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Carbon Capture and Storage as a stepping-stone to negative emissions.

An analysis of the factors impacting fossil energy CCS and the consequences for atmospheric carbon dioxide removal.

A thesis submitted in partial fulfilment of the requirement for the degree of

MASTERS OF RESEARCH

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by

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Abstract

Whereas ten years ago Carbon Capture and Storage looked to have a lot of promise, today it may be a climate solution whose time has passed. In 2005 the IPCC had released a Special Report lauding the potential of CCS, major demonstration projects were being initiated and the G8 had announced that it expected CCS to play a major role in combatting climate change. Fast forward to 2016, and demonstration projects have stalled or been cancelled, the G8 has moved on and CCS is conspicuously absent from the Nationally Determined Contributions coming from the December 2015 Paris Climate meeting (COP21).

This thesis questions if CCS should be abandoned so quickly. It is increasingly acknowledged that carbon dioxide removal will be required in the second half of the century and that bio-energy CCS is the primary candidate to provide this removal. This thesis argues that without the diffusion of fossil energy CCS over the coming decades, the ability to ramp up bio-energy CCS will be compromised.

The factors that may shape the future of fossil energy CCS are analysed from the perspective of relevant stakeholders. It is shown that although feasible, it is not in any individual stakeholder's interest to invest significant capital to ensure its success. This thesis contends that there is a strong case for further evaluation of CCS incorporating considerations of total cost of mitigation and the likely need for negative emissions.

Statement of Authorship

I state that this thesis titled, *"Carbon Capture and Storage as a stepping*-*stone to negative emissions: An analysis of the factors impacting fossil energy CCS and the consequences for atmospheric carbon dioxide removal"* is truly my original work. This work was done wholly during my candidature for the degree of Masters of Research at Macquarie University. Neither this thesis nor any part of it has been submitted for any other degree or at any other university. Other sources or materials consulted are clearly cited throughout the thesis and listed in the bibliography. Where I have quoted from the work of others, sources are always given. With the exception of these quotations, this thesis is entirely my own work.

21st April 2016

Bryan Maher

Units, Conversion Factors and Acronyms.

The following decimal unit prefixes are used:

Name	Symbol	10^n
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}

Conversion Factors

Unit 1	Unit 2
1 GtC (Carbon)	3.664 $GtCO_2$ (Carbon Dioxide)
1 ppm (parts per million)	7.77 $GtCO_2$
1 peta Joule (PJ)	277.8 GWh
1 MW of power @ 30% capacity provides 2.628 GWh of energy/y	

Acronyms.

5 AR	(The IPCC's) Fifth Assessment Report
ATSE	Australian Academy of Technological Sciences and Engineering
BECCS	Bio-energy Carbon Capture and Storage
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
COP	Conference of Parties
DAC	Direct Air Capture
EIA	Energy Information Administration (US Federal body)
EMF	Energy Modelling Forum (Stanford University)
EOR	Enhanced Oil Recovery
FECCS	Fossil-energy Carbon Capture and Storage
GCCSI	Global Carbon Capture and Storage Institute
GHG	Green House Gas
HELE	High Efficiency Low Emissions
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
LNG	Liquefied Natural Gas
MCA	Minerals Council of Australia
NDC	Nationally Determined Contribution
OEM	Original Equipment Manufacturer
ppm	parts per million
ROI	Return on Investment
SRCCS	Special Report on Carbon Capture and Storage (IPCC report).
SRM	Solar Radiation Management
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change

Chapter 1: Introduction and Overview

Positioning CCS as a Carbon Dioxide Mitigation and Removal Process

At the Paris Conference of Parties (COP 21) one hundred and ninety five of the world's nations recommitted to a goal of limiting warming to "well below" 2-degrees and to "drive efforts" towards a 1.5 degree goal (UNFCCC 2015b). However, when the emission commitments of these 195 nations are added together, they are not adequate to achieve the 2-degree goal, let alone to limiting warming to 1.5-degrees. In fact it has been calculated that even should these commitments be fully implemented, but no follow up commitments made, temperature increases by 2100 will likely be in the region of 3.5-degrees relative to the 1850-1900 period (Climate Interactive 2016).

There is growing agreement that to meet either of these goals, a climate strategy that includes both reducing carbon dioxide emissions and removing carbon dioxide from the atmosphere is required. This is made clear early in the fifth and latest IPCC Assessment Report, AR5. The first paragraph in the foreword to the 'Mitigation of Climate Change' volume states that it provides a "comprehensive and transparent assessment of relevant options for mitigating climate change through limiting or preventing greenhouse gas (GHG) emissions, as well as activities that reduce their concentrations in the atmosphere" (IPCC 2014a, p. vii).

The mitigation options outlined throughout the report are well known and include energy efficiency, renewables and the application of carbon capture and storage to fossil energy emissions. However, the issue of negative emissions receives less policy engagement (Lomax et al. 2015). Nonetheless, of 116 scenarios included within AR5 that are consistent with a 2-degrees goal, 101 require net carbon reduction in the second half of the century (Fuss et al. 2014). There are various approaches to carbon dioxide removal (CDR), but the approach most widely discussed throughout AR5 is bio-energy carbon capture and storage (BECCS).[1]

The common factor that provides the ability to both reduce CO_2 emissions and reduce CO_2 atmospheric concentrations is carbon capture and storage. Fossil-energy CCS (FECCS)

[1] The terms "Carbon Dioxide Removal" (CDR) and "Negative Emissions" are both frequently found in the literature and are used interchangeably through this thesis.

mitigates carbon dioxide emissions, most significantly those originating from coal fired power stations (but also potentially from other sources such as gas power and steel making), while BECCS theoretically provides the ability to reduce atmospheric concentrations of carbon dioxide by burning sustainably harvested biomass and capturing and storing the resultant emissions.

According to the IPCC, and as will be discussed on pages 35-37, omitting CCS from the suite of climate strategies drives up total mitigation costs much more than would omitting other options such as widespread diffusion of renewables or nuclear (IPCC 2014a, p. 15). However, somewhat perplexingly, CCS does not appear to be front and centre in the minds of policy makers. The negligible attention CCS received in the Nationally Determined Contributions reported from the COP 21 meeting (UNFCCC 2015c) is a recent telling example.[2] This thesis examines the puzzle as to why the most cost effective emissions control technology is receiving so little attention. Additionally the thesis also investigates the logical hypothesis that fossil energy CCS may be a stepping stone to eventually achieving negative emissions through bio-energy CCS. Should this prove to be the case, and for reasons of cost efficiency, it seems reasonable to assume that CCS should play a significant role in the fight against global warming.

CCS's (most specifically FECCS's) potential for combatting climate change has long been recognised but doubts persist over whether this potential will be realised. A significant milestone in raising the profile of CCS was the IPCC's Special Report on Carbon Capture and Storage (SRCCS) (IPCC 2005). This report highlighted CCS's potential to achieve mitigation levels at least equal to the contributions of nuclear or renewables (p. 352). The SRCCS focused primarily on FECCS and while BECCS was acknowledged, the likely imperative of CDR was not widely discussed in 2005. In addition to the IPCC, bodies such as the International Energy Agency (IEA 2013) and the G8 (2009) have announced their expectation that CCS would play a key role in combatting climate change throughout this century, but with the emphasis changing from FECCS to BECCS as the century progresses. However although there are many reports highlighting the potential of FECCS, actual commercial implementation for power generation is limited to one site: Canada's

[2] Frequently referred to as *Intended* Nationally Determined Contributions prior to the COP meeting. For consistency purposes, I have dropped the word "Intended" throughout this thesis.

Saskpower's Boundary Dam (Saskpower CCS 2014b) which came on line in 2014.[3] Indeed there are signs that research and interest in CCS appears to be waning. CCS development has been sporadic with well-publicised initiatives such as FutureGen in the US (Snyder & Drajam 2015) and Australia's ZeroGen (Lion 2010) stalling or being abandoned. There are also growing arguments that CCS is not cost effective (Lilliestam, Bielicki & Patt 2012; van der Zwaan & Tavoni 2011) and that issues with regard to transport and long-term storage are not resolved (Spreng, Marland & Weinberg 2007).

CCS development and diffusion is a complex issue with political, economic and technical challenges that need to be overcome for it to make a significant contribution to the mitigation of CO_2 emissions and concentrations. Multiple parties are involved or potentially will be involved in determining the fate of CCS. Resource and energy companies are typically proponents of FECCS, as without it they may end up with oil, gas and coal reserves that are unusable. However, their willingness to invest in the required technologies remains an open question. Others claim FECCS is an unlikely technology that is being used as a deception by the coal industry to perpetuate the use of its product (Pearse, McKnight & Burton 2013). Alternatively, some caution of the risks that FECCS will lock in coal as a long term energy source (Kirchsteiger 2008). Additionally, nuclear and renewables are competitors to FECCS in a carbon constrained energy market and the cost competitive deployment of FECCS could impact their growth potential. Meanwhile, large-scale deployment of BECCS remains an academic consideration and has yet to significantly enter the public debate.

The on-the-ground experience raises the question whether the expectations of the IPCC, IEA and the G8 are misplaced. If they are, then the implications for an effective climate strategy should be carefully considered; both in the provision of cleaner energy in the medium term and the likely requirement for negative emissions as the century progresses.

Research Question.

This thesis investigates two separate but inter-related issues. First, does FECCS provide a stepping-stone to future negative emission via the widespread diffusion of BECCS? And

[3] SaskPower Boundary Dam coal fired power station captures 1 $MtCO_2$/y for enhanced oil recovery application.

second, considering the motivations of various FECCS stakeholders, what are the prospects for FECCS in the near to medium term future?

The role that FECCS may play in enabling the longer-term transition to CDR via BECCS receives little attention in the literature. This thesis provides a first pass analysis of the dependency that BECCS may have on FECCS. Regarding the second issue, the role and future of FECCS is well studied; however, much of the literature is single issue focused and is located within the disciplines of chemistry, geology, politics, energy economics and business. I recognise that some writers do take a cross disciplinary approach to FECCS, see for example the work by David Victor (a political/technical perspective) or Nils Markusson and others (a socio-technical perspective) (Markusson et al. 2012; Victor, D 2011). However, there is ongoing scope for consideration of the issues from a systems viewpoint where the interconnectedness and impacts of self interested stakeholders and local decisions are considered (Senge & Sterman 1992). In fact Robert Keohane (2015) laments the lack of engagement from political scientists in the area of climate change, despite exceptions such as David Victor. This thesis takes a cross-disciplinary view of the interacting forces driving and restraining CCS including the coal industry, the financial markets, competitive forces, innovation processes and political dynamics.

Methodology

The two research questions are analysed through two related but differing processes.

The novelty of the stepping-stone question comes from the fact that there appears to have been little work done on contrasting both forms of CCS. The literature on BECCS is growing but it remains a relatively new area of research; however, there is extensive literature on FECCS. My analysis thus proceeds through an examination of the two sets of literature, drawing inferences as to the relationship between the key processes that together form carbon capture and storage. This necessitates a broad, but given the space constraints, a relatively high level review of diverse sets of literature including technical, regulatory and social. Similarly establishing the feasibility of BECCS and how it compares to other CDR approaches requires detailed and quantitative analysis of new literature, some of which was being published as this thesis was being prepared.

The potential for successful diffusion of FECCS is assessed through a stakeholder analysis whereby the various actors that are either promoting or restraining FECCS are considered.

The stakeholder selection process was intuitive, but also assisted by the IPCC's AR5. In its analysis of risk and uncertainties, AR5 identified the following as stakeholders: the individual, industry, different levels of government and the international community (via international agreements) (IPCC 2014a, p. 159). For the purposes of this analysis I have mirrored the AR5 approach and identified the stakeholders as the public, industry (specifically the coal industry, the renewables industry, relevant OEMs), national governments [4] and the Green lobby. Their interests are counter-posed against the perspectives that I draw from IPCC reports (primarily AR5 and SRCCS) and other work from the broader epistemic climate community. Although this community holds little authority it exerts considerable influence and consequently I have included it as a stakeholder.[5]

Stakeholder analysis is a qualitative business orientated process that provides an integrated and systems perspective through which to examine CCS. It is commonly applied to environments where there are multiple actors with vested interests in an outcome and where each possess varying power and influence. For example, stakeholder analysis is frequently used in project management, as it can provide insights as to how various stakeholders can be managed to achieve desired outcomes (Varvasovszky & Brugha 2000). The development of FECCS diffusion can be perceived as the provision of a challenging global public good, or a massive world-wide project, that has a high dependency on the motivations of the actors involved. A separate and related purpose of stakeholder analysis is assessing the feasibility of success by identifying and assessing the interests of the various actors of the system (Grimble & Wellard 1997). This thesis will primarily focus on the latter purpose, i.e. it will assess whether relevant stakeholders are motivated to drive FECCS to meaningful diffusion. Stakeholder perceptions and intentions are frequently determined via survey (see as examples Reiner & Liang 2012; Setiawan & Cuppen 2013), however, due to the wide-ranging scope of the analysis, conducting primary research was outside the scope of this thesis. Rather the stakeholder analysis primarily proceeds through a broad ranging review

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[4] Although states have diverse interests vis a vis climate change, their limited investment in CCS enables a level of generalisation that would not be feasible in other climate policy areas.

[5] Whether the epistemic climate community is a stakeholder may be contentious, however much of the perspectives of other stakeholders are determined through analysing the output from the IPCC and academics working in the multiple disciplines of climate science.

of the literature considering financial motivations and past behaviour to infer future positions regarding FECCS. This includes business strategy and behaviour, considerations of the coal industry, technical and financial considerations, responses from the renewables industry and green groups and analyses of public opinion. To illustrate the position of stakeholders, appropriate techniques are employed such as case studies, (the Global Carbon Capture and Storage Institute) and analytical approaches from other writers, for example, David Victor's matrix analysing technology strategy where he considers investment attractiveness based on the parameters of "lock-out" and "appropriability" (2011, p. 130).

Scope and Boundaries

The analysis in this thesis is limited to coal fired power generation and bioenergy CCS. The concept of Carbon Capture and Use (CCU) will not be explicitly considered other than where it impacts the cost competitiveness of carbon capture and storage. Additionally the application to gas power, fugitive emissions, industrial processes or transport is excluded.[6] Coal is selected as it is the largest (EIA 2013) and most polluting (EIA n.d.-a) feedstock for electrical power generation and although the growth rate of coal is predicted to sharply decline its use will likely continue to grow through to 2035 (BP 2016; EIA 2013, p. 68). Bioenergy with CCS is also an important component of the climate change strategy in so far as it provides the opportunity to provide negative emissions (Gasser et al. 2015), (IPCC 2014a, p. 18); however the IPCC also recognises the significant uncertainty surrounding large-scale deployment of BECCS (ibid. p. 52.).

