A Post-Paris Literature Review of Negative Emissions Technology, and Potential for Ireland

Paul Price, Alwynne McGeever, Mike Jones and Barry McMullin

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Potential for Negative Emissions in Ireland (IENETS)

Web: www.ienets.eeng.dcu.ie **Twitter:** @ie_nets

Ollscoil Chathair Bhaile Átha Cliath
Dublin City University

Trinity College Dublin
Coláiste na Tríonóide, Baile Átha Cliath
The University of Dublin

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Executive Summary

Introduction

Most climate change mitigation scenarios analysed to date by the Intergovernmental Panel on Climate Change (IPCC), for efforts consistent with the goals of the Paris Agreement (keeping global average temperature rise "well below 2°C" over pre-industrial), rely on presumed deployment of so-called "negative emissions technologies" (NETs) at very large (global) scales within a small number of decades.

Negative emission technologies are composite technology systems or interventions which, on a full lifecycle basis, achieve net removal of one or more greenhouse gases from the atmosphere. Because of its long atmospheric lifetime, carbon dioxide (CO_2) has a dominant role in human-caused long-term global warming, so NETs typically focus exclusively on carbon dioxide removal (CDR). Example NET concepts include: Afforestation/Reforestation (AR), Bio-Energy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), and Enhanced Soil Carbon storage (SCS).

ie-nets is a two-year research project, funded by the Environmental Protection Agency of Ireland (EPA) Research Programme 2014-2020 (grant number 2016-CCRP-MS.36). The project is building Irish research capacity and contributing to national policy in this emerging area.

The overarching objective is to provide a detailed and rigorous assessment of the scale and speed of negative emissions technology deployment that is required by currently envisaged decarbonisation pathways (globally and nationally), consistent with the Paris agreement goals.

This report, the first interim deliverable from the project, presents a comprehensive review of the existing literature on the potential forms of negative emissions technology (NET), with a particular focus on technology options suitable for deployment in Ireland. This executive summary presents an overview and key results from the full review.

Literature Review aims and structure

The review focuses on the global NETs literature most relevant to Ireland, and on the existing Irish literature on land-use, bioenergy and conventional, fossil-fuel, carbon capture and storage (FFCCS) most applicable to the domestic development of substantive negative emissions to enable climate mitigation aligned with Paris ambition. The aim is to give a preliminary evaluation of the feasibility, timescale, capacity (both stock and flow) and indicative costs (capital and recurrent) of negative emissions technology deployment, both globally and specifically in Ireland.

As Ireland's climate policy is necessarily aligned with Ireland's ratification of the Paris Agreement the research emphasis is on examining deep decarbonisation pathways for the EU and Ireland, with and without NETs, that are aligned with meeting the 1.5ºC and “well below 2ºC” Paris temperature limits to global warming. In terms of total future emissions the global carbon budgets for these two temperature goals are very similar so they are frequently stated in this report simply as “well below 2ºC” or abbreviated as “WB2C”.

Climate action policy involving NETs to achieve a low-carbon transition will require political decision-making based on knowledge of: the IPCC-assessed and more recent peer reviewed climate science; governance of the remaining global carbon budget; a global overview of NETs and CCS; scenario modelling of future alternatives (with an understanding of underlying assumptions); risk and uncertainty assessment; and possible mechanisms to effect deep decarbonisation, including the development of NETs. This review is organised as follows:

Chapters 1 to 6 survey global literature relating negative emissions technologies to climate science, multi-lateral management of the remaining WB2C global carbon budget, and decision-making and mechanisms to achieve low carbon transition from current high emissions, highlighting both the costs of action and of inaction (the consequences of exceeding carbon budgets).

Chapters 7 to 9 review material specific to the Irish context:

- Chapter 7 gives an overview of Ireland’s distinctive emissions profile, national climate policy and the recently published National Mitigation Plan, existing climate-energy-economy modelling, and current EPA emission projections relative to possible mitigation pathways;
- Chapter 8 gives an estimation of Ireland’s possible remaining national carbon quota in terms of an equitable share of the global carbon budget;
- Chapter 9 presents Irish NETs-relevant literature particularly on bioenergy, forestry and soils in the context of global literature and provides a preliminary assessment of potential NETs capacity in Ireland.

Key Findings

Allocating the Global Carbon Budget (GCB)

In 2015, the Parties to the Paris Agreement agreed to limit global warming to ‘well below 2ºC’ and pursue efforts toward a lower limit of 1.5ºC above pre-industrial levels. Climate change will inequitably affect less developed nations, who have the lowest historic emissions. Due to the cumulative effect of CO_2 emitted into the atmosphere, delayed mitigation action will subsequently require substantially steeper nett decarbonisation pathways (WB2C).

The global carbon budget is the nett amount of CO_2 that can still be emitted without exceeding the WB2C temperature limit. At the end of 2017, it is estimated to be only ~800 (500-1100) $GtCO_2$. Annual global emissions are over 40 $GtCO_2$, including fossil fuel and land-use. If emissions continue at this rate, this total budget will be exhausted within 20 years. National carbon quotas derived from the global carbon budget may be a useful tool for resource sharing of the remaining carbon budget.

There are two main approaches to allocating the global carbon budget amongst nations:

- Inertia (grandfathering) quotas based on current national emissions or GDP share
- Equity quotas based on population share

Previously, as a partial outcome of the Kyoto Protocol, multi-lateral management of the global carbon budget has focussed on “top down” effort sharing frameworks. The Paris Agreement takes a “bottom up” approach using the Nationally Determined Contributions (NDCs) specified voluntarily by participating parties. Developed nation Parties have committed to acting first and fastest to undertake “economy-wide absolute emission reduction” (UNFCCC, 2015). However, the voluntary NDCs are currently collectively inadequate to meet the temperature goal.

Nett global CO_2 emissions need to be close to zero by mid-century for WB2C, requiring nett energy decarbonisation on average of 4% to 8% yr^{-1} as of 2015 (with the range reflecting continuing scientific uncertainty in the response of the earth system to anthropogenic forcing). Removing carbon from the atmosphere through negative emissions technologies (NETs) may ease the required mitigation rate of gross emissions if NETs can be rapidly developed and deployed at scale. The vast majority of integrated assessment model (IAM) scenarios compatible with WB2C assume large additional amounts of CO_2 removal through NETs being delivered at a rapidly increasing scale to at least the year 2100.

NETs Options

Removing CO_2 from the atmosphere through NETs can be achieved by biological or chemical capture. The captured CO_2 can be stored terrestrially in biomass and/or soils or geologically. Different capture methods vary in efficiency and resource requirement, and different storage options vary in long term security and technical availability.

We review the literature for six NETs options with potential relevance to Ireland:

- Soil Carbon Storage (SCS)
- Biochar (BC)
- Enhanced Weathering (EW)
- Afforestation/Reforestation (AR)
- Bioenergy with Carbon Capture and Storage (BECCS)
- Direct Air Capture with Storage (DACCS)

Considerations for NETs include relative carbon removal capacity, cost, readiness, vulnerability to re-release of captured carbon, vulnerability to future climate change, biodiversity risk, energy penalty and land pressure (Table 1).

*Table 1: A simplified schematic to summarise the main policy relevant considerations for utilising NET options in Ireland. High uncertainty indicated by **

	SCS	Biochar	EW	Afforestation	BECCS	CCS	DACCS
Carbon removal	Medium *	Medium	Medium	Medium	High	High	Very High
Readiness	Very High	Very High	Medium	Very High	Medium	Low	Very Low
Cost	Medium *	Medium *	Medium	Low	Medium	High	Very High
Vulnerability to re-release	High	High	Medium	Medium *	Low	Low	Low
Vulnerability to future climate change	Very High	High	Medium	High	Medium	Very Low	Very Low
Biodiversity Risk	Low	Low	Medium	High *	High	Low	Low
Energy Penalty	Low	Medium	High	Low *	Very Low *	Medium *	Very High
Land Pressure	Low	Medium	Low	High	High	Very Low	Very Low

Climate Mitigation Modelling Options

Modelling future climate-energy-economy outcomes of potential choices through time can assist decision-makers. There are a multitude of complex IAMs and energy system modelling options. A summary of some models used with descriptions and considerations can be seen in Table 2.

Table 2: An overview of model options used in climate mitigation research

Model	Description
Benefit-cost analysis	Employs socioeconomic, physical climate, damage function and discounting *modules* to estimate mitigation pathways providing a notionally “optimal” balance of benefits over costs. The results, including estimates of a social cost of carbon (SC-CO_2), tend to vary considerably.
Cost effectiveness analysis	Used in economic climate mitigation modelling, assumes that a target will be met with high certainty. Analysis then identifies the least notional cost pathway among alternatives that all meet that specific target constraint. Within a cost-effectiveness framework, near-term policies need to be aligned with a high probability of meeting a climate target, otherwise they cannot be judged to be cost-effective.
Energy system models	Detailed models of energy systems, including primary sources, conversion processes and final uses, allowing identification of alternative configurations (including evolution over time) that meet given energy use requirements and other constraints (such as GHG emissions). They typically incorporate cost-effectiveness modelling to rank or select among alternative configurations and transformation pathways that meet the given constraints.
Multi-level perspective models	Accounts for decision-making, carbon lock-ins and cultural path dependence. May result in more policy relevant analysis, especially if stringent mitigation carbon quotas are not reflected effectively in near-term policy
Life cycle assessment (LCA)	Consider all greenhouse gas emissions associated with a defined system (e.g. bioenergy crop production system), particularly to assess the GHG intensity per unit energy output.

Decision-making and risk assessment

WB2C targets imply absolute limits on future use of fossil fuels and on fossil fuelled economies. Decision-making within a risk assessment framework, given the WB2C global carbon budget, means restrictive management measures (e.g. equitable carbon quotas) are now advisable. In decision analysis, due to the plausible probability of severe climate impacts on global systems the difficulty of how to meet WB2C emission paths is secondary to the physical requirement of meeting the quota. Despite the scientific certainty that absolute reductions in emissions are required for effective climate change mitigation, uncertainty avoidance and short-termism among decision-makers in public and corporate governance are common. Policies that lead to inaction, delayed action, or insufficient action may result in politically unfeasible pathways, stranded assets, higher costs, or, ultimately, impacts that overwhelm feasible adaptation (locally or globally).

Achieving deep decarbonisation: role of NETs

Effective governance needs to enable climate change mitigation and prevent rebound effects. Regulation and carbon taxes continue to be strongly resisted by many actors in global, regional and national governance. Carbon markets and market-based carbon pricing (flexible mechanisms) are increasingly used globally, but their effectiveness in achieving verifiable mitigation is strongly contested. Carbon accounting, particularly in land use, is complex and often contested or questionable. Policy dependence on negative emissions requires policy statements committing to defined and quantified investment time-steps in research, institutional design, legal enabling and pilot project delivery. In the likely scenario that NETs are required to stay within a WB2C global carbon budget, CCS is an essential technology development priority because land-based NETs, targeting biogenic storage (SCS, AR, BC), have limited long-term value due to saturation and impermanence. Strong Monitoring, Reporting and Verification (MRV) is an additional consideration for NETs, and may be a significant cost for these NET options. Developing effective NETs at the speed and scale necessary to meet a WB2C carbon budget, even allowing for target overshoot, may have profound social, environmental and economic implications, especially due to competition with traditional agriculture and biodiversity.

Potential for Ireland

Annual CO_2 emissions for Ireland are now over 40 $MtCO_2$ yr^{-1}. Current projections predict continued rising emissions to 2035, indicating failed decoupling from economic growth may continue to outweigh any incremental improvements in carbon intensity.

In Chapter 8, five models are considered to estimate Ireland's carbon quota from the WB2C aligned global carbon budget (Figure 1). The models consider different weightings of inertia and equity. The remaining nett carbon equity quota for Ireland is estimated to be less than 600 $MtCO_2$ as of end 2017, which will be exhausted in less than 15 years at the current annual rate of emissions. And even a maximum inertia carbon quota of 1000 $MtCO_2$ will still be exhausted before 2040. Meeting Ireland's CO_2 quota would require an exponential reduction rate in nett annual emissions of over -4% yr^{-1} for inertia to over -7% yr^{-1} for equity. Current projections estimate CO_2 emissions instead *increasing* at rates of +0.5% yr^{-1} to +1.3% yr^{-1} and indicative figures from 2016 show annual Irish emissions increased by 3.5% yr^{-1} over 2015. Ireland's current emission projections therefore imply either tacit commitment to very rapid, large-scale, deployment of NETs, or quantitatively inadequate mitigation policy (relative to the committed Paris Agreement temperature goals).

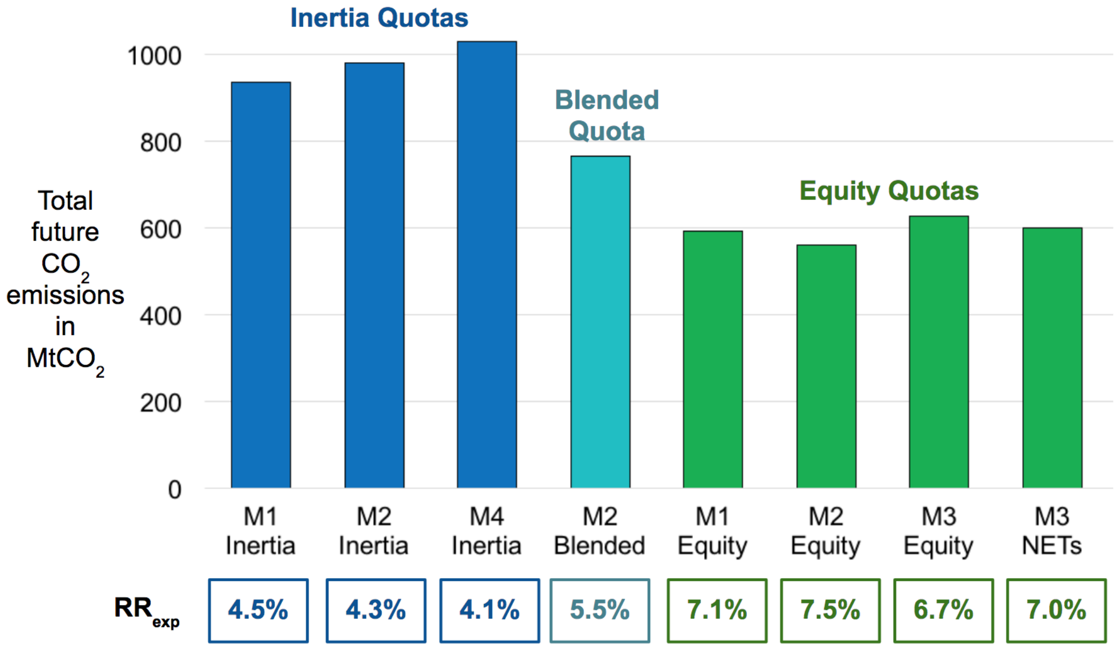

Figure 1: Estimates of Ireland's carbon quota (proportion of the global carbon budget) based on four distinct models (M1-M4) with varying weightings of inertia and equity. Percentage labels: Indicative annual emissions reduction rates required.

The most immediately deployable NETs options for Ireland are afforestation and soil carbon management. These are technologically mature and entail relatively low costs. However, these rely on impermanent land sequestration that may saturate within 20 years and will require continued MRV resources thereafter to retain the stored carbon.

Enhanced weathering may also be a theoretically feasible near-term option for Ireland, as it is technologically ready. However, it requires significant energy input, and would only yield nett negative emissions if energy for mining, grinding and transport becomes available from very low carbon sources.

Fossil Fuel with Carbon Capture and Storage (FFCCS) has been preliminarily investigated for Ireland, with promising storage potential understood from the Kinsale gas field. On this basis, Ireland could potentially deploy BECCS in future provided land area was available for bioenergy crops. As well as the significant undertaking of developing CCS infrastructure in Ireland, BECCS would also require major expansion of reliable bioenergy production and integrated greenhouse gas accounting mechanisms in place for biomass productions systems and energy use. Direct Air Capture with CCS may also be an option for Ireland, but is currently technologically immature, requires very low carbon energy inputs, and appears prohibitively expensive.

Assuming all policy, cost and socio-economic barriers to deploying NETs in Ireland were overcome, a preliminary assessment of *theoretical* NETs capacity in Ireland is estimated, on the basis of a notional land resource of up to 550,000 ha (16% of agricultural land) being available to terrestrial NETs (Figure 2). This exercise finds the highest individual NETs capacities could be achieved from development of BECCS and DACCS; lower capacities are from afforestation, enhanced weathering and soil carbon management, including biochar, which are time-limited primarily due to the saturation effect.

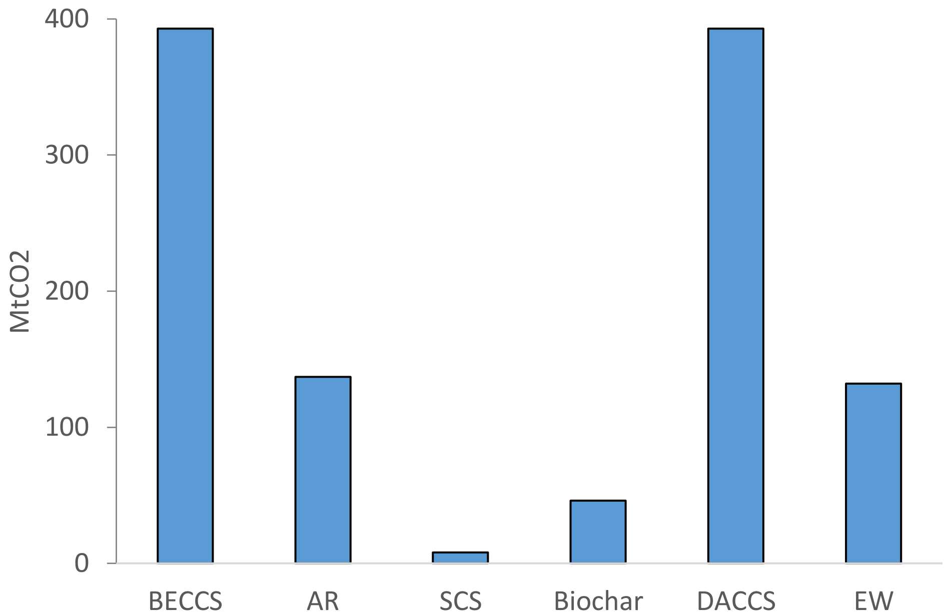

Figure 2: Estimated total cumulative CO_2 removal capacity of NET options in Ireland up to 2100, based on land area availability of 550,000 ha where relevant, and DACCS potentially being deployed to the same CO_2 removal capacity as BECCS.

Preliminary Conclusions

The most viable preliminary strategy that emerges for deploying NETs in Ireland, consistent with an explicitly Paris-aligned CO_2 nett emissions pathway, appears to be to maximise AR capture and storage now (at least up until 2035, with minimal harvest) while supporting the development of BECCS, with the view to allocating AR harvest biomass (beyond 2035) to BECCS when CCS costs are lowered and Irish soil carbon and forestry stock have saturated. However, if BECCS does not become ready or remains infeasibly expensive, the use of AR is limited by saturation and will only remove carbon up until a certain time limit (*c.* 20 years), after which no additional significant removals can be assumed. Additionally, carbon removed by AR is stored as biomass and soil carbon which is vulnerable to re-release and will require continued maintenance, monitoring and protection.

Hence, while this work informs policy discussions about the potential capacity for NETs in Ireland, the limitations imposed by permanence and saturation render NET options that are currently available (AR and SCS) high risk. Technological uncertainty and high costs render alternative options (BECCS and DACCS) presently unavailable at significant scale, and are therefore high risk to depend upon. Furthermore, Irish NET capacities estimated herein fall well short of the implied requirements of the emissions gap between estimated Irish CO_2 quotas and currently projected gross Irish CO_2 emissions.

Therefore, while our results indicate that NETs in Ireland may have significant carbon removal capacity and contribute towards achieving future net emission targets, **the highest priority and emphasis of Irish climate mitigation actions must continue to be immediate, significant and sustained gross emission reductions.**

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Abbreviations and Acronyms

AD: Anaerobic Digestion of biomass and bioliquid to produce biogas.

AR: Afforestation and Reforestation: Land-based CDR aiming to increase the carbon stock in forest trees and soils.

AR5: The Fifth Assessment Report by the IPCC, published 2013 to 2014, composed of three working group reports and a synthesis report, with summaries for policy-makers (SPMs)

atmCO_2: Concentration of carbon dioxide in the atmosphere in parts per million

ALCA: Attributional Life Cycle Analysis

BAU: Business As Usual.

BC: Biochar, made by pyrolysis of biomass producing energy and recalcitrant carbon for addition to soils.

BCA: Benefit Cost Analysis. Also called CBA. Optimises future mitigation and damage costs and benefits. Usually stated as a Net Present Value, as for the SC-CO_2.

BECCS: BioEnergy with Carbon Capture and Storage. Burning biomass in large electricity generating stations (possibly also using the waste heat) and also capturing the CO_2 to produce energy with nett negative lifecycle emissions.

CBDR+RC: "Common but differentiated responsibilities and respective capabilities". A key phrase in the UNFCCC concerning equitable climate policy action.

CBA: Cost Benefit Analysis. Also called BCA.

CBT: Carbon Border Tax

CCAC: Climate Change Advisory Committee, an expert advisory group set up under Ireland's Climate Action and Low Carbon Development Act (2015)

CCS: Carbon Capture and Storage. Methods that achieve capture of CO_2 from flue gases or from the atmosphere, followed by transportation by pipeline and then injection into geologically secure storage.

CDM: Clean Development Mechanism. The largest system of carbon permit emissions trading defined by the Kyoto Protocol, aiming to enable global mitigation at lower cost.

CDR: Carbon Dioxide Removal. Managed removal of CO_2 from the atmosphere to secure geological sinks by CCS and to less permanent sequestration in land sinks.

CEA: Cost Effectiveness Analysis. Assumes a target is met (implying infinite cost for failure).

CER: Certified Emission Reductions, certificates of emission reductions related to Kyoto CDM projects.

CLCA: Consequential Life Cycle Analysis

CO_2: Carbon dioxide, the main greenhouse gas targeted by climate mitigation policy due to the millennial scale global warming due to cumulative CO_2 emissions.

CO_2e: Carbon dioxide equivalent. Use to include CO_2 and all GHGs (including methane and nitrous oxide) in emissions totals. GWP_{100} is generally the conversion metric.

CoP: UNFCCC Conference of the Parties (next is Nov 2015, Paris)

DAFM: Department of Agriculture, Food and the Marine

DACCS: Direct Air Capture with Carbon Capture and Storage. CDR by extraction of CO_2 from air using alkali media, followed by transport and storage.

DCCAE: Department of Communications, Climate Action and Environment

DECLG: Department of Environment, Community and Local Government

DECC: UK's Department of Energy and Climate Change

DICE: A climate-economy BCA model.

EPA: Ireland's Environmental Protection Agency

ERU: Emissions Reduction Units, related to Kyoto's Joint Implementation programme.

ESM: Energy System Model or Earth System Model

ESOM: Energy System Optimisation Model

ESR: Effort Sharing Regulation of the European Union describing national targets for non-ETS emissions reduction by 2020 and as proposed for 2030.

ETS: Emissions Trading Scheme of the European Union covering large GHGs emitters with EU targets for aggregate EU ETS emission reduction.

EW: Enhanced Weathering using crushed ultrabasic silicate rock for CDR.

FFCCS: Fossil Fuel with Carbon Capture and Storage

FUND: A climate-economy BCA model.

GHG: Greenhouse Gas. A trace gas in the atmosphere that contributes to absorbing and retaining reflected solar energy (the greenhouse effect), keeping the Earth's surface warmer than it would otherwise be.

GGR: Greenhouse Gas Removal (typically synonymous with CDR or NET).

GMST: Global Mean Surface Temperature (as averaged from observations).

GWP: Global Warming Potential. A factor to compare different GHGs relative to the time-integrated radiative forcing of CO_2 over a period. In UNFCCC accounting GWP_{100} is for a 100-year comparison. GWP and other metrics produce very different comparison values depending on time horizon and gas properties.

HANPP: Human Appropriation of Net Primary Production. The proportion of NPP used by humans for food and energy production.

IAM: Integrated Assessment Models. Analytical models combining climate models with global, regional or national modelling of economic growth, energy-use and technologies. Used to develop scenarios informing policy options.

IEA: International Energy Agency

IPCC: Intergovernmental Panel on Climate Change

LCA: Lifecycle Cost Analysis

MMV: Measurement, Monitoring and Verification

MRV: Measurement, Reporting and Verification

Nett: Here used to describe total emissions minus total removals

N_2O: Nitrous oxide, a potent GHG with a GWP_{100} of 298 compared to CO_2 =1.

NETs: Negative Emissions Technologies. Methods that on a lifecycle basis achieve greenhouse gas removal (GGR) from the atmosphere.

NGO: Non-Governmental Organisation

NMP: National Mitigation Plan. Ireland’s mitigation policy statement.

Non-ETS: Non-traded national domestic emissions (transport, agriculture and buildings, limited by the EU 2020 target of a 20% reduction relative to 1990.

NPP: Climate Action and Low-Carbon Development National Policy Position. This is the Government’s current mitigation policy outline guiding the NMP.

NPP: Net Primary Production of biomass by photosynthesis (globally, nationally or by area).

OA: Ocean Alkalinisation. The addition of crushed basic rock to enable CDR.

ppm: parts per million

PAGE: A climate-economy BCA model.

PRG: Perennial Rhizomatous Grasses, such as Miscanthus

RES-E:EU 2020 Renewable energy penetration target for Electricity (for Ireland)

RES-H: EU 2020 Renewable energy penetration target for Heat (for Ireland)

RES-T: EU 2020 Renewable energy penetration target for Transport (for Ireland)

RDD&D: Research, Development, Deployment and Diffusion,

RF: Radiative Forcing. A measure of the heat trapping (energy imbalance) effect of atmospheric greenhouse gases or other climate pollutants; measured in Wm^{-2}.

SC-CO_2: Social Cost of Carbon Dioxide (also called the Social Cost of Carbon, SCC). A Net Present Value produced using BCA methods.

SCS: Soil Carbon Sequestration. Increasing carbon stocks in soils through improved land use management and the use of different crops or grasses.

SEAI:Sustainable Energy Authority of Ireland

SOC: Soil Organic Carbon

SPM: Summary for Policy-Makers, particularly the SPMs from the IPCC Assessment Reports.

SRF: Short Rotation Forestry, such as willow coppice.

SSP: Shared Socioeconomic Pathway: part of a modelling framework to facilitate the integrated analysis of future climate impacts, vulnerabilities, adaptation, and mitigation. The framework is built around a matrix that combines climate forcing on one axis (as represented by the Representative Forcing Pathways) and socio-economic conditions on the other. Together, these two axes describe situations in which mitigation, adaptation and residual climate damage can be evaluated.

tC: tonnes of carbon (1 tC is equivalent to 3.67 tCO_2 in the atmosphere).

TCRE: Transient Climate Response to cumulative carbon emissions.

tCO_2: tonnes of carbon dioxide.

UNFCCC: United Nations Framework Convention on Climate Change

WB2C: "Well Below 2ºC". Used as an abbreviation for the Paris Agreement temperature goal of limiting global warming relative to pre-industrial GMST. In terms of cumulative carbon emissions, a WB2C limit is typically interpreted as ensuring a 66% probability of not exceeding a 2ºC rise, and is quantitatively similar to the budget for ensuing a 50% probability of not exceeding 1.5ºC.

WG: IPCC Working Group. The IPCC has three Working Groups: WG1 reporting on the physical science of climate change; WG2 reporting on the observed and future impacts of climate change, and possible adaptation actions; and, WG3 on mitigation examples and options.

WMGHGs: Well Mixed Greenhouse Gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone. These GHGs rapidly disperse through the troposphere once emitted

WTO: World Trade Organisation

1 Climate and policy context for Negative Emissions Technologies

Summary

- The Paris temperature target, “well below 2ºC” (WB2C) corresponds to a remaining global carbon budget of future cumulative net CO_2 emissions. As of 2018 the WB2C global carbon budget is about ~800 (500-1100) $GtCO_2$. Annual global CO_2 emissions are over 40 $GtCO_2$ yr^{-1}, rapidly depleting the budget.
- The linear relation between cumulative CO_2 emissions and warming can inform policy aiming to limit to WB2C. Delay in achieving stringent mitigation effort increasingly steepens the required global nett decarbonisation pathway.
- NETs can theoretically extend the possibility of some continuing gross CO_2 emissions (globally or nationally), while still meeting the Paris temperature targets within a 2100 time limit but only if developed with sufficient speed and to sufficient scale.
- NETs employ biological (plant and algal) and chemical (alkali media) pathways of carbon dioxide removal (CDR) from the atmosphere, using land management and/or technological methods to store carbon in the biosphere or geosphere.
- Biogenic NETs, namely afforestation and reforestation (AR), ecosystem restoration, and soil carbon sequestration (SCS) including biochar (BC), increase total plant and soil carbon stocks. Sustainable harvest of plant stocks can be used to produce biochar (by pyrolysis of biomass) for addition to soils, or to produce biomass for burning in energy production that is equipped for bioenergy with carbon capture and storage (BECCS). Biogenic algal and ocean fertilisation NETs methods are also possible.
- Chemical NETs: Direct air capture (DAC) captures CO_2 from air passing over alkaline media, for storage using CCS. Alternatively, rocks containing alkali reactive minerals (such as olivine) can be ground into finer pieces or particles to enable spontaneous CO_2 removal to solid carbon products through enhanced weathering (EW).
- The radiative forcing effects of different GHGs are not easily equated with simplified metrics such as the GWP_{100} factors used in UNFCCC emission accountings to compare with CO_2. In particular, such metrics cannot be directly applied to cumulative GHG *stocks* (such as CO_2 global budgets or national quotas) as opposed to *flows* (annual emission rates). Policies and NDCs could be better aligned with best available science if they differentiated appropriately between GHGs.
- The natural sequestration available in land and ocean sinks is likely to decrease in future, and may be subject to increased probability of reversals given continued global warming due to future cumulative CO_2 emissions (until nett CO_2 flow is zero).
- CO_2 emissions are strongly related to fossil fuel use for energy. Methane emissions from wetlands and livestock agriculture are also increasing rapidly.
- The effectiveness of NETs in mitigation is potentially limited by large continuing emissions and carbon cycle limits including land-carbon saturation, leakage of stored carbon, and passing tipping points in the global climate system.

1.1 Introduction

Through the United Nations Framework Convention on Climate Change, the UNFCCC, the world's nations accept that rapid global warming is now occurring, caused by humanity's burning of fossil fuels and land-use choices, resulting in escalating, negative climate change impacts to human and natural systems (IPCC, 2014). Based on overwhelming observational and modelling evidence, from multiple sources in climate science, bioscience and ecology, the IPCC is categorical in its scientific advice to policy-makers:

> *Continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reductions of greenhouse gas emissions. (IPCC AR5 WG1, 2013, p. 19 SPM).*

In signing and ratifying the Paris Agreement, the nations of the world are now collectively committed to policy action "in accordance with best available science" and "on the basis of equity", that will achieve a global decarbonisation pathway aligned with limiting global mean surface temperature to "well below 2ºC above pre-industrial levels" and that "pursue efforts to limit the temperature increase to 1.5 °C" (UNFCCC, 2015). Scientifically, these targets translate to absolute carbon budget limits on future global nett CO_2 emissions. However, if continued at current rates, global CO_2 emissions will rapidly exhaust such a budget and even with radical emission reductions the Paris goals may rapidly become unattainable unless substantial 'negative emissions technologies', NETs, are also developed to be available at increasingly substantial scale starting in the very near-term. Some modelled estimates suggest the potential requirement for annual carbon dioxide removal (CDR) of billions of tonnes from the atmosphere to permanent geological storage or to less-permanent soil or forestry sequestration.

Political global agreement on stated target temperature limits to warming has now clarified the meaning of the 'level' described in the phrasing the original UNFCCC objective, to stabilise "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" (UNFCCC, 1992 Article 2). The evident serious impacts already being seen at 1ºC of warming (Yan et al., 2016) – including heat waves of increasing duration and intensity (Diffenbaugh et al., 2017), accelerating ice loss from the cryosphere (Ch. 4 IPCC AR5 WG1, 2013, pp. 319–320) and escalating global coral bleaching due to El Ninos boosted by ocean warming (Hughes et al., 2017) – are confirming past projections for impacts on human and natural systems stated in the "Reasons for Concern" from the IPCC Third Assessment Report (Ch. 19.6 IPCC AR5 WG2, 2014, pp. 1066–1079). As reported in AR5, further research updating the "Reasons for Concern" has revised temperature thresholds downwards, meaning that serious system impacts are likely to occur before reaching 2ºC warming. Furthermore, Article 4 of the Paris Agreement states:

> *In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with*

best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty. (UNFCCC, 2015 Article 4)

Reported global CO_2 emissions 'flat lined' in 2014 to 2016, largely due to economic conditions in China, but then rose by 2% in 2017 (Quéré et al., 2017) so may or may not be close to an ultimate peak. However, for a chance of 2ºC developed nations, particularly, will need to now make rapid reductions toward nett zero CO_2 emissions. The cumulative radiative forcing effect of CO_2 places severe limits on future global emissions if temperature targets are to be met. Continuing global emissions at the current historic high of about 40 $GtCO_2$ yr^{-1} implies that increasingly steep decarbonisation rates will be needed to meet the politically agreed temperature targets (Matthews et al., 2017) unless unfeasible amounts of negative emissions are included.

1.1.1 The possible role of negative emissions in mitigation pathways

Scenario modelling of possible global transformation pathways shows that extending limited future use of fossil fuels while enabling a 50% chance of limiting to 1.5ºC, or to well below 2ºC (at least a 66% chance) will very likely require substantial amounts of negative emissions, starting even well before 2050 (IPCC AR5 WG3, 2014, p. Ch. 6). Even though CCS and especially BECCS are unproven at the supposed scales, Integrated Assessment Model global scenarios limiting to "well below 2ºC" include large numbers of FFCCS plants to reduce emissions from fossil fuel and industrial processes, and BECCS generating plants to enable dispatchable electricity production with negative emissions (Peters and Geden, 2017). Planned large-scale carbon dioxide removal in land use and by more technologically complex NETs is assumed in IPCC climate-energy economic modelling but assessments focused on their potential, trade-offs and limitations in specific countries such as Ireland are missing (Fuss et al., 2014a). Global policies relying on these scenarios therefore tacitly assume large scale, early deployment of NETs, but NETs are technologically unproven and are not referenced in Nationally Determined Contributions, the pledges of the Parties to the Paris Agreement, so policy needs to move from targets to implementation of commensurate climate action, with or without NETs (Knopf et al., 2017). Therefore, Ireland and the EU, and all other nations, will quickly need to articulate a policy viewpoint of their own on negative emissions that will align 'ratcheted-up' mitigation action with quantitative pathway options meeting the Paris Agreement (Rogelj et al., 2016a), including the extent to which negative emissions are being relied on within likely estimates of national carbon quotas equitably derived from the global carbon budget (Gignac and Matthews, 2015).

Over the past decade the recognition that negative emissions may be required to meet climate stabilisation targets has spurred a very rapidly expanding research literature (Minx et al., 2017) examining the global potential for negative emissions technologies to remove CO_2 from the atmosphere and then store it, either in geologically secure reservoirs or, less dependably, in land-based sequestration in forests or soils (IPCC AR5 WG1, 2013). However, other than afforestation and unintended ocean fertilisation due to pollution, NETs remain largely undeveloped, or difficult to monitor as in soils. Carbon capture and storage, essential to BECCS and DACCS, is a working technology but low carbon prices and risk allocation for long term storage continues to limit deployment levels, especially compared to the large amounts of CO_2 storage being included in modelled low-CO_2 concentration scenarios – up to 4000 plants by 2030 compared to only tens planned by 2020 (Peters et al., 2017, p. 121).

1.1.2 Types and implications of Negative Emission Technologies (NETs)

Defined by basic pathway process, NETs can be classed as biogenic (plant or algal) or chemical based on alkali CO_2-reactive media (Lenton, 2014). Biogenic methods can be *plant-based* including Afforestation/Reforestation (AR) or BioEnergy with Carbon Capture and Storage (BECCS), burning biomass in power stations for energy and capturing and storing the exhaust CO_2, or *algal-based* methods, such as algal-BECCS and ocean fertilisation. Chemical *alkali-based* methods, include Direct Air Capture (passing air over alkali media), and Enhanced Weathering, grinding up basic and ultra-basic silicate rocks for spreading on land or ocean to absorb CO_2. In practical terms, NETs range between changes in land use practices (requiring relatively low technology and landscape-wide adoption in farming and forestry to achieve increased, long term, carbon storage in biomass and soils) to more highly engineered methods and facilities, including large power plants for BECCS and distributed units as in DACCS (Smith et al, 2015). Figure 1.1 shows NETs types, pathways and stages.

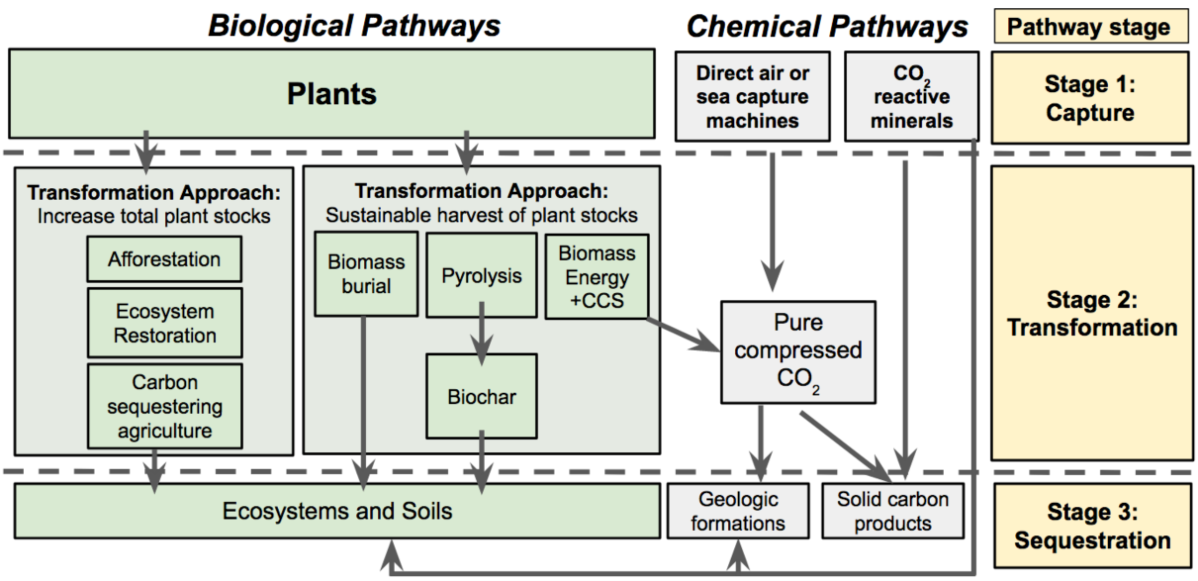

Figure 1.1 Negative emission technology types, pathways and stages. (Adapted from Deich, (2015).

Comprehensive assessment is urgently needed to examine NETs technical potential but also the social, economic, governance and engineering constraints to delivering carbon dioxide removal in reality (Lenton, 2014, p. 73). As Fuss *et al.* (2014a) set out, national-level research to establish the real-world feasibility for NETs – in the context of global climate action and sustainable development goals – is now critically important to examine and trial the technical potential, land-use implications, socio-political acceptability, and likely costs for negative emissions. Balancing the implications of climate action and inaction, for current generations and future ones, policy decisions to enable investment to investigate, deploy and achieve substantive negative emissions may have to begin now, in parallel with deep decarbonisation of ongoing fossil fuel and land use GHG emissions (Hansen et al., 2016).

1.2 Anthropogenic greenhouse gas emissions

Despite the complexity of Earth's climate system, many decades of climate science have arrived at understanding a surprisingly straightforward emergent property for the specific role of CO_2: global temperature rise is approximately linearly related to total cumulative anthropogenic emissions of carbon dioxide, such that every additional unit of CO_2 emitted to the atmosphere produces a corresponding increment of warming (IPCC, 2013, p. 1033). Human extraction and burning of fossil fuels takes carbon out of geologically secure stocks in the geosphere and adds it to the atmosphere and biosphere; deforestation and soil degradation also cause emissions due to nett loss of stored carbon. Unless NETs can be developed to achieve substantial CO_2 removal then a large proportion of the atmospheric CO_2 addition remains in the atmosphere, causing energy imbalance, and therefore global warming with ongoing climate change that is essentially irreversible on human timescales (IPCC, 2013, WG1 Ch. 12). Limiting CO_2 emissions quickly has a beneficial effect in limiting temperature change within ten years (Ricke and Caldeira, 2014) and limiting total future emissions will correspondingly avoid a related amount of global warming and potentially avoid tipping points toward non-linear change in the climate system such as ice sheet melt in Greenland and West Antarctica (Clark et al., 2016).

The *Global Carbon Budget*, a cooperative effort of the international climate science community (Le Quéré et al., 2016 is the eleventh annual publication) summarises emissions since 1750, giving an in-depth annual update of human-caused emissions as they perturb the stocks and flows in the natural carbon cycle. Note that the *annual* global carbon budget, of fluxes between geologic, land, ocean and atmospheric carbon stocks, needs to be distinguished from the *cumulative* global carbon budget corresponding to limiting global warming to a specified temperature. For fossil fuel updates the Global Carbon Budget relies on data from the annual BP Statistical Review of World Energy (BP, 2016).

