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Stranded Assets and Environment-related Risk

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Abstract

This thesis represents the first comprehensive attempt at providing conceptual and scholarly coherence to the topic of stranded assets and the environment. Over the last five years the topic has risen up the agenda and has become of significant interest to scholars and practitioners alike, as it has influenced a number of pressing issues facing investors, companies, policymakers, regulators, and civil society in relation to global environmental change.

The thesis reveals how the topic developed and emerged, notably through a unique first-person account based on autoethnography and close dialogue. Four self-contained papers demonstrate the wide applicability of stranded assets, and further existing, relatively well-developed literatures (namely carbon budgets and stranded costs) and also two much less developed literatures (namely the calibration of climate policy to minimise stranded assets and policy mechanisms to quickly and efficiently strand assets).

Though a significant amount has been written on stranded assets over a short period, there remain significant gaps in the literature. The thesis identifies substantial research opportunities, particularly to better connect our understanding of physical and societal environment-related risks; to improve our knowledge of perception and behaviour in relation to the creation and management of stranded assets; to expand the scope of work into new sectors and geographies; and to place stranded assets in an appropriate historical perspective.

Stranded assets is, if anything, a geographical concept. The thesis makes the case for economic geography as the disciplinary home for stranded assets. The sub-discipline can both contribute to the development of stranded assets as a scholarly endeavour and itself benefit from interacting with a topic that intersects with some of the most pressing contemporary issues related to environmental sustainability.

Word count: 275

Glossary of Key Terms and Abbreviations

Abbreviations

BECCS	Bio-energy with Carbon Capture and Storage
CAR	Carbon Asset Risk
CBI	Climate Bonds Initiative
CCGT	Closed-Cycle Gas Turbine
CCS	Carbon Capture and Storage
CDP	NGO; formerly Climate Disclosure Project
CDSB	Climate Disclosure Standards Board
CERES	Sustainability Leadership NGO
CFA	Chartered Financial Analyst
CISL	Cambridge Institute for Sustainability Leadership
COP	Conference of Parties
COP15	United Nations Climate Change Conference of Parties in Copenhagen
COP21	United Nations Climate Change Conference of Parties in Paris
CSR	Corporate Social Responsibility
CTI	Carbon Tracker Initiative
DAC	Direct Air Capture
DEFRA	UK Department for Environment, Food and Rural Affairs
EIA	U.S. Energy Information Administration
ENSO	El Niño Southern Oscillation
EPA	U.S. Environmental Protection Agency
ESG	Environmental, Social, and Governance
ESG/RI	Environmental, Social, and Governance/Responsible investment
ESRB	European Systemic Risk Board
ET	Energy Transition
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicle
FSB	Financial Stability Board
G20	Group of 20 Major Economies
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
IDB	Inter-American Development Bank
IEA	International Energy Agency
IEEFA	Institute for Energy Economics & Financial Analysis
NDC	Nationally Determined Contributions
IFC	International Finance Corporation
IGCC	Investor Group on Climate Change

IIGCC	Institutional Investors Group on Climate Change
IIRC	International Integrated Reporting Council
IISD	International Institute for Sustainable Development
ILO	International Labour Organization
IMF	International Monetary Fund
INCR	Investor Network on Climate Risk
IPCC	Intergovernmental Panel on Climate Change
LCDP	Low Carbon Development Pathways
LNG	Liquefied Natural Gas
NCD	Natural Capital Declaration
NETs	Negative Emissions Technologies
NGO	Non-governmental Organisation
OCGT	Open-Cycle Gas Turbine
OECD	Organisation for Economic Cooperation and Development
OPEC	Organisation of Petroleum Exporting Countries
PALD	Principle of Asset-Level Disclosure
PPA	Power Purchasing Agreement
PPP	Public-Private Partnership
PRA	Bank of England Prudential Regulation Authority
PRI	Principles for Responsible Investment
PV	Photovoltaic
RI	Responsible investment
SAA	Strategic Asset Allocation
SASB	Sustainability Accounting Standards Board
SCPS	Sub-critical coal-fired power station
SDGs	Sustainable Development Goals
SEC	US Securities and Exchange Commission
SRI	Socially Responsible Investment
SWF	Sovereign Wealth Fund
TCFD	Task-Force on Climate-related Financial Disclosure
UNEP	United Nations Environment Programme
UNEP FI	United Nations Environment Programme Finance Initiative
UNFCCC	United Nations Framework Convention on Climate Change
WBCSD	World Business Council for Sustainable Development
WEC	World Energy Council
WEF	World Economic Forum
WRI	World Resources Institute

Key Terms

Term	**Definition**
Decarbonisation	Reductions in the carbon-intensity of investments and portfolios.

Divestment	Divestment is a socially motivated activity of private wealth owners, either individuals or groups, such as university endowments, public pension funds, or their appointed asset managers. Owners can decide to withhold their capital—for example, by selling stock market-listed shares, private equities or debt— from companies seen to be engaged in a reprehensible activity.
Enhanced Engagement	Closer involvement by investors in the governance processes of businesses in which they invest; examples include shareholder actions and board participation in some corporations to ensure proper management of environment-related risks.
Green Indices	Allocation of investments in a portfolio by giving partial or full consideration to their scoring according to an index of environmental or sustainable performance metrics; examples of indices include the FTSE4Good Index Series.
Just Transition	Calls for greater attention to the inequalities generated by efforts to tackle climate change, particularly how a low carbon future can be achieved without undermining development and increasing inequality (both between regions and between generations).
Natural Capital	The world's stocks of natural assets which include geology, soil, air, water and biodiversity. Humanity derive a wide range of services from natural capital ('ecosystem services)' that make social and economic activity possible.
Responsible Investment	An approach to investing that aims to incorporate Environmental, Social and Governance (ESG) factors into investment decisions, to better manage risk and generate sustainable, long-term returns.
Screening	Investors choose to either 1) exclude some investments from their portfolios or 2) include some investments in their portfolios on the basis of specified environmental characteristics; examples include screening out certain companies in carbon-intensive industries, or that have histories of pollution.
Stranded Assets	Assets which have suffered unanticipated or premature write-downs, devaluations, or conversion to liabilities.
Stress Testing	Analysis of portfolio exposures to risks through simulation and other forms of statistical perturbation; for example, investors may run (actual or hypothetical) portfolios through a larger number of and/or more extreme future scenarios, such as different ranges of carbon prices and policy outcomes.
Systemic financial risk	The risk that an event will cause significant loss of economic value or be a shock that produces adverse effects for a significant part of an economic system.

The Taskforce on Climate-Related Financial Disclosures (TCFD)	Established in December 2015, this Task-Force was designed to set out specific recommendations and guidelines for voluntary disclosure by identifying leading practices to improve consistency, accessibility, clarity, and usefulness of climate-related financial reporting.

1 Introduction, methodology, and survey of the literature

Over the last five years the topic of 'stranded assets' created by environment-related risk factors, including physical climate change impacts and societal responses to climate change, has risen up the agenda dramatically. The concept has been endorsed by a range of significant international figures, including: UN Secretary-General Ban Ki-moon (McGrath 2014); US President Barack Obama (Friedman 2014); Jim Kim, President of the World Bank (World Bank 2013a; World Bank 2013b); Mark Carney, Governor of the Bank of England and Chair of the G20 Financial Stability Board (Carney 2015); Angel Gurría, Secretary-General of the OECD (Gurría 2013); Christiana Figueres, former Executive Secretary of the UNFCCC (Figueres 2013); Lord Stern of Brentford (London School of Economics 2013); and Ben van Beurden, CEO of Shell plc (Mufson 2014).

The emergence of the topic should be of significant interest to scholars and practitioners alike, as it has arguably influenced a number of pressing issues facing investors, companies, policymakers, regulators, and civil society in relation to global environmental change, for example:

- Measuring and managing the exposure of investments to environment-related risks across sectors, geographies, and asset classes so that financial institutions can avoid stranded assets (for example, see Financial Stability Board 2015; Caldecott et al. 2013; Generation Foundation 2013; Carbon Tracker Initaitive 2011; Caldecott 2011).
- Financial stability implications of stranded assets and what this means for macroprudential regulation, microprudential regulation, and financial conduct (for example, see Kruitwagen et al. 2016; Bank of England 2015b; Carbon Tracker Initiative 2011; Caldecott 2011).
- Reducing the negative consequences of stranded assets created as societies transition to more environmentally sustainable economic models by finding ways to effectively address unemployment, lost profits, and reduced tax income that are associated with asset stranding (for example, see Caldecott 2015).
- Internalising the risk of stranded assets in corporate strategy and decision-making, particularly in carbon intensive sectors susceptible to the effects of societal action on climate change (for example, see Rook & Caldecott 2015; Carbon Tracker Intaitive 2013; Ansar et al. 2013).
- Underpinning arguments by civil society campaigns attempting to secure rapid economy-wide decarbonisation in order to reduce the scale of anthropogenic climate change (for example, see Ansar et al. 2013).
- Keeping track of progress towards emission reduction targets and understanding how 'committed emissions'[1] should influence decarbonisation plans developed by

[1] Defined as the future emissions expected from all existing fossil fuel-burning infrastructure worldwide (Davis et al. 2010).

governments, as well as companies and investors (for example, see Pfeiffer et al. 2016; Davis & Socolow 2014; Davis et al. 2010).

These are some of the most important topics in current policy, investor, industry, and civil society discourses on the environment and look set to remain key for as long as societies continue to transition towards greater environmental sustainability.

Despite this, there have been few efforts to provide conceptual coherence to the topic of stranded assets (for example, see Caldecott 2015a; Caldecott & McDaniels 2014; Caldecott et al. 2013). As such this D.Phil. project aims to do the following: i) provide a firmer conceptual and scholarly foundation for stranded assets as a research topic, ii) shed light on how the topic developed so quickly in the first half of the second decade of the 21st century, iii) advance the academic literature on stranded assets through four original papers covering different facets of the topic, and iv) make the case for stranded assets to find a disciplinary 'home' in economic geography and for economic geography to embrace stranded assets.

The first two chapters together lay the foundation for chapters three to six, which are the four distinct academic papers. The first chapter sets out the scope, objectives, and structure of the thesis. It explains the methodological approach employed in a reflexive first-person account of how stranded assets developed. The chapter conducts a literature review of stranded assets charting its origins, recent developments, and growing significance. It then makes the case for stranded assets as economic geography and as a geographical concept.

Chapter two, through an approach drawing on autoethnography and close dialogue, sheds light on the interests and motivations of different groups working on stranded assets and how the topic emerged and spread. The chapter also identifies some broader generalisations and lessons that can inform the development, communication, and uptake of sustainability issues, particularly among those working in finance and investment.

The four self-contained papers that follow chapter two are focused on different areas of stranded assets and each contains details of the methodologies employed and relevant literature reviewed. As much of the initial work on stranded assets has concerned how carbon budget constraints might impact the value of upstream fossil fuel companies, the first paper builds on this literature by examining how negative emissions technologies could affect carbon budgets and whether this could impact asset stranding. This paper is complemented by a second that examines stranded generation assets in Europe and quantifies the impact on utility balance sheets. Like the first paper, this seeks to build on the existing literature on asset stranding, but is focused on the utilities sector – an area that has received less attention than upstream fossil fuel production.

The next two papers then apply stranded assets to areas where the literature is much less developed. The first develops the idea that calibrating climate policy in a similar way to how central banks calibrate monetary policy could help to achieve climate outcomes with the least amount of stranded assets. This paper examines the role of corporate solvency as a proxy for asset stranding and looks at how corporate solvency metrics could be used to objectively calibrate climate policy to help achieve optimal decarbonisation pathways. This paper draws on the climate policy literature, as well as on methods and tools used in management and business studies.

The fourth paper looks at how policymakers could intentionally strand the most polluting form of coal-fired power stations through a mechanism that also reduces the risk of political opposition from power station owners, operators, and employees. This paper is grounded in the climate policy and political economy literature.

The rationale for including these four academic papers in the thesis is to demonstrate the wide applicability of stranded assets, and to further existing, relatively well-developed areas (namely carbon budgets and stranded costs) and also two less developed areas (namely the calibration of climate policy to minimise stranded assets and policy mechanisms to quickly and efficiently strand assets). The four papers also roughly follow the chronological development of my thinking on stranded assets, as well as the development of work produced by others.

Annex I contains a complete list of publications (reports, working papers, journal articles, edited special issues, books, book chapters, talks and speeches, and comment pieces) that I have authored or co-authored on stranded assets. Only a minority of these publications meet the requirements of inclusion in this thesis and in addition to the formal requirements stated in University of Oxford regulations I applied the following filters to select the four papers: i) were they written in an academic style for the peer reviewed literature; ii) do the four selected demonstrate a logical sequence and together add up to more than the sum of their parts; and iii) of the publications that meet these criteria which do I consider to be the best or am the most proud of.

Chapter seven concludes by identifying substantial future research opportunities on stranded assets and highlighting limitations associated with this thesis and the work completed to date. It is followed by Annex I (discussed above) and Annex II that contains information on the co-authorship of papers contained in this thesis (where that is relevant).

1.1 Methodology for the insider's account: a hybrid approach inspired by autoethnography and close dialogue

In order to understand how the topic of stranded assets has developed and to shed light on the interests and motivations of different groups working on stranded assets, in this thesis I provide a reflexive first-person account of how my work on stranded assets and the environment developed and how that has interacted with the emergence of a substantial and growing literature. This account is found in chapter two of the thesis and is important for putting the topic, as well as each of the academic papers from chapters three to six, in the appropriate context.

The methodological approach draws on autoethnography and close dialogue. Autoethnography is a research method that is highly self-referential wherein the researcher is partially the focus of analysis (Castree et al. 2013). It involves participant observation, being embedded within a community, and is a reflexive approach aimed at exposing the positionality of researchers (Castree et al. 2013).

According to Adams, Holman Jones, and Ellis (2015) it possesses some of the following characteristics:

- uses a researcher's personal experience to describe and critique beliefs and practices;
- acknowledges and values a researcher's relationship with others;
- shows people figuring out what to do and the meaning of those efforts;
- uses reflexivity to interrogate the intersections between self and society; and
- deploys a wide range of processes and results in a variety of different written products.

The term autoethnography was first used in the mid-1970s and was associated with researchers rejecting the idea that they could achieve genuine objectivity (see Heider 1975). Rather than disguise the personal reasons for pursuing research, personal experience and subjectivity are made explicit and become part of the research (Butz & Besio 2009). The materials and data used in autoethnography encompass a range of sources, that include: recalling, collecting, interviewing, analysing self, and reflecting (Holman Jones et al. 2015).

Autoethnography has a number of potential attractions, including reflexivity, flexibility, and broad applicability. As a result it has been used widely in a range of disciplines including art, anthropology, criminology, geography, psychology, and sociology (Adams et al. 2015).

In relation to geography, Butz and Besio (2009) argue that the sort of reflexivity inherent in autoethnography is 'especially relevant to collaborative and participatory modes of research, which are becoming more prominent in geography…one of the objects of such projects is the collaboration itself, to which researchers are necessarily insiders.

Autoethnographic analyses seem entirely appropriate, even essential, to critically reflexive collaborative or participatory research' (Butz and Besio 2009, p. 1670). Given the growing significance of such modes of research in economic geography, and arguably across the social sciences, there is a surprising dearth of autoethnography in economic geography or in the geography of finance – one of the only examples of such work is Wai-chung Yeung's (2007) work on Chinese business networks.

Autoethnography has the potential to be constructively applied to my work on stranded assets because of my positionality. I have been a key 'insider' and 'influencer' – making the case for work on stranded assets and shaping research and other related activities in various ways and across different organisations. Producing a reflexive first-person account could therefore shed light on how stranded assets work developed and this could be useful and insightful for researchers in the area. It could also highlight biases and conflicts that would help scholars working on the topic to understand key motivations, which could in turn help to make their work more accurate.

In evaluating various autoethnographic approaches it was clear that of the wide variety of options, many would be unsuitable. For example, while I am sure my gender, sexuality, age, ethnicity, culture, and upbringing are all relevant in some way to how I perceive and have influenced work on stranded assets, I do not think they are sufficiently material to require foregrounding. While these issues can be important and are the focus of many autoethnographies, I think they are an unnecessary elaboration given my purpose, which is to shed light on how a new topic related to sustainability and the environment can emerge quickly and with impact.

Instead I have attempted a composite approach. It is perhaps best described as a blend of 'analytical autoethnography' (Anderson 2006) and 'close dialogue' (Clark 1998). Analytical autoethnography was proposed by Anderson (2006) and refers to, autoethnographic work that includes, '(1) complete member researcher status [i.e. the researcher is a member of the social world under study], (2) analytic reflexivity, (3) narrative visibility of the researcher's self, (4) dialogue with informants beyond the self, and (5) commitment to theoretical analysis' (Anderson 2006, p. 378). It was proposed in stark contrast to 'evocative autoethnography', which 'fractures the boundaries that normally separate social science from literature' (Ellis and Bouchner 2005, p. 744) and rejects, 'traditional realist and analytic ethnographic epistemological assumptions' (Anderson 2006, p. 377).

'Close dialogue' was proposed by Clark (1998) and is empirical research, 'based upon in-depth interviews, or close dialogues with industry respondents...[that] relies upon the intimacy or closeness of researchers to industry respondents, a level of personal commitment quite at odds with the conventional notions of scientific disassociation and objectivity' (Clark 1998, p. 73). It was pioneered in the context of economic geography, in particular the geography of finance and according to Clark (1998), 'close dialogue can involve complex relationships between interviewers and interviewees. Thus close

dialogue is a mode of case-study research, one that uses structured and unstructured interviews in the context of relationships between nominal equals to reveal the actual logic of decision making' (Clark 1998, p. 73).

Clark (1998) contrasts close dialogue with an approach based on 'stylized facts' used by economists to underpin research and how the associated theory-driven approach is too inflexible and divorces the researcher from reality. Instead Clark (2007) prefers to, 'work backwards and forwards between theory and the empirical word in a reflexive manner seeking *rapprochement* rather than climbing the ladder of theory to the peak of perfection' (Clark 2007, p. 191).

Close dialogue is a form of ethnography but is 'less about giving 'voice' to others' experience and values than it is about collecting the raw materials for empirical analysis and theoretical synthesis' (Clark 2007, p. 191). Clark (2007) sets out a number of ways that materials and data can be collected as part of close dialogue, including one-to-one interviews (the most usual way), collecting responses through conferences or colloquia, and industry-based research programmes.

The composite model I adopt has some of the following characteristics, with some closer to close dialogue than analytical autoethnography and vice versa:

- reflexive first-person account, based on 'insider' experience of different stakeholder groups;
- deep knowledge of multiple stakeholder groups brought to endeavour from previous professional experience and networks;
- exploration of positionality, but focused on professional identities and groups (e.g. civil society, academe, financial institutions etc.), *not* my own identity and characteristics (e.g. age, gender, sexuality etc.) or emotions;
- availability of extensive material and data, but available only selectively due to confidentiality; and
- lacking documented and systematic interview data.

In response to this attempted fusion of approaches, one might be tempted to ask the following questions: why are close dialogue and analytical autoethnography insufficient by themselves? What benefits are accrued from a composite of the two and have you made the right trade-offs? My response to these questions are as follows.

First, while close dialogue can generate empirical information to help us understand the emergent theory and practice associated with the rise of stranded assets, it would need to be structured and guided by a set of preconceived questions (see Clark 2007). My questions and interests in stranded assets were not preconceived, but instead evolved as myself and others created new information, new ideas, and new relationships. There was insufficient knowledge to pre-design a formal close dialogue process. It only became clear

after the fact that this was an area that would benefit from such a treatment.[2] Consequently, I have to work with the raw materials available to me at the time of writing and this necessarily constrains the methodological options.

Second, while many researchers undertaking close dialogue will have influenced the topics or subjects they are studying through prior academic research, my proximity to this topic is probably closer and my influence on it perhaps more significant than in some of these other cases. Ultimately whether this is true or not will be up to the reader, but assuming it is, there are clearly implications for my objectivity. It would make it hard for me to interview and interact with subjects without there being some other agenda cutting across the ideals of close dialogue. For example, an interviewee might be a funder of my research or a collaborator, or represent an organisation I might be trying to influence. An autoethnographic approach allows me to foreground these issues and allows such conflicts to become a way of shedding light on the topic, in contrast to close dialogue where the opposite might be considered true.

Third, while undertaking a properly designed close dialogue process is not an option for the reasons described above, there is still significant material for analysis that can be employed and would also be usefully employed in a close dialogue project. This is not simply an autoethnography based on my feelings or my emotions, but a project that can draw on important documentation and evidential material. These complement an auto-ethnographic approach and can make it more objective.

1.1.1 Material and data

I can draw on a significant range of different materials and data in my first-person account and to inform the entire thesis. The first is, of course, my own recollection. I also have a range of summary of proceedings, guest lists, agendas, minutes, speaking notes, and informal write-ups for at least 150 public and private events (from major international conferences to private roundtables, workshops, forums, symposiums, and colloquia) that I have organised, co-organised, or spoken at (as a keynote, panellist, discussant, or chair) on stranded assets since the start of 2011. In addition to this, I have a near complete record of emails covering the period 2010-16 (I have at least 45,094 emails with a reference to stranded assets); comprehensive calendar entries from 2011-16 (the 2010 data is lost); and a good record of files, notes, drafts, and proposals that I have written since 2010 on stranded assets. I also have all contracts and associated documentation that naturally accompany funded pieces of research.

Much of the correspondence I have is confidential. Many of the events I have organised or co-organised were private or under Chatham House rule and only some were public. I have also entered into various non-disclosure agreements with funders, employers, and subjects of research. Furthermore, I have obligations under the Official Secrets Act (1989)

[2] I would like to thank Professor Dariusz Wójcik and Dr Paul Jepson for suggesting this approach

and in accompanying confidentiality agreements for work I have conducted on stranded assets (and other topics) at the Bank of England as an Academic Visitor and in The Prince of Wales's Household as an Adviser to The Prince of Wales's Charitable Foundation.

These various obligations mean that I adopt the following approach in order to maximise the use of these extensive materials, while also minimising the risk of unintended breaches of confidence or the disclosure of sensitive information.

First, I almost entirely use the materials and data available to me to simply cross-check and verify my recollection of events. I do not undertake an aggregate analysis of this information or quote extensively from it. Second, in the limited number of cases where I do directly quote any of the materials or data, I only quote something that I have written and in the case of correspondence, do not disclose the name of any recipients. Third, I do not quote from any correspondence that is marked private, restricted, confidential, or sensitive. Fourth, I only disclose parties or quote third-parties where what they have written or said is published or from a public event.

1.2 What are stranded assets?

There are a number of definitions of stranded assets that have been proposed or are used in different contexts. Accountants have measures to deal with the impairment of assets (e.g. IAS16) which seek to ensure that an entity's assets are not carried at more than their recoverable amount (Deloitte 2016). In this context, stranded assets are assets that have become obsolete or non-performing, but must be recorded on the balance sheet as a loss of profit (Deloitte 2016). The term 'stranded costs' or 'stranded investment' is used by regulators to refer to 'the decline in the value of electricity-generating assets due to restructuring of the industry' (Congressional Budget Office 1998). This was a major topic for utilities regulators as power markets were liberalised in the United States and United Kingdom in the 1990s (see chapter 4 for further details).

In the context of upstream energy production and from an energy economist's perspective the IEA (2013) defines stranded assets as 'those investments which have already been made but which, at some time prior to the end of their economic life (as assumed at the investment decision point), are no longer able to earn an economic return' (IEA 2013, p. 98). The Carbon Tracker Initiative also use this definition of economic loss, but says they are a 'result of changes in the market and regulatory environment associated with the transition to a low-carbon economy' (Carbon Tracker Initiative n.d.). The Generation Foundation (2013) defines a stranded asset 'as an asset which loses economic value well ahead of its anticipated useful life, whether that is a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks' (Generation Foundation 2013, p. 21).

Different definitions for economists ('economic loss'), accountants ('impairment'), regulators ('stranded costs'), and investors ('financial loss') make it difficult for different disciplines and professions to communicate between each other about very similar and overlapping concepts. Caldecott et al. (2013) proposed a 'meta' definition to encompass all of these different definitions, 'stranded assets are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities' (Caldecott, Howarth, et al. 2013, p. 7). This is the definition used throughout this thesis and the definition most widely used in the literature.

While the environmental discourse appropriated the term in the 2010s and is focused on the environment-related risk factors that can strand assets (see chapter 2 for a discussion on why this happened), asset stranding in fact occurs regularly as part and parcel of economic development. As such it is not a novel phenomenon. Schumpeter (1942) coined the term 'creative destruction' and implicit in his 'essential fact about capitalism' (Schumpeter 1942, p. 83) is the idea that value is created, as well as destroyed, and that this dynamic process drives forward innovation and economic growth. Schumpeter built on the work of Kondratiev (1926) and the idea of 'long waves' in the economic cycle (Perez 2010).

Neo-Schumpeterians have attempted to understand the dynamics of creative destruction, particularly how and why technological innovation and diffusion results in technological revolutions. This gave rise to the idea of 'techno-economic paradigms' (TEPs), a term coined by Perez (1985), which captures the idea of overlapping technological innovations that are strongly inter-related and interdependent resulting in technological revolutions. Perez (2002) finds five such TEPs: the Industrial Revolution (1771-1829); the Age of Steam and Railways (1829-75); the Age of Steel, Electricity, and Heavy Engineering (1875-1908); the Age of Oil, the Automobile, and Mass Production (1908-71); and the Age of Information and Telecommunications (1971-present).

Each TEP was accompanied by the emergence of new sectors and stranded assets in redundant ones. For example, the Industrial Revolution ushered in mechanised cotton production in England that eclipsed India's cottage textile industry (Broadberry & Gupta 2005); the Age of Steam and Railways introduced railway networks that replaced canals and waterways (Bagwell & Lyth 2002); the Age of Steel, Electricity, and Heavy Engineering saw the end of sailing ships and the dominance of steam ships (Grübler & Nakićenović 1991); the Age of Oil, the Automobile, and Mass Production resulted in the rise of the automobile and the decline of railways (Wolf 1996); and our Age of Information and Telecommunications has seen the widespread adoption of digital communication and an information revolution, making analogue communication redundant and technologies from typewriters to telegraphs entirely obsolete. Within each TEP specific companies and brands, physical infrastructure, plant and machinery, and human capital, among other things, have become stranded.

Clearly then, stranded assets can be caused by many factors related to innovation and commercialisation, and these are part of the process of creative destruction articulated in Perez's TEPs and conceived by Schumpeter. Recent research on stranded assets has, however, sought to explore the idea that some of the causes of asset stranding are increasingly environment-related. In other words, that a combination of physical environmental change and societal responses to this environmental change, might be qualitatively and quantitatively different from previous drivers of creative destruction we have seen in TEPs. Moreover, such environment-related factors appear to be stranding assets across all sectors, geographies, and asset classes simultaneously and perhaps more quickly than in previous TEPs, and that this trend is accelerating – something that could be unprecedented.

1.2.1 Carbon budgets and stranded assets

From the late 1980s individuals and organisations working on climate and sustainability issues began to acknowledge the possibility that environmental policy and regulation could negatively influence the value or profitability of fossil fuel companies to the point that they could become impaired (Krause et al. 1989; IPCC 1999; IPCC 2001; IEA 2008). With the concept of a global 'carbon budget' – the amount of cumulative atmospheric CO2 emissions allowable for certain amounts of anthropogenic climate change – there

was a way to determine when impairments ought to begin given a certain climate change target (Allen et al. 2014). When the amount of fossil fuels combusted, plus the amount of carbon accounted for in reserves yet to be burned exceeded the carbon budget, either the climate or the value of fossil fuel reserves would have to give. This concept was dubbed 'unburnable carbon' by the Carbon Tracker Initiative (2011) and was popularised by the US environmentalist Bill McKibben (2011), among others, in the early 2010s.

Unburnable carbon quantified the disconnect between the current value of the listed equity of global fossil fuel producers and their potential commercialisation under a strict carbon budget constraint (Carbon Tracker Initiative 2011; Caldecott 2011). The idea that 'unburnable' fossil fuel reserves could become stranded assets sparked a significant discussion on the risk of investing in fossil fuels (Ansar et al. 2013). It has also helped to spur the development of the fossil fuel divestment campaign (Ansar et al. 2013).

Conjoined with and in parallel, the idea of a 'carbon bubble' also gained traction. This is the hypothesis that unburnable carbon would mean that upstream fossil fuel assets were significantly overvalued, potentially creating a financial bubble with systemic implications for the global economy (Carbon Tracker Initiative 2011; Caldecott 2011). This has inspired divergent responses – from qualified support to outright opposition (for example, see Royal Dutch Shell plc 2014; Exxon Mobil Corporation 2014; Weyzig et al. 2014; EAC 2014; Caldecott 2012a; King 2012).

Unburnable carbon and the carbon bubble were considered to be derived from work conducted and produced in the early 2010s. However, unknown to the proponents of this discourse in the early 2010s, these ideas actually originated much earlier. This only became clear in 2013-14 and was confirmed by interviews with authors of previously published work.[3]

Krause et al. (1989) were the first to explicitly make the case for unburnable carbon when they said, 'The mere fact that remaining allowable global carbon emissions are so limited means that any economic infrastructures built up mainly on the basis of fossil fuels risk early obsolescence. In effect, the tight carbon budgets implied by climate stabilization greatly reduce the long-term value of fossil fuels' (Krause et al. 1989, p. 164).

Krause et al. (1989) were also the first to make the explicit link between carbon budgets, fossil fuel obsolescence, and implications for financial markets (i.e. the carbon bubble), 'capital owners in the fossil industries would have to bear an indirect cost i.e., die risks and uncertainties of having to diversify into other business activities. For example, even a well-planned retrenchment [from fossil fuels] could create impacts on the value of stocks in the financial markets. Government financial incentives could be required to make these risks acceptable to capital owners.' (Krause et al. 1989, pp. 172-173)

[3] These were conducted by the author and took place in March-April 2016 at Stanford University.

Krause et al. (1989) made another significant contribution by highlighting how unburnable carbon is in complete contrast to assumptions used in the energy industry, '[a carbon budget] means major restrictions on the use of global fossil resources…[our carbon budget] figures clash with the conventional assumption that all conventional oil and gas resources would probably be consumed before a major shift away from fossil fuels would occur. Our analysis suggests that climate stabilization requires keeping significant portions of even the world's conventional fossil resources in the ground. Such a requirement is a stark contradiction to all conventional energy planning and illustrates the magnitude of the greenhouse challenge.' (Krause et al. 1989, p. 144).

The points are made in exactly the same way in publications more than 20 years later (for example, see Carbon Tracker Initiative 2011; Carbon Tracker Intiative 2013). Unfortunately, these novel ideas from the late 1980s were largely ignored and then forgotten. One can only speculate as to why this happened and why later work has managed to achieve greater traction, but it must inevitably have something to do with the fact that climate change is an imperative for many contemporary policymakers, businesses, and financial institutions, whereas it simply was not in the late 1980s and early 1990s.

1.2.2 From unburnable carbon towards environment-related risk

One tension within the 2010s discourse of stranded assets is the scope of risks that can cause asset stranding. Early on, some preferred to focus on the idea of scientifically derived carbon budgets being *directly* enforced top-down by governments in a coordinated way (in particular, see Carbon Tracker Initiative 2011). Others have been much more sceptical of coordinated international action and saw carbon budgets being introduced *indirectly* bottom-up through a panoply of different local and national policies, technological change and innovation, and social pressure, among other things (in particular, see Caldecott et al. 2013). The views of individuals and organisations has trended towards the latter view over time (see Hedegaard 2015), including those that originally preferred the 'direct top-down' model over the 'indirect bottom-up' one (for example, see Carbon Tracker Initiative 2015).

Relatedly, another tension has been the relative status of climate change versus the environment more broadly. Some have been more concerned with stranded assets created by international climate change policy (Carbon Tracker Initiative 2011), others have been more interested in the range of societal responses to physical climate change impacts that extend beyond unburnable carbon (Bank of England 2015b), and others have been concerned with both physical environmental change and societal responses to such environmental change (Bank of England 2015a; Caldecott et al. 2013). Again, the views of individuals and organisations has trended towards the latter view, which is more comprehensive and expansive, and has allowed for a wider range of interests to be engaged on the topic, such as those concerned with water risk and stranded water assets (see Lamb 2015) or in sectors that might be affected beyond fossil fuels, such as

agriculture (see Rautner et al. 2016; Morel et al. 2016; Caldecott et al. 2013). To underpin a more expansive interpretation Caldecott et al. (2013) proposed a typology for different environment-related risks that could cause stranded assets and this is set out below.

Figure 1: Typology of Environment-related Risk

	Class	Description
PHYSICAL	**Environmental challenges and change**	For example, climate change, water stress, and biodiversity loss.
PHYSICAL	**Changing resource landscapes**	Price and availability of different resources, such as oil, gas, coal and other minerals and metals. For example, Peak oil and the shale gas revolution.
SOCIETAL	**New government regulations**	Introduction of carbon pricing (via taxes and trading schemes), subsidy regimes (e.g. for fossil fuels and renewables), air pollution regulation, disclosure requirements, the 'carbon bubble' and international climate policy.
SOCIETAL	**Technological change**	For example, falling clean technology costs (e.g. solar PV, onshore wind), disruptive technologies, and GMO.
SOCIETAL	**Evolving social norms and consumer behaviour**	For example, fossil fuel divestment campaign, product labelling and certification schemes, consumer preferences.
SOCIETAL	**Litigation and changing statutory interpretations**	For example, court cases, compensation payments, and changes in the way existing laws are applied or interpreted.

Source: Caldecott et al. (2013)

Recent developments very clearly illustrate that environment-related risks, and not just those related to unburnable carbon, can have a significant impact on assets today, and these are likely to increase in significance over time (Caldecott et al. 2016). If anything, the available evidence suggests these are much more material, particularly in the short to medium term, than the risk of unburnable carbon or the carbon bubble (Caldecott et al. 2016). For example, air pollution and water scarcity in China threatens coal-fired power generation, which has changed coal demand and affected global coal prices (Caldecott et al. 2013); the shale gas revolution in the US has put downward pressure on coal prices in Europe, stranding new high-efficiency gas plants (Caldecott & McDaniels 2014); and the fossil fuel divestment campaign threatens to erode the social licence of some targeted companies and could increase their cost of capital (Ansar et al. 2013).

1.2.3 The stranded assets straw man

It is worth noting that there is a particular straw man argument that has been used in an attempt to dismiss the idea of stranded assets and it contains two parts (Caldecott 2015c). The first part is to raise doubts about the idea that there is unburnable carbon and then to conflate unburnable carbon with stranded assets. The second part is to argue that markets already price stranded assets risks effectively. These arguments have been made by Royal Dutch Shell plc (2014), Exxon Mobil Corporation (2014), Butler (2015), and Helm (2015).

We should not rely on the assumption that the world will stick to a 1.5℃ (or 2℃) carbon budget, objectors point out, so we should not be so sure that fossil fuel reserves that would take us beyond that limit will become stranded assets. These objectors may be right to be sceptical about the 1.5℃ constraint, but when it comes to stranded assets, they entirely miss the point.

This straw man is a conflation of 'stranded assets' with 'unburnable carbon'. The latter being one potential driver of asset stranding, but as we have already discussed, not the only one. The straw man argument suits those who want to discredit concerns about stranded assets (for example, some fossil fuel companies), as it is easier for them to secure traction attacking an effective 1.5℃ policy commitment as unlikely, than say falling costs of renewables, electricity storage, air pollution regulations, or water stress. The reason for this is that the former has yet to happen, but as we have seen, the latter factors are already transforming markets and stranding assets. It is easier to attack an unprecedented scenario than facts on the ground.

Even the claim that a 1.5℃ pathway is impossible is not true. Though probably quite unlikely, a 1.5℃ pathway is not something you can discount entirely. If it did come to pass, it would have significant implications for investors, companies, and governments. Given that 1.5℃ is a stated objective in the Paris Agreement, it makes sense as a useful analytical starting point.

But 2, 3, 4, 5, or 6℃ pathways could also have significant and systemic implications (Dietz et al. 2016; Economist Intelligence Unit 2015). Not achieving 1.5℃ will itself have significant impacts on asset values across the global economy. Whichever way you look at it, action or inaction on climate change will strand assets. You may think that a 1.5℃ policy induced carbon constraint is unlikely, but this does not mean stranded asset issues vanish.

The second line of objection is that investors and companies have levels of foresight and analysis that mean they are already pricing in these risks and so we need not worry. But the idea that investors and companies know about these risks and have a better understanding of them than anyone else is also wrong.

Even at the best of times, relatively simple risks can be mispriced by markets and known risks can be left ignored. As we shall discuss later in this thesis, this is often because of biases, misaligned incentives, and endemic short-termism (Carney 2015; Caldecott & Rook 2015; Kay 2012). These problems are also exacerbated when the risks in question are novel, and where the data, analytical tools, and methodologies are missing (Caldecott & Rook 2015). Add to the mix a lack of viable options to hedge risk (Cambridge Institute for Sustainability Leadership 2015), and there is plenty of scope for markets to be getting risk management wrong.

1.3 Stranded assets as economic geography: the case for a disciplinary home

Given the speed at which it has become an important topic, the academic literature on stranded assets is still relatively limited, primarily because of the comparatively long peer review and publication process for journals. Researchers, scholars, and practitioners have instead opted for the publication of working papers, research notes, speeches, government white papers, and reports to disseminate their work as quickly as possible so they can influence a fast moving discourse.

This means that the stranded assets literature currently depends heavily on the 'grey literature'. This leaves it susceptible to criticism, despite research showing that although published research is more likely to contain results from larger samples, methodological rigor does not appear to differ between the published and the grey literatures (Conn et al. 2015).