While the thesis is global in scope, there is a focus on the Australian coal environment. Australia is the world's sixth largest producer of thermal coal and second largest exporter of coal (after Indonesia) (IEA 2015, pp. 80-3). Australia generated 61% of its electricity from coal in 2013 compared to the EU's 27% in 2012 and the US's 33% in 2015 (EIA n.d.-b, p. 21; Eurostat 2015; Office of the Chief Economist 2015). Also Australia has been an early mover in CCS with the establishment of the Global CCS Institute and the development (and subsequent abandonment) of a large CCS demonstration project, "ZeroGen". Consequently with Australia having so much to gain from CCS there remains an open

[6] This is not to downplay the importance of emissions from these sources. For example the coal used in steel manufacturing produces significant emissions and currently has no cost effective low carbon alternative (IPCC 2014a, p. 758).

question as to whether it will make proportionate investments in bringing the technology to maturity.

The Scale of the Challenge

The term "meaningful" is used frequently throughout this thesis and it is important to put some context around this term before moving on. Meaningful is not a precise term but in the context of this thesis signifies that CCS is making a significant contribution to allow warming in excess of 2-degrees to be avoided. Twelve years ago, Robert Pascala and Stephen Sucolow (2004) identified a potential portfolio of 7 mitigation approaches, which they termed "wedges", that when taken together would be adequate to stabilise CO_2 concentrations at 500ppm, providing a "more likely than not" chance of achieving a 2-degree goal (IPCC 2014a, p. 13). Each wedge would grow to reduce carbon dioxide emissions by 1 GtC/y (3.66 $GtCO_2$/y). As a point of comparison this is equivalent to approximately 3,600 Boundary Dams. However since 2004, emissions have grown at 4% annually from 25 $GtCO_2$ (Pacala & Socolow 2004) to an estimated 39 $GtCO_2$/y (Le Quéré et al. 2015), which further increases the scale of the challenge. Nine years after Pascala and Sucolow, the International Energy Agency (2013, p. 22) has identified that CCS mitigation in the region of 8 $GtCO_2$/y (relative to a business as usual case) is required by 2050 to enable a less than 2-degree warming scenario with 3 Gt of this coming from coal power generation and 1.5 Gt coming from bioenergy production.[7] Consequently I conceptualise "meaningful" from a FECCS perspective as involving commercial widespread deployment of FECCS with applications numbering in the 3000 to 5000 region dependent on the quantity of CO_2 captured at each site. That 11 years have passed since the IPCC's Special Report on CCS for the delivery of only one commercial coal CCS plant provides a perspective on the challenge for the next 35 years.

The scale of CRD required will be determined by the success of carbon dioxide mitigation. Every tonne of CO_2 abated in the short term translates into a tonne of CO_2 that does not need to be removed from the atmosphere in the future. Likely volumes of required CDR will be discussed in Chapter 3, but to provide an indication of the size of the challenge, an analysis by Pete Smith and collaborators (2015) calculates the volume of BECCS at 12 $GtCO_2$/y, which would require a landmass of up to 700 Mha (about ¾ of the land area of

[7] The balance comes from Iron and Steel, Cement, Gas Power, Chemicals, Gas Processing, Refining and Pulp and Paper.

the USA) to supply the necessary biomass.

An important caveat should be highlighted. Although this thesis discusses the need for CDR it is not a given that CDR will be employed in the future. Future generations could accept global warming over 2-degrees and focus on adaptation to a new climate regime. Alternatively geo-engineering processes such as solar radiation management (SRM) may be found to be more practicable and affordable. However neither of these would preserve atmospheric and ocean chemistry similar to that in which many of the globe's existing species have evolved and both are likely to be fundamentally inequitable. Robert Keohane (2015) highlights the social injustice and political consequences of adaptation, highlighting that poorer countries such as Bangladesh have little capability to adapt and even with support from the North, "political discord will result." The consequences of SRM are not well understood and may include reduced precipitation and increased ozone losses (IPCC 2014b, p. 89). The IPCC also cautions that if SRM were terminated there is high confidence that surface temperatures would rapidly rise within a couple of decades and highlights concerns regarding intergenerational justice (ibid. p. 89). While I do not argue that CDR will (or necessarily should) by deployed, this analysis has a normative motivation of seeking solutions capable of both addressing global inequality while seeking to minimise the transformation of natural systems. In this context I argue that CDR deserves careful consideration.

Thesis Structure

Following this introductory chapter, Chapter 2 provides a brief history of CCS development and reviews some of the major coal based CCS initiatives showing that early optimism has not been justified. Chapter 3 addresses the stepping stone question, seeks to establish the need for carbon dioxide removal and examines the synergies that exist between FECCS and BECCS. It also considers alternative approaches to determine why BECSS appears to be the preferred approach to CDR. The focus of chapters 4 and 5 are on FECCS' stakeholders and the factors that will impact its success or failure. Chapter 4 examines how the diffusion of FECCS may impact the coal industry and considers the cost competitiveness of CCS versus alternative mitigation strategies. Chapter 5 assesses the attractiveness of CCS from a business investment perspective and whether further government investment is likely to kick start its diffusion. The opposition to CCS from competitive forces and Green groups is also examined. Chapter 6 provides a conclusion and considerations of possible future research.

Chapter 2: Brief History and Current Status of FECCS.

Introduction

This short chapter provides a background to the development of CCS illustrating how the IPCC has investigated and verified the technical feasibility of CCS although CCS would increase the cost of coal power.[8] The lessons learnt from the failure of initiatives in the US and Australia are considered as is the qualified success of a Canadian CCS project, which is currently the world's only operational coal power plant capturing carbon. It is shown how the use of the captured carbon dioxide for enhanced oil recovery (EOR) does improve the cost competitiveness of CCS. However, the CO_2 generated when the oil is combusted partly offsets the benefits from applying CCS at the point of power generation.

Early Developments

One of the earliest considerations of carbon capture was from Marchetti's (1977) analysis of the potential for carbon dioxide storage in the deep oceans. There was limited but growing activity through the 1980s such that the first International Conference on Carbon Dioxide Removal (ICCDR) was held in Amsterdam in 1992 (Blok 1992). This was followed up by subsequent conferences in Kyoto in 1994 and at MIT in Cambridge Massachusetts in 1996 (ICCDR-3 1997). Much of the early work on CCS was conducted at MIT under the direction of Howard Herzog, (see for example Herzog, H., Golomb & Zemba 1991; Herzog, HJ et al. 1996). In 1997 MIT was commissioned by the US Department of Energy to develop a white paper on CCS (Herzog, H, Drake & Adams 1997). The paper recognised that as of 1997, research investment into CCS within the US had been a paltry $10M and recommended an investment of $250M over the next 5 years (ibid, p. 3). Investment and interest in CCS has continued to grow. The ICCDR conferences morphed into the Green House Gas Control technologies conferences, also biannual with the last conference held in Austin Texas with over 1600 attendees (Green House Gas Control Technologies 2015).

[8] Although the focus of this chapter is FECCS it should be noted that there is some early work on applying CCS to ethanol production which is by definition BECCS although not BECCS for electricity generation (Karlsson & Bystrom 2011).

As previously mentioned a significant milestone in the development of CCS was the IPCC Special Report on Carbon Capture and Storage (IPCC 2005). This report was prepared in response to a request made in 2002 to the IPCC by the United Nations Framework Convention on Climate Change (UNFCCC) to consider issues relating to CCS including technologies, transport and storage options, cost and energy efficiencies and safety and barriers to the storage of CO_2 (ibid. p. 55). The importance of this report to the political environment and the fossil fuel industry was and remains significant. Had the IPCC dismissed or downplayed the feasibility of CCS the implications for the fossil fuel industries would have been substantial, as they would have been denied the possibility of a future solution to carbon pollution. Also the US had already initiated the $1B FutureGen project, a 275 MW coal fired power station incorporating CCS (Folger 2013). However while recognising that there were gaps in knowledge regarding some aspects of CCS (IPCC 2005, p. 15) the report forecast that by 2050, 30 to 60% of CO_2 emissions from electricity generation could be technically suitable for capture (ibid. p. 9). The report did recognise an increase in the cost of electricity with market prices rising from 4–5 USc/kwh at a pulverised coal reference plant to 6–10 USc/kwh at an equivalent plant with CCS (ibid. p. 10). However with the captured CO_2 used for Enhanced Oil Recovery this would drop to 5 – 8 USc/kwh.

Although there had been some concern over the objectivity of the SRCCS (Pearse, McKnight & Burton 2013, p. 170), overall the production of the report was a success and moved the understanding of CCS significantly forward (Narita 2010). De Connick and Backstränd (2011) recognise the SRCCS as a capacity building exercise and credit it with introducing CCS into the international policy agenda on climate change. Indeed the number of peer reviewed journal articles published on CCS increased fivefold the decade following the SRCCS compared to the 10 years prior to 2005.[9]

The SRCCS demonstrated that it was technically feasible to capture and store CO_2 from stationary power sources and that storage capacity is massive although regionally distributed (IPCC 2005, p. 9). In subsequent research Haroon Khesghi and others also recognised that costs had increased in the 7 years since the publication of SRCCS, public acceptance could

[9] ScienceDirect database search for "Carbon Capture and Storage". 22nd September 2015: 6,557 (1995 to 2005) vs. 30,683 (2006 to date of search).

be a barrier and importantly, that the dearth of global climate policy had resulted in low incentives and hence little tangible progress (Kheshgi, de Coninck & Kessels 2012). Nevertheless there continued to be significant optimism amongst much of the expert community even in the face of ongoing uncertainty. This was noted by Hansson and Bryngelsson (2009) who conducted a survey of CCS experts (from academia and industry but excluding representatives of environmental NGOs) who attributed this optimism to the organisational connection they had with the subject matter, a rationale backed by Gunther Tichy (2004) in his paper on over-optimism of experts.

Over the last decade this optimism has manifested itself with much activity but little tangible outcomes with SaskPower's Boundary Dam being the only coal power generating CCS facility. Ten years ago expectations were much higher. The European Union Spring Council in March 2006 stated that 10 to 12 full-scale demonstration plants should be up and running by 2015 and that CCS should be commercially viable for all new fossil fuel power plants by 2020 (Zero Emission Platform 2007, p. 2). However in an explanatory statement to a vote on CCS in the European Parliament in 2013 (Davies 2013) it was recognised that "sadly there is little to show for this initial enthusiasm". Of the 13 initial projects only one is still current (the White Rose project in the UK) and there is continuing uncertainty over the outcome of this project. The EU resolution attributed the lack of success of CCS through the proceeding decade to a lower than expected carbon price. It called for ongoing support and funding for CCS however also stated in an aside that may indicate limited support for CCS: "it would be even better if the Member States could reach these goals [of limiting GHG emissions] without the use of CCS" (ibid. point 6 of Motion). The resolution passed with a large majority, although what real outcomes will ensue have yet to be determined.

Major FECCS Initiatives

Australia's major power generation CCS project folded in 2010. The ZeroGen project was to be a 530 MW Integrated Gasification Combined Cycle (IGCC) plant with CCS of 60 – 90 $MtCO_2$ over its 30-year life (Granett, Greig & Oettinger 2014). The project was wholly owned by the Queensland government but received significant funds from the federal government and Coal 21, a Minerals Council of Australia (MCA) initiative supporting clean coal. After investment of $138m (ibid: p. 4) the project was terminated at the end of the pre-feasibility stage in 2010. As part of the "lessons learnt" the review document states "industrial scale, low emissions coal fired power projects incorporating CCS are not currently economic…The project would therefore have required significantly heavier and more ongoing financial support than had previously been thought" (ibid: p. xxii). The review also cautioned that industrial scale CCS is not simply a bigger version of demonstration scale and it is only at industrial scale that costs, performance, storage issues and local considerations can be fully appraised (ibid: p. xxii). These two "lessons learnt" provide notes of caution to the coal industry and the demonstration projects that are currently being planned. However notwithstanding this advice, the Callide Oxyfuel CCS demonstration project (an Asia Pacific Partnership Project based in Central Queensland) pressed on and successfully completed its demonstration phase in May 2015. Costing A$245M (with A$65M from the Australian Federal Government) this was a 30 MW power plant capturing 70 tCO_2/day which was trucked to Victoria for storage (Callide Oxyfuel Project 2015). The project will now take the next year to review what was learnt and consider next steps which may include the plant ultimately growing to 700 MWs (Rollo 2015). Whether Callide will become a failure like ZeroGen or a qualified success like Boundary Dam will send a signal for the future of FECCS.

FutureGen could be classified as the US's ZeroGen. Launched by President Bush in 2003 it was also planned to be an IGCC coal fired plant with CCS (Folger 2013). FutureGen was a joint Department of Energy / Industry Alliance with the industry component establishing a not-for-profit company called the FutureGen Industry Alliance. This company included from the beginning some very large fossil fuel and utility companies including BHP Billiton, Rio Tinto, Peabody Energy and American Electric Power. Xstrata, Anglo American and Caterpillar later joined the company (ibid: p. 9). Due to increasing costs of development in 2008 the Department of Energy (DOE) decided to discontinue its funding causing the project to stall. However in 2010 it was resurrected as FutureGen 2 with $1B of funding under the Obama Administration's stimulus package (ibid: p. 10). The project continued with plant, pipeline and storage issues largely addressed but once again the DOE has withdrawn funding (Marshall 2015). In a letter to the US Energy Secretary on 3rd February 2015, FutureGen's CEO Ken Humphries bemoaned the removal of funding, pointed out that the private sector had invested $25M over the life of the project and stated that "the world is watching what we do together" (Daniels 2015). Of course an alternate perspective may be that the world is watching what some of the world's largest mining and utility companies will, or will not do to ensure they validate a mechanism to potentially future proof their industries.