UNFCCC inventory data is reported for the territorial usage of each major type of fossil fuel (coal, oil and gas) and territorial land-use carbon flows. Each new Global Carbon Budget assessment assembles observed data for the global carbon budget in the previous year and gives a projection of fossil fuel emissions for the current year. The anthropogenic emission sources and their sinks necessarily satisfy the following balance equation as given by the assessment:

$$E_{FF} + E_{LUC} = G_{ATM} + S_{OCEAN} + S_{LAND}$$

The annual added increment of carbon dioxide from fossil fuels and cement E_{FF} and from land-use change E_{LUC} are emitted to the atmosphere, where about 45% remains as the amount G_{ATM} added each year to past atmospheric CO_2 accumulation. The remaining 55% is absorbed from the atmosphere, approximately evenly, by the ocean and land sinks, S_{OCEAN} and S_{LAND} respectively. If global nett negative emissions were achieved then the overall flows would be reversed: carbon dioxide removal from G_{ATM} to store CO_2 in land sequestration and in geological storage would result in incremental degassing from the ocean and land sinks back into the atmosphere, such that the full amount of previous emissions (not just the amount retained in G_{ATM}) needs to be removed to cancel the warming effect.

On average for 2006 to 2015, fossil fuels use and other industrial processes emitted 9.3 ± 0.5 GtC yr^{-1}, land-use change contributed 1.0 ±0.5 GtC yr^{-1}. In total, these emissions resulted in an annual increase in accumulated atmospheric carbon of 4.5 ±0.1 GtC yr^{-1} (adding more than 2 ppm yr^{-1} to the atmospheric concentration of CO_2). Decadal flow averages are provided from 1960. Cumulative emissions of CO_2 from fossil fuel and land-use sources are totalled up to the current year since 1750, the nominal start of industrialisation, and since 1870 (the IPCC reference year relevant to available data on global temperatures).

Prior to industrialisation the human perturbation of the Earth's carbon cycle is believed to have been generally small, other than significant land-use change such as deforestation. (Land-use change in GHG accounting is taken to mean a substantive change in long term land-use classification and does not include temporary changes in stocks or flows such as clear-cutting of forestry that will be replanted.) Since industrialisation began in the late 18th century, atmospheric concentrations of greenhouse gases, especially CO_2, have steadily increased due to human-caused emissions from fossil fuels and land use change – in the case of CO_2, from about 277 parts per million in 1750 to 399 ppm in 2015 (Le Quéré *et al.*, 2016). From 1870 up to 2016, the cumulative total of CO_2 emissions released by humanity has been 565 ± 55 GtC (2,075 ± 205 $GtCO_2$), about 75% from burning fossil fuels and 25% from land-use change. Greenhouse gas concentration in the atmosphere today exceeds levels from the last 800,000 years. From 1750 to 2011, 375 Gt of carbon has been released from fossil fuel combustion and cement production, with 9.5 GtC released in 2011 alone (Le Quéré et al., 2016). A further 180 GtC has been released from land use change. Of this, 240 GtC has accumulated in the atmosphere, with the remaining re-absorbed by the ocean and terrestrial systems. The human caused perturbation has increased CO_2, CH_4 and N_2O concentration by 40%, 150% and 20% respectively, from 1750 to 2011.

1.3 Impact of GHG emissions on climate and natural systems

1.3.1 Recorded and current impacts

The IPCC show ongoing increases of the global mean surface temperature (GMST) since the late 19th century, including warming of the troposphere and cooling of the stratosphere since the mid-20th century, and warming of the upper ocean since 1971 (IPCC AR5 WG1, 2013). The radiative energy flux of the earth has become imbalanced, with more solar energy entering than leaving, since at least 1970 and notable changes in wind circulation patterns can be seen. Changes have also been observed in precipitation and sea surface salinity. In ice extent, there has been significantly decreased Arctic and slightly increased Antarctic sea ice extent and glacier size and snow cover extent have been decreasing. Global mean sea level has risen by 0.19m from 1901-2010. Globally there has been an increase in frequency and strength of extreme weather events. Heat waves and heavy precipitation events have been more frequent, droughts have been worse and lasted longer and floods have been larger. Oceanic uptake of carbon has resulted in acidification, with significant ecological consequences. Oceanic oxygen concentration has decreased.

The change in climate observed is driven by increased radiative forcing due to anthropogenic activity: increased greenhouse gas concentrations due to fossil fuel burning and land use changes causing warming, and increased aerosol pollution, which in aggregate causes a lesser, offsetting cooling effect. Climate change influence on water, biogeochemical and carbon cycles may cause positive or negative feedback effects on increasing global mean temperature.

1.3.2 Future disruption to climate and natural systems from anthropogenic GHG additions

Near term changes in climate projected are sensitive to aerosol emissions, especially at a regional scale and in relation to the hydrological cycle. The global mean surface temperature is projected to increase by 0.3-0.7ºC from 2016-2035. Consequently, increased duration, intensity and spatial extent of heat waves is likely. Other near-term projected changes include higher mean zonal precipitation in high and mid latitudes, increased heavy precipitation events, changes in atmospheric circulation patterns, increased ocean temperatures and an ice free Arctic Ocean.

Long term climate changes projected include continued rising of globally mean temperatures, the extent of which depends strongly on future GHG emission pathways. With increased GMST, precipitation will increase generally with more frequent and intense extreme precipitation events, decreased Arctic sea ice is expected, with possible decrease in Antarctic sea ice also, permafrost will decrease, snow cover area will reduce, and ocean temperatures will warm. The ocean will continue to uptake CO_2, positive feedback from loss of carbon from frozen soils will occur, nutrient shortage will limit terrestrial CO_2 sinks, ocean oxygen content will continue to decrease, and global mean sea level will rise. Monsoons are likely to increase.

WG2 of the IPCC observed risks of altered hydrological cycles affecting resource availability, altered behavioural patterns or biodiversity, negative impacts on crop yields, increased climate extremes, increased vulnerability due to conflict. Potential future risks include intensified competition due to reduced renewable surface and groundwater resources, increased extinction risk of species, irreversible change in composition of ecosystems, submergence and flooding from sea level rise, marine ecosystem degradation from ocean acidification, disrupted crop production and undermined food security and stability, negative human health impacts, increased displacement of people, increased conflict risk and slowing economic growth.

1.4 The Paris Agreement

Within the 2015 Paris Agreement (UNFCCC, 2015) parties agree to hold the 'increase in the global average temperature to well below 2ºC above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5ºC'. The parties agree to reach global peak emissions as soon as possible, preserve and enhance greenhouse gas sinks and reservoirs, use voluntary international cooperation to reach national mitigation targets, enhance global adaptive capacity, minimise loss and damage, provide financial assistance from developed parties for developing parties, share technology, build capacity, enhance climate change education and public awareness, develop an enhanced transparency framework for action and support, periodically take stock of the implementation of the agreement and establish an implementation mechanism. Mechanisms for implementation involve developing voluntary Nationally Determined Contributions (NDCs), taking stock every 5 years and developing more ambitious new targets to peak GHG emissions as soon as possible and achieve net-zero carbon in the second half of the century.

1.5 The global carbon budget for "well below 2ºC"

A global carbon budget is the 'finite quantity of carbon that can be burned associated with a chosen 'safe' temperature change threshold' (MacDougall et al., 2015). The approximately linear response of long-term global warming to cumulative carbon emissions enables an estimated likely (66%) chance of constraining warming to below 2ºC if the total global carbon budget does not exceed 1000 GtC (3670 $GtCO_2$) from the year c. 1870 onwards (Summary for Policy-Makers, IPCC AR5 WG1, 2013, p. 27). Le Quéré *et al.* (2016) estimate cumulative emission from 1870-2016 are 565 ±55 GtC (2075 ±205 Gt CO_2), with 75% from fossil fuel and industry, and 25% from land use change. The estimated carbon budget is 590–1240 $GtCO_2$ from 2015 onwards while current CO_2 emissions are about 40 $GtCO_2$ yr^{-1}; from 2017, ~800 $GtCO_2$ remains in the carbon budget (Rogelj et al., 2016c). Rogelj *et al.* describe how, due to uncertainties in climate sensitivity, non-CO_2 emissions and future emission pathways, different types of climate model give carbon budget values or ranges, either: up to the time when the temperature target level is exceeded as Threshold Exceedance Budgets (TEBs, derived from complex climate models; or, as Threshold Avoidance Budgets (TABs) for avoiding the temperature target level of warming based on scenarios run on simple climate models, allowing for radiative forcing by non-CO_2 emissions; see Table 1.1 below (AR 5 Synthesis Report IPCC, 2014 Table 2.2).

Table 1.1: Cumulative CO_2 emission ranges from 1870 and 2011 in $GtCO_2$ consistent with limiting warming to less than stated temperature limits at different levels of probability (reproduced from IPCC 2014 AR 5 Synthesis Report Table 2.2)

Cumulative CO_2 emissions from 1870 in $GtCO_2$									
Net anthropogenic warming [a]	<1.5°C			<2°C			<3°C		
Fraction of simulations meeting goal [b]	66%	50%	33%	66%	50%	33%	66%	50%	33%
Complex models, RCP scenarios only [c]	2250	2250	2550	2900	3000	3300	4200	4500	4850
Simple model, WGIII scenarios [d]	No data	2300 to 2350	2400 to 2950	2550 to 3150	2900 to 3200	2950 to 3800	n.a. [e]	4150 to 5750	5250 to 6000
Cumulative CO_2 emissions from 2011 in $GtCO_2$									
Complex models, RCP scenarios only [c]	400	550	850	1000	1300	1500	2400	2800	3250
Simple model, WGIII scenarios [d]	No data	550 to 600	600 to 1150	750 to 1400	1150 to 1400	1150 to 2050	n.a. [e]	2350 to 4000	3500 to 4250
Total fossil carbon available in 2011 [f]: 3670 to 7100 $GtCO_2$ (reserves) and 31300 to 50050 $GtCO_2$ (resources)									

The carbon budget is a robust and simple concept that can be used to inform emission pathways to meet the 2ºC target (MacDougall et al., 2015). In providing stated carbon budget ranges, it effectively links climate response, economics and equity. It also incentivises decoupling of economic growth and fossil fuel burning, aiding the design of a low carbon global economy (Messner et al., 2010). While intuitively appealing, calculating the carbon budget is complex so it is impossible to assign a unique or precise budget to a given temperature target (Anderson and Peters, 2016). The carbon budget is sensitive, and may fluctuate in response to additional factors such as non-CO_2 climate forcing and permafrost melting (MacDougall et al., 2015). Hence while effective in facilitating policy making and developing emission pathways, there are inconsistencies in the budget ranges quoted for 1.5ºC and 2ºC temperature limits (Peters, 2016). As discussed further in Chapter 2, distributing the carbon budget through time to reach and maintain zero nett emissions is likely to require agreed multilateral allocation among nations and through time that will need to be managed in a fair and transparent way (Messner et al., 2010). Knutti et al. (2017) provide a thorough review of climate sensitivity estimates.

1.5.1 Climate sensitivity and velocity in relation to the global carbon budget

The equilibrium climate sensitivity, ECS (defined by the longer-term surface temperature response to a doubled atmCO_2 concentration) continues to have a wide scientific uncertainty range due to the multiplicity of variables in the climate system. This has been considered as a reason to delay mitigation action but in fact it is of little relevance to near-term climate policy as even if ECS values were to be at the lower end of the range this would only postpone exceeding 2ºC by about 10 years if emissions continue at current levels (Rogelj et al., 2014a). Lower ECS values, estimated based on historical temperature and weather observations for the past hundred years, fail to account for multi-century, climate system responses that only contribute 1 to 7% of current warming but ultimately dominate warming toward the long-term equilibrium calculated for doubled CO_2 (Proistosescu and Huybers, 2017). This finding shifts the ECS values significantly upward to a range of 2.2ºC to 6.1ºC

(5-95% confidence interval), and increases the risk assessment. Continued unrestricted burning of fossil fuels could easily result in atmCO_2 concentrations well beyond 550 ppm, potentially reaching two doublings of CO_2 above pre-industrial implying far greater eventual warming than the commonly stated climate sensitivity range for a single doubling.

Both the global carbon budget (the total amount of future CO_2 emissions) and climate velocity (the speed of global and local change due to continued high annual emission rates) are relevant in policy to enable societal low carbon transition pathways and the required adaptation of vulnerable human and natural systems (IPCC AR5 WG2, 2014, pp. 924–927 Ch. 16.6). As is being seen now in the accelerating global bleaching of coral reefs, high 'climate change velocities', (rates of current global warming) are causing mounting stress for natural systems that is likely to exceed the adaptation limits of many ecosystems (LoPresti et al., 2015). Of greater relevance to near-term climate policy are the transient climate response (TCR) at the exact time of doubled CO_2 and the transient climate response to cumulative carbon emissions (TCRE), likely between 0.8ºC and 2.5ºC per 1000 GtC (3,670 $GtCO_2$), the basis for the probabilistic carbon budgets (IPCC AR5 WG1, 2013, p. Ch. 12 see p. 1113 for details on TCRE and carbon budgets).

1.6 Current global GHG emissions totals, sectors and trends

Annual carbon emissions increased at a faster rate from 2000-2011 than from 1990-1999, with atmospheric concentration of CO_2 increasing at a rate of 2 ppm yr^{-1} from 2002-2011. After plateauing in the early 2000s methane concentration has begun to increase again since 2004, and nitrous oxide concentration has increased steadily over the last 3 decades. Annual GHG emissions are now at the highest level in human history reaching 49 (±4.5) $GtCO_2e\ yr^{-1}$ in 2010, a rise of +80% from 1970's level of 27 (±3.2) $GtCO_2e\ yr^{-1}$ (IPCC 2014). About 78% of the increase to 2010 came from burning of fossil fuels and from industrial processes, leading to 32 $GtCO_2\ yr^{-1}$, or 69% of emissions in 2010. Land-use related emissions in 2010 totalled 12 $GtCO_2e$ (from agriculture, deforestation and land-use change). Cumulative past CO_2 emissions from human-caused land-use change were larger than those from fossil fuels until 1970, but, by 2010, fossil fuel cumulative emissions (over 1340 ±110 $GtCO_2e$) were close to double those from past land-use change 680 (±300) $GtCO_2$. Despite the clear evidence of a need for immediate action to reduce future costs, and the useful metric of a carbon budget, emission pathways are not deviating from business-as-usual scenario and annual emissions have continued to grow.

Jarvis *et al.* (2012) point to the remarkably consistent growth in human energy use and (related CO_2 emissions) suggesting that the key mechanism to explain this phenomenon is a strong feedback relationship between climate and society, and find that current policies would have to be significantly strengthened for effective, rapid mitigation to be aligned with "well below 2ºC" emission pathways. Urging that these emission trends be reversed before the rapidly decreasing climate budget is used up, Friedlingstein *et al.* (2014) show that the recent and current context of "lower than anticipated carbon intensity improvements of emerging economies and higher global gross domestic product growth" is challenging the feasibility of deep decarbonisation. For the years 2014-2016, reported global CO_2 emissions plateaued, at least briefly, though at the highest level in human history at about 40 $GtCO_2$ yr^{-1} (IEA, 2017). This recent levelling off of emissions appears to be more connected to an economic slowdown in China, reducing demand for steel and coal, rather than being an effect of climate policy (Peters et al., 2017). In general, there is an ongoing, growing deviation occurring between climate-target based emission scenarios and actual emission trends (Anderson and Peters, 2016).

Additionally, global methane emissions are now growing again rapidly causing an increasing proportion of anthropogenic energy imbalance and climate change. The increase in atmospheric methane concentrations is most likely due to mainly biogenic causes – increased tropical wetland emissions and increased agricultural ruminant livestock and rice production – though likely also include increased fugitive emissions from coal mining and unconventional ('fracked') oil and gas production (Saunois et al., 2016).

1.7 Mitigation pathways and modelled scenarios

Most of the scenario literature on achieving stringent emission targets suggests global nett zero CO_2 emissions would be reached between 2060 and 2075 but near-term delay results in a requirement for earlier nett zero emissions, potentially requiring negative emissions to enable less stringent gross emissions reductions (Rogelj et al., 2015b; Rozenberg et al., 2015).

1.7.1 Delayed action limits future mitigation options

IAM pathways show that the more action is delayed, the higher the cost and the lower the achievability of options (Gambhir et al., 2015). Stocker (2013) projects that, under an assumed economic constraint of maximum emission reduction rates of -5% yr^{-1}, the 2ºC target will become unachievable by 2027, with increasingly severe (and likely unachievable) mitigation required as action is delayed; and the 1.5ºC target is already unachievable and we will pass a 2.5ºC warming limit as early as 2040. Huntingford *et al.* (Huntingford et al., 2012) also highlight the concerns of narrowing emission pathways options as time of inaction lengthens, with the position in 2020 determining flexibility for 2050 targets. Van Vuuren et al. (2015) also note concerns of fewer pathway options with delayed action, as well as increasing dependence on under-developed technologies. Rogelj *et al.* (2015b) also note that mitigation efforts such as reducing emissions and increasing energy efficiency need to be rapidly scaled up as the window to achieve 1.5ºC closes.

1.7.2 Differentiating between long-lived and short-lived climate pollutants

Human caused climate pollutants include greenhouse gases that cause warming and aerosol particles, such as black carbon, that also causes warming, and sulphate emissions that cause cooling by reflecting sunlight (Samset et al., 2018). The major anthropogenic GHGs producing significant current radiative forcing to change the global energy balance are the "well mixed greenhouse gases" (WMGHGs) – carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone – that rapidly disperse through the troposphere once emitted. Net anthropogenic effective radiative forcing (ERF) is currently about 2.3 ±1.2 Wm^{-2}

including 2.8 ±0.5 Wm^{-2} from the WMGHGs (IPCC AR5 WG1, 2013, p. Ch. 8). Different greenhouse gases have atmospheric lifetimes and different radiative forcing properties that affect the magnitude and longevity of their resulting temperature effect. Immediate, focused reduction of short term non-GHGs may provide some flexibility in meeting the carbon budget by reducing the rate of warming earlier but CO_2 reductions are needed to limit long term warming (Montzka et al., 2011). Rogelj *et al.* (2015b) considers the role of short lifetime climate pollutant (SLCP) GHGs, such as methane, hydrofluorocarbons (HFCs), black-carbon and sulphates, in calculating the carbon budget and meeting the 2ºC target. The release of these GHGs are related, technologically and economically, to CO_2 release and therefore not straightforward to fully decouple and target reductions of short term GHG mitigation. However, they estimate that the CO_2 budget could be up to 25% larger if stringent methane mitigation was employed. Solomon *et al.* (2013a) considers using focused reduction of SLCPs to 'trim the peak' on an emission pathway and buy time. However, even with effective mitigation of methane, CO_2 emissions would still need to peak within the next two decades and better metrics or separate targets for different GHGs need to reflect that different forcing agents have different strengths and lifetimes, rather than a single trading basket summarising forcing agents into notional "CO_2 equivalent" values (Solomon et al., 2013b).

1.8 Implications for Policy and Governance

A carbon budget and temperature limit are useful metrics to inform policy and decision makers for long term climate mitigation, but have limitations in their usefulness for short term actions (Tavoni and Van Vuuren, 2015). Chapter 5 and 6 of this literature review assesses decision-making and governance in climate change action in more detail.

1.8.1 Action under uncertainty

To address climate change in terms of risk assessment, global policy makers are advised to use the precautionary principle, whereby scientific uncertainty does not excuse inaction. Gollier et al. (2000) suggest that prevention effort occurs when prudence is larger than twice the risk aversion. Hence it is possible to implement immediate reductions under scientific uncertainty; and more uncertainty around future risk should induce stronger immediate prevention measures in society.

1.8.2 Need for a long-term perspective

Huntingford *et al.* (2012) highlight the need for a very long-term perspective when writing climate policies, rather than focusing on near-future 2020 or 2050 targets, policies should consider as far ahead as 2500. Van Vuuren *et al.* (2015) concur with this view, emphasising that policies developed in the next few years will have significant long term implications. Similarly, Luderer *et al.* (2016) question the political feasibility of future emission pathways, because (due to current weak policy climate) effective long term mitigation pathways would be characterised by fast, aggressive transformations of the energy system, higher costs and carbon prices and stronger traditional economic impacts. Pye *et al.* (2017) also suggest that a focus on 2030 could blindside the climate challenge. At a national level in the UK, ambitious targets focused on the short term fall short of achieving net zero by 2100. Hence there is a need for longer-term pathways to be considered in mitigation policy.

1.8.3 Equity

Sharing the carbon budget amongst nations in an equitable way is a significant challenge for multi-lateral management due to the historical disparity in per capita emissions and the finite nature of the carbon budget (Gignac and Matthews, 2015). Some countries are on low-carbon development trajectories and may not use all of their equitable carbon allocation, however this has implications for quality of life (Lamb, 2016). Global energy use per person since 1971 has increased slowly with the developed nations showing very high energy use compared with much lower energy use in the developing nations. An apparent long-term stability in highly inequitable energy use is evident, with the exception of China (Lamb, 2016).

The contraction and convergence method is a commonly cited approach for the international community to meet the climate targets. The method is described by (Gignac and Matthews, 2015) as ‘national or regional per capita emissions are first allowed to increase or decrease for some period of time until they converge to a point of equal per capita emissions across all regions at a given year.’

Sharing the carbon budget equitably is a daunting task that requires the integration of human values and scientific understanding. The recent voluntary pledges (NDCs) by the EU, US and China currently would not allow for additional emissions from any other countries if 2ºC is to be achieved, implying the expectation that other nations will have to accept 7-14 times lower per capita emissions. One proposal to counteract this inequality is a significant diplomatic effort to make new technologies quickly and widely available in the near future (Peters et al., 2015).

1.9 Conclusion

Negative emissions technology to remove CO_2 from the atmosphere, intending to reverse effects of past and continuing extraction of fossil carbon from geologically secure reservoirs, must achieve a comparable level of permanence to fossil stocks, i.e., storage on “timescales larger than tens of thousands of years” (IPCC AR5 WG1, 2013, p. 470). Shorter-term sequestration of carbon in land stocks, forests (biomass) and soils is non-permanent and likely to return carbon to the atmosphere (especially with continued global warming increasing rates of soil respiration and fire), such that warming is only delayed rather than avoided (IPCC AR5 WG1, 2013, p. 470). Restoring all feasible land carbon could only reduce atmCO_2 by 40-70 ppm by 2100 with another ~25% in potential drawdown resulting from the CO_2 fertilisation effect (Becken and Mackey, 2017, p. 73). Protecting and adding to existing carbon stocks in the terrestrial biosphere is an important mitigation action but in general it should be regarded only as replenishing past losses from forests and soils and should not be counted as an offset against past or continuing carbon emissions from burning fossil fuels extracted from geologic reservoirs (Becken and Mackey, 2017, p. 73).

Temporarily overshooting global carbon budgets aligned with Paris temperature targets yet still avoiding or minimizing the duration of temperature overshoot would depend critically on removing the excess carbon from the atmosphere to return to the stated budget limits within tight time constraints, and certainly by 2100 (MacDougall et al., 2015). Tokarska and Zickfeld (2015) use an Earth System Model to investigate the effect of achieving global negative emissions following different levels of temperature overshoot beyond 2ºC, finding that committed sea level rise takes several centuries to slow and reverse. In this modelling, removing CO_2 from the atmosphere to storage results in outgassing of CO_2 to the atmosphere, confirming the IPCC assessed evidence that for every tonne of CO_2 previously emitted in excess of any given budget, a full tonne (at least) will have to be extracted and stored in future to counteract the warming effect (see Fig. 6.40 IPCC AR5 WG1, 2013). This assumes, of course, that critical positive feedbacks have not been already triggered by the temperature overshoot (crossing so called “tipping points”).

Many authors consider the most prudent and plausible decarbonisation pathway to be an “immediate significant and sustained global mitigation, with a probable reliance on net negative emissions in the longer term” (Peters et al 2016). In ESM modelling, Jones *et al.* (2016) considers immediate NET deployment prominent in pathway options finding that the effectiveness of NETs may be dampened by the weakening and even potential reversal of natural sinks even under low emission pathways. Hence the perturbation to the carbon cycle from various pathways must be properly accounted for to predict how effective NETs, or any other pathway will be (C. D. Jones et al., 2016). Anderson and Peters (2016) point out that an over-reliance on NETs that may not succeed could lock society into a high emissions pathway. This is a criticism of many emission scenarios that they depend on technology that is either not yet proven at large scale or not sufficiently developed beyond theoretical study. They conclude by suggesting the following uncomfortable, but plausible, rationale for this over-reliance on NETs in scenario literature:

> *The promise of future and cost-optimal negative-emission technologies is more politically appealing than the prospect of developing policies to deliver rapid and deep mitigation now. (Anderson and Peters, 2016)*

2 Options for multilateral management of Paris-aligned remaining global carbon budgets

Summary

- Plausible emission pathways aligned with “well below 2ºC” (WB2C), meeting the corresponding global carbon budget, depend on early peaking of global CO_2 emissions followed by substantial and sustained emission reductions.
- To allow any substantial fossil fuel use after mid-century in WB2C pathways Integrated Assessment Models include large amounts of carbon dioxide removals (CDR), especially large scale BECCS combining energy production and negative emissions.
- Nett CO_2 emissions need to be close to zero by mid-century for WB2C pathways, requiring nett energy decarbonisation of average 4% yr^{-1} to 8% yr^{-1}, implying that NETs will need to start delivering significant CDR well before 2050 to permit continuing fossil fuel use.
- Multi-lateral management has typically focussed on “top down” effort sharing frameworks such as the mixed outcome of the Kyoto Protocol and its carbon market mechanisms (applied only to wealthier nations).
- A “bottom up” approach of asking for voluntary Nationally Determined Contributions (NDCs) to mitigation effort enabled the Paris Agreement. Existing NDCs globally fall far short of limiting to WB2C, so substantial, near-term “ratcheting up” of effort will be required in early revisions of NDCs.
- Wealthier nations, in accord with historic responsibility and capacity, have agreed to act first to undertake “economy-wide absolute emission reduction”.
- Effort-sharing principles, may allocate mitigation effort by *resource-sharing* of remaining global carbon budget among nations into national carbon quotas, or by cost-sharing of mitigation effort based on responsibility (historic emissions) and capacity (wealth).
- Resource-sharing can be on the basis of *inertia* quotas, ‘grandfathered’ (inequitably) based on current national emissions or GDP share of the global totals; or on *equity* quotas, based on global population share.
- Particularly for high per capita emitting parties/nations, there is significant moral hazard in policy over-reliance on negative emissions being available in future given currently large uncertainties in their potential and long-term reliability at scale.
- Rebound effects across governance boundaries and through time can greatly reduce mitigation effectiveness unless overall caps on absolute emissions aligned with carbon budget limits are enforced within boundaries and on trade across boundaries.

2.1 Multilateral management of GHG emissions and NETs

2.1.1 Inequitable climate impacts and equitable mitigation responses

At Paris in 2015, and since entering into force on 4 November 2016, Ireland and all parties to the Agreement have now committed to a joint obligation to peak and then cut global greenhouse gas emissions in line with limiting global temperature rise to "well below 2ºC" over pre-industrial levels and to "pursuing efforts" to limit the increase at 1.5ºC (UNFCCC, 2017). Global climate policy as embodied in UNFCCC negotiations and the Paris Agreement has adopted these goals because any lesser response is likely to risk far more severe damages (IPCC AR5 WG3, 2014, p. 290). This requires effective multilateral management to achieve early peaking of global emissions, followed by rapid, deep and sustained decarbonisation – as opposed to continuing to allow the possibility of unabated burning of all accessible fossil fuels, an extremely dangerous climate policy (Pierrehumbert, 2013, p. 14119). However, such multilateral management requires some global system of international institutions, agreements or inter-related markets, capable of actually delivering year-on-year progress toward climate stabilisation to limit the projected, accelerating trend of increasing damages due to exceeding global planetary limits, including climate change (IPCC AR5 WG3, 2014, pp. 318–19; Rockström et al., 2009).

Althor *et al.* (2016) show that most wealthy (highly climate polluting) nations are among those least vulnerable to climate change impacts, whereas many much poorer, low emitting nations are among the most acutely vulnerable; so, excepting strong efforts to the contrary, this inequity between "free riders" and "forced riders" is likely to worsen significantly by 2030 and beyond. This implies that richer nations with well above average per-capita emissions have a primary responsibility to lead decarbonisation effort within agreed or unilateral burden (and benefit) sharing allocations (IPCC AR5 WG3, 2014, p. Ch. 4). In general equilibrium economic modelling of cumulative global GDP for emission pathways within a 2ºC carbon budget, Matsumoto *et al.* (2016) find climate impacts on global socio-economic well-being (as measured by GDP) are minimised through peaking emissions before 2020 followed by earlier, deeper emission reductions enabling more moderate decreases later simply because shallow emission paths are less difficult to achieve than steeper ones. Nonetheless, climate policy has had very limited success in curtailing emissions (Helm, 2008), which currently remain on a trajectory toward 3 to 5ºC or more of global warming. In the opinion of Anderson and Bows (2012), such temperature increases would lead to a level of climate change impacts on societies and economies that may be incompatible not just with continuing economic growth, but with basic material security or even organised human society as we currently understand it.

Even if achieved, the initial pledges made in signing the Paris Agreement, the Nationally Determined Contributions (NDCs), indicate a current trajectory toward about 3ºC warming, so substantially greater mitigation effort will be required, with minimum delay, to avoid using up the carbon budget for "well below 2ºC" (Rogelj et al., 2016a). Anderson's (2015) "candid assessment" concludes that delayed mitigation over recent decades now dictates that meeting a 2ºC carbon budget requires radical emission reductions by wealthy high-emissions nations starting immediately. Identifying five clusters of nations by average life expectancy and per capita carbon emissions, Lamb *et al.* (2014) show that no nations in the wealthy, high-consumption cluster globally are within “Goldemberg’s Corner” – living over 70 years on average with less than 1tC cap^{-1} yr^{-1} (= 3.7 tCO_2 cap^{-1} yr^{-1}) – but example nations from the other four socio-economic clusters identified are represented, indicating that there are different low-carbon pathways to enable high welfare and low climate pollution.

2.1.2 Negative emissions: extending the carbon budget and moral hazard

Negative emissions could possibly play a socio-economic role by potentially increasing the gross emissions budget, easing the rate of reduction needed in the use of fossil fuels, if significant amounts of carbon can be stored nearly indefinitely on land and in secure geological reservoirs, but this remains unlikely unless doubts over technical feasibility, tipping point risks, cost, actual potential and ethical acceptability can be addressed (Field and Mach, 2017). Even if NETs could be successfully scaled up to an effective size, it is very unclear whether the cumulative socioeconomic impacts of that deployment would be significantly less that the alternative impacts of simply targeting equivalent reductions in cumulative positive emissions in the first place. Indeed, it can be argued that the apparent attraction lies not so much in a good-faith desire to reduce actual socioeconomic impacts, but rather in a perceived opportunity to defer politically or socially unpalatable choices for as long as possible (colloquially: “kicking the can down the road”). Field and Mach (2017) emphasise the need for ‘rightsizing’ the planned use of NETs relative to these risks, advocating the need for balanced and transparent approaches in mitigation planning.

Anderson and Peters (2016) argue there is a serious moral hazard in climate policy that accepts quantitatively inadequate near-term effort by depending on potential future mitigation (through NETs) that may never materialise. Such an approach unfairly and inequitably loads the risk of failure onto more vulnerable, lower emitters in the first instance, and then onto the generality of future generations. To avoid this, prudent and precautionary mitigation action should assume minimal future negative emissions, and become more lenient only later (if at all) when the potential is much more certain. This is the approach of the “roadmap” mitigation plan, set out by Röckstrom *et al.* (2017), which envisages a halving of total global emissions every decade henceforward. Both existing and new policies and actions (including NETs) can be best compared in climate action terms on a carbon budget accounting basis, by their increased or decreased commitment to future cumulative emissions (Davis and Socolow, 2014). In IAM modelling, an end-period constraint (i.e. 2100) on atmospheric CO_2 concentration (~450 ppm) in combination with allowing large negative emissions globally can result in large temperature overshoots around mid-century due to fossil fuel emissions that are only offset subsequently (if ever) by managed increases in terrestrial carbon stocks or geological stores (Blanford et al., 2014, p. 388). Such ‘pollute now, clean up later’ pathways including negative emissions highlight the potential for wishful thinking and moral hazard pointed to by Anderson and Peters (2016). In modelled, feasibility-cost scenarios of energy system transformation, Krey (2014a) find that technological feasibility is more difficult and overall costs are much higher without significant FFCCS and bioenergy, particularly for non-electricity sectors.

Nonetheless, even if the global amount of carbon removals delivered by NETs is at the high end of plausibility, above 10 $GtCO_2$ yr^{-1} by 2100, then very substantial and sustained cuts in fossil fuel use and in deforestation are still needed from now onward. However, as is shown in the IPCC WG3 pathways (IPCC 2014 AR5 WG3 Ch. 6) and in roadmaps for Paris-aligned decarbonisation (Rockström et al., 2017), the cuts are just not quite as big or as early as they would otherwise need to be. Therefore, the IPCC's AR5 assessment and more recent science clearly show that Paris-aligned climate action mandates a need for deep decarbonisation without delay, even as NETs are being researched, piloted and, if viable technically, economically and politically, then deployed quickly at scale (Rogelj et al., 2016c). The IPCC modelling for low concentration pathways has large uncertainties but research clearly shows that deep decarbonisation and carbon dioxide removal necessarily have to be jointly-planned as complementary within climate action that actually adds up to carbon quota pathways that will achieve climate stabilisation at the lowest possible level of warming (Kriegler et al., 2013).

Further sections in this chapter outline multilateral carbon management literature by: types of multilateral carbon management; the carbon budget science suggesting average global rates of decarbonisation; the basic justification for equitable action suggesting the need for burden and benefit sharing; equitable allocation principles as trialled and as proposed by literature; current NDC's relative to science-based average and equitable-based allocations; and the implications of this comparison for regional and national carbon quotas which will in future need to at least consider NETs (and FFCCS). Based on this chapter's review of multilateral allocation literature, Chapter 8 will produce an explicit outline formulation of an appropriate range of Irish carbon budgets and compatible emission pathway scenarios.

2.2 'Top-down', 'bottom-up', or both?

2.2.1 Carbon management, policy and rebound effects

As the IPCC describes, international cooperation for planned decarbonisation – within global, regional or national governance boundaries – requires some combination of 'top down' management, involving defined targets (or, more precisely, quotas) with enforced monitoring and penalties for non-compliance, and 'bottom up' actions, comprising contributions that are independently pledged by nations, sectors or individuals, possibly working within their own definitions of climate action that may or may not be linked with others (IPCC AR5 WG3, 2014). However, making the distinction less useful, individual mitigation agreements and activities very often encompass both top-down and bottom-up elements, covering a range of different levels of cooperation over means or ends, and different degrees of centralised authority (IPCC AR5 WG3, 2014).

In practice, all effective climate policy is inevitably both top-down and bottom-up, and, as discussed by Kirby (2013), both are necessary. It is the *super-wicked problem* (Lazarus, 2008) of how to coordinate the political will, societal license and sustained effort to enable a complementary mix of them that achieves global as well as local decarbonisation that has proven greatly more difficult. However, as long understood in business research, effective change programmes are result-driven rather than activity-driven (Schaffer and Thomson, 1992), so that within a collective of managers (such as nation states, perhaps) acting ‘bottom-up’ within their own governance area, all nonetheless meet defined and monitored (i.e. top-down) pathway objectives consistent with an overall goal (Kaplan and Norton, 2005). It is the need to meet critical system goals that drives necessary response activities, rather than undertaking activities that may well not add up to meeting the goal.

Alcott (2010) re-examines the common formulation *I=PAT* relating environmental impact to population, affluence and technology, identifying the mutual feedbacks between the ‘right side factors’, such that effort to limit one can increase others. Policy which accepts and targets top-down caps on impacts (e.g. total CO_2 quotas) on the left-side of the *IPAT* relation, by rationing polluting substances and/or collecting carbon taxes to internalise future costs in current prices, can potentially provide long-term certainty for society. This system approach is both appropriately results-driven, and, as importantly, essential because individually or locally targeting one ‘right side factor’, *P, A* and *T* inevitably results in rebound effects in the other factors or elsewhere, in the absence of a system cap.

Notwithstanding system management logic and the strongly evidenced, physical imperative to cut future cumulative global emissions to limit damages, caps are unpopular, so predominantly ‘bottom up’ approaches have been generally preferred to top down management in global, regional and national climate policy. Since it began in 1992 UNFCCC process has been based on a bottom-up approach to decision making that is intended to be collegial and diplomatic to ensure progress proceeds by consensus.

2.2.2 The Kyoto Protocol and the Paris Agreement in carbon management

The need for wealthier nations with large emissions to act first and fastest was recognised by all nations from the UNFCCC’s outset, so the Kyoto Protocol to the Framework Convention (UNFCCC, 1997) was intended to set-up ongoing binding commitments by developing nations to multiyear periods of emissions reduction. On 11 December 1997 the Kyoto Protocol (KP) was adopted and came into force as of 16 February 2005 committing 37 industrialised countries and the EU as a bloc to cut annual emissions by an average of -5% relative to levels in 1990 by a ‘first commitment period’ of 2008 to 2012 (UNFCCC, 1997). Four individual greenhouse gases are targeted by the KP, carbon dioxide, methane, nitrous oxide and sulphur hexafluoride; and two groups of GHGs, the hydrofluorocarbons and the perfluorocarbons. Flexibility in compliance was allowed through the Protocol’s three new emissions trading mechanisms – the Clean Development Mechanism (CDM), Joint Implementation (JI), and for international emissions trading (IET) – that enable signatories to pay for emission reductions achieved outside their territorial boundaries, often in developing nations (IPCC AR5 WG3, 2014, p. 1021). Such emissions trading markets are supposed to be strictly monitored to ensure ‘additionality’; that is, it should be demonstrated that the emissions putatively avoided would have definitely occurred otherwise (see further discussion in Chapter 6). Non-ratification of Kyoto by the United States and withdrawal by Canada further compromised the Protocol’s perceived effectiveness in limiting global emissions. Following years of UNFCCC talks, the Doha Amendment extended the Kyoto

Protocol process but it was not ratified by a sufficient number of nations to enter into force for a second commitment period.

The effectiveness of the KP continues to be questioned. Quantitatively, nine of the 36 participating countries exceeded their KP targets (by small amounts) and overall the aggregate commitment was exceeded by 2.4 $GtCO_2e$ yr^{-1} though Shishlov *et al.* (2016) claim that much of this was due to accounting "hot-air" including carbon leakage. Helm (2008) concludes that the Protocol had little real effect on global emissions and much of the EU reduction would likely have occurred in any case due to the move from coal to gas for electricity and heating, globalisation moving emissions intensive industries to developing countries, and higher oil prices in the 2000s. Aichele and Felbermayr (2013) find the Kyoto Protocol probably reduced emissions relative to the counterfactual of no-KP. The failure to secure agreement on a top-down regime of emission reductions at the 2009 Copenhagen CoP even led some (Rayner, 2010; Rayner and Prins, 2010; Victor and Kennel, 2014) to advocate for a 'reframing' of climate policy away from mitigating CO_2 emission reductions on the basis of political difficulty despite the physical imperative to limit cumulative CO_2 to limit future global warming.

Collectively the experience of Kyoto and Copenhagen led the UNFCCC to move toward a bottom-up approach of attracting pledges from almost all countries, "intended nationally determined contributions", which became non-binding NDCs with ratification of the Paris Agreement, thereafter to be the subject of a global stocktaking every 5 years from 2023 (Schleussner et al., 2016). Unfortunately, the chosen parameters and assumptions underlying NDCs vary widely by nation and are open to ambiguous interpretation creating significant uncertainty in the implied global carbon budget and related global warming commitment implied by their sum total (Schleussner et al., 2016). Rogelj *et al.* (2017, p. 6) show these uncertainties seriously affect projections of feasibility and costs. These uncertainties could be significantly eased by making deeper near-term reductions thereby avoiding additional reliance on uncertain amounts of future carbon dioxide removal. The undoubted political achievement of the Paris Agreement was certainly facilitated by the bottom up INDCs signifying commitment from nations, but to determine the next NDCs, the UNFCCC's "facilitative dialogue" among Parties and the IPCC's *Special Report on Global Warming of 1.5°C,* both due in 2018, will continue to confront the political preference for (as yet insufficient) bottom-up actions (and inactions) with the top down physical reality of escalating emissions commitment to the damaging climate impacts projected by science as the Paris temperature targets are breached, transiently or otherwise (Schellnhuber et al., 2016). The level of negative emissions implied by current NDCs within a Paris-aligned carbon quota will inevitably need to be identified and addressed in the upcoming UNFCCC facilitative dialogue in 2018 to take stock of collective efforts toward the 'global stocktake' set for 2023 for "updating and enhancing" NDC pledges (Article 14 UNFCCC, 2015).

Davis *et al.* (2013) point out that reaching the level of zero net CO_2 emissions required for climate stabilisation will be far from easy and requires a "fundamental and disruptive overhaul of the global energy system" through "an integrated and aggressive set of policies and programs". In the meantime however, without effective or commensurate mitigation globally, the physics of the Earth's climate continues to impose a particularly top-down, climate change response to anthropogenic emissions-driven global warming, with serious global consequences already underway (IPCC AR5 WG2, 2014 TS Part A). These consequences will continue to unfold for hundreds, and even thousands of years (Clark et al., 2016; IPCC AR5 WG1, 2013, p. Ch. 12). Increasing surface temperature (even transiently) also adds to risks of passing tipping points to more abrupt and irreversible system change(IPCC AR5 WG1, 2013, p. Ch. 12 p. 1114-1119; Lenton et al., 2008).

