1

Understanding Negative Emissions From BECCS

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1.1 Introduction

Changes in our climate are driven by human activity such as agriculture, deforestation and burning coal, oil and gas. The single most significant driver of climate change is the increase in the greenhouse gas carbon dioxide (CO_2) in our atmosphere from the combustion of fossil fuels. Efforts to limit the impacts of climate change focus on reducing the emissions of CO_2 and other greenhouse gases and adapting to live with the changing climate. In recent years, a third approach has gained significant attention: action to remove CO_2 from the atmosphere and store the CO_2 for long timescales (over hundreds of years). Recent negotiations under the UN Framework Convention on Climate Change (UNFCCC) delivered the 2015 Paris Agreement, which set a target of limiting global average temperature rise to 'well below 2 °C' (the 2 °C target having been agreed within the UNFCCC in 2010) while 'pursuing efforts to limit the temperature increase to 1.5°C' (UNFCCC, 2015). These are ambitious goals that will require immediate and radical emissions reductions if they are to be met. The idea of introducing 'negative emissions' is born out of the gap between the current trajectory in global emissions and the pathway necessary to avoid dangerous climate change. The most prominent proposal for achieving such negative emissions is to use biomass as a feedstock to generate electricity (or produce biofuels or hydrogen), capture the CO_2 during production and store it underground in geological reservoirs – biomass energy with carbon capture and storage, or BECCS for short. However, the negative emissions concept remains just that, a concept; in principle, technologies such as BECCS can deliver net CO_2 removal at a project scale, or potentially at a global scale sufficient to impact atmospheric concentrations of CO_2 and associated global average temperatures – but in practice, this potential has yet to be accessed at anything like a global scale. This book explores the challenges of unlocking negative emissions using BECCS.

Future climate change is most commonly explored using a suite of models that represent the Earth's climate system, the physical and socio-economic impacts of a changing climate and the greenhouse gases and other drivers generated by the global

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economy and energy systems. Integrated assessment models (IAMs) are used to create scenarios of future emissions that are used by climate and impact models. The growing and significant dependence on BECCS in future emissions scenarios in global IAMs has placed BECCS at the centre of the discourse around achieving targets of 2 °C global average temperature rise and, following the 2015 Paris Agreement, 1.5 °C. This reliance on BECCS hinges on its potential to remove CO_2 from the atmosphere in order to maintain a sustainable atmospheric concentration of CO_2 in a cost-effective manner.

There are many different technical options that could deliver negative emissions *via* BECCS and these vary in their technology readiness level (TRL). Some of the closer-to-market BECCS technologies are composed of component parts that have been proven and tested, but integration and deployment have not yet been demonstrated at commercial scale. Consequently, there remain significant uncertainties associated with BECCS performance and costs. Understanding the potential for, and implications of, pursuing BECCS requires an interdisciplinary approach. It has been suggested that BECCS could play a role in offsetting hard-to-abate sectors (e.g. agriculture and aviation) or enable delayed action on mitigation. While the atmospheric concentration of CO_2 continues to rise and policy objectives focus on limiting warming to 1.5 °C, it becomes increasingly likely that a means of delivering negative emissions will be required. Whether or not limiting warming to 1.5 °C is feasible without negative emissions remains unclear. In 2018, the IPCC will deliver a special report devoted to understanding the emissions pathways and impacts associated with 1.5 °C.

Despite its significance within the formal policy goals, there is very little practical experience of implementing the technology in commercial applications and limited research into the practicalities of implementation and conditions for accelerating deployment. Combining modern biomass energy systems with CCS not only presents technical and scientific challenges but, to be implemented at scales large enough to deliver global net negative emissions, also depends on other factors, such as geopolitics and supply-chain integration and may have significant societal implications. To understand BECCS, what it can offer and how it might contribute to climate-change mitigation, it is essential to consider the technical and non-technical constraints in a holistic manner.

This book aims to provide a comprehensive assessment of BECCS, describing the technology options available and the implications of its future deployment. While there is a rich literature relating to bioenergy and carbon capture and storage (CCS) separately, there is currently very little published research on the integration of these components. Our aim is to address this gap, bringing together technical, scientific, social, economic and governance issues relating to the potential deployment of BECCS as a key climate-change mitigation approach. The uniqueness of the book lies in bringing these subjects together and imposing order on the disparate sources of information. Doing this in a clear and accessible way will support a more informed debate around the potential for this technology to deliver deep cuts in emissions.