ZeroGen, FutureGen and the European experiences do not question the technical feasibility of CCS but rather demonstrate that the costs of making CCS a commercial reality are not justified given the lack of a substantial price on carbon. It is unclear to what degree CCS costs will decline as the industry matures, but for the industry to mature successful projects need to be brought on line. SaskPower the owners of Boundary Dam have established a consortium to share (and ultimately sell) knowledge on CCS. They claim that CCS costs will decline and estimate that their next project could be delivered with cost savings up to 30% (Saskpower CCS 2014a). However this assumption is questioned by a study of analogous developments: LNG plants, nuclear plants and SO_2 scrubbers (Rai, Victor & Thurber 2010). This study finds that the learnings arising from the diffusion of technology might not end up in cost savings but that costs could instead increase as cumulative capacity grows. The authors warn that the emphasis on aggressive deployment of CCS could have a negative impact on the cost curve and recommend greater emphasis on designing CCS R&D programmes.

Cost curve issues aside, what differentiated Boundary Dam from ZeroGen and FutureGen was that Boundary Dam has established a market for the use of the captured CO_2 for Enhanced Oil Recovery (EOR). This is the process of injecting CO_2 into oil wells to facilitate the recovery of marginal oil reserves. SaskPower doesn't release the price it receives for CO_2 and it is likely that the prices will fluctuate with the varying prices of crude oil. Robert Ferguson and collaborators (2009) calculate that with an oil price of US$70 a price of $35 /t$CO_2$ is achievable. However at time of writing (27th February 2016) the crude oil price is $32.78 (Nasdaq 2016) so the income stream to SaskPower may be highly variable over the 30 year life of the plant. Although it is clear that the EOR revenue contribution has influenced the business case for SaskPower, without having access to their financial modelling it is not possible to determine by how much.[10]

Making the assumption that EOR does increase the cost competitiveness of CCS then two further questions need to be asked: is there a sizeable market for captured CO_2 to enable it to make a "meaningful" contribution to carbon mitigation; and secondly should CO_2 be used

[10] The Boundary Dam CCS plant cost C$1,467M with C$240 of this coming from the Canadian Federal Government (Saskpower CCS n.d.).

for EOR if the objective of CCS is CO_2 mitigation. It appears that the answer to the first question is yes: Michael Godec and collaborators (2011) estimates that conservatively there is storage potential for 140 Gt of CO_2 which would release up to 470 billion barrels of additional oil. While the capture and storage of 140 Gt is certainly meaningful the release of an additional 470 billion barrels of oil gets to the question of should CO_2 be used for EOR. Ferguson et al. (2009) claim that EOR produces practically carbon free oil with 0.26 – 0.32 tCO_2 injected to release a barrel of oil. When combusted the oil will release 0.42 tCO_2 and hence the oil is between 62% and 76% “carbon free” (ibid). The 470B barrels of marginal oil obtained through EOR would release almost 197 $GtCO_2$ (470B x 0.42t). It may be argued that this oil would be accessed with or without the use of EOR. But Heleen de Coninck (2008) takes a counter view and argues that in the longer term more oil will be accessed and the date of “peak oil will be postponed. Consequently she argued against including CCS with EOR in the Clean Development Mechanism (CDM) for developing countries as “enhanced hydrocarbon recovery will lead to more GHG emissions” not less.

Conclusion

Although CCS has been demonstrated to be technically feasible its track record to date in getting sites up and running has been poor with only one commercial site in operation. That this site has required the sale of the captured CO_2 to make it financially viable has demonstrated that it is a sub-optimal mechanism for carbon mitigation. Chapters 4 and 5 will examine if these early setbacks are fatal for the fledging FECCS industry or can the financial weight of the fossil fuel industry spur CCS to break out of its development stage into widespread diffusion. Prior to considering these issues, I will next turn to the questions of the need for carbon dioxide removal and whether its removal via bio-energy CCS would be aided by the prior implementation of FECCS.

Chapter 3: The Need for a Stepping-Stone

Introduction.

Renewable energy, energy efficiency and nuclear are all likely to play in role in reducing the flow of CO_2 into the atmosphere, however it appears increasingly likely the carbon budget will be breached and we are on a trajectory towards a two, three or even four-degree warmer world (see for example Geden O 2015; Tollefson 2015; Victor, DG & Kennel 2014). The choices may then be limited to either adapting to a hotter world, employing geo-engineering techniques to control the temperature (e.g. solar radiation management) or removing CO_2 from the atmosphere to gradually reduce the temperature to whatever may be deemed an acceptable level. Adaptation and geo-engineering are complex and controversial subjects (see comments on pp. 7-8), but other than to acknowledge that either or both may be employed they are beyond the scope of this document.

This chapter examines the need for and the potential of carbon dioxide removal (CDR) with a focus on bio-energy CCS. While there are other options for atmospheric CO_2 drawdown, BECCS is the mechanism most often referred to by the IPCC and others.[11] The chapter commences by considering the relationship between fossil-energy CCS and bio-energy CCS and assessing to what extent the former is a stepping-stone to the latter. The scale of the BECCS challenge will be reviewed and alternative CDR technologies will be considered that could either augment or provide an alternative to BECCS. It is concluded that despite the immensity of the BECCS challenge, given the current technology and the difficulties of alternative approaches, BECCS is likely to be the least worse of the CRD alternatives. Furthermore without a firm foundation being established by fossil-energy CCS in the near future, establishing BECCS from a standing start in the middle of the century will be much more challenging. Finally, while technology, geopolitics and public acceptance of the need to act will all likely change during the century, an expectation of a sudden cornucopian solution shouldn't hold back near term action.

[11] For example BECCS is mentioned on 55 pages of the IPPCC AR5 WGIII Report, whereas CDR (an umbrella term that includes BECSS) was mentioned on 33 and Direct Air Capture (DAC) on 5 pages.

The need for Carbon Dioxide Removal.

In the AR5 synthesis report the IPCC signalled that from 2011 the world should emit no more than 1,000 $GtCO_2$ if it wished to have a greater than 66% chance of limiting warming to no more than 2-degrees greater than pre-industrial levels (IPCC 2014b, p. 64). Now following COP21, an aspirational goal of 1.5-degrees is being discussed: the equivalent budget for this goal being 400 $GtCO_2$ (ibid.). Per the most recent Global Carbon Budget report, over the 10 years from 1994 to 2014 the annual rate of CO_2 emissions was 36.3 $GtCO_2$ with 2014 coming in at over 39 Gt (Le Quéré et al. 2015). In 2014, Carbon Brief (2014) estimated that with the current level of emissions, we had less than 21 years before the 2-degree budget was used and only six years for the 1.5-degree budget. Unfortunately the commitments from the parties at the Paris CO21 meeting have not significantly changed the arithmetic. Following the meeting, the UNFCCC tallied up the Nationally Determined Contributions and calculated cumulative CO_2 emissions from 2011 to 2025 at 542 Gt and to 2030 at 748 Gt (UNFCCC 2015c, p. 9). The bottom line appears to be that should we be serious about a 1.5 or even a 2 degree goal, then net negative emissions will be necessary in the second half of the century. In fact a recent analysis calculates that the difference between targeting a 1.5 or a 2-degree goal is that net negative emissions will be required by the 2050s for the former and by the 2070s for the latter (Rogelj et al. 2015).

It is easy to underestimate the importance of the word "net" in the previous paragraph. Net means that more CO_2 is removed from the air than is being emitted into the air. Assuming that all stationary energy including the power for ground transport is provided carbon free, then CDR still has to cancel out all emissions for which a fossil fuel alternative has not been found[12] and additionally capture and store 7.77 $GtCO_2$ for every 1ppm reduction required (Le Quéré et al. 2015).[13] To be in a position to achieve net CDR in the latter decades of the century much earlier deployment of CDR is necessary (Gasser et al. 2015).

Fossil Energy CCS as a stepping-stone to Bio-Energy CCS

The importance of FECCS in acting as a bridge to BECCS receives little attention and it is difficult to find the future enablement of BECCS given as a reason for investment in FECCS

[12] As examples, these may include aviation fuel, metallurgical coal used in steel manufacture and ongoing land use change.

[13] To provide a concept of scale, James Hansen et al. estimates that 7.77 $GtCO_2$ if converted into carbonate bricks rather than buried would equate to over 2,500 Great Pyramids of Giza (Hansen et al. 2013).

now. The principal rationale for FECCS is as a CO_2 mitigation process, however as has been discussed, its progress to date has been slow and sporadic and as will be seen its medium term prognosis does not appear positive.

There is acknowledgement of FECCS as a prerequisite for BECCS by a number of writers. However these are frequently given as an aside rather than used as an important rationale for FECCS. In a geopolitical analysis of the importance of CCS, Filip Johnsson, Jan Kjarstad and Mikael Odenberger (2012) mention that BECCS will be dependent on successful diffusion of FECCS as BECSS alone is unlikely to establish a cost efficient infrastructure for transport and storage. A paper analysing the relationship between stranded assets and negative emissions technology, simply states "that unless conventional CCS is deployed at scale, the technology for negative emissions CCS might never be developed" (Caldecott, Lomax & Workman 2015). As a third example, in his recent book, Nicholas Stern appears to suggests that BECCS requires the prior development of CCS for power and industrial applications (Stern 2015, p. 29). Unfortunately, he doesn't elaborate on this point.

A more in-depth analysis of the dependency that BECCS may have on FECCS can be made by considering the relationships between the major processes of both forms of CCS.

Feedstock: The implications of using biomass rather than coal are significant. Biomass is less dense than coal, has a lower calorific value and higher moisture content (IEA 2012c, p. 27). Consequently greater volumes are required which impacts cost and energy use in transporting the biomass to the power plant. This can be partly addressed through the palletisation of the biomass however this process is also energy intensive and adds cost to the power generation process (Yassa 2015). Locating plants close to the source of the biomass can also partly address this issue, but may limit the options for co-firing (see below).

Separation Process: The separation process can occur either before combustion (e.g. Integrated Gasification Combined Cycle processes) during combustion (oxy-fuel systems) or post combustion (Koornneef, van Breevoort, et al. 2012). All technologies are similar regardless of whether the feedstock is coal or biomass (Sanchez et al. 2015), although there is a slight drop in efficiencies achieved through biomass (Corti & Lombardi 2004). The IGCC technology appears to hold the most promise (its use was planned for both the

ZeroGen and FutureGen projects) although it has yet to be proven at scale (Schilling 2011). Co-firing with coal and biomass may provide a bridging technology between FECCS and BECCS enabling a refinement of both technologies. Most CCS coal power sites could include up to 30% biomass (Karlsson & Bystrom 2011) and Joris Koonneef and collaborators (2012) estimate that this could increase to 50% by 2050. However, modifications to CCS plants will be required as the share of biomass grows or becomes exclusively biomass. Koonneef et al. (ibid.) point to fouling and corrosion due to biomass's higher moisture content. The investigation and resolution of these issues in the medium term will facilitate the later development of BECCS.

CO2 Transport: Once captured, the CO_2 whether it be from a coal plant, a co-firing plant or a dedicated biomass plant, is pressurised up to 100 bar (Koornneef, van Breevoort, et al. 2012) and fed into a pipeline network for pumping to a storage reservoir (IPCC 2005, p. 100). As increasing levels of bio-mass are introduced, the purity of the CO_2 stream will need to be managed; for example, Hydrogen Sulphide (H_2S) is corrosive and could impact the integrity of the pipeline network (Schilling 2011, p. 30). In its 2005 SRCCS, the IPCC reported 2,500 km of CO_2 pipelines transporting 40 $MtCO_2$/y, primarily to EOR sites (IPCC 2005, p. 29). The extent and destination of the current CO_2 pipeline network is not consistent with widespread diffusion of FECCS. However development of an appropriate network for FECCS and effective contaminant management processes would facilitate the future expansion of biomass derived CO_2.

CO2 Storage: As will be discussed later in this thesis, the integrity of CO_2 storage remains a contested issue (Ash 2015; Scottish Carbon Capture and Storage 2015). Nonetheless the issues are identical regardless of whether the CO_2 originated from fossil energy or bio-energy. Further validation or refinement of CO_2 storage is required during the early stages of FECCS diffusion to expedite the later diffusion of BECCS. The issue of storage capacity is discussed below but it should be noted that Caldecott, Lomax and Workman (2015) have expressed concern that if excessive capacity is used by FECCS, this may limit the future capacity available for BECCS. Given the large available capacity (Dooley 2013) this seems unlikely, although, it is an issue that requires ongoing monitoring.

Regulation: Domestic regulation and international agreements regarding the transportation, injection processes and long-term stewardship of storage sites need to be further developed and refined for FECCS (see broad examination of legal and regulatory issues in Havercroft, Macrory & Stewart 2011) Many of these regulations will be directly applicable to BECCS processes although additional regulations may be required on issues regarding land use and biodiversity management.

Public perception: In a meta-analysis of public perception across multiple countries it was found that the public does not hold strong views on CCS (L′Orange Seigo, Dohle & Siegrist 2014). The IPCC assumes this to be as a consequence of the "remote" nature of the issue (IPCC 2005, p. 36). The IPCC goes on to make the reasonable point that for CCS to be accepted (and I take this to mean FE and BECCS) the public has to realise the seriousness of the climate problem and recognise the need to act. While it may be reasonable to see FECCS as informing public opinion regarding the benefits and challenges of CCS, the scale of BECCS may have a greater impact on humanity and the biosphere in general and consequently may be significantly more contentious (see below).

Summary of the relationship between FECCS and BECCS processes.

	Feedstock	Separation process	CO_2 Transport	CO_2 Storage	Regulatory Frameworks	Community Acceptance
FECCS & BECCS	Different	Strong Relationship	Identical, but contaminants require management	Identical, but potential conflict for space	Strong Relationship	Some Relationship

The learning by doing opportunities that arise from the prior diffusion of FECCS are highly significant for the longer term implementation of BECCS. Consequently, it is reasonable to conclude that FECCS would indeed provide an important stepping-stone although there are important differences and challenges unique to BECCS that will be discussed in the next section.

Given this we have a quandary which can be expressed as follows: there is a growing acknowledgement that BECCS will be required; BECCS will be more challenging without the prior diffusion of FECCS; progress to date with FECCS has been sporadic with its future uncertain (to be discussed further in chapters 4 and 5), therefore the potential for BECCS may be significantly reduced. Consequently, there is an argument to stop simply considering FECCS as an end in itself but also as a means to an end. This is not to underestimate the value of mitigation, as every tonne mitigated now will be a tonne less to remove and store in the future, but there is a strong case that FECCS has a dual purpose: mitigation and BECCS preparation.