Fortunately, this is in the process of being rebalanced, with work on stranded assets increasingly being published in the peer reviewed academic literature (for example, see Caldecott 2017; McGlade & Ekins 2015; Jakob & Hilaire 2015; Caldecott & Mitchell 2014) and in the process of being produced within a number of disciplines and sub-disciplines, from macroeconomics (Batten et al. 2016; Campiglio et al. 2015) through to finance (Campiglio 2016; Battiston et al. 2016). This diversity and the appeal of the topic to a wide range of disciplines and sub-disciplines is important, particularly for the reasons outlined in the previous section. It creates the opportunity for the topic to be interpreted in different ways and applied to different contexts, potentially enabling the linking up of these disparate strands of work in the future, which may support inter-disciplinary collaboration.

While it means that the topic may be able to draw on the widest possible range of expertise, this approach has a concomitant risk – that as an emerging topic it is spread too thinly and then fails to establish itself properly. As such, there is a strong rationale for stranded assets to find a disciplinary home. This needs to be a discipline or sub-discipline that can help it to both develop firmer foundations and also explore new areas by providing ideas, concepts, and methodologies that can be usefully employed in answering some of the research questions identified in the previous section. It also needs to be a discipline supportive of producing research that interacts with and speaks to a range of 'real world' audiences and one that is suitably adaptable so as to encourage inter-disciplinary research.

Economic geography is a strong candidate as a disciplinary home for stranded assets. The sub-discipline can both contribute to the development of stranded assets as a scholarly endeavour and itself benefit from interacting with a topic that intersects with some of the most pressing contemporary issues related to environmental sustainability. It is also my contention that economic geography is better suited as a disciplinary home for stranded

assets than either environmental economics or environmental geography, which are two obvious alternatives. While both have important contributions to make – the latter particularly in terms of understanding the nature of environment-related risks and the former in terms of understanding the costs of environmental externalities for society – economic geography is better placed to engage with the wide range of research questions that the topic of stranded assets generates. Similarly, management and finance as disciplines have significant contributions to make, especially in relation to how corporations manage these issues and how financial institutions price environment-related risk, but have little to contribute in terms of other areas of concern, such as how stranded assets may or may not exacerbate spatial disparities and inequalities. Economic geography, as we shall see in the next section, has a sufficiently wide gamut of interests, theory, and empirical data to engage more successfully over a sustained period of time on the topic and across multiple research themes related to stranded assets.

1.3.1 Economic geography

Economic geography is both a sub-discipline of geography and of economics. Clark et al. (2000) bounds economic geography as being 'concerned with the spatial configuration of firms, industries, and nations within the emerging global economy in all its manifestations' (Clark et al. 2000, p. vii). Scott (2000) argues for something similarly broad and place-related, '[economic geographers] have generally and rather insistently focused on questions involving the spatial and locational (or, in another vocabulary, the urban and regional) foundations of economic life, and it is the remarkable collection of insights assembled under these signs that may be designated as "economic geography"' (Scott 2000, p. 19).

There are significant differences between economic geography as practised by economists and economic geography as practised by geographers (Clark 1998). Geographical economics has been much more narrowly focused on international trade theory, so called 'new economic geography'. In the new economic geography the goal is to devise a modelling approach that lets one discuss the economies of regions or countries within the context of a national or international economy in general equilibrium (Krugman 2000; Krugman 1996; Krugman 1993; Krugman 1991). Clark (1998) is critical of the 'stylized facts' that dominate intellectual reasoning within new economic geography, such as industry-regions and increasing returns to scale. Many other economic geographers are critical of geographical economics as practised by Krugman and his fellow economists (for example, see Scott 2006), not least because their work mirrors neoclassical location theory orthodoxies of the 1950s and 1960s that were previously discredited by economic geographers (see Hudson 2006).

Economic geography as practised by geographers is less easily defined than geographical economics and has undergone a number of significant periods of change. Scott (2000) identifies its rise as a sub-discipline within geography in the 1950s. The rise of Fordist mass production and a modern consumer society due to the long post war boom, fuelled

complex spatial disparities that generated exciting research questions for geographers and economists (Scott 2000).

One important strand of this early work was 'regional science', which was an expression of dissatisfaction with mainstream economics as a 'wonderland of no spatial dimensions' (Isard 1956, p. 25). Regional science combined elements of economics with elements of geography and attempted to 'rewrite neoclassical competitive equilibrium theory in terms of spatial coordinates' (Scott 2000, p. 21).

This early theme of plugging all too obvious gaps in neoclassical economics continued with 'behavioural economic geography'. This attempted to show that individual decision-makers were influenced by the quantity and quality of the information available, as well as their ability to use the information, and this could shed light on locational and geographic decisions (Pred 1967). The concepts of learning and perception in behavioural economic geography were added by Cox & Golledge (1969). For anyone familiar with the contemporary discourse on behavioural economics (for example, see Thaler & Sunstein 2008), this behavioural strand of economic geography feels incredibly prescient. It is perhaps these early predilections that also help explain why economic geographers have been so critical of the new economic geography and geographical economists, with their reliance on 'over-simplifications, abstractions, and stylised facts'.

As the post-war boom gave way to the oil shocks, stagflation, and the collapse of manufacturing industries in North America and Europe, economic geography responded by reinterpreting questions in terms of Marxist political economy (Scott 2000). Harvey (1973) sought to demonstrate how the forces of capitalism create geographies, in particular how capitalist production leads to uneven development and spatial divisions of labour that foster inequality (Scott 2000; Sheppard 2006). Over the 1970s and early 1980s economic geographers consequently tackled a wide range of urban and regional problems, particularly poverty, unemployment, deindustrialisation, and regional decline (Scott 2000).

The popularity within economic geography of Marxist political economy with its emphasis on grand structural processes, resulted in a backlash from the late 1970s onwards. The political and intellectual baggage of Marxian approaches were not only being abandoned in economic geography, but across the social sciences. In economic geography there was a growing recognition 'that the social and cultural contexts – within which market mechanisms are embedded – are crucial to the functionality of markets' (Sheppard 2006, p. 15). These social and cultural contexts, deprioritised in Marxist political economy, rose to the fore, 'uniqueness and difference had now turned into points of analytic interest rather than mere background noise, and with the affirmation of their investigative significance, any notion of theoretical totalization became correspondingly anathema' (Scott 2000, p. 21). This was accompanied by the rise of gender, and not just class, as a topic of significance for economic geographers (for example, see Massey 1984).

Economic geography then moved to focus on particular localities and concentrated on understanding the internal and external pressures that they faced, not least in the context of economic decline and industrial restructuring (Scott 2000). The resurgence of regional economies as a result of 'post-Fordist' industries then became of significant interest, for example Silicon Valley for high-technology manufacturing (for example, see Saxenian 1994) and the City of London for financial services (for example, see Thrift 1994). Vertical disintegration, inter-industrial transactional networks, and local labour markets with increasing returns effects were the main factors driving forward such post-Fordist regional economic development (Scott 1986).

With the end of the Cold War and markedly increased interconnectedness and international trade came a growing interest in the causes and consequences of economic globalisation, including in terms of the international division of labour (for example, Taylor & Thrift 1982), multinational corporations (for example, Dicken 1986), 'hypermobility' and the 'end' of geography (for example, Amin & Robins 1990; O'Brien 1992), innovation (for example, Simmie 1997), and social regulation and persistent local inequality (for example, Peck 1996; Peck & Tickell 1994).

Functional integration by sectors and corporations across economies, supported by different scales of related regulation from the regional to the national and international, has support the globalisation of finance and money (Scott 2000). In the geography of finance – a part of economic geography – scholars became interested in both the connection between finance and industry and 'the development of finance as a set of institutions distinct from the production of goods and services' (Clark & Wójcik 2007, p. 3). The former group focused on financial institutions as allocators of capital between companies, sectors, regions, and countries, as well as how the real economy was being shaped by the power of interests within global finance (Clark & Wójcik 2007). The latter group explore how financial institutions beyond banks and insurance companies, for example pension funds and asset managers, have developed and driven the globalisation of finance (for example, see Clark & Wójcik 2007; Clark 2007; Clark et al. 2006; Clark 2005; Clark 2003; Clark 2002; Wójcik 2002; Clark 2000; Clark 1997).

Economic geography has evolved from a focus in the post-war period on location and regional research interested in optimisation and spatial hierarchies, particularly in North America and Western Europe, into a sub-discipline grappling with some of the most interesting questions facing societies internationally – from inequality and unemployment through to globalisation and innovation. Even from this condensed survey of the literature, it is clear that the sub-discipline has responded to the great events and trends, which have in turn become important research questions for economic geographers. Economic geography has also shifted from the great theory-driven methodological approaches (for example, Marxist political economy) to more nuanced and empirically-driven research that dynamically informs and interacts with theoretical innovation (Clark 2007). This makes economic geography grounded and responsive to developments and concerns in the real world, and less susceptible to poorly substantiated

stylised facts and theoretical abstractions. We can see this tendency to focus on the big issues facing contemporary policymakers and decision-makers in recent work focused on understanding the causes and implications of the global financial crisis (for example, see Wójcik & MacDonald-Korth 2015; Wojcik 2013).

But despite economic geography's positive tendency to speak to contemporary concerns, it seems that the sub-discipline has largely failed to engage seriously on environmental questions (Dicken 2004). Looking at the economic geography literature it is indeed surprising how little has been written on environmental topics. They appear only in passing and recently in only a very limited number of contexts, for example: i) how environmental regulation shapes firms' location decisions (Tole & Koop 2011); ii) the emergence of new environmental markets, specifically carbon markets in Europe and the financial geography of these developments (Knox-Hayes 2009); and iii) the spatial adoption of renewable energy technologies (Graziano & Gillingham 2015). While these are important contributions, they are not particularly broad or deep wells of literature in economic geography, at least not yet. Environment-related questions, including the ones that economic geographers have so far decided to take on, are given a much more comprehensive treatment across the different sub-disciplines of economics. Environmental economics is itself a significant sub-discipline within economics.

Realising that this neglect is an anomaly given that this should be natural terrain for a discipline intimately concerned with location and context, and that it is one of the most pressing issues for a wide range of actors – from firms to governments to investors - a number of economic geographers came together to propose a new 'environmental economic geography' (EEG) in the mid-2000s (Gibbs 2006; Angel 2006; Hayter 2008; Bridge 2008). There has been a debate about what EEG should be focused on, what theories and concepts it could draw on, and how it should be bounded.

Bridge (2008) argues convincingly that EEG should focus on 'the difference that "environment" makes to processes we have traditionally considered to be (purely) economic' (Bridge 2008, p. 78). This is very much in the spirit of work on stranded assets to date. While other proponents of EEG have been content to be less discerning and simply bound it as research grounded in economic geography that addresses any element of the 'biophysical world' (Bridge 2008; Angel 2006). The debate has yet to be settled and unfortunately it appears that EEG has not yet succeeded in rising to the original challenge – of making the environment a topic of significant contemporary concern to economic geographers. There remains a very obvious gap between what economic geography is contributing to environmental questions and what it can and should be contributing.

1.3.2 Back to the future?

There is a strong case for economic geography to become a disciplinary home for stranded assets. It can play to economic geography's strengths and help to correct some of its weaknesses, particularly in relation to the environment. It can also build on or even

rejuvenate some of economic geography's oldest recurring themes and support the development of some of its newest research areas.

Economic geography's healthy scepticism of neoclassical economics and stylised facts, as well as its long-standing appreciation of behaviour and cognition, means that it is well positioned to examine the reasons stranded assets can happen and why this matters. To an economic geographer it is obvious that novel risks would be hard to comprehend and integrate into decision-making due to individual, cultural, and organisational biases and misaligned incentives. In contrast, in the world of the neoclassical economist, perfect information means there can be no stranded assets and that markets are already pricing in this information effectively (see Helm 2015).

The consistent focus of economic geographers on spatial disparities, inequalities, and the rise and fall of different firms, sectors, regions, and countries means that the sub-discipline should naturally be interested in how stranded assets could cause or change these processes. Understanding these issues and how they can be effectively managed to the benefit of society also requires deep historical and international perspectives – something the discipline can readily offer.

The topic of stranded assets has been so far preoccupied with the financial implications of asset stranding – both from a macroeconomic and microeconomic perspective. In particular, it has focused on how different types of financial institution can manage these issues, especially in terms of changes to practice, governance, and regulation, and what it might mean if they do not. The geography of finance's focus on the globalisation of finance and empirical work to understand processes and behaviours within finance can also be productively utilised to shed light on questions related to stranded assets.

In each of these areas stranded asset-related work has begun, but it lacks the coherence of a disciplinary home. Economic geography has an opportunity to be such a home and there are several reasons why economic geographers might want to invest the time in making this happen.

First, as discussed, economic geography can and should do better in relation to environmental concerns and should aspire to 'own' an environmental issue that is not already dominated by another discipline or sub-discipline. Stranded assets could finally give EEG the opportunity to live up to its potential.

Second, as many economic geographers have noted (Bridge 2008; Gibbs 2006; Sheppard 2006; Hanson 2006; Dicken 2004; Scott 2000; Clark et al. 2000), economic geography has been historically weak at influencing and informing policy. As we have seen, stranded assets has already achieved significant policy salience and as a topic is generating some very important policy questions at different levels – from the regional to the international. These policy issues are also gaining public recognition – something that economic

geography could do well to piggyback on. In effect, embracing stranded assets could help to solve the 'missing geographers' problem identified by Dicken (2004).

Third, stranded assets requires an inter-disciplinary, or even a 'trans-disciplinary', approach and economic geography is suited to this endeavour (Pike 2007). Other disciplines, in particular economics, have too much baggage to do this effectively. Economic geography's attractiveness rests on its strength through difference and ability to synthesise (Bridge 2008; Pike 2007; Bagchi-Sen & Lawton Smith 2006), and stranded assets plays to these strengths.

1.4 Conclusion

Stranded assets created by environment-related risk factors, including physical climate change impacts and societal and regulatory responses to climate change, have become increasingly prominent. The emergence of the topic should be of significant interest to scholars and practitioners alike, as it has arguably influenced a number of pressing issues facing investors, companies, policymakers, regulators, and civil society in relation to global environmental change.

I have set out a methodology drawing on autoethnography and close dialogue that allows me to use my extensive personal experiences as a key insider in the development of stranded assets, and to use comprehensive materials and data to verify and cross check my recollections. This approach will help to provide richness and insight that is meant to complement the literature review and lay the foundation for the four self-contained papers contained in chapters three to six.

While the environmental discourse appropriated the term in the 2010s and is focused on the environment-related risk factors that can strand assets, asset stranding in fact occurs regularly as part and parcel of economic development. As such it is not a novel phenomenon and is implicit in Schumpeterian creative destruction.

Unburnable carbon and the carbon bubble, one set of environment-related drivers of asset stranding, were considered to be derived from work conducted and produced in the early 2010s. However, these ideas actually originated much earlier from the late 1980s.

While a significant amount has been written on stranded assets in a short period of time, there remain significant gaps in the literature and there is a strong rationale for stranded assets to find a disciplinary home. This needs to be a discipline or sub-discipline that can help it to both develop firmer foundations and also explore new areas by providing complementary ideas, concepts, and methodologies. It also needs to be a discipline that produces research that interacts with and speaks to a range of 'real world' audiences and one that encourages inter-disciplinary research.

Stranded assets fits into a number of current and recurring themes within economic geography and this could be a suitable home for the topic. Stranded assets can help economic geography reach new audiences and economic geography can help stranded assets develop and grow by sharing and integrating important empirical and theoretical knowledge.

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2. The emergence of stranded assets: an insider's account from 2010-16

Apart from providing relevant references in the literature review, I have not yet sought to address my own positionality in the development of stranded assets since 2010. In this chapter I provide a reflexive first-person account of how my work on stranded assets and the environment developed and how that has interacted with the emergence of a substantial and growing literature. I also aim to shed light on the interests and motivations of different groups working on stranded assets and explore differences between groups relevant to understanding how the topic emerged and spread. I also identify some broader generalisations and lessons that can inform the development, communication, and uptake of sustainability issues, particularly among those working in finance and investment.

The methodological approach, as well as the material and data available to me for use in the production of this chapter, including constraints in the way this can be used, can be found in the preceding chapter. The first section of this chapter describes the context in which my work on stranded assets began and begins my first-person narrative account. The second section sees this account divided into two parallel tracks focused on two groups of people, organisations, cultures, and networks working on stranded assets, namely financial institutions and central banks.[1] The third section identifies gaps in my approach and concludes. This chapter, together with the preceding chapter, taken together provide important context for the subsequent self-contained papers in chapters three to six.

[1] Throughout I refer to both central banks and financial regulators as simply 'central banks'. The Bank of England, for example, is both a central bank and a financial regulator. A country's financial regulator is not necessarily the same institution as a country's central bank, but many central banks have some role in financial regulation.

2.1 Starting work on stranded assets

This section begins the narrative account of how I started working on stranded assets, as well as how my own professional context and the deeper undercurrents in environmentalism are relevant to understanding the rise of the topic.

In this first-person narrative I only highlight points that are relevant to the objectives of this chapter or events that are key from a chronological perspective. The narrative does not completely follow the sequencing of events, with some descriptions necessarily covering self-contained periods out of sequence, before I return to the chronological order. It would be unpleasant to read this chapter and impossible to write it if I included everything that has happened over a six-year period and so I have tried to make this the briefest possible account necessary to convey the key issues as I see them. It is also worth emphasising that my work on stranded assets needs to be understood in the context of work undertaken by others.

2.1.1 Climate Change Capital

I began thinking about and working on issues related to stranded assets in late 2010 to early 2011. At that time, I was a Vice President and head of policy and research at an asset management and advisory firm headquartered in London called Climate Change Capital (CCC). My role entailed providing advice to funds and clients on policy-driven markets and directing a thought-leadership centre called the CCC ThinkTank.

CCC had an asset management business with approximately US$1.5bn of assets under management split between four different fund strategies, with each being 'active' and non-listed. The first and largest of the fund strategies focused on carbon markets, in particular investing in projects that generated carbon credits under the Kyoto Protocol's 'flexible mechanisms', primarily the Clean Development Mechanism. The vast majority of these funds were invested in China and Southeast Asia, with some investments in Central Asia, South Asia, and Sub-Saharan Africa. The second fund strategy was clean tech private equity focused on European mid-stage companies with a proven business model looking for growth capital. The third focused on commercial property in the UK, investing in office buildings and making these more resource efficient. The fourth was focused on small-scale renewable energy infrastructure. The first three funds attracted capital from institutional investors, while the fourth met the requirements of UK retail investors taking advantage of certain UK venture capital tax reliefs. Other fund strategies were attempted at various stages of the firm's development, including listed equities and a renewable energy YieldCo, but the four fund strategies described here were a permanent fixture during my time at CCC (2009-13).

CCC's advisory business was focused on mergers and acquisitions (M&A), primarily in the EU though also further afield. We undertook capital raisings for projects and companies; acquired assets on behalf of investors and utilities; and sold assets to investors

and utilities. We also provided strategic advice to clients interested in climate change-related topics. My work straddled both the funds business and the advisory business, though I spent more time in the latter.

CCC was established in 2003-4 and wound down in 2014-15. It was one of the first, and was certainly one of the most prominent firms raising and deploying funds on climate change-related investments from the mid-2000s to the early-2010s. Many of the key figures in the sustainable finance and investment community, and indeed the pro-business environmental community more broadly, had spent some time at CCC at some stage in various different capacities. CCC was unusual for having made a significant and sustained investment in policy expertise, in particular trying to bridge the gap in mutual comprehension that exists between policymakers and politicians on the one hand and financiers and financial institutions on the other.

There were a couple of reasons for CCC's commitment to policy and regulation. First, CCC had been established as a private financial institution with a public goods mission, namely to support the transition to a low carbon economy. It was our view that for capital to shift at the scale and pace required to tackle climate change, better policy frameworks were urgently required. Part of the way CCC helped to improve policy was by sharing expertise with policymakers and helping them to create these frameworks in different contexts, whether internationally (e.g. the UN Framework Convention on Climate Change), regionally (e.g. the European Union), and nationally (throughout countries of operation, from the UK to China). In support of this objective we developed policy ideas and provided technical assistance, among other things. Our high profile in policy 'thought-leadership', in addition to generating public goods, also put the firm on the map and resulted in substantial 'free' marketing – a key argument internally that helped to justify continued investment in this work.

The second reason was that almost all investments related to tackling climate change – such as building new renewable energy infrastructure; creating and trading carbon permits; developing new early stage clean technologies; and installing energy efficiency measures – all require a detailed grasp of policy. Investments are made on the basis of policy frameworks and so understanding policy allows you to attempt to appropriately price policy and regulatory uncertainty. It also helps you to determine when and where assets should be bought or sold to profit maximise. Our policy capability was a differentiator and was intended to provide us with such insights. Consequently, it helped us to raise funds from asset owners and secure clients on the advisory side of the business that we might not have secured otherwise.

There were further reasons for the firm to engage actively on policy. Staff at all levels found it interesting and most worked at CCC because they were sympathetic to our public goods mission. So our policy capability provided something interesting, different, and exciting for staff – a helpful way to differentiate us from others and a 'soft' way of helping to attract and retain staff.

My role at CCC, as well as previous roles and concurrent voluntary directorships at environmental NGOs while I worked at CCC, required involvement with and indeed the shaping of, narratives related to the environment. What follows is a brief description of how these narratives were evolving as this context is important for understanding the motivations for my work on stranded assets.

2.1.2 Hopenhagen

Much of our work on policy at CCC, and almost all the work that groups concerned about tackling anthropogenic climate change had been conducting in the first decade of the 21st century, was focused on the 'opportunity' side of the equation. That is, making the case for and working on the implications of, new investment in cleaner technologies, whether renewable energy, energy efficiency, clean tech, and so on.

The rationale for focusing on opportunity made (and still makes) a lot of sense: it is seen to be more exciting and more optimistic (Futerra 2006). The narrative was essentially that tackling climate change and going 'green' would create lots of new jobs, new companies, and new industries, as well as save the environment. This story, brimming with positivity as it does, did not have much space for anything that might induce pessimism – all mention of cost, risk, and difficulty was closed down, and closed down quickly.

This framing ultimately impacted the priorities of those working on or in areas related to the environment and climate change. Study after study was commissioned focusing on trying to estimate how many new 'green' jobs would be created by building windfarms and solar parks, or through ambitious energy efficiency programmes (for example, see Greenpeace UK 2004, Bird and Lawton 2009, and Board 2010). This relentless focus on 'upside' was unbalanced and this had been getting under my skin.

One prominent example of the optimistic, opportunity focused tone was the Copenhagen climate change negotiations at the end of 2009, which I attended with many others. These negotiations were branded 'Hopenhagen' (BBC 2009) and I think it represented the apogee of this approach. In the end, 'Hopenhagen' turned out to be misjudged. The negotiations failed dramatically and this prompted much self-reflection among environmentalists. It is in this context at the start of 2010 that narratives and stories beyond unalloyed positivity were being developed at CCC and elsewhere.

2.1.3 Downside?

The problem with the opportunity framing is that it can only get you so far: 'The environmental challenges we face mean that we cannot continue to pursue two different strategies simultaneously: support for greener, low-carbon technologies, while continuing with business as usual in polluting sectors. We can't conveniently have it both ways.' (Caldecott 2011a)

In the case of climate change it is perfectly simple – the stock of cumulative emissions causes physical climate change impacts and the stock of emissions continues to expand unless we switch off the flow (Allen et al. 2014). My concern with how an unbalanced approach focusing only on the 'green' and ignoring the phase out of 'brown' was compounded in my mind by three other related worries.

First, the transition to a more sustainable global economy is likely to be a complex and challenging process, with significant value created throughout the economy, as well as lost. The implications of value destruction could be considerable – in terms of lost jobs and industries and the concomitant social pressures they generate. If the community of actors working on these issues continued to ignore them, then policymakers would be unprepared and would not put in place policies to minimise or manage such social pressures. Instead such pressures would be left unmanaged or only be addressed *ex post*, resulting in a political backlash against environmental policies, undermining the transition to sustainability. To me this seemed like a very serious medium to long-term threat to achieving environmental outcomes and I was surprised at how reluctant environmentalists were to talk about these issues.

Second, the same process of value creation and destruction would impact the value of assets across a wide range of sectors and this would have implications for investors. It was quite clear to me at CCC, where we were speaking to and advising a very wide range of different types of financial institution and investing ourselves, that these factors were not being factored into decision-making or being priced appropriately. If they were, the risk premium for assets exposed to these factors would be higher and these would most likely be assets that were environmentally unsustainable. Shifting the cost of capital in favour of 'green' and away from 'brown' would benefit environmental outcomes and aid risk management, as well as attract capital into areas that CCC specialised in. I felt that this was an excellent opportunity for reallocating capital more sustainably and would have a marked upside for financial institutions like CCC. It would necessitate significant changes in investment practice, require better aligned incentives, and probably also require changes in the governance of financial institutions.

Third, a successful transition to environmental sustainability resulting in overvalued and overcapitalised polluting assets becoming impaired could have financial stability implications given significant exposure to these assets throughout financial markets. In 2010-11 financial markets and policymakers were still working through (and arguably are still working through) the causes and consequences of the global financial crisis (GFC). The causes of the GFC (e.g. overvalued sub-prime mortgages and irrational exuberance) seemed to me to be analogous with the scenario I was contemplating here: i) polluting assets being overvalued because valuation did not take account of environmental sustainability and ii) evidence of 'frothiness' in some asset markets that would be affected - the ever larger investments and valuations in upstream oil, gas, and coal driven by the

'commodities super cycle' looked like a bubble that would burst and one that must do so if you believed that society would take action to tackle climate change.

It is perhaps easy to see why the 2010-11 period was fertile ground to be cogitating on the four related insights I outlined above: i) phasing out 'brown' has been neglected by environmentalists at the expense of promoting 'green' and this needs to be rebalanced; ii) pre-emptively managing the consequences of phasing out 'brown' is essential if the transition to sustainability is to succeed and sustain political support; iii) shifting capital away from 'brown' supports environmental outcomes and helps investors to manage risks that are currently mispriced; and iv) there could be financial stability implications associated with a sudden readjustment in the value of polluting assets and while on the face of it this might be good for the environment, it could have severe negative implications that ought to be managed. These four concerns and insights were linked together in my mind and laid the foundation for the work that I would now call 'stranded assets'.

Ructions in the world of climate change policy and environmentalism due to the collapse of Copenhagen helped people to question current approaches of trying to make the case for environmental action. This was happening at the same time as the GFC and its devastation were creating space for a more profound re-evaluation of financial and economic systems, with topics related to systemic risk and the role of finance in society gaining traction. This manifested itself across the social sciences and in politics and policy in a variety of different ways (see Wolf 2014). The idea that finance and investment had a significant role in shaping the environment and vice versa, while clearly pre-dating the GFC, was certainly 'turbo-charged' after the GFC.

The policy response to the GFC meant that financial regulation was in a state of flux, with new regulatory arrangements being drawn up and revised internationally. The one that caught my imagination and prompted me to consider the links between environmental factors destroying value and ultimately affecting financial stability was the creation of the Bank of England's Financial Policy Committee (FPC). The FPC was established in order to, 'contribute to the Bank's financial stability objective by identifying, monitoring, and taking action to remove or reduce systemic risks with a view to protecting and enhancing the resilience of the UK financial system'(Bank of England 2016a). The FPC was established as part of the Financial Services Act 2012 and was formally constituted on 1st April 2013. Prior to that, however, an interim FPC was created in February 2011 and the press coverage associated with that was a catalyst for me to start thinking about and writing about systemic risk and climate change.

2.1.4 The work begins

I have discussed the context in which I was operating, in particular the motivations at CCC. I have also discussed the prevailing atmosphere due to failure at Copenhagen and the GFC. Here I briefly cover how I began to articulate my concerns beyond CCC and

how I began to discover and collaborate with people of like mind working on similar and related issues. This will take us from late 2010 to the very start of 2012. Later in the chapter I split my first-person account into two tracks, focused respectively on central banks and financial institutions. The phase described in this sub-section is very much one of initial exploration and so is not readily separated into distinct tracks defined by different content, motivations, culture, organisations, and people. The separate tracks come later as differences and distinctions grow in importance.

One of the good things about being involved in 'thought leadership', by which I mean generating ideas that are new (or are at least novel) for a particular context and audience and successfully communicating them so as to achieve outcomes (whether public, private, social etc.) is that you are incentivised to communicate and disseminate your ideas far and wide. This was one of the more enjoyable parts of my role at CCC and something I had significant experience of at CCC and in previous roles.

I think there is a relatively standard and repeatable process to thought leadership. It begins with the high-level idea(s) or vision. This is followed by developing a firmer set of proposals, ones that are ideally practicable and plausible, but nonetheless sufficiently ambitious or disruptive to signal some breach with the status quo. Next comes finding a 'hook' for your proposals – a moment where people might be particularly receptive or interested in them. For example, this could be a government consultation or the fact that there is a large international meeting or some other major event. After the hook is found, the publication or dissemination of your idea and proposals takes place publicly. Depending on the type of idea, the sector within which you work, and how newsworthy your idea is, launching publicly can range from being a very big deal with significant press coverage and impressive high-level endorsements, among other things, through to simply being an op-ed, research note, or paper – something that puts down a marker and allows you to build momentum around an issue. The final phase is building support for your idea, making sure it reaches those 'influencers' who are able to carry it forward, and hopefully then turning it into action – ideally in the place and area where you wanted to effect change. Throughout each phase you are also constantly building support for your ideas by briefing others and planting seeds for the ideas, whether with colleagues, contacts, friends in your network, journalists, and so on.

In a CCC context there were commercial and public goods reasons for producing such thought leadership, as I have described previously. In a think tank, NGO, or academic institution these motivations are usually less commercial and more about societal change, though thought leadership is also undoubtedly undertaken for personal gain, ego, and other related reasons too. In non-commercial organisations it is part of the 'currency' that can help you secure funding from industry or philanthropy.

When it came to what became known as stranded assets, I proceeded along the thought leadership process I outlined above. As discussed, perhaps the most immediately exciting concept of the four I outlined in the preceding subsection was around systemic risk and

financial regulation. The first thing I did was to include references to this issue in items I was writing for myself or for others. The first recorded instance I can find of where I talked about systemic risk, climate change, and financial regulation was an op-ed I ghost wrote for the Chairman of CCC that was published in the *Financial Times* on the 28th November 2010. In this article I wrote (under the Chairman's by-line), '…investors have under-priced or largely ignored these [environment-related] risks…Finally facing up to these risks and pricing them appropriately is becoming unavoidable…as investors, fund managers and policymakers wake up to these systemic risks and seek alternatives, there are few options of the size required to displace high-carbon investments. Without credible options it will be too easy to continue with the status quo and so build up systemic risks and their associated consequences for the future.' (Cox 2010).

I also began drafting a comment piece under my own by-line in spring 2011, which was submitted to *The Guardian* on the 16th June 2011. During that time, I wrote comment pieces regularly for *The Guardian* and this was a natural outlet to put down a marker for some of my emerging ideas. I submitted the draft comment piece to the newspaper on the morning of the 16th June 2011 as this was the date of the first meeting of the Bank of England FPC and I had previously decided that I wanted to use that as the hook for the idea and the article.

The draft title of the article was 'Not again: Another systemic risk in our financial system that threatens future growth' and in it I called for 'horizon scanners in international financial institutions, regulators, together with policymakers and politicians, to manage the [carbon] bubble before it was too late.' Unfortunately, *The Guardian* decided not to run it that day as they did not have space and were confident of finding another hook for the article soon.

After several weeks I received an email from the editor suggesting an appropriate hook for my piece and that they wanted to publish the article the following day – on the 12th July 2011. The editor had amended the article slightly to make reference to the hook they wanted to use and asked whether I was happy for it to be amended in this way. After checking these edits through and adding my own I was happy for them to proceed with publication.

The hook for my article was going to be the publication of the Carbon Tracker Initiative's first report, 'Unburnable Carbon: Are the world's financial markets carrying a carbon bubble?' This was good news, as hearing about this new report and organisation revealed to me that others were thinking about similar issues. But I must confess that it was also a frustrating example of convergent thinking, particularly as it now looked like I had simply written my piece after having read their report, which was not the case.

One of the things that is important to note at this stage is that the nomenclature was not yet fixed. No one was consistently referring to these ideas as stranded assets. The term is mentioned twice in Carbon Tracker Initiative's 2011 'Unburnable Carbon' report, with

systemic risk, unburnable carbon, carbon bubble all being used interchangeably much more frequently. It is mentioned once in my own comment piece published on the same day, 'if the world acts on its climate change pledges, 80% of those reserves can never be burned and *are stranded assets* [emphasis added]' (Caldecott 2011b). It was only later, in 2013-14, that definitions emerged and the differences between them started being settled (although this process is still ongoing).

Many of these definitional issues are addressed in the first chapter. But I should say here that I think stranded assets rose to become the preferred term for four main reasons. First, 'stranded' is evocative language and we can all visualise what it means. Second, 'assets' signifies something of value and can apply to a broad range of physical and non-physical capital, it also has connotations associated with the finance and investment community. Third, there is lineage in the form of 'stranded costs' (see chapter 4) and 'creative destruction' (see previous chapter). Finally, I decided early on that this would be how I referred to it and thus plugged away doggedly for its use in other publications and in my work as it developed.[2]

Not everyone agreed with me however. I had distinguished colleagues saying I needed to find something that sounded more 'exciting' if the idea was to get any traction! But I think the tipping point really came with the media and use of stranded assets more and more regularly by journalists. We see the result reflected in the Carbon Tracker Initiative's second report published in 2013, 'Unburnable Carbon: Wasted Capital and Stranded Assets', where the term stranded assets is used as frequently as 'carbon bubble' and the term is also used in the title. Others have conducted research tracking the usage of the terms and how these have changed that back this up, see Harnett (2017 - forthcoming).

After the initial public forays in July 2011 from myself and the Carbon Tracker Initiative, we reached out to each other and met for the first time in mid-August 2011. In the interim period I was also having a variety of conversations with a wide range of people in my network about these ideas. Many were not particularly interested, though some were keen to explore them further. The case I made internally at CCC was that these arguments could be a significant future driver of demand for our funds and services and in any case, it was a good example of the thought leadership we should aspire to create.

In July 2011 I also applied for a Visiting Fellowship that I had seen advertised at the Smith School of Enterprise and the Environment at the University of Oxford. The Smith School was looking for new Visiting Fellows and these fellowships could be held part-time or full-time for up to one year. In the application you had to include a research proposal and mine was predictably on stranded assets. I proposed to spend one day a week up in Oxford working on this and had secured dispensation from CCC to do so.

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[2] I cannot know whether I swayed things decisively either way, but having some consistency from one actor early on may have helped to sway usage.

I proposed that my research at the Smith School be divided into three parts. The first part would attempt 'to understand the challenge in terms of value that might be lost…[and] research the extent of global, and particularly UK and European, financial exposure to high carbon, extractive and environmentally unsustainable investments.'

The second part would then look at 'how exposure and relative values, between high carbon and low carbon investments, could change over time and how this might affect different parts of the financial system…The purpose of this work would be to evaluate the health, soundness and vulnerabilities of the financial system as we proceed with a low carbon transition.'

The third part would look at 'how we could manage the challenges that might arise as a result. If this is indeed akin to a systemic risk in our financial system, what macroprudential instruments might be designed and deployed to help to restrain the build-up of risk? Could we change the risk-weightings used to calculate capital requirements? What steps can be taken in each part of the financial system? What is the role of regulators – nationally and internationally?'

I successfully secured the Visiting Fellowship and organised with the Smith School to begin this in January 2012. In addition to incessant pitching of the ideas to anyone who would listen and thinking about the concepts and potential lines of inquiry prior to starting the Visiting Fellowship, there were three key events in the second half of 2011 that are important to note.

In August 2011 I was invited to co-author, together with CCC's Vice Chairman, a section in the World Economic Forum's (WEF) The Global Competitiveness Report 2011-12 on 'Sustainability and the Financial System'. The Global Competitiveness Report is a high profile and widely read publication that includes an annual ranking of countries' competitiveness based on a number of indicators. At the time WEF were considering how to integrate sustainability factors into these rankings and we argued that a country's exposure to stranded assets could affect competitiveness 'if policy, technology, and markets work consistently to reduce returns in environmentally unsustainable areas while supporting sustainable ones, investing in high-carbon or extractive industries…could result in under-performing or even stranded assets…If this proves to be the case, could economies that reduce their financial exposure to unsustainable assets be exposed to less risk and thus gain a competitive advantage?' (Cameron & Caldecott 2011).

Writing our contribution and selling these ideas into WEF – a high level network dedicated to disseminating ideas among global 'influencers' – helped stranded assets to reach important audiences early on. These people and organisations could then socialise the ideas and encourage further work on them in their home country or home institution.

As the topic was starting to secure traction with different groups, I decided that it was important to convene some of the people then working on or considering working on these issues. I sent an email invitation to representatives of 15 organisations on the 31st August 2011 for a workshop to be held on 7th October 2011 at CCC in order to, 'bring together people working or thinking about doing work on the extent of financial exposure to high carbon investments and its implications given our desire for a transition to a sustainable global economy.' In the email I went on to add, 'This is very much a first meeting to find out who's doing what where…and to ensure that our work is as joined up as possible.'

The meeting took place and one of the key decisions was to support a proposal I had made, which was to draft a letter to the Governor of the Bank of England in his capacity as chairman of the FPC. The idea was that we would secure a large coalition of signatories to the letter and this would begin a formal engagement with the Bank, as well as have the added benefit of catalysing further attention and 'smoking out' other organisations and individuals interested in stranded assets.

I drafted this letter in November 2011 and finished it after receiving feedback while attending the Durban climate negotiations in early December 2011. I then spent time in December 2011 and January 2012 corralling contacts and organisations to sign the letter, as well as preparing a press release and related media activity to ensure that it secured significant public attention. On the 19th January 2012 I organized for the letter[3] to sent formally to Sir Mervyn King, the then Governor of the Bank of England[4], and a press release was also issued to the media at the same time. The letter was signed by 'a high-profile coalition of [20] investors, politicians and scientists' (Carrington 2012).