1.2 Climate-Change Mitigation

In its Fifth Assessment Report (AR5), the Intergovernmental Panel on Climate Change (IPCC, 2014) identified four so-called representative concentration pathways (RCPs), describing time-dependent ranges of atmospheric greenhouse gas concentration trajectories, emissions and land-use data between 2005 and 2100 (van Vuuren et al., 2011). Created by IAMs, each RCP is associated with emissions pathways that result in atmospheric concentrations correlated with different levels of radiative forcing; these are RCP2.6 (i.e. a radiative forcing of 2.6 W m^{-2}), RCP4.5, RCP6, RCP8.5 (IPCC, 2014). Greenhouse gas concentrations within each RCP are associated with a probability of limiting temperature rise to below certain levels; only the lower concentrations within RCP2.6 are considered 'likely' (i.e. associated with a greater than 66% chance) to limit global atmospheric temperature rise to below 2 °C, or 'more unlikely than likely' (i.e. a less than 50% chance) for 1.5 °C (IPCC, 2014). The RCPs provide a consistent framework for analysis in different areas of climate-change research – for example, by climate modellers to analyse potential climate impacts associated with the pathways (including projected global average temperature rise) and in IAMs to explore alternative ways in which the emissions pathways for each RCP could be achieved (i.e. mitigation scenarios) under different economic, technological, demographic and policy conditions (IPCC, 2014; van Vuuren et al., 2011). The shared socio-economic pathways (SSPs) offer a further framework for IAMs to explore alternative emission pathways, by detailing different socioeconomic narratives that are consistent with the RCPs (O'Neill et al., 2017).

Climate-change mitigation policies are focused around limiting the increase in the global average temperature as described earlier. Achieving these targets is dependent on tight limits to cumulative emissions of CO_2 (and other greenhouse gases) in order to stabilise their atmospheric concentration. The cumulative emissions associated with a particular temperature goal is known as a carbon budget – the remaining budget for a 66% chance of keeping temperatures below a 2 °C increase is 800 Gt CO_2 (from 2017) (Le Quéré et al., 2016). With global emissions currently at about 36 Gt CO_2/year, this equates to about 20 years at current emissions rates before the budget is exceeded; until emissions are reduced to near zero, atmospheric CO_2 concentration will continue to rise (ibid).

In this context, by offering a route to delivering negative emissions, BECCS appears to be an attractive approach to potentially enabling mitigation costs to be reduced, more ambitious targets to become feasible than would otherwise be possible or allowing a delay to the year in which emissions will peak by enabling removal of CO_2 from the atmosphere in the future (Friedlingstein et al., 2011; van Vuuren et al., 2013). Typically, scenarios that are 'likely' to stay within 2 °C include such an overshoot in the concentration achieved through large-scale deployment of carbon dioxide removal (CDR) techniques (i.e. BECCS or afforestation) (IPCC, 2014).

A large majority of the pathways that deliver atmospheric CO_2 concentrations consistent with the 2 °C target (and indeed many of those associated with temperature increases up to 3 °C) require *global net* negative emissions by about 2070 (Fuss et al., 2014). The range of CO_2 removal through BECCS assumed in the IPCC scenarios is typically between 2 and 10 Gt CO_2/year by 2050 (Fuss et al., 2014; van Vuuren et al., 2013) with a median value of around 608 Gt CO_2 cumulatively removed by 2100 using BECCS (Wiltshire et al., 2015). Global net negative emissions are achieved when the amount of CO_2 removed from the atmosphere is greater than emissions from all other anthropogenic (i.e. resulting from or produced by human activities Allwood et al., 2014) sources (Fuss et al., 2014). When discussing the contribution of negative emissions from BECCS, it is useful to distinguish between three metrics that are typically used (Gough et al., 2018), as described in Figure 1.1:

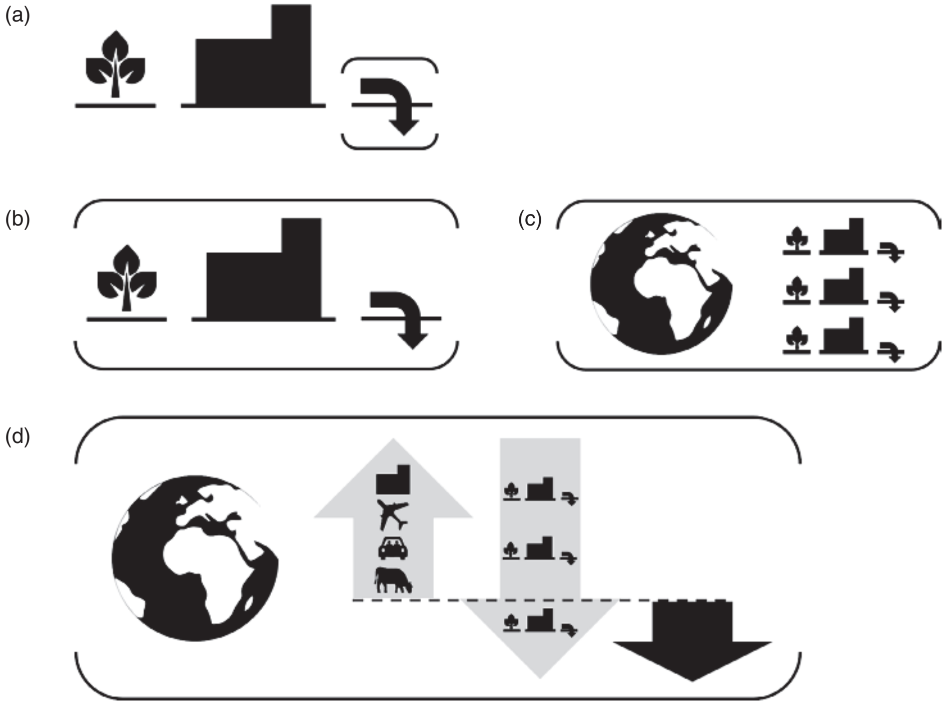

Figure 1.1 Schematic illustrating terminology for negative emissions from BECCS. (a) *CO_2 stored*, which can be calculated at a project, national or global level. (b) *Negative emissions*, which can be calculated at a project or national level, are achieved when the CO_2 removed from the atmosphere during biomass growth is greater than the CO_2 emissions from all the other processes in the supply chain. (c) *Global negative emissions*, the global sum of all negative emissions activity, this removes carbon dioxide from the atmosphere and can be used to 'offset' other anthropogenic CO_2 emissions. (d) *Global net negative emissions* occur when the global amount of negative emissions exceeds the CO_2 emissions from all other human sources, e.g. energy, transport and agriculture.

a) *CO_2 stored from BECCS systems*: this is the total CO_2 stored in a geological formation following capture in a CCS system and gives an indication of the geological storage capacity needed;
b) *Negative emissions from BECCS*: this is the net emissions from the BECCS supply chain, at a project scale, or cumulatively across all BECCS projects, accounting for system losses, emissions associated with land-use change and fossil fuel emissions;
c) *Global net negative emissions*: occur when the amount of global negative emissions (from all negative emissions approaches combined) exceeds the CO_2 emissions from all other human sources, e.g. energy, transport and agriculture.

Thus, global net negative emissions are used within the IAMs to offset outstanding anthropogenic emissions to deliver a 'net' emission trajectory in line with the RCP associated with a given temperature goal, such as 2 °C (Fuss et al., 2014). This is illustrated in Figure 1.2 to reveal how global net negative emissions are envisaged to contribute to keeping emissions within the carbon budget and the scale of the challenge (Anderson and Peters, 2016). Parties to the UNFCCC are required to submit Intended Nationally

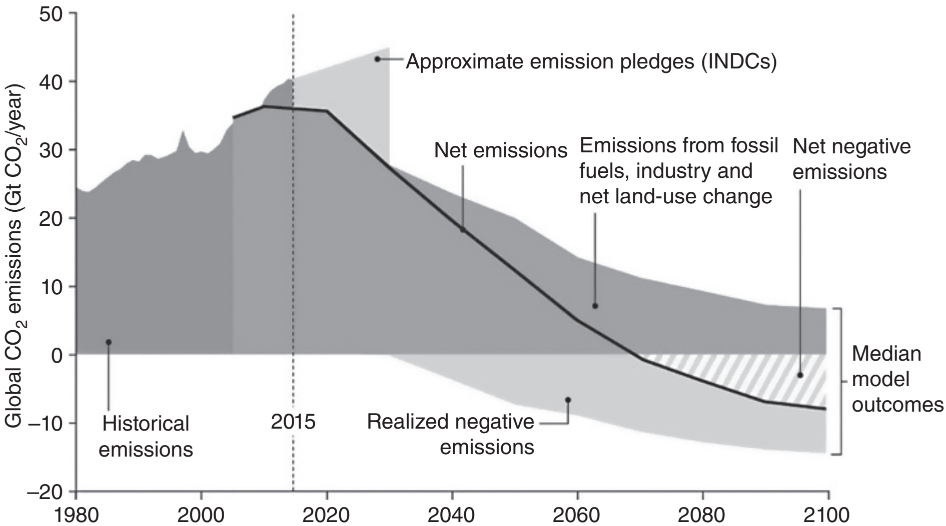

Figure 1.2 The role of negative emissions in relation to global CO_2 scenarios. Note that 'realised negative emissions' correspond to 'negative emissions described in Figure 1.1b and that 'net negative emissions in this figure correspond to 'global net negative emissions' described in Figure 1.1d. Source: Anderson and Peters (2016). (*See colour plate section for the colour representation of this figure.*)

Determined Contributions (INDCs); revised every 5 years, the INDCs are pledges for proposed emissions reductions at a national level. Figure 1.2 also shows that the current INDCs are not currently in line with the rapid decline in emissions necessary to stay within the budget – i.e. we are currently on track for an 'overshoot'. The further emissions rise above the 2 °C pathway, the greater the negative emissions required to stay within the total carbon budget. Results of the IAMs that describe alternative mitigation scenarios associated with achieving 2 °C include negative emissions from BECCS from around 2020 (Figure 1.1b,c), with global net negative emissions (Figure 1.1d) setting in around 2070 (Figure 1a in Fuss et al., 2014).