It is widely acknowledged that the time needed to transition to a new energy system is measured in multiple decades (Azar et al. 2010; Rai, Victor & Thurber 2010; Smil 2010, p. 142). Vaclav Smil (2014) provides data showing that it took coal 60 years (1840 to 1900) to increase its share of world energy supply from 5% to 50%. In comparison, oil went from 5% to 40% over 60 years from 1915 to 1975 and natural gas took 55 years from 1930 to reach 25%. Modern renewables remain under 5% and energy from both forms of CCS is insignificant. This data validates what many people readily acknowledge: that it is critical to accelerate the transition to low carbon energy. However there is an additional message contained within the data: to achieve negative emissions within 50 years, whereby a large share of the world's energy will be generated by sustainable bio-mass, the process cannot be delayed. FECCS can provide low carbon energy and also a solid framework for future BECCS. But BECCS will only happen if it is feasible and practicable, and importantly it must be at least as competitive as alternative CDR approaches.

The feasibility and practicality of BECCS

The amount of negative emissions needed in the future to keep warming below 2-degrees is dependent on the mitigation that can be achieved in the short to medium term. Gasser and his collaborators recognise the wide variability in this and put a large range on the probable need for negative emissions (2015). They provide a best-case estimate of between 1.8 to 11 $GtCO_2$ per year to a worst case of between 25.6 to 40.3 Gt per year. Associated required storage capacities are estimated at between 183 to 915 Gt (best case) and 3,660 to 5,856 Gt (worst case). In a slightly more recent paper, Pete Smith and a large team (2015) reports that there is consensus around a median figure of an annual removal of 12 $GtCO_2$. A third analysis from 2013 puts required removal at between 10 and 35 Gt/y with storage requirements this century of approximately 1,000 $GtCO_2$ (Tavoni & Socolow 2013). Although there is some variability in these estimates there is little doubt as to the scale of the carbon reduction challenge. As per the aptly title paper "Betting on Negative Emissions"

(Fuss et al. 2014), it appears that unless there is dramatic mitigation action in the very near future, the wager has been placed. The question remains what will be the probability of the wager being successful. At a macro level there are two aspects to this issue: is it feasible to capture the quantities of CO_2 necessary to reduce to atmospheric concentrations to an acceptable level? And secondly, are there adequate storage reservoirs available for this captured CO_2? I will turn to the second question first.

In a meta-analysis of the literature, James Dooley reports that there is a CO_2 storage potential of 13,500 GtCO2 effective capacity and 3,900 Gt of practical capacity and that the issue of CO_2 storage is unlikely to be a barrier to CCS deployment this century (Dooley 2013).[14] Given the storage requirement estimates given above this appears to be a valid claim and should also accommodate significant amounts of fossil energy captured emissions. However Christian Azar and others (2010) caution that although storage may be adequate, surprises, both physical and political may occur. The annual requirements are more than ten thousand times greater than is being achieved today so confidence in storage abilities remains at a theoretical level. The geography of political instability will also likely change during the course of the century, which may present issues where the CO_2 point source is in country A, the pipelines pass through country B and storage is in country C (Bugge 2011, p. 128). A final point on storage is the spatial relationship between the point source and the storage capacity. The IPCC has provided a first pass at mapping this relationship for current sources of fossil fuel emissions, however they recognise that more comprehensive work is required (IPCC 2005, pp. 22-4). Bio-energy sources may or may not correspond to fossil fuel emission sources identified by the IPCC, which could impact the real storage potential. Although it appears reasonable to have some confidence that adequate storage potential exists, this is not without caveats and considerably more investigation is required.

The issue of bio-energy CO_2 capture appears considerably more fraught and uncertain. Land, water, nutrients and finance are all key variables that impact on its feasibility. As the likelihood of the need for carbon dioxide removal grows the number of studies on the potential for BECCS also grows. The findings of two papers are provided in the table below

[14] "Effective" and "practical" capacity are taken from the Pyramid for CO_2 Storage Capacity which is mapped against increasing cost of storage and increasing certainty of storage potential (Bachu et al. 2007).

(Smith, L & Torn 2013; Smith, Pete et al. 2015).[15] The units in the papers have been aligned for comparative purposes and recalculated to volumes required for 12 $GtCO_2$ per year (i.e. consistent with Smith et al's (2015) analysis and at the low end of Tavoni and Sucolow (2013) and Gasser et al's (2015) analyses).

BECCS Resource Requirements for annual CO_2 removal of 12 Gt.				
Authors	Land Mha	Water km^3/y	Nitrogen Mt /y	Investment BUS$/y
Smith, P et al.	380 to 700	720	"Variable"	261
Smith, L & Torn	344 - 1563	2,500 - 11,300	27 - 125.	No data

Notes

1. Smith & Torn (2013) provides a summary and analysis of the literature that may account for the wide variability of data.
2. Smith et al. (2015) analysis is for a variety of feedstocks from crop residues to dedicated crops. Smith and Torn's (2013) data is limited to switchgrass crops.
3. Smith et al. (2015) specify that they calculate the additional use of water and caution that other studies calculate total use of water.
4. Smith and Torn's (2013) data include losses of over 50% (2.11:1) during the processing of the switchgrass crops from growth through combustion to sequestration.

Although the papers provide differing results (partly explained through the notes) their key findings highlight the magnitude of the task to capture and store the required amount of carbon dioxide. To put some numbers into perspective, 700 Mha equals about 3/4 of the land area of the United States; 2,500 km^3 of water is equivalent to about 10% of freshwater appropriated by humans (Postel, Daily & Ehrlich 1996) and according to Smith and Torn (2013), 125 MtN is more than the world's current annual nitrogen fertilizer production. The financing estimates provided by Smith et al. are investment costs and at $21.75/t ($261B/12Gt) do not appear to provide a total cost figure. A "hypothetical estimate" of US$70 to US$250 in today's dollars is reported by Duncan McLaren (McLaren 2012) which equates to an annual cost for 12 Gt of between US$840B and US$3T.

Three other points are worth mentioning with regard to widespread diffusion of BECCS. There will be an albedo effect in covering 700 Mha with new or different foliage. The albedo of dark plantation pine forest will differ from that of switchgrass or from eucalypt plantations. How this impacts the climate will require further study before implementation (Smith, Pete et al. 2015). Secondly through the dynamics of the carbon cycle, carbon that is removed and stored can be partially replaced by carbon from other sinks. James Hansen

[15] Smith and Torn (2013) is a meta analysis of the literature on ecological limits to bioenergy.

and others calculate that the extraction and storage of 100ppm by Direct Air Capture would result in a net atmospheric reduction of 52ppm (Hansen et al. 2013). How the carbon cycle will respond to CO_2 removal via biomass remains uncertain and, like the albedo issue requires further study (Fuss et al. 2014). Finally, this is likely to be a multi decade endeavour. Given that 1ppm of CO_2 atmospheric concentration equals 7.77 Gt, a reduction of 100ppm (say from 450 to 350) would take 65 years at 12 Gt/y. This raises the question as to whether as the world invests in adaptation there would also be political appetite to restore the atmospheric chemistry of the early 20th century (Meadowcroft 2013).

The uncertainties and the resource requirements regarding BECCS are undoubtedly challenging at the 12 Gt/y scale. However there appears to be no technical reason stopping the ultimate deployment of BECCS (Edmonds et al. 2013). Indeed it has been calculated that it is more cost effective to achieve CO_2 stabilisation targets with BECCS than with FECCS or without any CCS (Azar et al. 2010). But of course feasibility and practicality are not the same. BECCS raises issues of food security, bio diversity and socio-political acceptance (Smith, P & Canedell 2015). It would require unprecedented cooperation amongst the world's nations plus a significant global price on carbon (Edmonds et al. 2013), which I would expect, would dwarf the current challenges surrounding FECCS. An important if somewhat obvious caution given by a number of papers, see for example (Hansen et al. 2013; Smith, Pete et al. 2015) is that the potential for future negative emissions should in no way distract from the more immediate goal of deep emissions reductions. The rapid deployment of FECCS would address the issue of emissions reduction and build a foundation for future deployment of BECCS.

Alternatives to BECSS

The process through which CO_2 is taken from the atmosphere is largely irrelevant to its climate impact. As mentioned, BECCS is the CDR approach that receives most attention, particularly from the IPCC. However as the scale of the BECCS intervention needed becomes clearer, the consideration of alternative approaches grows. There are a number of comparative analyses of CRD approaches, (see as examples McGlashan et al. 2012; McLaren 2012; Smith, Pete et al. 2015; Williamson 2016) and it is beyond the scope of this thesis to critique them. However the question to consider is whether BECCS deserves its primary position in the listing of CRD candidates. If it is not likely to be competitive then its consideration and the rationale for FECCS to be developed as a precursor to its diffusion become moot points.

I will contrast two alternative approaches with BECCS, one natural: afforestation; and one high-tech industrial: Direct Air Capture (DAC). While this does not provide a fully comprehensive comparative analysis (Williamson lists 9 CDR approaches) it is indicative of the relative strengths / weaknesses of BECCS.

Assessment of parameters attributable to 3 CDR approaches.			
	Afforestation	BECCS	Direct Air Capture
Energy Demand (1)	Very Low	Net energy positive	Very high
Human Impacts (1)	High	High	Low
Bio-system Impacts (1)	Moderate	High	Low
Cost (1)	Moderate	High	Very high
Storage Capacity	Moderate (2)	Very high (2) (3)	Very high (3)
Security of Sequestration	Low to moderate (2) (7)	Contested (4) (5)	Contested (4) (5)
Location Flexibility	Moderate	Low	High
Albedo Issues (1)	High	Variable	None
Technology Readiness (6)	High	Moderate	Low

(1): (Smith, Pete et al. 2015); (2) (Smith, L & Torn 2013) ; (3) (Dooley 2013); (4): (Scottish Carbon Capture and Storage 2015); (5): (Ash 2015); 6: (McLaren 2012); (7): (Houghton, Byers & Nassikas 2015)

There are positives and constraints on each approach and some parameters such as technology readiness and costs will likely change over the course of the century. Even albedo, speed of biomass growth and resource requirements may change due to developments in genetic engineering and crop structural modification (Drewry, Kumar & Long 2014). The challenges for BECSS have been discussed in the previous section, however there are additional challenges for both afforestation and DAC. For DAC the energy required to run the capture plants is considerable. In Smith and collaborators (2015) this is estimated at 156 EJ/year. To put this into perspective, modelling by Azar and collaborators estimates the world's primary energy consumption in 2100 at between approximately 1,000 and 1400 EJ. (2010).[16] It is unclear where this energy could come from in a fossil fuel free world. In contrast, BECCS is a major provider of energy, with 170 EJ/y being supplied to the grid (Smith, Pete et al. 2015). Afforestation's key drawback is that the accumulation of CO_2 in trees saturates as the trees reach the extent of their growth so to achieve an annual reduction of CO_2 would require planting new forests annually in addition to protecting the existing forested lands (Smith, L & Torn 2013). Consequently the land required significantly exceeds that needed for BECCS (Humpenöder et al. 2014). However there is a partial counter argument that large trees in tropical forests can take up to a century to mature and continue to absorb CO_2 during this time (Houghton, Byers & Nassikas 2015). The security of the captured CO_2 through afforestation is also lower due to its vulnerability to fires, insects, droughts and human interference (Houghton, Byers & Nassikas 2015; Smith, L & Torn 2013).

While the challenges of BECCS are truly enormous, the alternatives appear to present even greater challenges. If the world is intent on "betting on negative" emissions, which appears to be increasingly the case, then BECCS is the likely leading candidate for diffusion. It is also likely that a portfolio of approaches to CDR will be taken and that some of these approaches may not yet be envisioned. As Tim Flannery points out, the world citizens of 1915 would have been unlikely to predict the jet engine or the nuclear power of 1950 (2015, Loc. 2582). Similarly, the spread of computing power and mobile communications in the second half of the 20th century could hardly have been speculated. There is much uncertainty as to what remedies may exist in 40 or 60 years' time, however to simply have faith in human ingenuity to develop a solution appears optimistic if not imprudent from a risk management perspective.

Conclusion:

Unless there is a significant breakthrough in CO_2 mitigation, and even allowing for a temporary bridging use of SRM, CDR will be necessary in the second half of the century. Although there are immense challenges to BECCS, the challenges with alternative approaches are likely to be greater and BECCS is currently the key CDR candidate for diffusion. The implementation of BECCS will be a decades long endeavour and

[16] As another point of comparison, I calculate that it would take 8,243,911 2MW wind turbines with a 30% capacity factor to provide the 156 EJ of energy necessary to achieve DAC.

development of FECCS in the short to medium term can provide some of the infrastructure for its implementation. This provides an additional, but largely unacknowledged rationale for FECCS diffusion. Given the absence of this rationale from discussions regarding the utility of FECCS, I will next consider if other factors can make FECCS diffusion a reality.

Chapter 4: Economic Stakeholders

Introduction

In our current era of economic globalisation, multinational corporations are powerful economic and political actors. Whether this is a force for good or bad is not addressed here. However, it is relevant in a consideration of business and economic stakeholders that influence the potential of FECCS to contribute to carbon mitigation. The chapter begins by considering business power and how it is adapting to climate change and then explores the frequently held view that coal is in terminal decline. Given that the demise of coal would result in significant stranded assets, the extent that CCS can help rescue these assets is considered including the role of carbon pricing in making CCS a viable business proposition. Finally I review the costs of mitigation strategies with a principal focus on Stanford University's Energy Modelling Forum (EMF) 27 study, the findings of which receive significant attention in the IPCC's AR5.

Business Power

In his book 'Earth Masters' Clive Hamilton says the following with regard to CCS:

> "…there is something deeply perverse in the demand that we construct an immense industrial infrastructure in order to deal with the carbon emissions from another immense industrial infrastructure, when we could just stop burning fossil fuels." (2014, p. 50)

On face value, the implementation of CCS does have a ring of perversity. However, in making his point, Hamilton overlooks the reality that regardless of which combination of CO_2 mitigation strategies are selected, the infrastructure challenge remains immense. Whether carbon neutrality comes from wind turbines or from captured carbon doesn't matter from a climate change perspective. What matters are the cost realities and the comparative strengths of the competing forces including the power of the business sectors and public opinion influencing corporate decision-making.