2.3 The Paris Agreement: "Best available science"

Even if the Paris Agreement fails to explicitly acknowledge a carbon budget framing to the temperature target, the physical science linearly relating cumulative CO_2 emissions to global warming enables quantitative climate policy assessment – on the basis of the remaining global carbon budget – to underpin policy analysis of multilateral management of global and regional climate policy (Frame et al., 2014). Climate science is now able to ascribe an associated, remaining global carbon budget confidence range for a specified probability of limiting global warming to a stated climate policy temperature goal (Matthews et al., 2009). Parallel assumptions are needed for non-CO_2 contributions to radiative forcing and reductions to the carbon budget (Peters, 2016) particularly due to methane from fossil fuel (extraction and leakage/fugitive emissions) and from land use (rice production and ruminant agriculture). Using the carbon quota range, science can indicate an *average* exponential or linear global nett decarbonisation pathway based on a stated quantitative combination of carbon budget, amount of temperature overshoot and negative emissions.

Science cannot be prescriptive, that is for politics, but the carbon budget framing provides an indicative global pathway that is useful as a world average rate for comparison with proposed global and regional or national pathways. Stocker (2013) finds that, if global emissions peak in 2017, and net negative emissions (on a global basis) cannot be reliably assumed to occur, then an exponential rate of global decarbonisation averaging at least 2.5% yr^{-1} is needed in every year onward, even to limit to an even (50%) chance of eventual 2ºC warming. The Paris Agreement goal of limiting warming to "well below 2ºC" above pre-industrial is ambiguous but is commonly being interpreted in recent climate science literature (Peters, 2016; Rogelj et al., 2016a) as requiring *at least* a 66% chance of avoiding 2ºC, so even more rapid emission reductions are needed to align action with the smaller carbon quotas for the Paris targets. Peaking global emissions and starting rapid decarbonisation as soon as possible enable feasible transition pathways to low carbon economies. Failure to meet and sustain this (already substantial) global mitigation rate necessarily implies reliance instead on rapidly increasing future rates of gross emissions reduction and/or rapidly increasing amounts of negative emissions (IPCC AR5 WG1, 2013, p. 1113).

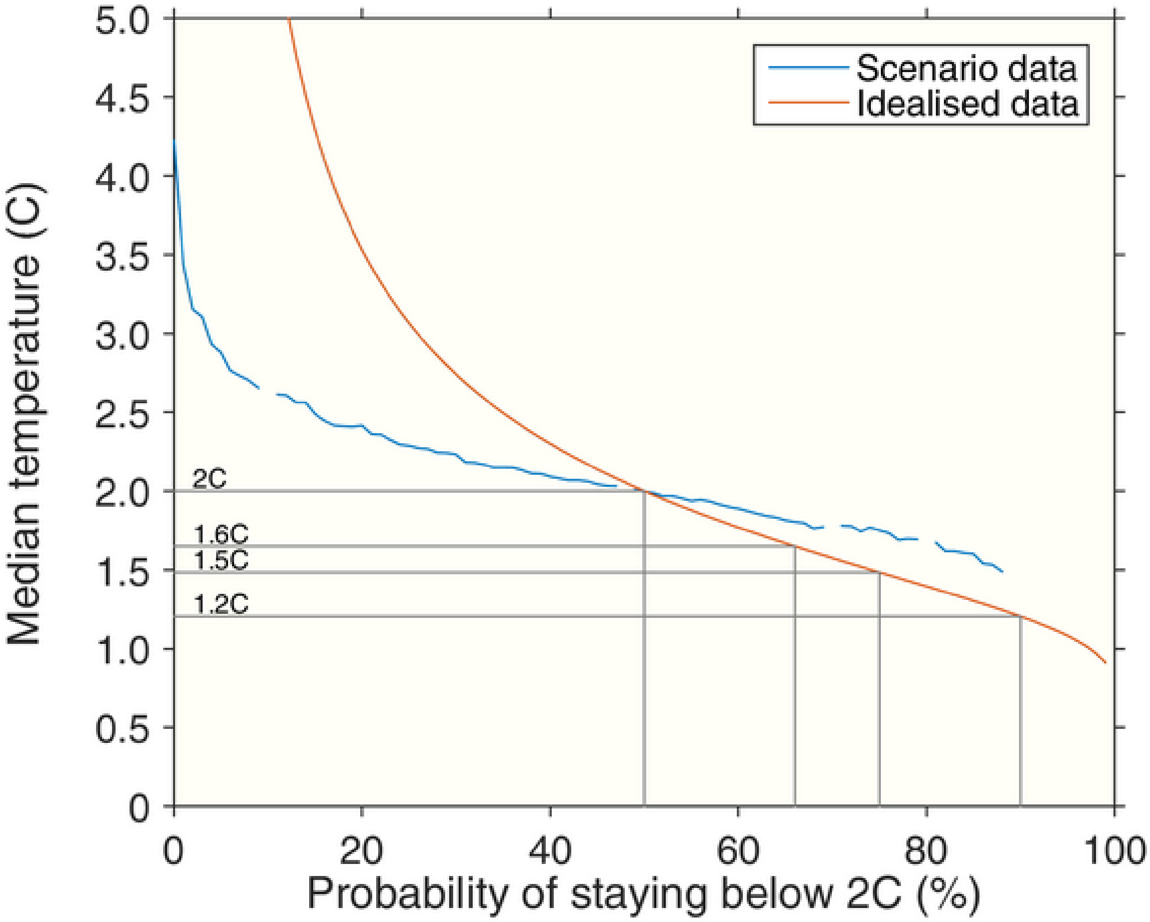

Figure 2.1: Relationship between probability of staying below 2ºC and the median temperature increase. (2016). Blue line indicates relationship for a range of future emission scenarios. Red line assumes IPCC-assessed statistical relationship.

This interpretation of "well below 2ºC" as meaning "at least a 66% chance of avoiding 2ºC" is possibly due to the convenience of having an IPCC AR5 stated carbon budget for this probability and also the perceived feasibility of meaningful probabilities of avoiding 1.5ºC, see Figure 2.1. This analysis investigating the ambiguity inherent in the Paris temperature target, finds the "at least 66% chance of avoiding 2ºC" budget to be approximately equivalent to a 50% chance of avoiding 1.6ºC, and so little different from the Paris goal of "pursuing efforts" to limit to 1.5ºC; though there are still large inconsistencies in the budgets due to model variations, definitional issues and non-CO_2 emissions. Peters (Peters, 2016) gives the remaining budget for a 66% likelihood of avoiding 2ºC as 850 ± 450 $GtCO_2$ (as of the end of 2015), the large confidence range being due to uncertainties in the temperature response of the climate system, the amount of future non-CO_2 emissions, and uncertainties in measuring past emissions. However, with higher emissions, high-end "fat-tail" risks (Wagner and Weitzman, 2015) and possible triggering of climate system tipping points, risk-appropriate climate policy determines a need for a precautionary approach while accelerating investments in all mitigation measures without delay (IPCC AR5 WG3, 2014, p. 172). Rockström *et al.* (2017) show that even if negative emissions are to play a significant future role in feasibly reducing nett global emissions to zero then deep decarbonisation of source emissions from the current very high emission levels will still nonetheless need to be achieved for a “well below 2ºC pathway:

> *Only deep emission reductions during 2020–2030 can enable [reliance on] BECCS to be scaled back or abandoned, while efforts to increase energy efficiency and DACCS continue”. Rockström* et al. *(2017)*

As Stocker (2013) and the best available science makes clear, to avoid “closing doors” to emission pathways aligned with the Paris temperature targets, definite choices and follow-through decarbonisation actions need to be made (much) sooner rather than later.

2.4 The Paris Agreement: “On the basis of equity”

Effort-sharing of mitigation among nations is ultimately critical to halting global warming. As acknowledged from the original United Nations Framework Convention on Climate Change (1992) effort needs to be differentially shared to ensure equitable climate action as exemplified in the key phrase in Article 4: “common but differentiated responsibilities and respective capabilities” (CBDR+RC). The UNFCCC Paris Agreement’s main stated target of limiting global surface warming to “well below 2ºC” combined with the science-defined range for the associated remaining global carbon budget (described in Chapter 1) gives a well-evidenced basis to assess and inform climate mitigation policy, to guide nations toward making the required societally transformations become *politically* possible, globally enabled and technically achievable (Knopf et al., 2017). ‘Equitable burden-sharing’ has been and continues to be a major point of contention within the UNFCCC that persists today, largely due to conflicting national- and vested self-interest, resolution of which continues to requires a consensus on the meaning of fairness (Meinshausen et al., 2015, pp. 3–4). Despite the globally agreed importance of CBDR+RC, enabling equity principles in international agreements that ensure burden sharing has been contentious and is complicated by relative changes in national income and emissions over time, especially related to rapidly developing nations such as China (IPCC AR5 WG3, 2014, p. 1021).

As discussed in IPCC WG3 Ch. 3 (2014), effective global climate mitigation policy will require sustained collective action based on (sometimes conflicting) ethical judgements of justice (what is ‘due’ to people) and value (what is good or beneficial) regarding rights and responsibility in distributive equity (see p. 219). Economic valuations may provide some guidance in decision-making about value (though not justice and rights) but economic methods inevitably implicitly embody value judgements affecting equity (pp. 223-225). Geoengineering, especially solar radiation management, but also negative emissions technologies, has been questioned on ethical grounds. For example, large-scale land-use change to enable BECCS could have negative outcomes on the well-being of local populations, on global food security or on biodiversity (IPCC 2014 WG3 Ch. 3). Examining the literature on climate resilient pathways that could best reduce climate damages, IPCC WG2 Chapter 20 (2014) identifies climate change as a direct threat to sustainable development, and mitigation as critically important to moderating impacts on human and natural systems.

The strong relationship of equity and sustainable development to climate mitigation trade-offs and benefits are detailed in the IPCC WG3 Ch. 4 assessment (2014). Equity encompasses both distributive equity (social justice in burden and benefit sharing) and procedural equity (enabling participation and fair consideration in decision-making), while sustainable development depends on the concept of equity *between*, as well as *within*, human generations (2014). Underpinning the Paris Agreement's references to the need for climate action to be undertaken on the basis of equity (Preamble and Articles 2, 4 and 14 in UNFCCC, 2015) there are three key justifications (IPCC AR5 WG3, 2014, pp. 294–295): first, that burden sharing morally requires allocation according to ethical principles of justice and value; second, within international law, that countries have the legal duty to act equitably in mitigating climate change; and third, positively, that effective climate mitigation must needs be collective so cooperation largely depends on motivating others by showing fair effort based on relative responsibility and capacity. In practice though, path dependency in governance and political economy, affected by powerful vested interests and norms of societal behaviour based on GHG intensive consumption, continue to hinder decision-making to enable coordinated climate mitigation action (IPCC AR5 WG3, 2014, pp. 294–295).

As described in the previous section, to be acting on the basis of equity, regions or nations with high per capita emissions (or wealth, giving capacity to act) will, at a minimum, need to show in future Paris Agreement stocktaking how they are achieving an effective decarbonisation rate (possibly including stated negative emissions) that is much more rapid than the average global rate derived from the well below 2ºC global carbon budget. For any temperature target, delays in achieving rapid global mitigation (including CDR delivery, if such a contribution is assumed) have a very serious steepening effect on the required decarbonisation rate. If delay continues, the subsequent decarbonisation rate can rapidly become first politically and economically unfeasible, and then physically impossible to achieve (Stocker, 2013). Mitigation delay, in itself, therefore inequitably transfers costs or impacts to the future – cutting off transformation pathways, reducing societal choices and lowering resilience to climate impacts (den Elzen et al., 2010; Friedlingstein et al., 2014).

2.5 Mitigation burden-sharing: allocating the global carbon budget

2.5.1 Resource-sharing and cost-sharing allocation principles

Principles of equitable burden-sharing in international climate policy are fully discussed in IPCC WG3 4.6.2 (2014), and include: responsibility, often based on present or historic total emissions; capacity, or ability to pay for or to deliver mitigation; equality, as in access to current and future rights to emit GHGs; and the right to development in meeting basic needs, particularly in poorer countries. These principles are just as applicable to consideration of NETs within global, regional or national mitigation planning. 'Resource-sharing' (sharing the 'resource' of the global carbon budget) and 'effort-sharing' (sharing the *costs* of mitigation), are complementary classes of burden sharing frameworks, respectively addressing the 'tragedy of the commons' and free-rider aspects of the climate policy collective action problem (2014). Given a bounded global carbon budget aligned with a stabilisation temperature target, an equal per capita approach is the most obviously "equitable" allocation principle. However, for countries with emissions high above the global average this may impose extreme immediate reductions. Accordingly, transitional emission rights, allocated in a way reflecting *de facto* current emissions, have also been proposed. Per capita emission frameworks can also extend to historic as well as future national cumulative emissions, differing proposals varying by initial date, population, and basic survival vs. "luxury" emissions and emission paths. 'Effort-sharing' frameworks aim at fairly sharing the costs of mitigation aligned with a stated target pathway or atmospheric CO_2 concentration.

The question then becomes, what is fair and who will pay? The proposed answers are generally set in proportion to differing stated interpretations of responsibility and capacity. Climate policy architectures based on alternative allocation frameworks are usefully tabulated in IPCC WG3 Table 13.2 (2014, p. 1022). A quantitative comparison of regional mitigation costs according to different allocation principles is attempted in IPCC WG3 6.3.6.6 (2014; see also Pan 2014). A requirement for continuing overall economic growth is stipulated as a constraint in most modelling so technology deployment (including NETs and CCS) that can, in principle, achieve absolute decoupling of emissions from economic growth, is critical to projected mitigation costs. In the idealised case of a global carbon price the projected relative regional costs proved to be highly unequal – for example, OECD costs are about a fifth of 'Middle East and Africa' – implying the need for very large economic transfers from richer nations to support mitigation and adaptation in poorer ones (see Figure 6.27). Exploring the IPCC WG3 database of scenarios (IIASA 2014), Tavoni and van Vuuren (2015) find that regional carbon quotas directly show the regional CO_2 contribution to warming, therefore a regional scenario quota indicates the level of regional climate policy effort. However, if real-world, actual policies do not follow "first best" ideals (rational-actor, whole-economy optimal changes) then costs are inevitably greater than modelled (van Vuuren 2015).

Inevitably, as Schuppert, and Seidel (2015) illustrate in examining the German Advisory Council on Global Change proposal (WBGU, 2009), all such allocation frameworks are open to critique, and, above all, their adoption is subject to political and societal will in the context of varied current political economies and path dependent inertias across an inequitable world (Knight et al., 2017). At present, the disparate Paris NDCs are very far from expressing a clear "well below 2ºC" carbon quota allocation framework. Despite this lack of clarity, if followed through, then they would nonetheless indicate some significant collective intent. This would still need to be swiftly intensified, especially by the major absolute emitters: China, USA, EU and Japan (Jiang et al., 2017).

2.5.2 Resource-sharing according to *inertia* and *equity*

Raupach *et al.* (2014) analyse multilateral resource-sharing of a global fossil fuel CO_2 budget (exclusive land use CO_2 emissions) for a 50% chance of exceeding +2ºC warming (estimated as 1400 $GtCO_2$ from 2013 onwards) on a range between two end-point metrics: 'inertia' (also known as 'grandfathering'), meaning sharing the remaining global budget based the current national fractions of current emissions; and, 'equity', per capita sharing of the budget based on national population. The analysis takes into account: likely changes in national population (not a large factor); the possible inclusion of GDP into the sharing principle (producing moderate but not large adjustments in allocations); and responsibility for historic emissions, which does not change the overall rate but greatly shifts the remaining share of emissions to developing nations and requiring far more effort of developed nations that harnessed large amounts of fossil fuel energy. Delaying mitigation has by far the highest effect on the rates required.

In the Raupach *et al.* (2014) analysis, under '*inertia'*, poorer developing nations would likely have insufficient access to energy for needed development, and under '*equity'*, richer developed nations would face very high decarbonisation rates (regarded as "unfeasible", politically, economically and/or technically). A 'blended' allocation, half-way between inertia and equity, is also given as a 'contraction and convergence' principle, and charts are given showing the regional carbon quotas and mitigation rates for all three options (see Figure 2.2). However, even with this global carbon budget that is larger than a Paris-aligned "WB2C" one, average global decarbonisation rates are already high at over 5% yr^{-1}, starting from 2013 onwards. Alternatively, with a 10-year delay in peaking global emissions, the required subsequent global mitigation rate increases to 9% yr^{-1}. Interestingly, using consumption, rather than territorially based accounting does not change country shares significantly as the consequent decreases in the exporting nations' emissions are offset by the persistence of growth in their manufacturing emissions. As Raupach *et al.* (2014) point out, accounting for negative emissions in mitigation planning is mathematically straightforward at every scale (from global to sub-national sectors).

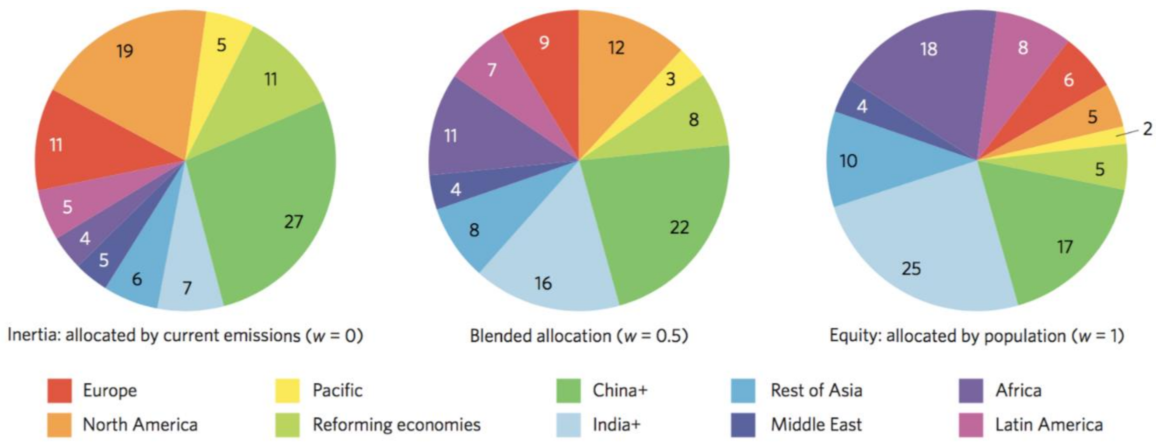

Figure 2.2: The share of an available global carbon budget allocated to 10 regions under three sharing principles based on equation (2), with sharing index w = 0, 0.5 and 1. Shares are calculated using equation (2) with emissions (f_i) averaged over last five years of data, and population (p_i) averaged over a five-year period centred on the time at which world population reaches nine billion. Reproduced from Raupach et al. *(2014).*

Anderson and Bows (2011) analyse remaining 2ºC quotas (based on varying probabilities of avoiding 2ºC increase) on the simple equitable allocation principle of dividing it between

(Kyoto Protocol) Annex 1 and non-Annex 1 nations using conservative assumptions. For a “37% chance of not exceeding 2ºC” the equitable remaining carbon budget for Annex 1 nations is already exhausted now or will be within the next 10 years unless radical emissions reductions at far greater rates than current politically contemplated begin immediately. In contrast to many studies it concludes: “There is now little to no chance of maintaining the rise in global mean surface temperature at below 2ºC, despite repeated high-level statements to the contrary”.

To meet the “likely 2ºC scenarios” in the IPCC WG3 database, Pan *et al.* (2014b) base a very different analysis on the moral principle of equal per capita cumulative emissions (EPCCE), allocating every person globally an immediate, equal emission right per year (Figure 2.3). This means that developed nations have already exhausted their emissions budgets under this scheme requiring financial and technical transfers to developing nations, through mechanisms like the Green Climate Fund, to enable their mitigation efforts, avoiding high GHG development pathways. Presumably, in the developed nations, planning a faster pathway to net zero CO_2 emissions and achieving negative emissions would lower the requirement to make such transfers.

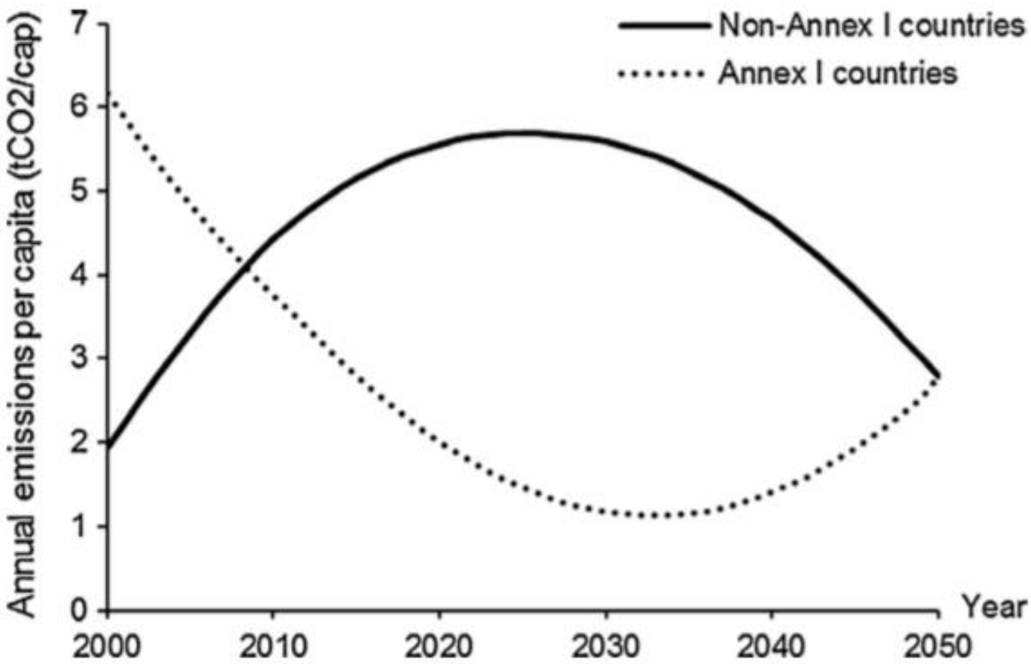

Figure 2.3: Schematic indication of Non-Annex I and Annex I country per capita emission pathways (from Pan et al. *2014).*

Sargl *et al.* (2016a) examine the use of the Regensburg Formula to enable contraction and convergence bringing all countries to equal per capita emissions by a stated future year and within a carbon budget. In the Regensburg model, unlike EPCCE, all nations’ annual emissions proceed nearly linearly toward the target, so developing nations which start out below the target per capita emissions are awarded a lower cumulative emissions quota than in other convergence formulae. This, combined with ignoring historical responsibility for emissions, gives more future emissions to the richer developed nations. As Sargl *et al.* (2016) state, “the Regensburg Model is the most favourable option for industrialized countries”, however, by the same token, they conclude that a Regensburg pathway can also be considered the minimum equitable effort if the principle of converging per capita emissions is accepted.

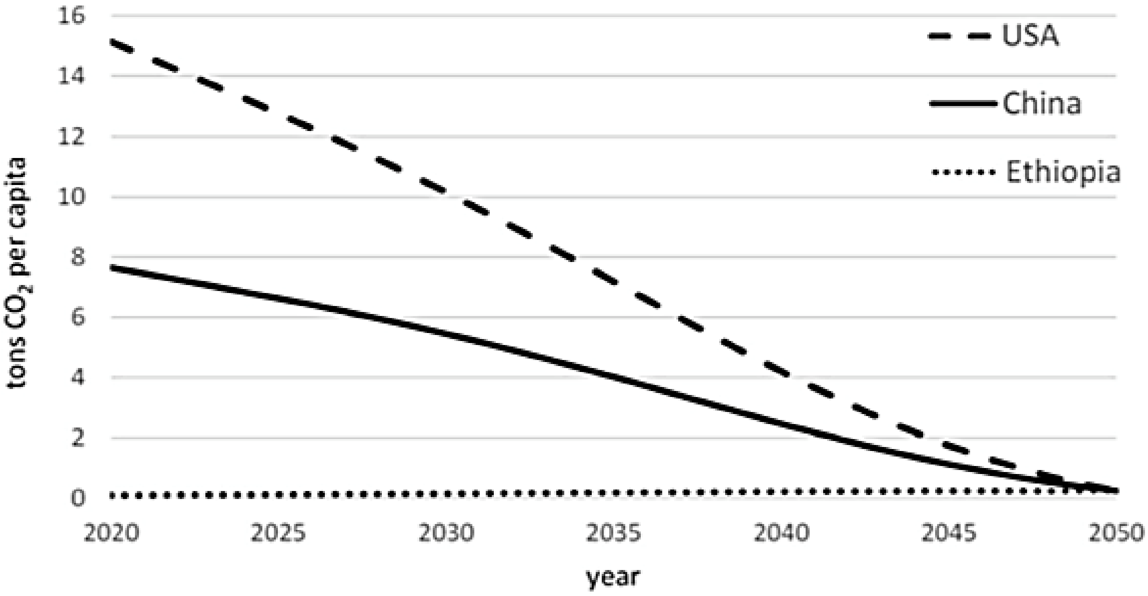

Figure 2.4: Schematic indication of country per capita emissions pathways (taken from Sargl et al. *(2016a).*

For “well below 2ºC” pathways, however defined, the need for multilateral planning, governance and mechanisms to ensure emissions quota allocation urgently needs to overcome resistance to it otherwise societal options to reach the 2ºC goal will quickly narrow (2016). Raupach *et al.* (2014) conclude by highlighting the contrast between the imperative of reducing emissions to prevent climate impacts on global human and ecological systems and the inertia in carbon-intensive human socioeconomic systems, as follows:

> *For the emergence of long-term, cooperative solutions to anthropogenic climate change one essential element is an ability to perceive the consistent global consequences of local actions, given great differences in national economies and histories. The social capital that underpins cooperative governance of the commons takes time to evolve, but the biophysical realities of climate change demand solutions within decades. This is why the development of new perspectives on the sharing challenge is vital. (2014).*

2.5.3 Cost-sharing according to responsibility and capacity

The Climate Equity Reference Framework (CERF) takes the UNFCCC principle of “common but differentiated responsibilities and respective capabilities” (CBDR+RC) as a basis for a more comprehensive, cost-sharing allocation of mitigation effort toward achieving the Paris temperature targets (Holz et al., 2017). The CERF “fair shares” method focuses on near-term costs and emissions only to 2030, making it difficult to compare with the Raupach and Regensberg methods (except by heuristically extrapolating the CERF allocation emission paths beyond 2030). In the CERF method, *responsibility* is based on cumulative emissions since a selected start year (from *high* based on an 1850 start, to *low* based on 1990). *Capacity* is based on national GDP normalised in terms of purchasing power parity, while also progressively allowing for differences in wealth *within* nations by exempting per capita income below a certain level – typically set at the global poverty line of about $16 per day (Holz et al., 2017). A “luxury” threshold above which *all* per capita income counts as capacity to pay for mitigation may also be specified.

In the online CERF tool (EcoEquity and SEI, 2017), users set outline parameters. One of three mitigation objectives are chosen: “strong” (>66% probability of limiting to 2ºC); weak” (between a 33% and a 50% probability of limiting to 2ºC); and, “G8” (having much less than 33% chance of limiting to 2ºC). Also selected are: the starting year for cumulative emissions responsibility (1850, 1950 or 1990); development threshold; and one of three methods of estimating domestic emissions reductions.

2.6 Paris pledges (NDCs) relative to Paris targets and equitable allocation

Even if the NDC pledges made at Paris are achieved and continued after 2030, global warming of 3ºC appears likely because total emissions would far exceed the global carbon budget for even relatively low probabilities of avoiding 2ºC (Knutti et al., 2016). Meinshausen *et al.* (2015) explore an alternative ‘diversity aware leadership’ approach to allocation involving leadership by a major economy such as the EU, USA or China, to achieve a target considered to be fair by all other countries. This framework fuses the need for leadership (as an essential for successful negotiation) with the need for perceived fairness – the avoidance of relative gains or losses in bargaining. In an illustrative default case, they find a ‘likely’ 66% chance of limiting to of 2ºC would require: 2025 targets of 67% below 1990 levels for the EU28, and 54% below 2005 for the USA; and a 2030 target of 32% below 2010 for China. To give some estimate of the level of ambition that 2ºC aligned climate leadership (and ‘followership’) actually requires, note that for the EU (and USA before it announced its intention to withdraw from the Paris Agreement) these targets are more than double current NDC pledges. Increasing ambition in this way would require some significant combination of additional domestic mitigation effort, negative emissions and/or increased international mitigation support. Based on a framework embodying six equity principles, Pan *et al.* (Pan et al., 2017) similarly find that the EU and USA lack equitable ambition in their NDCs for a “well below 2ºC” target and only India, if it met its most ambitious pathway, would be aligning action with any serious aspiration for a 1.5ºC limit.

To identify cost-optimal, Paris-aligned mitigation pathways, Robiou du Pont *et al.* (2016) assess the IPCC WG3 scenarios with at least a 66% chance of limiting to 2ºC according to five IPCC-defined allocation approaches. For the national/regional level, the EU’s NDC is aligned with three of the approaches, India and the USA with two and China’s with only one.

The claimed cost-optimal feasibility of 2ºC pathways in this study contrasts markedly with the higher urgency of mitigation indicated by Rockström *et al.* (2017) and moral hazard in over-confident reliance on future achievement of negative emissions (Anderson and Peters, 2016). In the absence of top-down enforcement of carbon management, bottom-up NDC contributions are likely to be more optimal for individual nations or blocs that may be incentivised to free ride for protection against other free-riders.

2.7 Chapter Conclusions: multilateral management of the remaining WB2C global carbon budget

In summary, under the Paris agreement framework, the current, combined, Nationally Determined Contributions fall well short of the ambition required by the stated temperature goals (Peters et al., 2017) and will need to be dramatically strengthened in the course of the planned "facilitative dialogue" in 2018 and then the first five-yearly stocktaking scheduled for 2023 (Rogelj et al., 2016a). None of the NDCs of the major emitters is aligned with either "inertia" or the "equity" resource-sharing allocations of mitigation effort. Research finds that the EU and USA in particular would need to effect far more ambitious targets to be action on the basis of equity. Given the announced by the USA of its intention to withdraw from the Paris Agreement, this research will need to be updated.

Any consideration of simply including pledges to achieve negative emissions in NDCs must be tempered by the significant doubts about NETS development identified by Fuss *et al.* (2014a) setting out major research challenges on: physical constraints on BECCS, climate system responses to negative emissions, costs and financing, and barriers in governance and acceptability. As Peters *et al.* (Peters et al., 2017) point out, fair and ambitious NDCs need to include "a companion set of pledges on technology research and innovation" (including NETs and CCS) or else show how their NDC pledges fulfilling the Paris Agreement can deliver a "well below 2ºC aligned pathway" without them.

To inform low-carbon transition policy Chapter 8 looks at the range for an equitable quota for future CO_2 emissions in Ireland based on the principles and models discussed in this chapter for multilateral management of the remaining cumulative global carbon budget associated with the Paris temperature targets.

3 Negative Emissions Technologies

Summary

- NETs can be categorised by: method of CO_2 capture, biogenic or chemical; pathway method; and storage type and permanence – land or geological.
- Factors in ranking the mitigation potential of NETs include: readiness, technology complexity, difficulty of additionality assessment, land use impacts. These factors may interact creating effects that need to be recognised in policy plans.
- NETs focused on land storage of carbon are less costly and readier to deploy than using geological or ocean storage. Ongoing management needs to prevent current loss of land carbon and secure additional land-based CDR.
- Biogenic NETs (afforestation, biochar, soil carbon sequestration, and ecological restoration) rely on increasing net primary productivity and increasing the land ecosystem uptake of atmospheric carbon.
- Maximising forest and soil carbon uptake provides a small carbon store relative to ongoing fossil fuel emissions.
- CCS: For carbon capture and storage, CDR permanence in geology is likely high. Despite large potential storage volumes and tested technology, CCS has not been deployed to date at large scale for long-term CO_2 storage.
- BECCS: The technical potential of BioEnergy with CCS to produce substantial energy with negative emissions has led to large scale inclusion in IAM scenarios delivering ambitious mitigation. BECCS at some level appears technically achievable but IAM projections for very large scale bioenergy inputs to BECCS appear quantitatively unrealistic.
- BC: Biochar mitigation potential may be significant but reviews show significant inconsistencies in data. Biochar CDR Effectiveness increases with higher pyrolysis temperatures, which may reduce its soil enhancement characteristics.
- AR: Afforestation and reforestation have global potential for significant additional CDR but land use requirements may compete with other land uses and harvest (for bioenergy or otherwise) would limit nett increases in forestry carbon stock.
- DAC: Direct air capture technology requires geological storage (CCS), is energy intensive and is currently assessed as much more expensive than other NETs; but it has minimal land use requirement, offers very large theoretical capacity, and costs can be expected to fall significantly with large scale deployment experience. It may be essential to negate emissions from sectors such as aviation currently regarded as otherwise very difficult to decarbonise.
- EW: Enhanced weathering is expensive, having large energy, transport and application costs, especially due to the small grain size of crushed basic silicate rocks required to maximise CDR.
- Significant knowledge gaps are apparent across all NETs, CCS and in the mitigation policy potential for NETs, particularly at nation-level scale.

3.1 Introduction

NETs are a complex area of research and development, operating in a contentious context. There will likely be many trade-offs and compromises in implementing and deploying NETs. NETs are characterised by several environmental, economic and social limits which complicates policy development. Research to address knowledge gaps is required but given the time lag for NET to be effective, uncertainties cannot be used to justify inaction. The following sections will discuss in more detail the potential, limitations, knowledge gaps, future research and deployment of Carbon Capture and Storage (CCS), Bioenergy with Carbon Capture and Storage (BECCS), Biochar (BC), Afforestation and Reforestation (AR), Direct Air Capture (DAC) and Enhanced Weathering (EW) in the context of achieving global negative emissions.

3.2 Carbon Capture and Storage

3.2.1 Introduction

The research literature on Carbon Capture and Storage (CCS) has grown substantially in recent years. 94% of publications related to CCS have been published since 2005 (Karimi and Khalilpour, 2015). The literature is closely coupled with international law and collaboration networks (Karimi and Khalilpour, 2015). The increased interest in CCS in recent years is due to its potential in climate mitigation, most notably in its potential as an enabling capability for negative emissions. There is a strong dependence on this type of technology for most of the IPCC’s 2ºC IAM scenarios, which informed the Paris Agreement commitment to limit temperature rise to “well below 2ºC” over pre-industrial. However, the feasibility and potential of CCS is complex, with many necessary considerations to be made about the technology, and its social, economic and political limitations.

CCS may be a critical component of a transition strategy to a low carbon economy, but many barriers exist to its widespread use (Karimi et al., 2016). Some criticisms of CCS are: the technology is insufficiently developed to be so heavily relied upon as it is untested at a large scale; non-climate risks to the environment or human health due to CO_2 leakage; large costs associated with capture and storage; and the concern that CCS-reliance will be misused as a concept to justify continued fossil fuel burning and business as usual, reducing incentive for reducing fossil fuel burning and increased use of renewable energy. There are also many complications to policy and decision-making around the implementation of CCS.

3.2.2 Potential

The burning of fossil fuels may not stop completely in time for the 2ºC temperature targets based on the current use of renewable sources being too marginal. Therefore it has been argued that one of the most effective and realistic pathways for rapid climate mitigation is large scale CCS and increased energy efficiency (Wennersten et al., 2015). Promising results have been reported by Matter *et al.* (Matter et al., 2016) with the success of CO_2 injected into basaltic lavas in Iceland and mineralised into a stable form removing the leakage risk. In this “Carbfix” project, residual CO_2 from a geothermal power plant was dissolved in water and injected into basaltic lavas (Gale et al., 2011). Results show 95% of the CO_2 was mineralised in just 2 years. Hence it is possible to store CO_2 in a way that is safe for both the environment and human health. Nonetheless, much the more commonly cited and proposed applications of CCS are based not on geothermal (or other low-carbon) energy sources but on fossil fuel (FFCCS[3]); and not on storage via mineralisation but on direct injection of CO_2 into deep, porous, rock strata, sealed by overlying non-porous strata. Limited scale working examples of these techniques can be seen in Canada and Norway today.

3.2.3 Limitations

While the direct global warming impact of fossil fuel power plants might be reduced by ~82% with FFCCS, other environmental hazards such as increased air pollution increase (Cuéllar-Franca and Azapagic, 2015). This highlights the risks of taking a non-comprehensive approach to climate change mitigation. When considering the feasibility and potential of CCS, all potential impacts must be fully considered and measured, not just the factors relevant to emission pathways and temperature targets. A fully integrated approach must be adopted that takes full account of all the implications for the environment and human health associated with FFCCS deployment.

3.2.3.1 Immature technology

While CCS has been successfully deployed at a local scale with working examples in Canada, Iceland and Norway, many critiques highlight that large scale deployment and operation of CCS has not yet been achieved and it is imprudent to rely so heavily on a relatively untested technology for achieving future emission pathways. Galiegue and Laude (Galiegue and Laude, 2017) however, considers that a focus on large scale deployment impedes a sustainable transition and narrows the vision for deployment, and actually operating CCS at a smaller scale is a fundamental step towards large scale implementation and should be encouraged.

3.2.3.2 Storage Sites

There are risks associated with the storage sites used for CCS, most particularly around potential leakage or seismic activity. Whether or not the CO_2 injected into porous rock strata is retained underground is governed by ‘the complex relationships between reservoir depth, reservoir temperature and pressure, and the state and density of stored CO_2 (Miocic, 2016). Storage site selection will be one of the key features of successfully operating CCS (Thronicker et al., 2016). Benson (Benson, 2005) notes the importance of carefully assessing any potential for seismic or volcanic activity when selecting potential storage

[3] Throughout this review FFCCS is used to denote the use of CCS to abate CO_2 emissions from direct fossil fuel combustion, but also potentially applying to CO_2 production in more general industrial processes, such as cement manufacture.

sites. Seismic activity can also be induced by CO_2 injection, and therefore care must be taken in monitoring and modelling a storage site (Verdon and Stork, 2016). The type of storage site will likely be a greater limit on CCS deployment than the amount of storage space (Selosse and Ricci, 2017). Features that need to be considered when selecting a suitable storage site include capacity, suitability for injection of CO_2 and its ability to confine the CO_2 for long time periods and not leak. Failed storage sites have significant environment and health and safety implications (Guen et al., 2017). In an assessment by Miocic *et al.* (Miocic et al., 2016), existing storage sites generally retained CO_2 well, with a minority having CO_2 leakages through fault lines. Careful storage site selection, testing, modelling and monitoring must be a high priority and suitably resourced in any deployment plans for CCS.

3.2.3.3 Energy

Another significant impediment is the energy required for CCS reduces the overall energy efficiency of the plant. Energy is required for the capture process (including post-capture CO_2 compression), for the pipeline transport process (dependent on the pipeline length) and for the injection process into the storage reservoir, with the capture process generally assessed as being the heaviest demand (Herzog and Dan Golomb, 2004). The input of resources to sustain FFCCS has been estimated at up to 40% higher per kilowatt hour than non-CCS fossil fuel electricity generation (Krüger, 2017). FFCCS plants have lower operational efficiency and current costs are only suggestive (Hammond and Spargo, 2014).

3.2.3.4 Cost

CCS currently lacks an effective business case and incentives for the cost of applying it. Presently it is simply cheaper to emit CO_2 without CCS (Wennersten et al., 2015). The type of capture technology employed, and associated cost, will depend on the type of power plant and fuel burned (Leung et al., 2014). Selosse and Ricci (Selosse and Ricci, 2017) find that the cost of transport is also an important limit on CCS. Reynolds and Buendia (2017) note the absorption properties of organic rich shales and the usability of CO_2 to enhance oil recovery. Currently enhanced oil recovery (EOR) is the most mature storage option because the economic benefit of more oil incentivises CCS injection (Leung et al., 2014). However, the EOR process requires a significant proportion of the injected CO_2 to be immediately re-released (with the recovered oil) rather than stored, and, of course, also leads to additional indirect CO_2 production (from combustion of the additional oil). Given that the majority of oil combustion is in transport applications, where CO_2 capture is not technically feasible, the nett lifecycle effect of FFCCS coupled with EOR is almost certainly increased, rather than reduced, CO_2 release to atmosphere. Accordingly, while EOR might conceivably contribute financial support for the development of CCS technology in the short term, it cannot provide a basis for sustained, large scale, CO_2 emissions reduction. Large variability in cost estimates of CCS, up to a factor of 5, exists in the literature (Akbilgic et al., 2015). This impedes deployment as there is no clear consistent message on cost estimates needed for effective policy making.

Akbilgic *et al.* (2015) identify the main drivers of cost estimates as the increased cost of producing electricity, the decreased efficiency and the significant capital cost associated with power plants with CCS. As a result of this, CCS is currently heavily dependent on government funding or enhanced oil recovery revenue (Kuch, 2017).

3.2.3.5 Public Perception

Public awareness, acceptance and support for CCS will be a crucial factor in its effective, rapid deployment, most particularly in driving of political will and not impeding establishment of local projects (Wennersten et al., 2015).

