants. The group will be established by CCSA, the Energy Technologies Institute, The Crown Estate and the Ecofin Foundation, and be led by the Ecofin Foundation. The aim of the group will be to secure ways, together with the UK Government, of making UK CCS projects bankable, and reducing their cost of capital.</td>
</tr>
</tbody>
</table>
The UK CCS Knowledge Transfer Network

This will be led by the CCSA. Its aim will be to enhance cost-saving (and value-enhancing) potential for CCS projects by promoting and facilitating the flow and review of knowledge and information, for both Industry and Government, following on from early projects in the UK and elsewhere. This will identify key gaps that stakeholders should address in order to ensure that CCS plays its full potential in the broader decarbonisation of the UK energy system.

Source: CCS Cost Reduction Task Force (2013)

For significant cost reductions, the Task Force stressed the importance of the right landscape for the UK’s CCS development, including credible and long-term UK commitment to CCS by government and industry, which includes a recognition of the role of CCS in the future generation mix, as well as a coordinated plan for transport and storage, and an appropriate underpinning regulatory landscape; multiple operating full chain CCS plants that build on the current commercialisation programme; and continued engagement with the financial sector, so that the industry and government jointly create access to low cost finance for CCS (CCS Cost Reduction Task Force 2013). With the right landscape in place, the Task Force developed the potential cost reduction trajectory for CCS, anticipating that the first set of projects may have costs around £161/MWh in 2013 (CCS Cost Reduction Task Force, 2013).

However, Expert O1 and C4 argued that the reluctance of the Coalition Government to commit to a 2030 decarbonisation target (as advocated by the Climate Change Committee and the previous Government) could be viewed as likely to delay development. Expert O4 stressed that a full scale CCS demonstration project can provide more thorough information for regulatory framework in terms of health and safety. Since the two CCS commercialisation projects were selected from the second competition programme, many experts were optimistic about the UK’s CCS development and expected the Government would keep the promise of £1billion capital investment. After the sudden turn of CCS policy whereby the Government withdrew the capital fund in November 2015, experts urged that the Government should provide a revised roadmap for CCS development, and at least retain the momentum of CCS R&D in the UK.
In addition, the generally deteriorating investment environment for fossil fuel power plants in the UK has slowed down private investments in fossil fuel infrastructure in current market because electricity wholesale prices have dropped. Increases in solar and wind farms in recent years have helped drive down electricity prices. The renewable energy generators can still profit with the low prices because of government subsidies; however, conventional power stations such as fossil fuels cannot be switched off quickly, thus resulting in an oversupply of electricity and further price drops (Clark, 2016). The negative pricing would discourage energy companies from investing in new power stations, especially for those generated by fossil fuels (Clark, 2016).

4.3.5 The Function of Market Formation

According to Bergek et al. (2008), for a new, developing TIS, markets may be very immature, or even not exist because uncertainties surrounding the new technology result in less competitiveness in terms of price/cost and performance, while the customer demand profile may not have been articulated. Hekkert and Negro (2011), therefore, suggested that creating a protected space is essential for a new technology/TIS to grow, including the establishment of temporary niche markets and/or the creation of temporary competitive advantages such as tax reduction (Kemp et al., 1998; Schot et al., 1994). This research thus investigates this function in aspects of potential niche markets and the Government’s protective intervention for low carbon electricity with CCS.

CCS with enhanced oil recovery (EOR) or enhanced hydrocarbon recovery (EHR) is recognised as an important niche market for the TIS because the captured CO₂ can be used to increase the amount of oil or gas that can be extracted from an oil or gas field (Rai et al., 2010). The captured CO₂, therefore, becomes an economically valuable commodity that can reduce the costs of the whole CCS chain. The UK Government set up EOR/EHR as a preferable criterion for the second CCS commercialisation programme in the 2012 CCS Roadmap (DECC, 2012a); however, following the cancellation of the programme, there will be no CCS operation with EOR/EHR in the UK in the near future. Apart from the lack of CO₂ supply with CCS, the development of EOR/EHR in the UK Continental Shelf (UKCS) has stagnated because of the
significant decline of oil price in recent years and the absence of a clear legal and regulatory framework (SCCS, 2015).

For the market of low carbon electricity, the Electricity Market Reform (EMR) has introduced a scheme of feed-in tariffs (FITs) combined with contract-for-differences (CfDs) for low carbon electricity including CCS, yet the scheme encountered difficulties in the contract details for CCS, as CCS involves not only electricity companies, but also those associated with transport and storage, according to Expert O7. This system guarantees the price received by the generators if the wholesale electricity price is below an agreed level. Measures designed to benefit CCS, such as capacity payments and emissions performance standards, will be useful, but the overall viability of projects will likely be decided by the electricity strike price. Until this is established, industrial projects are unable to make accurate financial evaluations of, or investment decision for, potential projects.

In June 2013, the Government set out the proposed CfDs strike prices for renewables, but not yet for CCS, because CCS is still undergoing its cost discovery process, so a strike price is difficult to set and is subject to bilateral negotiations. It is suggested that, if prices are set pre-FEED, a range is used and that the final price is negotiated within the range on FEED completion. Expert C1 and C4 also suggested that setting of the strike price will need to be made on a project-by-project basis as there is too much variation between CCS projects for standardisation. As the different CCS technologies carry different cost and risk structures, it’s not a case of “one size fits all”.

Since the White Rose and the Peterhead Projects won the Government’s capital funding in the second competition, many experts have urged the Government to speed up the establishment of the appropriate FITs CfDs scheme for CCS and the negotiations for initial strike prices in order to keep the momentum for CCS development beyond the competition. Some suggestions for CCS CfDs include allowing renegotiation of CfDs strike price after construction to remove construction risks from the project; indexing the CfDs strike price to fuel prices to remove fuel price risks; and presenting a viable CfDs counterparty so that counterparty risk is minimised (CCS Cost Reduction Task Force, 2013).
4.3.6 The Function of Resource Mobilisation

Resources, including financial and human capital, need to be mobilised for all activities within the TIS as it evolves (Hekkert & Negro, 2011). Financial resources mainly comprise funding for R&D projects and capital investment for demonstration and commercialisation projects, while human resources are mobilised mostly through education in specific knowledge fields such as science, technology, management and finance (Bergek et al., 2008). Accordingly, this function was investigated in the two major aspects.

In the early 1990s, CCS R&D projects were funded by the EU’s Research Framework Programmes whilst companies in the sectors of power generation, oil and gas, or other industries started their own CCS R&D, mostly with internal support. As a former technology director in a power sector OEM company, Expert C4 recalled,

“We found that there was some support for R&D from the EU in that area. It was a very difficult time for our company, for R&D, because there had been the changes in the British electricity industry that no longer did we get money from the companies, from the electricity companies, and so we had to look for money from new places. And we found EU had some rather easy money in this area, so we went after that money. Besides, our parent company actually was very supportive of us funding CCS research.”

(Expert C4)

Funding for research from research councils is currently sufficient, but project funding, particularly post-demonstration stage, is more in doubt (Expert C5). Moreover, uncertainties of CCS development, especially for the slow progress of demonstration and commercialisation programmes, still impede the investment of venture capital, as Expert O6 observed,

“And venture capital would be very unlikely at the moment because the projects are very big and of high risk, so venture capitalists wouldn’t be interested, or would require impossible rates of return.”

(Expert O6)
The human resource of CCS is currently seen as sufficient, but continual training needed to start soon to ensure sufficient human capital available if CCS industry ramps up (Expert C4 and C5). An increasing number of training courses aimed at CCS are materialising, including dedicated Masters-level courses. In addition, the Government-funded UKCCSRC has held CCS winter and summer schools since 2012 for early career researchers to obtain knowledge and information on CCS research being undertaken in the UK by both industry and academia (Expert C7).

However, experts warned that the uncertainties arising from the Government’s previous hesitation had led to a number of companies withdrawing from active work on CCS (Expert C1, C4 and C5). There is a serious risk that postgraduate students currently being trained for CCS will not find work in the industry and that, if an industry does subsequently develop after a hiatus in activity, there will not be an adequately trained workforce to service it. To this end, a government commitment to a substantial and quantified build of CCS demonstration/commercialisation projects in the UK would be hugely beneficial.

4.3.7 The Function of Creation of Legitimacy

The creation of legitimacy can help a TIS well evolve in terms of public/social acceptance as well as compliance with or overthrow of existing relevant institutions (Bergek et al., 2008; Hekkert & Negro, 2011). Parties with vested interests generally resist the change brought by an emerging new TIS, while advocacy coalitions can create legitimacy for a new TIS by initiating the development of a new technology, putting it on the agenda, mobilising resources and lobbying for favourable policy and regulations (Hekkert & Negro, 2011). For CCS TIS in the UK, the Government has made new policy to support the development, along with the advocacy coalitions formed by the existing industrial actors, such as the Carbon Capture & Storage Association and the Advanced Power Generation Technology Forum. This research, then, focuses on the status of public support and the positions of environmental non-government organisations that have impaired this function.

A lack of public support is seen as a potential blocking mechanism. The study by Shackley et al. (2005) found that the public tended to support CCS once they learnt
that CCS can reduce CO₂ emissions to the atmosphere, but were also concerned about whether CCS would be the only low carbon energy technology to make significant cuts in CO₂ emissions and the uncertainties and risks of the whole set of CCS, such as possible leakages of high pressure CO₂ around transport pipelines and storage sites that could damage human health and the environment. Shackley and Gough (2006) also indicated that, with provided information about CCS and considering other low carbon alternatives, the public may prefer CCS to nuclear power, but prefer renewable energy, such as solar and wind, to CCS.

Expert O3 pointed out that the level of general public awareness of CCS is still low and suggested that the media can play an important role in informing the public on CCS. When informed of CCS as an environmental advantage to reduce CO₂ emissions and its socioeconomic benefits, such as job creation, the public express considerable acceptance; however, the public tend to be less trusting in CCS if they are informed of the uncertainties and risks of the technologies (Expert O3).

Some experts argue that public acceptance would not be a problem for the UK’s CCS because the Government has opted for offshore storage, which lessens the problem of Not in My Back Yard (NIMBY) and also because pipelines that can be used for CO₂ transport already exist (Expert C4, C5, T1, S1 and S3). The safety issues are well understood and can be managed by prudent engineering, as already is the case for the extensive infrastructure used for transport and storage of natural gas. Further R&D is expected to improve margins of safety.

“So far it [CCS transport] hasn’t [been a problem]. We’ve done quite a few consultations now and we’ve got some more planned for September of this year [2013]. We’ve had a reasonable reception in the Yorkshire area. I think you have to recognise that you get different responses in different parts of the country. So Kingsnorth didn’t get acceptance, maybe because it was in the south east of England and it was a large, new, coal fire powered or whatever, whereas Drax is in existence. There seems to be a stronger link with the jobs potential and potential for helping regenerate the region in the Yorkshire area, and that’s proving helpful, so it doesn’t have to be an insurmountable obstacle. […] but there’s always someone who has got this thing being built close to their back yard who is not too keen but you’ve got to try and show that you’ve
chosen the most reasonable route that causes the least disruption that you can. I think it would be okay.”

(Expert T1)

Expert S2, with expertise in CO$_2$ storage, also considered that the public acceptance of CCS would not be a big problem for the storage part in the UK, but for the transport part. The expert also argued that higher electricity cost associated with CCS will impact the public acceptance.

“I don’t think it's [the public acceptance of CCS] a big problem in the UK, certainly not for the storage itself which is a long way offshore and certainly the early storage would probably be in a depleted oil field or gas field and a long way offshore. [...] There might be some problems with pipelines. If you've got a power station that's 50 kilometres from the shore or 100 kilometres you need a long pipeline and I think, you know, it's getting permission to lay that pipeline could be quite difficult. People accept pipelines full of natural gas because we need it, we obviously need natural gas to run our central heating, but if it's something like CO$_2$ people mightn't be quite so happy.”

(Expert S2)

However, Expert C1 and C7 indicated that one of the reasons that E.ON withdrew its Kingsnorth CCS project was the public protest, especially by environmental activists.

“There was a huge amount of public protest against the new coal fired power plant. So we had climate camps and site invasions and a huge amount of not necessarily local opposition because the local community was quite supportive of the coal fired power plant, but there was a significant national pressure group against new and largely unabated coal on the site. So that did not help to make the project development easy.”