The transition from fossil fuel is a complex process and needs to take into account the role and power of business in shaping government policy decisions. The fossil fuel industry has considerable power and although the renewable industry is growing, its relative size remains small. To take two examples, Infigen Energy, a leading wind producer in Australia had revenue of A$134M in 2014/15 (2015) compared to Whitehaven Coal's A$763M revenue

(2015) for the same period with both companies reporting significant losses for the year. On a global level, Iberdrola S. A. one of the world's largest renewable energy companies had revenue of €30B (2015) compared to Exxon Mobil's US$412B (2015). Although other factors such as organisational reputation (see below) will play a role in company influence, big companies generally pay more taxes, employ more people and exert more influence in policy making. The directors and senior officers of corporations have a responsibility to optimise performance while working within the legal frameworks of the jurisdictions where they operate. And as performance is frequently measured by the metrics of revenue and profitability, the corporation's considerable influence will focus on advancing these goals.

Although Doris Fuchs and Markus Lederer (2008) say that there is surprisingly little research on the power of business, business will generally be diligent and pragmatic while protecting their interests (Jensen & Sandström 2012). As an example, Australian resource companies, under the banner of the Minerals Council of Australia successfully lobbied to overturn the proposed Resources 'Super Profits' Tax (MCA 2010). How businesses have lobbied and acted to protect their interests has received significant criticism. For example, Naomi Orsekes and Erik Conway (2010) provide a damning account of how industries (particularly tobacco and fossil fuel) have used their influence to progress what they considered to be their goals. Additionally, Orsekes with Peter Frumhoff have recently claimed that despite major oil companies acknowledging the emissions/climate relationship, they "remain firmly behind climate disinformation campaigns (Frumhoff & Oreskes 2015).

The pragmatism of business can be seen in its response to the growing likelihood of climate change reform. Irja Vormedal (2011) argues that the lobbying that has resisted regulatory climate policy has now changed and the US has crossed a tipping point in business strategies which is more acceptable GHG legislation. Jacob Grumbach (2015) is more circumspect: although he recognises the growing support for climate reform amongst the fossil industry he remains sceptical that their support is genuine. Given Orsekes and Conway's account (2010) it is easy to see any positive action by resource companies as "greenwash". Nonetheless many US companies remain supportive of cap and trade polices (Geman 2012) and two of the world's largest mining companies have voiced their support for carbon pricing and prudently include a price on carbon when evaluating investment decisions (BHP Billiton 2015; Rio Tinto 2012). It is fair to say that corporations will overwhelmingly operate to their self-interest, and although there may be some recalcitrants, (see note on

Peabody below) it may now be in their best interests to recognise that a tipping point has been crossed and they need to exercise their business power "to shape potentially inevitable climate legislation" (Grumback 2015).[17] Before considering this in the context of CCS it must be considered if coal is already in terminal decline and as a consequence there is no battle to be fought.

Is Coal Dying?

This is an important question when considering the future CCS: if coal is being phased out then why bother investing in CCS? Also, as will be shown, continued use of coal without CCS is not compatible with the carbon budget, so if coal is to continue to play a major role in the world energy mix then CCS is an important element in the strategy to mitigate CO_2 emissions.

It is not hard to find reports announcing the demise of coal. The Australian Greens assert that the "Global Demand for Coal is in terminal decline" (The Greens 2015). Greenpeace have recently released a report also called "Coal's Terminal Decline" (Myllyvirta 2015). However the perception of the decline of coal appears to be principally a Western phenomenon although The Greens and Greenpeace may contest this. Jan Steckel, Ottmar Edenhofer and Michael Jakob (2015) show that the increased carbon intensity of energy production in China, India and other developing countries since the late 1990s is caused by the increased use of coal. In fact the two coal mine proposals receiving the most media attention in Australia, Shenhua and Carmichael are to be developed by Chinese and Indian interests respectively with the coal destined for seaborne trade to their countries or wherever a market can be found. Regardless of whether Adani's Carmichael proceeds or not, according to the Piyush Goyal, the Indian Energy Minister, (in an ABC Four Corners interview) the Indian government has plans to open "nearly sixty plus mines in the next five years" (Thompson & Richards 2015). The US's Energy Information Administration predicts that electricity generation from coal will grow by about 40% between 2015 and 2040 (EIA 2013, p. 5), although coal's contribution to the world's electricity generation will decline

[17] The US coal company Peabody Energy can likely be classified as a recalcitrant. In its 2014 US Securities and Exchange Commission Filing it referred to the *perceived* impacts of coal combustion on global climate change (Peabody Energy Corporation 2015, p. 29) (my italics). Note that Peabody Energy recently filed for Chapter 11 protection.

from 40% to about 35% during the same interval.[18] Similarly the latest BP Energy Outlook (BP 2016) predicts that coal's growth will slow dramatically but nonetheless will grow by 0.5% p.a. between 2014 and 2035 which equates to a cumulative growth of 11% over the 21 years.

The driver of thermal coal's use will be the number of coal-fired power stations in operation; their operational life and how many more come on line. In an analysis for CoalSwarm and the Sierra Club, Christine Shearer et al (2015) identify 557 under construction and another 1,620 in a preconstruction phase. Nonetheless they assert that "China's faces a capacity glut", and "India's coal boom has withered" and that based on recent experience only 50% of those plants in preconstruction will be built. But even with a 50% completion rate, the emissions from these 1,367 plants (557 + 1,620/2) will come to 113 $GtCO_2$ given a 40-year plant life. Operating coal plants produced 14 $GtCO_2$ in 2012 and it has been calculated that the new plants commissioned in 2012 will produce 19 $GtCO_2$ throughout their 40-year combined life (Davis & Socolow 2014). With neither BP nor the EIA seeing peak coal occurring within the next 25 years, the reality is that, given the numbers above, another 25 years of coal growth is not compatible with a 2-degree carbon budget without CCS. As will be discussed, there are formidable forces arrayed to prove the BP and EIA predictions wrong, however there are similarly considerable stakeholders who have a vested interest in ensuring that their coal assets do not become "stranded".

Stranded Assets and the threat to coal

The reality of a 2-degree goal and a 1,000 Gt budget means that without CCS the majority of coal must remain in the ground. An analysis by Christophe McGlade and Paul Ekins (2015) show that combustion of known global reserves of coal (both hard and lignite) would produce in the region of 2,000 $GtCO_2$ while coal resources would produce more than an additional 5,000 $GtCO_2$.[19] They also calculate that 887 Gt (82%) of coal reserves must be left in the ground to enable the 2-degree goal. Coal prices have declined from over US$80/t (2009) to US$62/t in 2015 (EIA 2015c) so taking a conservative price of US$60 stranded

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[18] Due to the introduction of more efficient coal generation, the rate of growth of coal may be lower than rate of growth of electricity generated by coal.

[19] "Reserves" are the amount of coal that can technically and economically be expected to be produced. "Resources" are the amount of coal that are estimated to be in the geological formation.

reserves have a value in the region of US$53T dollars.[20] A Citigroup report estimates the value of all unburnable fossil fuel reserves (coal, oil and gas) could be over $100T (Channel et al. 2015). As a comparison the Global GDP in 2014 was just under $78T (Word Bank 2015).

These numbers certainly have shock value and pose the question whether CCS can save the fossil fuel industry from the threat of mitigation actions commensurate with a 2-degree goal. There is a growing campaign for institutions, pension / superannuation funds and sovereign wealth funds to divest their fossil fuel assets. In May 2014 Stanford University (Stanford 2014) announced it would divest from coal. This was followed in October 2014 by The Australian National University (ANU 2014) when it announced it was removing 7 fossil fuel companies from its investment portfolio. Other influential and important organisations divesting from fossil fuel include the Church of England (2015) and on a larger scale the Norwegian Sovereign Wealth fund (Schwartz 2015). While these actions send a clear signal to the fossil fuel industry a study from the University of Oxford (Ansar, Caldecott & Tilbury J 2013) finds that divestment process will have little impact on the share price of companies as divestments are likely to be picked up by neutral investors particularly if there is a short term discount to be obtained. It also points out that in reviewing previous divestment campaigns including tobacco and South African apartheid, only a small amount of divestible funds were actually withdrawn.

Divestment campaigns aside, there is an increasing focus on the link between a global carbon budget and the financial valuations of fossil fuel companies (Leaton 2013; Mercer 2015). A report from Mercer (2015) (sponsored by the International Finance Corporation and the British and German Governments) states that returns from the coal industry could drop from "anywhere between 18% and 74% the next 35 years". The G20 recognising the threat of stranded assets has requested the Financial Stability Board to review how the financial sector can take account of climate related issues (G20 2015). But falling returns and reducing share prices do not in themselves signal the end of coal. As we have seen coal is expected to grow (albeit at a declining rate) for at least the next 20 years. Governments need to ensure that electric power continues to be provided to their citizens, and if that power

[20] Note the coal price is used for illustrative purposes only as the price is likely to fluctuate significantly over coming decades.

currently comes from coal, then in the absence of alternative power sources and regardless of the financial viability of the power generator, the coal will continue to be burnt. Additionally, approximately two thirds of the world's coal reserves are owned by governments rather than by listed companies and consequently are less influenced by the vagaries of the global financial markets (Leaton 2013, p. 14).

The issue of deteriorating organisational reputation and divestment processes are mutually reinforcing. A University of Oxford study (Ansar, Caldecott & Tilbury J 2013) highlights organisational stigmatisation as having a longer term impact on company value than divestment due to increased regulatory uncertainty. Adani's proposed Carmichael coalmine (referred to earlier) is a case in point. Adani's environmental and governance track record in India (Betigeri 2015) is being used by community campaign groups such as GetUp (2015) to fight the development of the coal mine, even in the face of clear government support. GetUp and other organisations pressured the Commonwealth Bank to terminate its relationship with Adani and celebrated when the relationship concluded.[21] Whether the Carmichael mine proceeds is yet to be determined however the 60 Mt/y peak production (Queensland Government 2015) should be seen in the context of the 1,500 Mt/y domestic Indian coal production forecast for 2020 (EIA 2015b). Regardless of the merits of either side, the anti-Carmichael campaign illustrates that by questioning and stigmatising a company's strategies, community campaigns can impede their progress.

Would the action against Adani have been any different if the coal from Carmichael was to be burnt in a power station with CCS? This isn't a totally fair question as the protests surrounding the Carmichael mine were not solely due to the CO_2 emission from the coal. They also concerned the impacts of dredging and increased shipping on the Great Barrier Reef and concerns over reptilian species in the areas surrounding the proposed mine. However the issue of warming resulting from the emissions from Carmichael coal was a key driver for much of the action against Adani, with Australian scientists writing an open letter to the World Bank warning of the potential emissions of over 700Mt of CO_2/y from the Galilee Basin at peak mine production (Hamilton 2015). The capture and storage of these emissions would have eliminated this objection.

[21] Adani claimed that it had cancelled the bank's contract (Hagermann 2015).

CCS and a carbon price can enable more coal use

McGlade and Ekins (2015) also calculated that by applying CCS, an additional $68 Gt of coal could be used, or in dollar terms a freeing up of US$4.1T of value. They claim that the relatively modest effect of CCS is due to its late introduction, its expense and the rate at which it can be deployed. A higher estimate of CCS's potential to free up coal use is given by Nico Bauer and others (2015). They determine that CCS could enable at least a doubling of coal use between 2030 and 2100 with up to an additional 5 Zetta Joules of energy coming from CCS coal during this period. 5 ZJ equates to 190 Gt of thermal coal and has a value of $11.4T, using a coal price US$60/t.[22]

Although the numbers may be contested, the question remains as to whether the promise of greater use of coal will drive the take up of CCS. Victoria Clark and Howard Herzog (2014) provide a qualified yes to this question arguing that should policy drivers strand assets then CCS can rescue them if the resultant energy is competitive with alternatives. The two aspects of this will be considered in turn: the policy drivers necessary for CCS and CCS's competitive position vis-a-vis alternative mitigation approaches.

Policy drivers can take multiple forms from strict regulation to carbon pricing. Without a price on carbon there are few drivers for resource companies or utility operators to walk away from their assets. A price on carbon on the other hand forces the enterprise to consider the future value of investments knowing that it will pay a price for each ton of CO_2 emitted, or to put it another way will save money for each ton abated. Even though there is no globally implemented carbon price, many companies are already proactively factoring in a carbon price when valuing assets. For example BHP Billiton has built in a carbon price in its valuations since 2004 with its long forecast set at US$50/t $CO_{2\text{-}e}$ (2015, p. 11). It is unlikely that a carbon price alone will enable the development of CCS in coal power generation in the short term. Estimates of the levelised cost of electricity (LCOE) (i.e. the total life cycle costs of electricity production including capital expense, fuel, financing etc.) provide some insight as to the need for carbon pricing. The Australian Academy of Technological Sciences and Engineering (ATSE) (Burgess 2011, p. 12) forecast the 2020 levelised price of electricity from an unabated coal fired power stations to be in the region

[22] 1 kg of thermal coal contains 25.46 MJ of usable energy (Coal Marketing International 2015)

of A$100/MWh. Coal power with CCS is projected to vary from A$150 to A$200/MWH depending on the type of coal and the technology used (ibid.). Given that approximately 1t CO_2 will be produced per MWh of coal powered generation (EIA n.d.-a) a price of A$50 to A$100/t is necessary to drive the deployment of CCS.[23] This figure is broadly on par with the Global Carbon Capture and Storage Institute (GCCSI) (Irlam 2015, p. 1) which identifies a carbon price of US$48/t to US$109/t to make US coal fired CCS plant equivalent to unabated coal plants. The IEA reports (2013, p. 56) that the Norwegian carbon tax of US$51/$CO_2$ was instrumental in Statoil's Sleipner CCS project. Although it cost over US$100M to construct and costs US$17 to sequester each ton, still saves Statoil from paying tax on approximately the 100 MtCO_2 it injects each year. While this is not a coal example, it does show how carbon pricing can influence organisational decision-making.

However there is a large gap between where we are now and what is needed to enable CCS. The European Union has the longest running carbon cap and trade system and the price (as at 19/2/2016) for a European Emissions Allowance (i.e. the currency of European carbon trading) is €5.07/tCO_2 (European Energy Exchange 2016). In fact it is argued that when fossil fuel subsidies are taken into account the global average price of CO_2 is less than zero (Wagner et al. 2015).