There has been an increasing body of research on public perception of CCS (L'Orange Seigo et al., 2014b). Buhr and Wibeck (2014) assess the intention behind communication on CCS and whether the objective is to increase dialogue or convince. They identify varying assumptions about public involvement, ability to understand complexity, interest and the value of public opinion. Broecks *et al.* (2016) suggest that the primary purpose of CCS (climate protection) is less persuasive than arguments for energy production and economic growth. This complicates the communication and public engagement challenge. One important driver of public perception is risk perception (e.g. leakage, explosions, and seismic activity). Nation-specific cultures influence public acceptance due to factors such as institutional strength, tolerance of uncertainty, societal roles (Karimi et al., 2016). L'Orange Seigo *et al.* (2014) identify the biggest barrier to achieving public acceptance as low awareness, with their results finding only 28% of Europeans had heard of CCS. L'Orange Seigo, Dohle, and Siegrist (2014) identify a knowledge gap on the social context of deployment, rather than risk perception. They argue that the key need for progression is pursuing acceptance locally at a project level, rather than overall societal acceptance.

3.2.3.6 Business as usual incentive?

Another concern about CCS is that it will be used to justify the continued burning of fossil fuels and de-incentivise or distract from other climate mitigation actions such as increasing renewable energy and energy efficiency while decreasing energy demand. It is possible the idea of non-binding commitments to future deployment of CCS might be used as an excuse for inaction. Azar *et al.* (2006) proposed that CCS with fossil fuels could meet the (then) global targets at half the cost. Krüger (2017) highlights that CCS promises to somehow 'solve the climate problem independent of drawn-out political disputes and without changing production and consumption patterns', and suggests that many consider that the large-scale deployment of CCS may be a more realistic option than changing the structure of production and consumption patterns (Krüger 2017). Hammond and Spargo (2014) also highlight that CCS permits the continued burning of fossil fuels while reducing emissions.

3.2.4 Knowledge Gaps, Future Research and Deployment

Martínez Arranz (2016) considers CCS to have been hyped up with high expectations and commitments, when in reality it is typified by low outcomes and slow progress to date. In order for CCS to be effective it must be deployed imminently on a large scale. However, progress has been slow with many barriers to implementation. Hence adequate contingencies must be in place and continued support for alternative technologies and pathways must be maintained. Marshall (2016) discusses FFCCS in an Australian context. He describes FFCCS as ‘fantasy technology’ used to justify continued coal use and assuage political anxiety and discomfort, and also highlights the reality of the situation with no large-scale testing, uncertainty on how to monitor leaks and no major ongoing investment from coal companies. It is therefore imperative that other climate mitigation options be developed and implemented along with ongoing deployment of FFCCS, and that FFCCS is not used to distract from or undermine the development and implementation of other mitigation technologies and actions.

Bioenergy complements CCS development by coupling the two in BECCS. BECCS provides notionally “carbon neutral” energy and takes CO_2 out of the atmosphere (Azar et al., 2006). Muratori *et al.* (2017) proposes the focus be moved away from role of CCS in fossil fuels, and towards scenarios of CCS with biofuels (BECCS) in energy production.

3.2.4.1 Deployment

In order for CCS to be fully implemented, community support, reduced risks, robust policies and a favourable CCS market are needed (de Coninck and Benson, 2014). However, CCS struggles in a context of weak government climate action, low carbon prices, public uncertainty and high costs (de Coninck and Benson, 2014). Currently CCS deployment progress remains slow, while it continues to be a central component of emission scenarios. CCS requires significant regulation and market support for successful implementation (Scott et al., 2013).

In 2005 the IPCC released a technical report and summary for policy makers on CCS technology (Metz and Intergovernmental Panel on Climate Change, 2005). This report considers the potential, current status, geography of source and storage, cost, risks, leakage, regulation, implications and knowledge gaps and summarises the technical perspective on sources, capture, transport, storage, uses.

Future climate governance will be determined by decisions about continued use of fossil fuels. The controversy around CCS could, in itself, cause problems and challenges in the area of international climate policy (Krüger, 2017).

3.2.4.1.1 Europe and UK

At a European level, the European CCS project network[4] is an example of how knowledge sharing helps create policy for effective deployment and enable development (Kapetaki et al., 2016). EU policy provides generous funding for CCS without cost-cutting breakthroughs. The development of this policy context was the result of strategically framing CCS with strong supporters and weak alternative options, as well as actively targeting policy discourses (Martínez Arranz, 2015)

[4] http://www.ccsnetwork.eu/

In the UK a recent competition worth 1 billion GBP for research and development in CCS was cancelled, with future funds being allocated to research cost-reduction of CCS. A recent report on the role of FFCCS in a lowest cost decarbonisation of the UK was released (BEIS UK, 2016a). This report found FFCCS is absolutely essential for least cost solution. It highlights the need for early decisions due to long lead times. Recommended actions included: to establish an FFCCS delivery company to provide power stations, transport and storage infrastructure; set up economic regulation; incentivise FFCCS; and use FFCCS certificates and FFCCS obligations in the private sector. It proposes that FFCCS can compensate for limited emissions reduction in harder to decarbonise sectors. With FFCCS being an important component of least cost emission scenarios for the UK, concern exists around any delay in FFCCS deployment, such as that imposed by cancelling the research and development competition. ETI ESME modelling suggests that a ten year delay could cost the UK up to 2 billion GBP yr^{-1} from 2020 onwards (UKCCS Research Centre, 2017). Future projections of the use of FFCCS in the UK have been reduced from 14% by 2035 to just 2% of total electricity generation (BEIS UK, 2016b).

Hence while implementation is complicated with many challenges to delivering robust policies, examples of developing action plans can be seen emerging at a regional, national and local level. These proposals are typified by calls for knowledge sharing, market incentives and least-cost solutions.

3.2.5 Conclusion: CCS

CCS is at an operational but limited scale of development, but is heavily relied upon in future scenarios to climate change. Significant risks, uncertainty and cost exist around the capture, transport and storage of CO_2. However, working examples have been demonstrated in Norway, Canada and Iceland. Hence large-scale deployment may be possible. To achieve the scale necessary, barriers such as cost, public perception, and technology and policy development need to be overcome.

3.3 BECCS

3.3.1 Introduction

While many mitigation options can decrease gross emissions, BECCS offers the potential to actually decrease the atmospheric CO_2 levels (Mohan, 2016). Selosse and Ricci (Selosse and Ricci, 2014) define BECCS as 'a process in which CO_2 originating from biomass is captured and stored in geological formations' (Figure 3.1). The majority of 2ºC IAM scenarios heavily rely on BECCS to deliver the global warming target (Vaughan and Gough, 2016). Literature on bioenergy is characterised into two strands by Creutzig *et al.* (Creutzig et al., 2015). One highlights the significant contribution potential toward mitigating emissions and displacing fossil fuels; the other focuses on the risks and uncertainties of large-scale deployment of bioenergy crops and potential associated emissions. There is now a large amount of literature available that is specific to BECCS. Main themes in the literature include its feasibility, uncertainties, deployment and technological development.

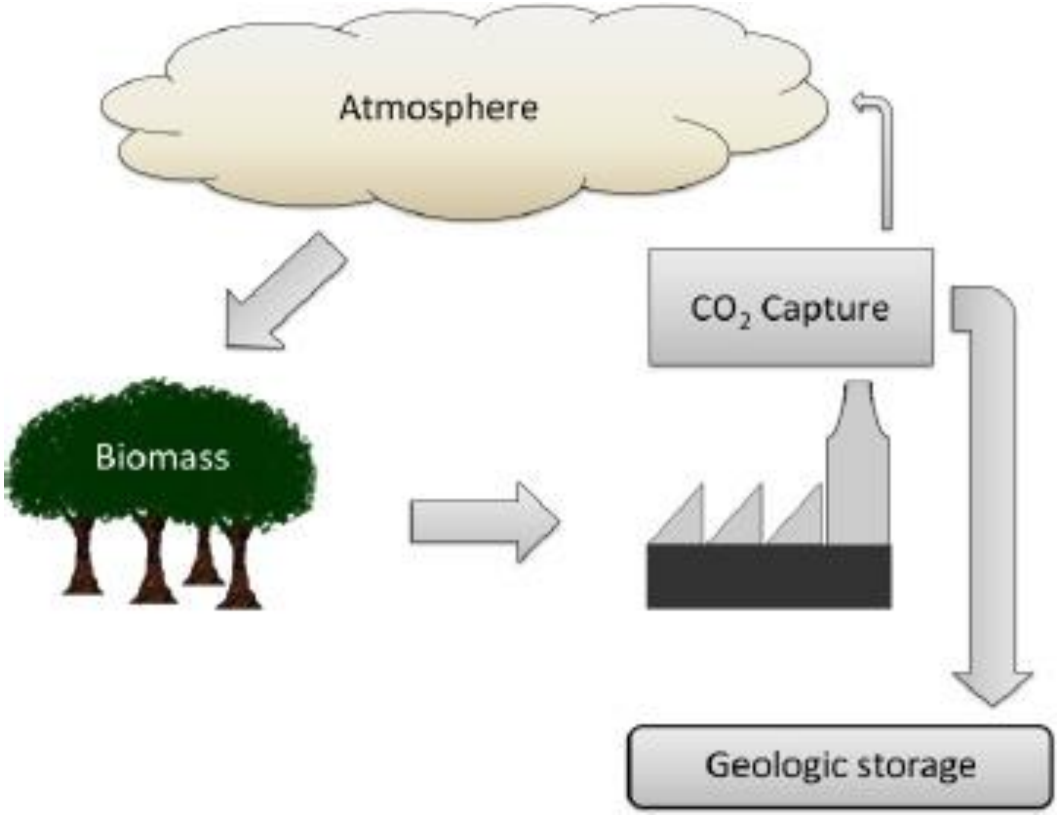

Figure 3.1: Schematic of BECCS: burning biomass for heat and/or energy, capturing CO_2 (potentially pre- or post-combustion) and storing it underground (Image reproduced from: globalccsinstitute.com).

3.3.2 Potential

BECCS is currently considered the negative emissions technology with the most immediate potential to reduce emissions (Quader and Ahmed, 2017). Potential biomass resources are significant when the many diverse forms are considered (Milne and Field, 2012). Evidence suggests that well managed biomass does not necessarily require CCS to be carbon negative, dependant on harvest frequency, nutrient turnover and previous land use (Milne and Field, 2012). However, most research finds BECCS to be the most viable option to utilise biomass to produce low carbon energy products and enable negative emissions (Selosse and Ricci, 2014). It is suggested that it offers an economically and environmentally viable option to achieve emission targets (Selosse and Ricci, 2014). One estimate is that BECCS could globally achieve negative emissions of 10.4 $GtCO_2e\ yr^{-1}$ by 2050 (Koornneef et al., 2012).

A key attraction of NETs in general, and BECCS in particular, is their potential role in offsetting difficult to mitigate sectors (Rhodes and Keith, 2008). Another strength is that CCS deployment in general (the parallel deployment of both FFCCS and BECCS) reduces the overall bioenergy requirement (within any given climate mitigation scenario) thereby reducing pressure on food crop prices, relative to cases where CCS is not available (Muratori et al., 2016). In practice, CCS is mostly being used or proposed to date with coal power plants, arguably risking a continued fossil fuel lock-in. Large scale BECCS could be feasible and offers a way to develop CCS while also progressively decoupling from fossil fuels and avoiding continued lock-in (Vergragt et al., 2011). Muratori *et al.* (Muratori et al., 2017) argues that cost effective mitigation scenarios require strong deployment of both FFCCS and BECCS, but with BECCS progressively becoming the more dominant CCS application.

3.3.3 Limitations

Fuss *et al.* (Fuss et al., 2014b) draws attention to the realistic physical constraints on BECCS imposed by biodiversity, food security and long term storage options.

3.3.3.1 Biodiversity and Food security

The implications for biodiversity and food security from wide-scale biomass production is a major theme of the literature on BECCS (Selosse and Ricci, 2014). Simply, the capacity and earth system impacts of BECCS is still not comprehensively studied. At the large scale required to be effective, BECCS systems would impose trade-offs with food production and biodiversity, and have impacts on forest extent, biogeochemical cycles and biogeophysical properties (Boysen et al., 2016). Biomass production may damage native ecosystems, disrupt ecosystem services and reduce biodiversity (Rhodes and Keith, 2008). Hence the ecological cost of BECCS must be fully considered when assessing its regional or local feasibility. For example, Pang *et al.* (2017) found in a case study example in China, biofuel production is ecologically unsustainable, despite high negative emission values achieved. Additional environmental trade-offs exist specific to CCS (Oreggioni et al., 2017), as discussed in Section 3.2.

There are major land use implications of deploying wide scale BECCS. Research finds that BECCS with first generation bioenergy feedstocks will not meet scenario targets even with irrigation and fertilisers, though second generation feedstocks might work with fertiliser and highly efficient CCS. Unless major technological advancement occurs, scenarios may underestimate how much bioenergy resource (and therefore land) is actually needed to achieve mitigation modelled by BECCS (Kato and Yamagata, 2014). This pressure on land area appears likely to contribute to an inevitable conflict with food production and biodiversity.

3.3.3.2 International management

Another issue for BECCS from a global perspective is that of ‘biomass justice’. The majority of the ‘available’ land under consideration is in developing countries (Rhodes and Keith, 2008). Additionally, while climate change mitigation is an international issue, nation-specific strategies need to be developed. Research is required at a more local level for effective deployment of BECCS in the specific context of any given country’s opportunity, and mechanisms for international collaboration and effort sharing need to be developed. For example, South Korea has abundant biomass in its existing forestry (64% land cover) but limited geologically suitable options for storing CO_2 due to volcanic and seismic activity. Lack of literature on geographically explicit BECCS applications is arguably limiting policy design (Kraxner et al., 2014).

3.3.3.3 Technology

The technology maturity of BECCS is another potential limitation (Selosse and Ricci 2014). As previously discussed, there are many technological considerations and requirements for the future success of CCS. From a cost perspective, energy from BECCS is even more expensive than energy from FFCCS (Akgul et al., 2014). Additionally, the combustion chemistry of co-firing biomass with fossil fuels is complex with potential concerns around toxic emissions (Akgul et al., 2014)**.** There are also supply chain barriers in the development of biomass resource and processing facilities (Akgul et al., 2014). In addition, herbaceous biofuel plants have a relatively high potassium content compared to wood. This forms corrosive potassium chloride in boilers during burning (Milne and Field, 2012)**.** Amine scrubbing captures CO_2 from flue gas but is expensive (Milne and Field, 2012).

3.3.3.4 Prediction and accounting complications

Deployment of BECCS at the scale assumed in IAMs is highly uncertain due to the limited deployment of CCS technology to date and potential biomass land requirements. Vaughan and Gough (Vaughan and Gough, 2016) find the assumptions about BECCS are realistic for CCS, but unrealistic for the scale of bioenergy deployment, and governance and societal support for BECCS. They argue that the greatest area of uncertainty is biomass production. Another problem is carbon accounting systems that omit emissions from land conversion and burning of biomass, making the assumption that burning biomass is unconditionally carbon neutral (Searchinger et al., 2009). Assumption of carbon neutrality of bioenergy is a dangerous over-simplification when calculating the benefit of BECCS, especially with long-rotation woody biomass (Oreggioni et al., 2017). It is imperative that the CO_2 released from the supply chain is fully quantified (Mac Dowell and Fajardy, 2017). Mohan (Mohan, 2016) highlights the major need for international life cycle accounting measures for BECCS.

3.3.4 Knowledge Gaps, Future Research and Deployment

3.3.4.1 Knowledge Gaps

There are many unknowns about the cost of connecting bio-processing to infrastructure with CO_2 storage sites and global bioenergy scenarios are quite contentious, hence it would be prudent not to exaggerate BECCS potential (Gough and Upham, 2011). Edmonds (2013) considers alternative strategies in the context of land use and energy policy and suggests that there are feasible mitigation pathways that do not require BECCS.

Some of the literature warns that the unproven potential of BECCS may become a dangerous distraction and could double the cumulative global CO_2 emissions (Fuss et al., 2014a), leading to overshoot of the temperature limit (Vaughan and Gough, 2016). There are also impacts on trade patterns to consider that depend on the capacity of BECCS to permit continued use of, or displace, fossil fuels (Muratori et al., 2016). Biomass plantations will only be sufficient if coupled with simultaneous emissions reduction measures, therefore potential to abate business as usual pathways is limited (Boysen et al., 2016).

BECCS offers significant potential but also serious risks. The impact of BECCS systems have mostly been considered from a regional perspective in the literature, but will ultimately be highly dependent on local factors (Creutzig et al., 2015). Some key barriers to BECCS identified by (Quader and Ahmed, 2017) include the suitability of land use for BECCS, carbon cycle response to negative emissions, cost estimation and socio-institutional barriers. These corroborate the concerns of socioeconomic challenges and climate system uncertainties identified by (Kraxner et al., 2015). They also highlight uncertainty in achieving the scale necessary on time, technological issues and feedstock potential. Additionally, Rhodes and Keith (Rhodes and Keith, 2008) discuss the limited availability and cost of conversion technologies, as well as the aforementioned scale of biomass production, environmental, social and economic concerns. Muratori *et al.* (Muratori et al., 2016) highlights that the viability and economic implications of deploying BECCS at scale is poorly understood. Kemper (Kemper, 2015) notes the following contributing issues: little experience with large-scale BECCS demonstration plants, gaps in climate policies and accounting frameworks, missing financial instruments, unclear public acceptance and complex sustainability issues

BECCS could lead to affordable carbon negative electricity by co-firing fossil fuels and biomass. In the UK, the carbon price needs to reach 120-175 GBP tCO_2^{-1} to incentivise transition to carbon negative energy. Increasing biomass availability reduces cost of electricity generation but may be limited by land availability (Akgul et al., 2014). Co-firing with fossil fuels has been argued to be the best short term option for BECCS as biomass facilities are inefficient today due to their small size (Milne and Field, 2012).

Working examples and research innovations in BECCS have recently been demonstrated. For example, in Brazil, CO_2 is captured and stored when fermenting biomass to ethanol (and combusting biomass for electricity). This could supply a substantial amount of transport and electricity energy at relatively small cost increase and significantly lower emissions (Moreira *et al.* 2016). There is also ongoing research to improve the efficiency of energy generation with BECCS. Bui, Fajardy, and Mac Dowell (Bui et al., 2017) present a heat recovery approach that significantly increases the energy efficiency of a BECCS plant by 38% higher heat value. Hetland *et al.* (Hetland et al., 2016) consider which approach is better, to co-fire biomass in existing large coal plants with CCS or building multiple smaller biopower units. The amount of CO_2 captured per tonne biomass is the same, but co-firing enables more efficient energy production. Mathisen *et al.* (2011) presents a case study in Norway combining a gas power station with CCS and supplementing power by burning biomass in a separate small plant to run capture, but conclude the resultant system is very expensive. Many market niches in industry are also being identified for deployment of BECCS (Möllersten et al., 2003).

Predicting the deployment and potential of BECCS is complicated by high uncertainty in technology, politics and climate effects (Creutzig et al., 2015). However the literature is clear that uncertainty should not deter development of beneficial options (Creutzig et al., 2015). Selosse and Ricci (2014) predict the use of CCS on fossil fuels in rapidly developing countries, with industrialised countries using BECCS and developing countries using a varied approach. All BECCS systems currently involve fossil fuels at some point in the production system. BECCS deployment is complicated due to the wide range of potential biomass material, conversion technologies (thermal and chemical) and capture and storage options. Co-firing is the most attractive short term option (Quader and Ahmed, 2017). Future deployment options require case-specific cost benefit analyses (Hetland et al., 2016). In Europe, using BECCS in the power sector may allow significantly lower levels of decarbonisation in the building and transport sector. The EU energy system may cost 14% more if it was decarbonised by 2050 (Rodriguez et al., 2016).

BECCS cannot be deployed in isolation, research and policies must address links to natural systems (Kemper, 2015). Tokimatsu, Yasuoka, and Nishio (2017) find the 2ºC target is achievable with significant forested land use. (Luckow et al., 2010) highlight that using diverse flexible biomass sources reduces the pressure for risky wide-scale deployment. For example, they propose the use of agricultural and forest residue biomass in the first half of the century, with dedicated biomass crops in the second half.

Recognition of BECCS in emissions trading is required to facilitate its deployment (Carbo et al., 2011). BECCS can help achieve temperature targets and may be cheaper, provided a temporal overshoot (in radiative forcing, and, potentially, global temperature) is tolerated. However, the cost benefit is lost if temporal overshoot is not allowed. (Azar et al., 2013). BECCS would require subsidies to be deployed, contributing to climate mitigation being a net burden on tax revenues (Muratori et al., 2016). Competition from other renewables like solar and wind may limit the use of biomass and hence the mitigating capacity of negative emissions from BECCS (Mac Dowell and Fajardy, 2017). Fridahl (2017) finds that, while 87% of IAMs presume use of BECCS to achieve 2ºC mitigation scenarios, BECCS has very low priority compared to other technologies amongst UNCCC delegates. Edström and Öberg (2013) find that a lack of awareness limits funding for developing BECCS and suggest that the next step is to set up small scale units to increase awareness in industry and policy.

3.3.5 Conclusion: BECCS

In conclusion, BECCS is a heavily relied upon NET in most IAM 2ºC scenarios. BECCS has the potential to produce energy and achieve net negative emissions, but there are still many barriers to deploying BECCS at the scale required to meet the IAM assumptions. These barriers include trade-offs with biodiversity and food security, international management, technological limitations and the misleading assumption (specifically embodied in current EU policy) that all bioenergy is unconditionally carbon neutral. Ongoing research innovations continue to progress BECCS towards achievability at a large scale and BECCS will likely begin as co-firing with fossil fuels in the short term. Scaling up BECCS capacity will require careful consideration of implications for natural systems, recognition in emissions trading schemes and increased awareness amongst international leaders.

3.4 Biochar (BC)

3.4.1 Introduction

Most arable agriculture soils have become a carbon source, losing their organic carbon, while also releasing methane and nitrous oxides (Stavi and Lal, 2013). One option to change soils from a carbon source to a carbon sink, and reduce methane and nitrous oxide emissions, is through applications of biochar. Biochar is defined by (Rasul et al., 2016) as a 'pyrolysis technique that converts biomass in absence or limited oxygen and controlled conditions of temperature and pressure to a carbon rich compound'. Biochar is considered to have significant negative emissions potential, possibly with fewer disadvantages than other NETs (Smith, 2016). As well as its climate change mitigation capacity, biochar is also considered a potential benefit to global food security (Idowu, 2017) due to improved soil fertility and water holding capacity as well as a possible stimulation of yields.

(Minx et al., 2017) have pointed out that although research on biochar has made a large contribution to the recent literature on NETs it is primarily of a technical nature and has not made a significant contribution to policy-focussed work. A comprehensive systematic review of biochar literature by Gurwick *et al.* (2013) considers the topic in more detail. Potential climate change mitigation is the focus of most studies. The climate change mitigation capacity of biochar is dependent on the assumption that the biochar can persist long term (>1000s years). Gurwick *et al.* (2013) found several gaps in the literature attempting to justify biochar claims, most notably in the understanding of biochar's influence on ecosystem processes, biochar decomposition rates and variation in residence times. They conclude that current (2013) data is insufficient to determine the effect of biochar on whole-system GHG budgets. The literature studies are characterised by diverse environmental conditions, feedstocks, and study designs.

3.4.2 Potential

(Verheijen et al., 2013) have estimated that global sequestration potential of biochar could be from 71-130 $GtCO_2$ over 100 years. Stavi (2013) estimates that applying biochar on degraded and deforested lands and agroforestry systems alone (1.75 billion ha globally) could sequester 2-109 GtC (18-400GtCO_2).

Biochar increases carbon sequestration, and also increases soil fertility (Lorenz and Lal, 2014) and nutrient and water availability, as well as supressing diseases and improving soil quality (Rasul et al., 2016; Subedi et al., 2017). Biochar is particularly beneficial for tropical soils where degraded soil quality threatens agricultural productivity and sustainability (Agegnehu et al., 2016). Its co-production in waste water treatment increases sustainability (Miller-Robbie et al., 2015). Biochar is argued to be superior in carbon sequestration and reducing GHG emissions than alternatives such as hydrochar or dried biomass (Schimmelpfennig et al., 2014) and is considered one of the most feasible options to mitigate the climate impact of agriculture (Stavi and Lal, 2013).

3.4.2.1 Biochar and Bioenergy Crops

Biochar may be most effectively deployed in multi-functional bioenergy systems, increasing the systems potential to achieve net negative emissions (Ubando et al., 2014; Woolf et al., 2014) by being co-produced during the burning biomass to make energy (Z. Wang et al., 2014). Biochar applications can also improve bioenergy crop productivity on marginal lands (Koide et al., 2015). Land use change emissions from establishing bioenergy crops might be offset by applying biochar, due to sequestration and increased yield reducing land area requirements (Kauffman et al., 2014), although this has not been consistently found to be the case (McClean et al., 2016).

3.4.2.2 Biochar and soil emissions

Biochar could potentially reduce soil emissions of N_2O associated with agricultural activity. Black carbon interacts with the nitrogen cycle and biochar potentially could reduce NOx emissions (Cayuela et al., 2013). This has been proven in the laboratory, although limited field studies have demonstrated contradictory results. (Nelissen et al., 2014) tested seven different biochars and found reduced N_2O and NO emissions. Additionally (Mukherjee et al., 2014) found N_2O significantly decreased by 92% in degraded soils but CO_2 and CH_4 emissions were not significantly altered. Similarly, Fidel, Laird, and Parkin (2017) found biochar mitigated N_2O, but didn’t significantly alter CO_2 emissions. Shen *et al.* (Shen et al., 2014) showed that adding straw biochar to rice paddies reduces its gross climate impact (contributions from both N_2O and CH_4, aggregated via GWP-100 equivalence factors). Whereas Xiang *et al.* (Xiang et al., 2015) found biochar had only a slight negative effect on N_2O emissions, but this effect was increased when coupled with optimal fertiliser use. Brassard, Godbout, and Raghavan (2016) considered 76 types of biochar from 40 studies and found biochar with low N were best at mitigating N_2O emissions. (Schimmelpfennig et al., 2014) demonstrated that NH_3 emission reduction only occurs if biochar is neutral or slightly acidic. Biochar’s capacity to reduce N_2O emissions is therefore dependent on many factors, and the priority for effectiveness should be an appropriate ratio with N fertiliser (Feng and Zhu, 2017). The mechanism for influencing N_2O flux is poorly understood and appears to be biochar and soil specific (Lan et al., 2017).

(Han et al., 2016) found biochar reduced CH_4 emissions under ambient temperatures, and even more so under elevated temperatures and CO_2. (Jeffery et al., 2016) found a relationship with flooding and pH in the capacity of biochar to decrease CH_4 emissions. Trade-offs may exist, as (Singla and Inubushi, 2014) found biochar increased CH_4 emissions, but lowered N_2O emissions, possibly due to the effect of more carbon available to microbial communities.

Preliminary research does suggest biochar may be used to reduce nitrous oxide and methane emissions from soil in certain contexts but results are variable, and limited by a lack of long term field studies but the mechanisms involved require further research.

3.4.3 Limitations

There are several limitations with biochar (Jeffery et al., 2015) and inconsistencies exist in the literature about how beneficial biochar really is (Butnan et al., 2016). Biochar could have negative impacts on air quality, climate and biogeochemical cycles (Lorenz and Lal, 2014; Ravi et al., 2016). Dependant on feedstock and pyrolysis conditions, biochar may also contain detrimental levels of toxic compounds or heavy metals (Subedi et al., 2017). In addition, many accounting estimates ignore the warming effect of reduced albedo reflection due to darker soil colour from biochar (Verheijen et al., 2013). Furthermore, the environmental benefit of biomass pyrolysis to make biochar is partly undermined by the need to use fossil fuels to ignite the relatively inflammable material, particularly at a small-scale (J. R. Jones et al., 2016).

3.4.3.1 Trade-Offs in Biochar production

Studies are emerging that consider the qualities and strengths of different types of biochar (Butnan et al., 2016). Feedstock type and process conditions cause variation in the characteristics and effectiveness of biochar (Subedi et al., 2016) with varying pH, nutrients, respiratory activity and capacity to trap CO_2 (Fornes et al., 2015). Trade-offs between carbon sequestration capacity and nutrient benefit affect choice of pyrolysis method and feedstock material during biochar production (Crombie et al., 2015). A trade off also exists between the amount of biochar required (burn material at lower temperatures) and long term stability of carbon (Saez de Bikuna Salinas et al., 2016). Biochar requires burning at over 360ºC to become resistant to decomposition (Mimmo et al., 2014) and the higher the pyrolysis temperatures, the more carbon is sequestered (Brassard et al., 2016)

3.4.3.2 Effectiveness of Biochar Application

The effect of biochar applications on yields and climate mitigation will be crop and site specific. It will be most beneficial to improved soil quality and yield in tropical weathered soils and soils of poor quality, and least effective in inherently fertile soils that make up most agricultural soils today (Lorenz and Lal, 2014). The yield benefit is also higher in acidic sandy soils (Subedi et al., 2017). In tropical degraded soils, adding biochar increased maize yields, but only mitigated GHG emissions under certain conditions, with some cases of increased aggregate GHG emissions in the short term (Agegnehu et al., 2016). Another field study found the opposite, where biochar enhances carbon sequestration but had no significant effect on yield (Keith et al., 2016). Additionally, for sequestration to be effective relative to CO_2 persistence in the atmosphere, carbon must persist in soil on a time scale of hundreds to thousands of years; the chances of this can be improved if the biochar carbon reaches deeper soil layers. More studies into mechanisms for surface applied biochar to be translocated to deeper soils are needed (Lorenz and Lal, 2014).

3.4.4 Knowledge Gaps, Future Research and Deployment

Payment to farmers is a necessary mechanism to implement climate mitigation and ecosystem support services (Stavi and Lal, 2013). Biochar is more beneficial in low carbon soils than high carbon soils. Yield and stability should be prioritised in deployment (Yadav et al., 2017). Widespread use of biochar in agriculture faces many barriers. Residence time might be a lot shorter than previously estimated, financial incentives are not yet in place and uncertainty exists around the full effect on crop yields (Bach et al., 2016).

3.4.4.1 Knowledge gaps

Biochar literature is characterised by considerable knowledge gaps and is still addressed at a superficial level. A review by Tammeorg *et al.* (Tammeorg et al., 2016) summarises our current understanding and future research priorities focused in the areas of: “soil biodiversity and ecotoxicology, soil organic matter and greenhouse gas (GHG) emissions, soil physical properties, nutrient cycles and crop production, and soil remediation”. Future research priorities need to address specific mechanisms, their trade-offs and long-term interactions as well as:

> *… functional redundancy within soil microbial communities, bioavailability of biochar’s contaminants to soil biota, soil organic matter stability, GHG emissions, soil formation, soil hydrology, nutrient cycling due to microbial priming as well as altered rhizosphere ecology, and soil pH buffering capacity. (Tammeorg et al., 2016)*

Other knowledge gaps highlighted in the biochar literature include:

- Economic and life cycle assessments at a site specific basis (Stavi, 2013).
- Further investigation into claims that benefits of biochar has been overestimated. (R. Fidel et al., 2017).
- More long term field scale studies to develop production and quality standards (Subedi et al., 2017).
- Better understanding of the underlying mechanisms of GHG emissions from biochar amended soils (R. B. Fidel, Laird, and Parkin 2017) (Brassard et al., 2016) (Jeffery et al., 2015).
- Investigation of the environmental impact of large-scale biochar applications(Ravi et al., 2016).
- Investigation of the effect of soil temperature on biochar amendments (Grunwald et al., 2017), especially under future climate change scenarios.

3.4.5 Conclusion: Biochar

Biochar production and application may have significant if limited CO_2 removal potential of 0.7 GtCe yr^{-1} (2.6 $GtCO_2$ yr^{-1}) globally (Smith, 2016), and could help achieve negative emissions in the future. Biochar can sequester CO_2 into a stable solid form that may be stored long term if the soil is managed correctly, and may also reduce the emissions of other GHG in the soils it is applied to, under certain criteria. Biochar has also demonstrable co-benefits such as increased crop yields and improved soil quality. However variable results challenge the overall effectiveness of biochar with trade-offs during production to consider between biochar quality and quantity. Uncertainty also exists in biochar applications regarding the specific mechanisms of biochar interactions with soil GHG emissions, the long-term storage of surface applied biochar and potential negative environmental impacts. Further research is needed to fully support biochar claims, develop and deploy biochar effectively, and address the knowledge gaps.

3.5 Afforestation/Reforestation

3.5.1 Introduction

The land-use sector can be used to reduce emissions and increase carbon uptake, but is currently responsible for 17-32% of global GHG emissions. This is primarily due to direct emissions from agricultural soils and livestock, as well as indirect agricultural emissions and land use change. Estimating the global emissions from conversion of land to agriculture has the highest uncertainty (6 ±3 $GtCO_2e$ yr^{-1}), contributing to such a wide total range (Bellarby et al., 2008). Forestry can be used to change the land-use sectors from a source to a sink in two ways: reducing emissions by avoiding deforestation and increasing carbon uptake (CO_2 removal) by afforestation. Afforestation is defined as the planting of trees on lands which historically have not contained forest cover (IPCC AR5 WG3, 2014). Currently there are both decreasing deforestation rates and increased afforestation. Total European forest area has increased by 25% since 1950 (Fuchs et al., 2013). However, European forests have emitted 3.1 GtC since 1750 despite considerable afforestation, because of wood extraction (Naudts et al., 2016). The optimum use of forestry for mitigation differs between regions. It is argued that the priority should be to reduce deforestation in Latin America, the Caribbean, Middle East and Africa and increase afforestation in OECD-1990, EIT and Asia (Smith et al., 2014). Land carbon stocks can be increased by afforestation that enables sequestration in soils and in biomass (vegetation and litter). Afforestation could change the overall land-use sector from a net source to a net sink by the mid-century and is argued to provide a cost efficient strategy for removing carbon from the atmosphere (Humpenöder et al., 2014).

Advantages of afforestation are that it can be deployed immediately, provides co-benefits and ecosystem services and it is generally unlikely that public acceptance will be an issue (Humpenöder et al., 2014). However, despite being immediately deployable, it takes time for forests to establish and maximise carbon uptake, storage of carbon in the soil is limited by factors such as the soil saturation point – maximum restoration of the land carbon buffer is estimated to be 187 GtC (Mackey et al., 2013), equivalent to less than 20 years of fossil fuel and cement emissions – and storage of carbon in forest biomass is vulnerable to future harvesting.

3.5.2 Potential

Future scenarios have suggested a maximum estimate of 2580 Mha afforestation globally, sequestering 860 $GtCO_2$ to the end of the century but with serious impacts on food prices (Kreidenweis et al., 2016). These modelled scenarios indicate that confining afforestation to the tropics and enabling freer international agricultural trade could achieve 60% of the maximum cumulative sequestration while greatly limiting impacts on food security. In 2030, at a carbon price up to 100 USD tCO_2^{-1}, estimates from forestry sector studies on mitigation potential range from 0.2-13.8 $GtCO_2$ yr^{-1}. This wide range is partly due to the different range of options considered in the studies (Smith et al., 2014). Based on a range of IAMs, afforestation could cumulatively remove 200-700 $GtCO_2$ by 2100 (Tavoni and Socolow, 2013). These studies indicate that afforestation has significant climate change mitigation potential through sequestration of CO_2 into soil and biomass. However, the wide range in estimates of annual rates and total cumulative sequestration of CO_2 also highlight significant uncertainty about the likely maximum mitigation potential of afforestation.

3.5.2.1 Afforestation and Sequestration

Afforestation removes CO_2 from the atmosphere, adding to the biomass stock and the solid carbon stock. Neither of these two stocks are as stable and permanent as geological storage of fossil fuels (Mackey et al., 2013). CO_2 sequestered into biomass is vulnerable to be re-released through decomposition, forest fires and harvesting, including combustion to meet increased bioenergy demands. The soil carbon stock may be somewhat more stable than the biomass, provided the carbon added to the soil can stabilise and that the soil is not disturbed.

3.5.2.2 Soil Organic Carbon (SOC) stock

Average carbon sequestration rate in soil (assessed to a depth of 100cm) after 41 years from forest establishment on agricultural soil is 0.65 MgC ha^{-1} yr^{-1} and 0.24 MgC ha^{-1} yr^{-1} under arboreal and shrub forestry respectively (Ulery et al., 1995). Converting cropland to forest could increase global SOC by 1.9% yr^{-1} (Han et al., 2017). The impact of afforestation on SOC stock depends on many factors, including climate, former land-use, forest age, forest type, soil type (clay content), nitrogen deposition and management practices. Ecosystem simulation modelling by Mitchell *et al.* (2012) also shows the carbon storage changes associated with land use change, including afforestation replacing agricultural use which can have a short-term climatic warming effect. Time is also a very important component with land use change to forestry characterised by an initial loss of SOC followed by a recovery phase of varying length. Bárcena *et al.* (Bárcena et al., 2014) found that "afforestation in Northern Europe had a positive effect on SOC stocks approximately 3 decades after land-use change, with the exception of afforestation on grasslands" but changes are small within a 30 year perspective. This is due to the effects of previous land use, soil type and SOC content. Grasslands tend to have higher levels of soil C than other land use types such as croplands, heathlands and barren lands. These SOC rich soils tend to maintain the same carbon levels after afforestation and not become sinks. In contrast, afforestation from cropland (SOC-depleted) had a significantly positive SOC effect, and coarse soils and volcanic soils were most prone to gain SOC after afforestation in Europe (Bárcena et al., 2014). Afforestation increases the biomass carbon stock when converted from grassland, but decreases the SOC (Burrascano et al., 2016). Additionally (Han et al., 2017) found afforested arable land had significantly higher SOC, especially in the top soil due to higher rates of litter and root production and protection of organic matter by stabilistation and protection of matter associated with mineral particles. Compared to agricultural land use, afforestation leads to long term stability of soils and increased carbon stabilization in soil aggregates due to decreased soil erosion and reduced disturbance.

3.5.3 Limitations

3.5.3.1 Albedo and evapotranspiration

CO_2 mitigation from land use change to forestry might be counteracted by changes in albedo, evapotranspiration, and aerodynamic surface roughness length (Burrascano et al., 2016), undermining the mitigation potential of afforestation (Jones et al., 2012; Vuuren et al., 2013)**.** The albedo effect is especially significant in boreal zones where albedo changes have been shown to offset the consequences of CO_2 removal. By restricting afforestation to non-boreal areas, potential carbon removal will be lowered by 8% (Kreidenweis et al., 2016). Tree species also matters, as broadleaf trees have less negative effect on albedo than needle leaf trees (Littleton et al., 2016). Additionally, afforestation could have region-specific effects on flooding and fire regimes.

3.5.3.2 Land area

On a land area basis, afforestation is estimated to require over five times the land area as BECCS to achieve similar levels of carbon removal (Humpenöder et al., 2014), despite the advantage of having lower cost than BECCS (Smith et al., 2015). 2800 Mha of afforestation could remove 703 $GtCO_2$, compared to only 500 Mha of BECCS removing 591 $GtCO_2$ (Humpenöder et al., 2014). Humpenöder *et al.* (2014) reports that these modelled results are highly sensitive to carbon prices, and lower afforestation costs are dependent on long crediting periods. Carbon removal rates due to afforestation will decline as less land is available and forests mature. One proposal to counter this considers harvesting the trees and burying the wood to protect the biomass carbon, and then replant the forest and increase the mitigation capacity of afforestation, however this study calls for further investigation as it does not consider the effects of 'nutrient loss, disturbance to the forest floor, biodiversity, cost, lifetime of stored wood, and unintended consequences' (Zeng et al., 2013).

3.5.3.3 Food Prices

Maximising afforestation, to 2580 Mha globally and to sequester 860 $GtCO_2$, could increase global food prices four fold by 2100 due to competition for land (Kreidenweis et al., 2016). This food price impact can be reduced if afforestation is restricted to areas where it will be most effective (Kreidenweis et al., 2016). More research and development is required for yield increasing technology for food to accommodate the land requirements of afforestation significant enough to be effective at climate mitigation (Kreidenweis et al., 2016). Given the very low resource and land-use efficiency of livestock production in terms of GHG emissions per unit protein produced and per hectare (Nijdam et al., 2012), Herrero *et al.* (2016, p. 5) estimate that reduced meat consumption could result in spared land available for up to 4.6 $GtCO_2e\ yr^{-1}$ of CDR if afforestation of pasture land is assumed, though the spared land could also be used to be produce larger amounts of food or for biomass production for bioenergy.

3.5.3.4 Biodiversity

Another trade-off exists between afforestation and biodiversity. For example, total carbon storage is larger in forests than in grasslands but grasslands support more endangered species (Burrascano et al., 2016). Plantation forestry aimed at maximising carbon stocks through longer rotation length may be better for biodiversity than bioenergy forestry, but that effect may be offset by increased stocking rates and reduced thinnings to maximise carbon (Pawson et al., 2013).

3.5.3.5 Management

There is uncertainty about future climate change impact on soil carbon stocks and forests (Smith et al., 2014). Different types of planted forest exist depending on the purpose each is established and managed for e.g. production of forest products (bioenergy) or for carbon sequestration in *carbon forestry*. Pawson *et al.* (Pawson et al., 2013) estimate that 4% of global forests are plantations, and these have an important role of offsetting the need to extract resources from natural forests. Forest management will have to adapt in response to climate change, this will involve changes in species, rotation length, thinning, pruning, extracting bioenergy feedstock and large-scale afforestation. In light of afforestation efforts, plantation forest specific vulnerabilities to future climate change need to be considered.