(Expert C1)

Among those environmental non-governmental organisations (NGOs), Greenpeace has been campaigning against burning coal for energy for a long time and was the one aggressively protesting at the Kingsnorth power station. The success of the campaign was highlighted as a pivotal milestone in preventing new coal in the UK, as E.ON
decided to cancel the plan of building a new coal-fired power station at Kingsnorth following the campaign, even though the station would be equipped with CCS (Greenpeace, 2016). Some environmental NGOs, like Greenpeace, have doubted the feasibility of CCS, not only because the technology hasn’t been proven at scale on a commercial power plant, but also it is not yet economically viable, not to mention the risks around the transport and storage of CO₂. Before the technology is commercially realised, the Government’s policy to approve new coal stations that are ‘Carbon Capture Ready’ was considered as a “dangerous distraction” by a group of environmental NGOs, including Greenpeace, the World Wide Fund for Nature (WWF), Friends of the Earth and the Royal Society for the Protection of Birds (RSPB) (Greenpeace, 2008). In their joint statement on coal and CCS, they concerned that the Government’s competition programme to demonstrate CCS technology at a relatively small scale could be used to legitimise much larger new-built ‘Carbon Capture Ready’ coal-fired power stations. Nevertheless, they urged that the CCS demonstration scheme should focus on exploring technical and economic feasibility, and that a strong regulatory framework should be established to ensure the safety of CO₂ transport and storage (Greenpeace, 2008; WWF, 2008).

However, some other environmental NGOs are very keen on CCS, as they recognise that it is the only technology available to largely reduce CO₂ emissions from not only fossil-fuelled power plants, but also heavy industries; for instance, Third Generation Environmentalism (E3G) and Green Alliance are two among them proactively supporting CCS in the UK. E3G started to promote CCS development when it was founded in 2004 and assisted in establishing the collaborative project of Near Zero Emission Coal (NZEC) in 2005 between the European Commission and China, and the UK and China, with the aim of developing and demonstrating CCS (E3G, 2015; European Commission, 2017). Since then, E3G has continued to pursue related policies, regulations and initiatives on CCS and especially phasing out coal in the electricity sector, as the organisation stressed that CCS is not an excuse for continued fossil fuel extraction (E3G, 2015). In similar mind, Green Alliance revealed its support for CCS in 2008 and brought together voices from politics, industry, academia and NGOs with the common perspective on facilitating CCS in the collective report of a last chance for coal - making carbon capture and storage a reality (Green Alliance, 2008). Along with the Carbon Capture and Storage Association (CCSA), Green
Alliance later held the Towards a UK CCS Roadmap conference to suggest potential
development by drawing on the regulatory and financing experience from the US
(Green Alliance, 2009). In 2011, E3G and Green Alliance participated in the creation
of the ENGO Network on CCS with other environmental organisations all around the
world, including Clean Air Task Force, Natural Resources Defense Council, The
Climate Institute, The Pembina Institute, World Resources Institute, Environmental
Those members of the network share knowledge and work together on domestic and
international policies, regulations and initiatives to support the safe and effective
deployment of CCS (E3G, 2013a; 2013b).

Nevertheless, increases in public awareness, education, engagement and media
exposure of CCS are still suggested as necessary to improve this function. As Shackley
and Gough (2006) suggested, prior knowledge of climate change and recognition of
the need for large CO₂ emissions reduction would help the public to consider CCS
necessary. In addition, the UKCCSRC has worked to coordinate responses to public
discourse on CCS and respond to government consultations. Moreover, the two
projects from the second competition programme, the Peterhead CCS project and the
White Rose CCS project, have also conducted public engagement and consultation to
enhance the public acceptance for better project developments. For the Peterhead CCS
project, the plan and strategy for stakeholder and public engagement and
communications have been made in the project’s FEED study, while the initial
progress and result can also be found in the study (DECC, 2016). For example, the
engagement and consultation events within which the project was represented or which
the project conducted with community stakeholders in 2013 and 2014 are listed below
(DECC, 2016).

- Representation at the Boddam Gala, May 4th, 2014;
- Representation through a Stand at the Wild About Aden, July 14th and 15th,
  2014;
- Briefings to Boddam Community Council, October 29th, 2013, August 19th,
  2014 and February 10th, 2015;
- Briefings to Peterhead Community Council, November 20th, 2013, August
  20th, 2014 and February 17th, 2015;
• Community Newsletter, distributed to 15,000 homes, September 2014;
• Representation through a Stand at the Rural Life Heritage Fair and Vintage Tractor Working Day at Aden Country Park, September 28th, 2014;
• Meeting with Theatre Modo and organisation of the Shell/Theatre Modo Fireworks Display, Aden Country Park, Aberdeenshire, October 31st, 2014

4.4 Interactions with other Innovation Systems

The formation and growth of the UK’s CCS innovation system are affected by other innovation systems, including the innovation systems of the EU, Norway and several related sectors, such as electricity, oil and gas. The interactions with these systems have nurtured the UK’s CCS development in every function of the innovation system, as shown in Figure 4-2. This section explores the system interactions and provides evidence from expert interviews and secondary literature.

![Figure 4-2: Interactions of the UK’s CCS TIS with other innovation systems](source: Figure amended from Markard and Truffer (2008))
4.4.1 Interaction with the EU’s Innovation System

Research Framework Programme

The EU’s support of CCS R&D was important for the early development of the UK’s CCS, as some companies and academic institutions had perceived the need to develop CCS and sought support from the EU, while there were no clear CCS policy or substantial support from the UK Government. The EU has supported research, development and demonstration of clean coal and CCS technologies since the Third Framework Programme (1990-1994).

In the early 1990s, the European Commission started to support CCS research and development (van den Broek et al., 2010). The Third Framework Programme (1990-94) covered the first CCS activities (mainly CO₂ capture research), and, in 1993, a funded study was coordinated by The British Geological Survey (BGS) dealing with the possibilities of underground disposal of CO₂ as part of the Joule II Non-nuclear Energy Research Programme. In 1998, the Saline Aquifer CO₂ Storage (SACS) Project was established with European Commission support and started to collect relevant information about the injection of CO₂ into the Utsira formation and similar underground structures around the North Sea.

In the Fifth Framework Programme (1998-2002), the EU contributed some €16 million to support nine projects, worth over €30 million of total investment, including two projects on CO₂ capture, six projects covering CO₂ storage and storage monitoring, and one Thematic Network. In the Sixth Framework Programme (2002-2006), the EU increased the support to 18 projects with €70 million, worth about €150 million of total investment. Most of those projects in the Fifth and Sixth Framework Programme involved participants from the UK, as shown in Appendix E.

Expert C1 and C7 reveal that, in the 2000s, electricity companies such as E.ON started to be interested in CCS as it became a research priority for the European Commission and the regulation of ‘Carbon Capture Ready’ gradually emerged in the UK. E.ON started CO₂ capture R&D in about 2002 and 2003, beginning with oxy-fuel combustion and then increasingly interested in amine post-combustion capture. The
company also carried out basic tests with those technologies, a series of pilots and then moved them up to the point where they can be applied in power stations.

In addition, perceiving the carbon emissions agenda as being a risk to its main business, which was coal power stations, Doosan Babcock started to develop CO₂ capture technologies in the early 1990s and obtained R&D funding from the European Union for its early CO₂ capture projects, including oxy-fuel and post-combustion.

**CCS Directive**

The EU CCS Directive on Geological Storage of Carbon Dioxide (Directive 2009/31/EC) came into force in June 2009 (European Commission, 2009a). This Directive is an enabling Directive, which means it does not require CCS to be developed, but, if an EU Member State or company chooses to develop a CCS project, then the provisions of this Directive must be followed. The Directive focuses on the establishment of a legal framework to regulate carbon dioxide being safely and permanently stored in geological sites, but does not cover capture or transport in great detail, while it also covers requirements for site selection and exploration, permitting and monitoring, corrective measures in case of leakage, liabilities, transfer of responsibility, and third party access to the transport and storage networks (European Commission, 2009a).

The CCS Directive is implemented in the UK mainly through the Energy Act 2008 (Chapter 3), which introduced a new regulatory framework to facilitate the offshore storage of carbon dioxide (HM Government, 2008). In addition, Section 36 of the UK Electricity Act 1989 (licensing of power plants), has been amended to implement the CCS Directive requirement that all new combustion power plants over 300MW must be constructed as CO₂ Capture Ready (CCR), while the Department for Energy and Climate Change published a guidance note on CCR in 2009 (DECC, 2009).

**EU Emissions Trading System**

In October 2003, the EU Emissions Trading Directive (Directive 2003/87/EC) (EU ETS) came into force, which “establishes a scheme for greenhouse gas emission
allowance trading within the Community in order to promote reductions of greenhouse gas emissions in a cost-effective and economically efficient manner” (Article 1) (European Commission, 2003). CCS was not included in the original 2003 Directive; however, it was later included in the revised 2009 version (Directive 2009/29/EC). This version includes CCS explicitly in Annex I (activities which are covered by the EU ETS), and emissions captured, transported and stored according to the CCS Directive are considered as not emitted (European Commission, 2009b). However, the EU ETS does require that, if any stored CO₂ does escape to atmosphere, allowances must be purchased (at current market prices) and surrendered to cover the release of emissions (European Commission, 2009b).

Figure 4-3: Carbon Price Floor Illustration (in real 2009 prices & calendar years)

Source: Figure reprinted from Budget 2011, HM Treasury

In the UK, Expert C1, C4 and O2 indicated that, currently, the cost of carbon emissions levied via the EU ETS and the UK’s Carbon Price Floor (CPF) is not big enough to push power companies or industries to invest sufficiently in and implement CCS. As Expert C4 commented on the EU ETS,

“The ETS gave a certain number of allowances to each country, free. And then the country shared those allowances amongst the power stations. And that
meant that it didn’t cost them very much in the first five years, but from 2013 the country has to auction the allowances. But the auction prices are so low, less than ten Euros a ton, that although they have to go through all the process, it’s very cheap, it’s not a penalty. People were expecting that the cost of an allowance would be twenty Euros a ton, or thirty Euros a ton now, but it’s gone down to less than ten, so it’s not a serious penalty.”

(Expert C4)

However, some respondents argued that the CPF trajectory reaching £30/tCO₂ in 2009 prices by 2020, according to Budget 2011, as shown in Figure 4-3, would result in UK firms facing significantly higher energy prices than those of competitors abroad, and raise energy bills for households. This is because EU ETS carbon prices are now substantially lower than was expected when the CPF was introduced. Accordingly, the UK Government announced at Budget 2014 that the CPF would be fixed at £18 per tCO₂ from 2016-17 until 2019-20 to support UK business competitiveness and help to restrain increases in household energy bills, while still maintaining the incentive to invest in low-carbon generation.

**NER300**

NER300 is a financing instrument managed jointly by the European Commission, European Investment Bank and Member States, so-called because the revised Emissions Trading Directive 2009/29/EC contains the provision to set aside 300 million allowances (rights to emit one tonne of carbon dioxide) in the New Entrants’ Reserve of the European Emissions Trading Scheme for subsidising installations of CCS and innovative renewable energy technology. The allowances have been sold on the carbon market and the money raised will be made available to projects as they operate.

The UK’s White Rose CCS project has been selected for the NER300 award, which is an important potential source of funding for the project, as well as providing a strong signal for CCS in Europe.
System Function Interactions with EUIS

The contributions that were made by the EU innovation system (EUIS) to the UK’s CCS innovation system can be observed through system functions, as outlined in Table 4-3. From the very early stage of the UK’s CCS development, the EUIS had set the goal and plan of CCS R&D (F4, F2) and continuously funded CCS R&D projects through the research framework programmes (F6, F1). While the UK Government set out to develop CCS in the 2000s, the EUIS further bolstered the development with forming a coalition of stakeholders to advise on CCS (F7), establishing the European CCS Demonstration Project Network to exchange knowledge and experience (F3), and launching a cap and trade system (EU ETS) to impose a price/cost on CO₂ emission (F5). The EUIS’s interventions in the system functions provided substantial and consistent supports for the CCS development in the UK, in spite of the Government’s hesitation at times.

Table 4-3: System Function Interactions of the UK’s CCS TIS & EUIS

<table>
<thead>
<tr>
<th>System Functions</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1: Entrepreneurial Activity</td>
<td>Since the early 1990s, the European Commission (EC) has supported CCS R&amp;D in the UK through the research framework programmes.</td>
</tr>
<tr>
<td>F2: Knowledge Development</td>
<td>The EU-funded projects in research framework programmes have produced reports, papers and know-how.</td>
</tr>
<tr>
<td>F3: Knowledge Diffusion</td>
<td>In addition to the cooperation projects in research framework programmes, the European CCS Demonstration Project Network was established in 2009 to share knowledge and experiences among members, including the UK’s Don Valley CCS Project.</td>
</tr>
<tr>
<td>F4: Guidance of the Search</td>
<td>The research priority on CCS was created through the EU’s research framework programmes in the 1990s. Under the 2030 policy framework for climate and energy, CCS has been recognised as an important role to reach the EU’s long-term emissions reduction goal.</td>
</tr>
</tbody>
</table>
The EU’s CCS Directive on the safe geological storage of CO₂ is implemented in the UK through the Energy Act 2008.