By the end of January 2012 the small group that had discovered themselves over the course of 2011 had achieved some tangible outcomes. In particular, the first coordinated action on stranded assets in the form of a coalition sending a letter to the Bank of England. The letter received significant attention and stranded assets was increasingly perceived as the 'hot new' topic. An agenda for research was also being formed and on the 25th January 2012 I made my first trip up to Oxford as a Visiting Fellow at the Smith School to work on these issues. Others were also developing and implementing plans for future work. In short, we had an exciting new topic with very significant possibilities. Momentum meant we also had interest from the media and a growing number of individuals and organisations from around the world keen to get involved.

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[3] The text of the letter can be viewed here: http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/Letter_to_Bank_of_England_Financial_Policy_Committee-19th_January_2012-Final.pdf

[4] The letter was also copied to the Chancellor of the Exchequer; the Secretary of State for Foreign and Commonwealth Affairs; the Secretary of State for Innovation, Business and Skills; the Secretary of State of Energy and Climate Change; the Secretary of State for Environment, Food and Rural Affairs; the Chairman and Chief Executive of the Financial Services Authority; the Chief Executive of the Committee on Climate Change; and the Chief Executive of the London Stock Exchange.

2.2 Central banks and financial institutions

In this section I split my first-person account into two parallel tracks. These are less chronological and more focused on drawing out the salient points and issues facing each group of issues and organisations. I try to shed light on the motivations of different stakeholders working in these areas and some of the challenges that emerged.

2.2.1 Central banks

The letter to the Bank of England received a reply from Sir Mervyn King less than two weeks later on the 1st February, 2012.[5] He welcomed the letter and invited us to have a meeting with Andy Haldane, at that time the Bank of England's Executive Director for Financial Stability.[6] In his reply King also highlighted three tests that the Bank would apply to examine whether there were any financial stability implications of the kind we had hypothesised. First, 'that the exposures of financial institutions to carbon-intensive sectors are large relative to overall assets.' Second, 'that the impact of policy and technology working to reduce returns in high carbon areas is not already being priced into the market, either through lower expected returns or higher risk premia discounting these returns.' Third, 'that any subsequent correction would take place over an insufficiently long period of time for the relevant financial institutions to adjust their portfolios in an orderly manner.' He concluded by saying, 'The necessity of all three conditions being met raises a question in our minds as to whether or not this is a potential threat to financial stability.'(King 2012)

This framework for the evaluation of our hypotheses and his 'three tests' were a significant contribution and helped to inform the development of research priorities. I was confident that the first test would be met – exposure was demonstrably large relative to overall assets, particularly in the UK. I was also confident that the second test would be met – there was extensive evidence of investors mispricing all sorts of material factors and environment-related risks were among them. I was less sure about our ability to meet the third test – that corrections could be disorderly. This hinged on scenario analysis and whether there were robust and plausible scenarios with financial stability implications (see Caldecott, Tilbury, and Carey 2014).

The meeting with Andy Haldane promised in King's letter took place on the 20th April 2012 and in this meeting we focused on the three tests and the evidential base we had to support our case. Four financial institutions, two NGOs, and two academic institutions were represented at the meeting with Haldane at the Bank of England's offices on Threadneedle Street. It was clear at the meeting and in subsequent conversations that substantial further work was necessary and this really put into perspective how much

[5] The text of this letter can be viewed here: http://www.smithschool.ox.ac.uk/research-programmes/stranded-assets/fpc_bank_of_england_response.pdf

[6] At the time of writing he is now the Bank of England's Chief Economist

new analytical work would need to be done, as well as some of the constraints that central banks faced while engaging on this topic.

These constraints were significant and limited their room for manoeuvre. They included the following: first, statutory constraints, such as the remit of the Bank of England and its powers set out in legislation. Second, the bandwidth of central banks to engage with new topics given the very significant post-GFC issues, such as major changes to financial regulation and the deployment of unconventional monetary policy. At the time, there was also no expertise on climate change or the environment within the Bank of England or to my knowledge in any other major central bank, which further limited their capacity to engage. Third, the widely held view among central bankers that their job should not entail considering societal outcomes beyond achieving monetary policy objectives, particularly inflation targeting. Fourth, that central bankers are through training, and perhaps also temperament, inoculated against special pleading from interest groups. There is a view that central banks should not consider narrow sectoral interests under any circumstances.

These constraints make a great deal of sense, otherwise central banks would be pulled back and forth by various sectoral interests and ultimately become distracted from their core monetary policy objectives. However, the resulting small 'c' conservativism that resulted meant that the Bank of England and its sister central banks were cautious about engaging on new topics like ours. This was deeply frustrating. There appeared to be significant scepticism from King as a result, despite curiosity and interest from Haldane and others, that perhaps reflected a generational difference.

While the Bank agreed to 'include this [stranded assets] in the list of topics we regularly discuss with market participants, to assess whether or not this is a risk of which they are aware and the extent to which they are taking it into account in their investment decisions' (King 2012), it turned out that this did not mean particularly much. The Bank would simply look out to see if stranded assets was included as a response in their semi-annual Systemic Risk Survey, which they sent out to chief risk officers (CROs) and risk managers across a range of financial institutions. As part of this survey they ask CROs and risk managers to identify the risks that they 'believe would have the greatest impact on the UK financial system if they were to materialise' (Bank of England 2016d). Respondents then identify their top five risks and rank them in order of potential impact.

This seemed deeply unsatisfactory and fundamentally quite flawed. Prior to the GFC financial institutions had systematically proven that they were unable to spot significant risks to the stability of the financial system, let alone report them to the central bank (Crotty 2009; Wolf 2014). Moreover, there must surely be risks that a central bank would consider more of a risk than the market and vice versa. The central bank ought to think of and consider risks that markets might not foresee or currently fail to pick up.

My view was that the Systemic Risk Survey should be designed as a way to monitor both types of hypothesised risk - risks that market participants had self-reported and risks that the Bank itself thought could be a risk. Without this, all the survey is doing is picking up what certain people within a sample of financial institutions think are the most significant risks at a certain point in time. Not whether their view of particular risks had changed over time (unless they happen to be in the top five risks reported). There was no flexibility within the Survey for the Bank to suggest risks and ask market participants for a view, even if these were very standard risks that the Bank retained a watching brief on, for example, a deterioration in the global economic outlook or high inflation.

Quite clearly the risk we were asking the Bank to consider was very unlikely to be detected in the System Risk Survey even if financial institutions thought it was an issue. Even if they agreed that it was a risk, they almost certainly would not have identified it as a top five risk. The Survey seemed a wholly inadequate horizon scanning tool, but was to be the primary mechanism through which they wanted to test our hypotheses. I was very sceptical of their efforts as a result.

The communications with the Bank also became less regular and their interest seemed to wane. These developments were not encouraging and stranded assets seemed to have largely dropped off the Bank's agenda by the Autumn of 2012. I think this inevitably reflected the capacity available to consider issues that seemed beyond the immediate scope of dealing with the aftermath of the GFC, such as implementing significant and complex new regulations (such as Basel III and Solvency II); conducting newly enhanced stress tests of financial institutions; and enhancing standards of financial conduct. Add to the mix the succession planning (and associated internal jostling) caused by the retirement of the then Governor of the Bank of England, and stranded assets looked like it was unlikely to get back on the agenda any time soon.

Fortunately, this lack of interest was temporary and interest was rekindled by Sir Mervyn King's successor, Mark Carney. Carney's appointment as Governor was confirmed on 26th November 2012, with him joining the Bank on 1st July, 2013. This period of transition between the old Governor's retirement and the new Governor's appointment coincided with the lull in Bank interest in stranded assets. It ended in early 2014, six or so months after Carney started work at the Bank.

In December 2013 the UK's Department for Environment, Food and Rural Affairs (Defra) invited the Bank of England to prepare a voluntary report on how climate change adaptation might affect the Bank and its remit. This was something quite normal and Defra had already asked many public and non-departmental public bodies to voluntarily prepare such reports. The Bank formally accepted in April 2014 and this became the hook that justified a scaling up of interest internally. In addition, in June 2014 the Environmental Audit Committee of the House of Commons recommended that 'the Financial Policy Committee of the Bank of England should regularly consult with the Committee on Climate Change to help it monitor the risks to financial stability associated

with a carbon bubble' (Bank of England 2016c). This prompted a formal reply from Carney, where he referenced the fact that the Bank would be producing a climate change adaptation report in response to Defra's request earlier that year (Bank of England 2016c).

The combination of a formal Defra request, plus additional parliamentary scrutiny of the issue, meant that the Bank had to formally and systematically engage on stranded assets. This necessitated resourcing and capacity, in the form of a small team formed within the Bank, together with external experts brought into the Bank in order to support their work. I was one of the people seconded in and spent much of late 2014 and the first nine months of 2015 working intensively with the Bank in the run up to Carney's speech on climate change at Lloyd's of London on 29th September 2015, which is where they also published their written response to Defra, *The impact of climate change on the UK insurance sector: A Climate Change Adaptation Report by the Prudential Regulation Authority* (Bank of England 2015b).

The external pressure on the Bank from Defra and parliament, was in part shaped by civil society efforts and advocacy. So although Bank interest in the topic waned for around 18 months between autumn 2012 and summer 2014, interest among other groups grew rapidly, which ratcheted up pressure on the Bank to act when it was ready to re-engage under new leadership.

External developments were combined with favourable internal changes within the Bank itself. The most significant of these was of course the change in Governor and a resulting shift in the Bank's attitude towards new topics. Reflecting this change was the creation of a new 'One Bank Research Agenda' (OBRA) for the first time, with this being launched in February 2015 (Bank of England 2015a). OBRA was different from previous research agendas at the Bank, which had focused exclusively on its core competencies in monetary policy and macroeconomics. In contrast, OBRA was wide ranging and included topics not usually considered within the remit of central banking. This was a major departure from the past. Not only was environmental change explicitly included, but also topics such as demographics, inequality, digital currencies, and artificial intelligence (Bank of England 2015a). The two specific questions that OBRA set out in relation to climate change were: 'What are the effects of environmental and climate change on the economy and the financial system?' and 'What role, if any, do central banks have in addressing systemic environmental risks? (Bank of England 2015a). So not only were there now externally driven processes (i.e. Defra adaptation report and parliamentary scrutiny) but also an internal driver of Bank work, the OBRA.

A further external process was also relevant – the Paris climate change negotiations in December 2015. The UN Framework Convention on Climate Change (UNFCCC) and its then Executive Secretary, Christiana Figueres, together with the French government, promoted something called the Paris Action Agenda. This was in large part about mobilising actors, particularly non-state actors, to put pressure on governments ahead of the set-piece negotiations in Paris. This was part of efforts to ensure that conditions were

favourable for a high-ambition outcome at Paris, which was ultimately secured successfully.

Financial institutions were one of the priorities of the Paris Action Agenda and much effort was invested in mobilising institutions internationally. The City of London received significant attention as part of this effort, partly because of its proximity to Paris and Bonn (where the UNFCCC is headquartered) and its comparative internationalisation (many other financial centres are generally more focused on large home markets). The Bank of England's growing interest also made the City of London particularly important. Securing support from other central banks internationally using the Bank of England as an example of leadership on climate change was a priority for the Paris Action Agenda.

External pressure of this kind, where the Bank was in a leadership position and able to influence others in order to achieve a good outcome at Paris, was clearly a factor in encouraging work by the Bank in this area, though one that is very hard to define. I doubt whether the Bank, and specifically Carney, would have gone out on such a limb on climate change had it not been for this concurrent international process.

It is worth emphasising here that the Bank of England was the first central bank to embrace stranded assets as a topic. The work at the Bank continues in this area and on other related topics, including green finance. It has set a precedent that is being adopted by other central banks (see Financial Stability Board 2015; European Systemic Risk Board 2016; DeNederlandscheBank 2016) and has demonstrated how a single, well-placed, and highly respected institution can transform a topic and give it the oxygen to grow. Without Bank support, stranded assets would be less well established as a topic than it is today.

As I have discussed, Bank support and interest seemed very unlikely to materialise when I first engaged with the Bank in January 2012 and may not have been forthcoming at all had it not been for the fortuitous combination of growing external pressure articulated in ways that enabled the Bank to engage formally (i.e. Defra and Parliament), a significant change in leadership that reformed the scope of the Bank's research agenda, and a major time sensitive international process.

2.2.2 Financial institutions

The financial system is a complex ecosystem of institutions that have very different, and often highly specialised, roles and functions (Haldane & May 2011). Different parts of this investment chain, including but not limited to, actuaries, asset owners, asset managers, accountants, banks, central banks, data providers, governments, investment consultants, lawyers, ratings agencies, and stock exchanges all have different clients, motivations, and cultures.

Each individual part of the investment chain is highly complex – there are multiple different types of firm within each part of the chain. For example, the ecosystem of asset owners is itself multifaceted, from pension funds (public, private, DB, DC etc.) through to insurance companies (life, general, marine etc.), sovereign wealth funds (politicised, non-politicised, OECD, non-OECD etc.), and family offices (old money, new money, large, small etc.) – each with a different set of challenges and considerations for asset-liability matching. The same complexity is repeated in other parts of the investment chain, often with even greater differentiation. Moreover, these institutions vary enormously between place – geography, culture, and regulation – as well as in terms of practice, meaning that, for example, an asset manager in Shanghai is going to have a very different way of doing things from one based in either Sydney or San Francisco (see Clark & Wójcik 2007).

Through my work on stranded assets I have engaged with an incredibly diverse mix of financial institution across a wide range of geographies in a variety of different ways and settings. I have also engaged with different people within the same organisations – from those where stranded assets might be of obvious and immediate interest (e.g. ESG specialists) through to those that might have many other pressing concerns and extremely tight time budgets (e.g. CEOs, CIOs, and Chairpersons).

Given the complexity of the system, it is impossible to perfectly capture how one part of the investment chain might view an issue, let alone the system as a whole. Where work has been done to systematically understand how stranded assets is viewed and treated within a particular part of the investment chain, it has drawn on close dialogue and confined itself to a particular group and financial centre, or has been a comparison between a group across financial centres. Recent work of this kind includes Caldecott and Rook (2015) on investment consultants in London and Harnett (2016) comparing pension funds in London, Sydney, and Melbourne. Other studies of this kind that are forthcoming include research on ultra high-net-worth individuals in Northern Europe and the East Coast of the United States (Caldecott and MacDonald-Korth 2017 – forthcoming) and on university endowments in the Anglosphere (Kampmann 2017 – forthcoming).

Instead of honing in on a specific part of the investment chain to divine further insight, important though that is, here I try to bring together my patchwork of experiences to articulate some broader observations on the interaction of financial institutions with stranded assets. I focus on issues that I do not think are covered sufficiently elsewhere in the discourse. I also try to tease out what has and has not worked in terms of engaging with financial institutions and what this might mean for the future of the topic.

2.2.2.1 Complete hot air?

There is a large and growing literature concerning some of the common characteristics that make it hard for financial institutions to take account of risks that are novel, non-linear, and medium to long term (Kay 2012). These include endemic short-termism, misaligned incentives, and misinterpretations of fiduciary duty, among other things (for

example, see Kay 2012; Carney 2015). These are all issues that make it hard for financial institutions to engage with stranded assets and topics related to environmental change more broadly.

Another such characteristic that befalls some finance practitioners, and that is particularly relevant to stranded assets, is climate scepticism. Climate sceptics reject the notion of anthropogenic climate change or dispute the scientific consensus of its likelihood and severity (for example, see Whitmarsh 2011; Poortinga et al. 2011). Though this is entirely my own subjective opinion, it has been my experience that there is a higher proportion of climate scepticism among finance practitioners than in other comparably high skilled parts of the economy. I do not intend to speculate on the reasons for this here, nor where specifically this manifests itself most acutely, but whatever the reason, it unfortunately makes arguments that hinge on climate change much less likely to gain traction within financial institutions.

One of the many reactions to stranded assets, particular when framed purely in unburnable carbon terms (i.e. stranded assets caused by carbon budget constraints introduced by international climate policy), reflects this increased tendency. It is summed up perfectly by a quote from a sell side oil and gas analyst reported in the *Financial Times* in late July 2011 when asked to comment on the Carbon Tracker Initiative's first report, 'I think it's a bollocks subject. I'm not interested in this kind of subject. I think this is complete hot air' (Johnson 2011). I have seen and heard many similar reactions and this quote is entirely unsurprising as a result.

To be fair, this reaction and many like it may not be because of any climate scepticism, but are made for other legitimate reasons. But my point is merely that my hypothesised prevalence of climate scepticism among finance practitioners increases the likelihood that they will disengage from conversations or too readily dismiss views contrary to their view on climate change.

One implication of this, is that in order to engage with financial institutions and finance practitioners on stranded assets, it has been important in my experience to avoid falling over on this first hurdle. Starting with climate change first, for example as the only or most significant environment-related risk that can strand assets, immediately places you at a disadvantage. While this situation has improved since 2010-11, it still remains the case that the climate sceptics in a group will immediately 'switch off'. You then only appeal to those that are directly interested in climate change. Everyone else in the 'middle' who could be persuadable would rather avoid rubbing their climate sceptic colleagues up the wrong way, particularly if they are more senior (which they often are). As a result, a majority become disengaged and the dialogue does not progress. My subjective and entirely unscientific view is that among a sample of finance practitioners at least 20% of people are sceptics, 70% are indifferent, and 10% are directly interested in climate change.

In my experience a much more effective way of engaging with financial institutions has not been to go straight for the climate change argument, but rather to frame the phenomenon of stranded assets more generally and broadly, prior to narrowing it down towards specific environment-related risks and opportunities, including those related to physical climate change impacts and societal responses to climate change.

In this approach, the argument for taking account of stranded assets and the environment does not hinge on your view of anthropogenic climate change and does not rely on assumptions about international processes and international policy. As it happens, there seems to be a disproportionately large proportion of finance practitioners sceptical of the ability of governments to deal with any major complex international problem and so that is the other premise to avoid – the premise of concerted international action.

2.2.2.2 Motivations

The different inter- and intra-institutional motivations that exist within the investment chain have been critical for the uptake (or not) of stranded assets. These dynamics are poorly understood, but I think they are fundamental and more work to understand these motivations is essential.

'Inter-institutional motivations' capture the incentives that different parts of the investment chain have with each other. One particularly important example of this is asset managers attempting to secure mandates from asset owners. Another is the sell side, who are promoting, creating, and selling product to the buy side. Both groups have significant incentives to adopt and market new ideas and investment hypotheses to their clients (asset owners and asset managers respectively), so as to win mandates and sell product.

'Intra-institutional motivations' capture the incentives of different roles (or individuals) within financial institutions and is essentially about how different functions make the case for the allocation of finite resources within an organisation. For example, it is probably easier to make the case for some internal marketing budget to be spent on promoting existing but weak ESG practice, instead of making the case for a significant upscaling in capability to enhance ESG practice.

Personal motivations are also important and are bound together with inter- and intra-institutional motivations. For example, a senior executive who is close to retirement could have a strong incentive to 'play it safe' and so in those cases reforms might be less likely to be made or pursued.

Failing to understand these different overlapping motivations can give the outsider a very inaccurate interpretation of how financial institutions might react to or treat new information or ideas. Capturing these inter- and intra-institutional motivations is an

objective of close dialogue and associated research, but is rarely done to inform civil society efforts to influence the alignment of finance with sustainability.

2.2.2.3 Towards mainstreaming

Since 2010 stranded assets has become a topic of interest to many financial institutions and finance practitioners. Stranded assets arguments have underpinned developments in practice that are successfully shifting capital away from 'brown' and towards 'green' based on an enhanced understanding of environment-related risk (for example, see, Caldecott et al. 2016). It has also provided the basis for the fossil fuel divestment campaign, the fastest growing divestment campaign in history (Ansar et al. 2013), with the movement currently claiming that 534 institutions with $3.4 trillion of assets have committed to partially or fully divest from fossil fuels (Go Fossil Free 2016). These strides have been significant, but to what extent has stranded assets become 'mainstreamed'?

Mainstreaming, where ideas, practices, or norms become regarded as normal, has unquestionably been an explicit priority of my work on stranded assets. It is undoubtedly an objective shared by others working on stranded assets too. But there are two main challenges of tracking progress towards this goal.

First, the definition of mainstreaming that I and others have is undefined. It is not just a question of the term or idea entering the lexicon, which I think stranded assets has achieved among specialist and many non-specialist audiences. Mainstreaming is also about changing practice – both improving best practice and the 'state of the art', as well as ratcheting up the quality of what could be called 'routine practice'. The threshold for the achievement of mainstreaming, whatever that threshold is, also needs to be irreversibly reached across multiple parts of the investment chain in a wide range of different markets. It is not sufficient for the threshold to be fleetingly met in one or two parts of the investment chain and in one or two parts of the world – it is permanently mainstreaming a topic across the financial system with its inherent breadth, depth, and complexity. Finally, it should also be about outcomes, in terms of capital being more likely to flow in the direction we would expect if stranded asset risks were appropriately understood and then integrated into decision-making. If these different criteria have to be met to achieve mainstreaming, and I think they probably should be, then this is a very high bar indeed.

Second, detecting progress towards the achievement of mainstreaming is difficult. Not least because of the aforementioned lack of definition, but also because of the 'echo chamber'. For those of us working within a domain or field it is hard to differentiate change among 'usual suspects' versus change in the 'real world'. While it can be very comforting to attend one of the many conferences organised on stranded assets and meet with people I know already and hear about the progress they are making, it can provide a lopsided and entirely unrealistic impression of what is actually going on outside. In the case of stranded assets, this is exacerbated by press coverage. The quantity of references

in newspapers, magazines, and other media to stranded assets has increased dramatically (see Harnett 2017 - forthcoming), but a lot of this coverage is consumed by the same usual suspects and written by correspondents who write on the environment and climate change. This can further reinforce an impression of rapid change and mainstreaming, when actual real world progress has been much slower.

Nonetheless, I have detected a perceptible shift among financial institutions over the 2010-16 period that is real and meaningful, although perhaps still some way from the achievement of mainstreaming. These include the following changes:

First, the fact that the Bank of England and other central banks, by showing sustained interest in stranded assets at the highest levels, have forced functions within financial institutions that were not previous engaged on anything to do with stranded assets to now become engaged. For example, Solvency II requires every insurance and reinsurance firm to conduct its own risk and solvency assessment (ORSA) and to submit this to the regulator for approval in order to be licensed to operate (Bank of England 2016b). After the Bank of England's pronouncements on stranded assets it is likely to be the view of insurers and reinsurers that their ORSAs should include some reference to these risks to avoid the possibility of their ORSAs being rejected or further interrogated. This moves stranded assets from the category of being entirely optional into something that is now fundamental to securing regulatory approval to operate.

Second, the aforementioned involvement of central banks and regulators has also helped to shift the terms of the dialogue within financial institutions. It has been the norm in many institutions for ESG specialists or those with a direct interest in stranded assets topics to 'sell upwards' to their senior management. This means they identify topics or ideas that are likely to be approved by their superiors – which inevitably means that some topics or ideas are rejected and that the ambition of what is sold up is lower than they might want in order to secure internal support. In most organisations this inevitably places a premium on low cost, uncontroversial, and non-disruptive proposals. These may also be the least effective proposals for the integration of stranded assets into investment decision-making.

This situation may now be changing. One thing that I have noticed recently, particularly in the run up to the Paris climate change negotiations in December 2015 and in the six months after it, has been CEO and CIO level engagement from many more institutions than has previously been the case. The involvement of the central bank, for example in convening meetings at these levels, means that there are new opportunities for CEOs and CIOs to be more ambitious and also be competitive with each other in person. They can then instruct downwards and get their teams to implement what they have committed to voluntarily with their peers and with the regulator. This is a new dynamic for many firms, though its implications and durability are yet to be seen. Moreover, whether the central bank, which has the necessary convening power, will continue to be deploy finite resources into these efforts is also uncertain.

Third, developments in practice are starting to catch up with the theory. Unfortunately, the tools available to manage exposure to stranded assets created by environment-related risks have been rather limited to date. As Caldecott et al (2016) point out, the vast majority of analysis that is undertaken is usually done 'top down', where financial institutions look at company-level voluntary reporting and focus on measures of carbon emissions and intensity to differentiate between companies. Even if company-level reporting is accurate and up-to-date (in many cases it is not), this is an overly simplistic approach that attempts to measure a wide range of environment-related risk factors (often with widely varying degrees of correlation) through one proxy metric (carbon emissions). While this might be a useful exercise, more sophisticated 'bottom up' approaches can yield improved insights for asset performance and if appropriately aggregated, company performance (Caldecott et al. 2016).

There are also significant new analytical possibilities. Existing data can be analysed using techniques involving artificial intelligence and machine learning, while new data can be made accessible from sources previously unavailable, such as remote sensing and 'big data' (Caldecott et al. 2016). These new frontiers are complemented with extant international efforts to enhance and improve the consistency of disclosures that can support the management of stranded assets (for example, see Task Force on Climate-Related Financial Disclosures 2016 and Sustainability Accounting Standards Board 2013, as well as efforts to improve integrated and narrative reporting, for example, see Eccles and Krzus 2015).

In addition to these developments, new products are being launched regularly, such as indices that are weighted away from the risk of stranded assets (Fossil Free Indexes n.d.), exchange traded funds that employ such indices (State Street Global Advisors 2016), and credit ratings integrating stranded asset risks (Standard & Poor's 2014; Center for International Environmental Law 2015). These examples do not fully capture the rapid innovation taking place across the investment chain in relation to environmental risk and opportunity, of which stranded assets has been a disproportionately important part.

While this innovation across the investment chain is exciting, it is too early to tell whether this will result in successful mainstreaming. The innovation is largely limited to pockets of excellence in Northern Europe (particularly the UK, France, the Netherlands, Norway, Sweden, and Denmark) and parts of the United States (particularly the Bay Area). The conversations in Asian financial centres are much less mature and in many emerging economies this is simply not an issue of concern. While initiatives such as the UNEP Inquiry into the Design of Sustainable Financial System are promoting these topics internationally and are placing particular emphasis on building awareness in less developed economies, the reality is that innovation in terms of practice has been incredibly lopsided, and perhaps understandably so given that innovation usually has to begin somewhere before spreading outwards (see Breschi & Malerba 2001).

Another issue is that key intermediaries along the investment chain, particularly investment consultants, are hindering the uptake of these new practices and this could yet be a major blockage to mainstreaming stranded assets (Caldecott & Rook 2015). Unpicking the causes of this, which are unfortunately both complex and diverse, will not be straightforward and requires a degree of asset owner coordination that has so far been lacking (Caldecott & Rook 2015).

2.2.3 Broader reform agenda

One of the things that has become clear to me is that it is very hard, if not impossible, to disentangle what needs to happen for financial institutions to take account of stranded assets from broader reforms to finance and investment. If financial institutions could only just extend their time horizons many of the factors that make stranded assets a knotty issue would be addressed (Carney 2015).

Clarifying fiduciary duty and addressing some of the perverse incentives of liquidity requirements would each go some way towards encouraging this long-termism. Asset owners also need to have the courage and conviction necessary to create longer-term mandates for asset managers, and this should be more natural given the long tail of future liabilities that many asset owners have (Investec Investment Institute 2016). Ultimately the paradigm of getting to long-term results via a series of short-term positions will need to change (Investec Investment Institute 2016).

Developments and innovations in the practice of analysing stranded asset risk can only achieve so much if they must operate in an institutional environment that is endemically short term. Stranded assets work should therefore not just be about innovation in practice, but also about understanding and ensuring that changes in governance, fiduciary duty, and incentives promote a form of long-termism that properly takes account of the environment.

2.3 Conclusion

This chapter has attempted to provide a reflexive first-person account of how work on stranded assets and the environment developed from 2010 to 2016. It has allowed me to transparently set out and explore some my own motivations and the context in which my work began. The approach has also allowed me to explore the motivations and constraints of others, particularly central banks and financial institutions. These may provide useful signposts for the growing number of people and organisations attempting to interact with finance and investment from a sustainability perspective.

While the chapter has concentrated on two groups – central banks and financial institutions – I could have written about other groups at length too, such as civil society, policymakers, companies, or the media. Each of these groups has had a critically important role in developing stranded assets as a topic. These groups have not been given an appropriate treatment here primarily because of the need to bound this work in some way. In terms of deciding the two groups to focus on here, it was simple – these are the two groups where work on stranded assets was targeted first. And so understanding the development of work focused on central banks and financial institutions can provide insight into how this work expanded into other areas over time.

While I would argue that my first-person account is the key strength and primary purpose of this chapter, the fundamentally subjective nature of the account is a significant weakness for those that seek unadulterated objectivity. This chapter does not and cannot, I am afraid, provide that. But I hope my account provides scholars with materials and insights through which they can develop more objective views of how the topic of stranded assets developed in the first half of the second decade of the 21st century. I also hope it further highlights how stranded assets – given its importance and applicability in a wide range of contexts informed by geography – is eminently suitable as a topic of concern for economic geographers.

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Chapter 3

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Negative Emissions Technologies and Stranded Assets

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Abstract

Negative Emissions Technologies (NETs) could extend carbon budgets and potentially reduce the risk of carbon intensive assets becoming stranded assets. This paper estimates the extent that such technologies may be able to do this by 2050 and 2100 and the implications for potential stranded assets facing policymakers, investors, and firms. Answers to these questions are currently absent in the literature, which is surprising given that the availability of NETs is a key uncertainty for asset stranding in the future. Finally, we argue that actors should be sceptical of NETs altering their exposure to asset stranding, even if they are successfully deployed at scale. This could have implications for risk assessments undertaken by firms and their investors.

Keywords

Negative Emissions Technologies; Carbon Budgets; Stranded Assets; Unburnable Carbon; Carbon Dioxide Removal; Carbon Capture and Storage.

Glossary

BECCS – Bioenergy with Carbon Capture and Storage
CCS – Carbon Capture and Storage
CDR – Carbon Dioxide Removal
CO_2 – Carbon dioxide
DAC – Direct Air Capture
EJ – Exajoule
GHG – Greenhouse Gas
GGR – Greenhouse Gas Removal
Gt – Gigatonne(s)
$GtCO_2$ – Gigatonnes of carbon dioxide
IPCC – Intergovernmental Panel on Climate Change
NET – Negative Emissions Technology
ppm – Parts per million
tCO_2 – Tonnes of carbon dioxide

Introduction

The concept that 'unburnable carbon' could cause carbon-intensive assets to become 'stranded' has emerged as a topic of significant interest to policymakers (Friedman 2014; Gurría 2013), financial institutions (HSBC 2015; BlackRock 2014; Standard & Poor's 2014), financial regulators (Bank of England 2015b; Bank of England 2015a; Carney 2015; Financial Stability Board 2015), and companies (Royal Dutch Shell plc 2014; Exxon Mobil Corporation 2014). Unburnable carbon are the fossil fuels that must be 'kept in the ground' to avoid breaching carbon budgets[1], in particular those implied by international targets (Pfeiffer et al. 2016; McGlade & Ekins 2015; Carbon Tracker Initiative 2011; Caldecott 2011; Krause et al. 1989).

'Stranded assets' are assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities (Caldecott et al. 2013). Though they are regular feature of economic systems and a phenomenon inherent in the 'creative destruction' of economic growth (see Schumpeter 1942), the concept has recently been appropriated to refer specifically to environment-related factors that can cause asset stranding, particularly unburnable carbon as a key driver of such stranding (Caldecott 2015).

Negative Emissions Technologies (NETs)[2] have the potential to remove carbon dioxide (CO_2) from the atmosphere and thus could extend carbon budgets and reduce the risk of carbon intensive assets becoming stranded assets. NETs are a family of technologies that encompass diverse options (see Table 1 below) and these have been subject to increased scrutiny as the majority of mitigation pathways that limit average warming to less than 2°C imply NETs deployment at multi-gigatonne scale from mid-century (Fuss et al. 2014; Anderson 2015; Gasser et al. 2015). Understanding the implications of reaching such scale and what this might mean for carbon-intensive sectors if some or all of this deployment materialises is critical for a range of actors.

[1] Carbon budgets represent estimates of the amount of CO_2 that may be released into the atmosphere before it becomes unlikely that the 2°C target can be avoided. Based on the IPCC (2013), current carbon budgets are 900, 1050 and 1,200 $GtCO_2$ under 66%, 50% and 33% probabilities, respectively. In 2010, gross annual greenhouse gas (GHG) emissions totalled ~50 $GtCO_2$-equivalent. Ocean and land sinks absorb just over 50% of the emissions resulting in net atmospheric emissions increasing by around 22 $GtCO_2$/year and therefore an average ~3 ppm increase of atmospheric CO_2 concentration per year, although the fraction absorbed by these sinks is falling (Le Quéré et al. 2009). The exact amount of ppm reduction will be dependent on the extent of outgassing that will take place from present sinks which store substantial amounts of carbon.

[2] Also referred to as Carbon Dioxide Removal (CDR) or Greenhouse Gas Removal (GGR).

Table 1: *Summary of six of the most widely discussed NETs*

NET	Description	Storage Medium	Estimated Abatement Cost
Afforestation & Other Forestry	Planting or replanting forests on cleared or abandoned land; managing forests to enhance uptake	Biomass and soil organic carbon	$<20-100/tCO$_2$[1]
Agricultural Land Management	Changing land management practices to increase organic carbon levels in soils	Soil organic carbon	Cost-negative to $100/tCO$_2$[2]
Biochar	Converting biomass through pyrolysis to a solid, stable 'char' product that can be added to soils	Stable char product in soils	$0-135/tCO$_2$[3,4]
Bioenergy with Carbon Capture and Storage (BECCS)	Capturing CO_2 released during any biomass combustion or other conversion processes and storing it as a supercritical fluid in geological reservoirs	Supercritical CO_2 in geological storage	$45-250/tCO$_2$[4,5]
Direct Air Capture (DAC)	Extracting a near-pure CO_2 stream directly from the air using sorbents and storing it as a supercritical fluid in geological reservoirs. Sorbents are then regenerated through heating or other treatment	Supercritical CO_2 in geological storage	$40-600/tCO$_2$[4,5]
Ocean Liming	Adding lime (calcium oxide) produced from high-temperature calcination of limestone to the oceans, thereby enhancing their uptake of CO_2	Dissolved carbonate / bicarbonate in oceans	$72-159/tCO$_2$[4,6]

Notes: [1]Canadell & Raupach (2008); [2]Smith et al. (2008); [3]Roberts et al. (2010); [4]N. McGlashan et al. (2012); [5]McLaren (2012); [6]Renforth et al. (2013)

As such, here we estimate the extent that NETs may be able to extend carbon budgets and over what time horizons. We also investigate the likelihood and possible implications of this for policymakers, investors, and firms. These questions are currently absent in the literature, which is surprising given that the availability of NETs is a key uncertainty for stranded assets created by unburnable carbon.

Material and methods

Many NETs are at an early stage and face substantial technical challenges before they are ready for deployment, let alone deployment at scale (Williamson 2016). The development of appropriate governance and policy frameworks is also a necessary prerequisite for these technologies, and these are at early stages of discussion (Royal Society 2009).

With the nascent state of the NETs evidence base in mind and the substantial uncertainties involved, this paper does not seek to make detailed projections. Instead, we set out the presently available evidence as to the technical limits of some of the most promising technologies, focusing on the key limiting factors and uncertainties, and estimate the level of effort that would be required to achieve this potential. Technologies presented here are limited to those that have been relatively well-explored in the scientific literature, and were selected based on early indications that they may be able to attain substantial (>1 $GtCO_2$/year) sequestration rates globally without demonstrably unmanageable environmental side effects. This allows us to characterise optimistic and conservative scenarios for the technical potential of NET deployment, relating the feasibility of each to the impact that they may have on global carbon budgets to 2050 and 2100. For our calculations, we use carbon budget figures from the Carbon Tracker Intiative (2013) as they provide budgets for both 2050 and 2100 as well as a cumulative budget.

The technologies considered are Afforestation and Reforestation, Agricultural Land Management for soil carbon, Biochar, Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), and Ocean Liming. Other proposed NETs, notably Ocean Fertilisation and Enhanced Silicate Weathering, are not considered, owing to particularly large scientific uncertainties over their feasibility, effectiveness, and environmental impacts at large scale (Hartmann et al. 2013; McLaren 2011; Williamson et al. 2012).

To see whether carbon budgets can be extended, we emulate the methodology used by the Carbon Tracker Initiative when it assessed the role of CCS deployment on carbon budgets. It calculated the 'extra space' that would be created in carbon budgets if the International Energy Agency's (2013) CCS technology roadmap was implemented and found that a total of 125 $GtCO_2$ could be optimistically sequestered by 2050; equivalent of 2.5 years of present gross annual emissions. We repeat this exercise for NETs, characterising possible NET deployment scenarios up to 2050 and 2100 based on the latest literature on technical potentials and limiting constraints on NET deployment. The unit of negative emissions used is a $GtCO_2$ removed and for

illustrative purposes key figures are also expressed in terms of the change in atmospheric CO_2 concentration in ppm[3].

Outlook to 2050[4]

The 2050 estimates for NETs technology deployment are summarised in Table 2 below. There appears to be significant negative emissions potential in the period to 2050, particularly through NETs that rely on natural biological systems. These may also have lower capital requirements and fewer technical barriers than other NETs.