Naudts *et al.* (Naudts et al., 2016) argues that not all forest management strategies contribute to climate change mitigation. By putting more unmanaged forestry into production (extracting wood and possible conversion to more productive species), albedo is being lowered and carbon released. In Europe there are now significantly more conifers and less unmanaged forest land compared with 1750 (Naudts *et al.* 2016). Globally, wood extraction occurs in 64 to 72% of the forest area (Naudts *et al.* 2016). Carbon stock in living biomass, coarse woody debris, litter and soil was assessed (via simulation) to be 24%, 43%, 8% and 6% lower respectively in managed compared to unmanaged forests (Naudts et al., 2016). Therefore forest management needs to be accounted for in climate mitigation pathways that rely to any significant extent on carbon stocks and sinks in forestry. It is uncertain whether we can design a forest management strategy that can both mitigate climate change by increasing forest carbon stocks while also sustaining wood and bioenergy production and general ecosystem services (Naudts et al., 2016). Nabuurs *et al.* (2013) argue that distinct warnings of carbon saturation in Europe's forest biomass sink can already be detected due to forests coming into a dynamic equilibrium with forest management including a downward trend in afforestation area expansions (reduced from 500,000 ha yr^{-1} between 2005 to 2010 from 700,000 ha yr^{-1} previously), decreasing stem volume increment (annual growth), and increasing natural disturbances, storms and drying that may be boosted by climate change.

3.5.3.5.1 Bioenergy Demand

Recent EU-level targets by the European Commission aim to achieve 20% primary energy from renewable resources, 42% of which is expected to come from biomass (European Commission, 2013). The management of plantation forest to meet bioenergy demands and the implications for climate mitigation potential of afforestation efforts must be carefully considered. Forest biomass combustion is currently accounted as "carbon neutral" in the energy sector, assuming that the carbon accounting occurs in the land use sector, but this does not account for possible soil C loss from harvesting practices, or the plant growth and ongoing carbon sequestration that would occur in the absence of bioenergy production (Hudiburg et al., 2011). "Broad-scale bioenergy production may have important environmental and economic implications, which may not necessarily result in major greenhouse gas emission savings" (Burrascano et al., 2016). Policies must be designed so that established forests are not cut down again and release the carbon stored (Kreidenweis et al., 2016)

3.5.3.6 Policy coherence and governance

The question remains whether afforestation, under its aforementioned limitations, can effectively mitigate climate change significantly. Haim, White, and Alig (Haim et al., 2016) found that afforestation efforts were typified by problems with leakage, in some cases over 100%. This is due to the effect of intensification of agriculture on the remaining land that could offset the carbon sequestered by the afforested agricultural land. There is therefore a need for region specific GHG mitigation policies that considers implications of policy on other regions' activities and accounts for the carbon market.

Littleton, Vaughan, and Joshi (Littleton et al., 2016) considered a range of global afforestation scenarios and found significant limitations from albedo effects and propose that afforestation's "importance to future efforts to mitigate the effects of climate change is likely to be minor". Elberg Nielsen, Plantinga, and Alig (Elberg Nielsen et al., 2014) estimate that, in the USA, if carbon emissions were priced at 50 USD tCO_2^{-1}, an additional 200 $MtCO_2$ yr^{-1} would be sequestered through afforestation. Nabuurs *et al.* (Nabuurs et al., 2013, p. 795) conclude that continued afforestation in Europe delivers mitigation gains but is only one part of a spatially-diversified set of forest management policies that conserve and increase forest carbon stocks within an integrated land use strategy coherent with whole-economy climate policies.

There are also issues of policy coherence, as a carbon management focus policy direction may detract from or contradict other policies, such as biodiversity, as discussed by

(Burrascano et al., 2016). For example grasslands are good for carbon storage, particularly SOC, and biodiversity but are often targeted land areas by afforestation policy because combined biomass, litter, deadwood and soil in forestry will store more C (175 tC ha^{-1} compared to 126 tC ha^{-1} for grassland (Burrascano et al., 2016). Policies reflect the limited attention paid to the conflicts between carbon management and biodiversity conservation. There is also an inherent incoherence in the continuation of deforestation while attempting to increase of afforestation. Kreidenweis *et al.* (Kreidenweis et al., 2016) points out that deforestation must cease before afforestation can be seriously considered as a means to mitigate climate change.

3.5.4 Knowledge gaps and Future Research

Some knowledge gaps identified in the literature to be addressed by future research include

- The need for more novel studies that investigate the SOC dynamics and storage mechanisms of afforested soil (Han et al., 2017)
- Addressing the uncertainty (40-100+%) in the C storage of forested lands (Lehtonen and Heikkinen, 2015; Scharlemann et al., 2014)
- Investigate unknowns in land use change and disturbance, dynamics of plant communities and historical data (Menichetti et al., 2017)

3.5.5 Conclusion: Afforestation/Reforestation

In conclusion, afforestation is an option to remove carbon dioxide from the atmosphere that is already ongoing, not pending any technological developments and is argued to be more cost effective than other NETs (see estimates of mean cost from Smith et al., 2015, US$87/tCeq for afforestation and reforestation, compared to US$132/tCeq for BECCS, US$1600-2080/tCeq for DAC and US$1104/tCeq for EW). The effectiveness of afforestation for climate change mitigation depends on the stability and protection of the CO_2 sequestered into the soil and biomass stocks. While afforestation rates increase, scaling up this mitigation strategy will incur trade-offs with food prices and biodiversity, and mitigation potential may be offset by albedo effects and combusting biomass to meet future bioenergy demand. Future policy should employ methodologically comparable, full life cycle assessments of the greenhouse gas profile of a managed plantation, and should be designed coherently with other environmental policies such as biodiversity. Knowledge gaps that could be addressed by future research include understanding the mechanisms of carbon storage and reducing uncertainty about the forest carbon stock and land use change effects.

3.6 Direct Air Capture

3.6.1 Introduction

Direct air capture can be defined as "an industrial process that captures CO_2 from ambient air, producing a pure CO_2 stream for use or disposal" (Ishimoto et al., 2017; Keith, 2009). The concept of using DAC for climate mitigation was first introduced by Lackner in 1999 (Sanz-Pérez et al., 2016). DAC works by passing air over a material that absorbs CO_2. There are three main operating mediums: aqueous solutions of strong bases, amine adsorbents, and inorganic solid sorbents (Broehm et al., 2015). The resultant stream of CO_2 can be stored in geological formations via CCS or, in *carbon utilisation*, use in industry, usually offering far less, if any, long term sequestration. The key difference between DACCS and other applications of CCS is that DAC removes CO_2 directly from the atmosphere, instead of from flue gases from the burning of fossil fuels or biomass. This presents the challenge of extracting CO_2 from much lower concentrations in ambient air, compared to the relatively more mature technology of extracting it from flue gases.

3.6.2 Potential

Advantages of DAC are many. It has fewer social concerns and negative side effects than other NETs (Ishimoto et al., 2017), such as the land area conflicts and emissions accounting issues with BECCS and afforestation. The location of DAC is flexible because it extracts CO_2 from ambient air, and therefore can be located conveniently near consumers or storage facilities for the resulting CO_2 product (Broehm et al., 2015). Like other NETs, DAC combined with CCS can also offset emissions from all sectors, can remove past emissions, and potentially allows continued burning of fossil fuels that decouples near-term mitigation efforts from replacing or retrofitting existing infrastructure (Yousefi-Sahzabi et al., 2014). However, to achieve this, very large rates of removal would be required and currently no large scale working examples exist (Broehm et al., 2015) therefore any such near-term mitigation policy commitment to continued high fossil fuel use within a "well below 2ºC" pathway, based on DACCS, relies on very large investment in DACs, significant carbon price rises and still risks non-delivery of significant CDR (Larkin et al., 2017).

3.6.3 Limitations

The main limitation is cost of implementation, scalability and energy requirements. There is a significant cost for the energy and materials required to move large quantities of air in DAC (Yousefi-Sahzabi et al., 2014). Deployment is not helped by the very large range of cost estimates (Ishimoto et al., 2017). How to calculate the cost is debated and varies with estimates ranging from 100 USD tCO_2^{-1} to 550 USD tCO_2^{-1} if DAC was implemented within the next 25 years, and fall significantly in the longer term to 40-140 USD tCO_2^{-1} (Broehm et al., 2015). Some estimations of cost are as low as 30 USD tCO_2^{-1} if scaled up and mass produced (Yousefi-Sahzabi et al., 2014). While other estimates are as high as 568 USD tCO_2^{-1} (Smith et al., 2015). There are also major uncertainties about capital cost of plant design and materials, with estimates ranging from 300 million to 3 billion USD for a system that captures 1 $MtCO_2$ yr^{-1} (Broehm et al., 2015). Therefore, the current costs of DAC are highly uncertain and *may* prove to be prohibitively high compared to other mitigation options such as BECCS (Ranjan and Herzog, 2011). Nonetheless, some speculate that it may still have a significant role in long term climate mitigation (Kriegler et al., 2013) if costs could be reduced by innovation (Ishimoto et al., 2017; Sanz-Pérez et al., 2016; T. Wang et al., 2014). However, these studies indicate that DAC is currently an immature technology that is currently far from enabling CDR at large scale.

3.6.3.1 Energy inputs

High energy demand is another factor that may limit the potential of DAC (Ishimoto et al., 2017). Unlike BECCS, DAC does not have an energy output, and actually requires substantial energy to operate, entailing a net energy cost. There is significant variation in amount and quality of input energy needed for different types of proposed DAC system (Broehm et al., 2015). It is estimated that DAC will likely require 6-10 GJ tCO_2^{-1} thermal energy and 1.1-1.9 GJ tCO_2^{-1} of electrical energy (Broehm et al., 2015). This high energy requirement is because capture from atmosphere requires 1.8-3.6 times more energy than technology to separate CO_2 from flue gas, due to the much lower concentrations of CO_2 (Broehm et al., 2015), so, thermodynamically, DAC compares unfavourably with CO_2 capture from point sources (Pritchard et al., 2015). DAC therefore needs a dedicated source of very low carbon energy, as using conventional (unabated) fossil fuel power would potentially release more CO_2 than would be removed in the DAC process (Ranjan and Herzog, 2011). Additional energy would also be needed for CO_2 compression (to ~150bar), and transport and injection into a storage site.

3.6.3.2 Water

Another limiting factor is water use because DAC could have a potentially very large water requirement of up to 50 tH_2O tCO_2^{-1} captured, with an average estimate for capture of 5-13 tH_2O tCO_2^{-1} (Broehm et al., 2015).

3.6.4 Conclusion: DAC

In conclusion, DAC offers the in-principle possibility to directly remove CO_2 from the atmosphere. However, given its cost and technical limitations, it would be a risky policy decision to rely heavily on future DAC availability at this stage (Ranjan and Herzog, 2011). It is possible that new materials emerging may make DAC more feasible (Sanz-Pérez et al., 2016). However, Pritchard *et al.* (Pritchard et al., 2015) warns that it is inappropriate to be distracted by DAC when point sources of GHG emissions have not yet been substantially or completely decarbonised. An over-optimistic expectation of DAC could reduce policy motivation for other mitigation options. Pilot scale DAC deployment to better characterise the possible technology options and costs could be beneficial, but, on the basis of current knowledge, it appears that overall mitigation pathway planning should not assume or rely on large scale DACCS availability (see overview of DAC and DACCS in NRC (US), 2015, pp. 67–74).

3.7 Enhanced Weathering

3.7.1 Introduction

Enhanced weathering (EW) is defined as the "application of crushed silicates to the landscape to accelerate their chemical breakdown to release base cations and form bicarbonate that ultimately sequester CO_2" (Beerling et al., 2016). Hartmann *et al.* (2013) provides a detailed overview of chemical weathering as a climate change mitigation strategy. Calcium and magnesium-bearing silicate rocks react with and sequester CO_2 in air. This already happens naturally but can be accelerated through increasing the mineral surface area by crushing rock, and applying it to soils to concurrently increase soil C sequestration (Beerling, 2017; Hartmann et al., 2013). This can be deployed by applying the crushed materials to agricultural soils, open oceans and coastal zones (Meysman and Montserrat, 2017). During dissolution of silicate minerals, dissolved CO_2 will convert to bicarbonate, increasing soil and eventually ocean alkalinity, combatting soil and ocean acidification (Hartmann et al., 2013).

3.7.2 Potential

The material with the most potential is one rich in cations, has a fast dissolution rate and is abundantly available, such as olivine in mafic and ultramafic rocks (Hartmann et al., 2013) (Meysman and Montserrat, 2017). Moosdorf, Renforth, and Hartmann (Moosdorf et al., 2014) estimates that 0.5-1 tCO_2 can be sequestered per 1t of rock, with an energy cost ranging from 1.6-9.9 GJ tCO_2.$^{-1}$ Modelling by Taylor *et al.* (Taylor et al., 2015) projects that EW could lower atmospheric CO_2 by 30-300 ppm by 2100 if applied at a rate of 1 to 5 kg m^{-2} yr^{-1} to 2000 Mha of tropical areas. EW has the most potential in the tropics (Hartmann et al., 2013) where there is high humidity, temperatures and rainfall (Meysman and Montserrat, 2017). Globally there is 12 Mkm^2 of cropland that could have significant mitigation potential if enhanced weathering is deployed, as a co-benefit to food production (Beerling et al., 2016).

EW has many potential co-benefits. The alkaline bicarbonate generated ultimately ends up in the ocean. This mitigates another major environmental issue of ocean acidification. EW can be used on land already producing crops, therefore there is no necessary land conflict and it doesn't compromise food security. It also decreases fertilizer and pesticide use and costs (Beerling, 2017). By releasing other nutrients (Si, P and K), EW may increase productivity, further removing CO_2 from the atmosphere. For example, crop yields have been found to increase by up to 50% in the case of rice under silicon fertilisers (Hartmann et al., 2013). EW also reduces N_2O loss through pH buffering further benefiting both crop production and the global climate (Kantola et al., 2017).

Globally Smith *et al.* (2015) estimate that sustained EW could remove about 3.7 $MtCO_2$ yr^{-1} by 2100, requiring a mean estimated energy input of 46 EJ yr^{-1} with a wide range of potential costs giving a mean value of ~300 USD tCO_2^{-1}.

3.7.3 Limitations

Limitations to consider with EW include the effect of pore water saturation, dissolution kinetics, plants, soil processes and negative impacts from altering pH levels in natural ecosystems. There is also a risk of increased airborne dust and implications for human and animal health. While mafic and ultramafic rocks containing suitable minerals such as olivine are abundantly available, deploying EW would require significant development of mining and transport infrastructure. Transport of such large quantities over potentially long distances may significantly undermine the mitigation potential if transport is fossil fuelled (Hartmann et al., 2013). There is a high energy requirement and associated CO_2 emissions to grind the material to suitable grain sizes (Meysman and Montserrat, 2017). The most potential for EW to be effective is in tropical areas. However, these regions are densely forested, a landscape that is logistically unavailable to spread rock material. Hence the land area is restricted to arable regions, limiting land availability (Meysman and Montserrat, 2017). Other barriers include cost, social acceptability and the possibility of unknown consequences (Taylor et al., 2015).

3.7.4 Knowledge Gaps and Future Research

There are still many uncertainties about long term impact EW with a prominent lack of field experiments in the literature (Beerling, 2017). There are many unknowns about the ecological and biogeochemical impacts of EW at scale (Hartmann et al., 2013). Future research needs to consider the ecosystem impacts from released weathering products (Meysman and Montserrat, 2017). Another unknown is the effect of adding silicate minerals to soil on the organic matter pool. Adding silicate minerals could potentially promote SOC loss through decomposition and it is unknown whether the initial increase in microbial activity (decomposers) will be counterbalanced by the increase in plant productivity (Dietzen and Harrison, 2016). Moosdorf, Renforth, and Hartmann (Moosdorf et al., 2014) identifies future research priorities for weathering rates and side effects as well as addressing social acceptability and governance. Beerling *et al.* (Beerling et al., 2016) considers EW to be limited by economic cost and energy requirements, suggesting that its role in effective mitigation will be in a context contributing to the 2ºC target as part of a portfolio with multiple NETs. The CDR report by NRC (2015, pp. 46–56) provides a useful overview of EW and current research.

3.7.5 Conclusion: Enhanced Weathering

In conclusion, EW has potential to increase removal and sequestration of CO_2 from the atmosphere, with many co-benefits for soil quality, productivity and combatting ocean acidification. Its potential may be limited by energy requirements, emissions and cost. While EW enhances an already occurring natural process, future research must address the potential side effects at an ecosystem level of deploying EW at large scale.

4 Energy-economy-emission system modelling of climate mitigation pathways, with and without negative emissions

Summary

- Modelling future climate-energy-economy outcomes of potential choices through time can assist decision-makers if models are skilful and projection uncertainties are clearly stated. However, modelling outputs need to be used with care as they are readily subject to misinterpretation.
- IAMs and energy system modelling can be extremely complex, resting on historic assumptions and on medium and long-term economic projections that often lack inherent physical basis to allow predictability (unlike the Earth climate system's near-linear warming response to cumulative CO_2 emissions).
- *Benefit-cost analysis* combines socioeconomic, physical climate, damage function and discounting modules to estimate mitigation pathways providing an 'optimal' balance of benefits over costs. The results, including estimates of a social cost of carbon, are often highly contested, having a very large range of values.
- *Cost effectiveness analysis,* as used in economic climate mitigation modelling, assumes that a specified climate target will be met with high certainty. Analysis then identifies the least-cost pathway among alternatives that all meet that specific target constraint. Within a cost-effectiveness framework, near-term policies need to be aligned with a high probability of meeting a climate target, otherwise they cannot be judged to be cost-effective.
- *Energy system optimisation models* can be used to investigate alternative least "notional cost", decarbonisation pathways over the next few decades, but often assume a single decision-maker with perfect foresight.
- 'Second-best' and multi-level perspective analysis, accounting for myopic decision-making, carbon lock-ins and cultural path dependence may enable more realistic, policy relevant analysis, especially if stringent mitigation urgency is not otherwise being adequately addressed in near-term policy.
- Life cycle assessment (LCA) and marginal abatement cost curves (MACCs) can be useful but are typically subject to complex, interacting uncertainties and need to be interpreted with care, especially when comparing different studies or in ranking options.
- IPCC AR5 IAM scenarios are arguably unrealistic in assuming globally uniform and rising carbon prices, long-term planning and rational decision-making to achieve "cost effective" WB2C decarbonisation by 2100.
- IAMs for energy and land use for WB2C include large amounts of CDR through NETs, especially depending on large scale BECCS. Modelled future mitigation costs rise steeply if NETs such as BECCS and DACCS do not become available at scale in future, within the projected cost and performance levels.

4.1 Types of modelling aiming to assist in climate mitigation policy decision-making

This chapter gives an overview of the forms of modelling – socio-economic, energy, land and climate – used in integrated assessment and other more focused modelling that can inform climate mitigation policy. The usefulness and limitations of different modelling approaches are discussed, especially in regard to the costs of action and inaction, and in assessing the future role of negative emissions technology. Given the urgency of agreed Paris Agreement target-aligned climate mitigation, including the possible need for global nett negative CO_2 emissions, achieving the necessary rapid transformation in global, regional and national energy systems and land-use management requires difficult choices to be made. The academic community has aimed to inform decision-makers by developing models to assess the costs and challenges of different future climate mitigation pathways to explore the alternatives using a variety of modelling approaches (Sathaye and Shukla, 2013). All model-makers and users of model output do well to bear in mind the well-known observation by Box (1976) that "all models are wrong but some are useful". Because the future is always unclear, modelling that reflects best understanding of natural and human systems can help to explore multiple alternative pathway scenarios through future decades. It is best if models are as simple as possible to give useful information and no simpler, the main test of usefulness being an ability to match observations and make projections skilfully[5] (Schmidt and Sherwood, 2015).

Intercomparison between models can also help in confirming model abilities but there is a key distinction to be made between modelling of physical systems, such as Earth's climate, that are 'structurally constant' (Scher and Koomey, 2011) as they obey physical laws (though they can still display tipping points, transitions into new and distinctive dynamic regimes), and modelling of human systems such as societies and economic systems that are far more structurally inconstant, being more prone to intrinsically unpredictable changes. Depending on their focus and intended use, models used in pathway assessment can have very different geographic scales from global to local, and different temporal scales from years to centuries. The model complexity and fineness of 'time slicing' (the time spacing between calculation steps) determining the computational time for each scenario run. Multiple runs with varying initial state and parameter values are often needed to test the sensitivity of the model to varying goals, assumptions and uncertainties.

Moss *et al.* (2010 Box 1) gives a concise summary of three main groups of models and analytical frameworks in climate change research:

- Integrated assessment models (IAMs), analysing the potential development of human systems, including energy use, economic output and human interaction with the climate system and land use. Energy system models (ESMs) of different levels of detail are incorporated in IAMs and are also commonly employed in

[5] "Skill" is used here in the technical sense of "forecast accuracy".

national and regional analysis.

- Physical climate models, ranging from highly complex atmosphere-ocean general circulation models (GCMs) to simplified climate models that are commonly incorporated into IAMs to project the climate system responses to projected human socio-economic activity;
- Impacts, adaptation and vulnerability (IAV) models using a wide range of methods to inform decision-makers about possible and likely risks to human and natural systems.

Global and large-region IAMs have been extensively used in economic assessments of climate policy assessments, primarily focused on two main approaches – benefit-cost analysis (BCA)[6] and cost-effectiveness analysis (CEA) – both of which attempt to assess the relative economic benefits and costs of climate change mitigation with the objective of identifying optimal costing of pollution or recommending optimal policy pathways. Many IAM and ESM approaches continue to assume idealised (arguably unrealistic), 'first-best' conditions: the modelling is set up as if there is only a single decision-maker acting with perfect foresight, and within highly efficient markets operating with perfect information. Scenario results then give a solution path which is notionally optimal (relative to these assumptions), often over several decades, based on economic history, and on technology assumptions for future development, supply and demand, also based on experience. This is typical of energy system modelling that aims to integrate cost choices over long periods.

Increasingly though, models attempt to examine more realistic, 'second-best' options by incorporating 'landscape effects', due to path dependent inertia, and 'lock-in' effects perpetuating GHG-intensive behaviour in policies, institutions and among vested interests and society. Second-best policy landscapes are addressed by constraining processes and responses and by varying initial conditions in sensitivity analyses. For the five Shared Socioeconomic Pathway (SSP) narratives directed toward CEA-IAM modelling for IPCC AR6, including second-best, fossil-fuelled and/or highly inequitable alternative futures, a set of quantified constraints are being specified for each narrative to give a shared basis of group inputs for scenario runs undertaken by each of the IAM models managed by modelling teams worldwide (O'Neill et al., 2017).

4.2 Economic modelling of climate mitigation costs and pathways:

4.2.1 Limitations of economic climate cost modelling

The numerical inputs and outputs of economic modelling (like much of economics) can give the impression of analysis that is free of normative or political choices; however, many of the monetising assumptions, the overlooked (non-monetised) sources of wellbeing, and distributive choices made in benefit-cost analyses estimating the 'costs' of climate policy are, in practice, profoundly normative (Ackerman et al., 2009). By making conservative

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[6] Benefit-cost analysis (the term used by the IPCC WG3) is synonymous with cost-benefit analysis

assumptions about the possible rates of socio-economic change, these models are often biased toward the interests of the present generation and wealthier nations and actors thereby potentially continuing existing dominant power structures and perpetuating existing high-emissions systems (Ackerman et al., 2009).

Climate policy costs from IAMs can therefore be described as being highly dependent on modelling assumptions:

> *The "cost" of climate policy is not an observable market price; rather, it is a construct shaped by the modelling apparatus and its explicit and implicit assumptions. (2013, p. 156)*

Growth rate assumptions for economies, energy use, population, production and consumption have large effects on the modelled (monetary) costs and benefits of mitigation action. Many co-benefits and adverse co-impacts within mitigation pathway modelling are frequently ignored or commonly given zero value by both BCA and CEA IAMs because they can be difficult to quantify (Ürge-Vorsatz et al., 2014). Failing to include co-benefits may seriously underplay the benefits of mitigation action thereby inflating the apparent cost, or *vice versa* for adverse co-impacts. Difficulty in quantification does not, in itself, mandate a presumption that these divergences from model outcomes would be negligible. The very complexity of IAM process-modelling including contested (frequently value-laden) assumptions, omitted benefits of action and uncertainties, raise substantive doubts as to model usefulness in guiding climate mitigation decision-making. For example, one detailed study of CCS across models found that the projected levels of CCS use could not be explained from CCS-specific factors; rather, the model interactions were complex to the point of resisting analysis (Koelbl et al., 2014, p. 474).

The cumulative beneficial value of avoiding very long-term, global negative impacts from climate change, air pollution and deforestation are often overlooked. This may yield policy inputs that are relatively more palatable for decision-makers constrained by short (political) time and space horizons; but it is potentially to the severe detriment of long-term and aggregate human welfare (Scrieciu et al., 2013; Stern, 2016). Stern argues that IPCC AR5 report seriously understated the "grossly misleading" limitations of BCA-IAMs which are unable to deal with path-dependency of energy (and food) systems or, conversely, do not include the scale of learning and speed of technical change needed to cut fossil fuel use, preserve biodiversity and stop deforestation. Presenting policy makers with costs of mitigation versus a business-as-usual baseline is identified as profoundly unhelpful given the plausible potential for high and possibly catastrophic impacts on economic activity (and broader qualitative wellbeing) under such supposed "business-as-usual" conditions. Dynamic stochastic computable general equilibrium (DSGE) models, which explicitly acknowledge uncertainty, and agent-based models (ABMs), that attempt to give a stronger role for interacting agents in societies and economies, are advocated by Stern as possible advances in modelling. However, these possible improvements in socio-economic modelling do not address the major problems identified in defining damage functions and discount rates. Keen (2011) argues that all equilibrium modelling is structurally unable to model

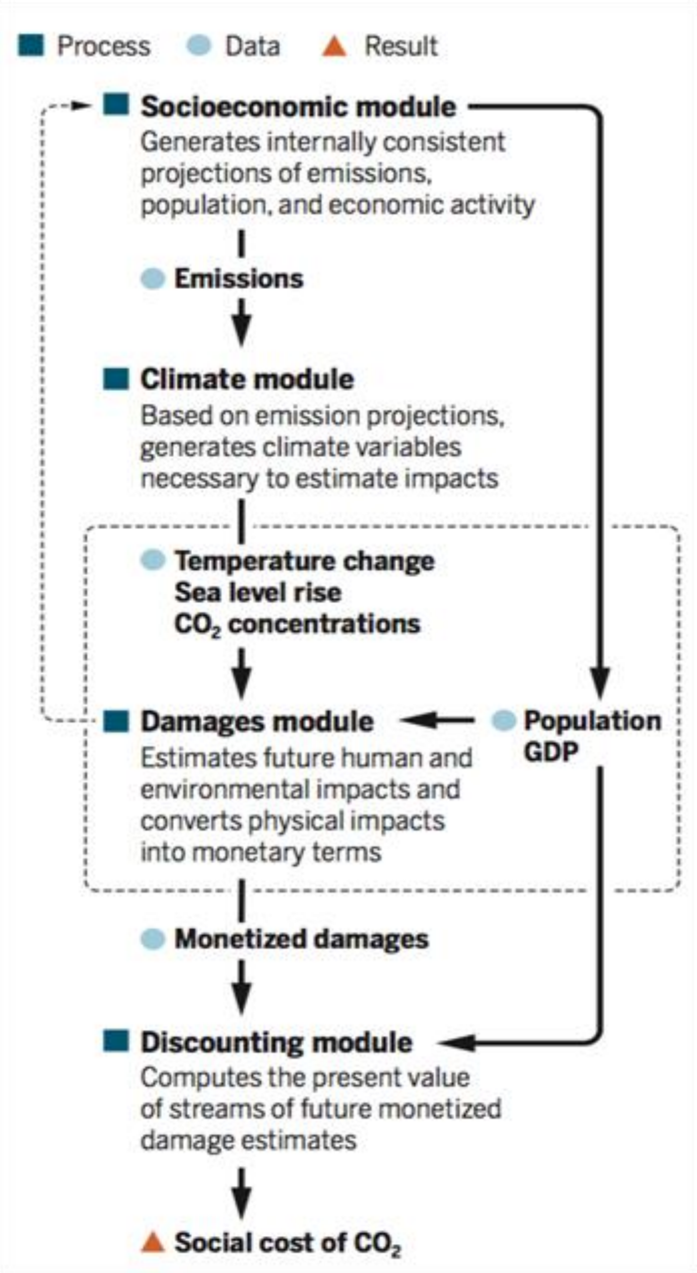

Figure 4.1: The four modelling components (modules) used in Benefit Cost Analysis Integrated Assessment Models in calculating the social cost of CO_2. Reproduced from Pizer (2017).

intrinsic instability in financial systems leading to boom and bust, and DGSE is a poorly evidenced adjustment that fails to address this problem.

Overall, there is a scientific obligation on all modellers to be explicit about the caveats, serious shortcomings and major assumptions in both BCA and CEA IAM modelling. Users of model outputs have an attendant obligation to be similarly cautious. Modellers also need to correct policy-makers and others who misinterpret findings or be clear when past advice has been ignored. The full costs of inaction as well as the benefits of action also need to be made clear relative to past or present modelling of cost-optimal pathways (Luderer et al., 2013).

4.2.2 Benefit-cost analysis (BCA)

Benefit-cost analysis IAM modelling has typically been used to give a global and large-region ('top down') macroeconomic assessment estimating a balance between the costs of mitigation inaction against the costs of action, especially over the very long term. The resulting *social cost of carbon* (SC-CO_2) aims to represent a present value marginal cost of emitting an additional tonne of greenhouse gas pollution. In general, BCA-IAMs, such as the commonly used DICE[7], are not constrained or driven by politically agreed (science-informed) climate change limits, but claim to estimate the

[7] DICE "Dynamic Integrated model of Climate and the Economy" created by William Nordhaus.

cost of climate damages sufficiently well to enable 'economically efficient' choices in climate mitigation policy. Therefore, even if BCA-IAM could be assumed to provide an accurate costing of climate damages there is potential for technical and ethical conflict between BCA climate modelling that can allow emissions to exceed politically agreed (scientifically informed) limits on the basis of claimed "economic efficiency'. Each time step in BCA-IAMs follows a chain of sub models (often called modules), in order to: approximate the emissions of a large scale socio-economic-energy system; estimate the resulting response of Earth's climate system using a physical climate model; calculate the consequent total future damages (using highly uncertain damage functions, under contested value systems); and finally weight the outcome using a discount rate according to some descriptive and/or values-based assessment of how such (uncertain) future costs are taken to be (less) valued in the present (as compared, say, to relatively more certain costs of tangible present events or actions).

The SC-CO_2 values[8] computed by BCA-IAMs are typically expressed in misleadingly precise monetary figures, often without explicit confidence ranges despite the contested value systems embodied in them, the inherent structural inconstancy in economic forecasting, and very large predictive uncertainties, especially in assuming highly questionable damage functions that clearly equate to inadequate accuracy (Ackerman et al., 2009; Pindyck, 2013; Scrieciu et al., 2013; Stern, 2016). Unsurprisingly, different BCA-IAMs give an extremely wide range of estimates varying from near zero to many hundreds of dollars per tCO_2 (van den Bergh and Botzen, 2014) up to essentially infinite values if plausible catastrophic climate damages are included, even if they appear to be low probability or, usually more correctly, if we do not have any clear idea of their probability (Weitzman, 2009). The inputs and outputs for BCA-IAMs are based on average values at large aggregate scales so they are close to useless for describing local and short-term costs or outcomes, especially for vulnerable or exposed communities.

4.2.2.1 BCA estimates of the social cost of carbon SC-CO_2

Though the results are highly contested, much academic effort has been, and continues to be expended in calculating the long-term benefits of acting to mitigate climate change (by avoiding damages) balanced against estimated costs to society of reducing emissions to avoid damages. Values of SC-CO_2, stated according to the relevant future year and related discount rate, are commonly used by the USA and other countries (UK Government, 2017; US EPA, 2016, pp. 3–4) as a shadow price to evaluate the carbon costs and benefits of alternative climate and energy policy decisions. The 'social cost of carbon', SC-CO_2, computed by Benefit-Cost Analysis integrated assessment models (BCA-IAMs), is generally defined as the net present value estimate of the marginal future damage (up to some time horizon), usually globally, due to one additional tonne of carbon dioxide emissions. Despite

[8] Although called the 'social cost of carbon', sometimes SCC, this term is used as shorthand for the social cost of carbon dioxide, and more usually abbreviated as SC-CO_2

the exact values typically presented (without confidence ranges) the spread in values between the three major BC-IAM models, and even between different users of the same model, indicates the large degree of disagreement in the underlying assumptions being made. The estimates of SC-CO_2 may be open to critique but, as the US courts have found, "[w]hile the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero" (US EPA, 2016, p. 2). Similarly, within the models, while likely damages for a particular impact may be highly uncertain, the uncertainty range is then tacitly known to be large; accordingly, just because the damage cannot be assessed or quantified with precision, does not mean it can or should be accounted as zero. So, for SCC values, some estimate needs to be made, perhaps best based on expert elicitation (Oppenheimer et al., 2016; Pindyck, 2016).

Using a benefit-cost (BC) analysis – essentially setting a greenhouse gas damage function against an abatement cost function within an economic growth model and applying a discount rate to weight the result relative to some estimate of future vs current value – has been the dominant economic approach to costing and planning climate mitigation since the work of Nordhaus that formed the basis of the DICE BC-IAM (1991). These models aim to maximise the present value of the aggregate future utility ('utility' being a presumed, and value-laden, overall measure of wellbeing) for humanity. The calculation is based on a chain of four component modules, incorporating data from observations and modelling to produce a social cost of carbon. Each step in this chain of modules is subject to uncertainties and contestation. As Pizer (2017) illustrates (see Figure 4.1), emissions projections from a socioeconomic module are input into a physical climate model module to estimate impacts (such as CO_2 concentration, temperature rise, sea level rise, crop harvests). These in turn are input into a damages module to estimate monetised damages and finally a discounting module applies a discount rate to enable final calculation of an SCC value.

William Nordhaus developed the DICE global model (Nordhaus, 1993) as a series of equations representing a simplified economy-climate-damage-discounting model subsequently embodied in a spreadsheet model that continues to be widely used by many researchers to produce estimates of SCC (see summary by Newbold, 2010). A regional variant of the model called RICE examines alternative climate policy approaches by regional blocs or individual countries finding that internationally cooperative policies are less costly and achieve deeper emissions reductions than non-cooperative ones (Nordhaus and Yang, 1996). Two other global models similarly widely used in estimating ranges for the SCC are FUND (FUND, 2015), developed by Richard Tol, and PAGE, developed by Chris Hope, a version of which (PAGE2002) was used in the analysis of climate mitigation pathways for the UK Treasury report, the Stern Review on the Economics of Climate Change (Stern, 2006; Zedillo, 2007). DICE, FUND and PAGE are all 'reduced form' models that lack an explicit energy model, instead using exogenously determined emission pathways (Zedillo, 2007, p. 62), typically still reliant on the now outdated SRES scenarios (WMO/UNEP, 2000).

In 2010, the USA published estimates of CO_2 mitigation benefits based on SCC estimates made using an average of DICE, FUND and PAGE finding, giving a central, current value of 21 USD tCO_2^{-1} updated to 37 USD tCO_2^{-1} in 2013 (US EPA, 2016, pp. 3–4) (a steadily increasing SCC through time is an output from these models). However, critiques indicate that even on a partial inclusion of damage costs these are serious underestimates of likely US damages: Johnson and Hope (2012) find values 2.6 to 12 times larger based on lower discount rates more appropriate to long time horizons and equity weighting to allow for relative income levels; and, Ackerman and Stanton (2011) find "worst case" SC-CO_2 values of 900 USD tCO_2^{-1} in 2010, rising to 1,500 USD tCO_2^{-1} in 2050, using a precautionary assessment that costs risks due to the recognised uncertainties in climate response, resultant damages, catastrophic risk and discount rates. Nonetheless, as estimated using DICE by its originator Nordhaus (2017), the SC-CO_2 has increased from 17 USD tCO_2^{-1} to 31 USD tCO_2^{-1} due to changing assumptions (see Table 4), but still assuming a higher interest rate than the Stern Review (2006), and a damage function that (like Stern) assumes limited global climate damages even with high end projections of global warming. However, as Figure 4.2 indicates, the accuracy of BCA and SC-CO_2 values are highly doubtful due to the extreme divergence among damage functions (see comparison of extreme divergence among DICE damage functions in Fig. 4 Pezzey and Burke, 2014).

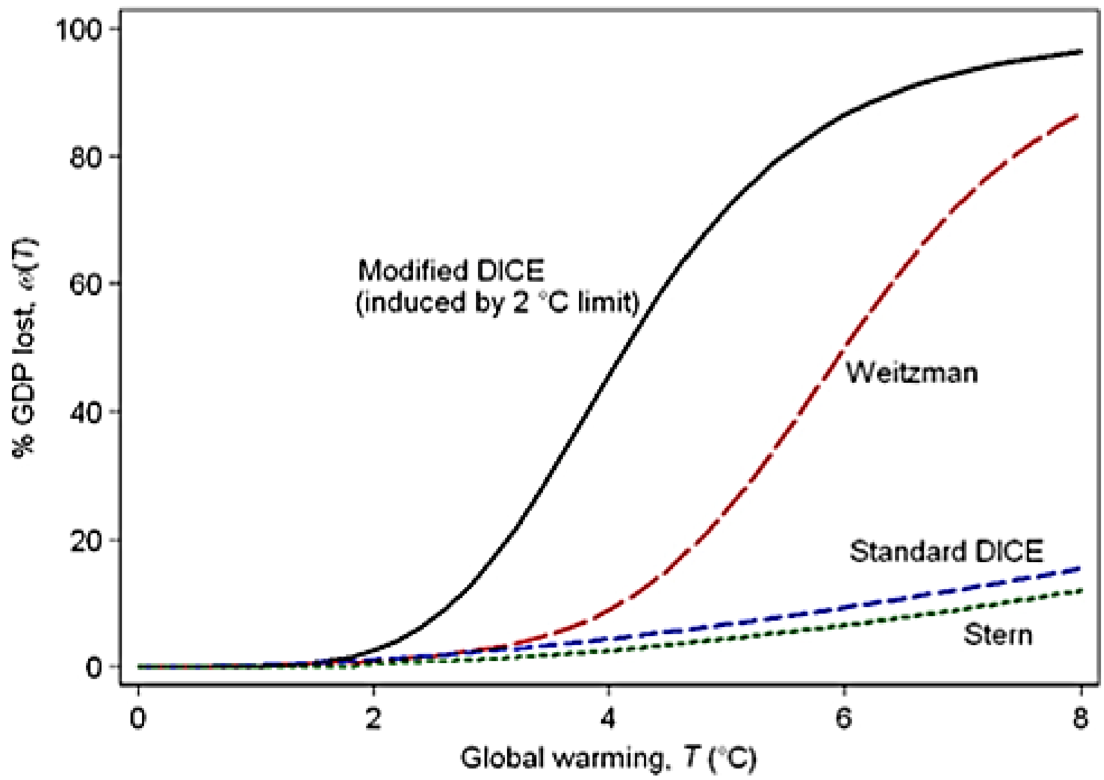

Figure 4.2: Comparing large disparities between alternative DICE damage functions, reproduced from Pezzey and Burke (2014).

The UK also uses a similar framework for SCC values with similar values (UK Government, 2017). Using the updated PAGE09 model, Hope (2011) gives a central SC-CO_2 value of 100 USD tCO_2^{-1} for continued 'business as usual' emissions. In a peer-reviewed NGO study, Ackerman and Stanton (2011 see Fig. ES-1) illustrate how a very wide range of SC-CO_2

values, ranging from 28 to 893 USD tCO_2^{-1}, results from variations in discount rate and damage functions.

Precautionary policies to minimise regret generally produce larger SC-CO_2 estimates (Dietz, 2011). Revesz *et al.* (2014) argue that the SC-CO_2 is a valuable metric in policy despite the wide range of values and deep uncertainty. This may be true in the sense that previous and existing policy around the world continues to value CO_2 damages at zero or lower rates than the USA and UK. Ireland's Public Spending Code bases its recommended 2017/18 shadow price of 7 EUR tCO_2^{-1} on the European Climate Exchange futures offers market pricing on the EU ETS, with recommended carbon prices for cost benefit analyses of 10 EUR tCO_2^{-1} in 2020, 35 EUR tCO_2^{-1} in 2030, 78 EUR tCO_2^{-1} in 2020, 100 EUR tCO_2^{-1} in 2020 (DPER, 2014).

However, Van den Bergh and Botzen (2014) describes the BCA IAM-produced SCC values as "gross underestimates", especially when generated using low discount rates and calculates a lower bound to SC-CO_2 of 125 USD tCO_2^{-1} for high impact / low probability outcomes where risk aversion is substantially incorporated (2014). As this study and the above summary indicates, all SCC estimates must be treated with a high degree of caution, particularly because the DICE, FUND and PAGE 'policy optimising' BCA IAMs are likely to underestimate the SCC by setting discount rates too high and damage risk premiums too low (see Ch. 3 IPCC AR5 WG3, 2014, p. 247).

4.2.2.2 BCA component modules

Given the contestation involved in critiquing SCC estimates it is useful to clearly identify which IAM component module (socioeconomic, climate, damage or discounting) is the source of the particular uncertainties and questionable assumptions at issue (Pindyck, 2013; US NAS et al., 2017; Ch. 3, IPCC AR5 WG3, 2014, pp. 245–249). The following discusses overall issues, followed by looking at the descriptions and issues with each of the four module areas of IAMs.

The DICE, FUND and PAGE models are benefit cost analysis IAMs (BC-IAMs) that include damage and discounting modules to enable SCC calculation but lack detailed energy-technology modelling. Dietz & Stern (2015, p. 576) provide a seven point summary of the equations and functions, By contrast, cost effectiveness IAMs (CEA-IAMs) such as those produced for IPCC AR5 WG3 assume that an agreed climate stabilisation target will be met and so do not include damage and discounting modules, instead including far more detailed energy (supply and demand) and technology processes and, sometimes, also land use modelling (Ch. 3 IPCC AR5 WG3, 2014, p. 247). The following comments therefore all apply to modules of BC-IAMs but only the comments on socioeconomic and climate modules apply to the CE-IAMs used for the scenario runs recorded in the IPCC WG3 database.