<table>
<thead>
<tr>
<th>F5: Market Formation</th>
<th>The EU emissions trading system (EU ETS) was established to reduce industrial greenhouse gas emissions, including CO₂ from power generation and energy-intensive sectors.</th>
</tr>
</thead>
<tbody>
<tr>
<td>F6: Resource Mobilisation</td>
<td>EC has funded CCS R&amp;D projects through the research framework programmes. The UK’s White Rose CCS project has also been awarded a funding under the EU NER300 Programme.</td>
</tr>
<tr>
<td>F7: Creation of Legitimacy</td>
<td>The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) was founded in 2005 by a coalition of stakeholders to advise the EC on CCS.</td>
</tr>
</tbody>
</table>

Source: this research

### 4.4.2 Interaction with Norway’s National Innovation System

The early stage of the UK’s CCS development was involved in the collaboration with Norwegian oil companies and research institutions, mainly through the Sleipner Project, including the participation of the British Geological Survey (BGS) in the monitoring of the Sleipner CO₂ storage site in the North Sea (Expert S2). The project, operated by Statoil in the North Sea about 250 km off the coast of Norway, is the first commercial scale project dedicated to geological CO₂ storage in a saline formation (IEA, 2003). The CO₂ from Sleipner West Gas Field is separated, and then injected into a large, deep, saline formation 800-1000m below the seabed of the North Sea (Perkins, 2010).

According to Fuchs (2015), the concept of CCS in Norway stemmed from a study conducted for Norway's largest oil company Statoil by the Norwegian research institution SINTEF between 1986 and 1988. During that period, the report ‘our common future’ of the Brundtland Commission about the growing tension between economic growth and ecological deterioration was published (Burton, 1987), while, as Norway's prime minister, Brundtland introduced a world’s first carbon tax on CO₂.
emissions, which was designed for the off-shore oil and gas sectors in 1991 (Sumner et al., 2009).

In order to avoid carbon tax, in 1992, Statoil opted to inject the CO$_2$ in the Utsira formation, a large aquifer southwest of Norway with a capacity of probably more than a hundred times the European annual CO$_2$ emissions (Holloway, 1996a). Statoil thus made available a research budget of €1.25-2.5 million per year to simulate the distribution of CO$_2$ in the Utsira formation (Korbol & Kaddour, 1995). Hereby, Statoil cooperated with SINTEF and the Trondheim-based technical university NTNU, and initiated commercial R&D efforts to apply a CO$_2$ separation unit offshore (Karstad, 2002). In this R&D process they aligned with Kvaerner, one of Norway’s largest technology vendors. Following these R&D programmes, Statoil invested €94 million in the separation and storage components, and started operations in 1996; sequestering 1 Mt CO$_2$ each year (Berger et al., 2003).

During 1998, a group of energy companies, together with scientific institutes and environmental authorities in Norway, Denmark, the Netherlands, France and the UK, formed the Saline Aquifer CO$_2$ Storage (SACS) Project Consortium with European Commission support and started to collect relevant information about the injection of CO$_2$ into the Utsira formation and similar underground structures around the North Sea. BGS was the major participant in the project working on time-lapse 3D seismic data from Sleipner, acquired in 1994, prior to injection, and again in 1999, 2001, 2002, 2004, 2006, 2008 and 2010 with around 11 million tonnes of CO$_2$ in the reservoir at the time of the last survey. Through innovative processing and analysis, the data confirm that the CO$_2$ is confined securely within the storage reservoir (BGS, 2013).

Because of the Sleipner experience, BGS has strongly influenced the development of CCS in the UK, such as providing advice to the Department of Energy and Climate Change (DECC) in the development of the UK regulatory framework for CO$_2$ storage (implemented in 2012), advice on the storage part of the UK’s CCS Roadmap (DECC, 2012), and advice to DECC on the UK’s CCS Demonstration Competition Programme. Moreover, BGS has produced many papers on CCS, including two important ones, highlighted by Expert S2: (1) Measuring pressure performance of a large saline aquifer during industrial scale CO$_2$ injection: The Utsira Sand, Norwegian North Sea (Chadwick et al., 2012); and (2) History-matching flow simulations and time-lapse
seismic data from the Sleipner CO₂ plume (Chadwick et al., 2010). According to Lovell (2009), CCS experts at BGS have played a pioneering role in technical matters and have influenced views of CCS feasibility in Britain and globally.

**System Function Interactions with Norway’s NIS**

From the perspective of system function interaction, Norway’s innovation system directly influenced the development of the UK’s CCS on CO₂ storage, especially in the functions of entrepreneurial activity (F1), knowledge development (F2) and diffusion (F3), and resource mobilisation (F5), as described in Table 4.4. The Norwegian government’s carbon tax policy in 1991 not only stimulated the development of CCS in Norway (F4, F5), but also facilitated the collaboration between Statoil and The British Geological Survey (BGS) on CO₂ storage in the North Sea. BGS benefited greatly from the collaboration and accumulated extensive knowledge and experience on CO₂ storage, which also contributed to the CCS development in the UK.

<table>
<thead>
<tr>
<th>System Functions</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F1: Entrepreneurial Activity</strong></td>
<td>The British Geological Survey (BGS) collaborated with Norwegian oil companies and research institutions through the Sleipner Project in the monitoring of the Sleipner CO₂ storage site in the North Sea.</td>
</tr>
<tr>
<td><strong>F2: Knowledge Development</strong></td>
<td>Through the collaboration, BGS produced many important reports and papers, including the Best Practice Manual for the Storage of CO₂ in Saline Aquifers.</td>
</tr>
<tr>
<td><strong>F3: Knowledge Diffusion</strong></td>
<td>In addition to public reports and papers, key members of the Sleipner project, such as BGS, Statoil and SINTEF, shared their findings through workshops and conferences, and provided advice to other CCS projects.</td>
</tr>
<tr>
<td></td>
<td>The North Sea Basin Task Force, established in 2005 by the Governments of the United Kingdom and Norway, and composed of public and private bodies from...</td>
</tr>
</tbody>
</table>
countries on the rim of the North Sea, also helped to develop common principles for managing and regulating the transport, injection and permanent storage of CO₂ in the North Sea sub-seabed.

F4: Guidance of the Search

In the late 1980s, the Brundtland Commission published the report ‘Our Common Future’, revealing the environmental concerns. The Norwegian research institution SINTEF suggested the concept of CCS for oil companies.

F5: Market Formation

In 1991, the Norwegian government introduced a carbon tax for different fuels and sectors, which triggered Norway’s largest oil company, Statoil, to investigate options for cost-effective CO₂ handling at their offshore Sleipner West gas field, including the underground storage of CO₂ in geological formations.

F6: Resource Mobilisation

For the Sleipner project, in addition to the EU’s funding, Statoil made available a research budget of €1.25-2.5 million per year to simulate the distribution of CO₂ in the Utsira formation, and invested €94 million in the separation unit and started operations in 1996.

F7: Creation of Legitimacy

Besides lobbying activities of various environmental and industrial interest organisations, the increased public awareness of climate change and the more stringent GHG emission reduction targets formulated by governments have created more legitimacy to support CCS development.

Source: this research

4.4.3 Interactions with Sectoral Innovation Systems

It is notable that experts from industries indicated that most of their CCS collaborative projects are from original collaborators or sectoral networks, such as the UK’s Advanced Power Generation Technology Forum (APGTF) (Expert C1, C3, C4, C5, T1, T3 and S2). The APGTF is an industry-led stakeholder group and was formed in 1999 to provide the focus for the Power Generation Sector in the UK for research, development and demonstration activities on near-to-zero and zero emission technologies from fossil fuel, biomass, and associated technologies; since 2005 its main focus has been on carbon abatement technologies, especially carbon capture and
storage (APGTF, 2014). Respondents from power sectors considered that the APGTF plays an important role for CCS knowledge sharing and diffusion in the UK, as the forum holds workshops every year to provide updated information on CCS development in terms of technology and policy (Expert C1 and C4).

The system interaction also exists in the steel sector. Expert C3 indicated that, in the early 2000s, Corus (renamed Tata Steel in 2010), along with other European steel companies, decided to research and develop technologies that can significantly reduce CO₂ emissions from the steelmaking industry, thus initiating the project of ultra-low carbon dioxide steelmaking (ULCOS). The main reasons for Corus to develop CCS were the commitment to CO₂ emissions reduction and the significant financial impact of CO₂ emissions-related legislation. However, Expert C3 indicated that the UK Government has neglected industrial CCS, including the steel industry, until recently.

“We, and some others, have been pushing that industrial CCS should have received far more priority for quite some time, particularly, in relation to the so called clusters, whether they be in Teesside, Yorkshire or in Scotland, whatever, that if clusters look to be the most economic way of doing CO₂ transportation and storage, and if that was the case then you needed the industrial sectors involved sooner rather than later. The government was 100 per cent focused on power. So, for a number of years it was quite hard to get them to understand that it was important to look at industrial CCS. That that is/has changed, so they’re starting to look at it more seriously, which is good.”

(Expert C3)

**System Function Interactions with SISs**

The interactions of the UK’s CCS innovation system with other sectoral innovation systems were involved in every system functions, as those sectors that emit great amount of CO₂ would be directly affected by the CCS policy and regulation, and need to sustain their future businesses, as outlined in Table 4-5. Companies in the sectors of fossil fuels power generation, oil, steel and other heavy industry were set to develop CCS, mainly because of the guidance and funding of the EU’s research framework programmes, even before the UK Government took a position on CCS (F4, F6). As
the EU and the UK’s CCS policies became clear and sound, companies in those sectors sought collaborations on CCS R&D (F1, F2), built up networks for sharing knowledge and experiences (F3), and founded the CCS Association to influence the ongoing development and establishment of CCS policy and regulation (F5, F7). As important stakeholders in the UK’s CCS innovation system, companies in those sectors took action on every system function to ensure the development in line with their interests.

Table 4-5: System Function Interactions of the UK’s CCS TIS & SISs

<table>
<thead>
<tr>
<th>System Functions</th>
<th>Interactions</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1: Entrepreneurial Activity</td>
<td>Since CCS became a research interest in EU’s research framework programmes, companies in the sectors of fossil fuels power generation and oil and gas have started CCS R&amp;D in collaboration with each other or/and universities.</td>
</tr>
<tr>
<td>F2: Knowledge Development</td>
<td>Besides their own R&amp;D, companies in the sectors participated in the CCS R&amp;D projects from the EU or the UK Government, producing reports, papers and know-how.</td>
</tr>
<tr>
<td>F3: Knowledge Diffusion</td>
<td>Companies in the sector of fossil fuels power generation established the network of the UK’s Advanced Power Generation Technology Forum (APGTF) for CCS knowledge sharing and diffusion.</td>
</tr>
<tr>
<td>F4: Guidance of the Search</td>
<td>The EU and the UK’s policies on CCS and the commitments to CO₂ reduction direct the sectors to develop CCS.</td>
</tr>
<tr>
<td>F5: Market Formation</td>
<td>In addition to EU ETS, companies in the sectors have also been levied the carbon price floor (or carbon price support) rates for their CO₂ emissions.</td>
</tr>
<tr>
<td>F6: Resource Mobilisation</td>
<td>In addition to self-invested R&amp;D, companies in the sectors also sought funding from the EU or the UK governments. Companies also collaborate with universities for the CCS training programmes.</td>
</tr>
<tr>
<td>F7: Creation of Legitimacy</td>
<td>Companies in the sectors founded the CCS Association to promote the business of CCS and to work with the UK</td>
</tr>
<tr>
<td>Government and EC in developing an appropriate regulatory framework for CCS.</td>
<td></td>
</tr>
<tr>
<td>Source: this research</td>
<td></td>
</tr>
</tbody>
</table>
4.5 Dynamics of the UK’s CCS Innovation System

The interactions of system functions are important for the reinforcement of a technological innovation system. The investigation of the functional interactions thus becomes a good way to analyse and evaluate a given innovation system. This research explored the functional interactions of the UK’s CCS innovation system in three periods, as set up in Section 4.1.

Period: 1990s

In this period, the functional dynamics started with the Function of Guidance (F4), which was triggered mainly by the EU’s CCS research priority and the Norwegian Government’s carbon tax policy. Industry and academia in the UK then sought funding from the EU (F6: Resource Mobilisation) for collaborative R&D (F2: Knowledge Development) and small-scale demonstration projects (F1: Entrepreneurial Activity), while some companies even mobilised their own financial resources to support CCS R&D. The accumulated capacity of CCS R&D in the UK thus increased the expectations about further technological solutions, which, in turn, strengthened the Function of Guidance (F4). The functional dynamics in this period are shown in Figure 4-4.