Table 2: *Estimates of technical potential to sequester CO_2 in 2050*

NET	2050 Potential (per year)	Assumptions	Notes
Afforestation and Other Forestry	1-3 $GtCO_2$, 0.13-0.38 ppm	Conservative estimates of available land area and carbon yields	Higher estimates for afforestation may conflict with land used for food production or energy crops
Agricultural Soil Carbon	1.4-3.9 $GtCO_2$, 0.18-0.50 ppm	Suitable land areas and attainable annual sequestration rates	Fewer trade-offs with other land uses; saturation and risk of impermanence limit cumulative potential
Biochar	~2.2 $GtCO_2$, ~0.28 ppm	Pyrolysis of 60 EJ per year (3 Gt per year) bioenergy residues and wastes	May conflict with other demands for residues and wastes; assumes 80% stability over century timescales
BECCS	~1.5 $GtCO_2$, ~0.19 ppm	Constrained by CCS roll-out and integration with bioenergy, using IEA projections for 2050	Bioenergy supply is a less limiting constraint than CCS development to 2050.
Direct Air Capture	~0.25 $GtCO_2$, ~0.03 ppm	This figure assumes sequestration at a scale equivalent to the current US market for Enhanced Oil Recovery	High costs give it very little role pre-2050 in 'optimal' mitigation models
Ocean Liming	~0.25 $GtCO_2$, ~0.03 ppm	This figure assumes all existing lime wastes from cement production are used for carbon capture	No detailed projections / models available, but similar challenges to DAC

For sequestration through managing natural carbon sinks (new forests and agricultural soils), the chief constraints on the technical potential are the rate that carbon can be consistently sequestered per unit area per year, and the area of land over which they can be deployed. Such biological carbon storage is available today and already widely practised, yet is arguably less permanent than other forms of storage, and vulnerable to re-emission through future land use or climate change. The

[3] A 1 ppm change is equivalent to 7.81 $GtCO_2$ removed from the atmosphere. However, carbon cycle feedbacks between the atmosphere and other carbon reservoirs, especially equilibration with the ocean inorganic carbon pool, mean that sequestration of 7.81 $GtCO_2$ is likely to lead to a true reduction of somewhat less than 1 ppm, depending on the method used (Vichi et al. 2013).

[4] Further details, including assumptions, can be found in the supplementary materials.

potentials in Table 2 are therefore conservative 2050 estimates based on the latest IPCC analyses of land use to mitigate climate change (Nabuurs et al. 2007; Smith et al. 2007; P. Smith et al. 2014).

Biochar and Bioenergy with Carbon Capture and Storage (BECCS) are similarly limited by the rate of photosynthesis, here via the amount of biomass feedstock available. We take conservative estimates of these values to arrive at 2050 figures for each. BECCS in 2050 is further limited by the slow anticipated development of physical generation and CCS infrastructure (International Energy Agency 2013), so the likely 2050 total remains low.

Direct Air Capture and Ocean Liming are not limited by land area or by the availability of any feedstock, but nonetheless are substantially limited by technology maturity, capital requirements, energy use, and infrastructure (McLaren 2012). While there are no detailed analyses of the roll-out of these technologies, they both depend on CCS infrastructure to scale beyond niche uses. Absent ground-breaking advances in these technologies, it is unlikely either will reach more than a fraction of anticipated total CCS capacity in 2050.

We find that between now and 2050, there may be the technical potential to attain negative emissions of the order of 120 $GtCO_2$ cumulatively (~15 ppm reduction), with the vast majority of this potential coming from afforestation, soil carbon improvements, and some biochar deployed in the near term[5].

This potential represents an extension of the 2050 carbon budget by 11-13% for a 50-80% probability of meeting a 2-degree warming target. More industrial technologies (DAC, Ocean Liming, and BECCS) that rely on CCS are likely to have very limited potential by 2050, largely due to limits imposed by CCS development and more significant technical and policy challenges. Their contribution here to the pre-2050 potential is only around 20 $GtCO_2$ (2.5 ppm), or an extension of only ~2% of the 2050 carbon budget.

Outlook to 2100[6]

Cumulative negative emissions potential between now and 2100 is very poorly understood. The long-term performance, costs, feasibility, and impacts of large-scale deployment of the technologies that provide the bulk of post-2050 potential – BECCS, DAC, and Ocean Liming – are highly uncertain, and the wider social, political,

[5] The lower bounds of ranges given in Table 2 account for saturation of biological sinks and potential impermanence of carbon stored in forests, soils and biochar.
[6] Further details, including assumptions, can be found in the supplementary materials.

environmental, and economic context in which they would be deployed are also well beyond our ability to predict accurately. Rather than attempting to do so, we outline two scenarios, low and high, in order to estimate a range of different deployment potentials.

For afforestation and soil carbon sequestration, our high and low scenarios explore the possibility of 'saturation': whether net carbon flows into ecosystems can be maintained throughout the century or reach an equilibrium post-2050 (P. Smith et al. 2014).

Assuming fewer constraints on CCS in 2100, the potential of BECCS is much higher, determined instead by humanity's ability to source sustainable bioenergy feedstocks and the lifecycle efficiency of the production and conversion process. Note that we assume feedstocks dedicated to biochar remain constant, with additional biomass used for BECCS; since BECCS sequesters a higher fraction of the carbon in a tonne of biomass, this assumption maximises the potential negative emissions flow.

The greatest, and most uncertain, increase could come from the most 'technological' options of DAC and Ocean Liming. There are no obvious physical limits to annual removal by these methods, besides the industrial infrastructure and energy use needed to do so. The low estimate therefore imagines infrastructures equivalent to the comparable existing industries of upstream oil and cement production, respectively. High scenarios imagine flows of CO_2 several times this scale, which would make carbon removal among the largest industries on Earth. The low scenario would require energy inputs on the order of 5-10% of today's global energy consumption, according to published estimates.

In principle, sequestration of over 1,000 $GtCO_2$ cumulatively might be possible in the second half of the century, but reaching this depends on extreme rates of NET deployment after 2050. The high and low estimates for 2100 negative emissions technical potential through each route are summarised in Table 3.

Table 3: *High and low scenarios of technical potential to sequester CO_2 in 2100*

NET	2100 TP – Low (per year)	Low Scenario Assumptions	2100 TP – High (per year)	High Scenario Assumptions
Afforestation & Other Forestry	0 $GtCO_2$, (0 ppm)	Saturation of new forests; additional land used for bioenergy	1-3 $GtCO_2$, 0.13-0.38 ppm	Sustained forest expansion
Agricultural Soil Carbon	0 $GtCO_2$, 0 ppm	Saturation of soil sinks	1.3-3.9 $GtCO_2$, 0.17-0.50 ppm	Sustained increases in soil carbon e.g. through wider restoration
Biochar	2.2 $GtCO_2$, 0.28 ppm	As 2050; extra biomass goes to bioenergy / BECCS	2.2 $GtCO_2$, 0.28 ppm	As 2050

BECCS	5 $GtCO_2$, 0.64 ppm	60 EJ per year to BECCS at 80% efficiency	>16 $GtCO_2$, >2.0 ppm	>200 EJ per year to BECCS at 80% efficiency
Direct Air Capture	3.7 $GtCO_2$, 0.47 ppm	An oil industry-sized DAC system	>10 $GtCO_2$, >1.3 ppm	No obvious fundamental limit; 10 $GtCO_2$ per year represents ~2.5x oil industry
Ocean Liming	2.75 $GtCO_2$, 0.35 ppm	A cement industry-sized Ocean Liming system	>10 $GtCO_2$, >1.3 ppm	No obvious fundamental limit; 10 $GtCO_2$ per year represents ~3.5x cement industry
TOTAL	13.7 $GtCO_2$, 1.75 ppm		>40 $GtCO_2$ >5 ppm	

Cumulative Negative Emissions Potential and Limits

Based on the assumptions in Tables 2 and 3, the potential magnitude and timing of cumulative negative emissions available through this century using different methods are estimated. For the period 2050-2100, where uncertainty is highest and the technical potentials are least well-constrained, we develop a low-deployment and a high-deployment case for each technology. Table 4 reviews the assumed deployment patterns used for each scenario, also shown graphically in Figures 1 and 2.

Table 4: *Assumed patterns of scale-up over time used for cumulative totals*

NET	Deployment pre-2050	Post-2050 – Low Potential	Post-2050 – High Potential
Afforestation & Other Forestry	Linear scale-up to 2 $GtCO_2$ per year 2020-2050	Linear fall to zero 2050-2100	Constant flow of 2 $GtCO_2$ per year to 2100
Agricultural Soil Carbon	Linear scale-up to 2.6 $GtCO_2$ per year 2020-2050	Linear fall to zero 2050-2100	Constant flow of 2.5 $GtCO_2$ per year to 2100
Biochar	Linear scale up to 2.2 $GtCO_2$ per year 2020-2050	Constant flow of 2.2 $GtCO_2$ per year to 2100	Constant flow of 2.2 $GtCO_2$ per year to 2100
BECCS	Linear scale up to 1.5 $GtCO_2$ per year 2030-2050	Linear scale-up to 5 $GtCO_2$ per year in 2100	Linear scale-up to 16 $GtCO_2$ per year in 2100
Direct Air Capture	Linear scale up to 0.5 $GtCO_2$ per year from 2040	Linear scale-up to 3.7 $GtCO_2$ per year in 2100	Linear scale-up to >10 $GtCO_2$ per year in 2100
Ocean Liming	Linear scale up to 0.5 $GtCO_2$ per year from 2040	Linear scale-up to 2.75 $GtCO_2$ per year in 2100	Linear scale-up to >10 $GtCO_2$ in 2100

Figure 1: Assumed pattern of NET deployment over the century – Low Scenario

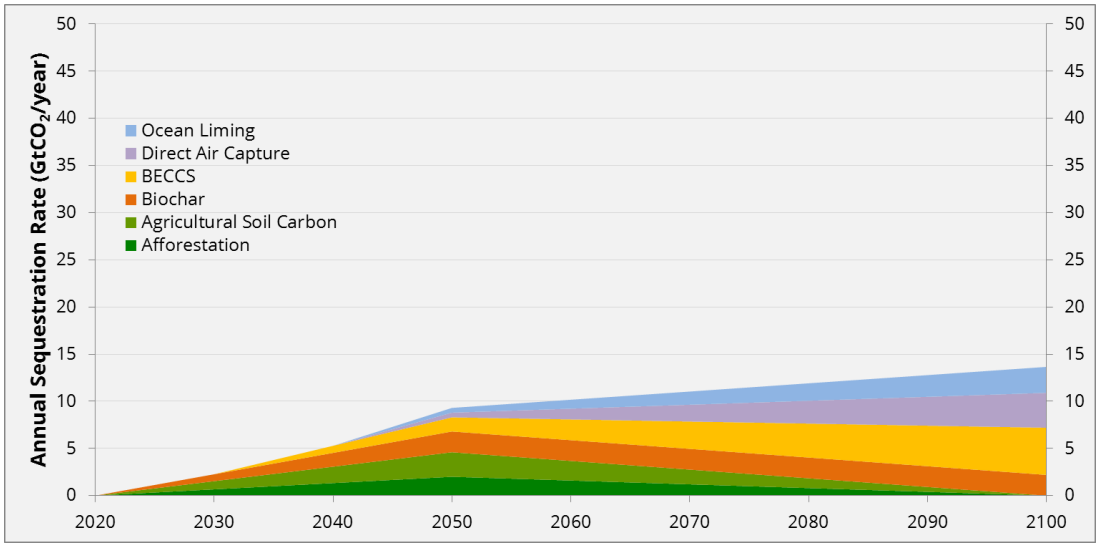


Figure 2: Assumed pattern of NET deployment over the century – High Scenario

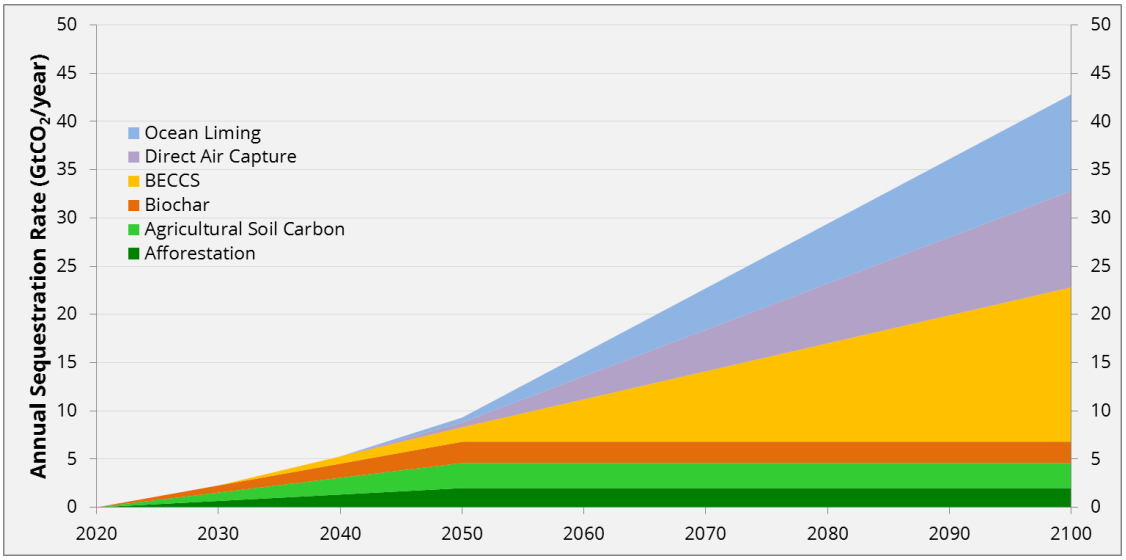


Table 5 and Figure 3 summarise the cumulative figures reached through this assessment. In both the table and figure, post-2050 cumulative figures include pre-2050 potential.

***Table 5:** Summary of order of magnitude of cumulative potential sequestration for different technologies and scenarios for 2020-2050 and 2020-2100.*

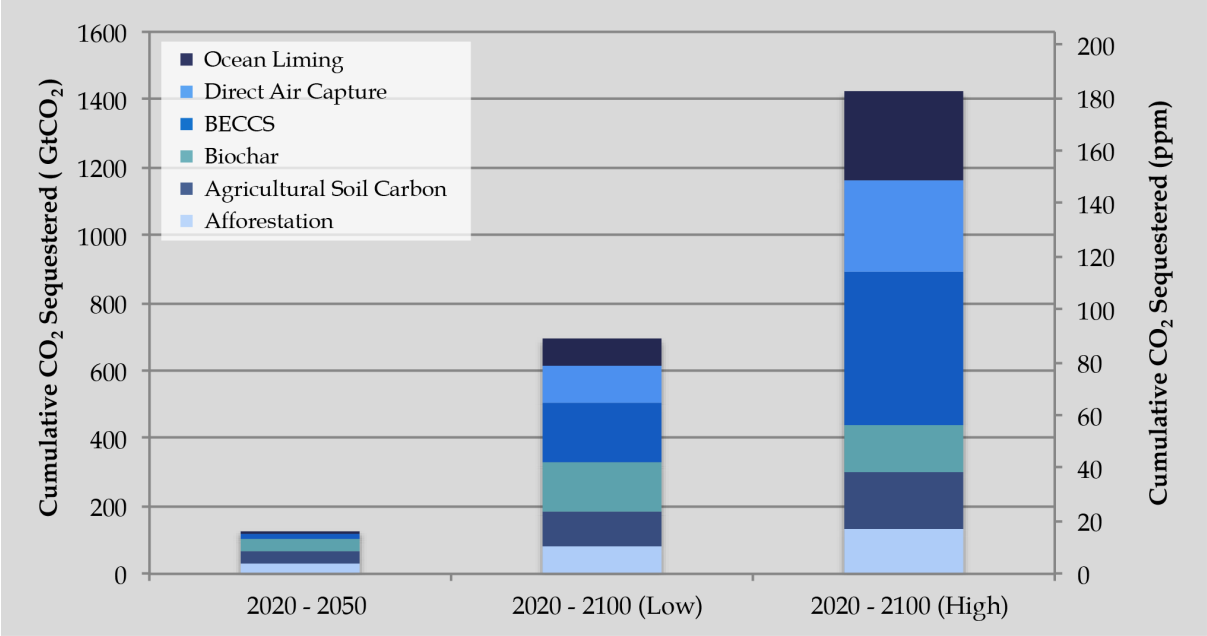
NET	2020-2050 Potential	2020-2100 – Low Potential	2020-2100 – High Potential
Afforestation & Other Forestry	30 $GtCO_2$	80 $GtCO_2$	100 $GtCO_2$
Agricultural Soil Carbon	39 $GtCO_2$	104 $GtCO_2$	130 $GtCO_2$
Biochar	33 $GtCO_2$	143 $GtCO_2$	143 $GtCO_2$
BECCS	15 $GtCO_2$	178 $GtCO_2$	453 $GtCO_2$
Direct Air Capture	2.5 $GtCO_2$	108 $GtCO_2$	>260$GtCO_2$

Ocean Liming	2.5 $GtCO_2$	84 $GtCO_2$	>260$GtCO_2$
TOTAL ($GtCO_2$)	~120 $GtCO_2$	~700 $GtCO_2$	>~1,300 $GtCO_2$
TOTAL (ppm)	~15 ppm	~90 ppm	>~165 ppm

Several conclusions are apparent from Figures 1-3. First, the bulk of cumulative sequestration potential for all NETs under our assumptions occurs in the period after 2050, owing to the timescales of scale-up, delays before deployment of some techniques, and simply the longer time period over which techniques could act. This long-term potential is also dominated by those technologies that are the least developed (BECCS, DAC and Ocean Liming). Both of these elements mean the majority of the ultimate potential is subject to the largest uncertainties.

Second, the role of afforestation, soil carbon methods, and biochar could nevertheless be cumulatively very significant. As more readily deployable technologies, they will likely dominate the total 2050 potential. But if they can be scaled up in the near term, this 'head start' may also give them a larger share of cumulative 2100 potential relative to those with fewer technical constraints (BECCS, DAC and Ocean Liming) than the figures for annual potential would suggest: they form around 50% of total potential for the low scenario and 33% of the high scenario.

Figure 3: *Illustrative cumulative sequestration potential of different NETs to 2050 and 2100.*



Finally, we reviewed limits on cumulative storage capacity of the key carbon reservoirs to determine the extent to which such capacity might constrain the cumulative negative emissions potential. Table 6 summarises various estimates of cumulative sink capacity, and is broadly adapted from Lenton (2010).

Table 6: *Estimated limits on cumulative storage capacity of the key carbon sinks used by NETs*

Form of Carbon	Location	Storage Capacity $GtCO_2$	Assumptions	Implications for Negative Emissions Potential Scenarios
Biomass	Permanent new forests	550[1]	Historic deforestation losses	Lower estimates including economic/social constraints on land availability could constrain total potential
		60-540[2]	2100 range reported by Lenton	
Soil Organic Matter	Agricultural, grassland and peatland soils	160-330[3]	Historic soil carbon losses; assume 67-100% can be restored	Pessimistic estimate may constrain total potential
Biochar in Soils	Cropland only	820[2]	1.6 Gha, 140 tC/ha	No constraint this century
Pressurised CO_2	Oil and gas fields	675-900[4]	Based on IPCC estimates	If only the better characterised storage in abandoned oil and gas fields is considered, this may constrain total potential; there is no constraint if deep saline formation capacity is available
	Unmineable coal seams	15-200[4]		
	Deep saline formations	1,000-10,000[4]		
	All storage	400-2,000[5]	'Cautious' assessment (See S.I.)	Lower estimates could severely constrain total potential for DAC, BECCS and perhaps Ocean Liming
Dissolved carbonate & bicarbonate	Oceans	1,400[6]	1% increase in ocean carbon pool	No constraint this century, but will require further research on environmental impacts and appropriate international agreements

Notes: [1]Canadell & Raupach (2008); [2]Lenton (2010); [3]Lal (2004); [4]IPCC (2005); [5]McLaren (2012); [6]IPCC (2013)

The cumulative technical potential of all NETs considered between now and 2100, in scenarios of maximum deployment, may be of the order of ~700-1350 $GtCO_2$, or 90-170 ppm. This represents an extension of the global carbon budget of 70-140% or more (for an 80% chance to remain below 2°C) or 45-90% or more (for a 50% chance). Reaching even the lower bound of this range, however, would already require deployment of negative emissions and CO_2 storage infrastructure on an improbably massive global scale.

It is worth highlighting from Table 6, that the availability and accessibility of geological storage for CO_2 is a key uncertainty. If ultimately realisable storage is towards the low end of current estimates due to physical, technological, or political factors, this could severely constrain the total negative emissions attainable through BECCS, DAC, and in some cases Ocean Liming in the 2050-2100 period. This is especially true if capacity is also used for capture and storage of fossil emissions, including those combusted to fuel DAC or Ocean Liming plants.

Discussion of implications for carbon-intensive assets

We have estimated how NETs could extend carbon budgets and provide more time to reduce emissions, thereby potentially altering the risk profile of carbon-intensive assets that could become stranded. Given the significant uncertainties and deployment challenges we have examined, it would be foolhardy for an owner or operator of carbon-intensive assets to assume that NETs will fundamentally alter the carbon budgets that they may face due to climate policy and regulation. This is particularly the case for point source emissions from power stations and alike, as there are already a number of viable options to deal with these emissions. It would be hard to argue that resorting to uncertain NETs prior to undertaking a variety of mitigation options would be an economically or socially desirable course of action. Considering the technological, socio-political, and economic barriers facing the more scalable NETs, it is extremely unlikely that a situation will be able to develop whereby a fossil fuel intensive sector could operate alongside a large-scale negative emissions sector.

Sectors with non-point source emissions where technical and economic barriers to mitigation are particularly acute would have the most to gain from NETs deployment – aviation and agriculture being two prominent examples. Biological processes in agriculture mean that a certain amount of emissions of carbon dioxide and other greenhouse gases are unavoidable (P. Smith et al. 2014; Snyder et al. 2009). In aviation, emissions can only be reduced so far given the current dependency on the jet engine and associated high-energy density liquid fuels (Caldecott & Tooze 2009).

In the absence of technical solutions, it could make sense for policymakers concerned with emissions from these activities to develop NETs in order to cover the 'residual' emissions generated after feasible mitigation actions are taken. A large share of negative emissions potential might also be 'no regrets' if the NETs developed were afforestation, soil carbon improvements, and biochar, which may have co-benefits (such as enhanced soil fertility), but do not depend on CCS and have fewer downside risks. They also have lower upfront capital costs and fewer uncertainties than other NETs. Matching the development of these no regrets NETs with the scale of residual emissions from stubborn non-point source emitters like agriculture and aviation, if feasible, would create a target deployment rate that could be supported by governments and industry alike. More work would need to be done to design and test the feasibility of such deployment pathways.

Businesses operating in these sectors have an obvious interest in ensuring that NETs, particularly of the no regrets variety, are developed quickly and at the lowest possible cost. Forestry, soil carbon improvements, and biochar appear to have the lowest costs and the most potential between now and 2050, and would make a logical area for

policymakers and the private sector to focus attention and resources on. CCS technology is key for post-2050 NETs potential and ensuring that this is available for DAC, Ocean Liming, and BECCS after 2050 is critical if globally significant deployment potential for these technologies is to be available. This should be another priority area for public-private collaboration.

Extending carbon budgets through NETs may buy time for owners and operators of assets at risk to exit their investments or put in place ways to manage their risk exposure. This paper has estimated that the technical potential for NETs by 2050 is in the order of 120 $GtCO_2$ cumulatively, which is approximately 2.5 years of current global greenhouse gas emissions. While this may buy some time, there are several important caveats:

- carbon budgets and the policies applied to implement them are not in sync, so a larger carbon budget is unlikely to perfectly translate into commensurately 'softer' policies and regulations;
- technical potentials are often much higher than ultimately realised potentials (an issue emphasised throughout this paper); and
- policymakers might not 'bank' a projected and uncertain carbon budget extension in the near term, but decide to wait until NETs deployment is successful. Due to the effects of discounting, this would then have little impact on firm or investor decision-making today.

The geographical and sectoral distribution of costs and benefits associated with NETs are highly uncertain. The spatial distribution of NETs development, production, deployment depends on the nature of the technology in question and will vary considerably between them. The benefits of successful deployment accrue to everyone and so there are significant free-rider issues. To what extent NETs might affect competition between coal, gas, and oil and influence the distribution of carbon budgets between fossil fuel basins is uncertain, but could be factored into existing scenario analysis (McGlade & Ekins 2015). This would help us to understand the potential winners and losers from large-scale NET deployment – for example, would oil benefit the most, due to its role in producing transport-related non-point source emissions? These and related questions would be productive areas for further research.

But the fact remains, that even if NETs were deployed successfully at sufficient scale to increase carbon budgets for sectors like agriculture and aviation, this would not protect 'business as usual'. The extent to which sectors might benefit from NETs deployment depends on the cost of NETs and who bears these costs – variables subject to significant uncertainty. If the sectors that benefit pay a proportion of development and deployment costs, as may reasonably be expected through the 'polluter pays'

principle, business models would still be affected. So even sectors that might be 'bullish' or optimistic about NETs and their implications for future business would be wise to temper this optimism. With or without NETs, should carbon budgets be translated into policy constraints it will impact their activities and in ways that are difficult to predict.

Conclusion

While we find that between now and 2050, there may be the technical potential to attain negative emissions representing an extension of the 2050 carbon budget by 11-13% for a 50-80% probability of meeting a 2-degree warming target, successful NETs deployment would not mean business as usual for carbon-intensive assets. Sectors (and consumers) will have to pay directly or indirectly for the cost of mitigation actions, and quite probably the cost of negative emissions deployment to address overshoot and stubborn emissions from non-point sources.

NETs deployment therefore addresses risk on the one hand (by potentially extending carbon budgets), and creates it on the other (through new and uncertain costs). NETs should not be seen as a *deus ex machina* that will save the day. Consequently, businesses and investors need to factor the risk of stranded assets created by unburnable carbon into their business planning and strategic asset allocation processes. Scenario planning and regular assessments of how carbon budgets are being translated into policy and regulation are likely to be important.

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Supplementary Information

Outlook to 2050

Technology assumptions

Afforestation and **Agricultural Soil Carbon** enhancement are both negative emissions 'technologies' with relatively low capital requirements and costs, sometimes paying for themselves in co-benefits and improved productivity (Canadell & Raupach 2008; Smith et al. 2008; Scopel et al. 2012), and are both already practised widely for various reasons. The key factors limiting their technical potential by 2050 are the area of land that will be available for these methods and the per-hectare rate of carbon sequestration they can attain.

Agricultural techniques improving soil organic carbon levels typically achieve lower average per-hectare rates of sequestration than afforestation, since they do not achieve the permanent build-up of large above ground stocks of carbon that forest biomass achieves. However, they have the advantage that they do not remove land from food or energy production, and often improve yields and soil health (Victoria et al. 2012; Lal 2004; Branca et al. 2013). A comprehensive review of agricultural methods for the IPCC identified global biophysical potential (i.e. with no economic or social constraints) of 1.4-3.9 $GtCO_2$ per year net carbon sequestration through agriculture and soil restoration by 2030 (Smith et al. 2008).

Afforestation and reforestation can sequester carbon relatively rapidly at approximately 1-5 tonnes (3.7-18.3 tCO_2) per hectare per year (Bonner et al. 2013; Lenton 2010; Richards & Stokes 2004). The key uncertainty in estimates is the area of land that will be available and suitable for afforestation, since this depends on future trends in agriculture and food demand, as well as land area dedicated to non-forest energy crops. The IPCC 4AR gave a range of 1.3-4.2 $GtCO_2$ per year mitigation potential through all forestry by 2030 at <\$100/tCO_2, although around half of this represents avoided emissions (associated with reduced deforestation and forest degradation) rather than true negative emissions (Nabuurs et al. 2007).

The review of estimates by Lenton (2010) reports a similar range of 2050 technical potential of 0.75-5.5 $GtCO_2$ per year through afforestation alone depending on the area of degraded, marginal, and abandoned land expected to become available. Global availability of land for afforestation is very difficult to predict, and depends on many uncertain quantities including global population, diet, trends in the efficiency and intensity of the food system, and the strength of ecological restrictions preventing conversion of natural ecosystems, as well as competition for land due to rising

demand for bioenergy (Pete Smith et al. 2014; Powell & Lenton 2012; Lenton 2010). While the upper ends of given ranges may well be plausible for more optimistic scenarios, they are less robust to assumed trends in these key variables, and also assume that none of this land is required for energy crops. Here, therefore, we take a conservative estimate in this range of 1-3 $GtCO_2$ per year of negative emissions in 2030. Since the available land area is the key limiting factor, we assume that these potentials remain constant to 2050, with any further 'spare' land that does become available being used for bioenergy, discussed further below, rather than further afforestation.

Biochar and **Bioenergy with Carbon Capture and Storage** (BECCS) also rely on photosynthesis as the initial capture CO_2, but aim to convert the resulting biomass to a more stable, secure form of storage (solid char or CO_2 stored in geological reservoirs), extracting useful energy, and other co-benefits at the same time (McGlashan et al. 2012). Like afforestation and agricultural soil methods, these approaches will also be constrained by land area and biological productivity, this time through the availability and mobilisation of sustainable biomass. In storage terms, BECCS is also ultimately constrained by the availability of geological storage sites and the extent to which those sites are successfully developed; biochar is ultimately constrained by the area of land where it can be applied and the maximum safe biochar holding capacity of soils (Lenton 2010).

There have been many attempts to estimate the amount of biomass that can be sustainably mobilised for bioenergy, and estimates range over orders of magnitude from near-zero to well above current world energy supply (Slade et al. 2014). The resource is typically divided into wastes and agricultural or forestry residues for bioenergy, which can be realised simply through better use of existing biomass flows, and energy crops such as willow or energy grasses, which require land to be dedicated to bioenergy.

Most estimates for residue and waste potential are between 20 and 100 EJ (exajoules) per year by 2050, with 50-60 EJ per year an average figure (Slade et al. 2011; Slade et al. 2014). Assuming an average energy density of dry biomass of about 18 GJ/tonne, this corresponds to around 3 Gt biomass per year, or 1.5 Gt carbon (Lenton 2010; Slade et al. 2014). Energy crop estimates are much more variable, since they are sensitive to both energy crop yield and land available, and the latter itself depends on highly uncertain global population, diet, food crop yields, and food system efficiency (Slade et al. 2014; Powell & Lenton 2012). In the worst case, almost no energy crops are possible in 2050 without impacting global food security or converting natural ecosystems, but other studies identify areas of more marginal land of 100-400 million hectares that conservatively could yield energy crops on the order of a further 60-120 EJ per year, ~3-6 Gt biomass per year.

The same biomass resource clearly cannot be used for biochar and BECCS. Following Lenton (2010) and Powell & Lenton (2012), we assume that residues and wastes (~60 EJ optimistically) are more suited to conversion to biochar via pyrolysis, and energy crops are fed into efficient BECCS systems that attain higher rates of negative emissions per tonne of biomass. However, there is no reason in principle why energy crops could not be used for biochar to reach larger scales, and the actual realised deployment of each will depend on relative technological and market development, and their relevance to different specific contexts. Scenarios for both biochar and BECCS are upper bounds, as in reality any biomass resources that are developed will likely be in demand for a wide range of different end uses.

Biochar can be produced from a range of feedstocks through pyrolysis, the thermal decomposition of biomass when heated to several hundred degrees in the absence of oxygen (Sohi et al. 2009). One form of the process, slow pyrolysis, can convert on the order of 50% of the carbon in biomass into stable carbon-dense char, with the remainder converted to various gases and bio-oils that can be used for energy (Roberts et al. 2010; Sohi et al. 2009). Since biomass is roughly 50% carbon by mass, a biomass resource of 60 EJ per year (3 Gt biomass per year) would yield a negative emissions potential from biochar in 2050 of approximately 0.75 GtC per year, or 2.75 $GtCO_2$ per year. However, there is some uncertainty around the long-term stability of char in soil under different conditions, with some risk of partial decomposition over century timescales (Lehmann et al. 2009). We therefore follow Roberts et al. (2010) in conservatively assuming only 80% of the carbon (2.2 $GtCO_2$/yr) can be considered long-term sequestration.

CO_2 capture processes proposed for BECCS may capture 90% or more of the CO_2 released through biomass combustion (Koornneef et al. 2012; MacDowell et al. 2010). The net life-cycle removal, however, depends on emissions associated with supply, processing and transport of biomass, and on any emissions associated with direct or indirect land use change, which is highly dependent on the particular feedstock, supply chain, and wider factors such as policy safeguards (IEA Bioenergy 2011; Koornneef et al. 2012). Estimates of production emissions range from around 2-30% of total carbon present in the biomass (Koornneef et al. 2012). Land use change emissions are harder to constrain, but risks can be reduced by sustainability standards and an emphasis on residues, forestry, and energy crops rather than food crop feedstocks (IEA Bioenergy 2011). Most estimates for the technical potential of biomass supply from energy crops account for sustainability constraints and exclude land currently used for food production. However, higher estimates of eventual potential (>100 EJ per year) are more likely to entail higher risks of conflict with agriculture, forests, and

other ecosystems, and thus significantly higher risks of land use change emissions (Slade et al. 2014).

Studies have assumed different figures for the net storage 'efficiency' of BECCS, the percentage of total biomass carbon removed from the atmosphere on a life-cycle basis, ranging from 50-90% (Smith & Torn 2013; Lenton 2010; Koornneef et al. 2012). We cautiously assume an average figure of 70%, with the caveat that this figure is likely to decrease for increasing scales of biomass supply. Converting 60-120 EJ of energy crop resource using BECCS would therefore yield negative emissions on the order of 1.1-2.3 GtC per year or 4.2-8.4 $GtCO_2$ per year. More detailed modelling by Koornneef et al. (Koornneef et al. 2012), conservatively assuming that 61 EJ residues and wastes and 65 EJ energy crops can all be used for BECCS, reach a comparable upper estimate of 10.4 $GtCO_2$ per year by 2050, leaving approximately half that from energy crops alone.

However, rollout of the CCS element, and integration of CCS with biomass conversion technologies, appear likely to constrain BECCS more strongly in 2050 than biomass availability. The latest IEA CCS Roadmap (IEA 2011) anticipates a total of about 7.8 $GtCO_2$ per year to be stored in 2050, of which only around 1.5 $GtCO_2$ per year is associated with bioenergy. The larger potential negative emissions flows implied by anticipated biomass supply are therefore unlikely to be realised until the second half of the century.

The final NETs considered here, **Direct Air Capture** (DAC) and **Ocean Liming** (OL) rely on chemical processes to draw down CO_2 from the air. They are thus not limited in the same way by available land area or biological productivity, but instead by capital requirements, industrial plant and infrastructure rollout, and energy use (McLaren 2012; Keith et al. 2005; McGlashan et al. 2012).

Direct Air Capture refers to any system that uses chemical sorbents to extract CO_2 directly from the atmosphere, and then releases it as a concentrated stream through the regeneration of this sorbent. Leading designs aim to use strong alkaline solutions or amine-based resins as the key sorbent (Goeppert et al. 2012). Like Bioenergy with CCS, DAC produces a stream of concentrated CO_2 gas or liquid rather than a stable form of carbon such as biomass, carbon, or dissolved carbonate. It is therefore also entirely dependent on successful development of downstream technologies for geological or mineral CO_2 storage, and like BECCS it may be ultimately limited by geological storage space.

Ocean Liming refers to the process of adding benign soluble alkalis, typically calcium oxide (lime) or hydroxide, to the oceans. This addition alters ocean carbonate

chemistry, converting dissolved CO_2 to bicarbonate and carbonate ions and driving increased uptake of CO_2 into the oceans (Kheshgi 1995; Renforth et al. 2013). The principle method for producing the calcium oxide required is calcination, or thermal decomposition, of limestone, a process widely practised in industry to produce lime for cement production, among other uses (Renforth et al. 2013).

In principle, since the main effect is increased uptake of CO_2 in the oceans, Ocean Liming can achieve negative emissions without downstream CO_2 storage. However, calcination of limestone itself releases CO_2, and the high-temperature heat required for this process today is derived from fossil fuel combustion, also a CO_2 source. In this context, Ocean Liming can only yield good life cycle sequestration with current technologies if most of this CO_2 is captured and put into geological storage (Renforth et al. 2013). The situation may be improved in future through the use of solar calcination kilns (reducing emissions associated with fossil fuels) and through new processes that use silicates, rather than limestone, as a feedstock (reducing emissions from the calcination itself), both of which would reduce its reliance on CO_2 storage (Renforth & Kruger 2013).

Both DAC and OL are therefore constrained by similar factors in the near term. Both have relatively high capital costs and expected total abatement costs, both require working CO_2 transport and storage infrastructure, and both are at a relatively early stage of demonstration as NETs relative to point source CCS.

Given these considerations, it is unlikely that either approach will reach more than a small fraction of the total CCS capacity projected by the IEA CCS Roadmap in 2050. Optimistically, we estimate that DAC and OL could sequester on the order of 500 $MtCO_2$ per year between them in 2050, 5-10% of total CCS capacity in the IEA's 2°C scenario (IEA 2011). This is equivalent to the total if DAC were deployed on the scale of existing Enhanced Oil Recovery markets, and if existing lime waste flows from cement production were used for Ocean Liming (Renforth et al. 2011; Renforth et al. 2009). For comparison, one integrated assessment modelling study that incorporates Direct Air Capture projects significant deployment only from 2065 (Chen & Tavoni 2013).

Outlook to 2100

Technology assumptions

The large uncertainties present in assessing 2050 technical potentials become far larger when considering the deployment of these technologies, many of which do not yet even exist at commercial scale, in the second half of this century. This is particularly

true for DAC and OL, which are the least technically developed systems and, unlike biological approaches, are not fundamentally constrained by biological productivity and land area. This section therefore develops an illustrative high and low 2100 scenario for each NET, using generous and conservative assumptions respectively. For DAC and OL, there is no clear physical quantity providing an absolute limit on the annual sequestration. For these technologies, we therefore try to give some sense of the level of global effort and infrastructure required to attain a given level of negative emissions by relating it to the scale of comparable existing industries.

Forestry and **Agricultural Soil Carbon** enhancement have high near-term potential, but their long-term cumulative value may be limited by both saturation of the carbon sinks and the risk of re-emission of stored carbon (Lenton 2010; Smith et al. 2008).

'Saturation' refers to the fall in net sequestration rate over time in forests or other ecosystems as they reach an equilibrium between net growth and net decay of organic matter over several decades (Pete Smith et al. 2014). Maintaining a continuous global negative emissions flow through forestry or agriculture would require continuing expansion of forested or managed agricultural area, or periodic removal of mature trees to prevent saturation. Such harvested biomass would need to be converted to stably-stored carbon elsewhere (e.g. through biochar or BECCS) to provide true negative emissions.