How carbon pricing and carbon markets will evolve around the world remains to be seen. In addition to Europe, California (California Environmental Protection Agency 2016) has an established market and China's market is a work in progress (Zhang 2015). However the US at a Federal level has struggled with the implementation of a cap and trade system and the implementation and subsequent removal of an Australian carbon price has been well reported (Sussman 2015; Twomey 2014). Without a substantial price on carbon (either through a carbon tax or a cap and trade mechanism) it is difficult to make a strong business case for CCS. However this also applies to a greater or lesser extent to other low or zero carbon energy sources. Which source is most cost optimised is considered next.

[23] An analysis by the US Energy Information Administration contrasts the LCOE with the Levelised Avoided Cost of Electricity (LACE) (i.e. a measure of the economic value of a candidate utility project) and shows a 2020 projected difference of $14/MWh between conventional coal and advanced coal with CCS although the conventional coal plant carries an emissions fee of $15/t (EIA 2015a).

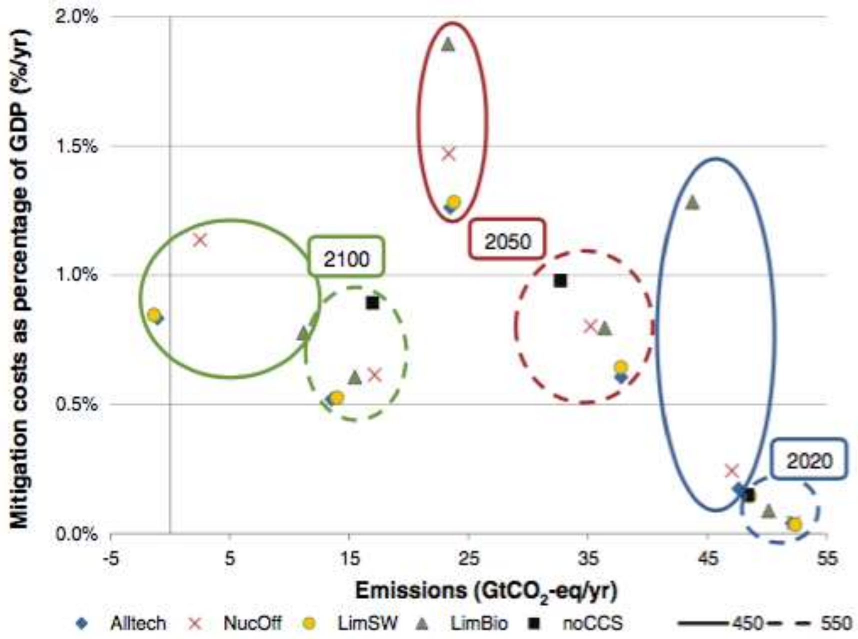
The most cost effective means possible

Recalling Clive Hamilton's claim on page 27 regarding the building of "an immense industrial infrastructure" the question arises, what infrastructure options are the most cost effective to achieve the 2-degree goal? The IPCC's AR5 (IPCC 2014a, p. 15) addresses this question by looking at the increase in total discounted mitigation costs resulting from omitting or limiting various technologies in order to keep CO_2e less than 450ppm (which provides a 'likely' prospect of staying below a 2-degree temperature increase). It states that without CCS, costs would increase in the range of 29 to 297% with a median of 138%. In comparison, phasing out nuclear power would increase cost by 7%, limiting wind and solar by 6% and limiting bio energy by 64% (median numbers given). The relevant section of the IPCC table is reproduced below.

	Consumption losses in cost-effective scenarios[1]				Increase in total discounted mitigation costs in scenarios with limited availability of technologies			
	[% reduction in consumption relative to baseline]			[percentage point reduction in annualized consumption growth rate]	[% increase in total discounted mitigation costs (2015–2100) relative to default technology assumptions]			
2100 Concentration (ppm CO_2eq)	2030	2050	2100	2010–2100	No CCS	Nuclear phase out	Limited Solar/Wind	Limited Bioenergy
450 (430–480)	1.7 (1.0–3.7) [N: 14]	3.4 (2.1–6.2)	4.8 (2.9–11.4)	0.06 (0.04–0.14)	138 (29–297) [N: 4]	7 (4–18) [N: 8]	6 (2–29) [N: 8]	64 (44–78) [N: 8]
500 (480–530)	1.7 (0.6–2.1) [N: 32]	2.7 (1.5–4.2)	4.7 (2.4–10.6)	0.06 (0.03–0.13)				
550 (530–580)	0.6 (0.2–1.3) [N: 46]	1.7 (1.2–3.3)	3.8 (1.2–7.3)	0.04 (0.01–0.09)	39 (18–78) [N: 11]	13 (2–23) [N: 10]	8 (5–15) [N: 10]	18 (4–66) [N: 12]
580–650	0.3 (0–0.9) [N: 16]	1.3 (0.5–2.0)	2.3 (1.2–4.4)	0.03 (0.01–0.05)				

(IPCC 2014a, p. 15)

This IPCC data appears to be primarily taken from Stanford University's Energy Modelling Forum Study 27 (EMF 27) (Stanford University n.d.), which investigated various options for mitigation including CCS (both fossil fuel and bio-energy), nuclear, wind and solar and bioengineering. In an overview of the study Elmar Kriegler et al (2014) emphasise the value of CCS for industrial emissions (e.g. steel manufacture) where alternatives are not currently available and also highlight the importance of BECCS in achieving negative emissions. In another paper, Jasper van Vliet and collaborators (2014) provide an analysis of the mitigation costs as percentage of GDP against emission levels in 2020, 2050 and 2100 for 450 and 550 scenarios. Their calculations conclude that achieving a 450ppm target without CCS is not feasible and that with a 550ppm goal a "no CCS" scenario would cost 1% of global GDP in 2050 compared to "no nuclear", about 0.75% GDP or limited solar / wind about 0.6% GDP. Their chart, contrasting mitigation costs with emission levels for 450 and 550ppm scenarios is given below.



Alltech = All technologies available; NucOff = Nuclear energy is removed; LimSW = Limited Solar and Wind; noCCS = CCS not implemented. (van Vliet et al. 2014)

The EMF 27 study appears to be the most holistic analysis of cost modelling taking into account complementary technologies and incorporating the likely future need for negative emissions and the cost implications of rapid decarbonisation in the “noCCS” scenario. There are other studies worth mentioning as they give alternative perspectives even if they are more limited in scope. The ATSE study referenced above (Burgess 2011) forecasts cost comparisons in 2040 of coal CCS at about \$140/MWh compared to wind at about \$90/MWh. A direct comparison between coal CCS and concentrated solar power (CSP) (Lilliestam, Bielicki & Patt 2012) estimates that to replace all coal power in the US and Europe with coal CCS would cost around US\$425B compared to \$380B for comparable replacement with CSP. As a further example, the University of Melbourne/ Beyond Zero Emissions’ Stationary Energy Plan (2010) calculates that Australia could supply all of its stationary energy with renewable energy within 10 years for a cost of \$370B or approximately 3% of GDP per year. Other papers such van der Zwaan and Tavoni (2011) for nuclear / CCS comparisons and Delucchi and Jacobson (2011) for global renewables deployment also show CCS falling short from a cost comparison point of view.

The key point to draw from this analysis is that none of these papers are in conflict with the EMF 27 findings. EMF doesn't claim that a GWh of energy with CCS is cheaper to an equivalent amount from any alternative low emissions technology. But rather that without FECCS / BECCS incorporated as meaningful components of the climate strategy it will be considerably more expensive to achieve the 450ppm (2-degree goal), or as per the van Vliet et al. (2014) analysis, not possible.

Conclusion

Business power is a real force in our society and business will use its power to influence policy decisions. But business is also usually pragmatic and conscious of how negative reputational image can impact the market for its products and ultimately its value. The volume of coal resources is not compatible with a 2-degree carbon budget and even with the application of CCS, much of the world's coal will be become stranded. However CCS can free up significant extra value, potentially over US$10T, and provide energy at the ZJ scale while transitioning to lower carbon intensive energy sources. Overall the exclusion of CCS (fossil and bio) will significantly increase the cost of mitigating warming even though on a point-to-point comparison other low emissions technologies are cheaper.

Given the above, we might expect the prospects for CCS to be positive. However as has been shown in Chapter 2, its track record to date has not been good. The next chapter will consider the potential future of CCS.

Chapter 5: The prospects for Fossil Energy CCS

Introduction

Given its track record to date, it is hard to put a positive spin on the prospects of FECCS. In Chapter 2 we saw how large projects in Europe, Australia (ZeroGen) and the US (FutureGen) have stalled or been cancelled. In late November 2015 it was reported that the UK parliament had announced it would withdraw funding from a £1B competition to support a flagship UK CCS project (Carrington 2015). The Global Carbon Capture and Storage Institute reported in 2012 that there was a pipeline of 75 "large scale" projects (which they define as over 100,000 tCO_2/y sequestered) including 8 operational sites. By the 2014 report the pipeline had reduced to 55, albeit now with 13 operational (Global CCS Institute 2012, 2014). In the previous chapter it was shown how Stanford University's Energy Modelling Forum 27 had concluded that the exclusion of CCS would significantly increase the costs of achieving the 2-degree warming goal. Will the world pay this additional cost or can CCS recover from the setbacks and make the contribution necessary to provide a more cost effective mitigation pathway?

This chapter continues the examination of stakeholders and the role they are playing in driving or restraining FECCS. Business stakeholders will again be considered, but this time from the perspective of their propensity to invest in CCS. The attractiveness of CCS investment is considered with investment in other high efficiency low emissions (HELE) technologies. Government's track record in backing CCS is reviewed with the Australian initiated Global Carbon Capture and Storage Institute provided as a case study. Finally issues of public acceptance of CCS and the ideological and competitive questions surrounding green opposition to CCS are considered.

Will anyone fund CCS?

As has been seen in Chapter 4, the fossil fuel industry is powerful and has much to gain from successful implementation of CCS through the freeing up of 'stranded assets', however this will only occur if there are policy mechanisms that force business's hand. But as Chapter 2 discussed, CCS is still very much a nascent technology and even with the successful launch of the SaskPower Boundary Dam plant, significant investment in research and demonstration plants is still required to improve CCS's competitive position. Indeed, Boundary Dam's cost competitiveness was considerably aided by the sale of CO_2 for enhanced oil recovery but this use significantly reduces the utility of CCS as a climate change mitigation process. Without ongoing investment, CCS will remain a curiosity regardless of the expectations of the IPCC.

Business Investment

David Victor considers how a business may approach a technology strategy in his book "Global Warming Gridlock" (Victor, D 2011, pp. 128-33). He reasons that the attraction of technology research investments will be a function of the 'appropriability' of the technology and the potential for 'lock out'. 'Appropriability' refers to the extent to which a company can achieve value from its investment should the innovation be a success and 'lock out' indicates high barriers to entry due to high investment costs or a highly established or regulated market. Victor lays this out in a matrix with his examples given below.

		Lock Out	
		High	**Low**
Appropriability	**High**	Medical Drugs	Internet Technologies
	Low	Energy	Traditional Agriculture

"The attributes of innovation and their implications for technology strategy"
David Victor (2011 p.130).

Victor provides Medical Drugs as an example where high lock out exists due to the high investment in R&D required for product development including long lead time in clinical trials and high regulation through bodies such as the US Food and Drugs Administration. However appropriability is also high as strong intellectual property laws can limit product leakage for the patented life of the product, potentially providing high investment returns to the pharmaceutical company. Energy innovation has high lock out due to the highly established and regulated nature of the industry, but this is not compensated by high appropriability. In contrast to medical drugs, energy is a generic product (think petrol or electricity), it is difficult to patent and differentiate so appropriability is low. High lock out / low appropriability is the most unattractive position on the matrix from the perspective of investors in innovation.

Of course "CCS" in itself is not a product, but a process made up of multiple technologies and systems such as the separation units, transport systems, injection systems and storage management (see Markusson et al. 2012 for a discussion of the complexities of integrating CCS components). For a utility company to negate the impact of a carbon price or a coal company to free up its ‘stranded’ coal reserves all elements of the process must work in unison. I believe it is fair to position component parts of the CCS process in the attractive upper left quadrant of the matrix and companies are indeed working in this area (see for example the GE patent for CO_2 recovery from IGCC plants by Anand, Joshi & Maruthamuthu 2012). However, full implementation of CCS will face regulatory uncertainty (see Havercroft, Macrory and Stewart’s examination of emerging legal and regulatory issues relating to CCS (2011)) and potentially community concerns regarding the storage of the CO_2 (L′Orange Seigo, Dohle & Siegrist 2014) placing it in the high lock out column. And should a corporation hypothetically develop a fully integrated CCS system its appropriability would be low, as the ability to diffuse the process to a global market would likely suffer significant intellectual property leakage, particularly as it can be seen as a public good.[24] Hence it is hardly surprising that large coal or utility corporations are not investing heavily in CCS. Indeed as was seen (page 12) when the US Government withdrew funding from FutureGen, there was no desire from the FutureGen Industry Alliance companies to continue to collectively fund the project.

However industry continues to hype the potential of CCS and the concept of ‘clean coal’. Within Australia, the Minerals Council has promoted the Coal 21 initiative which initially was set up in 2003 to research and develop CCS through a voluntary levy of its members (MCA 2015). Following a review in 2013, it now states (ibid.) that due to changes in technology and economic conditions it is now focused on “adapting overseas technology developments to Australian conditions rather than developing (and therefore reinventing) new technologies”. At the same time as Coal 21 is moving away from CCS research, it is also funding the promotion of the social and economic benefits of the use of coal, both domestically and overseas (Brewster 2014). This promotion is evident in the MCA’s 2015 media campaign “Little Black Rock” (Evans 2015) which promotes the benefits of coal through print, TV and social media using the by-line “Coal it’s an amazing thing”. The campaign includes significant focus on coal technology with acknowledgement of CCS and also an increasing focus on High Efficiency Low Emissions (HELE) technologies such as Super-critical and Ultra Super-critical power plants. As has previously been mentioned there are frequent criticisms that the coal industry keeps dangling the elusive carrot of ‘clean

[24] As an example see Scott Barrett’s discussion of IP issues in the pharmaceutical sector (Barrett 2007, pp. 184-5).

coal' as a win-win for the climate and society. The prominent Australian public intellectual, Robert Manne (2008) has called clean coal and specifically CCS, Australia's "permanent alibi…an excuse for not changing our ways". As has been mentioned, Australia is the world's sixth largest producer of thermal coal and second largest exporter of coal (IEA 2015), so the reliance of overseas technology development could be seen as an abrogation of responsibility. However another view is that as CCS is in the too hard segment of Victor's matrix, there is no true commercial motivation for significant investment by coal companies. The HELE technologies may have higher appropriability, but these are more the domain of high technology original equipment manufacturers (OEMs) such as GE and Hitachi. It is worth briefly considering if these can provide a reasonable alternative to CCS or potentially a stepping-stone for future CCS diffusion.