![Diagram showing the functional dynamics of the UK’s CCS TIS in Period 1990s](source: this research)
However, the blocking mechanism for the TIS is not evident in this very early stage, except that the privatization of the utility sector and national laboratory facilities in the 1990s led to less explicit energy policy and the sharp decline of public funding for energy R&D in the UK (Scrave & Watson, 2009).

Period: 2000 to 2011

The expectations on further CCS development that were created from the previous period were considered to enhance the Function of Guidance (F4) in this period in terms of the Government suggesting CCS to achieve decarbonisation targets in Energy Reviews and Energy White Papers, and action on CCS regulations. In addition to the EU’s support of CCS R&D, the UK Government started to mobilise financial resources for CCS development (F6), especially for the first CCS demonstration competition programme. Although the competition ended up with no winner, two Front End Engineering Design (FEED) reports were produced that contributed to the Functions of Knowledge Development (F2) and Knowledge Diffusion (F3). The functional dynamics in this period are shown in Figure 4-5.

Figure 4-5: The Functional Dynamics of the UK’s CCS TIS in the Period 2000 to 2011

Source: this research
In this period, while the TIS started to gain momentum for development, two major blocking mechanisms can be highlighted, including the environmental NGOs’ protest against new coal-fired power plants being built (F7) and the Coalition Government’s austerity and hesitation with CCS (F4, F6). According to Expert C1 and C7, one of the major concerns for the Kingsnorth CCS project’s withdrawal from the first competition was the environmental activists’ aggressive protest at the Kingsnorth power station. According to Expert C4, O1 and O9, the Coalition Government’s austerity and hesitation with CCS had impeded the TIS’s development, including the reduction in the demonstration projects funded by the Government, the delay of the CCS policy and the failure of the first competition. As a result, some companies such as BP downgraded their CCS R&D in the UK and/or moved the capacity to other countries.

The Government’s termination of the first competition blocked the £1 billion in funding support for the remaining bidder to build a full chain CCS demonstration project. As a result, industrial actors’ confidence was shattered, and the UK’s CCS progress was further delayed, though the capital funding was later moved to the second competition. To this end, such action by the Government can be considered a trigger for a vicious cycle in the UK’s CCS TIS. Nevertheless, problems with the first competition were identified, and lessons were learnt to improve the second competition, according to the DECC’s 2012 CCS Roadmap (DECC, 2012a). For example, the Government’s commercial position needed to be further clarified for risk allocation purposes, and a more realistic and reliable timetable was required to be set out to avoid further delays that could increase procurement costs (DECC, 2012a).

**Period: After 2011**

Although the first demonstration competition programme failed, the momentum of the UK’s CCS development increased, with accumulated R&D capacities from the functions of knowledge development and diffusion. The Government, thus, reinforced CCS policy with the announcement of the UK’s CCS Roadmap (F4), including the second commercialisation competition with £1 billion capital fund (F1, F6), a £125m R&D funding programme (F2, F6) and a CCS research centre (F3). Two CCS commercialisation projects were selected and funded for FEED studies in the second
competition, which could further contribute to the functions of knowledge development and diffusion (F2, F3). In addition to the EU ETS, the Government set up the carbon price floor and started developing the Feed-in Tariffs with Contracts for Difference for CCS to enhance the Function of Market Formation (F5). As the development of CCS continued in the UK, the issue of public perception and acceptance gradually emerged. The two commercialisation projects thereby conducted public engagement and consultation to reduce potential counteractive resistance (F7), which, together with the Function of Market Formation, could also affect the Function of Guidance. The functional dynamics in this period are shown in Figure 4-6.

![Figure 4-6: The Functional Dynamics of the UK’s CCS TIS in the Period After 2011](source: this research)

However, although the TIS was reinforced with the Government’s CCS policy in 2012, several blocking mechanisms became crucial, including cost issues of CCS demonstration and deployment, insufficient market incentive and failure to diffuse key knowledge, while the Government’s austerity and hesitation continued to terminate
the second competition. The UK CCS Cost Reduction Task Force has identified key sources of cost reduction covering the whole CCS system and suggested improvements for further development (CCS Cost Reduction Task Force, 2013). Except the EU ETS and the UK’s amended Carbon Price Floor, the unclear details of the Feed-in Tariffs with Contracts for Difference for CCS cannot provide sufficient market incentive. Some confidential knowledge related to design optimisation in the FEED studies is considered to be shared to facilitate the development. According to Expert C8 and O7, the Department of Treasury’s arbitrary decision to cancel the capital funding for the second competition has damaged the TIS; as a result, many companies lost confidence in the UK’s CCS and downgraded their CCS R&D.

The performance of the UK’s CCS innovation system can be evaluated by the evolution of the functional interactions and dynamics in the three periods. The number of the key functions that were involved in the interactions increased from four (F1, F2, F4, F6), to five (F1, F2, F3, F4, F6), then to seven. The increase in function interactions also shows the reinforcement process of the innovation system, as the initial four functions interacted continuously and gradually encompassed the other functions to enhance the performance of the innovation system.

However, several blocking mechanisms were identified and considered to weakened every functions of the TIS, including the environmental NGOs’ protest against new coal-fired power plants being built (F7) and the Coalition Government’s austerity and hesitation with CCS (F4, F6), cost issues of CCS demonstration and deployment (F1, F2), insufficient market incentive (F5) and failure to diffuse key knowledge (F3). If the blocking mechanisms were not addressed and improved, the functions would be involved in vicious cycles so that the performance of the TIS would be downgraded.
Chapter 5. Conclusions

5.1 Introduction

This research intended to explore the effect of the Government actions on CCS development in the UK. For a holistic understanding, the analytical framework of Technological Innovation System developed by Bergek et al. (2008) was employed in this research to study the UK’s CCS development, the related government actions and their effects. With the TIS framework, this research assessed the UK’s CCS development in seven functions, including entrepreneurial activities, knowledge development, knowledge diffusion, guidance of search, market formation, resource mobilisation and creation of legitimacy. Through an analytical approach, this research has been able to meet the aim of the research and answer the research questions. With respect to the first research question, the development of the UK’s CCS TIS was reported with empirical evidence and the main drivers of and barriers to the development were also identified and discussed. This research also found the interactions of the UK’s CCS TIS with other innovation systems and provided empirical evidence for the second research question. The third research question was answered with policy recommendations for future CCS development in the UK.

5.2 Key Findings and Policy Recommendations

For each system function, key findings plus implications and recommendations for future CCS policy are summarised below.

F1: Entrepreneurial Activity

This study has found that government support in this function is still insufficient: remaining at small-scale experiments and hesitating over large-scale demonstration or commercialisation. In 2012, the UKCCSRC established the PACT centre (Pilot-Scale Advanced Capture Technology facilities) for small-scale experiments of industrial and academic R&D. Before that, power generation and industrial companies had started
their own small-scale R&D projects, but many did not continue mainly due to the lack of market incentives, and the policy and financial support of the UK Government.

When it came to large-scale demonstration, the first CCS demonstration competition ended up with no winner, but two FEED (Front-End Engineering and Design) reports, because the Government failed to proceed with the capital investment.

As the second CCS commercialisation competition launched by the Government in 2012 seemed to rebuild the momentum of the UK’s CCS development, many experts from industry and academia expressed optimism towards the development during the period when the expert interviews were conducted. However, in 2015, the Government cancelled the £1billion capital funding for the two CCS commercialisation projects from the second competition, which shattered the confidence of those companies in investing CCS.

The Government should have kept the commitment to CCS development and the promise of £1billion capital funding for the two large scale CCS commercialisation projects. Although being disappointed with the Government’s withdrawal of the £1billion investment, some experts suggested that there are still tasks that can proceed, such as small-scale R&D projects for further reducing CCS costs or next generation CCS technology.

**F2: Knowledge Development**

Before 2011, most CCS R&D projects in the UK were funded by the EU’s framework programmes, while some industrial companies also funded their own CCS R&D in the early stage. However, the UK Government’s effort to facilitate CCS knowledge development has been widely recognised since 2012 by academia and industry because of the 4-year £125m coordinated R&D and innovation programme, with the result of around 100 projects covering the whole CCS system, including fundamental research and understanding, development and demonstration of CCS components and next generation technologies, and pilot scale projects to bridge the gap between research and commercial scale deployment.
As there will be no large-scale CCS demonstration or commercialisation projects in the UK in the near future, the Government should keep up the effort to support further CCS R&D toward lower cost and/or next generation technologies. Industrial companies and academic entities might seek R&D collaborations with large-scale projects in other countries for more advanced, practical knowledge development.

F3: Knowledge Diffusion

The UK Government set great store on CCS knowledge diffusion with the establishment of the UK’s CCS Community Network in 2009, and, later, the network became part of the UK CCS Research Centre that was built in 2012. Experts from academia and industry have recognised and benefited from the network, as two network meetings are held every year for sharing updated CCS knowledge among a wide range of participants from academia, industry, government and non-government organisations. For example, Expert T3 indicated that it was the meetings held by the UKCCSRC through which he can obtain new R&D information on pipeline materials for CO₂ transport. His company thus can collaborate with certain academic research teams for further development. Another important network that has contributed to CCS knowledge diffusion in the UK is the APGTF (The Advanced Power Generation Technology Forum), formed by stakeholders in the power generation sector to facilitate the development of near-to-zero and zero emission technologies with a recent main focus on CCS. The APGTF holds annual workshops for updates on CCS R&D and policy, and also for knowledge exchange, with participants not only from industry, but also from academia and government.

The networks have facilitated CCS knowledge diffusion and also the collaborations among companies, universities and research institutes. The Government should continue to support the networks for further knowledge diffusion of CCS R&D.

F4: Guidance of Search

The early development of CCS in the UK was mainly affected by the EU’s research priority on CCS and Norway’s carbon tax policy that indirectly led to BGS’s
participation in the Sleipner project of carbon dioxide storage under the North Sea. Although the UK Government began to mention CCS in the 2003 Energy White Paper, following this, there was no clear or sufficient guidance from the Government, with the disappointing outcome of the first CCS demonstration competition programme in 2011. The Government made a great effort to strengthen CCS policy in 2012 with the announcement of the UK’s CCS roadmap and the second CCS commercialisation competition with £1billion capital investment, and the establishment of the UK CCS Research Centre with a £125m, 4-year, co-ordinated R&D programme. During the period of this research in conducting interviews, many experts demonstrated their optimistic attitudes towards the UK’s CCS development, as the Government’s funding for CCS R&D and commitment of capital investment for commercialisation projects had boosted CCS R&D capacity in the UK. However, the Government’s decision to cancel the £1billion capital investment in November 2015 has greatly damaged the confidence in the UK’s CCS development. The Government should have stuck with the original plan for the commercialisation projects and kept the promise of £1billion capital fund; however, with the sudden turn of CCS policy, the Government should at least retain the momentum of CCS R&D in the UK and provide a revised roadmap for CCS development.

F5: Market Formation

The function of market formation is considered weak in the UK and, thus, the strength of market pull is still too small to support CCS development. The market formation involves the carbon price of the EU Emissions Trading System (EU ETS), the UK’s carbon price floor and the Feed-in Tariffs with Contracts for Difference. Aside from the EU ETS, the Government can leverage the carbon price floor and the Feed-in Tariffs with Contracts for Difference to speed the development of CCS in the UK. The carbon price floor that is counted as an additional cost would damage the industry if the rate is set too high and the technology is still immature. With that concern, the Government has revised the carbon price floor at £18 per tonne of carbon dioxide (t/CO₂) from 2016-17 to 2019-20. However, as the details of the Feed-in Tariffs with Contracts for Difference are not clear yet for CCS, the Government should quicken policy making for the full range of CCS, including not only electricity companies, but
also those associated with transport and storage. The clear details of the Feed-in Tariffs with Contracts for Difference for CCS can help companies investing in CCS to estimate precise returns and provide market incentives.

**F6: Resource Mobilisation**

Uncertainties about the Government’s CCS policy have weakened the function of resource mobilisation, especially because the first competition programme failed and the second one was cancelled with the change of the Government’s commitment to the £1billion capital investment. After the first competition programme ended, some companies had moved their R&D and financial resources to other CCS projects outside the UK (Scrase & Watson, 2009; Carbon Capture Journal, 2010; Expert C4 and O7). The crucial physical infrastructure on CCS has not been built yet, as the Yorkshire-Humber CCS Trunkline project for CO\(_2\) transport and storage that was incorporated in the White Rose CCS project has been suspended following the cancellation of the second competition programme. Moreover, a possible surplus of human resources has been highlighted, for the delays of demonstration and commercialisation projects cause problems for students trained at postgraduate level for CCS who will not find work in the industry (Expert C4). As for financial resources, the capital investment for demonstration and commercialisation projects is still unavailable as venture capitalists cannot ensure reasonable returns with the high risks and uncertainties of the technologies and the Government policy; nevertheless, the R&D funding from the Government and the EU has been considered sufficient.