1.3 Negative Emissions Technologies

To date, climate-change mitigation has focused on ways to reduce the amount of greenhouse gases emitted to the atmosphere by reducing energy consumption or through the use of alternative technologies (such as renewable energy technologies) that emit less greenhouse gases. However, in the context of the rapidly diminishing carbon budgets described in Section 1.2, possibilities for geoengineering the climate have been raised; geoengineering is defined as 'deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change' (Royal Society, 2009). Approaches for geoengineering include solar radiation management (reflecting the sun's energy back into space, for example, by cloud brightening or stratospheric aerosol injection) or removing CO_2 from the atmosphere (so-called CDR or negative emission technologies) (Royal Society, 2009; Vaughan and Lenton, 2011; McLaren, 2012). By removing CO_2

from the atmosphere and storing it underground, thus delivering 'negative emissions', BECCS can be considered part of this latter type of climate intervention. BECCS can be used to reduce emissions, i.e. mitigation, by, for example, co-firing biomass with coal in a power plant with CCS. Some consider it to be a form of climate-change mitigation rather than a geoengineering approach (Boucher et al., 2013). Others suggest BECCS is mitigation because it can be used to 'offset' hard-to-abate sectors. But there are those who consider BECCS at a scale sufficient to deliver global net negative emissions (see Figure 1.1d) to be geoengineering the climate, due to its large-scale intervention in the Earth system (Royal Society, 2009).

Later we set BECCS in the context of other CDR approaches. Solar radiation management approaches are not addressed in this book. CDR approaches seek to enhance existing carbon sinks (such as ocean or forest systems) or, like BECCS, create novel carbon sinks (i.e. using geological formations for CO_2 storage) (Vaughan and Lenton, 2011). CDR approaches can be classified according to the means of CO_2 capture or removal and their means of storage or sequestration. Tavoni and Socolow (2013) distinguish between biological and non-biological capture (i.e. 'drawdown' from the atmosphere) and storage processes. Others distinguish between whether capture is direct (i.e. chemical) or indirect (i.e. biological) and four types of storage (mineralised, pressurised, oceanic, biotic) (McLaren, 2012). Table 1.1 summarises the main families of negative emissions approaches currently considered in the wider literature. The purpose of this type of classification is to support understanding of the different types of approaches associated with delivering negative emissions. Although the approaches are highly heterogeneous, grouping them in this way may also help signpost where certain issues or challenges might be applicable to several quite different approaches, or identify potential conflicts between approaches (for example, BECCS and Direct Air Capture may both require large volumes of underground storage).

1.4 Why BECCS?

It is clear from Section 1.2 that the categorisation of negative emissions technologies covers a wide variety of extremely different approaches, the unifying feature being their potential to remove CO_2 from the atmosphere. This book focuses on the group of technologies that combines bioenergy feedstocks for energy conversion processes linked to industrial capture of CO_2 for subsequent geological storage – otherwise known as BECCS.

Assessments of key negative emissions approaches have considered technical status, potential capacity and limitations; these place BECCS at a TRL between 4 and 7, depending on the particular approach under consideration (Lomax et al., 2015; McLaren, 2012). TRLs, originally used by NASA but now widely applied, provide a means of comparing the maturity of different technologies, from the lowest level, TRL1, up to TRL9 when a system is mass deployed. Other negative emissions approaches may be considered to be at higher TRLs than BECCS but are more limited in their potential at sufficiently large scale (i.e. above 1 Gt CO_2/year); for example, those sequestering CO_2 in materials such as magnesium silicate cement (limited by demand for cement) or timber in construction (limited by demand for timber and availability of a sustainable supply of timber) and land-based approaches such as forest restoration and peatland

Table 1.1 Negative emissions approaches, classified according to the type of capture and storage processes involved.