HELE technologies and CCS tend to be lumped together under the term clean coal but as Soichi Itoh from Japan's Institute of Energy Economics points out, while there is no such thing as 'clean coal', various options exist for cleaner coal (Itoh 2014). The IEA (2012b) provides emissions data for the differing kinds of HELE technologies compared to conventional 'subcritical' technology. A subcritical plant typically has emissions of 881 $gC0_2$/kWh compared to a supercritical plant of 798 and ultra-supercritical of 743 gCO_2/kWh (ibid. p. 284).[25] HELE technologies use less coal per kWh and have efficiencies from 35 to 45% compared to 25% for subcritical plants (ibid. p. 285). Currently approximately 28% of global installed capacity has HELE technologies, up from 20% in 2008 (ibid. p. 65). An additional benefit of HELE technologies (ibid. p. 283) is the ability to remove Nitrous Oxide and Sulphur Dioxide, improving air quality and thus providing an additional drive for adoption.

To put these numbers into a global warming perspective, the Coal Industry Advisory Board's (2015) submission to the IEA in preparation for COP21 claims that should the average global efficiency of coal power plants increase to 40% then that would abate CO_2 emissions by 2 Gt annually which is approximately equal to India's annual emissions. The technology to achieve this is available; however, HELE technologies remain more expensive than subcritical plants and given that the expected life of a power plant is over 40

[25] A further advance is Integrated Gasification Combined Cycle (IGCC) however this technology has not yet been widely diffused. IGCC was intended for the unsuccessful ZeroGen project.

years even with optimistic scenarios it is unlikely that HELE plants will outnumber subcritical plants before 2035 (IEA 2012c, p. 16). And even if the transition to ultra-supercritical plants miraculously occur overnight, there remains the issue of the 743 grams of CO_2 being emitted for every kWh of energy produced. Or to put it another way, should Australia replace all its coal generation with ultra-supercritical plants coal fired electricity would still generate 384 $MtCO_2$/y (Office of the Chief Economist 2015). While the 2 Gt abatement hypothesized by the Coal Industry Advisory Board would be welcome, it is not sufficient to enable the continued use of coal while remaining within a 2-degree carbon budget. However a transition to higher efficiency plants is an enabler for the ultimate diffusion of CCS. CCS imposes an efficiency penalty of approximately 10% (Koornneef, Ramírez, et al. 2012) on the operation of a power plant. Consequently the application of CCS to a 25% efficient subcritical plant would not present an effective business case. An IEA study (2012a) on the potential for retrofitting of CCS to operational plants concludes that CCS is only appropriate for newer HELE technology plants. Unfortunately the IEA also estimates (2012b, p. 282) that almost 50% of coal capacity in 2050 will still be subcritical and hence unattractive candidates for CCS.

HELE technologies are the focus of ongoing R&D by companies such as GE who clearly see it as a vibrant market. Whether these technologies provide an adequate return on investment for the utility companies will be influenced by the cost of coal and the expectations of a price on carbon. Legislation such as the US Clean Power Plan (Environmental Protection Agency 2015) which has a specific "building block" focused on HELE also drives the take up of the technologies. The diffusion of HELE technologies could potentially be accelerated by an alliance of environmental actors and powerful industry groups lobbying the US government to influence the global take up of the technology. This approach is described in Elizabeth DeSombre's Baptists and Bootleggers paper (1995) however although feasible it seems unlikely. HELE on its own does not adequately mitigate CO_2 emissions and, as with CCS, can be seen by environmental groups as a stalling tactic to prolong the use of coal.

From a CCS perspective, HELE does provide an important foundation for carbon dioxide separation processes. According to GE's leader of CCS policy and regulatory activities, Norman Schilling, (2011, p. 28), the development of HELE technologies has made the capture of CCS feasible although further R&D work is required to reduce costs and improve efficiency. Schilling points to policy and regulatory uncertainty as the principal barrier to CCS (ibid. p. 35). It should be assumed that Schilling is echoing his company's position but he is supported by the findings of a US Government (2010) interagency task force on CCS, which found that although none of the barriers to CCS were insurmountable, legal issues (e.g. long term liability), regulatory frameworks and financial incentives that supplement carbon prices all need to be addressed to move CCS forward. Clearly these are issues for government and the public sector whose actions, or lack thereof, will be considered next.

Government Action

Prior to the December 2015 COP21 meeting, the countries of the world (with very few exceptions) submitted their "Nationally Determined Contributions" (NDCs) outlining their goals and actions to mitigate GHGs through to 2030. Many included priority areas for mitigation. Of these, 90% nominated renewable energy as a priority area and about 86% energy efficiency. Just two per cent included CCS as a priority area (UNFCCC 2015c, p. 34). Interestingly China's NDC does refer to CCS with the captured CO2 being used for enhanced oil recovered (Chinese Government 2015). However as was seen on page 14 this partly defeats the purpose of CCS as a mitigation process. My analysis of the NDCs of other major emitters, the US (US Government 2015), India (Indian Government 2015) and Australia (Australian Government 2015) does not find any reference to CCS although India does specify that all new coal power stations will be equipped with HELE technology. While the NDCs do not preclude the future diffusion of CCS, they do indicate that CCS is far from front and centre in government's climate policy considerations creating a disconnect between the expectations of the IPCC and national initiatives.[26]

As seen, given the position of CCS in the bottom left hand corner of Victor's matrix, it appears unlikely that CCS will become a reality without public investment. But given the defunding of ZeroGen and FutureGen plus the recent British announcement to defund the CCS "competition", this prospect appears to be receding rather than becoming more likely. Governments frequently have budget pressures and it could be argued that the defunding of the two projects referenced above plus the recent UK decision were simply responses to

[26] Note that although very few identified CCS as a priority, CCS was mentioned in the NDCs of 10 countries (Primap: Potsdam Institute n.d.)

these pressures. But policy decisions are also influenced by a multitude of other factors including change of government, change of leadership within government and media, business and public sentiment. These factors make long-term commitment to CCS projects uncertain. It is not difficult to understand industry's frustration at the inconsistent policy signals they receive from government. In a press release following the UK government's decision in November 2015 to withdraw funding from CCS one of the key contenders, Shell UK stated, "Shell is disappointed at the withdrawal of funding for the CCS Commercialisation Competition… We have worked tirelessly over the last two years to progress our plans for this project." It goes on to say that it remains committed to CCS, however its confidence in government has been impacted (Shell UK 2015).

The experience of the Global Carbon Capture and Storage Institute (GCCSI) set up by the Australian Government in 2009 provides another example of how the vagaries of politics, budget priorities and lukewarm commitment has impacted the progress of CCS. In an announcement at the G8 meeting in L'Aquila Italy in 2009, Australia's then Prime Minister, Kevin Rudd committed \$100M per year to fund the GCCSI stating that its mission was to "get large scale carbon capture and storage projects done around the world, not just discussed." (Rudd 2009). Rudd had secured Jim Wolfensohn the former President of the World Bank to chair a five member advisory panel and all governments of the G8 became founding members plus over 100 of the world's major energy companies (ibid). The GCCSI had an auspicious start, but almost 7 years on it is hard to argue that it has achieved the aspirations of its founding members and those present at L'Aquila. Initially the Australian Government lived up to its promise of \$100M per annum but following the Queensland Floods and Julia Gillard's election as the new Prime Minister, the 2011/12 budget was reduced to \$25M to divert funds to what the Department termed "natural disaster recovery and rebuilding". (Resources Energy and Tourism Portfolio 2011, pp. 19, 31). Two years later, when the then Minister for Resources and Energy, Gary Grey put forward his department's proposed budget, funding for the GCCSI had been removed from the estimates out to 2016/17 (Resources Energy and Tourism Portfolio 2013, p. 25). Nor was it likely that the new Liberal led coalition government will reinstate funding for the Institute. Prior to its election in 2013, a Liberal Party media release, "Our Plan to get the budget under control", included \$300M of savings from redirecting funding from the CCS Flagships Program (Liberal 2013). Now in government, the Coalition's Emissions Reduction Fund White Paper makes no mention of the GCCSI or indeed of carbon capture and storage

(Department of the Environment 2014). There appears to be no space in the Coalition's climate strategy for CCS.

Without government funding the Institute must survive on the subscriptions of its members and whatever other revenue it can generate from other sources. Unfortunately its membership base has also declined over the last 7 years. Although the governments of Japan, Australia, the US and the USA remain members, the governments of France, Germany, India, Indonesia and Russia have disappeared from the membership list (Global CCS Institute 2010, 2015b).[27] Perhaps unsurprisingly, it is difficult to find press releases announcing these countries' membership cancellations.

The funding that the GCCSI receives from its members is not disclosed, however it is unlikely that without significant government funding the Institute can realise the mission announced by Prime Minister Rudd in 2009. Whereas Rudd stated the CCS should be done and not just discussed, the Institute's activities now focus on the later, not the former. In its most recent Annual Review its two objectives are now stated as "Authoritative knowledge sharing" and "Fact-based influential advice and advocacy" (Global CCS Institute 2015a, p. 3). As previously mentioned the SaskPower facility cost almost C$1.5B so the Australian government's $100M a year would not in itself make CCS a reality. However the lack of these funds makes the challenge of rapid and broad diffusion of CCS all the more difficult.

The experience of the GCCSI demonstrates the precarious nature of significant public funds from one country being invested for a broader global public good. Then PM, Tony Abbott is reported as saying about the GCCSI "Frankly if we are the only country that is backing it and funding it, it is never going to happen" (Morton 2010). More recently the current PM, Malcolm Turnbull committed Australia to join with other major economies in supporting "Mission Innovation" which has an aim to double clean energy innovation over the next five years (Turnbull 2015; UNFCCC 2015a). Whether CCS will obtain some of these funds, or indeed if these funds will eventuate remains to be seen.

[27] In 2010 China's membership was listed as The Government of the People's Republic of China. It is now listed as The Government of the Peoples Republic of China as Represented by the National Development and Reform Commission (NDRC).

Opponents of CCS

The mitigation of CO_2 is unquestionably a major global challenge, whose solution appears best served by taking a multi-strategy approach. Pascala and Socolow (2004) neatly divide these strategies into Giga-tonne Carbon 'wedges' including renewables, nuclear, CCS and others. Consequently it may be assumed that any CO_2 mitigation process would be welcomed. However competitive forces, frequently bound up with ideological perspectives ensure that, as is the case with nuclear, not everyone wants to see CCS become a reality.

As was seen in Chapter 4, traditionally the lobbying muscle has been predominantly with the fossil fuel industry, but the renewables lobby is fighting back with narratives that are not only pro renewables, but frequently anti CCS (and nuclear). The need for "persuasive discourses" are most critical during the innovation stages of new energy technologies (Stephens & Jiusto 2010). This is when governments and venture capitalists need to be convinced to support R&D and early commercialisation for a new initiative. In the increasingly competitive energy environment, putting forward a persuasive discourse supportive of your technology may also include questioning the efficacy of potential or perceived competitors. Green groups often focus on promoting the development and diffusion of renewable technology, and while being pro renewable does not always equate with anti-CCS it frequently does. Bellona, a Norwegian Environmental NGO actively supports CCS and the WWF is "apprehensive" and calls for further research but is not anti-CCS (Bellona 2016; WWF Global 2016). Two prominent Green groups that lobby against CCS are The Sierra Club (see for example Gavin Jabusch 2015) and Greenpeace (see below). Their principal arguments include cost, safety concerns and the effectiveness of CCS as a CO_2 mitigation process.

In 2015 Greenpeace published two significant documents: Energy [R]evolution (Teske, Sawyer & Schafer 2015) and Carbon Capture SCAM (Ash 2015). Energy [R]evolution is subtitled "100% Renewable Energy For All" and at 330 pages is a comprehensive analysis of multiple scenarios that could enable a more energy efficient and renewable powered world. It also puts forward its opposition to CCS (pp. 228-229) and includes an argument against nuclear power on the following page. At first blush it appears to be a scholarly and in-depth analysis that demonstrates that the world can stay within the carbon budget based on energy efficiency and widespread diffusion of wind and solar. It is not my intention to question the contents of the document; however, it should be recognised that although the report is frequently referred to as a "Greenpeace" document, it is in fact jointly published by the Global Wind Energy Council (GWEC) and Solar Power Europe in addition to Greenpeace. These organisations are lobby groups for major listed corporations such as Vestas, Siemens, GE Energy and Iberdrola (GWEC n.d.), and DuPont, Enel and Canadian Solar (Solar Power Europe 2015). It is reasonable to expect that these companies will wish to highlight the potential for their product while casting doubts on the efficacy of competing technologies, specifically, CCS and nuclear. The reader of Energy [R]evolution should consider this when evaluating its contents.

The title of Greenpeace's second 2015 publication "Carbon Capture SCAM: How a False Climate Solution Bolsters Big Oil" leaves the reader in little doubt as to its theme. It outlines the failures of CCS projects (which I have covered in Chapter 2), the high probability of CO_2 leakage, and that CCS is more expensive per tonne of CO_2 captured than either wind or solar. Given the title, a balanced view should not be expected. But there are other sources that make alternative claims. The IPCC Special Report on CCS (IPCC 2005, p. 14) asserts that given appropriate selection and management of reservoirs, containment is "very likely" to exceed 99% over 1,000 years.[28] Similarly as discussed on page 35, the IPCC's AR5 (IPCC 2014a, p. 15) highlights how it is significantly more expensive to achieve a 450ppm goal without CCS. Greenpeace claims to be an "independent global campaigning organisation" (Greenpeace International 2015) but given the partnerships evident in the Energy [R]evolutions report it is not unreasonable to see the hand of the renewables industry and Greenpeace's inherent ideology in the Carbon Capture SCAM report.