4.2.2.2.1 <u>Socioeconomic module assumptions, projections and limitations</u>

Being based on neoclassical, economic equilibrium growth models, the most common socioeconomic assumptions in climate economics are that economic growth will continue at an assumed constant average rate into the future, that decision-makers are rational, and that information is uniformly available (Nordhaus, 2017, p. 1518). Unfortunately, as Keen (2011, pp. 251–269) and others have pointed out following the global financial crisis, neoclassical equilibrium economics fails to provide dynamic models that effectively represent key empirical phenomena such as market crashes or change from growth to contraction in depressions. Northrop (2017) gives a simple Kaya-based analysis stressing the fully global decoupling required to ensure continued global economic growth and yet cut emissions by 4% yr^{-1} to 8% yr^{-1}, in line with a >66% chance of avoiding 2ºC carbon quota, concluding, “Optimism that economic growth can proceed without causing severe climate disruption is uninformed by the data. The optimists simply have not done the math.” In a long-run, hindcasting experiment with the DICE BC-IAM, Millner and McDermott (2016) use US economy data for 1870 to 2010 to test the model’s neoclassical Ramsey growth model, finding that it has limited predictive power and suggesting it “could be subject to structural errors on the temporal scales relevant to climate policies” (p. 8678). Four recommendations are made by Millner and McDermott: economic assumptions in BC-IAMs should be testable if at all possible; BC-IAM components should be tested; policy makers need to consider estimates from tested, structurally different IAMs; decision-making needs to explicitly acknowledge that economic models (unlike physical climate models) have very limited (and highly contested) predictive power and may thus be fundamentally misleading as guides to prudent/effective policy with long term time horizons.

Pollitt and Mercure (2017) show that the top-down Computable General Equilibrium (CGE) models, used in the socioeconomic modules of both BC- and CE-IAMs, are inherently biased against decarbonisation actions by using finance assumptions that “crowd out” low carbon investments in modelling because the starting point (including the finance sector) is typically treated as already representing an optimal *de facto* use of resources (p. 10). More empirically-based, non-equilibrium models are found to be more empirically realistic. Therefore policy-makers need to be aware of the severe limitations endemic in the use of CGE, the most common economic modelling method, and the lack of empirically robust economic modelling in general.

Socio-economic modelling and carbon costing also fails to account for raised costs of system change due to *carbon lock-in* – first described in detail by Unruh (2000) – the technological, agent and institutional system inertia of economies reliant on existing fossil fuelled energy causing physical, economic and socio-political “barriers to diffusion” slowing and reducing the assumed effectiveness of mitigation policies and technologies (Seto et al., 2016). Updating the work of Unruh (2000) in a systematic review, Seto *et al.* (2016) identify and describe three major classes of this type of path dependency (Table 4.1): infrastructural and technological, institutional, and behavioural – all of which tend to co-evolve, interact and mutually-reinforce to perpetuate the status quo in policy and outcomes. Escaping lock-ins is easier if costs of transition are low but, if not, alternative ‘decarbonisation lock-ins’ need to be induced and fostered by societal and social change through the cooperation of actors across sectors including governmental, non-governmental, public and corporate areas where motivation to achieve decarbonisation pathways overlaps. Demonstrating carbon lock-in, Bertram *et al.* (2015) apply nine energy-economy models and find that that near-term reliance on continued electricity generation from existing coal infrastructure is not a cost-effective global mitigation action. Increasing energy efficiency is found to increase energy system flexibility and to lower mitigation costs but it cannot cut reliance on coal electricity sufficiently to prevent sub-optimal mitigation with increased costs – suggesting an economic imperative for early retirement of coal-fired power stations, a finding that would presumably extend to peat-fired generation in nations where that is occurring, such as Ireland and Finland (see also the geographical distribution of fossil fuels unused when limiting global warming to 2ºC, McGlade and Ekins, 2015).

Rebound effects are commonly excluded in IAM and ESM socio-economic modelling of mitigation effectiveness, particularly in energy efficiency studies (Section 3.9.5 IPCC AR5 WG3, 2014). These effects potentially undermine the reliability of model results, even within the CGE framework because cost savings being spent at any time on the same kind of activity (direct rebound) or on different activities (indirect rebound) may generate additional emissions that cancel out the supposed reduction, in whole or in part. In principle, cost savings that are retained as invested wealth[9] may result in macroeconomic rebound effects that may be very large globally and over the long term, even exceeding 100% yr^{-1} in energy use and emissions (Berners-Lee and Clark, 2013; Jarvis et al., 2012; Saunders, 2000). This possibility of rebound exceeding 100% (“backfire”, or nett *growth* in emissions arising from efficiency measures) is strongly contested but it is notable that many of the studies rejecting large rebound effects, and global macroeconomic rebound in particular, are based on regional and short-term studies (as listed in Chakravarty et al., 2013; and in energy efficiency, Ryan and Campbell, 2012), as detailed in Herring and Roy (2007).

Table 4.1: Summary of three types of carbon lock-in and their key characteristics. Reproduced from (Seto et al., 2016).

Lock-in type	Key characteristics
Infrastructural and technological	■ Technological and economic forces lead to inertia ■ Long lead times, large investments, sunk costs, long-lived effects ■ Initial choices account for private but not social costs and benefits ■ Random, unintentional events affect final outcomes (e.g., QWERTY)
Institutional	■ Powerful economic, social, and political actors seek to reinforce status quo that favors their interests ■ Institutions are designed to stabilize and lock in ■ Beneficial and intended outcome for some actors ■ Not random chance but intentional choice (e.g., support for renewable energy in Germany)
Behavioral	■ Lock-in through individual decision making (e.g., psychological processes) ■ Single, calculated choices become a long string of noncalculated and self-reinforcing habits ■ Lock-in through social structure (e.g., norms and social processes) ■ Interrupting habits is difficult but possible (e.g., family size, thermostat setting)

[9] Holmes (1999, p. 3): “An investment can be defined as any act which involves the sacrifice of an immediate and certain consumption in exchange for an increase in future consumption.” Note that invested global wealth is continuously earning an income largely based on credit at interest offered to emission-generating activities so that investment earnings produce emissions, on average, at the global per dollar carbon intensity of GDP. In this global sense money and wealth perhaps act as a useful proxy for future emissions.

4.2.2.2.2 Physical Climate module description and limitations

Unlike the socioeconomic and damage modules used by economists, the general circulation models (GCMs), constructed by climate scientists using physical laws and equations to model the Earth's climate system, have been thoroughly tested and found to be skilful through hindcasting against recorded climate data (Cowtan et al., 2015), especially when natural variation is allowed for (Risbey et al., 2014). Though significant stochastic variability and structural uncertainties/unknowns remain, the proven skilfulness of climate change models, being based in physics, is considerably greater than economic models, which attempt to deal with socio-economic systems. Given a projected emissions pathway by a socioeconomic module, climate models give relatively high confidence projections of future temperature rise.

Nonetheless, the uncertainties in climate modelling are important. These are, predominantly, climate sensitivity, tipping points and, as part of climate sensitivity, the near-term ocean and land sink responses to continued global warming. For benefit-cost analysis, a crucial concern is the shape of the probability density function for climate sensitivity, particularly in the 'fat tail'[10] (Weitzman, 2009) of the distribution that may be associated with events with low (or unknown) probability but very high impact. These include catastrophic discontinuous damage to biosphere-level systems greatly increasing mitigation costs to insure against disasters that, *inter alia*, have the potential to undermine effective functioning of the global economy itself (Wagner and Zeckhauser, 2016). Freeman *et al.* (2015) find that even the apparent "good news" of the IPCC's revision of likely equilibrium climate sensitivity range from AR4's 2ºC-4.5ºC (best estimate 3ºC) to AR5's 1.5ºC-4.5ºC (with no best estimate given) is in fact "bad news" because the increased uncertainty regarding future societal well-being inevitably raises SC-CO_2 estimates.

Tipping points and tipping elements in Earth's climate system (Lenton et al., 2008) are often omitted from the behaviour of physical climate models, including the simplistic climate modules in IAMs, and are commonly mis-characterised (Kopp et al., 2016). Lenton and Ciscar (2013) show that there are multiple climate tipping points and elements that IAMs often misleadingly and simplistically assume are only "high impact – low probability". Current global emission trajectories are toward very significant global warming of 4ºC or more yet some tipping point thresholds will likely be passed at much lower levels of warming even before 2ºC, including the loss of Arctic sea-ice this century and the beginning of slow but irreversible ice sheet loss in Greenland and Antarctica. The tipping points and elements noted could all be defined as catastrophic changes yet the economic literature generally fails to recognise or distinguish them. Assessing the economic effects of crossing tipping points Lenton and Ciscar find that assessment of climate impacts need to look at dynamic effects over time.

[10] Technically, the tail of a probability density function is said to be 'fat' if it approaches zero more slowly than exponentially.

4.2.2.3 Damage module assumptions and limitations

Damage functions in BCA-IAMs relate the supposed average fractional loss in global output (equated to GDP) to the level of global warming. However, the extreme range of damage functions used in IAMs is indicative of the high uncertainty regarding damages. The IPCC assessment warns that the reliability of the damage functions in benefit-cost IAMs is low as they typically do not include up to date damage estimates, continuing instead to base damages on now obsolete emission pathway scenarios developed for AR4 (Ch. 3 IPCC AR5 WG3, 2014, p. 247). Wilson *et al.* dismiss the typically simplistic climate impact assumptions of BCA-IAMs referring to “the atheoretical and weakly empirical basis of 'damage functions' which parameterize the impacts of climate change on the economy” (Wilson et al., 2017, p. 17).

Introducing the “Dismal Theorem”, Weitzman (2009) shows that even the possible existence of a fat tail in the damage function distribution of plausible outcomes in the climate sensitivity probability density function and/or in damage function, exposes the global decision-maker in a BCA to potentially unlimited losses. Given that it is likely to be impossible to estimate or even constrain the probability of these global-level disastrous outcomes, the qualitative climate policy outcome of the Dismal Theorem, outweighing any effect of discount rate weighting, is for “a very strong form of a ‘generalized precautionary principle’”. This effectively suggests that, within the conventional framing of BCA, it would be worth paying an arbitrarily large fraction of current wealth for near-term radical decarbonisation measures to insure against such uncertain, but indefinitely large, negative outcomes. Weitzman suggests that giving a CBA estimate, including specific, supposedly “optimal”, SC-CO_2 values, is inherently misleading given the structural uncertainty involved in the climate response.

Detailed economic climate damage estimates such as Hsiang *et al.* (2017) giving spatial mapping of substantial economic impacts on different sectors (crop yield, crime rates, labour rates) for the USA if emissions follow an RCP8.5 (“business as usual”) emissions pathway on are now beginning to appear which, as Pizer (2017) comments, does offer the potential to greatly improve and refine damage functions used in modelling. However, the geographical scope of damages considered will need to be greatly increased to the global scale if confidence in the damage functions of global climate policy BCA IAMs is to be increased.

Large or increased uncertainty in the assessed probabilities for climate sensitivity or other parameters affecting climate impacts is frequently cited by as a reason to delay or reduce mitigation action (Dunlap and Jacques, 2013; Freudenburg and Muselli, 2013; Lahsen, 2013). However, to the contrary, for the escalating damages related to tipping points and ever greater impacts at higher warming, producing a so-called convex damage function (Dietz and Stern, 2015), it is mathematically the case that large or increased uncertainty in fact *increases* the expected damage costs of climate change (Lewandowsky et al., 2014b). This fact appears to be widely unappreciated by policy-makers and others who may be tempted to think otherwise or imply that doubt due to uncertainty is a reasonable argument for inaction (Hansson, 2017). For example, increased uncertainty about climate sensitivity results in increased anticipated damages and therefore an increased social cost of carbon from unmitigated climate pollution (Lewandowsky et al., 2014a); they summarise as follows:

> *Contrary to the claim by some researchers that uncertainty presents a barrier to scientifically-informed policy decisions* (Allenby and Sarewitz, 2011; Sarewitz, 2004)*, any appeal to scientific uncertainty actually implies a stronger, rather than weaker, need to cut greenhouse gas emissions than in the absence of uncertainty* (Allenby and Sarewitz, 2011, p. 14)*.*

Howard (2014), in a strongly-referenced report produced for US NGOs, lists omitted or poorly quantified damages in BCA-IAMs, providing detailed descriptions of the DICE, PAGE and FUND damage functions, and discusses ways to improve damage assessment in IAMs.

4.2.2.3.1 Discounting module assumptions and limitations

Two different types of discount rate need to be identified: the *welfare discount rate*, also known as the ‘rate of pure time preference’, a judgment weighting of the well-being of future generations relative to the present (though at this point current generations can also certainly anticipate significant damages within their own lifetimes); and the *goods discount rate* reflecting an average return on capital investment as “descriptively evidenced by capital market rates” (Nordhaus, 2017, p. 1520). The growth-corrected discount rate equals the discount rate on goods minus the growth rate on consumption. Dietz (2011), using the PAGE model, finds that BCA welfare and SC-CO_2 are indeed critically sensitive to the Dismal Theorem, fat tail effects outlined by Weitzman for climate sensitivity but discounting can be relevant to BCA values depending on exactly how fat the tail might be. Stern (2016) points out that models commonly assume future generations will be far wealthier, ignoring the potential for substantial climate damages, and also discount the future as less important than the present, contrary to most widely subscribed systems of human ethics (see discussions of values and well-being in 3.4 and sustainable development in 4.2.1, IPCC AR5 WG3, 2014).

In calculating the social cost of carbon the assumed aim is to maximise the present value of aggregated human well-being by minimising the sum of climate action costs and long climate pollution damages. This implies a utilitarian ethical philosophy of “the greatest good for the greatest number”, or at least the greatest “average good”, with “good” measured narrowly as total reported market transactions (GDP/GWP). The welfare discount rate of pure time preference used in the SC-CO_2 calculation to weight the value of future generations welfare relative to the present, is a source of strong disagreement among economists as to whether this should be relatively high, thereby greatly reducing the value placed on the wellbeing of future generations, as in the values as high as 3% typically used by Nordhaus in the DICE model, or very low as in the Stern Review, which used 0.1%. Ackerman (2007) provides a useful and clear guide to the controversy and technical details regarding discount rates used by Stern, Nordhaus and others in BCA.

Roser (2009) differentiates between genuine discounting as weighting of present versus future values, giving the time-preference of the current generation, and ‘non-genuine’ “discounting as representing opportunity cost”, which determines the *means* by which utility is transferred forward into the future. In the latter, there is no weighting of relative utility between generations, the discounting is just a calculation to decide between options on an investment basis. Roser's main point though (p. 15) is that policies, especially for multi-generational problems like climate change, should not be judged on the basis of the effects on long-term aggregate utility *at all*, thereby rejecting the entire utilitarian framework foundation of calculating a social cost of carbon. Instead, a deontological alternative, altogether avoiding a requirement to consider discount rates or *any* weighing of values, is proposed. By passing on a threshold amount of utility (in resources, stable climate, clean air etc.) to future generations there is no pressure to 'maximise' wellbeing, only to ensure sufficient utility for all future generations. Provide that threshold is met, then the present generation need not achieve more toward future well-being. On the other hand, if the current generation is not passing on such a threshold of sufficient resources then enabling even small increases in future utility mandates potentially very large near-term investments in future wellbeing. Roser's discussion, which is careful to show the nuances of the argument, usefully unpacks the philosophical and normative choices implicitly being made in climate economics; showing that such analyses are not simply "objective", empirical representations in mathematical frameworks, but are, in fact, deeply value-laden.

4.2.3 Cost-effectiveness Analysis CEA

Cost effectiveness models, such as the "process-based" IAMs produced for AR5 WG3 (Wilson et al., 2017) and energy systems modelling, aim to identify optimal and sub-optimal scenario pathways that stay within an inviolable emission reduction goal, such as the Paris temperature goals, that has been set by others (Koomey, 2013). CEA avoids the difficulties of damage estimating and discounting inherent in BCA models. Therefore, CEA concentrates effort on only the first two components of economic climate modelling: socioeconomic, to forecast emissions according to projected economic, technical and land use; and simple climate models to forecast a climate response to the emissions. CEA aims to calculate a "least cost" pathway of changes in the socio-economic-energy system through time to meet the particular imposed emissions pathway or overall target.

In CEA modelling, exceeding the externally (politically) specified 'safe' target is assumed to be unacceptable: in economic terms, the shadow price of exceedance is effectively deemed to be *infinite* (Ackerman et al., 2009, p. 312). A defined carbon budget target (such as "well below 2ºC") or emissions pathway is therefore a definite requirement to be met with certainty by the cost effectiveness methodology. An absolute goal is therefore properly regarded as a *feature* of CEA – rather than a "limitation" that fails to consider "economic efficiency", as an IPCC AR5 chapter executive summary incorrectly states (IPCC AR5 WG3, 2014, p. 154 Ch. 2). A major problem with asserting policy-relevance for CEA is the fact that if the political will and societal commitment to meet the declared goal or pathway does not exist or falters then the essential precondition of carrying out CEA (for public policy purposes) becomes void, except in stating that the (diverging) policy is, by definition, *not* cost-effective. This in itself is a highly policy-relevant difficulty that may be too easily left unreported or unstated by the research community. Logically, where declared international or government policy claims a cost-effectiveness focus yet past cost-effectiveness advice has not translated into corresponding policy, as continues to be the case with many CEA-IAM recommendations, then the assumed policy relevance of CEA becomes questionable. This is a key assumption for cost-effectiveness: if current policies are not aligned with meeting a target then they cannot properly claim to be acting cost-effectively[11].

Usually the core socioeconomic modelling approach in CEA modelling is process-based (Wilson et al., 2017), involving a 'bottom-up' approach based on large and detailed database of processes, technologies and energy supplies, driven by (often) exogenous[12] macroeconomic assumptions about future development pathways and costs. Typically, these top down macroeconomic functions use neoclassical general or partial equilibrium growth models to provide base economic growth rates and likely total energy requirement values used in CEA to interact with the bottom-up technical processes to give large-scale global or regional modelling of notional "optimally cost effective" (relative to the model inputs, structure and parameters) transformation pathways.

4.3 Integrated assessment models in IPCC AR5 analysis of climate mitigation pathways

4.3.1 Development of IPCC modelling up to AR4

As detailed at length by the IPCC assessment (IPCC AR5 WG3, 2014 Ch. 6) global warming outcomes resulting from differing transformation pathways are being explored by research teams around the world. Computer models, 'process-based integrated assessment models', incorporate a socioeconomic module, outputting a GHG emissions profile from projected energy and land-use systems over time (commonly up to 2100), and a climate system module, outputting the correlated near- and long-term Earth system response (in terms of temperature and atmospheric GHG concentrations) to the anthropogenic emissions. Climate and mitigation modelling around the world requires commonly defined scenarios –

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[11] For example, Ireland's Climate Action Act requires the Government to have regard to "likely future mitigation commitments of the State and the economic imperative for early and cost-effective action" (Oireachtas, 2015, Article 4 (7.a.ii)). The Climate Change Advisory Council is also given a remit to make recommendations it "considers necessary or appropriate, in relation to the most cost-effective manner of achieving" a low carbon transition (Oireachtas, 2015, Article 4 (7.a.ii)). Given the strict requirement of cost-effectiveness to meet a target, now expressly articulated (via the Paris Agreement) as aligning mitigation action with "well below 2ºC", a consistent economic interpretation of these injunctions would be to ascribe an infinite cost to failure in order to judge the relative cost-effectiveness only of alternative policies that *all prudently satisfy this target*.

[12] Exogenous model assumptions and parameters cannot be changed by modelling outputs, such as damage cost, whereas endogenous ones can be so affected.

alternative sets of baseline emissions assumptions, initial conditions and target emission pathways – to enable intercomparison for cross-checking of results and verification. Shared scenario modelling also allows researchers from different (physical/biological science and social science) backgrounds to coordinate work in producing new mitigation options toward climate stabilisation goals. The collected results of the scenario modelling, are available online (IIASA, 2014).

Moss *et al.* (2010 see Fig. 1) details the development of physical climate modelling from Arrhenius' estimates of warming in 1896, through to the first General (atmospheric) Circulation Model (GCM) in 1969 and the development of resource scenario modelling in the 1970s (becoming mainstream in futures modelling in the 1980s and later socio-economic modelling). The first strong GCM indications in the 1970s and 1980s that warming would soon be discernible from background natural variation are noted, and then Moss gives an overview of the development of IPCC modelling scenarios.

The first generation of IPCC scenarios was called IS92, produced with the First Assessment Report in 1992. The third and fourth Assessment Reports (TAR and AR4) used a second group of scenarios abbreviated as SRES, from the Special Report on Emissions Scenarios, which are still being used in the socio-economic module of BCA-IAM models such as DICE and PAGE. However, neither the I92 nor the SRES scenarios included climate change mitigation or adaptation measures. The qualitative I92 scenarios outlined possible warming outcomes across the range of uncertainties in consumption growth, technology and population along different economy-energy pathways. The SRES generation of scenarios provided quantitative pathways of plausible GHG and SLCP (Short Lived Climate Pollutant) emissions related to narrative storylines sketching out associated future fossil fuel use, deforestation and degree of economic convergence in global development (Moss et al., 2010, pp. 749–750).

4.3.2 Scenario development for AR5

Up to AR4, modelling was primarily sequential, proceeding from socioeconomic emission projections to climate response and then to impact modelling, with no feedbacks between these major components. However, following an expert meeting in 2007, a new, parallel approach was decided on, by first building a small set of new "benchmark emissions scenarios" called "Representative Concentration Pathways", RCPs (IPCC, 2008; Figs. 3 & 4 in Moss et al., 2010). This simplification increases the speed and reduce the cost of computation and so expands the computing time available to model complex feedbacks between parallel socio-economic, climate and impact processes, and to carry out repeated runs meeting only a limited set of RCP outcomes.

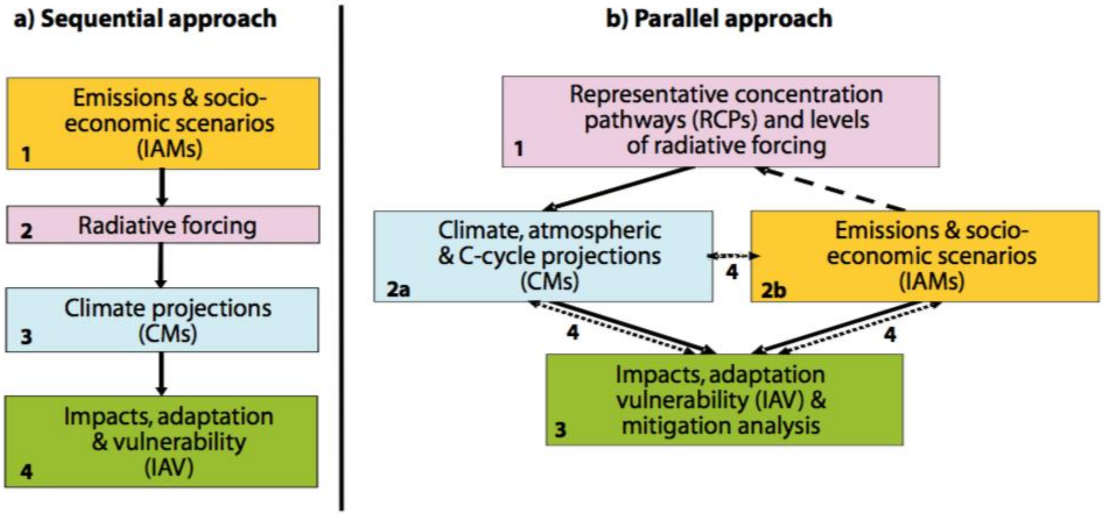

Figure 4.3: Approaches to the development of global scenarios: (a) earlier sequential approach; (b) proposed parallel approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Arrows indicate transfers of information (solid), selection of RCPs. Reproduced from IPCC (2008)

Each of the four RCPs defines an emission trajectory constrained by a stated combination of radiative forcing (RF) and atmospheric GHG concentrations by 2100 that are not dependent on the output of the socioeconomic module. By providing shared initial datasets of radiative forcing pathways to both climate modellers and socio-economic IAM process modellers can work simultaneously on model experiments and model revisions, as shown in Figure 4.3, enabling many more alternatives of socioeconomic scenarios to be undertaken to explore alternative solution pathways that can interact with a parallel physical climate model, producing ensemble projections, combining to enable integrated assessments (see simplified guide to RCPs by Wayne, 2014). Moss *et al.* (2010) summarises the RF, CO_2e concentration and pathway description of the four RCPs (Table 4.2).

Table 4.2: The four Representative Concentration Pathways (RCPs) adopted as a basis for IAM scenario modelling from Moss et al. (2010), Table 1).

Name	Radiative forcing	Concentration (p.p.m.)	Pathway	Model providing RCP*	Reference
RCP8.5	>8.5 W m^{-2} in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE	55,56
RCP6.0	~6 W m^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM	57,58
RCP4.5	~4.5 W m^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM	48,59
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE	60,61

* MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.

Rogelj *et al.* (2012) use historical constraints and temperature projections to compare the outputs from older SRES and the newer RCP climate projections in relation to the likelihood of reaching different levels of equilibrium warming. Table 4.3 reproduces a brief summary of the comparison.

Table 4.3 Comparing newer RCPs with older SRES scenarios. Reproduced from Table 3 in (Rogelj et al., 2012).

RCP	SRES scenario with similar median temperature increase by 2100	Particular differences
RCP3-PD	None	The ratio between temperature increase and net radiative forcing in 2100 is 0.88 °C $(W\ m^{-2})^{-1}$ for RCP3-PD, whereas all other scenarios show a ratio of about 0.62 °C $(W\ m^{-2})^{-1}$; that is, RCP3-PD is closer to equilibrium in 2100 than the other scenarios.
RCP4.5	SRES B1	Median temperatures in RCP4.5 rise faster than in SRES B1 until mid-century, and slower afterwards.
RCP6	SRES B2	Median temperatures in RCP6 rise faster than in SRES B2 during the three decades between 2060 and 2090, and slower during other periods of the twenty-first century.
RCP8.5	SRES A1FI	Median temperatures in RCP8.5 rise slower than in SRES A1FI during the period between 2035 and 2080, and faster during other periods of the twenty-first century.

Following development of the RCPs a second phase of scenario development by earth system modellers (modelling both the physical climate system and the carbon cycle including land use) produced ensemble model runs consistent with the RCPs. In a third phase, an expert workshop in 2010 produced a report developing a narrative framework of Shared Socioeconomic Pathways (SSPs), each SSP having a descriptive storyline and a group of quantified criteria defining the overall type and direction of society. Each narrative is assumed to be independent of climate change projections to enable assessment in conjunction with climate module outputs to illuminate relationships between two key policy dimensions of mitigation and adaptation (IPCC, 2012, pp. 1–2). Ebi *et al.* (2014) outlines the concepts underlying the SSPs, Kriegler, *et al.* (2012) discusses the need for and use of the SSPs, and O'Neill, *et al.* (2017) gives full details on the most recent iteration of SSPs. As shown in Figure 4.4, the five SSP narratives are top-down qualitative descriptions of different, quantitatively described, parameter combinations of system inertia and societal choices to be used in different models to give policy pathways. These give more realistic 'second-best' projections based on socio- and political- economic alternatives, to avoid focusing only on idealised bottom-up projections that ignore infrastructural carbon lock-in and path-dependent agent behaviour among vested interests and energy consumers.

Figure 4.4: Narratives for shared socioeconomic pathways describing world futures in the 21st century O'Neill et al. *2017*

4.3.3 Summary of AR5 Database scenarios

As summarised in Annex II of IPCC WG3, the AR5 Scenario Database contains the data output from 1,184 scenario runs from 31 process-based CEA-IAMs spanning a wide range of temperature and atmCO_2 outcomes to 2050 and 2100. A full assessment and explanation of the transformation pathways shown by the Database modelling is given in Chapter 6 of AR5 WG3, with a section specifically covering carbon dioxide removal (Section 6.9.1 in IPCC AR5 WG3, 2014).

The socioeconomic modules mostly have general or partial equilibrium economic coverage and feedback, the climate module may be lacking altogether or be restricted to temperature change (land use may also be included), and there are varied cost measures providing feedback for energy system costs, consumption loss, GDP loss or welfare loss.

Many mitigation cost metrics, each with uses and limitations, are used in the economic analysis in models (Krey et al., 2014b, pp. 1291–1293), see also IPCC (Section 6.3.6 in 2014). *Emissions price*, the marginal cost of reducing emissions by one unit (generally tCO_2, or per tCO_2e using GWP-100 equivalence factors), is commonly measured by models but these are not actual costs, which comprise all measures achieved at costs lower than the emissions price. The emissions price given may be underestimated because of other policy measures effectively subsidising mitigation. Discount rates approximating long-run, capital market interest rates (commonly 4%-6%) are used in the AR5 models but they only change the timing and speed of mitigation in achieving a set target (which must be met), unlike discounting in BCA-IAMs that can strongly affect the stringency of mitigation action. Similarly to BCA-IAM discounting though, larger discount rate values in cost-effectiveness modelling increases apparent near-term mitigation costs relative to (the notional present value of) future mitigation costs. This has the tacit effect that, for notionally "cost optimal" action, progressively more effort is deferred as far as possible into the future.

Two strong (and contested) assumptions underpin the comparability of mitigation cost estimations in the AR5 Scenario Database models (Annex II 2014, pp. 1291–1292). First, a uniform price of carbon is globally applied by a stated date and then steadily increased thereafter in line with increases in calculated marginal emission reduction costs. Second, global markets are idealistically assumed to be efficient without lock-in effects or other market failures. The scenario studies consistently show that total global costs of mitigation rise with passing time and with more stringent (lower atmCO_2) targets. Carbon costs also rise if these parameters are adjusted to allow non-uniform carbon pricing and inefficient global markets. Low global consumption loss estimates are given by the AR5 model scenarios reaching 430-480 ppm CO_2e equating to only a 0.06% annual reduction in GDP output averaged to 2100 compared to baseline growth of 2% yr^{-1} (IPCC, 2014, p. Fig. SPM.13 AR5 Synthesis Report). However, given the real-world lock-ins preventing high and uniform carbon prices, imperfect markets, and political barriers to equity transfers to ensure distributional economic fairness, these are likely to be significant underestimates. Trainer (2017) is strongly critical of the AR5 costings, finding that renewable energy sector costs to meet strong emission targets are likely to be far higher than assumed suggesting that consumption losses would be greater and implying a need for much reduced global energy consumption to reduce emissions, consistently with the given emissions pathways.

In a “first comprehensive analysis” to evaluate the process-based IAMs, as used in the modelling and scenarios in the AR5 Database, Wilson *et al.* (2017) describe a framework based on climate model evaluation to assess their adequacy based on five criteria: *appropriateness* of purpose and design to application; *interpretability* in simplicity of analysis and communication of output; verifiability of model code by third-party review; *credibility* judged by user confidence in quality of output; and, *usefulness* in giving full ranges of policy options and implementation challenges. Unlike the relative structural constancy between past and future in the Earth’s climate system, the socioeconomic processes represented in IAMs can be structurally inconstant with dynamic and uncertain baselines (Scher and Koomey, 2011). Wilson *et al.* (2017) briefly notes studies of process-based IAMs in historical simulations and examples of tests of generalisable historical patterns for economic growth and technology diffusion are given (p. 18-23). Inter-comparison studies of the CEA-IAMs (see Table A.II.15 in Krey et al., 2014b Table A.II.14) are increasingly focusing on second-best and effort-sharing outcomes. However, it is clear from this study that detailed IAM intercomparison and hindcast testing is lacking, model complexity may be high requiring detailed sensitivity analysis to determine drivers of changes (Koelbl et al., 2014), and, notwithstanding their technical detail, there are significant limits to their predictive power due to socio-political and financial dynamics.

4.3.4 AR5 Database scenarios meeting Paris temperature goals in 2100 with or without NETs

As discussed in detail in *Assessing Transformation Pathways*, Chapter 6 of IPCC AR5 WG3 (2014), the AR5 Scenario Database (IIASA, 2014) stores the output from 31 CEA-IAM models and 1,184 scenarios most of which were generated in nine intercomparison exercises. Of these scenarios, only 116 limit atmospheric concentration to 430-480 ppm CO_2e, equivalent to 2.5-3.1 W m^{-2} radiative forcing, by 2100 (see Fig. 6.32 IPCC AR5 WG3, 2014) – corresponding to limiting to 2ºC with 66% likelihood. Of the 76 lowest CO_2 trajectories, as discussed by Anderson and Peters (2016 see note 16) only 2 scenarios have no negative emissions, 71 have above zero and up to 20 $GtCO_2$ yr^{-1}, and 3 reach more than 20 $GtCO_2$ yr^{-1}. Sorting these 76 for 'Radiative Forcing Overshoot', 13 do not overshoot, 25 overshoot by <0.4W/m^2, and 38 overshoot by >0.4W/m^2.

A further 40 scenarios reach the same atmCO_2 threshold but by more challenging pathways, following a baseline path and then imposing a uniform and increasing global carbon price from 2020 (24 scenarios) or after 2030 (16 scenarios) to drive cost-effective mitigation from those points onward (Peters, 2016). In Annex II, as shown in Table A.II.16 (Krey et al., 2014b), the scenarios for use in the AR5 WG3 report are characterised by: *climate target* (determined by 2100 CO_2e concentrations and radiative forcing or carbon budgets); *global carbon budget* up to 2050 and 2100; *overshoot* of 2100 CO_2e concentration or radiative forcing levels; scale of deployment of carbon dioxide removal or *net negative emissions* (see Figure A.II.9 in Krey, Masera, *et al.* 2014); and, *policy configuration*, such as immediate mitigation, delayed mitigation, or fragmented participation by countries.

The two scenario runs that have no negative emissions (both from the *Phoenix 2012.4* model) have already proven to be highly unrealistic. Each show a large drop in global fossil fuel emissions between 2010 and 2020 (~35 percentage points relative to peak), modest further reduction between 2020 and 2070 (~15 percentage points relative to peak) and then abrupt elimination between 2070 and 2080 (~50 percentage points relative to peak) (see Figure 4.5). While the specific pathway details could presumably be varied somewhat, these serve to illustrate the very high rates of mitigation implied by a "well below 2ºC" limit if negative emissions are excluded.

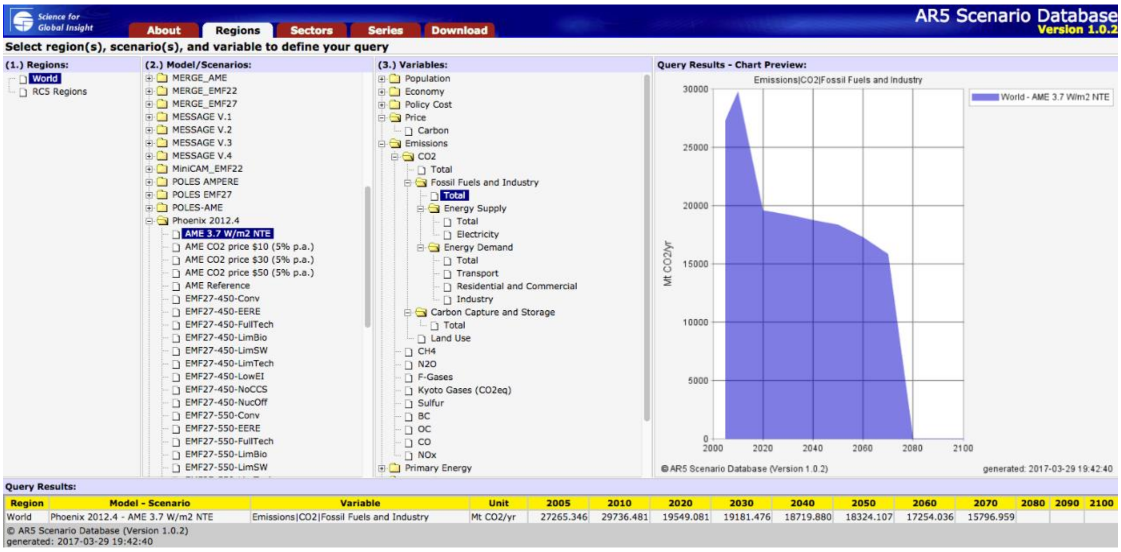

Figure 4.5: A screenshot of Phoenix 2012.4 scenario output from the AR5 Scenario Database (for illustration only)

In Figure 4.6, atmCO_2 trajectories are shown as generated for 2010-2100 from data in the AR5 Database for the 116 scenarios minimising atmCO_2 in 2100, showing that many of them are relying on technological carbon dioxide removal to reduce CO_2 levels rapidly after peaking. Given that atmCO_2 is already (in 2017) at ~406ppm (monthly average, seasonally adjusted), it is notable that some trajectories peak somewhere below ~410ppm, but some overshoot to above 450 ppm.

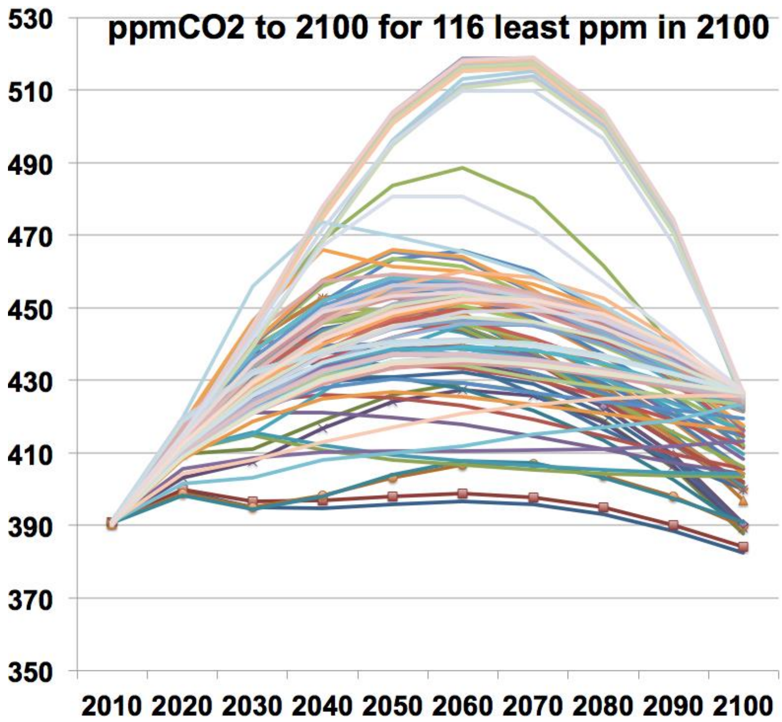

Figure 4.6: Atmospheric CO_2 AR5 Database pathways ranging from no overshoot to large overshoot for the 116 scenario runs with the lowest atmCO_2 in 2100. Chart generated with data from IIASA (2014).

4.4 Other approaches to climate change mitigation and energy system modelling

Given the BCA and CEA limitations noted above this section describes alternative efforts to extend these model-types or develop alternatives, whether complex models or simplified calculations.

4.4.1 Economic and energy decarbonisation pathway modelling extended to include equity and policy landscape criteria

Ackerman *et al.* (2013) outlines CRED (Climate and Regional Economics of Development), an economic climate mitigation model that includes global equity criteria, optimises interregional resource flows and estimates mitigation costs (not damages) using empirically derived marginal abatement cost curves (MACCs) which are exogenous to the model. Optimal climate policy output in this model – pooling all savings globally, balancing consumption and abatement equitably among nations – results in effective mitigation but very large, income-lowering capital transfers from rich nations to developing ones enabling them to avoid (or "leapfrog") carbon intensive development. Constraining pooling of savings to 10% or 0% enables climate stabilisation if the time preference discount rate is very low (as per the Stern Review's 0.1%) but with a higher discount rate (1.5% as per Nordhaus) climate stabilisation is not achieved without considerable equitable transfers and pooled savings.

4.4.2 Target-consistent carbon pricing

The social cost of carbon gives an estimate of the present value of future human welfare benefits resulting from avoiding emitting an additional tonne of CO_2. As an alternative approach Barbier and Burgess (2017) use standard economic depreciation accounting methods to model the AR5, "greater than 66% chance of less than 2ºC" global carbon quota (1010 $GtCO_2$ from 2010), as a non-renewable asset in order to calculate the *user cost* for different emissions scenarios. The 'resource' is assumed to be completely exhausted by constant subtractions in a finite time, and constant unit total rents are gained from extraction and production usage. World interest rates determine global capital allocation. In a BAU economic scenario of global emissions growing by 2% yr^{-1} the quota is exhausted by 2028 at a cumulative global social cost of US$26 trillion dollars (equivalent to roughly half of world annual GDP). Constraining emissions at current levels (no emissions growth) extends the budget only to 2031 at a user cost of US$23 trillion. Reducing emissions at 2.6% yr^{-1} extends the budget to 2040. Increasing the emissions mitigation (reduction) rate to 5% yr^{-1} fully avoids exceeding the 66% / 2ºC quota (i.e. with no abrupt exhaustion year "cliff"), with (by definition) a user cost of zero. This "radical emission reduction" pathway is therefore effectively valued at a US$26 trillion dollars benefit (by 2028) relative to the BAU pathway. This model is target specific, unlike BCA-IAMs, in respecting a 2ºC global carbon quota. It uses basic economic tools and shows that, according to its specific economic criteria, and even without reference to climate damage, strong mitigation policy is adjudged as highly economically beneficial.