Approach	Capture	Storage	Description
Biomass energy and carbon capture and storage (BECCS)	Biological Indirect	Geological Pressurised	Power generation using biomass feedstocks followed by CO_2 capture from flue gases for subsequent geological storage
Direct air capture (DAC)	Non-biological Direct	Geological Pressurised	Uses chemical sorbents to absorb and then release CO_2 for subsequent geological storage
Ocean fertilisation	Biological Indirect	Biological Oceanic	Addition of nutrients to enhance growth of photosynthesising organisms, which eventually fall to the ocean floor
Ocean liming	Non-biological Indirect	Non-biological Oceanic	Calcium or magnesium oxides (lime) dissolved in sea water to increase the ocean absorption of atmospheric CO_2
Enhanced weathering	Non-biological Indirect	Non-biological Mineralised	Finely ground silicate rocks are dissolved in oceans or soils, these absorb CO_2 and are eventually sequestered in shells of organisms
Biochar	Biological Indirect	Biological Biotic	Heat treatment of biomass, locking up the carbon and can be used as a soil improver
Afforestation	Biological Indirect	Biological Biotic	Establishing and maintaining forests that have not previously been forested for a given period (e.g. 50 years) (UNFCCC, 2015)

Source: McLaren (2012) and Tavoni and Socolow (2013). Reproduced with permission of Elsevier.

and wetland habitat restoration, which is limited by land availability and climate impacts (McLaren, 2012). Chapter 5 considers TRL for BECCS approaches in more detail.

BECCS has further advantages, compared to other CDR or negative emissions approaches, that electricity (or liquid biofuels or hydrogen) is generated during the process and it is broadly compatible with current energy and social infrastructures (McGlashan et al., 2012). Although it is often described as being the most mature or least costly of the alternative negative emissions approaches (Kriegler et al., 2013; McGlashan et al., 2012) and, given its prominence in the mitigation pathways described earlier, there is relatively little research into the challenges and viability of bringing BECCS into mainstream commercial deployment. There are around 15 pilot-scale BECCS plants across the world, and the first large-scale BECCS project is a corn-to-ethanol plant in Decatur, Illinois, storing 1 Mt CO_2/year in an onshore saline aquifer; an overview of the status of these projects may be found in GCCSI (2016). BECCS is therefore dominant among the options with the potential to deliver large-scale negative emissions over the next 10–20 years.

BECCS is featured as the dominant emissions technology in the IAM model runs, alongside, to a much lesser extent, afforestation (i.e. establishing and maintaining forests that have not previously been forested for a given period, e.g. 50 years) (UNFCCC, 2013). IAMs calculate cost-optimal pathways to satisfy carbon budget constraints; thus, a key feature of BECCS is its role in energy supply; allowing the production of a commodity (e.g. electricity) while delivering negative emissions makes it an attractive option in cost-optimised scenarios. However, although there is limited commercial experience of integrated BECCS systems, the component technologies and techniques are well developed. Although, at the time of writing, IAMs started to include other negative emissions technologies such as direct air capture (Detlef van Vuuren, personal communication) and enhanced weathering (Taylor et al., 2016), BECCS dominates the negative emissions scenarios; understanding both the technical and non-technical constraints on its potential is critical to the feasibility of these scenarios. This book aims to unpack the issues associated with developing integrated BECCS systems at scales sufficient to deliver global net negative emissions.

1.5 Structure of the Book

In the following chapters, we set out and consider the key issues associated with the challenge of using BECCS to deliver negative emissions. The book is divided into three sections, described later, covering: BECCS technologies (describing the various technologies involved in BECCS systems); BECCS system assessments (considering key system characteristics across the life cycle and the relative performance of technical systems) and BECCS in the energy system (including the role of BECCS as a mitigation approach, its role within integrated assessment modelling, governance and supply-chain accounting frameworks and its social and ethical implications). Thus, the book sections reflect increasing scales of analysis, moving from consideration of the component technologies (Part I) that may contribute to the overall operation of a BECCS system (Part II) to the role of BECCS within the wider energy, climate and societal systems (Part III).

As an edited book, the chapters reflect the specific viewpoints of the different authors; BECCS remains a controversial technology in relation to the current significance placed on it within global climate-change assessments and the implicit reliance on it within the Paris Agreement. Different perspectives anticipate different extents for its potential. Our aim here is to present some of the key arguments associated with the deployment of BECCS to deliver negative emissions from a variety of perspectives; in the final chapter, we aim to bring these arguments together to consider if and under what circumstances BECCS may provide a route to unlocking negative emissions on a global scale.

1.5.1 Part I: BECCS Technologies

This section describes the biomass energy and carbon capture components of BECCS technologies. The four chapters in this section present the issues related to the supply of biomass for use in energy systems (Chapter 2), the specific issues that the use of biomass feedstocks brings to CO_2 capture (Chapters 3 and 4) and the techno-economic performance of these systems (Chapter 5). In contrast, the processes that occur after CO_2 capture (i.e. those involved in compression, transport and geological storage) are the same as those used for fossil CCS and hence are beyond the remit of this book.