Experts urged that the Government should rethink the financial support for demonstration and commercialisation projects in the aftermath of the cancellation of the £1billion capital investment for the second competition programme (Energy & Climate Change Committee, 2016). At least, the Government should maintain the momentum of funding R&D projects for cost reduction or next generation technologies, as well as fostering sufficient CCS workforce (Energy & Climate Change Committee, 2016). Considering the financial constraints on domestic demonstration projects, the current international collaboration can help the UK’s CCS expertise be tested and further developed in other countries, such as the Boundary Dam CCS Project in Saskatchewan, Canada, and the Guandong CCS Project in China.
F7: Creation of Legitimacy

Public understanding of CCS in the UK has been considered insufficient, but some experts suggested that it would not cause great resistance to the UK’s CCS development (Expert C4, C5, T1, S1 and S3). One of the main reasons is that the storage sites are located under the North Sea, which lessens the problem of NIMBY (Not in My Back Yard) (Expert S2 and S3). Another reason is that the existing gas transmission system can be re-used for CO₂ transport, especially in Scotland, which could avoid the impact on building new pipelines (Expert T1). However, E.ON withdrew its Kingsnorth CCS project from the first CCS competition programme, partly because of the protest camp around the site against the plan for a new coal power station with CCS (Expert C1). The Peterhead CCS project and the White Rose CCS project from the second competition, therefore, conducted public engagement and consultation to communicate with communities and stakeholders for better project developments with less resistance. In spite of cancelling the capital funding for the second competition, the Government claimed that “CCS continues to have a potential role in the long-term decarbonisation of the UK” (DECC, 2016b); therefore, continued public engagement and consultation is required not only for local communities with specific projects, but also for enhancing public perception.

International Collaborations

If the Government’s support for CCS commercialisation never recovered, the UK’s CCS expertise can seek international collaborations to be tested and further developed with demonstration projects in other countries. The scale-up experience can then be brought back to the UK with fewer costs. This suggestion is in line with the Government’s recent low carbon policy, The Clean Growth Strategy, which reaffirms its continuing support for CCS development, not only for domestic R&D but also for international pilot projects in countries with a fossil fuel-intensive energy sector, though the capital investment for CCS demonstration or commercialisation is no longer available (DBEIS, 2017b). The UKCCSRC has also recognised that cooperating with international CCS R&D activities can help to accelerate the development of UK CCS capacity, especially because overseas collaborations can
allow the UK to share the cost and risk of R&D and have access to facilities that may not be available in the UK, such as large-scale CCS projects (UKCCSRC, 2014).

In the UKCCSRC’s International Engagement Strategy, Canada has been prioritised as a country with high levels of CCS activities, especially because of the world’s first large-scale CCS commercialisation project, SaskPower’s Boundary Dam CCS Project (UKCCSRC, 2013a). In May 2013, the UKCCSRC signed a Memorandum of Understanding with SaskPower to link the academic R&D programmes with the practical experience on SaskPower’s Boundary Dam CCS Project and to collaborate in improving costs and performance of CCS (Carbon Capture Journal, 2013a). The UKCCSRC has recognised the significant impact and value to its research base for the link with the Boundary Dam CCS Project and also expected to extend the collaboration (UKCCSRC, 2015).

Another important international collaboration is the Guandong CCS Project in China as the UKCCSRC considered China as a priority country for its high level of CCS activity (UKCCSRC, 2013b). In September 2013, the UKCCSRC, Scottish Carbon Capture and Storage (SCCS), Guangdong Low-carbon Technology and Industry Research Centre and the Clean Fossil Energy Development Institute signed a ten-year Memorandum of Understanding for collaborating on the research, development and demonstration of innovative carbon capture, utilisation and storage technologies (Carbon Capture Journal, 2013b). This collaboration project has enabled the UK’s researchers and the Chinese industry to share expertise and exchange staff for the commercialisation of the Guandong CCS Project (Carbon Capture Journal, 2013b).

In addition to the two large-scale CCS projects, the UK also supports and participates in overseas CCS projects in other countries, including Australia, Indonesia, Mexico, the Netherlands, Norway, South Africa, South Korea and the United States (UKCCSRC, 2017). If there will be no CCS commercialisation project in the UK in the short term, those international collaborations would thus be beneficial opportunities for the UK to enhance its CCS expertise and capacity.
Support for Carbon Storage Industry

If a full-chain CCS demonstration project is not affordable, the UK Government should at least help build a carbon storage industry in the North Sea to take the potential advantage of reusing existing infrastructure from the declining oil and gas industry at relatively low cost and financial risk (SCCS, 2015; Ambrose, 2016). The existing oil and gas infrastructure in the North Sea that faces decommissioning as the oil and gas fields reach the end of their lives are urged to be repurposed for CO₂ storage (SCCS, 2015). Apart from the large CO₂ storage asset beneath the North Sea, the UK also possesses the decades of oil and gas industry knowledge, skills and experience that are useful for CO₂ storage, such as selecting secure storage sites (SCCS, 2015).

In addition, the potential for CO₂ enhanced oil recovery has also been recognised to extend the life of oil fields on the UK Continental Shelf for up to 15 years by boosting oil production from mature fields (ERP, 2015). CO₂ enhanced oil recovery can thus deliver extra domestic oil revenues and jobs with postponing decommissioning while the cost of CO₂ storage can also be reduced. To this end, the synergy between CO₂ enhanced oil recovery and CCS is suggested for developing a CO₂ storage industry in the North Sea, which can serve not only the UK but also other neighbouring countries (SCCS, 2015).

However, the challenge of the short timeframe available for developing such CO₂ storage industry in the North Sea has been highlighted as the UK’s CCS development has been kept delayed (SCCS, 2015), the cancellation of large-scale CCS projects in particular, while the clock is ticking for many oil and gas fields on the UK Continental Shelf, including the decommissioning of 214 fields across the North Sea being forecast to take place from 2017 to 2025 (Oil & Gas UK, 2017). In order to meet the challenge, changes to the tax regime have been proposed to quicken the transition from conventional oil production to CO₂ enhanced oil recovery and CO₂ storage, including changes to the tax relief regime for decommissioning and modifications to the offshore tax regime for reducing tax burden on CO₂ enhanced oil recovery (ERP, 2015).

As the cost of decommissioning is incurred as part of the lifecycle of the field, the Government has developed the legal framework, Decommissioning Relief Deeds, on the tax relief regime for decommissioning costs (HM Treasury, 2012). That is, oil and gas companies can claim tax relief on the costs of decommissioning when fields stop
producing while the value of the benefits depends on the amount of tax paid during the life of the field (HM Treasury, 2012). However, the tax relief for decommissioning has not yet been made transferrable to a new business for extending the life of mature fields, including CO₂ enhanced oil recovery and CO₂ storage because of the difference with the definition of the field’s operation (ERP, 2015). Moreover, CO₂ enhanced oil recovery in the North Sea has high upfront capital cost, as well as high risks due to oil price variability and the recovery performance of the fields; therefore, interventions to the offshore tax regime are urged to support the early development of CO₂ enhanced oil recovery, such as Brown Field Allowance for “additionally-developed oil fields” (ERP, 2015; DECC, 2015c).

Therefore, in order to seize the opportunity of redeveloping the declining oil and gas facilities and take the advantage of the immense CO₂ storage in the North Sea, the Government should take action on changes to the tax regimes, including transferrable tax relief for decommissioning and modifications to the offshore tax regime (ERP, 2015; SCCS, 2015). The transition to the CO₂ storage industry with CO₂ enhanced oil recovery can be accelerated, while the huge costs of decommissioning and rebuilding for new operations from scratch can be saved, along with the delivery of additional taxable oil revenues (ERP, 2015; Thomas, 2017).

5.3 Contributions to TIS Literature

The lack of empirical studies on system interactions in the TIS literature has been highlighted in the study of Jacobsson and Bergek (2011). Because the development of the UK’s CCS innovation system involved other innovation systems, this research took the opportunity to investigate the interactions of the UK’s CCS TIS with the EU’s innovation system, Norway’s innovation system and sectoral innovation systems. It was intended that this research be able to contribute the empirical evidence of system interactions to the TIS literature. Key findings on system interactions are summarised below.
Interaction with the EU’s Innovation System

The UK’s CCS innovation system has been affected by the EU’s innovation system on CCS in every function. The EU’s research priority on CCS provided early guidance for the industry and academia in the UK, while the R&D funding from the EU’s framework programmes has been supporting the UK’s CCS entrepreneurial activities and knowledge development. The EU-funded CCS R&D projects that usually involved various participants from industry and academia also facilitated knowledge diffusion. Moreover, the EU Emissions Trading System established a market for CO\(_2\) emissions, although the carbon price is still too low to stimulate CCS development. The UK’s CCS innovation system has overall benefited from the interaction with the EU’s innovation system on CCS, and the influence is expected to continue, especially for the UK’s unstable CCS policy.

Interaction with Norway’s Innovation System

Norway’s innovation system on CCS contributed to the early development of the UK’s CCS innovation system, especially for the CO\(_2\) storage. The Norwegian Government’s carbon tax policy drove Statoil to invest in developing CO\(_2\) storage technologies that led to the SACS (Saline Aquifer CO\(_2\) Storage) project with funding from oil and gas companies, the EU and the Norwegian Research Council. Because of the participation in the SACS and the follow-up projects, the BGS (British Geological Survey) has developed knowledge and obtained experience with monitoring and modelling the distribution of injected CO\(_2\) in saline aquifers, which benefited the CCS development in the UK. The interaction between the two innovation systems continues, as BGS takes part in the collaborative R&D project with Statoil and SINTEF for long-term monitoring technologies for CO\(_2\) storage at the Sleipner field.

Interaction with Sectoral Innovation System

The sectoral innovation systems have also interacted with and contributed to the CCS innovation system in the UK, especially for the fossil fuel power generation sector. The Advanced Power Generation Technology Forum (APGTF) was established within
the UK’s power generation sector to facilitate the development of carbon abatement technologies, including CCS. The network of APGTF has enhanced the functional performances of knowledge development and diffusion with yearly technical workshops and publications. According to Expert C1, C3, C4, C5, T1, T3 and S2, many CCS entrepreneurial activities come from the original sectors or industries such as fossil fuel power plants, electricity companies, oil and gas companies, and other heavy industrial firms, while they also tended to seek collaboration within the existing sector or network. In addition, new start-up or small firms also engage in the TIS with financial support from the public sector, such as Innovate UK (formerly Technology Strategy Board), as well as the private sector, such as the Carbon Trust and Shell’s Springboard programme for low-carbon innovation (Expert C8, C9 & S6). The sectoral innovation systems are thus considered to continue with impacts on the CCS innovation system for their most common and/or vested interests.

**Reflection on the Strengths and Weaknesses of the TIS Approach**

Throughout the analysis of the UK’s CCS development, the TIS approach has demonstrated its strengths in assessing an innovation system with the focus on a certain set of emerging technologies and with the holistic analytical framework in terms of structure and functions, as well as the identification of drivers of and barriers to the system development. Although the TIS approach shares several similar analytical elements with the SIS approach, such as actors, networks, knowledge and institutions, the major difference between these two approaches and the main advantage of TIS for this research is how they set a system’s boundary. That is, the SIS approach defines the system’s boundary with a set of products and places substantial emphasis on the processes of transformation of the existing system (Malerba, 2002). However, the TIS approach establishes system boundary by technological domain and can focus on new, emerging systems with the ability to develop new business opportunities (Coenen & Díaz López, 2010). This advantage of TIS has been demonstrated with the analysis in this research as CCS is a set of emerging technologies with new business development in the UK.

As focusing on new, emerging technologies, the TIS approach can assess an innovation system in the early stage of the development, while there might usually be insufficient
data for analysis. This is another advantage for analysing the UK’s CCS with the TIS approach in comparison with the ST-systems approach because those cases that were successfully analysed by the ST-systems approach had involved major technological transitions with changes in societal functions so there had been sufficient historical data for proper analysis, such as the transition from sailing ships to steamships, 1780-1900 (Geels, 2002), biogas development in Denmark and the Netherlands, 1973-2004 (Raven & Geels, 2010) and a case study of Dutch nuclear energy, 1945-1986 (Geels & Verhees, 2011).