It should be noted that the underlying "counterfactual" scenarios here assumes that, if the specified "hard" carbon quota is exhausted, emissions would then be forced to halt abruptly, regardless of the (then) economic consequences. While this is clearly socio-politically implausible, it arguably represents a correct "rational" assessment of the appropriate trade-off against the uncertain, but unbounded, economic costs that would be potentially associated with exceeding the quota. Accepting the politically agreed "well below 2ºC target as a hard limit is also a crucial assumption in the 116 "cost effective" scenarios from the CEA-IAM AR5 Scenario Database that meet the "well below 2ºC" radiative forcing level by 2100. Of course, the tacit implication is that the Barbier and Burgess "optimal", "well below 2ºC", scenario may well imply overall economic contraction (economic "degrowth") in the short-term to invest in demand reduction and energy supply decarbonisation; but that, even if so, such "loss" also would be outweighed by the unbounded loss associated with exceeding the quota.

These are essential distinctions from the "orthodox" BCA-IAM climate economics modelling which, even while allowing for climate "damages" arising from exceeding any given quota (often allowing eventual warming well above 2ºC), still ensures (via non-zero discount rate) that damage estimates are necessarily finite (bounded). Likewise, CEA-IAM modelling for pathways exceeding "well below 2ºC" could be considered policy-*irrelevant* because, at Paris, nations have accepted that their climate policy actions *will be* in accord with respecting this temperature goal. Therefore, if nations are not following technology and fuel mix advice from near-term CEA-IAM optimal pathways for "well below 2ºC" scenarios then they are not acting cost-effectively, such that the modelling is effectively being ignored and is arguably of limited policy value.

4.5 Energy system modelling

4.5.1 Energy system models: types and uses

Després *et al.* (2015) provide a useful typology of the many IAM, energy system, economy-energy-environment and power (electricity) sector modelling tools in common use worldwide to assess system changes over time. The overall projection period can extend to many decades, as needed in assessing energy system CO_2 emissions, or be much shorter as for electricity generation and grid analysis where time steps on the order of a second are needed to assess dynamic grid stability. Individual time step length is determined by the analysis period length, computing time needed per time step and the number of repeat runs with varied initial conditions to produce a sufficient ensemble of model runs. Simulation models start from initial conditions, which can be adjusted for each new run, and then the model results of the time step become the input for the next time step; the whole run then shows the system evolution and ensembles of many runs show the sensitivity to initial conditions. Following a different computational logic, optimisation models attempt to optimise for particular criteria at each time step and toward a particular target.

Energy System Models (ESMs) aim to give a detailed representation of energy system processes and development, and energy sources to attempt to identify cost-effective decarbonisation pathways given imposed constraints, such as an emissions pathway to an end-date or cumulative emissions target, or reaching 100% renewable electricity or energy. "Top-down" energy system models may be devised at global, regional or national levels. They are typically driven by exogenous final demand projections, potentially including changes in end-use efficiency. They may qualify the relationship between primary and final demand to reflect changes in transformation efficiency. They sometimes include behavioural factors such as the elasticity of substitution among technologies, meaning how exchangeable they might be. This will then depend on the degree of system inertia due to resistance from vested interests, infrastructure lock-in or consumer preferences (Martinsen, 2011, p. 3328). Bottom-up models aim to optimise energy system balance (particularly electricity given the variability of non-biomass renewable energy) through time to plan and facilitate cost-optimised decarbonisation pathways (Martinsen 2011). The technology, carbon intensity and energy parameters usually rely on empirically derived 'experience curves', also known as technology learning curves. Modules in a model are referred to as "soft-linked" if the user transfers information between them after each iteration, or "hard-linked" if the feedback of data between them is automated (Martinsen 2011).

In a review of the feasibility implications of energy decarbonisation scenario modelling Loftus *et al.* (2015) provide a simplified classification of four general approaches to energy system assessment (though many approaches are hybrids) as follows:

- *Top–down, scenario-based back-casting methods*: starting with a final target these methods choose from a preselected set of low-carbon technologies (often preferentially excluding some options entirely) to produce scenarios that meet the target. For example, Jacobson, & Delucchi (and Delucchi and Jacobson, 2011; 2011) only include wind, water and solar and exclude nuclear and biomass energy and CCS.
- *Top–down integrated assessment energy system modelling,* here confining the IAM term to economy-energy-environment (EEE) modelling focused on energy supply and demand scenarios. Linked modules identify energy technology process evolution that is achieved at 'least cost' given the cost-effectiveness limits set for the model. Constraining models by excluding or limiting some options allows the relative costs and feasibility of options to be explored.
- *Bottom–up energy systems modelling*: often highly detailed, technology-rich, models with pre-set economic and total energy use pathways that are then required to meet a decarbonisation pathway using the technology learning curves and costs inputs for the available technologies and alternative energy mixes and fuel costs. The IEA-developed MARKAL and TIMES models are examples of this approach that are often combined with a hard- or soft-linked economic model for regional or national use as in the IrishTIMES model (see further discussion in Ch. 7).
- *Bottom-up technical or techno-economic assessments*: ESMs based on rankings such as abatement potential and cos, as used by McKinsey (Nauclér and Enkvist, 2009) in producing marginal abatement cost curves (MACCs), or including non-economic criteria, as used by the World Wildlife Fund (WWF, 2007), to develop a decarbonisation scenario based on actions in order of these rankings.

‘Hybrid modelling’ incorporates both top down and bottom up elements as in many applications of TIMES and MARKAL that integrate with a top-down economic model. At the global scale, the International Energy Agency (IEA) uses a large scale simulation, the World Energy Model, to produce its annual World Energy Outlook, and a top-down sectoral analysis called Energy Technology Perspectives, based on four soft-linked models for energy conversion, industry, transport and buildings (Chiodi et al., 2015b; IEA, 2016). The TIMES energy conversion model generator and the MARKAL model it was derived from, are used across 70 countries to produce technology-rich models of multi-regional, national and local energy systems (Chiodi et al., 2015b, p. 5). These Energy Technology System Program Analysis (ETSAP) models conserve energy flows from supply through to consumption, using an economic optimising model to find least “notional-cost” solutions through time within environmental and technical constraints, based on a large database of technologies using technology-specific cost assumptions through time for investment, operations and maintenance, fuel and asset costs. Bottom-up, energy system models such as MARKAL/TIMES aim to give a sufficiently accurate representation of technologies and cost interactions over time to inform energy mix and climate policy choices aimed at achieving long term pathways over decades into the future (Chiodi, Giannakidis, *et al.* 2015). Optimal, notional least-cost pathways assume “first best” choices of fuels and technologies solely based on their model-derived least-cost at a particular time step or over a period but can be constrained to give second-best pathways and to show sensitivity to choices.

While output from this modelling is typically described as providing “least cost” solution pathways to given energy system transformation constraints, it is important to emphasise that this is relative only to a database of specific cost *estimates*. These estimates have diverse degrees of empirical foundation and uncertainty, and these uncertainties are then generally compounded (amplified) by the application of diverse, uncertain hypotheses regarding their evolution over time. These cost projections typically have to extend many decades into the future. Accordingly, we here use the term “notional-cost” to mark these intrinsic methodological qualifications.

Apart from uncertainties in the assumptions for technology-specific development, other technical limitations of MARKAL/TIMES modelling are in the time resolution of the model and in relation to power system operations and planning. Computationally it is difficult to evaluate small time increments in long-term modelling. In the particular case of electricity systems, technical operation ultimately requires energy balance on high resolution time scales (sub-minute) with significant spatial constraints (reflecting spatially distributed supply and demand, interacting with constrained transmission and distribution capacities). Accordingly, identifying feasible electricity system transformation pathways potentially requires specialised modelling at high resolution in time and space (so-called “grid integration studies”), especially if large amounts of variable/intermittent renewable energy production is introduced to the system. ESMs focus on direct sectoral emissions, and can often omit or incorrectly allocate indirect emissions, particularly from fossil fuel imports, that – in a UK example analysed through input-output carbon modelling – potentially double the marginal abatement cost of energy supply mitigation (Daly et al., 2015).

Additional serious non-technical limitations of energy system models arise from political, economic and socio-cultural factors embedded in the macro-economic assumptions and 'policy landscape' that are exogenous to the modelling. The output of ESMs is often tied to the exogenous macro-economic assumptions being made and these energy systems model outputs provide only very limited interactions with the macro-economy inputs. For example, the (exogenous) pathways of economic growth, regulatory costs, and total energy use often rely on economic models with their own limitations. In terms of climate justice, the focus on 'least-cost' (even if only uncertain "notional-cost") elicits the question: 'least cost for whom?' – Just those in a particular place at the current time, or including costs to others elsewhere or future generations? Or, even within some specific time and place envelope, least-cost for which societal actors (individuals, social classes, businesses, the state etc.)? Similarly, the 'second-best' policy reality of carbon lock-ins that could increase costs and decrease the feasibility of meeting stringent decarbonisation targets are not well represented in bottom-up ESMs, suggesting practical trade-offs are required between model efficacy and confidence (Strachan and Usher, 2012).

4.5.2 Multi-Level Perspective Models

Energy system models usually make 'first best' assumptions including uniform carbon pricing and rational, cost optimal decision-making in a context of perfect information and low policy and actor landscape inertia. Geels develops a 'Multi-Level Perspective' (MLP) to address lock-ins and a theory of socio-technical transitions (Geels, 2010; 2014) in which niche technologies can be supported and rapidly grown, in the face of lock-ins, if supported by groups of powerful actors (Li and Strachan, 2016 see Section 1.2 for summary of MLP approach in sec). In research "inspired" by the MLP and developed from previous work (Li et al., 2015), Li and Strachan (2016) use BLUE, a new model featuring both multiple actors and alternative policy landscapes, to look at the example of the UK energy system across power, heat and transport sectors. They conclude that 'second-best', carbon lock-in conditions of policy landscape and actor inertia can greatly delay and obstruct decarbonisation efforts. In simplified terms, the model scenarios characterise inertia from high to low on 2-axes: policy landscape on the basis of increasing CO_2 tax level and lifestyle (using increasing public and cycle/pedestrian modes of transport); and sensitivity to carbon pricing from small with individual decisions dominating, to large scale social planning to optimise societal costs and benefits (Li and Strachan 2016). The scenario outputs indicate that achieving a 50% decarbonisation relative to 1990 is a severe challenge even in the lowest inertia scenario. Deeper transformation requires combinations of (hypothetically) far cheaper low carbon energy, much higher carbon taxes and/or radical reductions in energy use with associated lifestyle change.

4.6 Modelling low carbon transition in energy systems

4.6.1 Low-carbon transition energy planning

A general assessment of the overall drivers and trends of global energy demand and supply (including electricity generation) is given in IPCC AR5 WG3 Ch. 5.3.4 (2014) with other key sectors briefly summarised in 5.3.5. Global per capita energy use increased by 31% from 1971 to 2010, with higher increases of 60 to 200% in developing regions though these regions still on average have less than half the 1970 per capita energy use of the more developed 'economies in transition' and OECD nations. Global decarbonisation rates over this period were only 0.3% yr^{-1}, six times lower than required to cancel out the 2% annual increase in energy use (IPCC 2014 AR5 WG3 Ch.4). Almost all IPCC-assessed scenarios project increasing global energy requirements that exceed improvements in energy efficiency, making absolute decarbonisation of energy essential to meeting the modelled energy requirements (IPCC 2014 AR5 WG3 Ch.4). The assessment states: "The relationship between economic growth and energy use is complicated and variable over time", yet Figure 5.7 shows world GDP/capita to be very highly correlated with fossil fuel combustion. Given this strong relationship, the evident possibility for serious mitigation policy that average energy use might therefore need to fall and total economic growth may need to level out or drop in some managed way ("degrowth") until decarbonised energy supply catches up with demand (with serious distributional implications) is outlined by Anderson and Bows (2012) but is not mentioned in this part of the IPCC assessment.

Current and projected global energy supply and its decarbonisation are assessed in detail in IPCC AR5 WG3 (2014) Chapter 7 and energy demand (consumption) sectors are discussed in Chapters 8 to 11 on industry, transport, buildings, agriculture and forestry. For overall context, Chapter 5, Figure 5.1 summarises global annual GHG emissions for 1970 to 2010. This shows that the energy supply sector (including extraction, fuel transportation and electricity generation) nearly tripled emissions from 6 $GtCO_2$ to 17 $GtCO_2$, transport emissions more than doubled from 2.8 $GtCO_2$ to nearly 7 $GtCO_2$, heat energy emissions for buildings grew from 2.5 $GtCO_2$ to 3.2 $GtCO_2$, and waste emissions almost doubled from 0.7 $GtCO_2$ to 1.4 $GtCO_2$. Industrial emissions rose only slowly from 5.4 $GtCO_2$ to 6.0 $GtCO_2$ (11%) between 1970 and 2000, but then grew dramatically by a further 46% to 8.8 $GtCO_2$ by 2010 as a result of globalisation including a very rapid growth in carbon intensive exports from middle income countries, especially China.

The low emissions pathways assessed as most cost-effective in energy emissions mitigation rely on a wide portfolio of options including energy efficiency improvements and transition to low-CO_2 energy: non-bioenergy renewables (hydro, wind, solar, tidal, wave etc.), nuclear power, fossil fuel with CCS and bioenergy with and without CCS (Sections 7.5, 7.8.1, 7.11

and Figure 7.7 giving comparison of lifecycle emissions and levelised cost of electricity[13]. The assessment summary (p. 516) sees reductions in the carbon intensity of energy supply as key in most low global atmCO_2 transformation pathways with nuclear, renewable energy and fossil fuel with CCS rising to 80% share of global primary energy in electricity generation specifically by 2050, and eliminating all unabated (without CCS) fossil fuel electricity generation by 2100. As noted above though in Section 4.4, most low atmCO_2 IPCC transformation pathways currently assume large amounts of BECCS by 2050 and even more by 2100 to enable even FFCCS use to continue to 2100, despite the major risks of, and challenges to BECCS development that is still in its early stages (see Sections 7.5.5, 7.9, 11.13 in IPCC AR5 WG3, 2014).

Edenhofer *et al.* (2013) survey the economics of renewable energy, reviewing the public policy perspective of social objectives justifying renewables, the market failures inhibiting optimal deployment, and policies to address these failures. This study includes both bioenergy and wind-wave-solar as renewables even though the carbon neutrality and benefits of bioenergy depends on sustainability criteria (Edenhofer *et al.* (2013). Decision-making in planning low-carbon transition energy systems needs to consider economic, technical, societal and environmental concerns as well as meeting a carbon budgeted emission pathway within least (estimated) cost. In 183 studies classified by Strantzali and Aravossis (2016), a variety of decision support methods have been described including, *life cycle analysis* (LCA) of impacts, *benefit cost analysis* (BCA) to evaluate the private and external costs, *multi-criterion decision-making analysis* (MCDA) that enables the inclusion of factors that are not easily monetised, and *outranking methods* that allow a ranking of alternatives that are otherwise not comparable.

All the methods have drawbacks and although LCA and BCA are found to be most common, the inherently multi-criteria nature of the low carbon transition suggests that MCDA should be used in addition to LCA and BCA to address the full range of issues. Abdmouleh *et al.* (2015) gives a review of regulatory framework mechanisms being used globally in policies to advance renewable energy share (including biomass), identifying successes and failures to enable improved energy policy-making. Funding sources, subsidies and feed-in tariffs, electricity pricing and tendering, taxes and tax breaks, legal frameworks, renewable portfolio standards, regulation of grid access, support for renewable energy technology and socio-political support are all discussed. The difficulty of incorporating many smaller, decentralised, intermittent renewable electricity generators into a grid developed for centralised electricity generation is identified as a primary barrier. Demand side management (energy conservation, efficiency and storage) and smart grids are ways to

[13] The 'levelised cost of energy' LCOE is used to compare energy supply technologies in terms of a long-run cost per energy unit average including a discount rate. An LCOE background, formula, simplifications and is given in the IPCC AR5 WG3 Annex II

reduce the high cost of relying on new infrastructure to integrate renewables into electricity systems.

Renewable energy resources have large theoretical potential to replace fossil fuels but the short-term potential and enabling technologies are critical to decarbonisation prospects (see Ellabban et al., 2014 giving a survey of renewable energy sources and outlooks). Kempener, *et al.* (2015) compares IEA-ETSAP energy system models across 26 countries using the REmap modelling tool developed as part of a global renewable energy roadmap to examine national renewable energy potentials. The REmap tool is found to be useful for policy-makers in overview comparisons between nations and for scoping renewables options, but does it not include the detailed analysis of trade-offs between technologies, lock-ins and pathways that are accounted for in ETSAP modelling, and which provide deeper understanding especially for meeting ambitious renewable energy targets within infrastructure limits. The dominance of centralised electricity generation is being challenged by an increasing share of distributed renewable generation to give a hybrid electricity system based on decreasing percentage share of fossil fuel energy and increasing generation from renewable energy. (Note that the IEA modelling generally counts bioenergy as unconditionally carbon-neutral.) Shivarama *et al.* (Shivarama Krishna and Sathish Kumar, 2015) provide a comprehensive overview of renewable energy integration into hybrid systems, covering optimal sizing and configuration of local generation, storage and demand, with a summary of energy management algorithms and controls to ensure reliability and grid integration. Also looking at optimal hybrid system planning, Bahramara *et al.* (2016) reviews the HOMER software developed by the US National Renewable Energy Laboratory (NREL) and in use worldwide.

Modelling the interaction of the UK's Carbon Plan with land requirements and water resources indicates probable conflicts between energy demands and emissions reduction and land and water services (Konadu et al., 2015). The integrated energy-land-water analysis by Konadu *et al.* finds that, out of four low-carbon energy scenarios, only their "Higher Renewables, more energy efficiency" pathway meets their "no regrets" environmental parameter. A "Higher CCS, more bioenergy" scenario shows high levels of bioenergy crops are found to conflict with food production from land use.

For climate mitigation, globally, it is clearly essential that the knowledge gained from all of this research is passed on by developed to developing nations and that they receive assistance in achieving very low carbon development of electricity and energy systems.

4.6.2 100% wind-wave-solar?

Researchers have modelled transition to 100% renewable energy systems in different ways. One critical distinction is whether bioenergy is included as a renewable (as in Mathiesen et al., 2011), or bioenergy is excluded, restricting 'renewable' to wind, wave and solar energy (citing ecological or other constraints). Pleßmann *et al.* (2014) models a 100% renewables, global electricity supply based on existing sectoral share (between electricity and non-electricity energy sectors) assuming only solar and onshore wind power complemented by energy storage (in batteries, high temperature energy storage with steam turbines, and power to gas) finding it possible with an upper limit notional electricity cost of €142 MWh^{-1}. This study does not attempt to anticipate the electrification of the heating and transport sectors. In two parts, Jacobson and Delucchi (2011) and Delucchi and Jacobson (2011) controversially assert that providing all global energy for all human uses only through use of wind, water and solar power is possible at a total present-value cost similar to today. Part I describes proposed renewable energy systems and characteristics relative to current and projected global energy demand. Part II, providing gross global costings, explores reliable balancing of power grids to account for variable and intermittent non-biomass renewables – using interconnection of regional grids, greatly-increased hydroelectric supply for base load, and storage including: site-specific (pumped, flywheel, compressed air), batteries in electric vehicles, and hydrogen production. In a meta-analysis of global and national (OECD country) energy modelling studies focusing on high-share renewables in power systems, Cochran *et al.* (2014) find agreement that renewable energy sources can reach a high share of national or regional electricity generation and can do on an hourly basis while still ensuring grid balance. Studies of 100% renewable energy are highly contested particularly regarding consideration in balancing supply with demand at all times across complex systems with multiple, variable generation. Though the literature shows energy efficiency to be important, a lack of demand-side research is common in energy modelling despite being agreed on as critical to high share renewables integration (2014). Critically reviewing global decarbonisation scenarios, Loftus *et al.* (2015) find that those scenarios excluding nuclear or CCS from their energy portfolio rely on much faster global energy intensity of GDP reductions than others and require three to five times as much additional installed electricity generation capacity (50,000 GW) by 2050, reflecting the much lower capacity factors (average vs peak capacity) of variable renewable generation sources.

Pietzcker *et al.* (2017) evaluates the ability of current process-based IAMs to represent wind and solar electricity sector costs and resources on the basis of electricity sector dynamics and variable renewable electricity (VRE) criteria. Using the most recent data to update the models and a US$30 tCO_2^{-1} carbon price (increasing by 5% yr-1) from 2030 expands the projected VRE share by 24% to an average model-share of 62% of electricity generation.

Jacobson, *et al.* (2015) extends the earlier low-cost, 100% wind-water-sun claim to supplying all US energy needs for electricity, heating, cooling, transport and industry, under many conditions using a "grid integration model". In a short comment, Bistline and Blanford (2016) dispute Jacobson & Delucchi's "100% renewables" claim, noting: first, unrealistic assumptions of 'no load loss' based on very high energy storage availability and unconstrained transmission availability; and second, unachievable grid balancing on the necessary hourly and all-year basis given the seasonal, diurnal and intermittent nature of wind and solar causing renewable energy to have decreasing returns to scale. Overall the 100% renewables path is seen as resulting in significantly greater costs (for any given decarbonisation constraint) than in the IPCC-assessed low-carbon pathways (where, as discussed above in this Chapter, the IPCC scenarios rely on significant NETs deployment, even though current estimations of costs can only be regarded as guesswork, at best). More substantively, Clack *et al.* (2017) directly contest the Jacobson *et al.* (2015) "low cost, 100% renewable" claim, detailing objections to claimed modelling errors, inappropriate models and implausible assumptions for hydroelectric and variable renewables based on insufficient evidence, concluding: “Policy makers should treat with caution any visions of a rapid, reliable, and low-cost transition to entire energy systems that relies [sic] almost exclusively on wind, solar, and hydroelectric power”. In particular, Clack *et al.* find that Jacobson, *et al.* do not in fact undertake a “grid integration model”, as claimed, because the grid modelling fails to match supply and demand, with margins and reserves for generation failure and frequency regulation, that is fully spatially and temporally coordinated across a grid with all transmission lines included and that details capacity expansion potential, power flow, distant load matching and siting of renewables under likely variability of loads.

From the above literature, it seems evident that setting a 100% wind-wave-solar only target as a basis for modelling is either used as an assumption to provide a comparison to other scenarios or else based on a risk assessment that sees involvement of nuclear energy, bioenergy and CCS as too high-risk to consider, regardless of cost or technology readiness. If there is a real intention to meet the Paris temperature targets (and related global carbon budgets) then global society needs to decide on balancing risks, for example of nuclear power development relative to 100% renewables. Loftus *et al.* and Clack *et al.* agree that *a priori* elimination of options can be counterproductive and costly, particularly in setting out possible low-carbon transformation pathway alternatives for societal consideration. Given that the risks of exceeding “well below 2ºC” warming are agreed to be unacceptable, and given the urgency of the associated global carbon budgets the logical aim should evidently be to consider all technologies and measures that will combine to reduce energy-related CO_2 emissions to zero as soon as possible.

4.6.3 Modelling of electricity grids with a high share of intermittent renewables

In a literature review and proposed typology of long-term energy models and electricity sector models, Després, *et al.* (2015) find that modellers need to combine the advantages of these models given the common scenario requirement for increasingly high shares of intermittent renewables over time in the electricity sector to meet decarbonisation pathways. Long-term energy system models (such as MARKAL and TIMES) give a full overview of an energy system but a simplistic representation of electricity grid operation. Such analyses can be combined with the grid integration modelling of more detailed electricity sector models (2015) that enable fuller assessment of intermittent renewables integration. MacDonald *et al.* (2016) argue that grid extension across the US using high-voltage direct-current transmission and use of solar and wind could reduce system CO_2 emissions by 80% relative to 1990 without increasing the levelised cost of electricity (LCOE), using 2030 as the reference year for a cost-minimized electrical power system with a 14% increase in electricity demand above a baseline of 2006–2008. Heuberger *et al.* (2017) distinguish the widely used LCOE and ‘system value’, which accounts for integration cost, renewables siting and individual component cost, concluding that integrated electricity and energy system assessment is needed for optimal investment. Spiecker and Weber (2014) examine five alternative policy scenarios for the European electricity market finding that low carbon pathways inevitably results in high costs compared to conventional (unabated) fossil fuel generation. Demand development is found to be a major driver in detailed evolution of the scenarios. Renewables often push wholesale prices transiently to zero even though overall system costs are increased by these heavily subsidised renewables. Low carbon progress is further threatened by low fossil fuel prices unless carbon taxes/fees correct them (2014). Spiecker and Weber concludes that Europe-wide coordination of renewables subsidies and policies combined with electricity transmission upgrades and interconnection become more important over the next decade to integrate intermittent renewables generation.

Niet *et al.* (2017) discusses incorporating risk assessment into different kinds of energy and electricity system modelling. Based on this literature review energy systems are analysed using a financial portfolio analysis, which quantifies risks within the model's structure based on a risk premium (the extra amount that society is willing to pay to minimize risk) and endogenously hedges against these risks. Applying this method to a case study for the currently fossil fuelled electricity system in Alberta, Canada they show alternative possible pathways with earlier or later incorporation of intermittent renewables depending on risk. They find that it is essential to analyse jurisdictions separately as they have different potential energy sources and grid connectivity but the analysis method can be widely used to show the effect of risk premiums on optimal technology mix.

In an environmental science analysis, Gibon *et al.* (2017) evaluate the health benefits and ecological costs of different forms of low carbon electricity using LCA and impact assessment that quantifies environmental costs in terms of a common indicator such as ecosystem quality or human health (rather than monetising system damages and externalities as economic analysis might more typically do). They conclude that increased bioenergy can have significant damaging ecological impacts due to GHG emissions, land use change, water toxicity, air pollution and biodiversity loss but other renewables, FF-CCS and nuclear have net ecological, air pollution and climate benefits by comparison to continued use of unabated fossil fuels. The climate and environmental impacts of high-share variable renewables (wind and solar) and FFCCS in Europe are assessed by Berrill *et al.* (2016) in an LCA based on 44 electricity scenarios, including large scale electrification of the transport and heat sectors. Using primarily unabated natural gas in 2050 emits 1400 $MtCO_2e$, coal with CCS emits 480 $MtCO_2e$, and an even mix of wind and solar 120-140 $MtCO_2e$ (incorporating pumped hydro and battery storage). However, the wind and solar infrastructure results in far greater land use impacts than natural gas systems and more mineral resource depletion than fossil fuels. Wind power has lower resource needs and emissions than solar for given final energy contribution though much depends on physical location and the available resource.

4.6.4 Grid flexibility and energy storage

Lund *et al.* (Lund et al., 2015) review a wide range of flexibility measures for managing high fractional-shares of intermittent renewables on electricity grids using: grid extension through interconnection; increasing supply side flexibility (in power station response, curtailment[14] and "combined heat and power"/CHP use); storage (pumped hydro, compressed air, hydrogen, batteries, flywheels, superconducting magnetic energy storage, supercapacitors, power to gas); and demand side approaches across the household, service and industrial sectors. Infrastructure flexibility using super grids, smart grids and microgrids are discussed by Lund *et al.* with attention to the smoothing effects (on intermittency of wind, solar) of spatial distribution. Advanced battery technology, vehicle to grid and renewable power to energy service (P2Y) flexibilities are also detailed concluding that the large range of renewables, storage and grid management options, with significant expected price reductions, gives a "promising" outlook for future integration of high penetration variable renewables. Lund *et al.* also note that using a whole energy system approach incorporating transport and heat in modelling with electricity adds opportunities for flexibility as well as additional difficulties.

There are several recent reviews of energy storage (ES) in low carbon transition modelling. Mahlia *et al.* (2014) gives an overview and comparison of the many types of ES in use and/or in development. Aneke and Wang (2016) details real life examples globally including the performance of different ES types and discusses the barriers to deployment. Gallo *et al.* (2016) similarly review ES types and examples – including promising Solar-to-Fuel, Power-to-Liquids and Power-to-Gas, ES technologies – finding that no particular ES is ideal in all situations so case based analysis is required. Zerrahn and Schill (2017) review energy storage in modelling of electricity systems with high penetration of intermittent renewables and use a new, open-source model designed to analyse and evaluate long-term ES needs including assessment of the changes in market structure needed to incentivise and compensate ES for the delivery of system flexibility. A review by Castillo and Gayme (2014) focuses on the ES technologies most suited to reducing the grid balancing uncertainties due to the variability of non-dispatchable, intermittent renewable energy sources. With the same focus, Yekini Suberu *et al.* (2014) examines the current state of three ES technologies in detail – batteries, pumped hydroelectricity storage, and fuel cells – and, like Gallo *et al.,* concludes that the no single ES system is ideal in all circumstances. Zheng *et al.* (2014) use a benefit-cost energy acquisition model of electricity distribution companies to give optimal sizing and siting for battery storage thereby mitigating operational risk and reducing the required ES capacity.

Bussar *et al.* (2014) uses optimisation modelling to identify economically optimal technology mix pathways for the future European energy supply system (assuming 100% self-supply)

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[14] Using curtailment (curtailing available power production) as a balancing service relies on deliberate "over-provisioning" meaning that commercial arrangements need to provide a business model that supports it.

including high penetration intermittent renewables and ES for flexibility. In this study, short-term battery ES systems are needed where the potential for (lower cost) pumped hydro, most useful for medium-term storage, does not exist; hydrogen storage is useful for long-term, seasonal storage to collect energy at high generation times and recharge batteries at peak load periods.

4.7 Life Cycle Assessment Modelling

Attributional life cycle assessments (ALCAs) are commonly undertaken to produce comparable quantitative estimates of the lifecycle GHG or CO_2 emissions of products and activities by assessing direct, supply-chain emissions. Attributional life cycle assessment modelling is used to establish the net inputs and outputs for a bounded system over a technology or production life cycle. It is relevant to climate change mitigation in establishing the GHG emissions of a technology, product or process, so the outputs are essential inputs for technology and land use-rich, process-based IAMs and ESMs. As with all modelling, all assumptions, constraints and limitations should be made very clear in ALCA results because they are open to misinterpretation, or misapplication, particularly as they are highly sensitive to methodological choices. For example, to investigate this sensitivity De Rosa (2017) use alternative ALCA methodologies to establish the climate effect of structural timber products using 8 LCA scenarios (varying time horizon, land use change effects, climate metrics and forest stock inventory completeness) for the same case study. They find a large range of nett results for sawn structural timber when all life cycle stages and substitution effects are accounted for, from small nett sequestration of 24 $kgCO_2e\ m^{-3}$ to significant emissions of 3220 $kgCO_2e\ m^{-3}$.

ALCA results are highly dependent on the boundary defined for the analysis and its appropriateness to the process, policy or sector being studied. A major cause of confusion is that the so-called “carbon footprint” value (in mass of CO_2e) at one level of analysis can then be used as the emissions factor (the input efficiency or GHG-intensity value measured in mass of CO_2e per unit of activity) to calculate the carbon footprint at a higher level of analysis. An earlier British Standards Institute document makes this difference clear (see definitions British Standards Institution et al., 2008, p. 57), but the more recent revision does not. For example, in dairy production it is valid to define carbon footprint in $kgCO_2e$ of a single litre of milk CF_{litre} (as in O’Brien et al., 2014) but this is clearly not a direct indicator or, or proxy for, the *total “*carbon footprint” of a country’s annual dairy production CF_{total} (which would be given by $CF_{total} = [CF_{litre} / Litre] \times Litres_{Annual}$), which could be millions of tonnes. Increasing total production can easily cancel out some or all efficiency gains at the unit level such that total system emissions can even increase. Unpalatable though it may be, capping and reducing system emissions may well require cutting production by limiting activities in some sectors *as well as* increasing unit level efficiency.

A review by Plevin *et al.* (2014) discusses the limitations and merits of different types of LCA, concluding that (even beyond the variability in common ALCA methodologies) policy-makers are being misled by depending on the values given by ALCAs to evaluate the climate change mitigation benefits of one choice relative to another because the method’s simplifications are not reliably predictive of real world consequences. Problems include large variations in system boundary definition, use of alternative equivalence metrics for different GHGs, omitting non-GHG impacts such as aerosols (like black carbon and sulphates), critical baseline choices, missing or non-explicit counterfactuals for inputs, failure to include indirect effects (such as indirect land use change), and ignoring the fact that choices are often not substitutable, and that indirect and scale effects occur resulting in feedbacks and rebound that are not generally captured by ALCA methods. ALCAs give an average, static accounting of flows into and out of the boundary of analysis that does not reflect the full emissions effect (or other effects) of decisions on changes in policy on a specific activity. ALCAs are useful to attribute emissions of different alternatives, but should not be used to imply the outcome of choices without fuller examination. Consequential LCA's (CLCAs) are more qualitative, process-based and dependent on scenarios, but used alongside ALCA's can give greater understanding of dynamic system outcomes to enable more robust decision-making. In a literature review of CLCA though, Zamagni *et al.* (2012) find that CLCA methods like ALCAs are inconsistently applied and are best thought of as a modelling approach rather than a modelling principle applying defined rules. Zamagni *et al.* find CLCA to be useful in three particular areas: better formulation of LCA research questions and system boundaries; modelling of deeper mechanisms and linkages including markets; and a more dynamic, conceptual view of systems.

Marvuglia *et al.* (2013) undertakes a survey of different equilibrium model CLCA methods and proposes a CLCA method to analyse biogas production, particularly looking at ILUC effects. Using a CLCA and net energy analysis (comparing energy return on energy investment) for distributed electricity generation uptake, Jones *et al.* (2017) find the combination of methods enable a deeper understanding of potential near- and long-term system change. As Plevin *et al.* also describe, CLCA is noted as having four major differences from ALCA: identification of wider system changes, double counting is possible if CLCAs are added (due to boundary overlaps), CLCAs use marginal rather than average data, and CLCAs display far greater uncertainty due to the complex relationships being modelled. In practice CLCAs are akin to scaled down versions of process-based IAMs in that they include economic modelling and socio-economic processes extending through time.

4.8 Marginal abatement cost curve (MACC) analysis

Marginal abatement cost curves (MACCs) have frequently been provided in climate policy analysis, as listed by (Tomaschek, 2015); see (Teagasc, 2012) for an Irish example. MACC analysis provides estimates of emissions mitigation potential and costs but Kesicki and Strachan (2011) show that, as with ALCAs, their policy application can be misleading and biased if not used with care. More sophisticated approaches are generally needed to capture dynamic effects. Common shortcomings of MACC studies include absence of non-financial costs due to carbon lock-in effects, inadequate motivation or critique of discount rates, static market (quasi-equilibrium) representation that fails to give investment insights over time, carbon price assumptions are often not explicit and uncertainties are poorly represented.

Particularly in the forestry sector, costs have been underestimated due to costs not included in MACCs (for monitoring, implementation and organisation), and energy efficiency saving potential has often been overestimated because market barrier and adoption costs have been excluded. Including projected cumulative emissions savings over a decade are found to improve MACCs from the single year representation that is common.

Taylor (2012) examines the least (notional-)cost optimisation 'ranking problem' in MACCs. Where "negative costs" (revenue) are shown, MACCs are in fact mathematically misleading in establishing the total "cost" (revenue) or total emission savings (the key information) because they show the ratio of mitigation "costs" divided by emission saved. Confusingly, in this case, mitigation options with modest per unit revenue, but high emissions savings may therefore be ranked as lower priority than options that avoid far less carbon, but generate more "revenue per unit"; see discussion and charts in (Ward, 2014). The use of MACCs is therefore inadequate, in general, to give the economic profitability ranking of 'emissions saving' choices – meaning that policy advice giving these rankings needs to be revised. There is also difficulty in interpreting MACC-based choices when there are strong feedbacks between MACC categories (as in energy) as these feedbacks are not well represented within MACC calculations (Levihn, 2016). As with LCAs, Levihn recommends combining scenario and system approaches. Vogt-Schilb and Hallegatte (2014) caution that using MACCs to prioritise the cheapest abatement choices in the near-term can result in carbon lock-ins that make long-term costs greater. Far greater attention to long-term potential, investment timelines and implementation speed is therefore needed than is generally provided by MACCs. Ward (2014) finds the use of MACCs "is entirely inappropriate and leads to perverse and incorrect outcomes" including the choice of less profitable and higher emissions outcomes, particularly in ranking energy efficiency measures because they often feature a large number of "negative-cost" (revenue generating) options. MACCs can be used in ranking positive cost measures, but, even then, their use is confusing as net relative financial benefits are the aim of MACCs and these are not easily interpreted from these curves. Ward concludes (p. 822) that the misleading use of MACC in research and policy documents (especially for energy efficiency), is widespread but, being fundamentally flawed in mathematical terms, recommends that they should be avoided in favour of functions that directly relate net benefit to measures selected.

4.9 Modelling of negative emissions technologies in process models and energy system models

In principle, negative emissions can be straightforwardly included in modelled scenarios of future emissions: they can be simply accounted in modelling and inventories as a negative value in tonnes of CO_2 for a particular year. Integrating negative emissions over future pathways up to 2100 can thus potentially allow a larger carbon budget of gross emissions, and can, depending on timing, act to reverse radiative forcing and/or temperature overshoots in the middle of the period (Sargl et al., 2016a). However, in this case, it is very important that modelling outputs and policy-relevant projections need to show the time evolution of not just the *net* CO_2 emissions of a system pathway but also the gross emissions from each of fossil fuels, non-CO_2 climate pollutants, and land use, and the role of conventional FFCCS (if any), assumed, together with the corresponding gross removals (total negative emissions), so that the supposed contribution of NETs (and corresponding extension of fossil fuel use) is made very clear to model users (Vuuren and Riahi, 2011).

As with other mitigation technologies included in modelling, learning curves for NETs potential need to be described and quantified so that investment requirements can be explicitly identified and policies to enable NETs supported, including integration of greenhouse gas removal into emissions accounting, subsidies for early deployment and modelling co-development of bioenergy and CCS (Lomax et al., 2015). An IAM analysis by Kriegler *et al.* (2013) finds that inclusion of BECCS and then DACCS become key technologies for scenarios with higher carbon price climate policies and more stringent mitigation by reducing notional estimated costs (relative to currently assessed alternatives), given a model constraint of continued growth in GDP and resultant need for energy; but direct sectoral emission reduction (at source and through demand reduction) still provide a much greater share of overall mitigation achieved. Given the modelled costs over time, the study finds that BECCS, being initially less costly, is likely to be deployed far sooner than DAC, but due to likely limits on bioenergy supply BECCS is supplemented by DACCS for removal levels above 13-14 $GtCO_2\ yr^{-1}$. However, the study acknowledges that sustainability constraints beyond the scope of this modelling may well limit BECCS below the model's effective removal cap of 14-15 $GtCO_2\ yr^{-1}$. In particular, offsetting of (otherwise refractory) transport emissions within a 2ºC pathway (450 ppm CO_2e) is far more difficult in the absence of negative emissions from BECCS, requiring significant additional energy demand reduction; though, surprisingly, the study does not allow for the possible large scale electrification of transport.

If carbon dioxide removal through BECCS and DACCS are not available (at multi-$GtCO_2$ scale) in future then scenarios using an IAM find mitigation costs rise even more steeply than they would otherwise, particularly in the second half of the century (Kriegler *et al.* 2013). Similarly, Rogelj *et al.* (2016) also shows that scenarios including BECCS enable mitigation at lower costs because more (comparatively lower cost) fossil fuel energy can be used in creating GDP. Again however, even if CCS is assumed to become available at large scale, limiting global warming to well below 2ºC still requires the achievement of near-term, rapid reductions in gross emissions. Also like others, Rogelj *et al.* (2015a) note that strong mitigation of non-CO_2 climate pollutants decreases peak temperature in the physical modeling and also increases (somewhat) the available global CO_2 budget.

It is evident from the descriptions of these economy-energy-environment scenarios, as modelled in CEA-IAM's, that costs, potential and timelines for removal for CO_2 removal via BECCS and/or DACCS are highly speculative implying that very limited confidence can be ascribed to model results. Also, key assumptions can be difficult to find in papers, making comparability of these CEA-IAM studies difficult.

As noted in Chapter 3, several biophysical reviews identify ecological constraints (productive land, nutrients, water) on nett biological carbon dioxide removal by dedicated bioenergy that suggest a far lower estimate of terrestrial biological sequestration rates than those assumed by many of the IPCC WG3 IAM models (Boysen et al., 2017; Smith and Torn, 2013). Nutrient loss from repeated bioenergy crops or plantation harvest likely requires replacement with fertiliser leading to nitrous oxide GHG emissions that can significantly reduce or completely eliminate the putative climate benefit from ongoing bioenergy use without CCS (Smith and Torn, 2013, p. 93). Compared to WG3 models that include up to and even above carbon dioxide removal of 20 $GtCO_2$ yr^{-1}, this study suggests that biological removal even of as little as an additional 1 $GtCO_2$ yr^{-1} would represent a major negative disturbance to global land, water, phosphorus and nitrogen stocks and flows.