Chapter 2 provides an assessment of the overall extent of different forms of biomass at both the UK and international scales and the potential availability of these resources for the bioenergy sector, drawing upon current reports and published research. The use of these biomass resources should not impact the sustainability of other sectors, such as industries that directly compete for biomass resource, or the availability of land to meet demands for food. The interfaces between the supply of biomass for energy and the competing land and resource demands of industry are highlighted, providing an indication of the levels of biomass resource that may be used for energy end uses without causing adverse impacts to other sectors. Finally, the chapter draws on published research to provide an evaluation of the best uses of available biomass resource and to conclude whether there will be sufficient sustainable biomass for a future bio-CCS sector.

Chapter 3 first explores the different technologies and configurations used to attain CO_2 capture from biomass fuel sources, comparing post-combustion capture (based on air-firing) and oxy-fuel combustion capture techniques. For post-combustion capture, a range of separation technologies can be utilised to remove the CO_2 from the rest of the flue gas stream, including solvent-based (wet scrubbing) capture, which is assessed in detail, and membrane separation, which is overviewed briefly. The potential locations of steam extraction from the power plant to regenerate the capture solvents used for absorption are also considered. The relative merits of enriched-air firing and oxy-fuel options are evaluated, consisting of an assessment of flue gas recirculation configurations. As the nature of biomass is so dissimilar to fossil fuels in terms of composition and properties, the specific challenges associated with biomass utilisation under BECCS operating conditions are then outlined, focusing primarily on trace elements and impurities and their impacts on capture performance. The deployment potential of these various BECCS options is subsequently overviewed in light of these challenges, based on existing technical knowledge.

Chapter 4 gives an overview of the pre-combustion technologies used for the capture and storage of CO_2 for both power generation and chemical production processes. These techniques involve removal of CO_2 from a feedstock before combustion is completed, involving its conversion to a synthesis gas (syngas) containing predominantly hydrogen and CO_2; the CO_2 can then be separated from this gas mixture. The main technical features involved are detailed and the relevant chemistry is provided. The applications of this technology include uses for power *via* the integrated gasification combined cycle (IGCC) and uses in fuel refineries for syngas upgrading and liquid fuels. Applications based on conventional fuels are described and the opportunities and issues regarding their uptake into biomass systems are discussed, providing case studies and examples of ongoing research activity.

Chapter 5 describes a unique collaboration between industry, consultancies and academia in a study commissioned and funded by the Energy Technologies Institute (ETI) UK to explore the potential for BECCS technologies to be utilised to enable large-scale CO_2 removal from the air, at the same time producing electricity. The study compares an initial long list of 28 gasification or combustion technologies integrated with CCS (pre-, post- or oxy-combustion) and considers current progress towards market, likely future progress to market, cost, efficiency and feasibility, all with as many assumptions as possible harmonised across the investigated technologies. Detailed process modelling is conducted on a shortlist of eight of the technologies, which are considered to be most promising for wide-scale deployment by 2050. These technologies are co-fired power generation with amine scrubbing, oxy-fuel combustion, carbonate looping or utilising integrated gasification combined cycle (IGCC); and dedicated fully biomass fired power stations utilising amine scrubbing, oxy-fuel, chemical looping or IGCC. An important part of the results is an attempt to quantify the uncertainties associated with the parameters discussed, considering how far away from market they are.

1.5.2 Part II: BECCS System Assessments

This section explores the technical performance of various BECCS approaches and their component technologies at a project level. Quantifying the negative emissions from BECCS requires analysis across its entire supply chain from growing, harvesting, treating and transporting biomass energy to its combustion and through the CO_2 capture process and the subsequent compression, transport and storage of the CO_2. Currently, there is very limited experience of conducting such a life-cycle analysis for BECCS, and Chapter 6 sets out the requirements and challenges associated with conducting such an assessment. Looking in more detail at the performance of some of the component technologies, Chapter 7 focuses on the CCS elements and Chapter 8 explores the potential and performance of full-chain BECCS systems in the UK.

Chapter 6 examines the rationale for applying a supply-chain life-cycle assessment approach in order to assess potential emissions savings and critiques the importance of key decisions around choice of system boundary and assessment methods that directly affect results. There are many uncertainties with this emerging technology, including the possible greenhouse gas savings that have not been extensively verified. Key uncertainties are probed and recommendations made on methodological approaches that will deliver appropriately informed assessments of the actual emissions reduction potential associated with deployment of BECCS.

Chapter 7 presents parameters relating to the performance of power plants with carbon capture and storage (CCS), which can be characterised and evaluated according to a number of sustainability criteria; these can be based on well-established, often quantifiable, economic, energy-related and environmental (including climate change) criteria. However, CCS is at an early stage of research, development and demonstration (RD&D), and therefore many of the system performance characteristics need to be determined on a first of a kind (FOAK) basis. CO_2 capture facilities will hinder the performance of power plants and give rise to an energy penalty which, in turn, lowers the system (thermodynamic) efficiency. The levelised cost of electricity (LCOE) can then be used as an indicator of the impact of adding capture equipment on plant economics. Finally, the environmental performance of CCS developments can be assessed in terms of climate-change impacts (e.g. cost of carbon avoided or captured), as well as the effects on biodiversity, land use and water resources. Geological storage of CO_2 will, in many cases, have potential consequences for the marine environment. Such impacts vary as to whether they are on a global, regional or local scale and to which stage of the CCS life cycle they relate.