While pro-renewable may not always be synonymous with anti-CCS there is clearly a relationship. John Conner, the CEO of the Climate Institute, describes the situation well when he says that supporters of renewables see CCS as giving new life to their "ruthless adversaries, many of whom have been strident opponents of climate change" (Connor 2014). I cannot say if the authors of "Big Coal: Australia's Dirtiest Habit" (Pearse, McKnight & Burton 2013) are ardent supporters of renewables, but in a broad ranging criticism of the Australian coal industry they devote a chapter "Clean Coal Ruse" where they describe CCS and HELE technologies as ploys to extend the life of the coal industry. This is a common

[28] "Very likely" is a probability between 90% and 99%

theme and is reflected in the subtitle of Greenpeace's Carbon Capture SCAM: "How a False Climate Solution Bolsters Big Oil", by Giorel Curran (2012) and Hamilton (2013).

Distrust of the fossil fuel industry may also be a driver of safety concerns over CO_2 leakage. As mentioned the IPCC's SRCCS (2005) claimed that very high levels of containment can be achieved should the reservoirs be appropriately selected and managed. This was recently reinforced in an open letter to Christiana Figueres (Executive Secretary of UNFCCC), ahead of COP21 authored by leading CO_2 storage experts asserting that "The residual risk of leakage can be managed by well-understood procedures and presents very low risk of harm to the climate, environment or human health" (Scottish Carbon Capture and Storage 2015). But of course poor selection and management can negate the confidence regarding long term containment, either undoing the mitigation efforts and/or providing a localised health hazard. However CO_2 is lethal at high concentrations and this point is highlighted in Greenpeace's Energy [R]evolutions (2015, p. 229). Here it recounts the Lake Nyos disaster of 1986 where over 1,700 people which killed by a natural release of CO_2 from a lake formed over an extinct volcano (Sample 2005). The fear of a repeat of this tragedy could be highlighted by anti-CCS campaigners should CCS become a broadly diffused mitigation process. CO_2 reservoir site selection and ongoing controls must ensure that a Lake Nyos type event cannot happen and the pro-CCS lobby's persuasive discourse must emphasise the safety of CCS storage.

Given its track record it may be fair to look at the fossil fuel industry with suspicion and distrust. The recent exposé of Exxon's cover up of its knowledge of climate change (Goldenberg 2015), is another black mark on the industry's reputation. However recalling the "wedges" concept (Pacala & Socolow 2004) and the immense scale of the mitigation challenge, it may be time to recognise the necessity of employing all available options. Indeed more and more global resource companies recognise the reality of climate change and argue that it is legitimate for them to be part of the solution given that their products are a source of the problem (AngloAmerican 2010; BHP Billiton 2016; Rio Tinto 2012; Shell Global n.d.). While it may be easy to dismiss these statements as simple public relations, it is also fair to argue that it is important to work collaboratively with these giant organisations to ensure a broad-based solution to the challenge of mitigation.

Public Opinion

As was mentioned in Chapter 3, in 2005 the IPCC reported that assessing public opinion regarding CCS was difficult due to its remoteness and relatively technical nature of the issue. However, where the concept of CCS was accepted it was with reluctance rather than enthusiasm (IPCC 2005, p. 36). Subsequent studies have confirmed the lack of engagement of the public with CCS. Nicole Huijts et al found that not only does the public have little knowledge, but also has little desire for information and that consequently trust in professional actors is important with NGOs being more trusted than industry (Huijts, Midden & Meijnders 2007). In an examination of public perception of risk, it was found that CCS geological storage was unlikely to be considered as worse than current fossil fuel technologies (Singleton, Herzog & Ansolabehere 2009), although whether this should provide encouragement to CCS advocates is questionable. A more recent review study of public perception research (L′Orange Seigo, Dohle & Siegrist 2014) found that when people are informed about CCS, they rate risk just above the mid-point on a quantitative scale with nobody expressing a strong or extreme view. The key message from these studies appears to be that the public has yet to engage with CCS. However, as engagement takes place, the importance of influencing public opinion becomes clear with local opposition resulting in some projects being delayed or cancelled (Anderson, Schirmer & Abjorensen 2012). Given the importance of persuasive discourse in the early stages of innovation, the current lack of engagement can be seen as an opportunity for both CCS advocates and CCS opponents to shape perceptions.

Conclusion

The prospects for fossil energy CCS do not appear promising. Due to its low appropriability and high lock out there is little incentive for corporations to finance CCS. Government interest in CCS appears to be waning with less public investment in the technology. Other supports necessary from governments such as an effective price on carbon pricing and appropriate regulatory systems are not adequate. Calls from Green groups and renewable energy corporations to defund CCS are growing and given that societal engagement is minimal, CCS is unlikely to be rescued by civil society or grassroots campaigning communities. The following, concluding chapter will summarise the findings from the previous chapters and provide some final reflections on the FECCS-BECCS relationship.

Chapter 6. Conclusion

Introduction

This thesis set out to inquire if fossil energy CCS could provide a stepping-stone to negative emissions and to consider the associated question of whether it is in the interests of stakeholders to make FECCS a reality. Both questions present a puzzle and as was established in Chapter 1, both are important in tackling the challenge of climate change. The novelty in this thesis comes from linking both issues together. The stepping-stone question, (although it seems to be taken as a given by some writers), does not appear to have received serious academic consideration. My examination in Chapter 3 of the processes constituting both forms of CCS has shown that FECCS would indeed provide a strong foundation for the future implementation of BECCS. Should the diffusion of FECCS be inevitable, then this stepping-stone will be created by default. However as was shown in Chapter 2, the initial momentum of CCS appears to be stalling. Chapters 4 and 5 demonstrated that the medium term diffusion of FECCS appears increasingly unlikely. It even appears that the ongoing growth of coal and the desires of fossil fuel owners to safeguard their assets from becoming "stranded" do not present compelling reasons to ensure its future. Consequently any desire to reduce carbon dioxide atmospheric concentrations will likely be compromised with the leading CDR option requiring a longer time to ramp up to the required levels. A brief summary and discussion of both questions follows.

Question 1: FECCS as a Stepping Stone.

The relationship and synergies that exist between FECCS and BECSS was demonstrated in Chapter 3, albeit at a relatively high level. Nonetheless it is clear that both technologies will require similar separation processes, pipeline infrastructure, validation of storage capacities and storage integrity, legal and regulatory infrastructure and, importantly, acceptance by the public. Given the historical experience of a 50 plus year lead-time to transition to a new energy sources (Smil 2014) and the projected need for <u>net</u> negative emissions by the 2070s for a 2-degree goal (Rogelj et al. 2015) the challenge is imminent.

In addition to establishing the relationship between the two forms of CCS, Chapter 3 also explored the feasibility and practicality of BECCS and considered if it merited its position as the primary CDR candidate in much of the literature, including AR5. Without these conditions being met, whether FECCS paves the way for BECCS is of little interest. My analysis shows that BECSS is feasible and with current technology it appears to be the best (or the least worst) option. The practicality of BECCS is more open to challenge. Remembering the scale of land, water and nitrogen required for sequestration of 12 $GtCO_2$/y and given the multigenerational time frame necessary to reduce concentrations by 100ppm would future generations embark on such an endeavour? Pragmatically, this seems unlikely, but what if there are no alternatives?

Approaches such as Solar Radiation Management may provide a short to medium term alternative. However, as was established in the Introduction, this thesis took a normative approach of seeking to identify a pathway through which to maintain, as much as is possible, the pre-industrial environment. Future generations may decide that expediency trumps normative considerations and that will be their decision. Techno-optimists such as Tim Flannery (see his latest book Atmosphere of Hope: Searching for a Solution to the Climate Crisis 2015), may have confidence that a high technology solution can be found to address the normative concerns and enable carbon dioxide removal at the scale necessary. Given the recent pace of technology change, this may be a reasonable expectation, and indeed following COP 21, business leaders (Breakthrough Energy Coalition n.d.) and political leaders (Mission Innovation 2016) announced the intention to "reinvigorate and accelerate global clean energy innovation" (ibid.) through the doubling of clean energy R&D investment over 5 years.[29] Regardless of whether some of this clean energy money makes its way into CRD research, there remain the possibility that a technology may not be found and that in thirty or forty years' time the challenge of ramping up a BECCS solution may be too great. Perhaps then, the expedient SRM solution may become the default option.

Question 2: Analysis of FECCS stakeholders

Following the analyses in Chapters 4 and 5, I have positioned each actor in a basic stakeholder matrix. The most striking message from the table is that there are no stakeholders in the strongly supportive category. This point alone is likely to account for the ongoing neglect and potential demise of the technology. I will very briefly review these chapter's conclusions concerning the placement of each stakeholder, but it should be noted

[29] It is difficult to find follow-up information on the Mission Innovation initiative. The Official Launch Statement promised a follow-up meeting in early 2016. As at 18th April 2016, I haven't been able to find any communication regarding this promised meeting.

that each classification is a generalisation and the stakeholder groups should not be considered homogenous.

Strategic Position	**Stakeholder**					
	Climate Community	Governments	Coal Industry	Renewable Industry	Green Groups	Public
Strongly Supportive						
Passively Supportive	X		X			
Mixed		X				X
Not Supportive				X	X	

(Adapted from Varvasovszky & Brugha 2000)

Epistemic Climate Community: As highlighted in Chapter 1, the Climate Community provided the lens through which other stakeholders were analysed. Although the Community was not explicitly analysed, its consideration was inherent throughout this thesis. Given the profile that CCS has received from the IPCC and in general academic literature I maintain that it is reasonable to position this group as passively supportive. Organisations such as the International Energy Agency could be seen to be strongly supportive, although whether they can legitimately be included as part of the climate community may be contested.

Government: As was seen in Chapters 2 and 4, Governments have frequently been ostensible supporters of CCS, but CCS has proven itself time and time again as an easy climate initiative to drop. Examples given in Chapter 2 from the UK, the USA and Australia have demonstrated that when budgets are in difficulty or government's priorities change CCS is abandoned. Additionally by largely overlooking the role of CCS in their Nationally Determined Contributions for COP21, the governments of the world signalled their lack of commitment to CCS. Granted, governments are likely to be the least homogenous stakeholder and governments with more latitude to make unilateral decisions, e.g. China, may increase support for CCS should it appear to meet their wider interests.

Coal Industry: Given the value of the world's coal reserves discussed in Chapter 4, it may seem somewhat surprising that this industry is not in the "strongly supportive" row.

However industry investment is largely determined by the expected return and as was seen in Chapter 5 due to reasons of lock out and appropriability, CCS R&D is unlikely to be an attractive industry investment. HELE was seen as a more attractive investment option which can also serve as a public relations tool in the quest to position coal as a cleaner product. The CCS investment equation may change with a significant price on carbon (>$100), which is ideally globally applied. However this appears unlikely within the timeframe necessary. Another variable that could change the ROI equation is the potential to sell the captured CO_2. Currently enhanced oil recovery is a application of captured CO_2, however as was seen, this is suboptimal given the objective of lowering total emissions.

Renewable Industry: As a competitor to the coal industry it is to be expected that the renewables industry would not support a technology that would perpetuate the life of a competitor's product. This was illustrated in Chapter 5, by the alliance of the Wind and Solar industry groups and Greenpeace to produce the Energy [R]evolutions report criticising CCS technology.

Green Groups: Although Bellona is a notable exception; as was seen in Chapter 5, in the competition between CCS and renewables, Green groups generally back the renewable option. Specifically, Greenpeace and The Sierra Club are very vocal regarding the opposition to CCS.

The Public: Per the IPCC, the issue of carbon capture and storage remains remote and it is hard to position public opinion as either promoters or detractors of CCS (IPCC 2005, p. 36). As has been discussed in Chapter 5, this could change with a growing awareness of the seriousness of climate change potentially swinging opinion in favour of CCS or alternatively NIMBY driven concerns could make the selection of storage sites problematic.

This stakeholder analysis, drawn from Chapters 4 and 5, paints a broad picture of the prospects for CCS. Unquestionably individual exceptions can be found for each classification, but taken overall the situation does not auger well for the meaningful diffusion of CCS. Given Chapter 3's findings re BECCS, a hypothetical question is worth asking: would an acceptance that FECCS is a necessary stepping stone to the achievement of the 2-degree goal via BECCS change stakeholder positions on the matrix? Given the profit motive driving the two industry groups, their positions are unlikely to change significantly. How other stakeholders would respond can only be speculated but some movement up the matrix could reasonably be expected. Unfortunately this thesis cannot reach a definitive conclusion if such movement would be adequate to enable the successful and meaningful diffusion of FECCS.

As a final point, assuming the need for BECCS, and given that FECCS could facilitate its ultimate diffusion, there is a strong argument to fund the development of CCS as a global public good. Multiple examples of the provision of global public goods exist, from the program to eradicate smallpox to the development of the large hadron collider at CERN. There are also multiple means of funding the provision of such goods.[30] Given the reluctance of any individual stakeholder to progress CCS, it may be appropriate to consider its development as a matter of pressing global public policy.

Possible Future Research

In writing this thesis I have identified three interconnected but independent pieces of work that I believe merit further analysis.

First, continuing with the stepping-stone analogy, a logical question is whether it is more efficient (both in cost and time) to leap over the stream to BECCS without using the FECCS stepping-stone. This research would require a macro-level cross disciplinary analysis including, but not limited to, considerations of the value of stranded assets; optimal pipeline networks to accommodate CO_2 from both sources, optimal selection of storage reservoirs, and analysis of the potential that diffusion of FECCS would lock out or significantly delay BECSS. Due to the complexity of the issue, a country based analysis, rather than a global view may be appropriate.

A second area of research is to turn the question of this thesis around and ask if the future need for BECCS can provide an impetus for the near term implementation of FECCS thus creating a co-dependency between both forms. This issue was touched on in the stakeholder analysis but greater research as to how an acceptance of such a co-dependency would influence stakeholder's positions on the matrix may assist climate strategy development. Of

[30] For a discussion on the incentives to supply global public goods, see Scott Barrett (2007)

course for BECSS to provide an impetus for FECSS, presumes that stakeholders accept the need for BECCS.

Finally, and at a more macro level, the writing of this thesis highlighted that there is little engagement in the issue of BECCS (or CDR in general) amongst policy makers. However as was demonstrated, it is becoming more and more difficult to reconcile an avoidance of CDR with a 2-degree goal. Greater understanding of the scale of the challenge of CDR may prompt policy makers to associate FECCS and BECCS in policy considerations. Of course an alternative view may be taken from Oliver Geden's remarks: "Policy-makers view the IPCC reports mainly as a source of quotes with which to legitimize their preferences" (2015). Robert Keohane has argued that there was too little work on climate issues from a political science perspective (2015). Given the imminence, scale, and importance of CDR to climate goals, how policy makers and the political elites respond provides an important topic of inquiry.

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