A second limitation is the vulnerability of carbon stocks sequestered in biomass and soils (Canadell & Raupach 2008; Powlson et al. 2011). The carbon pool is in constant exchange with the atmosphere and so is vulnerable to re-release if conditions change. Climate change, natural disturbances such as wildfires, or future changes in land management may all lead to release, potentially reducing the security of stored carbon and the future sink capacity.

For the purposes of negative emissions potentials, we therefore consider a saturation scenario, in which flows decrease linearly to zero 30-50 years after they begin, and a continued sequestration scenario, where estimated 2050 flows are maintained at constant levels until 2100 by sustained expansion of forestry and soil carbon enhancement practices.

Biochar in principle entails lower risks of re-release than biomass and soil storage. Early results suggest a substantial fraction of the stored carbon can be stable in the soil on timescales of decades to centuries (Lehmann et al. 2009; Sohi et al. 2009). As discussed previously, there are still uncertainties over the long-term stability of biochar in different conditions (Lehmann et al. 2009), but our conservative estimate assumes only 80% stability over the long term. In both scenarios, we therefore assume

a constant stream of waste and residue feedstocks is converted to a constant flow of carbon sequestered in biochar (2.2 $GtCO_2$ per year). Since biochar produces a smaller negative emissions flow per unit of biomass than BECCS, any expansion of biochar at the expense of BECCS would reduce the total technical potential for sequestration.

Towards 2100, **Bioenergy with CCS** potential would be limited by the available biomass resource, (provided technology and CCS infrastructure were developed sufficiently). The total biomass supply available in 2100 is, of course, even more uncertain than that in 2050: estimates for energy crop and forestry biomass resource range from less than 60 EJ per year to more than 400 EJ per year (Slade et al. 2011; Slade et al. 2014), equivalent to a BECCS negative emissions potential of anything from less than 5 $GtCO_2$ per year to over 30 $GtCO_2$ per year, depending on future developments in food demand, energy, and food crop yields, the extent to which different areas of natural or semi-natural grasslands or forests are converted or taken under management and the extent to which we are prepared to accept negative side-effects of bioenergy supply. There are also likely to be conflicts between expanding bioenergy production substantially and other land-based NETs such as afforestation and reforestation that mean the high scenarios for both activities are likely overestimates of true potential.

Social and political factors will also affect whether a large-scale global biomass supply for energy use can be realised. Demand for biomass for other uses of bioenergy, and potentially other forms of BECCS with lower efficiency of capture, will reduce the potential further. The higher the estimates of 2100 BECCS potential, the more optimistic these assumptions must be.

Integrated assessment modelling that has implied a significant role for BECCS in changing the optimal emissions pathway, or allowing global net negative emissions in late century, has tended to settle on total bioenergy demand of 200-400 EJ per year (Azar et al. 2010; Kriegler et al. 2013; Edmonds et al. 2013; van Vuuren et al. 2013). The low and high deployment scenario chosen here represent 60 EJ per year and 200 EJ per year bioenergy supply used for power sector BECCS, respectively, representing approximately 5 $GtCO_2$ per year and 16 $GtCO_2$ per year negative emissions in 2100.

It is even more difficult to make any meaningful prediction of what scale either **Direct Air Capture** or **Ocean Liming** might achieve post-2050, since there is so little firm information on performance and cost of commercial-scale systems and they are not constrained by any single quantity such as land area. To complicate matters further, there are a range of different routes to apply the general concept, each with different resource requirements and scale up models. There may be no physical limits preventing tens of gigatonnes of negative emissions through these methods, while

'softer' financial, political, or social factors may make this unlikely – for example, McLaren (2014) has suggested that, considering the difficulty already evident in transforming and extending the global energy system, the significant energy requirements of DAC and OL systems at the required scale may constrain their expansion through competition for this limited resource. It is not, therefore, possible to define an ultimate 'technical potential' for either technology at this stage.

Here we attempt to give a sense of the plausible scale through comparisons to key global industries in existence today, and putting into context the resources needed to achieve a certain negative emissions flow by each method.

For the case of **Direct Air Capture**, the current oil extraction industry provides a natural scale benchmark for an industry that aims to sequester billions of tonnes of pressurised fluid in geological formations. Global oil production in 2011 was approximately 4.1 billion tonnes (IEA 2013). Equivalent Direct Air Capture and storage infrastructure might sequester a similar amount of CO_2. In reality, some proposed DAC approaches are likely to require high temperature heat produced from fossil fuel combustion, so the net sequestration would be reduced by the storage of emissions from this combustion (McLaren 2012). Assuming that this reduced efficiency of sequestration by an average of 10%, an oil extraction-sized DAC industry might therefore remove on the order of 3.7 $GtCO_2$ per year, or 1 GtC per year. Other storage systems such as mineral carbonation would be less directly comparable to oil production infrastructure, but the global industrial scale would be comparably vast.

Based on early assessments of DAC systems, such an industry might require around 5-7 EJ per year of electricity (Lackner 2009; Socolow et al. 2011; Baciocchi et al. 2006). If the more technically mature, but more energy-intensive, lime-soda process is used, the high temperature heat required may be 20-30 EJ per year (Socolow et al. 2011; Baciocchi et al. 2006). For context, global electricity supply in 2011 was around 80 EJ per year, and global natural gas production equated to ~117 EJ per year (IEA 2013).

A DAC industry on this scale would require a very significant global scale-up effort, but would not be unreasonably large relative to world energy use and the projected scale of CCS, so we take it as our conservative DAC deployment potential. It is not obvious what an 'upper limit' DAC scenario might look like. In principle, the technology could extract tens of gigatonnes of CO_2 per year, but reaching such a scale would entail an industry many times the scale of the oil industry today, and would require a substantial fraction of global electricity and perhaps fuel supply. The required capital investment and rollout rate of such an industry and accompanying energy infrastructure would need to be very high relative to historic precedents.

There is even less literature exploring the potential of large-scale **Ocean Liming** to remove large quantities of CO_2 from the atmosphere post-2050. We take a parallel approach to that described above, this time using the current global cement industry as a benchmark.

Global cement production is 3.4 Gt per year. Lime produced at this scale and distributed in the oceans would lead to approximately 0.75 GtC per year drawdown (2.75 $GtCO_2$ per year) (Renforth et al. 2013). Such an industry would require approximately 5 Gt limestone per year, and 8-14 EJ of high temperature heat, depending on the technology (7-12% of current natural gas supply). If fossil fuels were used to provide this heat, and CO_2 released captured, around 2 $GtCO_2$ per year would also need to be stored, although this could be reduced or eliminated significantly through different technologies such as solar-heated lime kilns or integrated silicate carbonation (Renforth & Kruger 2013; Renforth et al. 2013). Finally, shipping capacity would be required to disperse lime over the oceans. Renforth et al. (Renforth et al. 2013) suggest that up to 3.7 $GtCO_2$ (1 GtC) net removal per year might be accommodated with spare capacity on existing freight fleets, but larger industries may need a substantial dedicated fleet. Based on the authors' calculations, however, each further 3.7 $GtCO_2$ per year would require a fleet with total capacity of around 30 million tonnes, less than the average annual growth in bulk cargo shipping capacity in 2006-2010 (ISL 2012).

As with DAC, we take the cement-industry scale (2.75 $GtCO_2$ per year) as a conservative potential estimate, albeit one that would still require a very significant international deployment push. Rapid Chinese expansion of lime production reached 0.25 Gt per year capacity per year in 2000-2006, implying a potential scale-up time of the order of 15 years for such an industry (McGlashan et al. 2012). Again, industries several times this scale, removing more than 10 $GtCO_2$ per year, are in principle possible, but again would require extremely high rates of scale-up, development of dedicated shipping capacity and energy use making up a significant fraction of world supply.

Chapter 4

Title: Stranded electricity assets: implications of CCGT mothballing and closure for EU energy markets and policy

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Title: "Stranded electricity assets: Implications of CCGT mothballing and closure for EU energy markets and policy"

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Abstract

Many recently built, high-efficiency combined-cycle gas turbine (CCGT) power plants are being mothballed or prematurely closed across Europe. This paper assesses the scale of this phenomenon, examines impacts on firm value and strategy, and assesses responses by regulators in the UK and Germany. During 2012-13 ten major EU utilities announced decisions to mothball or close 20.08 GW of gas-fired capacity, 8.87 GW of which was built or acquired within the last ten years. Case analysis suggests that governments should implement competitive, market-based policies for capacity adequacy, and seek to limit discretionary subsidies that may introduce competitiveness asymmetries. Governance and policy gaps exist at national and regional levels regarding the appropriate treatment of stranded assets in the transition to energy decarbonisation.

Highlights

- Major EU utilities reported nearly €6bn in write-downs on gas power in 2012-13
- Mothballing actions announced in 2012-13 affect 20.08 GW of gas-fired capacity
- Stranded gas plants are affecting capacity mechanism implementation in European energy markets
- Managing stranded thermal electricity assets stands as important policy design challenge

Keywords

Stranded assets, gas-fired power, CCGT, capacity mechanisms, capacity markets, low-carbon energy

Main text word count: 7202

1. Introduction

An increasing number of recently built, high-efficiency combined-cycle gas turbine (CCGT) power plants are being mothballed or closed across Europe. Decreasing electricity demand, changing fuel costs, depressed carbon prices, and the increasing proliferation of low or zero marginal cost renewable generation have caused margins on gas-fired power stations to erode. New CCGTs are being rendered stranded assets[1] which pose negative cost burdens to utilities. In electricity markets with shrinking capacity margins, ageing electricity infrastructure and high renewables targets, the impacts of stranded assets may reduce investor confidence in baseload investments, and may lead to system security issues.

This paper examines this recent phenomenon of stranded gas-fired power plants in the European context and the implications which may arise for national energy security and climate policy objectives. At a European level, the market impacts of stranded thermal assets may affect the efficiency of an integrated EU energy market, investment decisions, and energy and climate policy alignment. These impacts call attention to the potential for stranded assets to act as barriers in the transition to energy decarbonisation. In this context, this paper aims to three empirical research contributions, including:

- An evaluation of the impacts of stranded assets on major firms, specifically by quantifying the level of current and proposed mothballing and closure of gas-fired power plants by ten major European utilities;

[1] We define stranded assets as those assets that have suffered from unanticipated or premature write-downs, devaluations or conversion to liabilities (see section 2.1.1).

- An examination of current issues for market design and regulation through comparative analysis of the implementation of capacity remuneration mechanisms in GB and German markets[2]; and
- A preliminary assessment of implications for trade, market integration, and climate and energy policy at the European level, and preliminary identification of issues for regulators to consider in delivering climate and energy policies that are aligned in their objectives.

In doing so, this paper aims to provide a theoretical contribution to the stranded assets literature by examining how stranded assets may occur in a climate change context, and what their impacts may be. Specifically, we comment on how the concept of a "stranded asset" may be changing vis-à-vis debate on systemic risks posed by high-carbon infrastructure investment.

This paper is organised in the following manner. Section two discusses the theoretical basis for our research, the analytical framework, and the methods employ. Section three presents the findings of our research, while section four discusses their implications. Section five provides conclusions and identifies areas for further research.

2. Methods

This section explains our analytical framework and research design by drawing on bodies of literature pertaining to stranded assets the power sector, economic theory relating to power market design, and policies to incentivise capacity investment. We then discuss the data sources and methodology employed.

[2] The rationale for this choice of markets is discussed in section 2.3.

2.1 Theoretical perspectives and relevant concepts

Baseload power plants become uneconomic to operate when their marginal cost of generation exceeds the market price for electricity over an extended period of time. Negative clean spark spreads[3] may mean that the plant is a continuously loss-creating investment, and that operations and maintenance costs do not warrant keeping the plant in operation. If a plant is either retired or mothballed before its capital costs have been recovered, firms may be left with reductions in expected future cash flows and significant unrecovered sunk costs. We view such plants as stranded assets, acknowledging that cases may differ according to permanence, reversibility, and typology.

2.1.1 Stranded assets in the electricity sector

With the onset of market liberalisation in the US and EU during the 1990s a considerable volume of analysis was undertaken to evaluate sunk costs in electricity investments rendered uneconomic through the introduction of competitive market structures (Baumol and Sidak, 1995; Cearley and McKinzie, 1994; Kolbe and Tye, 1996; Michaels, 1994). The introduction of competition into regulated electricity markets posed significant challenges for regulators needing to balance the costs of market transition and the legal process of deregulatory takings, and a significant body of literature evolved on this topic (Boyd, 1998; Brennan and Boyd, 1997; Crew and Kleindorfer, 1999; Maloney et al., 1997; Beard et al., 2003;). Broadly speaking, this literature examines the appropriateness of a government role in managing transaction costs from stranded assets, the central question being how to delineate sunk costs (spent ex-ante) from those

[3] Negative clean spark spreads indicate that the short run marginal cost of generation (including carbon emissions) is higher than the wholesale electricity price.

considered legitimately "stranded" – i.e. made unrecoverable through a change in policy (Michaels, 1994; Crew and Kleindorfer, 1999; Joskow, 2000). Debate regarding the optimal design of cost recovery and compensation policies produced divergent outcomes on the appropriate role of the government in compensating firms for stranded costs (Woo et al., 2003), with compensation methodologies (Garcia-Martin, 2001), legal and contracting considerations (Brennan and Boyd, 1997; Boyd, 1998) and market distortions (Joskow, 2000) arising as key issues. Whether or not sunk costs are legitimately "stranded" is a crucial issue in evaluating whether or not it is economically or socially desirable to compensate firms for unrecoverable investments. Long-term analysis has concluded that policies allowing for full recovery of a firm's stranded costs may not generally be socially optimal (Beard et al., 2003), and ex-post analysis of stranded cost compensation in utility sectors suggests that most compensation decisions have been politically rather than economically motivated (Guivarch and Hood, 2011). These insights are relevant in the context of climate policy, where firms in emissions-intensive sectors have devoted significant effort to influencing policy design (Kolk and Pinkse, 2005; 2007).

2.1.2 Stranded assets and missing money

Policies to facilitate the transition to clean energy in the EU (including emissions reductions targets and VRES support schemes) are impacting the competitiveness of different generation technologies, resulting in winners and losers. As utilities operating under liberalised and integrated markets are more exposed to competitiveness impacts from environmental compliance costs due to their need to pass compliance costs on to ratepayers rather than distribute them among taxpayers (Guivarch and Hood, 2011),

losers from regulation may devote considerable effort to lobbying against policies perceived to have negative impacts on the profitability of different assets. This has been examined in the context of climate and renewable energy policies, where incumbent EU utilities have applied significant effort to influence policy-making (Stenzel and Frenzel, 2008). In the case of European gas-fired power, owners high-efficiency gas plants are being directly affected by market dynamics and the indirect outcomes of regulation and policy choices. Disentangling the relationships between these drivers is important in assessing what role governments should play (if any) in mitigating costs to plant owners.

Beyond immediate impacts on firm competitiveness, loses from stranded assets are likely to have impacts on investment strategy. If incumbent firms cannot recoup the necessary return on current thermal investments, and new entrants cannot establish market capitalisation at the level necessary to finance new baseload assets, investment in new electricity capacity will decrease. For firms, the risk structure of capacity investment is opposite to that of consumers: in liberalized markets, firms have an incentive to under-invest in capacity as it may have a positive effect on wholesale and retail prices, and overinvestment in capacity may lead to stranded assets (Milstein and Tishler, 2012). In other words, at the margin, the societal value of incremental capacity is greater than the private market value to the producing firm.

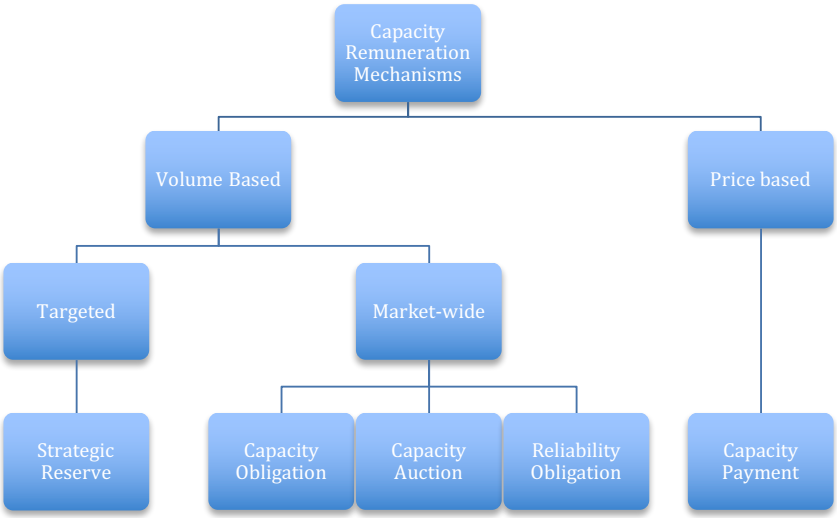
This issue is also reflective of the broader market failure of "missing money" in energy-only wholesale power markets – namely, that due to the instruments aimed at limiting peak prices (such as price caps, regulated bidding, etc.) and other factors, insufficient price inelasticity of demand means that the value of energy during scarcity periods is not high enough to stimulate new entry (Cramton and Stoft, 2006; Joskow,

2006; 2008; Cramton et al., 2013). An increasing penetration of low or zero-marginal cost renewable generation capacity is exacerbating this problem in the energy-only wholesale markets of Europe, resulting in decreasing capacity margins and a lack of investor confidence in the ability of the market to deliver necessary returns.

2.1.3 Capacity mechanisms and stranded assets

Across Europe national governments are becoming increasingly receptive to capacity remuneration mechanisms (CRMs) as a way to ensure supply security by remunerating existing capacity and de-risking new investment. In essence, CRMs aim to incentivise utilities to provide the socially optimal amount of system adequacy (the capacity margin), which is likely higher than the optimal level of investment for individual firms. CRMs may involve an array of different policy structures, and can be differentiated upon two levels: the degree to which capacity is made explicit, and the structure of financial incentives used to remunerate capacity provision (Figure 1).

Figure 1. Taxonomy of capacity remuneration mechanisms



Adapted from: ACER, 2013. Capacity remuneration mechanisms and the internal market for electricity - submission pursuant to article 11 of Regulation (EC) no. 713/2009. Agency for the Cooperation of European Regulators, July 30, 2013.

Over the last several decades, a range of different CRMs have been developed in power markets around the world. Various CRM designs have been shown to have widely different effects on investment and security of supply outcomes in different markets (see, for example, De Vries and Hakvoort, 2004; Larsen et al., 2004; De Vries, 2007; Batlle et al, 2007; Joskow, 2008; Batlle and Perez-Arriaga, 2008; Meulman and Méray, 2012; Cramton et al., 2013). The efficiency of a given capacity mechanism depends on the market design in which it is being implemented. In gross pools, such as the Irish/Northern Irish SEM market, direct capacity payments may make sense if generators are forced to bid at short-run marginal cost; in other markets, they may lead to overcapacity (Oren, 2005; Batlle and Rodilla, 2010). Experience suggests that market-wide, decentralised designs are likely more economically efficient and robust to gaming by generators in liberalised markets with liquid forward trading.

The rapid shifts in market conditions affecting baseload and mid-merit gas-fired power asset in Europe have lead some governments to push forward the implementation of policies to secure capacity adequacy through various mechanisms. CRMs are being implemented in an uncoordinated manner within the same market couplings, with different designs being implemented over different timeframes (see Table 1).

Table 1: Implementation of CRMs in Europe

Country/Market	Market Design/Reform action	Timeline
GB	Capacity Market with centralised descending-clock auction	First Auction in 2014 for delivery in 2018
Nordics (Nordpool)	Strategic reserve scheme	Currently implemented
France	Decentralised Capacity Obligation mechanism	Government approval of obligation mechanism November 2013, expected first delivery year to be 2017
Belgium	Strategic Reserve, tender launched for construction of new CCGT plant	Currently implemented
Germany	Direct contracting of reserve capacity by TSOs, future CRM currently under discussion	No firm mechanism planned, discussion likely to advance in 2015/16
Spain	Revision of capacity payment structure and tariff deficit mechanisms,	Currently implemented, options for future design under discussion
Italy	Revision of CRM to Reliability Options structure	Transition mechanism implemented, first year of Reliability Options delivery expected to be 2017
Greece	Reform of capacity payment mechanism currently under discussion	Methodology used to calculate capacity payments under reform, expected 2015

CRM structures which create new revenue streams for stranded assets may not deliver adequate capacity reserve margins if capacity prices are too low to attract the necessary investment. In addition, tradeoffs between consumer costs and environmental objectives may arise if high-carbon assets are retained in the system. In the absence of a

careful ex-ante design process, risk-averse regulators may implement short-term stop-gap solutions by allowing mothballed assets to re-enter the market.

2.2 Analytical framework, key propositions, and units of analysis

Recently there has been increasing interest in potential costs of stranded assets stemming from the physical and regulatory impacts of climate change. While a significant amount of this discussion has focused on the potential for systemic risks originating from "carbon bubble" arising from the mispricing of fossil-fuel reserves and energy infrastructure investment (Carbon Tracker Initiative, 2013), there has to date been few tangible examples of this problem within the economy. Here we examine what may be considered one of the initial instances of this issue within the power sector – interestingly, the stranding of cleaner assets as opposed to dirtier coal fired assets. While there has been some initial analysis of potential costs posed by stranded power infrastructure under climate change scenarios (IEA, 2013a), this paper delivers new empirical evidence to this issue by assessing impacts on firms, their responses, and implications for evolving regulatory environments.

Employing qualitative analysis of firm strategy and behaviour is useful to compliment quantitative analysis of the current market situation for gas-fired power. Utilities must manage complex social and reputational risks regarding clean energy policy and climate policies. There have been a number of studies examining strategic responses of utilities in response to climate and energy policy developments within the EU (Stenzel and Frenzel, 2008; Mo et al., 2012; Kock and Bassen, 2013; Kolk et al., 2013). This paper draws upon the body of research by examining how stranded assets are

treated as a strategic issue by firms, including how they may be used in the formulation of political strategies and debate around competitiveness.

The analytical framework for this research builds from three research questions, each focusing on a specific unit of analysis:

1. How have uneconomic CCGT assets impacted utilities in European power markets, and how have these actions influenced firm strategy?
2. What policies are governments developing in the UK and Germany to ensure adequate capacity investment, how they relate to uneconomic CCGT assets, and what are the attitudes of firms towards different policy proposals?
3. How might stranded assets have implications at the regional European level?

At a high level, our analysis is guided by two key propositions:

a. firms are likely to undertake strategic actions in accordance with investment risk minimization, cost minimization, and value maximization; and
b. Proposals for capacity mechanisms and short-term supply security measures in may create opportunities for utilities to manipulate the impacts of stranded assets in order to improve firm competitiveness.

In employing these propositions we seek to examine how firms may deviate from what behaviours aligned with principles of rational maximization of competitive advantage.

This paper employs two main units of analysis:

I. Ten major national and multi-national utilities European utilities[4] (hereafter referred to as "the sample firms") that implemented decisions and/or announced plans to mothball or close CCGT assets in response to persistently low or negative clean spark spreads during 2012-2013. Although not comprehensive on a pan-European scale, this selection of firms responds to those specific developments during 2012 and 2013, and aims to provide a snapshot of the situation facing major utilities;

II. Two countries (UK and Germany) which satisfy the following criteria from 2012 to the present:

   i) Firms have mothballed or closed CCGTs;

   ii) Capacity policies were implemented, or debate regarding capacity policy rapidly developed; and

   iii) TSOs made short-term payments to uneconomic plants outside of an existing or planned capacity policy process.

In discussing our results and analysis we make inferences about the broader state of European power markets, and focus on the regional level in order to impacts and implications for cross-border trade, market integration, and governance.

2.3 Methodology

A detailed literature review and news media search was undertaken to identify potential cases of mothballing decisions to serve as case studies. Based on assumptions of

[4] E.ON, RWE, EnBW, GDF Suez, Statkraft, Vattenfall, Centrica, SSE, Verbund, CEZ

a model new-entrant CCGT[5], a heuristic test was then applied to evaluate whether a mothballed or closed plant represented a significant negative P&L contribution to a firm's balance sheet. Certain values regarding investment return timelines were assumed in order to develop a high-level view of whether a mothballed plant would present a significant cost burden to its owner if capital costs were not depreciated. From industry sources and key informant interviews we estimate depreciation timelines of a model new entrant CCGT plant to be approximately 15 years for capital and 10-12 years for debt at standard investment hurdle rates. Therefore, based on our assumptions we consider that plants built within the last 10 years may not have fully depreciated capital costs, and therefore could present cost burdens to owners[6].

Employing these assumptions we undertook market research to ascertain the overall level of mothballing by major firms (in terms of total GW of capacity), and what proportion of this mothballing was of new, high-efficiency plants commissioned within the last 10 years – those plants which roughly conform to our heuristic model of a new-build CCGT, which would pose significant financial burden in terms of asset impairment. Analysis of financial statements and third-party information was undertaken to evaluate the financial impacts of mothballed and closed CCGTs on utilities in terms of asset impairment charges, equity, credit ratings, and debt. Policy documents, proposals, consultation responses and third-party analysis of capacity remuneration policy

[5] We assume that: a) the plant is mid-size (500 MW), high-efficiency unit (60% thermal efficiency) intended to run between baseload and a mid-merit load factor (50-70%); b) the plant has a competitive long-term gas supply contract, reducing price risk; c) the plant is integrated into the portfolio of a large vertically-integrated utility through which its output is traded and collateral requirements are managed (i.e. it is not an independent merchant Generator, and therefore requires less trading collateral); and d) the majority of its output is hedged forward with a mix of monthly and seasonal products with limited exposure to day-ahead spot volatility.

[6] We note that older plants could also pose cost burdens to owners if alternative financing instruments were put in place.

developments in the UK and Germany were assessed through an extensive literature review. Following this, position papers and news media sources were reviewed to assess the attitudes of different utilities towards capacity mechanism policy options, and the role of mothballed CCGTs in debates. A number of semi-structured interviews were undertaken with representatives of utilities, prominent analytics firms and international organisations. Due to confidentiality constraints within our research process, the results of these interviews are presented in this paper under Chatham House rules, and are referred to as "Industry sources" and "Analyst sources" respectively. We draw upon the insights of these qualitative data sources to substantiate publicly available information.

3. Results

During 2012 and 2013, the sample firms announced decisions to mothball or close gas-fired power plants in European countries. These decisions include immediate announcements, and planned future mothballing and closures. Collectively these decisions affected 20.08 GW of gas-fired capacity, 8.87 GW of which was either built or acquired within the last ten years. A comprehensive overview of currently implemented and planned future mothballing and closure decisions by the sample firms is presented in Table 2.

Table 2: Currently implemented and planned mothballing and closure decisions

Utility	Ownership share	Plant name	Country	Capacity (Mw)	Comm. date (Purchase)	Response
Centrica	100%	King's Lynn	UK	325	1997 (2001)	Deep mothballed
Centrica	100%	Roosecote	UK	229	1991 (2003)	Decommissioned
CEZ	100%	Pocerady	CZ	840	2013	To be shallow mothballed
E.ON	100%	Irsching 4	DE	545	2011	Deal struck to avert closure
E.ON	100%	Irsching 5	DE	425	2010	Deal struck to avert closure
E.ON	100%	Malzenice	SK	417	2011	Mothballed
E.ON	100%	Tazavanno 8	IT	300	2005	Mothballed
E.ON	100%	Ostiglia 4	IT	280	2008	Closed
E.ON	66%	Veltheim 4	DE	390	1975	Decommissioned
E.ON	100%	Staudinger 4	DE	622	1977	Converted to standby plant
EnBW	100%	RDK 4	DE	365	2008	Mothballing TBD
GDF Suez	100%	Cycofos	FR	490	2009	Summer Mothballed
GDF Suez	100%	Combigolfe	FR	435	2010	Summer mothballed
GDF Suez	100%	SPEM	FR	435	2011	Summer mothballed
GDF Suez	100%	Teeside	UK	1,875	1993 (2008)	To be decommissioned
GDF Suez	100%	Shotton	UK	210	2001 (2003)	Closed
GDF Suez	33%	Derwent	UK	210	1995 (2000)	Closed
GDF Suez	100%	Bergum BG	NL	504	1975	Closed
GDF Suez	100%	Harculo	NL	263	1982	Closed
GDF Suez	100%	Eems	NL	530	1987	Closed
GDF Suez	100%	Awirs 5	BE	294	1973	Closed
GDF Suez	100%	Herdersbrug	BE	480	1998	Conversion to peaking unit
RWE	100%	Moerdijk 2	NL	430	2012	Mothballed
RWE	100%	Weisweiler G	DE	272	2007	Mothballed
RWE	100%	Weisweiler H	DE	272	2007	Mothballed
RWE	100%	Emsland B	DE	360	1974	To be summer mothballed
RWE	100%	Emsland C	DE	360	1975	To be summer mothballed
RWE	100%	Gersteinwerk F	DE	355	1973	Mothballed
RWE	100%	Gersteinwerk	DE	355	1973	To be mothballed
SSE	100%	Keadby	UK	760	1996	Deep mothballed
SSE	100%	Peterhead	UK	1,840	1980	Partially mothballed
Statkraft	100%	Knapsack 2	DE	430	2013	Shallow mothballed
Statkraft	100%	Knapsack 1	DE	800	2007	Shallow mothballed
Statkraft	50%	Herdecke	DE	417	2007	Shallow mothballed
Statkraft	100%	Emden	DE	450	1972 (2009)	Deep mothballed
Statkraft	100%	Robert Franck	DE	510	1962	Deep mothballed
Vattenfall	100%	Magnum	NL	1300	2013	Shallow mothballed
Verbund	100%	Pt.-sur-sambre	FR	420	2009 (2011)	Final decision TBD
Verbund	100%	Toul	FR	422	2012	Final decision TBD
Verbund	100%	Mellach	AU	832	2011	Final decision TBD
Total	All plants			20079		
Total	< 10 yrs.			8877		

3.1 Market and Policy Drivers

Mothballing and closure decisions have been motivated by different market and policy factors affecting electricity, coal, gas and carbon prices. These drivers can be broadly described as:

I. Declining electricity demand
II. Inadequate carbon price signals, affected by EUA oversupply and the impacts of the financial crisis on economic growth
III. Increasing proliferation of renewable energy capacity
IV. Decreasing coal import prices motivated by international market dynamics

The global financial crisis resulted in significant reductions in EU electricity demand compared with levels projected in 2008-09. The financial crisis significantly affected carbon prices, with prices of EU Emissions Trading Scheme (EU ETS) allowances falling from nearly €30 in July 2008 to near €4.50 in January 2014. In European markets changes to merit order brought on by increasing renewable energy capacity (Bach, 2009; Nicolosi, 2010; Tveten et al., 2013) have curtailed expected load factors and significantly affected market prices, increasing volatility and affecting bidding behaviour. Recent studies have found that for every GW of RES fed into the German national grid, day-ahead electricity prices may be reduced by 1.10 to 2.40€/MWh (Von Roon and Huck, 2010; Cludius et al., 2013). Total merit order effects from wind and solar PV have increased from 5€/MWh in 2010 to more than 11€/MWh in 2012 (Cludius et al., 2013). In the UK, merit order impacts have affected power market

prices and access (Green and Vasilakos, 2010; Green et al., 2011; Eager et al., 2012) but these effects have arguably been less pronounced.

Significant decreases in EU coal import prices have been attributed to reduced demand for thermal coal in the US (Economist, 2013; Chazan and Wiseman, 2013), which has been driven by coal-to-gas fuel electricity switching facilitated by emissions regulations and impacts of the shale boom on domestic gas prices (Lu et al.; 2012; Praston et al., 2013). Analysts suggest that coal prices would need to increase by 80% in order for gas to be a competitive option for major European utilities (Gloystein, 2013), while industry sources have estimated that the load factor of the entire EU gas-fired fleet dropped from 45 to 34% between 2011 and 2012, with coal load increasing from 53 to 59% (GTPJ, 2013d).

3.2 Impacts on the sample firms

EU utilities have experienced substantial financial impacts from the adverse market situation for gas-fired power. As the market conditions for gas-fired generation deteriorated further in 2013, major EU utilities reported increasing impairment charges on thermal assets. Of the sample firms, six reported significant write-downs on EU CCGTs (Table 2). Based on financial information we estimate that nearly €6bn is attributed to write-downs on gas-fired power investments over the course of 2013. We note that this value is an approximation, as certain write-downs and impairments are not easily traceable to specific assets.

Table 3: EU utility impairments during 2013 – thermal and gas assets (€m)

Utility	Date	Total Impairment	Thermal impairment	Gas-power impairment	Assets noted
Statkraft	14-Feb-13	376	274	274	German gas-power assets
GDF Suez	28-Feb-13	2000	2000	2000	EU gas-power assets
SSE	22-May-13	693	362	> 327.80	UK CCGTs, coal assets
Verbund	12-Jun-13	1130	1030	659	Austrian and French CCGTs
Vattenfall	23-Jul-13	3462	2168	> 1,690.00	Dutch gas-power and coal assets
GDF Suez	31-Jul-13	200	200	200	Dutch, French and German CCGTs
RWE	14-Aug-13	800	800	> 800.00	Dutch thermal generation assets
Total		€ 8,661	€ 6,834	€ > 5,950.92	

Source: Authors' analysis, based on firm financial statements.

Beyond the devaluation or write-down of specific assets, the value of major EU utilities has been impacted by the long-term downturn in profitability of thermal generation business units. While profits have been somewhat protected by forward hedging over the last three years, the expiration of forward hedging in EU markets suggests a bleak outlook for EU power prices in negatively impacted firms whose asset base is not widely geographically or technologically diversified (Bloomberg, 2013). Impacts upon firm equity and market capitalisation have carried through to investors, with a number of utilities aiming to stem capital outflows by reducing dividends. Equity impacts have in turn carried through to credit ratings, with many EU and UK utilities suffering downgrades over the last five years. Those utilities that have been able to preserve credit ratings or limit further downgrades have benefited from geographical and sectoral diversification, along with reductions in spending and increased liquidity.

3.3 Impacts on capacity investment plans of the sample firms

The current market environment for gas-fired power generation in the EU is acting as a strong disincentive for investment in new generation capacity that is required

to replace aging infrastructure or units being decommissioned under the LCPD. Many utilities have adopted a "wait and see" approach to planned CCGT investments and upgrades that were expected to have broken ground over the course of 2012-13 have not taken place. Industry and analytical sources reported that perceived risk-adjusted discount rates on CCGT investments have changed significantly in recent years, influenced by market conditions and policy uncertainty at national and EU levels regarding emissions regulation, renewable energy support and transmission infrastructure development. Over the course of 2012-13 some utilities reported changes in risk premia applied in asset impairment testing due to policy uncertainty (EY, 2013), which may be inspiring changes in discount rates applied to new investments.

UK sample firms (Centrica and SSE) have postponed and cancelled planned capacity expansions, citing the effects of market factors upon cash flow as well as the impact of policy uncertainty (Centrica, 2013; SSE, 2013a). Increasing risk premiums have compounded capital availability issues for UK utilities, leading to disjunction between rising capital costs and expected investment returns (GTPJ, 2013a). Despite cancellations and decisions to postpone investments, many UK utilities have expressed confidence in the long-term need for new gas generation capacity. Increasing clarity on policies for capacity mechanisms and renewable energy deployment is likely to have a positive impact on investor confidence. Some Nordic and Continental sample firms (Statkraft, Vattenfall, E.On, RWE) have also cancelled or delayed proposed capacity expansions. Industry sources reported these decisions to be attributed to burgeoning over-capacity, increasing renewables deployment, merit order impacts on prices, fuel price differentials (Industry sources, E.ON, 2013a; RWE, 2013a, Vattenfall, 2013b; Statkraft,

2013a). Industry sources reported that tight capital constraints are influencing continental firms towards investments with a broader range of flexible services; for gas, this includes combined heat and power (CHP) units rather than energy-only CCGTs destined for baseload power generation (Industry sources; May, 2013).

3.4 Policy responses

Several EU countries have made significant steps towards the implementation of CRMs as a way to assuage system stability and investment profitability concerns of incumbent utilities. Here we focus on the UK (specifically the GB BETTA market, as Northern Ireland is part of the integrated SEM market) and Germany, as these two jurisdictions satisfy the criteria noted in section 2.2: namely, evidence of stranded gas-fired power assets, progress towards capacity mechanism development and implementation, and short-term payments to plant owners outside of a capacity mechanism. The UK and Germany are of specific interest in this context also due to their different market and geographical conditions, which we discuss briefly in the following section.

3.4.1 United Kingdom

Due to a number of different factors, including plant retirement cycles, emissions control regulations, and constrained financial capacities of incumbent utilities the UK may face decreasing capacity margins over the coming decade. Between 8 and 9 GW of GB coal and oil plants are forecast to close by 2015 due to the impacts of the LCPD (ENTSO-E, 2013). In its 2013 electricity capacity assessment report, the Office of Gas

and Electricity Markets (Ofgem) has forecast a decline in UK capacity margins until 2015/16, with a de-rated reference scenario margin of 4% (Ofgem, 2013).

Policy context

In June 2013 DECC decided to implement a capacity market system in order to ensure system adequacy from 2018 onwards (DECC, 2013a). Generators submit multiple sealed bids in a descending clock auction format to meet a predetermined capacity requirement (48.6 GW in the first auction). Pre-qualified existing CCGTs are eligible for one-year capacity contracts. New build capacity is eligible for contracts up to 15 years in length. The first auction was held on December 16th 2014, resulting in a clearing price of £19.2kW per annual. While this price was championed by government as an indicator of a successful competition, a low capacity price may turn out to have negative implications for capacity adequacy if existing plant leave the system. Key events and indicators to track in this regard include:

- The volume of non-qualified capacity not awarded contracts which leaves the system in advance of the delivery year;
- The volume of qualified capacity awarded contracts for 2018 which are mothballed in advance of the delivery year;
- The volume of capacity participating in the next capacity auction in 2015, and the development of the capacity curve for delivery years beyond 2018.