Chapter 8 presents the key findings from a recent assessment of the potential for BECCS to play a role in UK emissions reduction targets conducted by the Energy Technologies Institute UK (ETI). Bioenergy with CCS (BECCS) is a credible, scalable and efficient technology and is considered to be critical for the UK to meet its 2050 greenhouse gas emission reduction targets cost-effectively. Major advances in the fundamental science and technology development have been made by the ETI and others over the last 10 years, specifically in understanding: the costs, efficiencies and challenges of biomass-fed combustion systems with carbon capture; the opportunities for different bioenergy supply chains, based on particular feedstocks, to deliver negative emissions; the potential availability and sustainability of feedstocks relevant to the UK and the identification and assessment of suitable CO_2 storage sites around the UK and the infrastructure required to connect to them.

1.5.3 Part III: BECCS in the Energy System

In this section, chapters go beyond the project-scale analysis of BECCS to consider its role within the wider energy and climate mitigation system, and the issues associated with achieving global net negative emissions. We consider questions such as how the approach might fit within a cumulative emissions profile measured against a diminishing carbon budget in the context of 1.5 or 2 °C (Chapter 9); how it impacts mitigation scenarios developed within an IAM (Chapter 10); what policy challenges are associated with establishing, regulating and accounting for negative emissions at a global scale (Chapter 11) and what the social and ethical implications are of pursuing this path (Chapter 12).

Chapter 9 explores the role of BECCS technologies and the implications of their deployment for mitigating climate change. This chapter demonstrates how the need for negative emissions arises in order to reconcile the levels and rate of mitigation necessitated by the rapidly shrinking global carbon budget associated with the 2 °C ambitions of the Paris Agreement. BECCS is central to much of the integrated assessment modelling that meets the 2 °C target, and it is essential to understand the assumptions underpinning the modelling work informing climate policy; thus, we make explicit the assumptions within these models about bioenergy, carbon capture and storage and BECCS more specifically. The infrastructure challenges of developing the energy conversion technologies, CO_2 transport and CO_2 storage reservoirs are discussed, and given the current slow rates of deployment of CCS generally, we explore whether the required levels of negative emissions from BECCS can be achieved within the appropriate timescales.

Chapter 10 presents results analysed using the TIAM-UCL integrated assessment model to investigate the extent to which bioenergy with carbon capture and storage (BECCS) is critical for meeting global CO_2 reduction targets under different long-term scenarios out to 2100. The chapter also assesses the potential impacts of BECCS on mitigation costs under various scenarios at a global scale. Though previous work has suggested that BECCS can play a crucial role in meeting the global climate-change mitigation target, uncertainties remain in two main areas: the availability of biomass, which is affected by many factors including availability of land for biomass production; and the sustainability of bioenergy production, including consequences for greenhouse gas emissions. In order to assess the importance of these uncertainties, this chapter develops several scenarios by varying the availability of biomass (sustainability of the bioenergy production) and peaking year for greenhouse gas emissions under 2 and 1.5 °C climate-change mitigation targets at a global level.

Chapter 11 explores some of the themes around supply-chain rationales and scope of system, first established in Chapter 6, from a social policy and governance perspective. It dissects whether negative emissions are ‘real’ or simply a figment of the supply-chain boundaries and accounting procedures and considers applicable policy and incentive frameworks in an attempt to understand why there has been so little development to date. BECCS often emerges from IAMs as an essential component of the future energy system. This leads to a perceived need to implement BECCS systems at significant scale. However, making such a significant energy system transition is a huge undertaking that will require appropriate policy incentivisation. Existing global policy frameworks encourage low-carbon technologies, but often fail to take account of the human dimension and local impact trade-offs. BECCS involves mobilisation of local supply chains with impacts on relevant communities in different countries/regions. Combining these contributions to assess and verify net impact is challenging and not facilitated under current governance structures. This chapter explores the wider context for such incentives including regional and global implementation frameworks.

Chapter 12 explores some of the social and ethical issues relating to the use of BECCS to deliver negative emissions. It considers both the big questions relating to its potential role in a morally adequate response to climate change as well as the more specific social and ethical issues associated with deployment of the technology on the ground. The relationship between BECCS and the use of fossil fuels, how it sits relative to other mitigation options and in the context of other negative emissions approaches are also considered. The chapter identifies contexts in which BECCS might represent a sustainable as well as a just solution and how it might be received at a social and societal level. Reviewing current thinking on justice in the context of energy and climate change, paying particular attention to issues that are relevant to CCS, and specifically BECCS, we look in turn at distributional, procedural, financial and intergenerational aspects of justice. Results from an expert workshop convened to discuss issues of governance and ethics in CCS and BECCS are used to supplement the wider literature throughout the chapter.