In addition, the ST-systems approach emphasises more on niche-led disruptive innovation as a major driver of social-technical system change than on regime-led innovations like CCS (Winskel, 2012). This research has found that many early entrepreneurial R&D activities on CCS happened in the original regime, including in-house R&D and collaborations within the existing sector or network (Expert C1, C3, C4, C5, T1, T3 and S2). To this end, the suitability of the TIS approach has been demonstrated in this research as the approach can focus well on a regime-led innovation such as CCS in the UK with the aim of adapting rather than replacing the existing system (Winskel, 2012). Similarly, the TIS approach were also successfully employed to assess CCS development within the existing regimes in other countries such as the Netherlands, the United States (van Alphen et al., 2010) and China (Lai et al., 2012).

CCS might be considered as a technological niche if it is linked with CO₂ enhanced oil recovery, which provides economic viability for CCS (Rai et al., 2010; IEA, 2015). According to the UK Government’s CCS Roadmap, the second competition programme favoured potential CCS projects with CO₂ enhanced oil recovery for it can improve the economics of the whole CCS chain by giving CO₂ an economic value (DECC, 2012a), while the CCS Cost Reduction Task Force also highlights the importance of CO₂ enhanced oil recovery for further CCS development in the UK (CCS Cost Reduction Task Force, 2013). However, there have been no commercial CCS project with CO₂ enhanced oil recovery in the UK because the current low oil price has impeded operators’ investment in CO₂ enhanced oil recovery (OGA, 2016; Maslin, 2017). In this regard, the technological niche of CCS with CO₂ enhanced oil recovery has not yet existed in the UK; therefore, the TIS approach would be better
for analysing the UK’s CCS than the ST-systems approach, which concentrates on niche-led innovation.

Although this research intends to focus on the technological development of CCS, political issues around the development happen to be crucial for the UK’s CCS, especially because it relies heavily on the Government’s financial support for scale-up demonstrations. As Littlecott (2012) indicated, the change in government in 2010 postponed and even hindered the UK’s CCS development, especially due to resource cuts, and also insufficient political power to support CCS. For the second competition, Expert O7, who took part in CCS policy making, revealed that it was considered a political decision to withdraw the £1 billion in capital funding and cancel the programme, though the expert could not comment more on why the money was moved away. Moreover, the HC Committee of Public Accounts’ CCS Sixty-fourth Report of Session 2016-17 also concluded that the Treasury intervened in energy policy and impaired the Government’s long-term energy objectives in recent years (CPA, 2017). This is especially the case through cancelling financial support for CCS demonstration projects without fully considering the potential long-term benefits of the projects such as the infrastructure that can be shared with later CCS projects (CPA, 2017). The report thus urged that the Department for Business, Energy and Industrial Strategy should establish a mechanism with the Treasury to better assess the costs and benefits of energy policies with long-term and cross-sector considerations (CPA, 2017).

However, the TIS approach lacks measures in the political aspect for further analysis, though those critical political issues can be identified in this research (Jacobsson & Bergek, 2011; Kern et al., 2016). In order to address political issues for the TIS approach, Jacobsson and Bergek (2011) suggest investigating the decision making process for policy or legislative changes and the external forces that influence the involved policy makers. Geels and his colleagues (2017) also recognised the importance of the politics of policy for analysing low-carbon innovations as their developments are ‘inevitably political’. They suggest probing into the policymaking processes by theoretical models from political science so that more insights for affecting those processes can be obtained, such as political negotiations and compromises (Geels et al., 2017). To this end, the TIS approach can be further improved with the integration of political science for better understanding of policymaking and its politics.
5.4 Limitations of This Research

The data collection of this research might not be sufficient and updated, as the UK’s CCS development is still in progress, while the expert interviews of this research were conducted during 2012 and 2013, with additional six interviews in 2016 and 2017. After this period, there were changes with the UK’s CCS development, especially for the Government’s actions; therefore, the most recent information cannot be acquired for analysis, which would result in a gap between the findings of this research and the up-to-date development.

This research found little quantitative data available, during the period of data collection, such as patent data that can be analysed for better understanding of knowledge development and diffusion in a technological innovation system. In addition, according to several experts’ opinions, applying for patents is not common and popular for CCS technologies in the UK, at least for electricity companies and original equipment manufacturers. Thus, a patent analysis on CCS might not reveal the actual knowledge development and diffusion in the UK.

5.5 Areas for Further Research

This research employed only qualitative analysis with expert interviews and secondary literature review, mainly because the quantitative data were scarce or unavailable during the period of data collection. However, quantitative data analysis can provide further evidence for understanding functional performance. For instance, after the conclusion of the Government-funded £125m 4-year coordinated R&D and innovation programme, the produced papers can be collected for authorship or co-authorship analysis to observe the performances of knowledge development and diffusion. Therefore, as CCS development takes longer in the UK, quantitative data collection and analysis are suggested for future research.

In addition to quantitative analyses, political issues surrounding the development of CCS can be further investigated and elaborated in terms of the decision making process for legislative changes, and influences to the competence of involved policymakers.
International collaborations on CCS demonstration can also be further studied, especially for how the UK’s CCS expertise can be further developed in other countries with either more financial support or fewer costs.
Appendix A: Indicative Questions for the 7 system functions
(Source: van Alphen *et al*. 2010)

<table>
<thead>
<tr>
<th>F1: Entrepreneurial activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The number and the degree of variety in entrepreneurial experiments?</td>
</tr>
<tr>
<td>- The number of different types of applications?</td>
</tr>
<tr>
<td>- The breadth of technologies used and the character of the complementary technologies employed?</td>
</tr>
<tr>
<td>- The number of new entrants and diversifying established firms?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F2: Knowledge creation (development)</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The number and degree of variety in RD&amp;D projects?</td>
</tr>
<tr>
<td>- The type of knowledge (scientific, applied, patents) that is created and by whom?</td>
</tr>
<tr>
<td>- The competitive edge of the knowledge base?</td>
</tr>
<tr>
<td>- The (mis)match between the supply of technical knowledge by universities and demand by industry?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F3: Knowledge diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>- The amount and type of (inter) national collaborating between actors in the innovation system?</td>
</tr>
<tr>
<td>- The kind of knowledge that is shared within these existing partnerships?</td>
</tr>
<tr>
<td>- The amount, type and weight of official gatherings (e.g. conferences, platforms) organised?</td>
</tr>
<tr>
<td>- Configuration of actor-networks (homo, or heterogeneous set of actors)?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F4: Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Amount and type of visions and expectations about the technology?</td>
</tr>
<tr>
<td>- Belief in growth potential?</td>
</tr>
<tr>
<td>- Clarity about the demands of leading users?</td>
</tr>
<tr>
<td>- Specific targets or regulations set by the government or industry?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F5: Market creation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- What phase is the market in and what is its (domestic and export) potential?</td>
</tr>
<tr>
<td>- Who are the users of the technology how is their demand articulated?</td>
</tr>
<tr>
<td>- Institutional stimuli for market formation?</td>
</tr>
<tr>
<td>- Uncertainties faced by potential project developers?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F6: Resource mobilisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Availability of human capital (through education, entrepreneurship or management)?</td>
</tr>
<tr>
<td>- Availability of financial capital (seed and venture capital, government funds for RD&amp;D)?</td>
</tr>
<tr>
<td>- Availability of complementary assets (complementary products, services, network infrastructure)?</td>
</tr>
<tr>
<td>- Level of satisfaction with the amount of resources?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>F7: Legitimisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Public opinion towards the technology and how is the technology depicted in the media?</td>
</tr>
<tr>
<td>- What are the main arguments of actors pro or against the deployment the technology?</td>
</tr>
<tr>
<td>- Legitimacy to make investments in the technology?</td>
</tr>
<tr>
<td>- Activity of lobby groups active in the innovation system (size and strength)?</td>
</tr>
</tbody>
</table>
Appendix B: Patent Analysis

Patents have been used in research for a long time and been considered as “a measure and descriptive indicator of inventive activity” because they provide considerable research advantages (Taylor et al., 2003). Patents contain detailed and direct information on inventive activities for a long time series, and patent statistics also provide information on the rate and direction of innovative activities (Archibugi & Pianta, 1996; Pavitt, 1985). Patents are public documents and their public accessibility can also facilitate the enhancement of technical knowledge and benefit the better understanding of innovation process. From the study of Griliches (1990), there is a strong proportional relationship discovered between patent numbers and R&D expenditures by private firms. Accordingly, without sufficient information on R&D expenditures, plentiful patent data can be used instead as an indicator of inventive input. Moreover, patent data can reveal information on inventive activities outside a private firm, such as network or collaboration with government, academia, or other organisations (Griliches, 1990). In addition, the inventive activities measured by patent numbers can be expected to provide important information in research because the patenting process is costly and time-consuming and the granting of patent ensures the exclusive right to commercialise an invention.

However, there might be some problems with the use of patent data in research. Because not all inventions are patentable or patented (Archibugi & Pianta, 1996), to obtain a comprehensive picture of certain technological development cannot simply depend on patent analysis but should be complemented with other methods, such as expert interviews. Another problem is the qualitative homogeneity of patent counts. Analyses based on patent counts generally consider that each patent has equal weight but this is not a reality as some patents might be valued higher than others, for example depending on the level of commercialisation. To address this problem, patent renewal data have been seen as useful information on determining the value of each patent (Archibugi & Pianta, 1996; Pakes & Simpson, 1989). If the value of certain patent to its owner is still high, the owner must continue to pay the renewal fee to maintain the exclusive right. In addition, citation information on patents can also be used to address the problem because a patent with more citations implies higher social value or technological importance of that patent (Archibugi & Pianta, 1996).
In spite of some problems with patent data analysis, the advantages of patent analysis still considerably benefit this research as long as those problems can be carefully dealt with. Because patents provide public and detailed technical and organisational information over a long period of time, this research can obtain a major tendency of CCS development, including the evolution of patent ownership. With the reality of insufficient information on CCS R&D expenditures, patents as good parallels can also provide a better understanding of CCS development. Moreover, analyses of patenting activities which reveal information on events outside private firms, such as regulatory changes, can help this research realise the connections between CCS innovations and government actions (Griliches, 1990; Taylor et al., 2003).

The initial patent analysis of this research constructs a CCS patent dataset from the worldwide patent database managed by the European Patent Office (EPO) through the Espacenet searching platform. The searching conditions include “Y02C10” in the field of European Classification (ECLA) and “GB” in the field of application number. According to the ECLA system, patents related to CCS are classified into the group of “Y02C10”, followed by several subgroups, as shown in Table B. The application number generally begins with a two-letter country code while “GB” indicates the patent application was filed or granted by the UK. The latest searching access to the database was on 1st February, 2012. The searching result includes 365 patents, and the application dates of collected patents range from 19th September, 1913 to 7th October, 2010. To obtain initial understanding of UK’s CCS development, this research proceeds with analysis of calculating the yearly patent counts by their application dates, as shown in Figure B.

The tendency of the yearly patents counts shows a significant increase during 1969 to 1978, then inclines to decrease, and goes up again from 2003 to 2010. This research expects to proceed to further analyses of this trajectory. However, some problems might affect the usefulness of this initial data. There might be other relevant patents not included in ECLA’s CCS subclass due to the evolution of classification system and variations in the strategic decisions of applicants. A complementary keyword search of patent abstracts thus should be conducted with manual screening to include

---

other relevant patents and exclude those irrelevant. Opinions from patent examiners and technical experts can also help with these problems.

Table B. ECLA Classification on CCS and the Amounts of Assigned Patents

<table>
<thead>
<tr>
<th>Subclass</th>
<th>Definition</th>
<th>Amount of Patents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y02C10</td>
<td>CO₂ Capture or Storage</td>
<td>365²</td>
</tr>
<tr>
<td>Y02C10/02</td>
<td>Capture by biological separation</td>
<td>5</td>
</tr>
<tr>
<td>Y02C10/04</td>
<td>Capture by chemical separation</td>
<td>77</td>
</tr>
<tr>
<td>Y02C10/06</td>
<td>Capture by absorption</td>
<td>176</td>
</tr>
<tr>
<td>Y02C10/08</td>
<td>Capture by adsorption</td>
<td>83</td>
</tr>
<tr>
<td>Y02C10/10</td>
<td>Capture by membranes or diffusion</td>
<td>18</td>
</tr>
<tr>
<td>Y02C10/12</td>
<td>Capture by rectification and condensation</td>
<td>55</td>
</tr>
<tr>
<td>Y02C10/14</td>
<td>Subterranean or submarine CO₂ storage</td>
<td>14</td>
</tr>
</tbody>
</table>


² The total amount of assigned patents under the subclasses of Y02C10 exceeds 365 because a patent might be assigned to multiple subclasses. For example, the patent of GB2472369 (A) is simultaneously assigned to the subclasses of Y02C10/02, Y02C10/04, and Y02C10/06.
Figure B. Yearly Patent Counts of UK’s CCS Technologies from 1913 to 2010

Source: this research
Appendix C: The Approaching Letter for Expert Interview

Dear Sir/Madam,

As you are a renowned expert specialising in Carbon Capture and Storage (CCS), I am approaching you for an expert perspective on my doctoral study at Manchester Business School.