Outside the capacity market process, other actions have been implemented to secure capacity before 2018. In September 2014, the National Grid announced its decision to exercise its option to tender for Supplemental Balancing Reserve (SBR) to compensate

operators to keep plants that would otherwise be mothballed or closed available to generate electricity during the winter months of 2014-15 and 2015-16 (National Grid, 2013). This proposal would directly target plants recently rendered uneconomic to stay online if they can "demonstrate to (National Grid's) reasonable satisfaction" that they would "otherwise be mothballed or decommissioned" (National Grid, 2013). Tenders have been held for Winter 2014/15 and Winter 2015/16; with capacity costs equating to £15.57 per kW and £17.80 per kW respectively (National Grid, 2014b,c)

Firm attitudes

UK sample firms have been largely supportive of the implementation of a capacity market, given the insensitivity of energy prices to capacity scarcity and market conditions. However, some have expressed reservations that current implementation timelines are not likely to address the short-term capacity crunch projected for 2014-15. For example, SSE has expressed the importance of early payment availability "in order to keep existing plants on the system" (GTPJ, 2013a), and that an additional near-term auction system could be implemented to manage short-term capacity issues. UK sample firms have expressed somewhat sceptical views about the potential benefits of the SBR as a short-term mechanism, noting risk of further damage to price signals as incentives for capacity investment by bringing old plants into operation (Industry sources). Both Centrica and SSE have expressed reservations about the SBR as a short-term fix (Utility Week, 2013a), noting that potential for balancing service provision will do little to improve overall market conditions for generation investment (SSE, 2013b). International firms have criticised the SBR as it is likely to bring inefficient plants back into the market at public expense, distorting incentives for new investment (Utility Week, 2013b).

However, these firms subsequently entered the SBR tender, with some mothballed plant (Peterhead, Barry, and South Humber Bank) winning contracts (National Grid, 2014b,c).

3.4.2 Germany

Unlike the UK, Germany is not projected to face short-term capacity margin constraints. Current installed power capacity in Germany amounts to 174 GW, of which 80 GW is fossil-fuel base load (BNEF, 2013a). The security of Germany's large and diversified energy system has benefited from high levels of interconnection with other countries, which smoothed security issues during the closure of nuclear capacity (IEA, 2013b). However, the medium and long-term outlook for German capacity adequacy is hotly debated (Bracke and Schroder, 2012, ACER, 2013). Currently the German market is defined by over-capacity in both thermal and renewable generation, but this capacity is not evenly distributed throughout the country. Certain areas of southern Germany (specifically the state of Bavaria) may face serious capacity adequacy issues in coming years (IEA, 2013b).

Policy context

There have been several legislative actions undertaken as short-term solutions for localised supply security affecting the mothballing of German thermal assets. The most important of these has been the implementation of a 12-month moratorium on the closure of plants deemed "system relevant" by transmission service operators and *Bundesnetzaugenteur* (BNetzA), the federal regulatory agency (Deutscher Bundestag, 2012). The decree, valid until 2017, specifies that gas-fired assets considered system relevant shall be compensated for fixed costs if they are required for more than 10% of

total MWh capacity by system operators (ICIS, 2013a). In June 2013 new legislation specified the role of BNetzA in evaluating the need for thermal capacity expansion and the ability of responsible transmission system operators (TSOs) to tender for new reserve capacity.

Capacity policy in Germany has not progressed to a point of proposed legislation, but following reforms to the Renewable Energy Sources Act (EEG) in 2014, the German Ministry of Economic Affairs and Energy (BMWi) has delivered some initial analysis of various options for capacity markets. Following public consultation, a white paper is due to be finished in September 2015 (BMWi, 2014). The coalition agreement between the main CDU/CSU and SPD parties in late November 2013 indicates that, while capacity is sufficient at present, a capacity market is likely to be developed in the medium term in response to baseload capacity concerns towards 2020 (Energy Transition, 2014; ICIS, 2013b). The capacity forecast is to be technology neutral and integrated with a planned expansion of the grid reserve system. There exists the option to develop a tender model for grid operators' required capacity as a way to increase transparency in the current system-relevance legislation (ICIS, 2013b).

Firm attitudes

The system relevance legislation was first applied to determine compensation in response to E.ON's decision to mothball the Irsching 4 and 5 CCGT units, located in Bavaria. E.ON announced its intention to mothball units in March 2013, citing operational performance of less than 25% of expected running hours (Andersen and Patel, 2013). Following negotiations with TSO TenneT it was decided that E.ON would

receive compensation to cover fixed costs of the new units[7] which would allow them to stay within the system (Lang, 2013; TenneT, 2013). E.ON's settlement for the Irsching plants has provoked controversy among Germany utilities. Competitors have expressed reservations that Irsching is still participating in the wholesale market, albeit with a subsidy introducing competitiveness asymmetries. As the system-relevance legislation would regularly have specified that compensated plants be prohibited from participating in the spot market, it is unclear how future applications of the law may be applied. A lack of transparency in the decision appears to have undermined investor confidence, and utilities have raised concerns that market efficiency over the next few years may be compromised if compensation decisions go forward in a similarly ad hoc manner. However, many utilities have welcomed government acknowledgement that the closure of new flexible, high-efficiency baseload thermal generation is not an efficient outcome for energy decarbonisation policy (Industry Sources).

While German sample firms largely agree on the need for policy options to improve the market for gas-fired generation and address impacts of RES support policies, firms hold divergent attitudes towards the pros and cons of different mechanisms (Industry sources, Analyst sources). Statkraft has expressed support for a non-discriminatory market-based system – either via auctions or capacity obligations – as a cost-effective solution, comparable with 10% of total RES subsidies (Statkraft, 2013b). Statkraft has highlighted the need for competition to avoid subsidies for specific CCGT assets, suggesting that equal opportunity for government support is crucial for a competitive market (Statkraft, 2013b), and that the implementation of strategic reserves

[7] While the compensation amount was undisclosed, E.ON reported annual operating costs of 100m euro (Reuters, 2013a).

could affect investment incentives. Other utilities such as Vattenfall have opposed capacity markets (Morison, 2012), supporting strategic reserves as a preferable complement to energy-only markets. Proponents cite baseload capacity adequacy in Germany and the potential for capacity markets to incentivise old, inefficient plants to be reintroduced into the market and refinanced by consumers (Industry sources). One of the sample firms highlighted the low transaction costs associated with transforming existing winter reserve regulations into a strategic reserve scheme, and the potential capacity congestion benefits that could be gained by expanding the mechanism to include plants in neighbouring countries (Industry source). Other issues remain under debate, such as implications of different CRM structures for technological innovations (including energy storage and micro CHP), which will require increasing price volatility in order to become commercially viable (Industry sources, analyst source).

4. Discussion

The results discussed above illustrate how stranded power assets may have important implications for energy decarbonisation and system security objectives. Here we discuss key emerging issues at national and EU levels before examining remaining questions and policy implications.

4.1 National policies

In GB, risk of potential exploitation of capacity adequacy concerns (vis-à-vis gaming the capacity mechanism through mothballing plants) has been deemed low, and the low capacity price has been hailed as positive evidence of lively competition. However, prices are too low to incentivise investment, this may have negative longer-

term implications. If perceived as failure, this could potentially shift political environment against market solutions to secure capacity and system flexibility. This may in turn improve attitudes towards regulated solutions for securing flexible capacity – however, the degree to which this occurs is contingent on overall system dynamics and capacity margin in years to 2018. In the German context, stranded CCGT assets are motivating a capacity mechanism debate focused on keeping low-carbon assets in the system and addressing localised adequacy issues. While some firms that have mothballed recently constructed CCGTs are very supportive of capacity market implementation, competitors with diversified assets in Germany and neighbouring markets have opposed these proposals, instead preferring a strategic reserve.

Our analysis suggests that utilities are likely to weigh the benefits of stranded cost compensation with market-wide competition priorities as these firms broadly work towards similar policy objectives (securing policy certainty and improving investment risk). This is exemplified in the debate regarding transparency in the German system-relevance regulation and the UK supplemental balancing reserve, whereby compensation for individual stranded assets may potentially distort competitiveness. Beyond these asymmetries, the introduction of discretionary non-market policy mechanisms could potentially increase the ability of firms to manipulate decisions around stranded assets for strategic benefit. In this context, governments needing to manage short-term supply security issues should seek to limit discretionary payments to utilities, and take precautions to ensure that plants targeted for short-term service do not receive undue subsidies.

CRMs may interact with other climate and energy policies in unpredictable ways. The objective of capacity mechanisms is primarily to ensure system adequacy; however, such policies are likely to have implications for environmental aspects of energy policy. Important questions remain regarding the potential for CRM policies to deliver on flexibility and decarbonisation goals, and how such groups of policies should be aligned. The risk remains that capacity mechanisms which only reward long-term adequacy may not incentivise the flexibility characteristics of generation assets (including ramp-up speed and balancing potential) that will be become more important in the future. Considerations regarding flexibility must be understood in comparison with the broader framework of policies managing an energy market[8].

Interactions between CRMs, stranded assets and decarbonisation policy could have conflicting effects if policies are not aligned. Some analysts have promoted the use of capacity mechanisms at the EU level to improve risk premiums for low-carbon investments (Gottstein and Schwartz, 2010; Baker and Gottstein, 2013). However, the pros and cons of designing capacity mechanisms to facilitate environmental objectives must be evaluated within domestic climate policy contexts. Domestic carbon pricing actions are a pertinent issue: as the UK's carbon price floor has already inspired significant competitiveness concerns (resulting in a "freeze" of the escalation of the price ladder), picking low-carbon winners through a capacity market could reduce the efficiency of competitive price discovery for capacity. Within the rest of the ETS area, the potential for carbon pricing to motivate low-carbon investment could be affected by

[8] While the UK is taking steps towards incentivising and monetising flexibility through mechanisms like the short-term operating reserve and the demand-side balancing reserve, this debate is proceeding slowly in other EU countries. In Germany, policy actions to improve demand-side management and short-term system balancing may need to be advanced in addition with capacity mechanism actions in order to facilitate localised system balancing (Bertsch et al., 2013).

policy uncertainty, inadequate forward markets and investment timeframes.

4.2 Market integration, trade, and governance

Independent and uncoordinated implementation of different national CRM policies could have significant implications for EU energy market integration. While the implementation of the third EU energy package and the development of network codes illustrate important progress towards market integration objectives, the implementation of CRMs with differential treatment of national and foreign capacity could have significant impacts on competition between electricity generators and suppliers (Meulman and Méray, 2012; Baritaud, 2012). The unilateral implementation of CRMs in energy-only markets may have immediate short-term effects on prices and dispatch decision-making by utilities, as well as influencing investment choices (ACER, 2013). Beyond the presence or absence of CRMs between countries, the implications of CRM design differences for prices, competition and investment are unclear. Cross-border participation in CRMs remains a complex issue, and could have implications for mothballed assets stranded assets.

If plants are put at a competitive disadvantage by a neighbouring country's capacity mechanism, this may affect political incentives to increase interconnector capacity across borders. While the cross-border implications of national energy policies (exemplified by national RES subsidies) have so far been tolerated in EU markets, significant changes in the valuation of capacity, effects on wholesale prices and decreased competitiveness of domestic assets may negatively affect cooperation between EU member states. Over the long-term, utilities may reorganise planned investments to

move to where different capacity policies provide the most attractive revenue streams, with the implementation of capacity markets displacing energy prices as a primary driver of investment risk (Ozdemir et al., 2013). Effects on investment climates in different countries could exacerbate national system security, as well as increasing pressure on the profitability of assets pushed up merit order curves by international investment.

At the European level, updated guidance on state aid for environmental protection and energy released in 2014 by the European Commission specifically note the management of lock-in to fossil-fuel baseload capacity built on the back of capacity mechanisms (and the potential for these assets being rendered uneconomic) as a key priority for national governments (European Commission, 2014). Governance at the European level – including rules and regulations for cross-border participation – will have to follow, rather than guide, the implementation of mechanisms in many countries. Other current debates about the 2030 energy package – including the integration of RES support mechanisms and policies to optimise RES investment across states – may be significantly affected by CRM implementation. These issues have been particularly relevant for the political lobbying of utilities at the EU level, which firms have been increasingly active in pushing for reforms to improve markets for gas-fired generation and the investment environment for new capacity.[9]

[9] In October 2013 the heads of ten major EU energy companies lobbied the European Commission to reduce subsidies for renewable energy and strengthen the carbon market in order to secure a place for gas generation within the EU energy mix (De Clercq and Lewis, 2013).

4.3 Further issues

As CRM policies may involve high transaction costs and be hard to reverse if implementation delivers unexpected results, additional actions to support capacity adequacy and should be carefully examined at the regional level. Increasing harmonization between national energy regulators regarding security standards (including agreement on VOLL and LOLP values), system management protocols, and transmission standards could improve the potential for trading balancing services across countries as a way to alleviate system congestion issues. More far-reaching reforms and changes to market structure and design, such as splitting bidding zones in day-ahead and intraday markets within the EUPHEMIA dispatch mechanism (i.e. splitting countries into more price zones) could potentially deliver improved locational pricing and response. More complex actions, however, may not be relevant to the timeframes governments face in capacity planning.

Beyond system management issues, managing potential unintended consequences resulting from a lack of alignment between climate and energy policy stands as a major challenge. The cases of stranded CCGT assets examined here illustrate that the EU and individual national governments may not fully be prepared to deal with the consequences of clean energy for system stability and investment security. In this context, ensuring that gas generation plays an appropriate role within the transition to decarbonisation (while avoiding lock-in effects) stands as an important priority for EU-level energy system planning.

5. Conclusions

This paper has examined the implications of CCGT mothballing and closure for capacity mechanism policies in the UK and Germany in order to gain insights into the potential role of stranded assets in the transition to low-carbon energy. Our research illustrates this acute example of asset stranding had significant and rapid consequences for firm value, strategy, and ultimately policy. As part of this process, policymakers should consider the appropriate treatment (if any) of assets becoming stranded. Careful thinking is required on how the economic costs of asset stranding should be valued in the design and implementation of different capacity policies. Failing to do this will result in overly expensive CRMs, which could increase retail prices. Different stakeholders in the electricity sector – including, firms, investors and shareholders, regulators, and governments – may want to consider how stranded assets may interact with investment behaviour, capacity policy and energy market regulation.

If implementing capacity mechanisms, governments should seek to address capacity adequacy concerns through competitive, market-based policies. In addition to the objective of generation adequacy assessments undertaken by independent bodies, governments should consider potential interactions regarding flexibility and clean energy objectives in order for policies to be comprehensive, targeted and effective. Governments should think clearly about how different designs for capacity mechanisms may affect the competitiveness of different firms, and assess the potential for strategic behaviour by these firms around stranded assets. More broadly, governments should work to consider a range of actions that could increase investor confidence enough to achieve the objectives of a capacity mechanism without implementing unnecessarily costly policies.

At the EU level, more work should be undertaken to evaluate the implications of different energy market integration actions for stranded gas assets. Examining questions regarding potential competitiveness impacts of different capacity mechanisms and their relationships to stranded assets stands as an important research priority. At a higher level, more research is required to assess fundamental barriers to the viability of the EU's target energy market model brought on by conflicts between increasing VRES capacity and baseload generation within the marketplace.

Improving understanding of the changing political economy of stranded assets in the electricity sector stands as a priority for further research. More targeted quantitative research is required to understand the long-term costs and benefits of capacity mechanism implementation in the context of alternative and complementary actions to facilitate energy sector decarbonisation. Going forward, further examination of the potential impacts and implications of stranded electricity assets in the context of changing energy policies and different wholesale market designs stands as an important research priority at national and regional levels.

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Chapter 5

Title: Making climate policy more like monetary policy: calibrating climate policy through corporate solvency

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Making climate policy more like monetary policy

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Keywords:	climate policy frameworks, stranded assets, corporate solvency, policy calibration, Altman's Z-score
Abstract:	Abstract Rapid carbon abatement improves the chances that dangerous anthropogenic climate change will be averted; but if the rate of curtailment is unnecessarily fast it could cause excessive corporate failures – which would significantly add to the social cost of abatement. This paper proposes using measures of corporate solvency as an objective tool for policymakers to calibrate the optimal magnitude of climate change policies, and thereby achieve more efficient emissions abatement. We successfully demonstrate this policy analysis framework on the UK's Carbon Price Support (a carbon tax); and find that net of contemporaneous macroeconomic improvements, this policy did not impair the corporate solvency of energy-intensive industries. Policy Relevance Statement This paper is of interest to a wide range of actors, including policymakers at regional, national, and international levels across many different departments and ministries, from environment and energy through to economics and finance. It speaks to four important topics. First, how to minimise the stranded assets and social costs associated with delivering decarbonisation. Second, how to make climate policies as objective as possible, as well as transparent, so that decisions are aligned with emissions targets and that assumptions underpinning decisions are clearly communicated to markets. Third, providing mechanisms that are potentially robust to likely lobbying from fossil fuel interests. Fourth and more speculatively, building on nascent interest from central banks and financial regulators in climate change topics and exploring the potential to collaborate with or learn from this important community.

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Making climate policy more like monetary policy: calibrating climate policy through corporate solvency

Abstract

Rapid carbon abatement improves the chances that dangerous anthropogenic climate change will be averted; but if the rate of curtailment is unnecessarily fast it could cause excessive corporate failures – which would significantly add to the social cost of abatement. This paper proposes using measures of corporate solvency as an objective tool for policymakers to calibrate the optimal magnitude of climate change policies, and thereby achieve more efficient emissions abatement. We successfully demonstrate this policy analysis framework on the UK's Carbon Price Support (a carbon tax); and find that net of contemporaneous macroeconomic improvements, this policy did not impair the corporate solvency of energy-intensive industries.

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Introduction

Rapid carbon abatement improves the chances that dangerous anthropogenic climate change will be averted. But if the rate of curtailment is unnecessarily fast, it could cause excessive corporate failures – which would add to the social cost of abatement. At present, policymakers do not have a consistent way to quickly and accurately gauge what impact climate policies are having on corporate solvency. If they did and if these measures were applied correctly, the efficacy and cost-efficiency of climate policy could be improved.

In response to this shortcoming, we propose that metrics of corporate solvency be used as an objective tool for policymakers to calibrate the optimal magnitude of climate policies, and thereby achieve greater emissions abatement at lower social cost. In particular, solvency metrics could calibrate the optimal severity of climate policies and/or the generosity of industrial compensation. Financial regulators currently monitor and regulate certain aspects of corporate solvency for financial firms (such as capital reserve requirements) in order to reduce the risk of bankruptcy while simultaneously maintaining profitability. In a similar vein, policymakers could do likewise with respect to climate change policies which target carbon-intensive firms.

The most fundamental goal of climate policy is to incentivize industry to reduce carbon emissions and transition to lower-carbon processes and technologies. When firms face carbon-related; taxes, prices, or regulation; and restructure their businesses accordingly[1], it is expected that during this transition they will suffer some loss of solvency. However, if the firm goes bankrupt as a result of this regulation, not only will this restructuring not occur – possibly causing emitting industries to expand in less constrained jurisdictions (so-called carbon leakage), but social value will also be destroyed in the form of deadweight losses paid to liquidators and the dissolution of organizational capital. For example, in a meta-analysis of past studies on the cost to investors of corporate bankruptcy, Branch[2] estimates 12-20% of the firm's value to be lost in the liquidation process. Adding on the social costs arising from unemployment and new job search would magnify this figure further still. Finally, there is also the danger that a sudden industry-wide loss of solvency could incite a wider financial panic.

On the other hand an excessively lenient climate policy with low future carbon price expectations could fail to restrain industry from investments in long-lived carbon-

[1] See for example Requate and Unold (2003).
[2] Branch, B. (2002) The costs of bankruptcy: A review. International Review of Financial Analysis, 11: 39-57.

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intensive infrastructure[3] that could become stranded, and therefore potentially induce the need for a more rapid and expensive transition in future in order to meet fixed climate change goals. An ideal solvency trajectory for firms affected by climate change policy would therefore cause corporate solvency to initially decline – approaching but not exceeding 'distressed' levels - and then gradually improve to a new 'steady state' once the climate change transition had been achieved, at which point the regulation would continue but any compensation provided to industry could end. This sequence is depicted by the U-shaped solvency curve in Figure below. Although idealised, if Figure was adopted as a climate policy target, it could potentially improve the economic efficiency of carbon reduction across affected industries.

[INSERT FIGURE 1]

An additional advantage of using corporate solvency to calibrate climate change policy is the fact that this process would be comparatively objective. At present there is considerable potential for industrial outcry and political lobbying to bias how climate change policies are adjusted, with potentially negative social outcomes. Even when the need for regulatory change is obvious, many policymakers struggle to enact needed reforms, and even if successful often fail to do so in a timely manner. For instance, it is widely acknowledged that EU Emissions Trading Scheme (EU ETS) has failed to deliver a price signal consistent with its intentions since at least the beginning of 2012, when price levels stabilised below 5€/ton CO_2.[4] However, a plan to redress this situation was not approved by the EU Commission until 2014, and this plan is not due to be implemented until 2021. By contrast, a climate change policy based on corporate solvency could be adjusted relatively mechanically at each financial reporting period, and would automatically be sensitive to variations in the business cycle.[5]

The remainder of this paper applies this policy calibration framework to one of the most recent and significant additions to climate change legislation: the United Kingdom's Carbon Price Support (CPS). The CPS is an added surcharge to the Climate Change Levy (CCL): a pre-existing tax on the use of energy delivered to non-domestic users in the United Kingdom. It is a unilateral tax that the UK applied without the participation of any other EU member states in response to the chronic failure of the EU ETS to produce a consistent and meaningful price signal for

[3] An example of this may be the 19 highly-carbon intensive coal plants currently at various stages of planning in the EU (Mathiesen, 2014).
[4] In 2003 (well before the EU Emissions Trading Scheme's launch in 2005) the UK government regulator Ofgem expected price levels to have risen to 33-49€/ton by 2010 (Ofgem, Nov 2003), and the lowest price scenario for EU ETS permits forecasted for 2012 by McKinsey & Co was 20€/ton CO_2 (UBS, Sept 2003).
[5] Depending on the timeliness of financial reporting.

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industry to invest in low carbon technology; and a desire by the UK to meet its commitments to both generate 15% of electricity from renewable sources by 2020 and reduce greenhouse gas emissions by 80% of 1990 levels by 2050. The CPS is calculated based on a top-up payment to the price level of EU ETS permits. When the CPS is combined with the price of EU ETS permits it is known as the Carbon Price Floor (CPF).

[INSERT TABLE 1]

The CPS is a relevant case study for applying our proposed policy calibration methodology because it is one of the world's most recent and substantial carbon taxes and is administered in a large developed economy with good financial micro-data. Within industry it has also been widely claimed that the CPS has had a significant effect on the production costs of manufacturers[6]. EEF (the UK manufacturers' association) has claimed that the Carbon Price Support currently adds between five and ten per cent to the energy bills of energy-intensive companies, making them less competitive on the international stage[7], and that energy prices and green taxes are worrying the industry more than any other issue[8].

This paper continues as follows; first a literature review is presented on how optimal climate change policy is modelled in practice and the economic effects of climate policy generally. Next we outline how we measure corporate solvency and provide an overview of the data used in this study. Finally, we present the results on the effects of the CPS on the corporate solvency of energy-intensive firms and draw conclusions.

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[6] Energy price increases are most strongly felt in manufacturing, as energy expenditures are larger here than in any other industrial sector. However, within manufacturing there are a number of industries whose products are exceptionally energy-intensive. We examine the effect of the CPS on these sectors specifically.
[7] See Shankleman (2014).
[8] See Groom (2014).

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Literature Review

The idea of using objective economic statistics to calibrate the optimal strictness of policy measures is not new. With regard to monetary policy, central banks may use measures of economic output, unemployment, inflation, and other economic statistics to determine interest rates and to decide when to smooth the business cycle or avert financial crises.

In the case of climate change, when policy optimisation is assessed formally, it is usually based on modelled cost-benefit assumptions and either analyses the best form that policy could take - for example taxes, permits, or subsidy[9], or prescribes an optimal level of stringency and timing for a particular policy based on historical market dynamics and a specified emissions goal[10]. Refinements of these models explore how the optimality of this policy is influenced by relaxing certain assumptions, such by assuming that the damages anticipated from climate change are uncertain[11], that abatement technology improves over time[12], or that abatement policies are nationally unilateral.[13] Other analyses reject a quantitative cost-benefit framework for assessing climate change policies altogether, arguing that the complexity of climate change demands a qualitative analytical approach[14].

Although the effects of carbon regulation on certain aspects of economic performance are well documented[15], the authors are not aware of any previous studies of the effect of environmental regulation on corporate solvency. Nor was it possible to identify previous research on general economic effects attributable to the Carbon Price Support specifically. In the UK, economic analysis of carbon taxes has primarily focused on the Climate Change Levy (CCL) which began in 2001. Early research on this tax by the industry lobby group 'The Federation of Small Businesses' found that, net of various compensatory dispensations, the CCL made 30% of Small and Medium-sized Enterprises financially worse off, with the primary losers involved in plastics processing, hospitality, and retailing[16]. Another survey-based study by industry found that 42% of professionals in the energy industry felt that the CCL had caused a net increase in business costs[17]. Conversely, later academic

[9] See Nordhaus (1993); Strand (2013); and Wirl (2012).
[10] See Golosov, Hassler, Krusell, and Tsyvinski (2014); and Roughgarden and Schneider (1999).
[11] See Nordhaus (1994); Pizer (1999), and Baker and Shittu (2008).
[12] See Gerlagh, Kverndokk, and Rosendahl (2009); Goulder and Mathai (2000); Requate and von Dollen (2008); Ploeg and Withagen (2014); and Weber and Neuhoff (2010).
[13] See Bohringer, Carbone, and Rutherford (2012); Eichener and Pethig (2013); and Felder and Rutherford (1993).
[14] See van den Bergh (2004).
[15] See for instance; Abrell, Ndoye Faye, and Zachmann (2011); Chan, Li, and Zhang (2013); Yu (2011); Zhang and Baranzini (2004); and Zhao (2011).
[16] Federation of Small Businesses (2002). The climate change levy: Another cost for small businesses
[17] London Electricity (2002). Climate change levy report

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research by Martin, de Preux, and Wagner[18] analysed the effects of the CCL by employing an instrumental variable for CCL incidence on microdata of firm performance. They found that, although the CCL had a strong negative impact on the energy intensity of production and electricity use, no statistically significant economic effects were observed with respect to; firm revenue, employment, or plant exit from the UK.

In this paper we measure corporate solvency by constructing Altman's Z-Scores; produced with financial data from energy-intensive firms in the EU's 5 main economies. Altman[19] was among the first to put forward a quantitative model to predict corporate bankruptcy using financial data, and his various Z-Scores (for different types of firms) have been widely applied in industry and in academic research. The most recently published Altman's Z-Score for private manufacturing firms is reproduced below[20].

$$\textbf{Z-Score} = 0.717\mathbf{X_1} + 0.847\mathbf{X_2} + 3.107\mathbf{X_3} + 0.420\mathbf{X_4} + 0.998\mathbf{X_5} \quad (1)$$

$\mathbf{X_1}$ = Working Capital/Total Assets

$\mathbf{X_2}$ = Retained Earnings/Total Assets

$\mathbf{X_3}$ = Earnings Before Interest and Taxes/Total Assets

$\mathbf{X_4}$ = Book Value of Equity/Total Liabilities

$\mathbf{X_5}$ = Sales/Total Assets

Although Altman's Z-score was originally developed as a tool to predict future default, like this study, previous research such as Sauer[21] has also used comparisons in Altman's Z-Scores over successive years to highlight variations in financial condition and alert firm management of the need to adjust strategy and operations. Altman[22] himself also advocates the use of his Z-Scores for the measurement of corporate financial risk generally, as opposed to bankruptcy specifically. Commensurate with this view, Platt and Platt[23] found that Z-score profiles for failing businesses often exhibit a consistent downward trend as they approach bankruptcy.

[18] Martin, R., de Preux, L., and U. Wagner (2014). The Impact of a Carbon Tax on Manufacturing: Evidence from Microdata. Journal of Public Economics, 117: 1-14.
[19] See Altman, E. (1968) Discriminant analysis and the prediction of corporate bankruptcy. The Journal of Finance, 23(4): 589-609.
[20] Altman, E. (1983). Corporate Financial Distress. Wiley Interscience, New York.
[21] Sauer, T. (2002) How may we predict bankruptcy
[22] Altman, E. (2002). Corporate distress prediction models in a turbulent economic and Basel II environment. NYU Working Paper No. S-CDM-02-11.
[23] Platt, H., and M. Platt (1991). A note on the use of industry-relative ratios in bankruptcy predicti. Journal of Banking & Finance, 15: 1183-1194.

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A number of other common models exist for predicting bankruptcy, perhaps most notable in the UK is Taffler's Z[24]. However, Taffler's Z would not have been ideal as the metric for this study as it is constructed from listed firms only and the additional data requirements of this model would have reduced our sample size to statistically trivial levels.

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[24] Taffler, R. (1983). The assessment of company solvency and performance using a statistical model. Accounting and Business Research, 15(52) 295-308.

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Data and Analysis

As the most recently publicized Altman Z-Score for private manufacturing firms is based off of US firms and is now dated[25], this study produces an updated Altman Z-Score for contemporary energy-intensive firms in the EU.

This updated Altman Z-score is constructed by applying Altman's Discriminant Analysis methodology to private energy-intensive firms in the UK, Germany, France, Italy, and Spain between 2000-2014. These advanced economies were chosen as it was thought that firms in these countries would have characteristics, such as technology and management practices, most similar to those present in the UK. Firms were deemed to be 'energy-intensive' (and therefore included in the initial sample) if the European Commission defined them as such according to their primary SIC codes (see Appendix). Financial data from the most recent year available was collected on firms which either gone bankrupt or were active from Bureau Van Dyke. All firms in the relevant industries which could be identified in their description as 'retail or wholesale trading', and therefore not actually manufacturing firms, were removed. This yielded a dataset of 6,777 active firms and 177 bankrupt firms.

Discriminant Analysis of bankruptcy was run on the variables X_1-X_5 in Equation (1) above, with the exception that the Retained Earnings variable was proxied by the related variable 'Shareholder Funds' due to lack of data. This exercise yielded the following results;

[INSERT TABLE 2]

The results in Table 2 show that these five combined factors are a significant determinant of firm bankruptcy. The coefficients produced by this discriminant analysis are stated below.

[INSERT TABLE 3]

Surprisingly, the X_2 coefficient yields a negative value, implying that, counterintuitively, increases in the (Shareholder Funds/Total Assets) ratio increases financial distress[26]. One possible explanation is that companies with relatively high proportions of equity (low leverage) could in fact indicate that the company in question is having difficulty raising debt because of business problems that are not captured by its balance sheet. There are 85 firms in our sample which have data on

[25] More recent Altman's Z-scores were identified such as Appiah and Abor (2009), but these failed to be both derived from EU firms and in the private manufacturing sector.

[26] Discriminant Analysis was also run with a random sample stratified by country and industrial sector of 177 solvent firms on the 177 bankrupt firms. However, all coefficients on the five financial ratios from this exercise were unexpectedly negative, suggesting problematic sampling error.

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Retained Earnings. For these firms the correlation between the original value of X_2 (Retained Earnings/Total Assets) and the proxied value of X_2 (Shareholder Funds/Total Assets) was found to be 0.47. Given that the coefficient on X_2 is close to zero, we could also attribute this result to error in our proxy choice for X_2.

In an analogous fashion to Equation (1), the coefficients in Table 3 are then combined linearly to produce a contemporary, EU-based, Energy-intensive Industry Altman's Z-Score model, and applied to the financial data described below. Again, data on corporate financials for energy-intensive firms in the UK, Germany, France, Italy, and Spain was collected from Bureau Van Dyke's Orbis database. This exercise produced a total sample of 16,223 firms. Internet research was then conducted in order to remove firms which were; (i) involved solely in the retail and wholesale trade of energy-intensive goods rather than their manufacture[27], (ii) UK firms which had any production facilities outside of Great Britain (including Northern Ireland), (iii) German, French, Italian, and Spanish firms which had production facilities outside of these same four 'control' countries, and (iv) firms which are listed on a stock exchange[28]. Naturally only firms which had published all required financial data to construct Altman Z-Scores for the 2012 and 2013 financial years were retained. This produced a sample of 463 firms, 74 of which were UK based.

[INSERT TABLE 4]

Note that the effect of year-on-year currency exchange rate changes to financial statement values and inflation cannot be responsible for measured changes in solvency using Altman's Z-score. This is because the input variables in Altman's Z-score consist purely of financial ratios, which by construction are dimensionless, and therefore require no adjustments to make different currencies or years directly comparable.

Figure 1 below plots the distributions of 2013 UK and Non-UK Z-Scores. We test whether the UK firm Z-Scores are below those of Non-UK firms using a Kolmogorov-Smirnov test for differences in distributions. Note that regression analyses are less appropriate in this case because we are primarily interested in determining the comparative financial condition of firms and not in isolating or quantifying the effect of the CPS.

[INSERT FIGURE 2]

[27] Orbis classifies firms involved solely in the retail and wholesale trade of energy-intensive goods as in the same industry as those firms involved in manufacture. For our purposes this is an erroneous classification.

[28] Listed firms were removed in order to ensure comparability. Researchers use different models and thresholds to categorise the solvency of listed and non-listed firms, and therefore it would not be clear how to integrate them together. In any event, only 6 listed firms remained after the selection criteria i-iii were applied.

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[INSERT TABLE 5]

Surprisingly, the Kolmogorov-Smirnov test finds that the UK Z-Scores were in fact significantly greater than those from Non-UK firms in 2013. This implies that firms under the CPS were in an even stronger financial position than those that were not. A possible explanation for this counterintuitive result may be that economic conditions were generally better in the UK than the Non-UK sample, as evidenced by increases in UK GDP throughout 2013 of 1.73% versus 1.06% (Germany), 0.28% (France), -1.93% (Italy), and -1.23% (Spain)[29]. Fixed-effects regression analyses in Appendix B also support the conclusion that macroeconomic improvements negated the solvency effect of the CPS.

The lack of an observed change in corporate solvency suggests that the financial position of UK energy-intensive firms was not, net of macroeconomic conditions, heavily impacted by the CPS at the end of the 2013 financial year. To examine this assertion, we compare 2012-2013 Z-Scores for energy-intensive firms in the UK only.

Visual inspection confirms the similarity of Z-Score distributions between 2012 and 2013 for firms in the UK-only, and as expected, the Kolmogorov-Smirnov test does not reject the null hypothesis of equivalence of the 2012 and 2013 UK distributions. This result also suggests that the CPS had not put undue financial pressure on the firms most affected by it.

As a further robustness check, we also examine the change in corporate death (bankruptcy) rates for energy-intensive firms in the UK between 2012-2013 in Table 7. Again we find that not only did corporate death rates for these firms not increase between 2012-2013, they in fact fell marginally.

[INSERT FIGURE 3]

[INSERT TABLE 6]

[INSERT TABLE 7]

[29] Source: World Bank Data, GDP growth (annual %).

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Discussion

The Effect of the CPS

Given that; (i) 2013 Z-Scores for energy-intensive firms in the UK are statistically higher than Non-UK Z-Scores, (ii) 2012 and 2013 UK-only energy-intensive firm Z-Scores are statistically indistinguishable, and (iii) that the death rate of energy-intensive firms in the UK in fact decreased between 2012-2013, we can infer that energy-intensive firms in the UK were not under undue financial pressure as a result of the CPS. Therefore, we would argue that the industrial outcry against the CPS and UK policymakers' decision to freeze it in response was unwarranted.

However, a number of qualifications to this result should be noted. To begin with, even when including the CPS, the magnitude of total carbon taxation in the UK currently almost certainly falls short of the level that would be required to achieve international climate change agreements. For instance, research by Anthoff, Tol, and Yohe[30] estimated the optimal social price of carbon at 60-200$/tn CO_2. Should the UK or other countries raise carbon taxation to such levels, the effect on carbon intensive industries could be dramatic. Indeed, the Carbon Price Support was slated to rise to 70£/tn CO_2 by 2030 in order to address this very need, but industry pressure caused policymakers to indefinitely postpone further increases from 2015.

Our results may also have been influenced by other policy changes that contemporaneously (2012-2013) occurred both in the UK and control countries. However, in spite of this qualification, the most significant new policy affecting energy-intensive industries in the five countries and timeframe under study was the CPS, and therefore the potential for this particular source of bias is limited. Furthermore, even if confounding effects from such policies do exist, this would not affect our conclusion that corporate solvency remained relatively robust following the introduction of the CPS.

There is also the criticism is that it may take longer than a single financial year for the full effects of the Carbon Price Support to materialise. Nevertheless, previous research that has investigated time-varying effects of environmental regulation on economic outcomes tends to find negative effects initially, followed by positive effects in subsequent years.[31] Moreover for this study, extending the treatment period in attempt to capture a prolonged negative effect would increase the time-frame around which contemporaneous policy changes could bias results. While it is almost certainly the case that solvency responses to climate-related legislation do

[30] Anthoff, D., Tol, R.S.J., and G.W. Yohe (2009). Risk aversion, time preference, and the social cost of carbon. Environmental Research Letters, 4(2): 024002 (7pp).

[31] Kozluk, T., and V. Zipperer (2013). Environmental Policies and Productivity Growth: A Critical Review of Empirical Findings. OECD Economics Department Working Papers, No. 1096.

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develop cumulatively over a number of years, over even longer timeframes it has been argued by Porter[32] and Porter and van der Linde[33] that properly designed environmental policies can stimulate innovation that may partially or even fully offset the costs of compliance. In addition, it has also been shown by Xepapadeas and DeZeeuw[34] and Commins, Lyons, Schiffbauer, and Tol[35] that increases in production costs due to a carbon price lead firms to increase average productivity. Hence, long-term negative impacts of a carbon tax might also be less than those measured over the shorter-term, and potentially even a net positive to firm performance (a potentially cooler future world notwithstanding). Finally, this criticism would be easily addressed in practice via the continuous solvency monitoring proposed here.