1.5.4 Part IV: Summary and Conclusions

The final chapter (Chapter 13) of this book synthesises the key messages from across the chapters and identifies critical issues associated with moving from negative emissions at a project scale to global net negative emissions at a systems level. We identify four questions governing the potential for BECCS to provide a key to unlocking negative emissions: Do we need this technology? Can it work? Does the focus on BECCS distract from the imperative to radically reduce demand and transform the global energy system? How can BECCS unlock negative emissions?

References

Allwood, J.M., Bosetti, V., Dubash, N.K. et al. (2014). Glossary. In: *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx). Cambridge and New York: Cambridge University Press. Climate Change 2014 Synthesis Report Summary for Policymakers. Intergovernmental Panel on Climate Change.

Anderson, K. and Peters, G. (2016). The trouble with negative emissions. *Science* **354**: 182–183.

Boucher, O., Forster, P.M., Gruber, N. et al. (2013). Rethinking climate engineering categorization in the context of climate change mitigation and adaptation. *Wiley Interdisciplinary Reviews: Climate Change* **5**: 23–35.

Friedlingstein, P., Solomon, S., Plattner, G.K. et al. (2011). Long-term climate implications of twenty-first century options for carbon dioxide emission mitigation. *Nature Climate Change* **1**: 457–461.

Fuss, S., Canadell, J.G., Peters, G.P. et al. (2014). Betting on negative emissions. *Nature Climate Change* **4**: 850–853.

GCCSI (2016). *The Global Status of CCS*. Summary report. Canberra: The Global CCS Institute.

Gough, C., Garcia Freites, S., Jones, C. et al. (2018). Challenges to the use of BECCS as a keystone technology in pursuit of 1.5°C. *Global Sustainability*, In press.

IPCC (2014). *Climate Change 2014 Synthesis Report Summary for Policymakers*. Intergovernmental Panel on Climate Change.

Kriegler, E., Edenhofer, O., Reuster, L. et al. (2013). Is atmospheric carbon dioxide removal a game changer for climate change mitigation? *Climatic Change* **118**: 45–57.

Le Quéré, C., Andrew, R.M., Canadell, J.G. et al. (2016). Global carbon budget 2016. *Earth System Science Data* **8**: 605–649.

Lomax, G., Lenton, T.M., Adeosun, A., and Workman, M. (2015). Investing in negative emissions. *Nature Climate Change* **5**: 498–500.

McGlashan, N., Shah, N., Caldecott, B., and Workman, M. (2012). High-level techno-economic assessment of negative emissions technologies. *Process Safety and Environmental Protection* **90**: 501–510.

McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection* **90**: 489–500.

O'Neill, B.C., Kriegler, E., Ebi, K.L. et al. (2017). The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century. *Global Environmental Change* **42**: 169–180.

Royal Society (2009). *Geoengineering the Climate: Science, Governance and Uncertainty*. RS Policy Document 10/09, Spetmber 2009 RS1636.

Tavoni, M. and Socolow, R. (2013). Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change* **118**: 1–14.

Taylor, L.L., Quirk, J., Thorley, R.M.S. et al. (2016). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Climate Change* **6**: 402–406.

UNFCCC (2013) *Afforestation and reforestation projects under the Clean Development Mechanism: A reference manual*, United Nations Framework Convention on Climate Change, http://unfccc.int/resource/docs/publications/cdm_afforestation_bro_web.pdf (accessed 13 December 2017).

UNFCCC (2015). *United Nations Framework Convention on Climate Change*. Adoption of the Paris Agreement FCCC/CP/2015/10/Add.1.

Vaughan, N. and Lenton, T. (2011). A review of climate geoengineering proposals. *Climatic Change* **109**: 745–790.

van Vuuren, D.P., Deetman, S., van Vliet, J. et al. (2013). The role of negative CO_2 emissions for reaching 2°C: insights from integrated assessment modelling. *Climatic Change* **118**: 15–27.

van Vuuren, D., Stehfest, E., den Elzen, M.J. et al. (2011). RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C. *Climatic Change* **109**: 95–116.

Wiltshire, A., Davies-Bernard, T., Jones, C.D. (2015). *Planetary limits to Bio-Energy Carbon Capture and Storage (BECCS) negative emissions*. AVOID2 Report WPD2a. http://www.avoid.uk.net/2015/07/planetary-limits-to-beccs-negative-emissions-d2a/ (accessed 13 December 2017).