My study is to explore how the innovation system around CCS technologies emerged over time in the UK, and the main drivers of and barriers to further growth. My study particularly probes into what government actions have affected the development of UK’s CCS innovation system. To that end, I am conducting a series of interviews with experts in the field and would very much appreciate the opportunity to speak with you in person to obtain insights into the subject.

The interview will be conducted at your convenience, not last for longer than 1 hour and will be conducted on a semi structured basis; this means that I will ask you quite open-ended questions, and encourage you to talk freely of your thoughts and experiences, and offer any examples to support your views. I will prompt you or ask specific questions if I need further detail on particular issues.

The research is conducted under the normal ethical protocols governing university research activities. Confidentiality is a cornerstone of the ethical approach to research and your responses to my questions will remain anonymous in any analysis and reporting of the research. The interview will be audio-recorded, and the data will be lawfully processed, secured and not kept longer than necessary. If you decide to take part, you will be asked to sign a consent form. You are still free to withdraw at any time without explanation and without detriment to yourself.

The interview will be structured as follows. The first few questions explore how you and/or your organisation got involved with CCS. The second set of questions investigates your views on CCS development over time in the UK in terms of technological innovations, supportive resources (e.g. finance, human), and government policy and regulation. I would particularly like to understand your perspective on how the government actions facilitated or hindered CCS development.

I do hope and appreciate that you are able to spare the time to meet me and kindly let me know your possible time next week or in early April. If you have any questions about the study please do not hesitate to contact me via email yu-chia.ko@postgrad.mbs.ac.uk.

Yours sincerely,

Yu-Chia Ko
Appendix D: Interview Consent Form

Interview Consent Form

for the research project of

Exploring the Role of Government in the Emergence of a CCS Innovation System in the UK

The name of the researcher: Yu-Chia Ko.

If you are happy to participate, please complete and sign the consent form below.

1. I confirm that I have had the opportunity to consider the participation in the above research project and I agree to be interviewed by the researcher.

2. I understand that my participation in the study is voluntary and that I am free to withdraw at any time without giving a reason and without detriment to myself.

3. I understand that the interview will be audio recorded and the recorded data will be lawfully processed, secured and not kept longer than necessary.

4. I agree to the use of anonymous quotes.

I agree to take part in the above research project.

Name of participant and taking consent (print):

Date: ___________________________ Signature: ___________________________

_________________________________________
Appendix E: CCS Projects of EU’s 5th and 6th Framework Programmes

- CCS Projects under the 5th Framework Programme and UK Participants

<table>
<thead>
<tr>
<th>Project acronym</th>
<th>Topic</th>
<th>Total cost (€ million)</th>
<th>EU funding (€ million)</th>
<th>Coordinator</th>
<th>UK participants</th>
<th>Duration</th>
</tr>
</thead>
</table>
| AZEP            | Advanced Membrane Cycles | 9.3 | 3.4 | Siemens | • AREVA T&D UK Ltd  
• University of Ulster | 2001-2004 |
| GRACE           | Capture in Processes | 3.2 | 2.1 | BP | • BP | 2001-2003 |
| GESTCO          | Geological Storage Potential | 3.8 | 1.9 | GEUS | • BGS/NERC | 2000-2003 |
| CO2STORE        | SACS2 Follow Up on Land | 2.4 | 1.2 | Statoil | • IEA Environmental Projects Ltd  
• BP  
• Progressive Energy Ltd  
• BGS/NERC | 2003-2006 |
| NASCENT         | Natural Storage Analogues | 3.3 | 1.9 | BGS/NERC | • BGS/NERC  
• CRE Group Ltd  
• BP | 2001-2004 |
| RECODOL         | Enhanced | 3.4 | 1.7 | TNO | • CRE Group Ltd | 2001-2005 |
| WEYBURN         | Weyburn Monitoring | 2.2 | 1.2 | BGS/NERC | • BGS/NERC  
• CRE Group Ltd  
• Quintessa Ltd | 2001-2004 |
| SACS2           | Monitoring of Sleipner | 2.1 | 1.2 | Statoil | • BGS/NERC  
• CRE Group Ltd | 2000-2002 |
| CO2NET2         | Thematic Network | 2.1 | 1.4 | Statoil | • IEA Environmental Projects Ltd  
• Imperial College of Science, Technology & Medicine  
• Heriot-Watt University  
• ABB Alstom Power UK Ltd  
• Texaco North Sea U.K. Company  
• BP  
• Quintessa Ltd  
• Progressive Energy Ltd  
• BGS/NERC  
• Technology Initiatives Ltd | 2002-2005 |

Source: the European Commission’s Community Research and Development Information Service.


- **CCS Projects under the 6th Framework Programme and UK Participants**

<table>
<thead>
<tr>
<th>Project acronym</th>
<th>Topic</th>
<th>Total cost (€ million)</th>
<th>EU funding (€ million)</th>
<th>Coordinator</th>
<th>UK participants</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO2 Capture Projects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CASTOR</td>
<td>CO2 from Capture to Storage</td>
<td>15.8</td>
<td>8.5</td>
<td>Institut Francais Du Petrole</td>
<td>Imperial College of Science, Technology &amp; Medicine, Doosan Babcock Energy Ltd, Powergen UK Plc, BGS/NERC</td>
<td>2004-2008</td>
</tr>
<tr>
<td>ENCAP</td>
<td>Enhanced capture of CO2</td>
<td>22.2</td>
<td>10.7</td>
<td>Vattenfall AB</td>
<td>Alstom Power, BOC, University of Ulster, Doosan Babcock Energy Limited</td>
<td>2004-2009</td>
</tr>
<tr>
<td>CACHET</td>
<td>CO2 Capture and Hydrogen Production from Gaseous Fuels</td>
<td>13.45</td>
<td>7.5</td>
<td>BP Exploration Ltd</td>
<td>BP Exploration Ltd, Air Products Plc, E.ON UK Plc, Meggitt Ltd</td>
<td>2006-2009</td>
</tr>
<tr>
<td>Advanced CO2 Separation Projects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISCC</td>
<td>Innovative in situ CO2 Capture Technology for Solid Fuel Gasification</td>
<td>2.9</td>
<td>1.9</td>
<td>Universitaet Stuttgart</td>
<td>University of Ulster</td>
<td>2004-2006</td>
</tr>
<tr>
<td>C3-CAPTURE</td>
<td>Calcium Cycle for Efficient and Low-cost CO2 Capture using Fluidised Bed Systems</td>
<td>2.7</td>
<td>1.8</td>
<td>Universitaet Stuttgart</td>
<td>Cranfield University</td>
<td>2005-2008</td>
</tr>
<tr>
<td>Project</td>
<td>Description</td>
<td>Budget</td>
<td>Duration</td>
<td>Responsible Bodies</td>
<td>Co-Responsibles</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>--------</td>
<td>----------</td>
<td>-------------------</td>
<td>-----------------</td>
<td></td>
</tr>
<tr>
<td><strong>CLC-GAS POWER</strong></td>
<td>Chemical Looping Combustion CO2-Ready Gas Power</td>
<td>2.13</td>
<td>2006-2008</td>
<td>Chalmers University of Technology</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td><strong>DESANNS</strong></td>
<td>Advanced separation and storage of CO2</td>
<td>3.5</td>
<td>2006-2008</td>
<td>CNRS</td>
<td>Royal Institution, University of Manchester, University of Edinburgh, University of Saint Andrews</td>
<td></td>
</tr>
<tr>
<td><strong>HY2SEPS</strong></td>
<td>Hybrid Hydrogen CO2 Separation Systems</td>
<td>2.53</td>
<td>2005-2008</td>
<td>Foundation For Research And Technology Hellas</td>
<td>Imperial College of Science Technology &amp; Medicine, Process Systems Enterprise Ltd</td>
<td></td>
</tr>
<tr>
<td><strong>CO2 Storage Projects</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>CO2SINK</strong></td>
<td>In situ R&amp;D Laboratory for Geological Storage of CO2</td>
<td>23</td>
<td>2004-2010</td>
<td>GeoForschungsZentrum Potsdam</td>
<td>IEA Environmental Projects Ltd, University of Kent</td>
<td></td>
</tr>
<tr>
<td><strong>CO2GEONET</strong></td>
<td>Network of Excellence on Geological Sequestration of CO2</td>
<td>9.18</td>
<td>2004-2009</td>
<td>BGS/NERC</td>
<td>BGS/NERC, Imperial College of Science, Technology &amp; Medicine, Heriot-Watt University</td>
<td></td>
</tr>
<tr>
<td><strong>MOVECB M</strong></td>
<td>Monitoring and verification of CO2 storage and ECBM in Poland</td>
<td>2.67</td>
<td>2006-2008</td>
<td>TNO</td>
<td>IEA Environmental Projects Ltd</td>
<td></td>
</tr>
<tr>
<td><strong>CO2REMOVE</strong></td>
<td>CO2 Geological Storage: Research into Monitoring and Verification Technology</td>
<td>15</td>
<td>2006-2012</td>
<td>TNO</td>
<td>BP, Quintessa Ltd, BGS/NERC, Imperial College of Science, Technology &amp; Medicine, IEA Environmental Projects Ltd</td>
<td></td>
</tr>
<tr>
<td>Project</td>
<td>Description</td>
<td>Budget</td>
<td>CO2</td>
<td>Organisation(s)</td>
<td>Duration</td>
<td></td>
</tr>
<tr>
<td>------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------</td>
<td>-----</td>
<td>----------------------------------</td>
<td>--------------</td>
<td></td>
</tr>
<tr>
<td>CO2NET-EAST</td>
<td>CCS networking extension to new member states</td>
<td>0.32</td>
<td>0.29</td>
<td>Czech Geological Survey</td>
<td>N/A</td>
<td>2006-2010</td>
</tr>
<tr>
<td><strong>Projects with A Substantial International Dimension</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COACH</td>
<td>Cooperation Action with CCS – China-EU</td>
<td>2.62</td>
<td>1.5</td>
<td>IFP Energies Nouvelles</td>
<td></td>
<td>2006-2009</td>
</tr>
<tr>
<td>INCA-CO2</td>
<td>International Cooperation Actions on CCS</td>
<td>0.7</td>
<td>0.44</td>
<td>Institut Francais Du Petrole</td>
<td></td>
<td>2004-2008</td>
</tr>
</tbody>
</table>

Source: the European Commission's Community Research and Development Information Service.
Appendix F: CCS Pilot Projects in the UK

- Aberthaw Pilot Plant

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Aberthaw Pilot Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company</td>
<td>RWE npower, Cansolv Technologies Inc (part of Shell Group)</td>
</tr>
<tr>
<td>Location</td>
<td>Aberthaw (near Barry), Wales</td>
</tr>
<tr>
<td>Scale</td>
<td>Pilot</td>
</tr>
<tr>
<td>Construction</td>
<td>Retrofit</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>1500 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal, some biomass co-firing</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>3 MW (50 Tons CO2/day)</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>Post-combustion (Cansolv amine system)</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>No storage</td>
</tr>
<tr>
<td>Timing</td>
<td>Start: January 2013; Finish: 2015</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>GBP 8.4 million</td>
</tr>
<tr>
<td>Project Description</td>
<td>A post combustion capture pilot plant using Cansolv technology. Takes a slipstream from main station equivalent to 3 MW and captures up to 50 tonnes of CO2 per day. Operational from early 2013 with two year R&amp;D programme planed before consideration of scaling up. RWE has recently completed construction of a 3MWe carbon capture pilot plant at our coal-fired power station in Aberthaw. This will test technology to capture the carbon dioxide from the flue gases and will form a vital part of RWE’s research programme into carbon capture and storage technology. In January 2013, the Aberthaw Carbon Capture Pilot plant captured its first tonne of CO2. Over the next two years it will undertake an extensive R&amp;D programme to help better understanding of how this technology could be used to reduce carbon emissions at coal-fired power stations. RWE npower expects the Aberthaw plant to help it optimise CCS technology and provide an insight into reducing emissions from coal power stations and the viability of running a full-scale carbon capture facility in conjunction with normal power plant operations.</td>
</tr>
</tbody>
</table>
Ferrybridge CC Pilot100+

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Ferrybridge CC Pilot100+</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>Scottish and Southern Energy (SSE), Doosan Babcock and Vattenfall</td>
</tr>
<tr>
<td>Location</td>
<td>Ferrybridge Station, West Yorkshire</td>
</tr>
<tr>
<td>Scale</td>
<td>Pilot</td>
</tr>
<tr>
<td>Construction</td>
<td>Retrofit</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>490 MW/Unit</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal, small proportion of biomass</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>5 MW (100 Tons CO2/day)</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>Post-combustion (Doosan Babcock amine system)</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>No storage</td>
</tr>
<tr>
<td>Timing</td>
<td>Start: November 2011</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>GBP 21 million, including GBP 6.3 million awarded (Mar 2010) from UK Government (DECC), the Technology Strategy Board and Northern Way.</td>
</tr>
<tr>
<td>Project Description</td>
<td>Following completion of its construction phase, the Ferrybridge Carbon Capture Pilot (CC Pilot100+) was launched on 30 November 2011 as a collaborative project between Government and industry. The project will test amine based post combustion capture (PCC) technology on a real working power station. The test programme will run during 2012 and 2013 to optimise the process and components, and develop performance models. Much of the Ferrybridge capture plant has been built using components from a British supply chain. It uses real flue gases from Scottish and Southern Energy’s (SSE) Ferrybridge coal and biomass power station, capturing up to 100 tCO2 per day. As the largest carbon capture plant of any type in the UK at present, Ferrybridge is a significant step forward in the world of CCS as a critical bridge between research and commercialisation. The aim of the project is to prove the application of the amine solvent post combustion capture process under realistic operating conditions. It will also enable us to gain knowledge that will be invaluable in the near-term scale up and deployment of CCS and</td>
</tr>
</tbody>
</table>
move us closer to our long term aim: cost competitive CCS deployment by the 2020s.