Another possible criticism against the result that the CPS did not have a strong negative effect on solvency is that, since the CPS was implemented through the tax system rather than as a framework established in statute (as the EU ETS is), its repeal and/or amendment is a comparatively simple exercise (as turned out to be the case). Hence, energy-intensive firms may have discounted the threat that the CPS posed to their future profitability. And even though the tax itself would have impacted corporate financials to a degree, firms may not have responded as dramatically as they would have if they had believed the CPS was credibly a long-term policy: for example, by investing in less carbon-intensive production methods.

In spite of these methodological and practical qualifications, given that the purpose of this exercise is to demonstrate the practicality of using corporate solvency to calibrate climate policy generally and not identify an effect on solvency specifically, we believe that this analysis of the CPS is still instructive.

Solvency Levels and Optimal Policy

The question of where the optimal solvency threshold should lie is important for the practical application of this policy. For instance, it could be argued that either; (i) an average solvency level, (ii) a minimum solvency level for the most financially distressed firm, (iii) or a maximum solvency loss should be the relevant benchmark. Moreover, the policy goal may not just be solvency for affected firms but also their competitiveness, in which case, depending on the regulations also faced by international competitors, the optimal lower bound for solvency may need to be

[32] Porter, M. (1991). America's Green Strategy. Scientific American, 264(4): 96-168.
[33] Porter, M., and C. van der Linde (1995) Toward a new conception of the environment-competitiveness relationship. Journal of Economic Perspectives, 9(4): 97-118.
[34] Xepapadeas, A., A. DeZeeuw (1999). Environmental policy and competitiveness: the Porter hypothesis and the composition of capital, Journal of Environmental Economics and Management, 37:165-182.
[35] Commins, N., Lyons, S., Schiffbauer, M., and R.S.J. Tol (2011). Climate Policy and Corporate Behaviour. Energy Journal, 32(4): 51-68.

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raised in Figure from financial distress to some other higher level. The universal availability and timeliness of financial data will also influence the optimal threshold level. Since the financial position of firms may deteriorate between financial reports, it may be prudent to adjust thresholds upwards to add a margin of safety against rapid solvency losses. Of course, as in any such policy, it would be essential to ensure that firms could not 'game' their financial statements in order to present an artificially dire picture to sympathetic regulators. It may also be the case that within a given emissions target, it would not be possible to maintain the solvency of all affected firms. In such cases the emissions target may need to take precedence over solvency concerns, but nevertheless the use of policy calibration via solvency could still be an efficient way to minimize whatever bankruptcies may be necessary to achieve the desired emissions goal.

Future research may look to refining the Altman Z-Scores produced above, or compare other methods for producing metrics of corporate solvency, such as conditional probability models. Such research could also quantify and operationalize the 'optimal' trajectory of corporate solvency depicted in Figure 1 according to specific industries, macroeconomic conditions, financial reporting regimes, and climate change targets. Historical instances of other significant environmental regulation such as the sulfur dioxide emissions trading programme in the US or automobile emissions standards could also be evaluated from the standpoint of optimal corporate solvency trajectories for affected firms, improving our understanding of the efficiency of these interventions, and potentially suggesting implications for the improvement of current and future environmental policies.

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Conclusion

This paper has introduced the concept of solvency targeting as a means for policymakers to efficiently calibrate the optimal severity of climate policies and/or the generosity of industrial compensation. This has a number of potential advantages, including, but not limited to being objective and dynamic (policy responds to changing observational data and this can happen as quickly as the data can be collected, processed, and assured), as well as transparent (provides clarity on policy objectives and the mechanism by which policy stringency changes).

To test this approach, we retrospectively applied a solvency based measure to the UK's recent Carbon Price Support (CPS) policy to see whether weakening of the policy was justified in terms of protecting energy-intensive companies. The evidence uniformly points to the conclusion that energy-intensive firms in the UK were not under any significant financial strain as a result of the CPS, and therefore that the postponement of CPS price increases was unjustified.

In order to meet climate change targets, governments will need to increasingly introduce strict carbon reduction policies. The use of an objective mechanism to calibrate the stringency of climate policy could become a valuable tool for mitigating the social costs of this climate change transition, potentially minimising opposition to climate change policies, as well as reducing the opportunities for companies to claim they are suffering unduly as a result of such policies.

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Figures and Tables

Figure 1: Solvency Trajectory for Industries Affected by Climate Policy

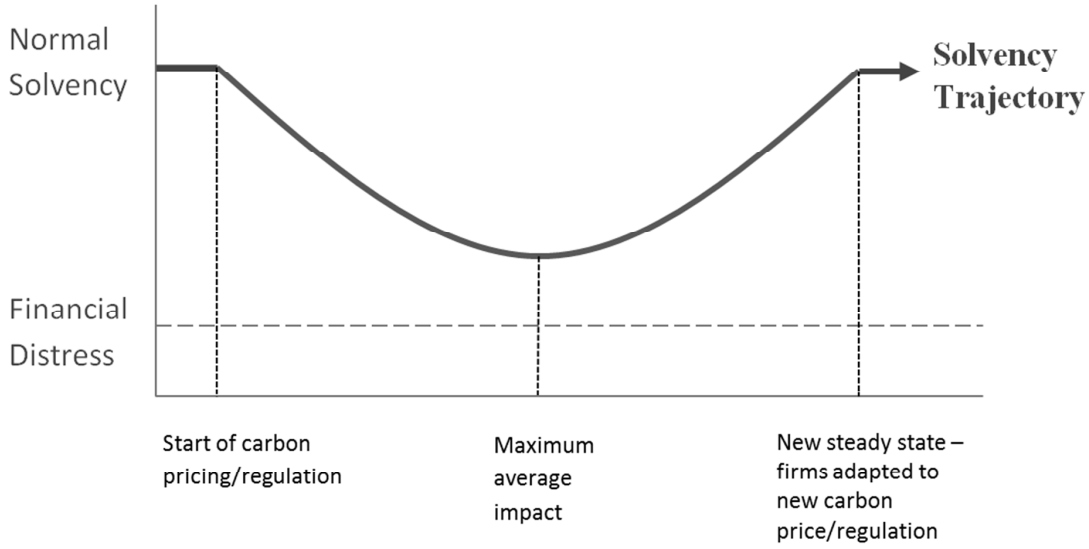


Table 1: UK Carbon Price Support History

	Announced	Start	End	Effect
Carbon Price Support (CPS) Tax on fossil fuels used to generate electricity (Northern Ireland Exempt)	March 2011	April 2013	April 2030	£4.94/ton CO2 in 2013, rising £9.55 in 2014, £18.08 in 2015 and incrementally to £30 in 2020 and £70 in 2030
CPS Price Freeze	March 2014	April 2014	April 2019	Frozen to £18.08/ton CO2 from April 1st 2015 until 2020
CPS Compensation Scheme	May 2014[36]	April 2013 (retroactively)	April 2020	Up to 80% of CPS paid returned for energy-intensive industries

Table 2: Discriminant Analysis Diagnostic Statistics

Canonical Correlation	Likelihood Ratio	F-Statistic	Probability
0.1317	0.98262	24.536	0.0000

[36] Approved by the EU Commission.

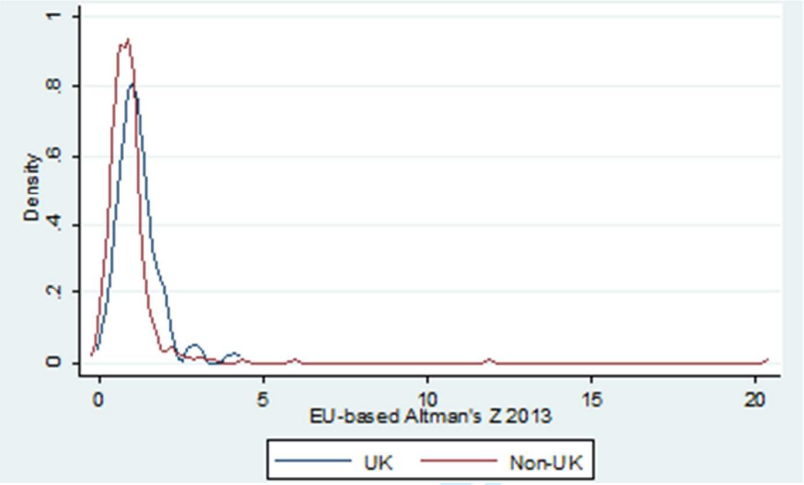
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Table 3: Discriminant Analysis Estimated Coefficients

X_1	0.9677312
X_2	-0.0472769
X_3	0.3463303
X_4	0.0632979
X_5	0.3756524

Figure 1: EU Energy-intensive Firms 2013 EU-based Altman's Z-Score Histogram; UK (n=74), and Non-UK (n=389)



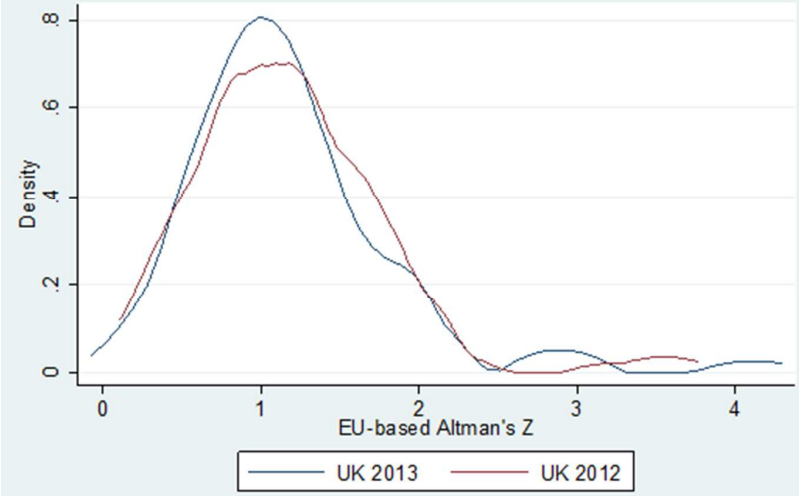
Kernel = epanechnikov, bandwidth = 0.1779

Table 5: Kolmogorov-Smirnov Test for Equality of 2013 UK and Non-UK Z-Score Distributions

	Largest Difference	**P-value**
UK > Non-UK	0.3001	0.000
UK < Non-UK	-0.0103	0.987
Combined Test	0.3001	0.000

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Figure 2: UK-only Energy-intensive Firms 2012 and 2013 EU-based Altman's Z-Score Histogram, (n=74)



Kernel = epanechnikov, bandwidth = 0.1779

Table 6: Kolmogorov-Smirnov Test for Equality of UK 2012 and 2013 Z-Score Distributions

	Largest Difference	P-value
2013 > 2012	0.0541	0.806
2013 < 2012	-0.0946	0.516
Combined Test	0.0946	0.895

Table 7: UK Business Deaths and Survival 2012 and 2013

	2012	2013
Deaths	665	690
Survival	6,190	6,410
Death Rate	10.80%	10.76%

Source: ONS Business Demography 2013. Represents annual data based on the 2007 SIC Code conversions of 2003 SIC Code data from Table 8 in the Appendix, and ending on November of the stated year.

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Appendix A

Table 8: European Union Official Energy-intensive Industries

2003 SIC Code	2007 SIC Code	Description
27.42	24420	Aluminium production
14.3	08910	Mining of chemical and mineral fertilizer minerals
24.13	20130	Manufacture of other inorganic basic chemicals
27.43	24430	Lead, zinc and tin production
18.1	14110	Manufacture of leather clothes
27.1	24100	Manufacture of basic iron and steel and of ferro-alloys
21.12	17120	Manufacture of paper and paperboard
24.15	20150	Manufacture of fertilizer and nitrogen compounds
27.44	24440	Copper production
24.14	20140	Manufacture of other orga nic basic chemicals
17.11	13100	Preparation and spinning of cotton-type fibres
24.7	20600	Manufacture of man-made fibres
13.1	07100	Mining of iron ores
24.16	20160	The following sub-sectors within manufacture of plastics in primary forms 24161039 – Low-density polyethylene 24161035 – Linear low-density polyethylene 24161050 – High-density polyethylene 24165130 – Polypropylene 24163010 – Polyvinyl chloride 24164040 – Polycarbonate
21.11	17110	The following sub-sectors within manufacture of pulp 21111400 – Mechanical Pulp

Table 4: Summary Statistics (n=463)

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	Min	Max	Mean	Standard Deviation
EU-based Altman's Z-Score 2013	-0.21	20.38	0.97	1.20
Δ EU-based Altman's Z-Score (2013-2012)	-2.62	11.35	0.04	0.67
Total Assets 2012 (£'000s)	8	3,060,205	32,019	171,384
Number of Observations				
Country				
UK	74			
Germany	33			
France	138			
Italy	216			
Spain	2			
Industry Sector				
Chemicals	156			
Metals	101			
Primary	7			
Textiles	146			
Paper	53			

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Appendix B

In order to test for the likely causes of the lack of a measured effect of the CPS on corporate solvency, we employ a fixed-effects estimation with respect to each firm's Altman Z-Score between 2012-2013. For control variables we use; Total Assets from the year before the CPS program (ie 2012), industrial sector, and change in macroeconomic variables: GDP, Inflation Rate, Unemployment Rate, and GBP Exchange Rate. Note that for non-UK firms, increases in the 'Δ Exchange Rate with GBP' variable corresponds to a strengthening of the Euro relative to the pound. For UK firms, the 'Δ Exchange Rate with GBP' variable is always zero.

A step-wise regression is run, sequentially incorporating first just the treatment variable (Carbon Price Support), second the firm specific controls, and finally the macroeconomic controls. We also run an interaction between the Carbon Price Support and Total Assets variable in order to test whether there may be a differential effect with respect to firm size; this might occur, for instance, due to economies of scale in the costs of CPS compliance.

A unique aspect of the Carbon Price Support as opposed to other studies of carbon prices is that approval for a compensation program for energy-intensive industries was not granted until over a year after the imposition of the tax (see Table 1)[37]. Hence, for the first year of the program the measured effect of the CPS on corporate solvency can be more accurately isolated.

[37] The EU ETS for instance used free permit allocations to affect this outcome, and countries imposing carbon taxes such as Finland, Sweden, and Norway all provided equivalent dispensations to their most vulnerable firms.

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Table 9: Fixed-effects regression by firm 2012-2013, n=463 (74 UK firms), EU-based 2000-2014 Z-Score.

VARIABLES	(1) Δ Altman's Z Fixed-effects	(2) Δ Altman's Z Fixed-effects	(3) Δ Altman's Z Fixed-effects	(4) Δ Altman's Z Fixed-effects
Carbon Price Support	-0.0101	-0.0325	-0.237*	-0.246*
	(0.0776)	(0.0823)	(0.132)	(0.137)
Total Assets 2012 ('000s)		-2.18e-08	-4.04e-08	-4.96e-08
		(1.79e-07)	(1.82e-07)	(1.86e-07)
Carbon Price Support×Total Assets 2012				2.34e-07
				(9.32e-07)
Metals		0.000290	0.0570	0.0581
		(0.0699)	(0.0869)	(0.0870)
Primary		0.0664	-0.00939	-0.00972
		(0.251)	(0.260)	(0.260)
Textiles		0.165***	0.211***	0.212***
		(0.0552)	(0.0802)	(0.0803)
Paper		0.0252	0.0508	0.0499
		(0.0925)	(0.106)	(0.106)
Δ GDP 2012-2013			0.333**	0.334**
			(0.152)	(0.153)
Δ Interest Rate 2012-2013			0.322	0.322
			(0.201)	(0.201)
Δ Unemployment Rate 2012-2013			0.772*	0.772*
			(0.422)	(0.422)
Δ Exchange rate with GBP 2012-2013			-0.867	-0.876
			(1.743)	(1.745)
Observations	463	463	463	463
R-squared	0.000	0.019	0.034	0.034

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1
Dependent variable is Δ Altman's Z-Score
Omitted industry sector dummy is Chemicals

As we can see from Table 9, with industry and macroeconomic controls the Carbon Price Support exhibits a statistically significant effect in the anticipated direction and at the 10% level, which can be considered significant given the one-tailed nature of this test. The macroeconomic control variables; 'Δ GDP' and 'Δ Exchange Rate' exhibit their theoretically expected signs, whereas the expected sign of 'Δ Interest

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For Review Only

Rate' and 'Δ Unemployment Rate' may be more ambiguous[38]. The control variables which demonstrate statistical significance are the Textile industry dummy, 'Δ GDP', and 'Δ Unemployment'. Although this analysis supports the conclusion that increases in GDP in the UK relative to control countries is responsible for the lack of a solvency loss as a result of the CPS, a notable limitation of these models is the low proportion of the total variance that the models explain.

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[38] For instance, net of GDP changes, increases in the 'Δ Unemployment Rate' variable could in fact be proxying for lower wage costs to the firm.

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Chapter 6

Title: Premature retirement of sub-critical coal assets: the potential role of compensation and the implications for international climate policy

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Abstract

To limit global emissions to a level consistent with a 2°C future, it is necessary to close 25% or 290GW of subcritical generation worldwide by 2020. The scale of proposed future premature closures might require compensation to be paid to asset owners. However, the potential role of compensation is not well understood. This paper provides an assessment of different models of compensation and sets out a possible international approach that could cost-effectively induce the closure of sub-critical coal assets through reverse auctions, minimising opposition to stranded coal-fired power stations.

Premature Retirement of Sub-Critical Coal Assets: The Potential Role of Compensation and the Implications for International Climate Policy

by Ben Caldecott and James Mitchell

Introduction

The international community needs to support pragmatic options for addressing the most significant contributors to anthropogenic climate change. One option, presented publicly by Christiana Figueres, executive secretary of the United Nations Framework Convention on Climate Change (UNFCCC), is the closure of subcritical coal-fired power plants. To limit global emissions to a level consistent with a 2°C future, it is necessary to close 25 percent or 290 gigawatts (GW) of subcritical generation worldwide by 2020.[1]

Since coal-fired plants are the least efficient and most greenhouse gas (GHG) intensive centralized generation technology, they are both vulnerable to regulation and a logical first step in any climate mitigation strategy. Furthermore, because subcritical plants typically represent the oldest part of nations' power generation fleets, they also represent a practical policy choice for closure by budget-constrained policymakers looking for cost-effective emission reductions.

While climate-oriented economic policy tools have typically enjoyed relatively broad support, the carbon prices necessary to close older subcritical generators are unrealistic under current political conditions. For example, an EU Emissions Trading System (ETS) carbon price of approximately USD $110/ton would be necessary to replace a typical existing coal-fired plant with a gas-fired plant in Germany; this is because an existing coal-fired plant needs only to cover its short-run costs whereas a new gas-fired plant needs to cover both short-run and capital costs.[2]

Strong evidence exists of the use and effectiveness of direct regulation in the closure of aging, highly polluting coal-fired generators worldwide. The rationale for closures varies from reducing carbon or particulate emissions to increasing fleet

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efficiency. Two examples of direct regulation can be found in the US and China. First, the U.S. Environmental Protection Agency (EPA) proposed direct regulations on new and existing power plants to limit GHG emissions. These GHG regulations, combined with impending Mercury Air Toxics Standards, are expected to close 60GW of coal-fired capacity in 2012-2020.[3] Second, China's Large Substitutes Small Program has required companies to close generators under 100 megawatts (MW), which are often the least efficient. This caused the closure of 77GW of capacity in the 11th Five Year Plan (FYP) (2006-2010) and is expected to cause the closure of 20GW of capacity in the 12th FYP (2011-2015).[4]

WHILE THESE CASES OF DIRECT REGULATION APPEAR TO BE INDUCING CLOSURE, THE SCALE OF PROPOSED FUTURE PREMATURE CLOSURES MIGHT REQUIRE COMPENSATION TO BE PAID TO ASSET OWNERS.

While these cases of direct regulation appear to be inducing closure, the scale of proposed future premature closures might require compensation to be paid to asset owners. Multiple arguments exist for doing this, but perhaps the most important is the need to 'buy out' political opposition to closures, which could delay or prevent a sufficiently ambitious closure program from taking place.

Still, the potential role of compensation is not well understood. Contemporary compensation literature focuses on the disbursement and auction strategies for carbon credits in schemes, such as the EU ETS, whereas compensation for the closure of generation assets by climate-oriented direct regulation is thus far unexamined.[5] Currently, energy sector mitigation models rely on the assumption that asset owners bear the costs of generator closures.[6] Given that subcritical generators represent 75 percent of worldwide coal-fired generation, and that compensation was paid to carbon-intensive energy generators in the form of carbon credits under the EU ETS and cash payments in the case of Australia's repealed carbon tax, this is not an assumption that policymakers can rely on.[7]

Better understanding of the precedents for compensation, identifying the best mechanisms for ensuring efficient compensation and value-for-money from finite public funds, and then developing politically acceptable compensation policies are critical for dealing with emissions from subcritical coal. In addition, by acknowledging the likely need of compensation early, more equitable results beyond the compensation of assets owners can be achieved.

Cases to Identify Compensatory Precedent

In order to better understand and predict the potential role of compensation in climate policy, three highly relevant cases are examined to identify compensatory precedent useful for predicting the potential role of compensation in future climate policies. These cases are the deregulation of US electricity generation, Australia's Contract for Closure program, and the Montreal Protocol. Each was selected

because of its relevance to the compensation for the premature closure of assets.

US Federal Energy Regulatory Commission Order 888

Federal Energy Regulatory Commission (FERC) Order 888 introduced competition into power generation in the U.S. electricity industry. Electric utilities and shareholders argued that they made investments because of specific government policies or because of incentives encouraging such investments. Now, with the introduction of competition, many assets, including power generators, were assumed to become stranded costs (the difference between the net book value of a generating plant limited to government-specified returns under rate-of-return regulation and the market value of that plant if it were required to sell its output in a competitive market) as competition drove electricity rates down and lower cost generators entered the market.[8] This was acknowledged in 1994 by the FERC, which agreed on whether stranded costs should be compensated if they were verifiable and directly related to the government's introduction of competition.[9]

Since Order 888, deregulation has taken place in seven of ten regional U.S. markets.[10] Ratepayers paid full compensation to firms for the introduction of competition into power generation; however, compensation was limited to assets that were the direct result of state or federal government policies.[11] Compensation for Order 888 was hotly debated and provides a robust theoretical framework with which to consider compensation for the closure of assets.

Australian Contract for Closure

Australia planned to implement the Contract for Closure program under the country's 2011 Clean Energy Future package, which meant the provision of AU$2 billion via the Contract for Closure program to "negotiate the closure of around 2000MW of highly emissions-intensive coal-fired electricity generation capacity by 2020."[12] After the selection of five coal-fired subcritical power generators for Contract for Closure in late 2011, negotiations for compensation payments began.[13] No agreements were reached by June 2012 and negotiations were cancelled in September 2012. This was due to disagreements about plant valuation.

Montreal Protocol and the Multilateral Fund

The Montreal Protocol and its implementation arm, the Multilateral Fund, represent the third case. The Protocol required that countries alter domestic policy in order to reduce production and consumption of ozone depleting substances (ODS). This success was the result of tense negotiations between developed and Article 5 nations about the issues of historical emissions, financial compensation, and intellectual property barriers.[14]

The Protocol established the US$2.7 billion Multilateral Fund, which directly compensates asset owners in Article 5 nations for closure costs and future profits as well as other losses. The inclusion of the Protocol provides the context with which

to consider compensation at the international level instead of solely domestically. Furthermore, the Multilateral Fund provides a particularly relevant case study given that it has advised the Committee of the Green Climate Fund—a potential source of international compensation money for mitigation.[15]

Grounds for Compensation

In the case of FERC Order 888, two rationales for the consideration of compensation in a U.S. context, legal and economic exist. The first rationale is legal. The Fifth Amendment—the takings clause of the U.S. Constitution—lays the legal basis for compensation.[16] Takings clauses generally require "the state to pay compensation when it takes property for public use."[17] In the case of infrastructure, this serves to reduce the regulatory risks for investors by "providing a guarantee against certain types of state actions."[18]

The legal 'takings' basis around FERC Order 888 was not clearly stated because the actual applications of the takings clause to infrastructure are along the lines of relational contracts, which infers that the terms are poorly specified because of the length and complexity of the relationship.[19] The validity of such protection for shareholders of U.S. public utility companies is debated along the lines of whether a contract exists between firms (including shareholders), regulators, and ratepayers.[20]

This relational contract holds two interpretations. The first interpretation states that the relationship between the government and firms was an explicit contract analogous to an agreement between two parties. Thus, because the introduction of competition diminishes a firm's revenues and returns as expected under rate-of-return regulation, a breach of contract has occurred and compensation is necessary.[21] This view is arguably extreme, given that no judicial ruling has ever required the payment of compensation for a regulatory action in the US.[22]

The second interpretation is that an implicit contract exists between firms (including shareholders), regulators, and ratepayers. The existence of an implicit contract rests on the difficulty of covering all contingencies in the contract between firm and government ex ante being an extremely costly procedure; as a result, judicial interpretation guided by efficiency and moral hazard ex post is necessary.[23]

The second rationale is economic. The two broad categories, equity and efficiency, make up the economic rationale. Arguments for compensation based on equity involve the distribution of risk. They hold that it would be unfair for shareholders to bear the full stranded costs of investments that were legally required on the behalf of utilities customers. Thus, customers should compensate utilities for a portion of stranded costs.[24] Work that found that returns for investors were too low to compensate investors for uncompensated deregulation further supported this view.[25]

Arguments about efficiency encapsulate concerns about long-term economic efficiency and total costs of outcomes. A main concern raises the issue that by not compensating for stranded costs, such costs will shift to other customers and shareholders. This, it is argued, will create a competitive asymmetry with new market

entrants who do not have to bear costs of uncompetitive assets.[26] A further concern is that the failure to compensate will lead to higher costs of capital in the future, as there would be some erosion of trust that government regulators will honor previous promises.[27] Those not in favor of compensation argued that no explicit or implicit contracts existed.[28]

The FERC allowed for the compensation of firms by ratepayers on the grounds of equity and efficiency based on the existence of an implicit contract between firms, government, and ratepayers. The cases of Australian Contract for Closure and the Montreal Protocol present major challenges to the application of these principles to the closure of subcritical assets by climate policies at the international level.

Relevance of Grounds of Compensation to Climate Policy Today

There are three precedents for compensation that are particularly relevant to climate policy. The first concerns government ownership of assets. If plants are government-owned, constitutional takings clauses (or their national equivalents)—the legal basis for claims of compensation—may be very complicated to apply. An assumption in FERC-related literature states that if government enacts policy that decreases the profitability of government-owned assets, the government takes the loss without compensation. This assumption is inadequate for the range of government company structures with private investors, such as in India.

In nations where compensation might be paid from international sources to the national government, this may raise issues of moral hazard.

Furthermore, in nations where compensation might be paid from international sources to the national government, this may raise issues of moral hazard (the situation in which a party is likely to take certain riskier actions because it does not bear the consequences of taking those actions) if there are private and government-owned generating assets.[29] Governments may have an incentive to compensate private firms less because they do not bear the costs of doing so. The Multilateral Fund overcame this issue by compensating asset owners directly.[30] However, these assets were privately owned.

Second, the basis of compensation on historical emissions within the Montreal Protocol suggests that compensation for the closure of generating assets by international policy will differ among countries according to their GHG emissions. In Montreal Protocol negotiations, India's strong dissenting voice made this a necessity for agreement. The nation's uncompensated transition costs would have accrued to US$1.2 billion, although it consumed only a small fraction of ODSs when compared with developed nations.[31] Thus, while considerations of contracts, efficiency, and equity may still apply in the consideration of how much to pay, it is

likely that the closure of assets in developing nations be paid by developed nations.

The third is that Australian Contract for Closure challenges the basis on which compensation is paid, and thus the purpose of compensation itself. U.S. electric utilities were subject to rate-of-return regulation and thus had nearly guaranteed rates of return. This allowed for the existence of an implicit contract. Compensation literature importantly assumes that competitive markets subject investment to bearing a large share of potential losses from risks, including regulatory risks.[32] When nations have a competitive market for power generation, the removal of the fundamental basis of compensation occurs.

Although Australia operates a competitive energy market where no guarantee of returns exist, Contract for Closure offered compensation to close five privately owned generators, despite theoretically having the ability to regulate their closure. Thus, there are alternative theories of compensation. Public choice theory suggests that compensation is actually discovered through a political marketplace. The purpose of compensation in this view is to buy-out groups with political clout that might otherwise obstruct policy making.[33] In this view, compensation principles as well as the political process produce the final outcome.[34]

Applications of this theory to issues similar to the premature closure of power stations are limited. One study investigates whether compensation is in fact a political buy-out. It models political economy and efficient compensatory outcomes between landowners, environmentalists, and taxpayers in hypothetical scenarios and concludes, "that compensation can prevent the exercise of political clout to impede socially desirable policies."[35] Despite the heavy criticisms of public choice theory, its conclusion, that compensation can be a sort of political buyout, is valuable for climate policy.[36]

The conclusion has particular relevance to Contract for Closure because the offer of compensation to close assets was extraordinary. In Australia, no previous precedent existed to suggest "that owners of capital assets should be compensated for changes in government policy that reduce the expected flow of income from those assets."[37] This raises questions about the purpose of compensation, suggesting that it is actually to reduce the incentive to lobby against legislation that would reduce profits from capital assets.[38]

Compensation Calculation Methods

Stranded costs came to be defined as "the difference between the net book value of a generating plant used for setting cost-based regulated prices and the market value of that plant if it were required to sell its output in a competitive market."[39] The FERC's recommended treatment and calculation of stranded costs in the U.S. uses the 'revenues lost' approach. This approach consisted of calculating annual expected profits under rate-of-return regulation, subtracting an annual competitive market value estimate from that, and then multiplying by the amount of years the utility could have expected to serve the wholesale customer.[40] Based on these estimations, the establishment of consumer surcharge mechanisms occurred in order

to enable utilities to recover stranded costs from ratepayers over time by comparing actual usage with the projected rate-of-return regulation scenario.[41]

The approach to compensation for ODS-manufacturing plant closures is similar, with the only difference in the approaches, taken by the Multilateral Fund, being that net present value (NPV) calculations are made to calculate lump sum payments. These lump sum payments are then made directly to asset owners. Criteria for calculating compensation for closure of ODS-producing plants are that NPV calculations should be made using "assumed profit margins, discount rates to be used in calculating the NPV of the profits forgone, inflation rates, projected production growth rates, remaining useful life, parameters on prices and costs."[42]

The approach taken by Australia in Contract for Closure did not define that for which plants would be compensated. The program sought to "negotiate the orderly exit, by 2020, of around 2,000MW of highly emissions-intensive coal-fired electricity capacity."[43]

Complications of Compensation Calculation Methods

Two issues arise which complicate the simple calculation of compensation based on future profits of generators. The first issue is net stranded costs. Writing about FERC Order 888, Hirst raises this issue, which states that utilities may have both stranded costs and stranded margins.[44] Thus, to avoid the over estimation of stranded costs, the net stranded costs of firms should act as the basis of compensation instead of gross stranded costs. Both stranded costs and margins are calculated by comparing actual profits or losses with a 'business as usual' scenario in which generation assets remain under rate-of-return regulation.[45]

Burtraw and Palmer, who model the effects of a hypothetical climate policy on US electric utilities, have more recently taken up this line of reasoning. They show that value-losing facilities lose US$50 billion in aggregate value under a hypothetical cap-and-trade policy. However, they find that the net lost value of only value-losing firms would be US$15 billion. The aggregate of the losses and gains of all firms is US$9 billion.[46]

The second issue is that of full or partial compensation. This is presented separately for the sake of clarity; however, it cannot actually be separated from issues of net compensation because of the likelihood of differing opinions about whether compensating at the firm or industry level constitutes partial compensation in itself. Here, it can be thought of as a further subset of stranded costs.

Considerable consensus in the literature favors the support of partial compensation for FERC Order 888. Martín argues that it may actually be more equitable to compensate partially than to compensate fully. If there is a guarantee of full stranded cost recovery, incentives will disappear for mitigating stranded costs, renegotiation of long-term obligations, aggressive marketing of available energy capacity, and avoidance of additional "strandable" investment. This would unfairly put firms who made actions to mitigate stranded costs at a disadvantage. Thus, he recommends partial compensation for utilities' stranded costs and allowing utilities

to retain a proportional amount of gain from mitigation strategies.

Relevance of Compensation Calculation Methods to Climate Policy Today

Subcritical power generation represents approximately 75 percent of worldwide coal-fired power generation.[47] Given that it is necessary to permanently close 25 percent of that by 2020[48] and that such closures will undoubtedly have to happen with limited funds, limiting compensation to asset owners is necessary.

Precedent suggests that offering less-than-full compensation is fair, reasonable, and pragmatic. It is fair because it does not erase the benefits to investors that transitioned to lower-carbon forms of generation before they were forced to by plant closures, which is an analogous argument to Martín's. It is reasonable because the delay between the global realization of the need to reduce GHG emissions, for which Burtraw and Palmer suggest the 1992 UN Conference on Environment and Development, and the realization of the goal provided investors ample time for "the realization of value from previous investments and the opportunity to alter new investments."[49] It is also pragmatic because it recognizes that compensation is likely to be part of the equation in any large-scale mitigation scheme (e.g. EU ETS, repealed Australian carbon tax).

Precedent suggests that offering less-than-full compensation is fair, reasonable, and pragmatic.

However, "in the case of closures caused by climate policy, governments need to be mindful of any precedent this would set."[50] The decision to compensate fully or partially for the closure of subcritical coal generators is likely to become precedent for further mitigation actions and policies. Funds for compensation will undoubtedly be limited, so the ramifications of creating precedent on levels of compensation may well determine the financial viability of later mitigation policies.

In determining how much to pay in compensation for the closure of assets, US deregulation and Contract for Closure offer valuable precedents. The ultimate failure of Contract for Closure was due to a large disparity in what firms requested (in terms of compensation) to close plants and what the Australian government was willing to offer. This is evinced by the Hazelwood generator's purported AU$3 billion self-valuation[51] and the government's total budget for the program: AU$2 billion.[52] Writing about US deregulation, Martín captures the problematic nature of valuing assets for public policy. Valuation is largely a function of estimated future profits. Thus, valuations based on future profits can become dynamic and politically malleable.

In order to limit compensation, policies need to be built in anticipation of political contestation. The establishment of a robust and equitable frame that defines which parties can participate and how those parties can participate can create an

effective way to do this. Definition of roles and involvement will help contain political contestation and escalation of compensation. The highly contested negotiations for the Montreal protocol suggest that this may also increase the probability of policy success.

Policy Proposal: Coal Closure Funds and Reverse Auctions

Proposed here is the use of compensation to close subcritical generators through the establishment of Coal Closure Funds (CCFs) and operation of reverse auctions. Countries (together or separately) could create CCFs that would be set up with taxpayer funds, through a levy on energy bills, and/or contributions from donors, philanthropists, and individuals. CCFs would pay owners of coal-fired power stations to permanently retire their assets. The assets would then be made inoperable, opposed to simply being 'mothballed.'

CCFs would operate by organizing a series of reverse auctions. Owners of coal-fired power stations would bid to receive a fixed price for each unit of generation capacity retired. The lowest bids would win the auction. Similar reverse auctions have been successfully used to reduce the number of fishing vessels and fishing permits in overfished areas, or to buy back abstraction licenses in areas suffering from water stress. Auctions could be run annually and could cover power stations in one country, regionally or globally, depending on the geographical scope of a CCF. Auctions could also be run for specific types of coal-fired power stations or those within a certain age range.

CCFs could also operate with a "degression" to incentivize coal owners to accept compensation sooner rather than later. For example, it could have a price cap for each auction and this would fall by a certain percentage each year. It could also offer more in total funds in early auctions and reduce the compensation kitty for later auctions. The result is that owners might be more likely to secure a better price the earlier they bid, encouraging early action.

In the U.S. and EU, where many coal-fired power stations are over thirty years old, the additional cost of inducing early closure could be relatively small as plants are nearing the end of their technical lives. There are also many investors who might jump at the chance of reducing their exposure to the regulatory and reputational risks associated with coal. As a result, relatively small CCFs could quickly close a large number of coal-fired power stations.

In other countries, particularly China and India, where large fleets of coal-fired power stations are newer, the funds required would have to be commensurately larger. Here, CCFs could concentrate on the oldest and most polluting power stations first. In addition, donor governments helping to pay for CCFs in developing countries, as well as early US and EU CCF implementation, could be part of a grand bargain to secure international climate action.

Notes

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7. Conclusion

This thesis represents the first comprehensive attempt to provide conceptual and scholarly coherence to the topic of stranded assets and the environment. In addition to reviewing the current state of the literature, the first two chapters shed light on how the topic developed and emerged, notably through a unique first-person account based on autoethnography and close dialogue. This account provides important context, and significantly, provides scholars with new materials and insights through which they can develop more objective views of how the topic developed, particularly among central banks and financial institutions.

The thesis has demonstrated the wide applicability of stranded assets, and has furthered existing, relatively well-developed literatures (namely carbon budgets and stranded costs) and also two much less developed literatures (namely the calibration of climate policy to minimise stranded assets and policy mechanisms to quickly and efficiently strand assets) through four self-contained papers.

In chapter three we found that NETs could extend carbon budgets and potentially reduce the risk of carbon intensive assets becoming stranded assets. This is a key uncertainty for the scale of future asset stranding from unburnable carbon. Although we found that NETs might be able to extend carbon budgets given optimistic assumptions, this is sufficiently uncertain and costly that actors should be sceptical of NETs being able to alter their exposure to asset stranding.

In chapter four we found that many recently built, high-efficiency gas-fired power stations had been stranded across Europe due to a combination of environmental regulation and renewables deployment, having a significant impact on firm value and strategy, as well as generating regulatory challenges for UK and German policymakers. We also found governance and policy gaps at national and regional levels within the European Union regarding the appropriate treatment of stranded assets in the process of electricity market decarbonisation. Remedying these issues will be important for a successful low carbon transition in the power sector.

In chapter five we found that measures of corporate solvency could be used as an objective tool for policymakers to calibrate the optimal magnitude of climate change policies, thereby maximising decarbonisation for the least amount of stranded assets. We successfully tested our approach on the UK's Carbon Price Support. This research spoke to four important topics. First, how to minimise the stranded assets and social costs associated with delivering decarbonisation. Second, how to make climate policies as objective as possible, as well as transparent, so that decisions are aligned with emissions targets and that assumptions underpinning decisions are clearly communicated to markets. Third, providing mechanisms that are potentially robust to likely lobbying from fossil fuel interests. Fourth and more speculatively, building on nascent interest from

central banks and financial regulators in climate change topics and exploring the potential to collaborate with or learn from this important community.

In chapter six we evaluated different models of compensation to owners of power generation assets, to see which models might be appropriate. Significant premature closures in the future might require compensation to be paid in order to diffuse political economy 'frictions' created by asset stranding. We proposed a novel international approach that could cost-effectively induce the closure of sub-critical coal assets through reverse auctions, minimising opposition to stranded coal-fired power stations.

7.1 Research opportunities

While much has been written on stranded assets in a short period of time, there remain significant gaps in the literature concerning what drives asset stranding and under what circumstances. Perhaps the most glaring imbalance in the literature has been the continued focus on listed upstream fossil fuel producers, particularly international oil companies listed on the New York and London stock exchanges. These companies own less than 5% of total global oil and gas reserves, versus the disproportionate amount held by states through national oil companies and other state-owned enterprises (Stevens 2016).

Upstream oil and gas production is just one of many sectors of the global economy that merits analysis and research on stranded assets. Studies have attempted to rebalance away from this focus on upstream energy to downstream (Caldecott & McDaniels 2014; Caldecott et al. 2015; Caldecott, Kruitwagen, et al. 2016) and midstream (Marks 2016), as well as to focus on sectors outside of energy, such as agriculture (Rautner et al. 2016; Morel et al. 2016; Caldecott et al. 2013), food (Howard et al. 2014), residential property (Muldoon-Smith 2015), and shipping (Prakash et al. 2016). Sectors where there are as yet unrealised opportunities for stranded assets-related research include transport, tourism, commercial property, and fisheries, among others.

This sector imbalance in the current literature is combined with a geographical one. Much of the work on stranded assets has focused on sectors in Australia, Canada, China, Western Europe, the Middle East, and the United States (Caldecott, Harnett, et al. 2016). There is comparatively little work looking at these issues in Africa, the Caribbean, Central Asia, Eastern Europe, Latin America, South Asia, or Southeast Asia (Caldecott, Harnett, et al. 2016). This is a significant omission, given the exposure of many of these regions to environment-related risk factors, the presence of extensive fossil fuel resources that may become unburnable, and the particular challenges and opportunities facing lower income and emerging economies.

In addition to these sectoral and geographical discrepancies, there are significant gaps in the literature on the environment-related risks that could strand assets. The risks that are perhaps best understood and where the most work has been done to quantify and

measure impacts spatially and temporally with good degrees of confidence, have been in relation to physical environmental change. For example, research to understand physical climate impacts, such as precipitation, flooding, heat waves, and other extreme weather events is significantly more mature in comparison to research focused on societal forms of environment-related risk, such as policy and regulation, norms, and litigation. So while we have sophisticated models that are used to dynamically estimate future flood risk, we have nothing nearing this capability in relation to estimating how regulation will impact sectors of the economy.

This divide in the breadth and depth of capabilities between the physical and the societal has two main origins. First, research on physical environmental change has been going on for much longer, arguably since the 1800s (for example Tyndall 1863), while research on societal responses to such changes is much more recent (see previous section). Further contributing to this is the fact that societal environment-related risks inevitably follow from physical ones as there is a lag-time between impacts being felt and understood, and societies responding to them.

Second, physical processes are observable and measurable, and consequently causal relationships are more readily established. As such, future outcomes can be estimated and quantified, whereas attempting to understand how societies singularly and plurally respond to anything, let alone environmental change, is fraught with difficulty. There is also a disciplinary gap between scientists and physical geographers on the one hand, and social scientists and human geographers on the other. The former are bound together by common modern scientific methods, whereas the latter straddle a far wider range of approaches and perspectives, some of which are in direct conflict with one another.

Enhancing our understanding of societal environment-related risks is a priority and one that the topic of stranded assets has taken on directly – after all the topic emerged from a concern with such risks (e.g. unburnable carbon and the carbon bubble). Another opportunity is bringing together physical and societal environment-related risks into the same framework. While stranded assets has also explicitly attempted to do this (see Figure 1 in Chapter 1 and Caldecott et al. 2013), it has been constrained by a lack of research attempting to understand the relationships and correlations between the physical and the societal, and between different types of societal risk (see Caldecott, Dericks, et al. 2016). For example, how does an increased frequency of extreme weather events impact social norms; how does that affect the likelihood of successful climate litigation; and how could this then change regulation that aims to support renewable energy deployment? Stranded assets are in large part going to be the result of these chains of causality, but little is known about how they emerge and how this might differ between different jurisdictions with different political, legal, and cultural traditions. It is self-evident that developing a better understanding of these issues will require an interdisciplinary approach.

Temporary versus permanent asset stranding is also a gap in the literature (Caldecott, Harnett, et al. 2016; Caldecott & McDaniels 2014a). This is the distinction between an asset that is devalued due to falling commodity prices or mothballed until market conditions improve and an asset that is closed down, dismantled, and no-longer operational. The distinction is of particular importance to civil society and policymakers, where there is an interest in permanently stranding polluting infrastructure in order to achieve environmental outcomes (Caldecott, Harnett, et al. 2016). There is also the related issue of residual value, even from a permanently stranded asset, for example the value of materials or chattels that can be resold. Caldecott & McDaniels (2014) identified how stranded gas-fired power stations in Europe have had their turbines removed and then exported to other jurisdictions – an example of such residual value being captured. Accountancy as both a profession and a discipline has much to contribute here and existing accounting rules and standards can be used to determine the relevant boundaries between them when appropriately interpreted (Caldecott et al. 2014; Association of Chartered Certified Accountants & Carbon Tracker Initiative 2013). These concepts are not new, nonetheless they are largely absent from the current literature on stranded assets.

The mirror to residual value are sunk costs, which are costs that cannot be eliminated, even by total cessation of production (Baumol & Willig 1981). In classical economic theory sunk costs are excluded from future business decisions, because the cost will be the same regardless of the outcome of a decision. In practice, the evidence suggests that sunk costs are regularly included in decision making. Through behavioural experiments Kahneman & Tversky (1979) set out how loss aversion leads to the 'sunk cost fallacy', which is the tendency to continue with activities already invested in even if such activities are not economically rational. Sunk costs and their potential to influence decision making in the context of stranded assets is another rich seam currently absent in the literature. The role of loss aversion in exacerbating the problem of stranded assets by encouraging companies and investors to 'throw good money after bad' could be a significant problem that needs careful and urgent attention.

Another distinction largely absent from the current literature is in relation to the differences between physical (or tangible) and non-physical (or intangible) assets. Most of the literature has focused on the stranding of physical assets, largely ignoring the latter. Ansar et al. (2013) is one of the few examples of work that examines how the stigmatisation of firms can affect reputational assets and the ability of firms to retain human capital. Caldecott & Rook (2015) also look at how investment consultants could strand their reputational and relational assets by not appropriately integrating sustainable finance theory and practice into the advice they provide asset owners. Non-physical assets – from brands, relationships, intellectual property, organisational capital, research pipelines, software, and human capital – require a much more substantial treatment in the stranded assets literature. This is particularly the case given that investment in non-physical assets exceeds that in physical assets in many developed countries, a trend that appears to accelerate as economies become more developed (OECD 2012).

Perception of environment-related risk and the behaviours that may or may not result from different perceptions is of central importance to stranded assets as a topic of interest to researchers and practitioners alike. If environment-related risks were observed, their materiality understood, such factors properly integrated into decision-making, and then acted on, stranded assets would be a much less knotty problem. But such risks are often not observed, let alone understood or acted on. Even when environment-related risks are observed, material, understood, and options exist to act on and manage such risks, institutions and individuals may still not act. This tendency results in mispricing and the misallocation of resources, including by governments, companies, and financial institutions.

There are likely to be many reasons for this. Kay (2012) refers to endemic short-termism in financial markets and Carney (2015) echoes this with his 'tragedy of the horizon'. Remuneration incentives, principal-agent problems, governance arrangements, organisational culture, liquidity requirements, misinterpretations of fiduciary duty, and diffuse shareholder ownership have all been cited as factors that contribute to the de-prioritising of the long term in favour of the short term (Caldecott & Rook 2015). Efforts to address these factors and extend the horizons of decision-making will probably make addressing stranded assets easier, particularly as many environment-related risks are likely to become more acute over time, with a subset only materialising in a significant way over the medium to long term.

However, there could be issues specific to environment-related risks that make them more challenging to grapple with than other risks. There are a number of reasons to think that this could be a possibility: the environment-related risks in question are largely novel; understanding them is complex and often requires an interdisciplinary approach that straddles the physical and social sciences; contemporary and historical data is sparse; and many of the risks are non-linear (Caldecott 2015). Unlike some other risks that governments, companies, and investors face, there are also a lack of viable options to hedge risk, and when these exist, they are relatively illiquid and immature (Caldecott 2015).

If correct, these hypotheses would have significant implications. Extending time horizons may not be sufficient to properly integrate environment-related risks into decision-making. Such risks may require further foregrounding for decision-makers and this may make regulatory responses, as opposed to voluntary ones, much more appropriate. This is an area that merits further consideration, particularly given the current focus on voluntary actions to support the integration of environment-related risks into decision-making, such as the Task Force on Climate-related Financial Disclosures (TCFD 2016).

Another hypothesis that requires further research is the idea that asset stranding caused by environment-related factors is likely to be more significant and places more value-at-risk than previous periods of 'intensive' stranding seen in the transition periods between

TEPs. Moreover, how did societies manage previous periods of intensive stranding and are there lessons that can be divined from these experiences? These are important questions for situating stranded assets within economic history and theories of economic growth and development. They are questions that would benefit from engagement with economic historians, who are yet to interact with the current discourse on stranded assets.

Stranded assets has been appropriated in unexpected ways too. For example, it has been used as a catalyst to help reconceive Protected Areas (PAs) as productive spatial assets (Caldecott & Jepson 2014; Jepson et al. 2015). The reframing of PAs in this way and the implication that such PA assets can become stranded, is being tested among nature conversation scholars and practitioners as a way of more effectively restating the case for PAs (Caldecott & Jepson 2014; Jepson et al. 2015). It could also have significant implications for PA management planning and the ability of PAs to attract investment and better manage risk (Caldecott & Jepson 2014; Jepson et al. 2015). There could be opportunities for the concept of stranded assets to be used in other areas not originally envisaged and this should inform how those working on stranded assets seek to engage with other disciplines.

These opportunities for further stranded assets-related research could better connect our understanding of physical and societal environment-related risk; improve our knowledge of perception and behaviour; expand the scope of work into new sectors and geographies; and put stranded assets into a historical perspective. This is a significant future research programme that needs to be properly situated to be successfully realised.

Reflecting on this, the thesis makes the case for economic geography as the disciplinary home for stranded assets. The sub-discipline can both contribute to the development of stranded assets as a scholarly endeavour and itself benefit from interacting with a topic that intersects with some of the most pressing contemporary issues related to environmental sustainability. It can help stranded assets to both develop firmer foundations and also explore new areas by providing ideas, concepts, and methodologies that can be usefully employed in answering the research questions identified in the thesis. Importantly, it is a discipline supportive of producing research that interacts with and speaks to a range of practitioner audiences and one that is suitably adaptable so as to encourage inter-disciplinary research.

This proposition should be attractive to economic geographers. Stranded assets has the virtue of fitting into a number of current and recurring themes within economic geography. Economic geography must do better in relation to environmental topics and stranded assets can provide EEG the opportunity to live up to its much vaunted potential. Stranded assets can also help economic geography reach new audiences and address the 'missing geographers' problem.

Economic geography's healthy scepticism of neoclassical economics and stylised facts, as well as its long-standing appreciation of behaviour and cognition, means that it is well

positioned to examine the reasons stranded assets can happen and why this matters. The consistent focus of economic geographers on spatial disparities, inequalities, and the rise and fall of different firms, sectors, regions, and countries means that the sub-discipline has a lot to offer in terms of understanding how stranded assets could cause or change these processes. In addition, the geography of finance's focus on the globalisation of finance and empirical work to understand processes and behaviours within finance can also be productively utilised to shed light on questions related to stranded assets and financial institutions.

While the growing diversity and appeal of stranded means the topic can draw on a wide range of disciplines, this approach has a concomitant risk – that it is spread too thinly and then fails to establish itself properly. This is arguably the most significant risk to the future development and longevity of stranded assets as a topic of both 'real world' interest and sufficient academic rigour.

7.2 Limitations and final reflections

This project has generated significant and novel contributions to an important emerging topic. Beyond the direct contribution of the four papers and the first-person account based on autoethnography and close dialogue, the D.Phil. project has made other contributions. First and foremost, its various projects have helped to galvanise a growing network of practitioners and scholars internationally to engage with stranded assets and apply its concepts to a range of research problems. This is hugely encouraging and this may now be self-sustaining. Second, through research that forms part of the broader D.Phil. endeavour (see Annex I for further details) change appears to have materialised in the real word – environment-related risks that were not considered before are now being considered, and at the margin, this may have helped to shift resources away from polluting activities and towards more sustainable ones. While this trend could be inevitable, this work may have had some small role in speeding up the consideration of such issues by an array of key decision-makers.

In the thesis I have argued strongly for economic geography to embrace stranded assets and vice versa. I came to this view through the process of the D.Phil. project and consequently none of the papers (or the journals targeted) have not been situated directly in economic geography. This is an omission that was unavoidable (I have only come to realise that economic geography is the right disciplinary home for stranded assets after doing the work and writing the thesis), but it is something I intend to correct in the future by producing work situated in economic geography and by encouraging economic geographers to engage with stranded assets.

If the four papers had been written and designed from the outset as economic geography papers, then I would be inclined to focus more on the distributional implications of NETs between countries and regions; the institutional causes of divergence between UK and German policymakers and regulators concerned with power markets; how measures of

corporate solvency might be complemented by other objective metrics, particularly focused on company relationships in industrial agglomerations and regions; and the social implications of compensation for stranded assets, particularly in terms of North-South flows and the capacity of institutions to disperse funds.

While I would argue that the first-person account contained in the thesis is a key strength, its subjective nature is also a potential weakness. I regret that due to constraints, particularly in terms of confidentiality, that more direct quotes from collaborators, partners, and colleagues have not have been used in the account. And although extensive materials and data have been used to comprehensively cross check and verify the recollection described in my first-person account, there will undoubtedly be different perspectives and interpretations of the events set out. There are also likely to be instances that I have neglected to mention due to space limitations or concerns about the flow and readability of the account, and possibly also due to straightforward errors on my part. Finally, the account should be considered in the context of work conducted by others that have worked on stranded assets and I hope that it spurs some reflection among others involved in making stranded assets the important topic that it has become today.

Though the D.Phil. project has partially answered some pressing questions, many more have also been raised. Simply, answers to these could help societies successfully manage environmental change and the transition to environmental sustainability. But answers of satisfactory quality will be less likely unless stranded assets becomes grounded in economic geography. This is critical for the next phase of the endeavour, not least as the topic extends into new spatial, temporal, behavioural, and cultural domains.

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Annex I: Author publications

This annex contains a list of publications that I have authored or co-authored on stranded assets. Not all of these have been referenced in the thesis, hence providing them here for the record.

Reports

Caldecott, B.L., Harnett, E., Cojoianu, T., Kok, I., & Pfeiffer, A. (2016) *Stranded assets: a climate risk challenge*. Report. Inter-American Development Bank (Washington, D.C., USA).

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Kruitwagen, L., MacDonald-Korth, D., & Caldecott, B.L. (2016) *Environment-related risks and the future of prudential regulation and financial conduct, 4th Stranded Assets Forum, Waddesdon Manor 6th March 2015*. Summary of Proceedings. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

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Caldecott, B.L. (2016) Diesel deception: the Volkswagen emission scandal and its aftermath. *Panel discussion*. 11th March 2016. Environmental Change Institute, University of Oxford (Oxford, UK).

Caldecott, B.L. (2016) The future of coal: implications for public policy and investors. *Institute of International and European Affairs Lecture*. 4th March 2016. Institute of International and European Affairs (Dublin, Ireland).

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Caldecott, B.L. (2016) Stranded assets: why should investors worry? *1st Stranded Assets Forum New York City*. 28th January 2016. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK) and Ceres (Boston, USA).

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development pathways are resilient to asset stranding. S*tranded assets and Multilateral Development Banks workshops*. 16th – 17th November 2015. Inter-American Development Bank (Washington, D.C., USA).

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Caldecott, B.L. (2015) Stranded assets and coal-to-liquids, coal-to-gas, and underground coal gasification. *Roundtable on coal-to-liquids, coal-to-gas, and underground coal gasification*. 10th November 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK)

Caldecott, B.L. (2015) Encouraging finance to flow to low carbon infrastructure. *University of Oxford-Jiangsu Province Low Carbon Policy Seminar*. 26th October 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK)

Caldecott, B.L. (2015) Introduction to the forum and how stranded assets relate to financial regulation. *4th Stranded Assets Forum: environment-related risks and the future of prudential regulation and financial conduct*. 23rd October 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK) and The Rothschild Foundation (Waddesdon, UK).

Caldecott, B.L. (2015) Road to Paris: taking the Wall Street shortcut. *Energy Symposium 2015*. 17th October 2015. Harvard Business School (Cambridge, USA).

Caldecott, B.L. & Jepson, P. (2015) A framework for Protected Area asset management. *Project for Protected Area Resilience launch event*. 8th October 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK) and JP Morgan (London, UK).

Caldecott, B.L. (2015) Stranded assets in forests and agriculture. *Chatham House Roundtable*. 1st October 2015. Royal Institute of International Affairs (London, UK).

Caldecott, B.L. (2015) Stranded assets and fossil fuel divestment. *Pioneering energy talk series*. 30th September 2015. Royal IG Windkraft (Vienna, Austria).

Caldecott, B.L. (2015) Resource scarcity, stranded assets, and what to do about it?: A case study of water stress and subcritical coal-fired power stations. *PRI in Person 2015: how are active owners tackling resource scarcity?* 8th – 10th September 2015. UN Principles of Responsible Investment (London, UK).

Caldecott, B.L. (2015) Stranded assets and development: ensuring low carbon development pathways are resilient to asset stranding. *Sino-UK sustainable low carbon transition seminar*. 29th – 30th July 2015. Foreign & Commonwealth Office (Shanghai, China), Smith School of Enterprise and the Environment, University of Oxford (Oxford,

UK), and Jiangsu Information Center (Nanjing, China).

Caldecott, B.L. (2015) Low oil prices and the role of the G20 in market stability. *The impact of low oil prices and the role of G20 in global energy governance*. 27th – 28th July 2015. Shanghai Institute for International Studies (Shanghai, China).

Caldecott, B.L. (2015) Stranded assets and subcritical coal: the risk to companies and investors. *HSBC Expert Roundtable*. 22nd July 2015. HSBC (Hong Kong, Hong Kong).

Caldecott, B.L. (2015) The future of UK gas production and supply. *Parliamentary Office of Science and Technology (POST) Roundtable Briefing: The Future of Natural Gas*. 16th July 2015. Houses of Parliament (London, UK).

Caldecott, B.L. (2015) Stranded assets: from investment hypotheses to investor action. *Thinking Ahead Institute Topical Day: Stranded Assets*. 6th July 2015. Towers Watson (London, UK).

Caldecott, B.L. (2015) Stranded assets and insurance. *Stranded assets and insurance roundtable*. 17th June 2015. Lloyd's of London (London, UK) and Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2015) International best practice for overseas investment: Implications for the AIIB, BRICS Bank and Silk Road Fund. *China Council for International Cooperation on Environment and Development (CCICED) Greening China's Financial System Workshop*. 4th June 2015. Deutsche Bank (London, UK).

Caldecott, B.L. (2015) Stranded assets and subcritical coal: the risk to companies and investors. *HSBC Expert Roundtable*. 29th April 2015. HSBC (London, UK).

Caldecott, B.L. (2015) Fossil fuel divestment. *Session on divesting from fossil fuels and investing in healthy energy*. 17th April 2015. Skoll World Forum (Oxford, UK).

Caldecott, B.L. (2015) Coal in Australia: stranded assets, policy implications, and divestment. *Sydney Ideas Lecture*. 30th March 2015. Sydney Environment Institute, University of Sydney (Sydney, Australia).

Caldecott, B.L. (2015) Subcritical coal in Australia: risks to investors and implications for policymakers. *BERN Seminar*. 26th March 2015. Balanced Enterprise Research Network, University of Sydney Business School (Sydney, Australia).

Caldecott, B.L. (2015) Australian Technologies Competition keynote: linking environment to economics, finance, and management. *Australian Technologies Competition launch event*. 24th March 2015. Australian Technologies Competition (Sydney, Australia).

Caldecott, B.L. (2015) Introduction to the forum and preliminary research findings. *3rd Stranded Assets Forum: investment consultants and green investment*. 6th March 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK) and The

Rothschild Foundation (Waddesdon, UK).

Caldecott, B.L. (2015) Stranded assets and the implications for pension funds. *Dealing with unexpected situations - a look at stranded assets and how you can best avoid them.* 3rd March 2015. European Pension Fund Investment Forum (Zurich, Switzerland).

Caldecott, B.L. (2015) Identifying and overcoming common barriers. *Conservation finance seminar: new bond financing structures for marine and terrestrial conservation* 19th February 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK), The Prince of Wales' International Sustainability Unit (London, UK), The Nature Conservancy (London, UK), and the Zoological Society of London (London , UK).

Caldecott, B.L. (2015) Environment-related risks and stranded assets. *Delivering our green energy future: impacts, risks, and investment opportunities.* 12th February 2015. Edinburgh Centre for Carbon Innovation (Edinburgh, UK).

Caldecott, B.L. (2015) Right to a sustainable environment? *Oxford Lawyers Without Borders 3rd Annual Conference: 21st Century Human Rights*. 7th February 2015. Oxford Lawyers Without Borders (Oxford, UK).

Caldecott, B.L. (2015) Developing finance and investment capabilities within environmental NGOs - the challenge and opportunity. *Developing finance and investment capabilities within environmental NGOs - how, where, and when?* 29th January 2015. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2014) Understanding the implications of climate change for investment returns and for beneficiaries. *Training for Trustees.* 11th February 2014. Association of Member Nominated Trustees (London, UK).

Caldecott, B.L. (2014) Environment-related risks and stranded assets. *UBS Smith in the City: Brussels.* 4th March 2014. UBS (Brussels, Belgium).

Caldecott, B.L. (2014) Environment-related risks and stranded assets. *UBS Smith in the City: Amsterdam.* 4th March 2014. UBS (Amsterdam, Netherlands).

Caldecott, B.L. (2014) Confronting and managing environment-related risks – opportunities for facilities management. *MEFMA Annual Conference.* 11th March 2014. Middle East Facility Management Association (Dubai, UAE).

Caldecott, B.L. (2014) Introduction to the forum and the topic of stranded assets. *1st Stranded Assets Forum.* 14th – 15th March 2014. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK) and The Rothschild Foundation (Waddesdon, UK).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Goldman Sachs Investment Manager Briefing*. 24th March 2014. Goldman Sachs (Sydney, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Centre for Climate Economics and Policy Lecture.* 25th March 2014. Crawford School of Public Policy, The Australian National University (Canberra, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Regulatory Institutions Network Public Lecture.* 25th March 2014. The Australian National University (Canberra, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Sydney Ideas Lecture.* 27th March 2014. Sydney Environment Institute, University of Sydney (Sydney, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *RIAA/IGCC Member Lecture*. 28th March 2014. Responsible Investment Association Australasia (Sydney, Australia), Investor Group on Climate Change (Sydney, Australia), and Citigroup (Sydney, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *National Australia Bank Lecture*. 31st March 2014. National Australia Bank (Melbourne, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Goldman Sachs Investment Manager Briefing*. 31st March 2014. Goldman Sachs (Melbourne, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Client Breakfast Briefing*. 1st April 2014. Norton Rose Fulbright (Melbourne, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Australian Superannuation Funds Briefing*. 1st April 2014. Responsible Investment Association Australasia (Melbourne, Australia) and AustralianSuper (Melbourne, Australia).

Caldecott, B.L. (2014) Stranded assets, environment-related risks and the challenges facing Australia. *Melbourne Sustainable Society Institute Public Lecture*. 1st April 2014. University of Melbourne (Melbourne, Australia).

Caldecott, B.L. (2014) Future challenges for energy assets. *Global Change Institute and International Energy Centre Public Lecture*. 3rd April 2014. University of Queensland (Brisbane, Australia).

Caldecott, B.L. (2014) Stranded assets and environment-related risk. *Norway Government Pension Fund Strategy Workshop.* 8th – 9th May 2014. Asset Management Department, Norwegian Ministry of Finance (Oslo, Norway) and Management Team, Norway Government Pension Fund Global (London, UK).

Caldecott, B.L. (2014) Respondent to 'The Energy Den'. *Progressive Energy Governance*. 21st May 2014. iGov, University of Exeter (London, UK).

Caldecott, B.L. (2014) Introduction to the forum and the issue of fossil fuel divestment. *2nd Stranded Assets Forum: endowments and fossil fuel divestment.* 4th September 2014. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK) and The Rothschild Foundation (Waddesdon, UK).

Caldecott, B.L. (2014) Environmental drivers of asset stranding and volatility in agricultural markets: implications for equities and farmland investments. *Ceres' water programme webinar*. 9th September 2014. Ceres (Boston, USA).

Caldecott, B.L. (2014) Re-framing Protected Areas as an asset class. *WWF-UK Lecture*. 16th September 2014. WWF-UK (Woking, UK).

Caldecott, B.L. (2014) Environment-related risk and the actuarial profession. *IFoA Lecture*. 23rd October 2014. Institute and Faculty of Actuaries (London, UK).

Caldecott, B.L. (2014) Stranded assets, investment risk, and low carbon energy. *2nd China Social Investment Forum*. 14th November 2014. China Social Investment Forum (Beijing, China).

Caldecott, B.L. (2014) Environmental stress testing. *Green Finance Working Group*. 18th November 2014. People's Bank of China (Beijing, China), Renmin University (Beijing, China), and UNEP Financial System Inquiry (Geneva, Switzerland).

Caldecott, B.L. (2014) Stranded assets and the UK Green Investment Bank. *Presentation to the UK GIB Board.* 19th November 2014. UK Green Investment Bank (Edinburgh, UK).

Caldecott, B.L. (2014) Climate risk and green investments. *Workshop on climate risks and green investments.* 21st November 2014. Norwegian Ministry of Climate and Environment (Oslo, Norway).

Caldecott, B.L. (2013) Green growth and private capital. *Green growth seminar for graduate students.* 28th February 2013. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2013) Shanghai: a future green financial capital? *Shanghai carbon finance workshop: the role of financial institutions in carbon markets*. 16th March 2013. Foreign & Commonwealth Office (Shanghai, China).

Caldecott, B.L. (2013) An introduction to the Smith School's Stranded Assets Programme. *Governance for sustainability: financial sector governance for natural resource sustainability conference.* 16th – 17th May 2013. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2013) Stranded assets and environment-related risk. *Church Investors Group conference.* 23rd June 2013. Church Investors Group (London, UK).

Caldecott, B.L. (2013) Stranded assets and environment-related risk. *Transitioning energy investment into clean technologies.* 16th July 2013. Edelman (London, UK).

Caldecott, B.L. (2013) Stranded assets and the food sector. *Forum for the Future report launch.* 29th July 2013. Forum for the Future (London, UK).

Caldecott, B.L. (2013) Stranded assets and environment-related risk. *Visiting delegation of senior representatives from Chinese financial institutions*. 30th July 2013. Foreign & Commonwealth Office (London, UK), Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK), and Trucost (London, UK).

Caldecott, B.L. (2013) Stranded assets and environment-related risk. *Adaptation academy: a professional development course in climate adaptation.* 29th August 2013. Global Climate Adaptation Partnership (Oxford, UK) and Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2013) The landscape of green investing. *The UK Green Investment Bank: priority sectors, eligibility criteria and borrowing powers.* 5th September 2013. Westminster Energy, Environment & Transport Forum (London, UK).

Caldecott, B.L. (2013) Green, low-emissions finance: the global state of play. *Third annual meeting of the San Giorgio Group.* 3rd – 4th October 2013. Climate Policy Initiative (Venice, Italy).

Caldecott, B.L. (2013) An introduction to stranded assets. *Stranded assets and the fossil fuel divestment campaign.* 8th October 2013. Aviva Investors (London, UK) and Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2013) Public-Private Collaborations. Global Green Growth Forum. 21st – 22nd October 2013. Danish Ministry of Foreign Affairs (Copenhagen, Denmark).

Caldecott, B.L. (2013) Policy: creating an enabling environment. *FT/IFC investing in climate business forum*. 1st November 2013. Financial Times (London, UK) and International Finance Corporation (Washington DC, USA).

Caldecott, B.L. (2013) Environment-related risks and stranded assets: the valuation of fossil fuel assets in emerging production regions. *The changing dynamics of global energy markets*. 4th – 5th November 2013. Chatham House (London, UK).

Caldecott, B.L. (2013) Towards a renationalisation of energy policies? *Europe's energy outlook: heading in the right direction?* 7th November 2013. Friends of Europe (Brussels, Belgium).

Caldecott, B.L. (2013) Stranded assets and environment-related risk. *Staff seminar*. 12th November 2013. Standard Chartered (London, UK).

Caldecott, B.L. (2013) Natural capital risks in agriculture. *Natural Capital Declaration seminar*. 18th November 2013. Natural Capital Declaration (London, UK).

Caldecott, B.L. (2013) Plenary opening address: managing risk and ensuring resilience – sustainability in investment, business and government strategy. *Cleantech innovation and investment summit 2013.* 20th – 21st November 2013. iQuest (Dublin, Ireland).

Caldecott, B.L. (2013) Risks for investors in clean and fossil-fuel energy. *Bloomberg New Energy Finance Leadership Forum 2013: attracting long-term finance to clean energy infrastructure*. 22nd November 2013. Bloomberg New Energy Finance (London, UK).

Caldecott, B.L. (2013) Stranded assets and environment-related risk. *Lecture to Oxford University Centre for the Environment M.Sc. students*. 27th November 2013. University of Oxford (Oxford, UK).

Caldecott, B.L. (2013) Expert reviewer feedback. *Workshop on Shanghai Pilot Emissions Trading Scheme and regional linkage*. 10th – 11th December 2013. Asian Development Bank (Manila, Philippines), Shanghai Finance Bureau (Shanghai, China), Shanghai Development Reform Commission (Shanghai, China), and Shanghai Environment and Energy Exchange (Shanghai, China).

Caldecott, B.L. (2012) The changing resource landscape and what it means for investors. *Bloomberg staff event*. 20th February 2012. Bloomberg (London, UK).

Caldecott, B.L. (2012) Financing retrofit in commercial property: investment funds and Climate Change Capital's experience. *International Energy Agency workshop on the future of energy efficiency finance*. 15th March 2012. International Energy Agency (Paris, France).

Caldecott, B.L. (2012) Sustainability policy. *Sustainable aviation biofuels workshop.* 22nd March 2012. Air Transport Action Group aviation and environment summit 2012 (Geneva, Switzerland).

Caldecott, B.L. (2012) Taking disruptive ideas to policy makers. *Can disruptive policies help deliver a sustainable finance system?* 23rd March 2012. The Finance Innovation Lab (London, UK) and WWF (Godalming, UK).

Caldecott, B.L. (2012) Trends in clean tech investment. *UK renewable energy trade mission.* 26th – 29th March 2012. University of the West Indies (St Augustine, Trinidad and Tobago).

Caldecott, B.L. (2012) Private finance panel. *Seminar on international climate finance.* 19th April 2012. London School of Economics and Political Science (London, UK).

Caldecott, B.L. (2012) Costs, benefits and mechanisms to realise gains. *Workshop on fuelling the future with energy efficiency.* 10th May 2012. International Energy Agency (Paris, France) and Ministry of Economy, Trade and Industry (Tokyo, Japan).

Caldecott, B.L. (2012) Credit enhancements: low-cost debt and loan guarantees for clean energy project finance. *Workshop on unlocking financing for clean energy in Kenya.* 15th May 2012. World Economic Forum (Nairobi, Kenya).

Caldecott, B.L. (2012) Government and private sector cooperation. *Re|Source 2012.* 12th – 13th July 2012. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Caldecott, B.L. (2012) Does low carbon development make economic and commercial sense? What are the business opportunities in renewable energy? *Indonesia's economic development: contributing to a sustainable growth pattern*. 11th – 13th September 2012. Wilton Park (Steyning, UK), British Embassy Jakarta (Jakarta, Indonesia), and Indonesian Ministry of Foreign Affairs (Jakarta, Indonesia).

Caldecott, B.L. (2012) Welcome and opening address. *Sir David King farewell symposium.* 5th December 2012. Smith School of Enterprise and the Environment, University of Oxford (Oxford, UK).

Other Publications

Caldecott, B.L. (2016) The future of climate-related disclosure. *The Economist Intelligence Unit Perspectives*, 29th February 2016.

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Caldecott, B.L. (2014) The solution to coal plants? Pay their owners to close them. *China Dialogue*, 19th September 2014.

Caldecott, B.L. (2013) Tackling high carbon stranded assets. *Energy World*, June 2013.

Caldecott, B.L. (2013) Are we facing a multi-trillion dollar agri-bubble? *Business Green*, 9th August 2013.

Caldecott, B.L. (2013) Will Old King Coal continue to be a merry old soul? VIP Comment. *Bloomberg New Energy Finance*, 29th August 2013.

Caldecott, B.L. (2013) What does divestment mean for the valuation of fossil fuel assets? *Business Green,* 8th October 2013.

Caldecott, B.L. (2013) Energy woes: We should replicate the best elements of Germany's power sector transformation. *The Independent*, 28th October 2013.

Caldecott, B.L. (2013) Steps to deal with emerging risks of stranded assets. *Pensions & Investments*, 5th December 2013.

Caldecott, B.L. (2013) Australia could be caught out by peak in Chinese coal demand. *China Dialogue*, 17th December 2013.

Caldecott, B.L. & Leaton, J. (2012) Bank of England's opportunity to tackle market failure. *The Guardian*, 6th February 2012.

Caldecott, B.L. (2012) BP missed the boat on solar energy. *Green Alliance Green Living Blog*, 7th February 2012.

Caldecott, B.L. (2011) Why high carbon investment could be the next sub-prime crisis. *The Guardian*, 12th July 2011.

Annex II: Co-authorship information

The papers contained in chapters three to six are co-authored. In accordance with the University of Oxford regulations, letters confirming co-authorship are contained in this Annex.

I am the lead author for each of the papers. For each paper I made a significant contribution to the conception, design, execution and interpretation of the research study; drafted, substantively reviewed, and revised the publication; and approved the final version of the publication. I conceived, managed or otherwise made a significant contribution to all the different aspects of the research study and the associated publication(s), including securing funding for the studies to take place.

Specific parts of papers that my co-authors led on are identified below:

- In chapter three my co-author, Guy Lomax, undertook the carbon budget calculations.
- In chapter four my co-author, Jeremy McDaniels, undertook the review of company annual reports and financial statements.
- In chapter five my co-author, Gerard Dericks, undertook the fixed effects regression.
- In chapter six my co-author, James Mitchell, undertook the review of FERC Order 888 and the Montreal Protocol.

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Confirmation of co-authorship

To Whom It May Concern:

I am a co-author and collaborator with Benjamin L. Caldecott on the research study and associated publication(s) entitled: Stranded Carbon Assets and Negative Emissions Technologies.

I can confirm that he/she made a significant contribution to the conception, design, execution and interpretation of the research study; drafted, substantively reviewed and revised the publication; and approved the final version of the publication. He/she conceived, managed or otherwise made a significant contribution to all the different aspects of the research study and the associated publication(s), including securing funding for the study to take place.

Yours faithfully,

Signed by:



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I am a co-author and collaborator with Benjamin L. Caldecott on the research study and associated publication(s) entitled: Stranded Generation Assets: Implications for European Capacity Mechanisms, Energy Markets and Climate Policy

I can confirm that he/she made a significant contribution to the conception, design, execution and interpretation of the research study; drafted, substantively reviewed and revised the publication; and approved the final version of the publication. He/she conceived, managed or otherwise made a significant contribution to all the different aspects of the research study and the associated publication(s), including securing funding for the study to take place.

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I am a co-author and collaborator with Benjamin L. Caldecott on the research study and associated publication(s) entitled: Making climate policy more like monetary policy: calibrating climate policy through corporate solvency?

I can confirm that he/she made a significant contribution to the conception, design, execution and interpretation of the research study; drafted, substantively reviewed and revised the publication; and approved the final version of the publication. He/she conceived, managed or otherwise made a significant contribution to all the different aspects of the research study and the associated publication(s), including securing funding for the study to take place.

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To Whom It May Concern:

I am a co-author and collaborator with Benjamin L. Caldecott on the research study and associated publication(s) entitled: Premature Retirement of Sub-Critical Coal Assets: The Potential Role of Compensation and the Implications for International Climate Policy

I can confirm that he/she made a significant contribution to the conception, design, execution and interpretation of the research study; drafted, substantively reviewed and revised the publication; and approved the final version of the publication. He/she conceived, managed or otherwise made a significant contribution to all the different aspects of the research study and the associated publication(s), including securing funding for the study to take place.

Yours faithfully,

James Mitchell

Signed by: JAMES MITCHELL, 25 NOVEMBER 2015

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