Website  
http://www.sse.com/Ferrybridge/TheCarbonCaptureProject/ProjectInformation/

- Renfrew Oxycoal2

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Renfrew Oxycoal2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>Doosan Babcock</td>
</tr>
<tr>
<td>Location</td>
<td>Renfrew, Scotland</td>
</tr>
<tr>
<td>Scale</td>
<td>Pilot</td>
</tr>
<tr>
<td>Construction</td>
<td>New</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>40 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>40 MW oxyfuel burner test rig</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>Oxy-fuel</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>No storage</td>
</tr>
<tr>
<td>Timing</td>
<td>Start: December 2007; Finish: 2011</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>GBP 8.2 million, including GBP 1.6 million from UK Government (DECC)</td>
</tr>
<tr>
<td>Project Description</td>
<td>The project, a test rig adapted specifically for testing oxyfuel capture technology (on pulverised coal) and applicable to both new and retrofit supercritical boilers, completed the test programme in early 2011. Testing of the 40MW oxyfuel burner took place under realistic operating conditions and included testing adaptation from air firing to oxyfuel firing. Following the successful test programme, it was concluded that the technology could be used on commercial scale plants. The Oxyfuel (Oxycoal 2) pilot project at Doosan Power System’s Clean Combustion Test Facility in Renfrew, Scotland started in December 2007. The project, a test rig adapted specifically for testing oxyfuel capture technology (on pulverised coal) and applicable to both new and retrofit supercritical boilers, completed the test programme in early 2011. Testing of the 40MW oxyfuel burner took place under realistic operating conditions and included testing adaptation from air firing</td>
</tr>
</tbody>
</table>
to oxyfuel firing. Following the successful test programme, it was concluded that the technology could be used on commercial scale plants. Key findings of the project include:

- increased knowledge, capacity and confidence in oxyfuel technology in the UK
- costs of an oxyfuel system are similar to an air firing plant
- no major furnace or boiler design changes are needed to adapt air firing to oxyfuel
- operating performance achieved was satisfactory for commercial scale plants

| Website | http://www.doosan.com/doosanheavybiz/en/services/green_energy/oxy_fuel.page |
## Appendix G: CCS Demonstration and Commercialisation Projects in the UK

- **White Rose Project**

<table>
<thead>
<tr>
<th>Project Name</th>
<th>White Rose Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>Capture Power Ltd, the consortium of Alstom, Drax and BOC</td>
</tr>
<tr>
<td>Location</td>
<td>Selby, North Yorkshire</td>
</tr>
<tr>
<td>Scale</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Construction</td>
<td>New</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>3960 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal, potential to co-fire biomass</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>426 MW (90% capture: 2 Mt/yr CO2)</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>Oxyfuel (Alstom)</td>
</tr>
<tr>
<td>Transport</td>
<td>Pipe (National Grid)</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>Offshore storage in saline formation</td>
</tr>
<tr>
<td>Timing</td>
<td>Intended Operational Year: 2016</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>£2 billion</td>
</tr>
</tbody>
</table>

**Project Description**

New stand-alone oxy-fired 426 MW gross unit at Drax power plant. Captured CO2 to be stored offshore. Transport by new pipeline - Yorkshire-Humber CCS Trunkline - being developed by National Grid Carbon. In January 2012, BOC enlisted to provide air separation technology. In December 2013, contract for two-year FEED study agreed with funding from DECC.

The world’s first commercial scale, full chain, carbon capture and storage coal-fired power plant is being proposed by developer, Capture Power. The White Rose Carbon Capture and Storage Project (White Rose CCS Project), will comprise a state-of-the-art coal-fired power plant that is equipped with full carbon capture and storage technology. The project is intended to prove CCS technology at commercial scale and demonstrate it as a competitive form of low carbon power generation and as an important technology in tackling climate change. It will also play an important role in establishing a CO2 transportation and storage network in the Yorkshire and Humber area.
The standalone power plant will be located adjacent to the existing Drax Power Station site near Selby, North Yorkshire, generating electricity for export to the national transmission network as well as capturing approximately 2 million tonnes of CO2 per year, some 90% of all CO2 emissions produced by the plant. The CO2 will be transported through National Grid’s proposed pipeline for safe and permanent undersea storage in the North Sea.

The GE power plant technology, known as oxy-fuel combustion, burns fuel in a modified combustion environment with the resulting combustion gases being high in CO2 concentration. This allows the CO2 produced to be captured without the need for additional chemical separation, before being piped for storage.

Capture Power plans to develop, implement and operate the White Rose CCS Project and National Grid will construct and operate the CO2 transport pipeline – the Yorkshire and Humber CCS Cross-Country Pipeline – and, with partners, the permanent CO2 undersea storage facilities at a North Sea site.

Website
http://www.whiteroseccs.co.uk/

**Peterhead Project**

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Peterhead Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>Scottish and Southern Energy (SSE) and Shell</td>
</tr>
<tr>
<td>Location</td>
<td>Peterhead, Scotland</td>
</tr>
<tr>
<td>Scale</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Construction</td>
<td>Retrofit</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>2177 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Gas</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>385 MW (1 Mt/yr CO2)</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>Post-combustion</td>
</tr>
<tr>
<td>Transport</td>
<td>Pipe (Shell), reuse of existing pipeline to St Fergus</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>Offshore storage in the Goldeneye depleted gas field</td>
</tr>
<tr>
<td>Timing</td>
<td>Intended Operational Year: 2017</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>N</td>
</tr>
</tbody>
</table>
Project Description

SSE and Shell are developing a CCS demonstration project at Peterhead gas power plant, retrofitting post-combustion capture to one of three 385MW turbines at the existing facility. CO2 will be transported by existing pipeline to St Fergus, then offshore for storage in Shell’s Goldeneye depleted gas field. In 2012 the storage project was granted the first UK licence for permanent sub-sea geologic storage of CO2. In March 2013 the project was selected as one of two preferred bidders for FEED study funding under the UK Government’s Commercialisation Programme. An announcement of FEED study contracts is expected in early 2014.

Website
http://www.shell.co.uk/gbr/environment-society/environment-tpkg/peterhead-ccs-project.html

- Captain Clean Energy Project

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Captain Clean Energy Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>Summit Power Group, National Grid, CO2DeepStore (a Petrofac subsidiary)</td>
</tr>
<tr>
<td>Location</td>
<td>Grangemouth, Scotland</td>
</tr>
<tr>
<td>Scale</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Construction</td>
<td>New</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>570 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>Injection: 3.8 Mt/yr CO2</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>IGCC Post-combustion</td>
</tr>
<tr>
<td>Transport</td>
<td>Pipe (National Grid)</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>Offshore storage in saline formation</td>
</tr>
<tr>
<td>Timing</td>
<td>Intended Operational Year: 2018</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>N</td>
</tr>
<tr>
<td>Project Description</td>
<td>New build IGCC coal power plant, based on Summit Power Texas Clean Energy Project design. CO2 storage planned through EOR in North Sea. CO2Deepstore have completed management buy-out of Petrofac’s interest in project.</td>
</tr>
<tr>
<td>Website</td>
<td><a href="http://www.summitpower.com/projects/carbon-capture/">http://www.summitpower.com/projects/carbon-capture/</a></td>
</tr>
</tbody>
</table>
### Teesside Low Carbon Project

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Teesside Low Carbon Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>Teesside Low Carbon Consortium (Progressive Energy, BOC, International Power (GDF Suez), Premier oil)</td>
</tr>
<tr>
<td>Location</td>
<td>Eston, Teeside</td>
</tr>
<tr>
<td>Scale</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Construction</td>
<td>New</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>850 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>Injection: 2.3 Mt/yr CO2</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>IGCC Pre-combustion</td>
</tr>
<tr>
<td>Transport</td>
<td>Pipe</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>Offshore storage in depleted oil and gas fields</td>
</tr>
<tr>
<td>Timing</td>
<td>Intended Operational Year: 2016</td>
</tr>
<tr>
<td>Estimated Cost</td>
<td>N</td>
</tr>
<tr>
<td>Project Description</td>
<td>New build IGCC with CCS power plant. Envisaged as anchor project for Teesside cluster. Storage planned in depleted oil and gas fields, Central North Sea, with some also in a saline aquifer and possibility for EOR.</td>
</tr>
<tr>
<td>Website</td>
<td><a href="http://www.teessidelowcarbon.com/">http://www.teessidelowcarbon.com/</a></td>
</tr>
</tbody>
</table>

### C.GEN Killingholme Project

<table>
<thead>
<tr>
<th>Project Name</th>
<th>C.GEN Killingholme Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>C.Gen and National Grid</td>
</tr>
<tr>
<td>Location</td>
<td>Immingham, North Lincolnshire</td>
</tr>
<tr>
<td>Scale</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Construction</td>
<td>New</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>470 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal; biomass and petcoke also considered as fuels</td>
</tr>
</tbody>
</table>
Don Valley Power Project

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Don Valley Power Project (formerly known as the Hatfield Project)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Company/Alliance</td>
<td>2Co Energy Ltd acquired Powerfuel Power Ltd and the Hatfield CCS project in May 2011</td>
</tr>
<tr>
<td>Location</td>
<td>Stainforth, South Yorkshire</td>
</tr>
<tr>
<td>Scale</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Construction</td>
<td>New</td>
</tr>
<tr>
<td>Power Plant Size</td>
<td>920 MW</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Coal</td>
</tr>
<tr>
<td>CCS Capacity</td>
<td>up to 5 Mt/yr CO2</td>
</tr>
<tr>
<td>Capture Technology</td>
<td>IGCC Pre-combustion</td>
</tr>
<tr>
<td>Transport</td>
<td>Pipe (National Grid)</td>
</tr>
<tr>
<td>CO2 Fate</td>
<td>Offshore storage in saline formation</td>
</tr>
</tbody>
</table>

Website: [http://www.cgenpower.com/kgh/index.html](http://www.cgenpower.com/kgh/index.html)
<table>
<thead>
<tr>
<th>Timing</th>
<th>Intended Operational Year: 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated Cost</td>
<td>£5 billion (The project was awarded €180 million from the European Energy Programme for Recovery (EEPR) in December 2009)</td>
</tr>
<tr>
<td>Project Description</td>
<td>The Don Valley Power Project was at the top of the list to receive a share of the EU’s NER300 funding; however the UK government not guaranteeing financial support of the project therefore Don Valley did not receive any NER300 funding. The project entered into the UK Government’s second CCS competition but was not chosen as one of the top 4 projects to receive funding, thereby being out of the competition. This, coupled with the lack of financial support from the EU, has made the future of the project uncertain.</td>
</tr>
<tr>
<td>Website</td>
<td><a href="http://www.2coenergy.com/don_valley_power_project.html">http://www.2coenergy.com/don_valley_power_project.html</a></td>
</tr>
</tbody>
</table>


Clark, P. 2016. UK power prices go negative as renewables boom distorts market. Financial Times, 20 May.