Larkin *et al.* (2017) examine cost-optimising, process-based CEA model scenarios which meet a greater than 50% chance of avoiding 2ºC, finding they give insufficient attention to the Paris Agreement nations' collective commitment to equity criteria and show an over-optimistic dependence on speculative NETs to deliver high levels of CO_2 removal, thereby unrealistically expanding the available carbon quota for gross emissions (effectively moving the goalposts) and failing to include scenarios requiring high levels of near-term emergency-level societal response, which are especially necessary if NETs cannot prudently be depended on. Combined with inadequate modelling of carbon-lock-ins, including social resistance to technology change (especially important for CCS in general and BECCS in particular) the IAMs consequently overlook the potential for, and required urgency of, near-term deep mitigation of gross emissions, particularly in respect to the Paris Agreement requirement for action in accord with equity. Assuming the possibility that NETs fail to deliver at scale, Larkin *et al.* (2017) develop alternative emission scenarios with sustained gross emission reduction rates of 5% yr^{-1} to 14% yr^{-1} for the groups of large emitting nations showing that, even with weak equity criteria, the chance of exceeding 2ºC is still imprudently high but also that this chance is strongly exacerbated by any and all delay in acting to achieve these hitherto uncontemplated rates of decarbonisation. These rates compare to the typical global average emission reduction rates of 2% yr^{-1} to 4% yr^{-1} given by AR5 IAM scenarios, some of which are already unambiguously obsolete (e.g. assuming a peaking of global emissions already in 2010).

4.10 Chapter Conclusion: Use in guiding climate mitigation policy

Models can assist or obscure. Models, no matter how complex, are necessarily simplified representations of reality that can only provide policy-relevant advice if they produce useful approximations of reality (ideally at least tested critically against historic data). As models become more complex, feedbacks between variables may lead to emergent properties of the model that may or may not reflect the emergent properties in a real-life system, and models may become so complex that the model-maker does not fully understand the interactions at work. Model-makers need to make sure that the output comes with clear explanation of its limitations, detail about the model assumptions and initial conditions, a listing of applied constraints and parameters, and, perhaps most important, plain language notes on correct interpretation for non-technical readers. Users of model output and the media, the public and others should be made fully aware of the need for care and the avoidance of interpretations or applications that are not legitimately supported or mandated by the actual modelling.

Despite these important caveats, modelling is an essential tool to explore potential futures. Now that the political realm has agreed on specific global temperature goals at Paris, a major normative decision has been taken that can guide the continuing use of models to outline a solution space to meet those goals with appropriate prudence and risk management.

5 Public policy decision-making and risk assessment in Paris-aligned emissions mitigation (with and without NETs)

Summary

- Based on ratification of the Paris Agreement, decision-making aligned with corresponding global carbon budget range needs to respect absolute limits on future use of fossil fuels and constraints on fossil fuelled economies, unless early investments ensure negative emissions and CCS become available at scale.
- In decision analysis (DA), planetary energy imbalance due to anthropogenic carbon emissions is a “simple problem”: limiting climate change requires limiting cumulative emissions while reducing nett annual CO_2 emissions from fossil fuel burning and deforestation to zero. Additionally, decisions limiting annual non-CO_2 emissions from agriculture and land use as well would reduce peak warming.
- Within the politically agreed, global and long-term risk level of “well below 2ºC”, decision-making in a risk assessment framework, requires precautionary, restrictive management measures (equitable national carbon quotas for example). In DA terms, such measures can only be relaxed if there is a “strict societal consensus on countervailing purpose or benefits” (Stirling, 2007).
- *Decision-making under ignorance* given finite likelihoods of plausibly very serious or catastrophic global impacts – from unanticipated effects, unknown tipping points or other surprises – increases the requirement for precaution.
- In risk terms, the very difficult (“wicked problem”) of exactly *how* to meet WB2C emission paths is therefore secondary to the precautionary requirement to limit cumulative CO_2 emissions and flows of shorter lived climate pollutants.
- At local and near-term risk scale, scientific confidence decreases (increasing uncertainty) and framing is contested (increasing ambiguity). Local and near-term risk assessments are therefore likely to be contrary to the global precautionary one unless they fully integrate the global and long-term risks.
- Carbon lock-in inertia in socio-political economic cultures, processes and institutions have been shown to significantly impede climate action and mitigation, causing costly delay despite the global and long term imperative.
- ‘Second-best’ policies resulting in insufficient action, due to failure to overcome lock-ins or failure to take a medium-term zero emissions goal seriously, are likely to result in progressive reliance on politically unfeasible pathways, stranded assets and higher costs.
- Uncertainty avoidance and short-termism in public and corporate governance to limit emissions are common, despite the very high scientific certainty that reductions in absolute emissions are required for effective climate change mitigation.

5.1 Paris-aligned national carbon quotas constrain policy choices

The Paris Agreement embodies a collective political decision, Decision 1/CP21 of the UNFCCC, agreed to and ratified by the Parties, informed by scientific risk assessments, that the potential climate impacts on human and ecological systems of not limiting warming to "well below 2ºC" (WB2C) over per-industrial are unacceptable. As such, on the basis of this decision, nations have apparently accepted this risk assessment as a guiding principle of their future national and regional bloc decision-making. Directly related to the Paris temperature targets, the "best available science' has defined a limited and rapidly diminishing global carbon budget range of future emissions that seriously constrains global and therefore developed nation emission reduction pathways. As acknowledged in the preamble to the Agreement (UNFCCC, 2015, p. 3, Note 17), analysis of the Parties' initial NDCs shows that they are collectively wholly inadequate to achieve the target. Very high current emissions are making short work of consuming the remaining WB2C carbon budget, potentially exhausting it within 20 years even if emissions 'flat line' at the current annual global level. Given that fossil fuel energy, industrial processes and land use are the primary human-caused drivers of global warming and the basis of much of the global economy, then all socio-economic policy in all nations now needs to be fully coherent with climate action that adds up to achieving substantial and sustained emission reductions aligned with limiting cumulative global emissions to the carbon budget range implied by the Paris temperature goals.

Any delay in reducing developed nation emissions implies even more rapid reductions later, or passing part or all of the burden to developing nations, or otherwise depending on achieving negative emissions at scale in future, over the long-term, to cancel out excess near-term emissions (Rogelj et al., 2016a)[15]. In the context of global carbon management, as the Paris Agreement indicates, if developed nations fail to achieve near-term reductions from currently high per capita emission levels they thereby tacitly take on the moral hazard inherent in depending on increased efforts in future, by others, or through realising net negative emissions on a global basis.

To enable climate action "on the basis of equity" and to show the leadership embodied in the Agreement logically requires nations to 'set out their sums'; specifically in relation to CO_2, this should be in the form of an equitable share ("quota") of the WB2C global CO_2 budget, within which detailed emission pathway options to zero net emissions can be identified. Paris-target aligned policy implies setting out domestic, sectoral gross emissions; finance for defined reductions in future emissions by other Parties, relative to their similarly defined share of the WB2C global budget; and financial planning for definite timeline-defined achievement of a defined amount of future carbon dioxide removal by NETs – to the extent

[15] Geoengineering through Solar Radiation Management (SRM), such as the speculative proposal for continuous injection of particles into the upper atmosphere to reflect solar radiation to produce cooling to cancel out some or all global warming, is not considered in this research project.

that such removal is required by each Party's overall mitigation responsibility, based (explicitly or implicitly) on their declared Nationally Determined Contributions. The Paris Agreement only sets out voluntary mechanisms to coordinate and impel increased ambition by the Parties, even though recognising the Paris Agreement targets directly implies that the "long-term dominates other short-term considerations" such that all other policies need to be aligned with climate change policy (Morgan, 2016, p. 3). However, Morgan suggests that the absence of any rapid moves to accelerate a coordinated, international programme of carbon management of pricing and regulation following the Paris Agreement "represents a collective violation of the precautionary principle. That is, Principle 15 of the 1992 Rio Earth Summit declaration, which states that lack of absolute certainty is not sufficient reason to defer prudential activity."

According to Druzin (2017), the stated intention of the US administration under President Trump to withdraw from the Paris Agreement seriously threatens to upset the "unique fragile nature of a multilateral environmental agreement". It is clear that the major risk in climate policy decision-making is continued inadequate action and inability to coordinate rapid, large scale, mitigation, despite decades of increasingly concerning warnings from climate science and research.

As in all other public policy areas, decisions affecting future socioeconomic and environmental outcomes must be made in the face of an uncertain future. Decision-making can be aided, but not made by policy scenario analysis and risk assessments that characterise the risks being accepted by policy action or inaction, the types of uncertainty involved, inherent limits to our understanding, and worst-cases that may require early precautionary measures (Hallegatte et al., 2016).

It is increasingly scientifically accepted that we live in the Anthropocene epoch (Waters et al., 2016) that is clearly discernible due to accelerating and globally pervasive human impacts from increasing per capita resource use and pollution, especially since 1950 (Steffen et al., 2015). The global impact of local emissions of GHGs necessarily means that national socio-economic decisions being made now which affect GHG emissions have global influence, with multi-millennial effects from decisions to enable or prevent CO_2 emissions.

Early global systems analysis, exploring 'limits to growth' through relatively simple global models computer calibrated to historic data, indicated some scenarios of consumption, population and pollution that could result in economic and environmental system failure during the 21st century (Meadows et al., 1972). Historical data since 1972 appears to show some basis for saying that global trends have been following the higher risk pathways of the unsustainable scenarios (Turner, 2014, 2008) and though the degree of such validation is disputed, the need to take such risk assessments seriously is not (Castro, 2012; see also response by Turner, 2013).

The scientifically-based, though tentative, proposal of ten "tightly coupled" planetary biophysical limits, defining a "safe operating space for humanity", suggests global limits are becoming clearer (Rockström *et al.*, 2009). Three of these limits have already been exceeded (biodiversity loss, nitrogen cycle and climate change), and serious, increasing anthropogenic impacts in the phosphorus cycle, ocean acidification, land use and freshwater use are evident. Though Rockström *et al.* are rightly cautious in defining their criteria, their evidence-informed conclusion clearly infers that humanity likely already has limited "freedom to pursue long-term social and economic development" and the operating space for expansion is rapidly being exhausted. While climate change adaptation opportunities have been identified, continued emissions and resultant global warming threaten to exceed limits of adaptation in many human and biological systems, especially those that are most directly exposed to impacts and/or vulnerable to them (see 16.4 in IPCC AR5 WG2, 2014 see). Commensurate mitigation to avoid reaching such limits is therefore strongly advised; but Oels (2013) finds that governmental responses are in fact moving in the opposite direction, away from consideration of *precautionary risk management* and toward *risk management through contingency* that prioritises national adaptation and security preparedness for 'inevitable' climate change impacts. National prioritisation of local resilience and avoidance of mitigation costs is politically understandable but runs directly contrary to aligning action within the Paris Agreement commitments to meeting temperature targets *equitably*.

Reviewing international documents and declarations since the 1970s, Gómez-Baggethun and Naredo (2015) identify three notable shifts in sustainability policy discourse: from analysis identifying economic growth as *damaging* to the environment to seeing growth as a *solution* to environmental and poverty problems; from a focus on developing *top-down regulation* to an emphasis on *bottom-up efforts and market-based mechanisms*; and from a focus on *political delivery* to an emphasis on t*echnical details and technocratic interactions.* Gómez-Baggethun and Naredo conclude that forty years have been wasted by obscuring the earlier, wide acknowledgement of likely biophysical limits and ecological vulnerabilities, thereby avoiding or deflecting discussion of distributional equity within those post-growth limits, in and between nations and across generations.

In this Chapter, literature relevant to decision-making in national and regional climate mitigation policy is further discussed in the context of climate impact risks and climate policy uncertainty.

5.2 Limits, risk and uncertainty in climate policy decision-making

As in all other public policy areas, decisions on climate mitigation policy must be made within current political and socioeconomic limits with regard to risk and uncertainty. Climate system response to past and future emissions and related uncertainties are briefly set out in the IPCC AR5 WG1 SPM (2013). The IPCC AR5 Working Group II report (2014), though primarily focused on impacts and adaptation, adopts a risk assessment framework throughout that is also applicable and relevant to mitigation decision-making. Key risk assessment terms are defined in IPCC WG2 (2014, see Background Box SPM.2), including h*azard, exposure, vulnerability, impacts, risk, transformation* and *resilience,* see IPCC WG2 Figure 1.1. Choices of climate change response policies benefit from integrated risk and uncertainty assessment (see full discussion of literature in Ch. 3 IPCC AR5 WG3, 2014). Climate policy decisions and judgments regarding risks and uncertainties have ethical, economic and social implications that involve questions of justice and value, responsibility, governance and distribution – concepts discussed in (see full discussion of literature in Ch. 3 IPCC AR5 WG3, 2014).

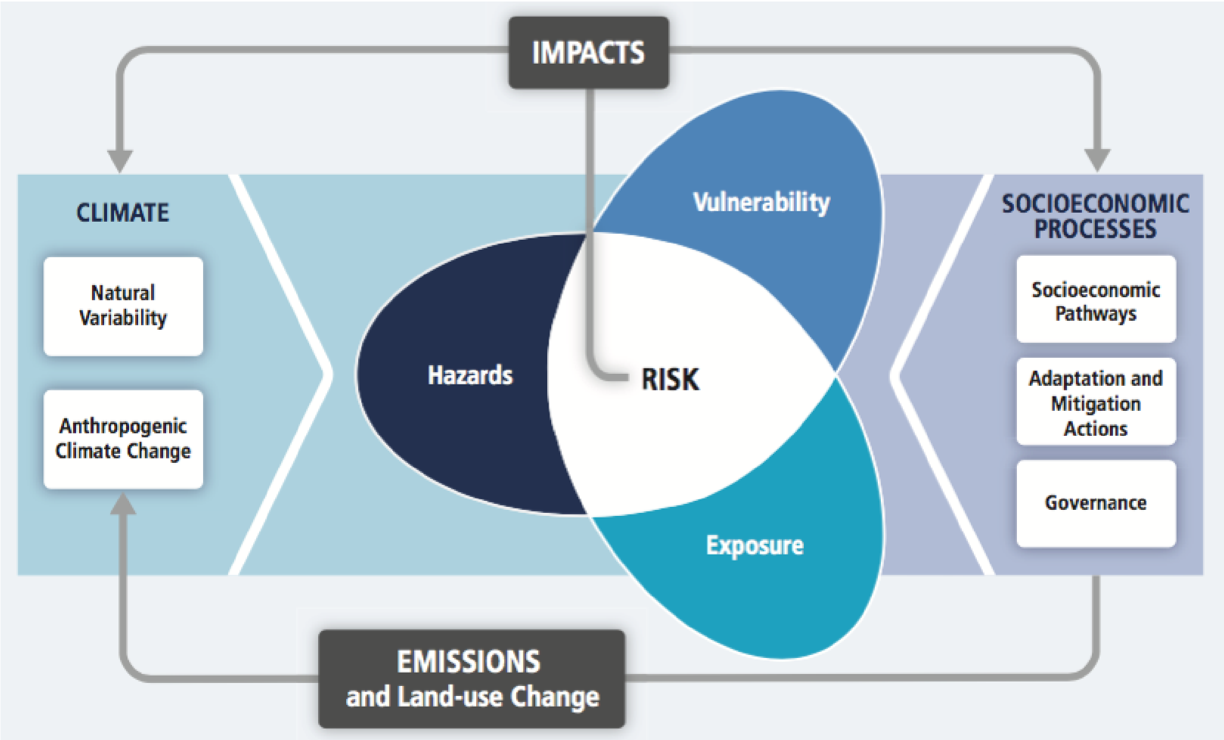

Figure 5.1: Defining the risk of climate impacts as an outcome of climate hazards (due to natural variability and anthropogenic climate change), exposure due to geographic location and vulnerability due to socioeconomic situation and choices. Reproduced from Figure SPM.1 (IPCC AR5 WG2, 2014).

Physical climate modelling using complex and simplified climate models, which feed into integrated assessment modelling, can provide quantitative projections of climate change, including indications of regional and global temperature change and precipitation. Collins *et al.* (2012) discuss trade-offs between model complexity and computational burden, and identify methods being used to improve projections including running ensembles of many simulations, Bayesian frameworks to combine model outputs, and comparing model outputs against past real-world data (hindcasting) to establish possible causal factors and eliminate others.

The term 'uncertainty' has different meanings depending on context. Scientifically, 'uncertainty' often refers to a *confidence interval,* defined by error bar limits or a probability density function, within which the actual value of a quantity is known to lie with confidence for a given methodology. The confidence range, the level of mathematical precision, can then be given within error bars that define the remaining uncertainty. By contrast, in public discourse 'uncertainty' often refers simply to situations of incomplete knowledge or disagreement, without necessarily implying any quantitative measure of degree of confidence (IPCC AR5 WG3, 2014, p. 155).

The IPCC WG2 framework above is usefully extended by Stirling (2007) and Hallegate *et al.* (2012). Hallegate *et al.* define risk and two kinds of uncertainty that must be faced in decision-making and scenario analysis. *Knightian risk* can be quantified on the basis of known probabilities describing hazard, risk and exposure as shown in the framework described by IPCC WG2. *Epistemic uncertainty* is possible due to due to inadequate models, parameter choices and weighting, and data, all of which are potentially reducible with increased knowledge, as well as unavoidable *aleatory uncertainty* that cannot be quantified due to chaotic dynamic behaviour in a complex system. The term *deep uncertainty* is used to describe aleatory uncertainty when many alternative, plausible outcomes are possible with unknown relative likelihoods or even relative ranking (2012). There may also be *ambiguity*, differing analytical world-views and diverging definitions of 'successful' aims (Kwakkel et al., 2010). Decision-making will inevitably adapt to circumstances over time, and realised outcomes will be contingent on the actual pathway of events that occurs.

Discussing risk and precaution in scientific advice to policy making based on a survey of risk literature, Stirling (2007) gives a useful characterisation of four possible states of incomplete knowledge. "Risk" is a state of knowledge where probabilities of occurrence and the extent of outcome can be well described (equivalent to Knightian risk, as above), a situation that is amenable to standard, rigorous risk assessment methods. "Uncertainty", equivalent to Hallegate *et al.*'s *aleatory uncertainty*, is a state where a type of outcome can be well described but not the probability of occurrence; this is often the case in complex, open systems. "Ambiguity" or *epistemic uncertainty* occurs when the probabilities of occurrence may be reasonably well understood but the meaning or importance of impact outcomes may be contested between cultural groups, academic disciplines or ethical belief systems. Where unexpected conditions, surprises or shocks seem possible, involving both uncertainty and ambiguity, decisions may need to be made under what is termed a state of *ignorance*, equivalent to Hallegate's definition of *deep uncertainty*. Stirling (2007) sets out these distinctions and gives corresponding sets of methods and approaches applicable to each state of knowledge, as shown in Figures 5.2, 5.3 and 5.4.

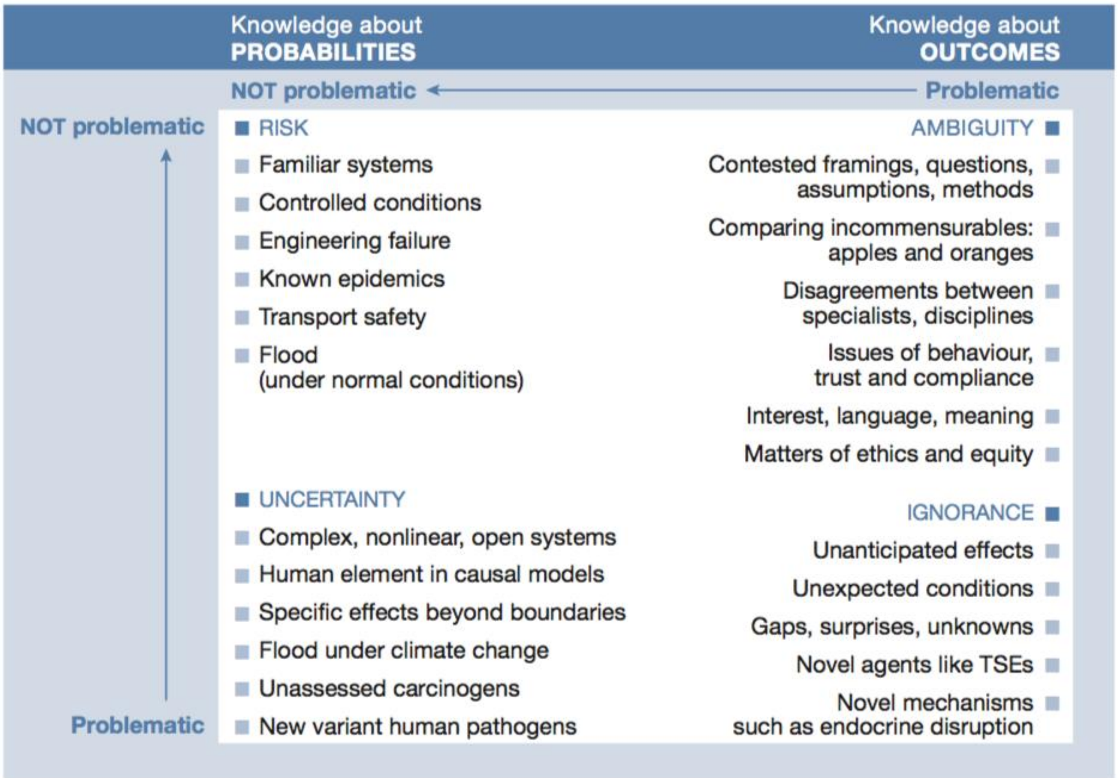

Figure 5.2: Contrasting states of incomplete knowledge, with schematic examples. Reproduced from Stirling (2007).

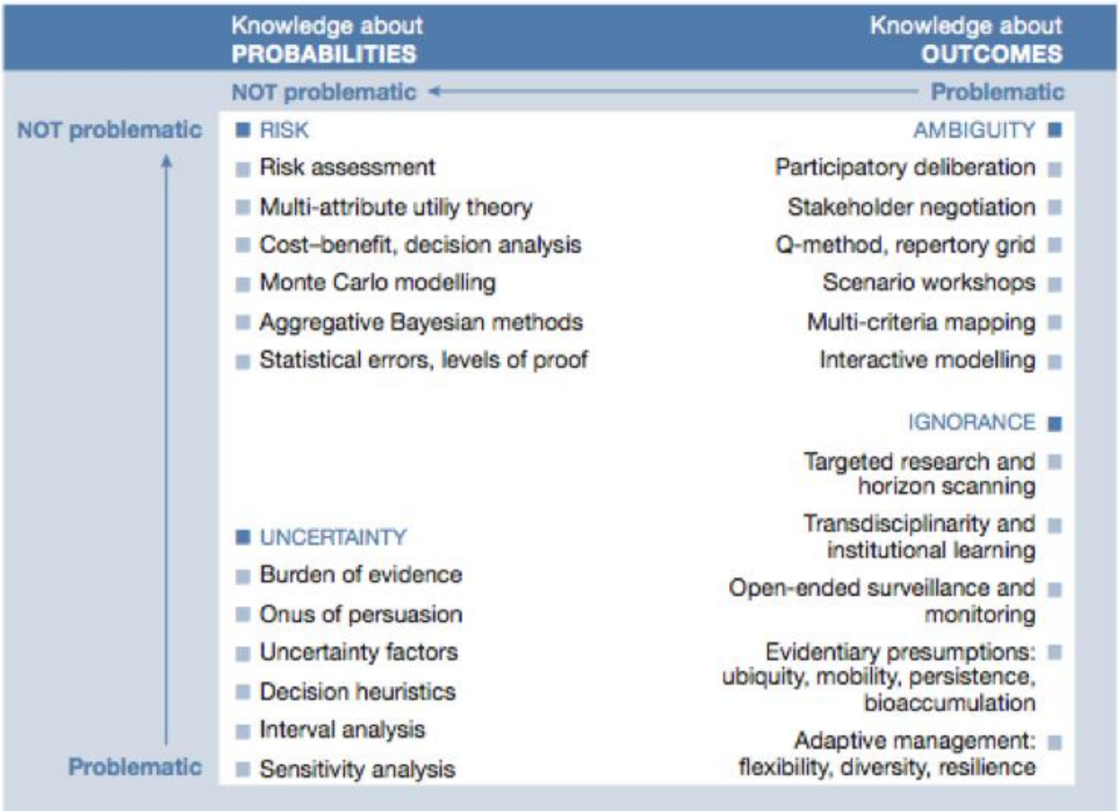

Figure 5.3 Identifying methodological responses to different forms of incertitude. Reproduced from Stirling (2007).

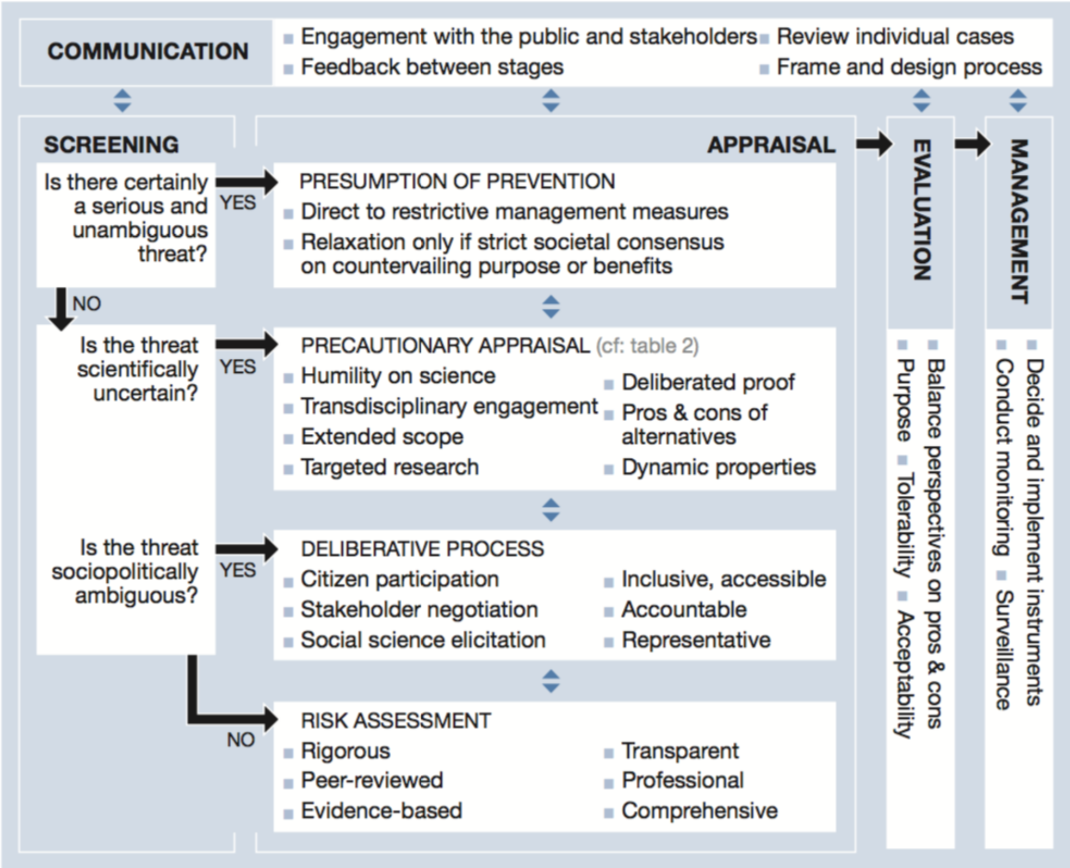

Figure 5.4: A framework for articulating precaution and risk assessment. Reproduced from Stirling (2007).

If there is a serious and unambiguous threat then the framework offered by Stirling (2007) suggests that a presumption of prevention is the correct response resulting in immediate restrictive management measures that can only be relaxed if there is a societal consensus on reasons *not* to exercise such a precautionary principle[16]. In the global and long-term context of anthropogenic global warming the UNFCCC process and the Paris Agreement have acknowledged the serious and unambiguous global threat from continued emissions and the need for immediate restrictive management. At this large scale, the scientific advice – as summarised in the IPCC "Reasons for Concern" relative to future cumulative emissions – has provided a risk assessment of the long-term probabilities politically accepted as a serious and unambiguous threat, indicating the need for "presumption of prevention" (Stirling 2007, see Figure 5.4). Problematically, the decision-making 'policy landscape' for climate mitigation policy at near-term decadal, cultural, and regional or national scales is subject to far more scientific uncertainty and socioeconomic ambiguity, creating local doubts about the

[16] United Nations 1992 PRINCIPLE 15: "In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

extent, speed and equitability of response needed, despite the global scale assessment and agreement requiring urgent and sustained action at scale.

When decisions to act or not to act are subject to deep uncertainty, ambiguity or ignorance, and may result in serious outcomes (as in many decisions relating to climate change policy), some type of appraisal or deliberative process is also required. Standard risk assessment alone is insufficient because it requires some quantitative estimate of probabilities of hazard impact occurrence so a risk assessment in the context of uncertainty and ignorance is needed, likely with a parallel deliberative process to address ambiguity (Stirling 2007).

Scenarios of varying qualitative and quantitative complexity are used to describe and explore alternative futures under such conditions of deep uncertainty (Lempert, 2002). Particular decision pathways may be judged according to their robustness, their ability to perform well over time across a range of different futures (Lempert, 2002, p. 7310). Robustness metrics and thresholds based on the optimistic or pessimistic attitude of the decision-maker have been proposed (e.g. maximin, maximax, optimism-pessimism rule, and minimax regret) but the uncertainty and potential for change in attitude also needs to be included in risk assessments under deep uncertainty (Giuliani and Castelletti, 2016). Robust Decision Making (RDM) and similar methods aim to search the 'decision space' for alternative decision pathways and actions (often with computational methods examining large data-sets), use exploratory modelling to sample and describe different futures, establish measures of robustness to system stresses, and identify key factors affecting robustness that can be monitored in future or prioritised in sensitivity analysis (Herman et al., 2015; Quinn et al., 2017, p. 126). Robust decision approaches, such as RDM, exchange emphasis on optimum pathways for lower sensitivity to uncertainties and more precautionary action (Lempert and Collins, 2007).

Good practice in scenario modelling demands that all parameters and their uncertainties are clearly identified giving both quantitative and qualitative indicators of confidence or lack of it, aiming for transparency and simplified interrogation of model results (Spiegelhalter and Riesch, 2011). Policy analysts, scientists and scenario modellers are advised to: "Communicate the estimates with humility, communicate the uncertainty with confidence" (Spiegelhalter and Riesch, 2011). This is because nuanced or unwelcome advice with significant attached uncertainties may not be what decision-makers want to hear so the temptation for the analyst to do otherwise, e.g., emphasising more welcome advice and limiting mention of caveats, needs to be consciously and deliberately avoided. Stirling (2007 p. 311) notes that reductive, science-based approaches to risk and modelling giving optimised pathways are most of all evident in energy policy yet energy literature itself shows far greater variability. If science points to significant risks of system failure, as with climate science, there is a danger that scientists and policy advisors can tend toward "erring on the side of least drama" in biasing policy advice toward suggesting less worrying outcomes than their projections actual properly suggest (Brysse et al., 2013).

The strong advice from climate science regarding the likely impacts of continued emissions is highly-policy relevant, strong evidence of a serious and unambiguous threat, yet on the whole the UNFCCC process including the Paris Agreement shows national decision-makers treating it more in terms of uncertainty and ambiguity. Actually delivering societal decisions that in fact result in cutting whole-economy emissions may indeed be a “super wicked problem” (Lazarus, 2008), but re-stabilizing global climate can also be defined as a physically simple problem: one of cutting annual net anthropogenic increase in radiative forcing to zero through some combination of policies possibly including large reductions in gross emissions and, possibly, negative emissions to balance a much lower level of continuing gross emissions (Knutti and Rogelj, 2015). This potential confusion for decision-makers, researchers and policy advisors can too easily obscure the basic reality that limiting climate change to well below 2ºC *physically requires* rapid reductions in gross global emissions, *no matter* how difficult or ‘wicked’ such reductions may be to achieve socially, economically or politically (and even if negative emissions deliver at some significant scale). Acknowledging *decision making under ignoran*ce, the existence of plausible and potentially catastrophic climate change impacts on global systems (Giang, 2016), only adds to the overwhelming economic and social imperative for precautionary action to address climate change (Heal and Millner, 2014). Parliamentary democracies in particular will likely require strong cross-party commitment to coherent climate mitigation policy that integrates global risks to enable the multi-level and whole-economy governance necessary to deliver sustained decarbonisation (Rietig and Laing, 2017).

5.3 Economic risks in climate policy choices: costs of action and inaction

5.3.1 Mitigation costs: contested economics

Based on Working Group 3 conclusions, the IPCC’s AR5 Synthesis Report (Pachauri *et al.*, 2014) states that mitigation costs increase with delayed mitigation and also if mitigation technologies (including negative emissions technologies) turn out to have only limited availability (for either technical or cost reasons). Increasing temperatures due to global warming accelerate economic damages that may weaken the resilience of socioeconomic systems or push them to failure. Without assuming negative emissions most integrated assessment models can limit projected warming to well below 2ºC only by very rapid decarbonisation beginning immediately, involving deep, rapid and effectively permanent cuts in fossil fuel use (and probable early use of CCS on fossil fuel emissions), ensuring that any residual anthropogenic gross CO_2 emissions fall below reliable, ongoing, primarily natural, removal.

Nonetheless, the Working Group 3 assessment, as summarised in Figure SPM.13, finds that global mitigation costs are easily “affordable” in the technical sense that the (modelled) reduction in annualised GDP growth rate growth rate would be very small if action begins now (as compared to a reference scenario where it is assumed that GDP growth would otherwise continue unimpeded, at least to the end of the analysis window – typically c. 2100). For example, WG3 presents an estimate that a baseline growth rate in world GDP of 2% yr^{-1} need only be reduced by an average of 0.06 percentage points (to 1.94% yr^{-1}) over the period to 2100. Chapter 6 in Working Group 3 (p. 2) suggests corresponding absolute reductions in global GDP of 4% in 2030, 6% in 2050 and 11% in 2100 (relative to what GDP would "otherwise" be estimated to be in each of those years).

The extraordinary, if not implausible, precision of the IPCC estimate and its associated confidence range, even in the face of deep uncertainty even about the reference case (BAU) and an extremely high likelihood of non-optimal and structural discontinuities, invites critique. Trainer (2017) finds the evidence given by Working Group 3 to support low mitigation investment costs is very weak, and shows evidence that the costs of achieving the renewable energy requirements would in fact be very high in absolute GDP terms by 2100. Although it has been suggested that a clean energy transition might be faster than the past relatively slow transformations in energy infrastructure (Roberts, 2016), Trainer argues that the only two viable policy options are for an enormous commitment to nuclear energy or a recognition that greatly reduced energy consumption levels are required by current high-consumers. Energy transitions need to be compared on a consistent basis, especially noting that increasing the deployment rate (a flow) of a low-carbon technology, from a low base, may be relatively rapid but this, in itself, is not the same as taking a large share of the existing system (a stock), which has typically taken much longer (Grubler et al., 2016). Far greater efforts are advised to enable better institutions and governance to encourage investment based on reliable and transparent regulation with or without carbon pricing (Grubler et al., 2016). In 'second-best' scenarios of non-optimal policies (carbon lock-in and low sensitivity to carbon pricing), Iyer *et al.* (2015) use an IAM to assess investment decisions in global electricity generation showing that costs are higher, and industrialised nations need to mitigate more, than in developing nations.

If the Paris Agreement temperature WB2C target is to be meaningful then it will be up to nation states and regional blocs to cooperate in delivering the necessary action to achieve rapid and substantive reductions in net emissions. But as Spash (2016) points out, the Paris Agreement can also be read as signifying a "commitment to sustained industrial growth, risk management over disaster prevention, and future inventions and technology as saviour". Likewise, Northrop (2017), using Kaya decomposition of past and projected global emissions, strongly disputes optimism that technological innovation in energy intensity and decarbonising energy can effectively absolutely decouple economic growth from total emissions (as contrasted with the ~1.94% yr^{-1}, compounded over 80+ years, suggested by WG3 as still compatible with absolute decarbonisation for a 2C temperature limit). The analysis finds required decarbonisation rates to meet the "well below 2ºC" goal are far in excess of those generally being contemplated, and therefore, like Anderson and Bows (2012), finds that fossil fuel-based global economic growth in the near-term (at least) is incompatible with achieving climate stabilisation. In an analysis of achieving the Durban 2ºC climate goal (UNFCCC, 2011), Jarvis et al (2012) show that society would now need to respond to global mean temperature change at a rate about ~50 times faster than the historical rate of renewable energy roll-out after 1990. Continuing global energy consumption growth at the historic rate would therefore require a decarbonisation (emission intensity reduction) rate of 13% yr^{-1}, far in excess of the historic 0.6% yr^{-1} decarbonisation rate. This implies that it may be necessary to countenance radical changes in the long-standing climate-energy-society feedback that has underpinned economic growth for the past 150 years, or else face escalating climate-triggered socio-ecological disruptions that will force radical, unplanned, changes in any case.

As noted in Chapter 2.2, using the I=PAT decomposition of emissions policy measures, Alcott (2010) notes that economic system emissions are a function of the dynamic system feedbacks between population, affluence and technology. Limiting or capping emission ('left-side' strategies), by enforcing a limit to pollution impact such as a carbon quota aligned with "well below 2ºC", would give investment and societal certainty. This, in turn, could drive cost-effective and societally-effective bottom-up responses from government and other relevant societal actors, via explicit "right-side", total impact-limiting measures and policies (or otherwise), but crucially doing so while preventing or limiting system level rebound (2010). Otherwise, particularly in the higher emitting nations, relying on "right-side" measures exclusively has serious implications for typical government and sectoral activity-based policies aiming to limit consumption on a sufficiency basis or increase energy efficiency. Such efforts are commonly claimed to cut emissions but have been repeatedly found to fall far short of realising the levels of system decarbonisation needed to align with effective climate stabilisation (Brockway et al., 2017; Herring and Roy, 2007). As Jarvis *et al.* (2012) point out, at the global level, large improvements in energy efficiency have not in fact led to absolutely limited or reduced emissions, as consumption per capita in particular, and also population, have increased in parallel. It is a reasonable conjecture that these nullifying effects have been, in part at least, due to the cost and energy savings from efficiencies that have then become available to be spent on additional activities and investments that ultimately lead to more emissions. A strong 'top-down', societal commitment to a regional or national GHG (or carbon) quota enables more robust decision-making including assessment of as-yet unproven possibilities including the extent of negative emissions to be invested in, planned, rolled out or achieved over time, so that these and other options can be stated within nationally determined contributions in future climate policy.

5.3.2 Stranded assets: unburnable carbon and early retirement of infrastructure

The absolute limit to the amount of carbon that can reach the atmosphere if global warming is to be limited to WB2C means that a very large proportion of the world's known reserves of fossil fuels will need to remain underground, unburned, except insofar as their corresponding CO_2 emissions could be prevented from adding to anthropogenic warming (e.g., via carbon capture and storage, NETs, or geoengineering). *Unburnable carbon'*, the descriptive term for this reality, originated in a 2011 report by the not-for-profit financial think tank Carbon Tracker (2011; see also Carbon Tracker Initiative, 2013), with a rapid increase in the term's usage thereafter (Hendrick et al., 2016, p. Fig. 1). Using a TIMES integrated assessment model, McGlade and Ekins (2015) give estimates indicating the proportions and geographic distribution of coal, oil and gas that would need to remain unused from 2010 to 2050, based on a global carbon quota for a greater than 66% chance of limiting global warming to 2ºC. The results imply that, to be commensurate with a political commitment to avoiding 2ºC warming, over 80% of known coal reserves and all Arctic oil should be classified as unburnable, and therefore these, together with the associated global fleets of fossil fuel marine transport (Sharmina et al., 2017) and fossil fuelled infrastructure, are potentially 'stranded assets' that may not be accounted by nations or corporations as investments that will result in future profitable production. Similarly, new capital investments in long-lived, new and existing fossil fuel electricity generating plants may also be stranded assets based on the 'emissions commitment' implied by their future working life relative to the global carbon budget (Davis et al., 2010). 'Commitment accounting' of future emissions due to infrastructure reveals the cumulative carbon commitment of fossil fuel energy infrastructure and shows nominally 'committed emissions' (absent future asset stranding) rising by 4% yr^{-1}, reaching 307 $GtCO_2$ (range 192-432 $GtCO_2$) in 2012 alone (Davis and Socolow, 2014).

The increasing supply and use of natural gas is often advocated as a lower carbon 'bridge fuel' from carbon to renewables. However, natural gas (primarily methane, CH_4) is 75% carbon by mass and its CO_2 emissions per unit energy, while less than coal or oil, and are still high. Additionally, CH_4 if released (unoxidised) to atmosphere is a potent greenhouse gas in its own right. Based on published leakage rate data, Hendrick *et al.* (2016) find that as much as 59-81% of global natural gas reserves should be properly regarded as unburnable carbon due to the potential loss of 'unleakable' methane (i.e., over and above the CO_2 emission commitment associated with combustion). Zhang *et al.* (2014) find that natural gas power plants with substantial methane leakage can cause more near-term global warming than a coal-fuelled power plant producing the same power output; though the natural gas plant would contribute significantly less persistent warming over the long term. Thus, although natural gas has a long-term CO_2 climate benefit compared to coal, ongoing system leakage of methane greatly reduces that benefit and this is compounded by the resultant delay in introducing near-zero carbon technologies, potentially by more than 24 years, due to coal-to-gas system change (Zhang et al., 2016). A WB2C pathway for electricity generation with continued large-scale fossil use, whether coal or gas, likely requires CCS to abate emissions. In stark contrast new, unabated, coal- and gas-fired electricity generation projects are in fact still being built out and actively planned, globally.

The estimate by Davis and Socolow shows that the remaining carbon commitment of already existing fossil fuelled electricity infrastructure alone (most of it in middle and high-income nations) represents about 40% of the remaining WB2C global carbon quota. Pfeiffer *et al.* (2016) find that even with a relatively large 50% chance of 2ºC emissions carbon quota (significantly exceeding the Paris Agreement constraints), and even if all other sectors follow a pro rata decarbonisation pathway, then, given already committed emissions, after 2017, no new unabated fossil fuel electricity generating plants can be built (except in the very limited case of *early* replacement of the highest emissions plant by newer, relatively lower emission plant). By compiling a database of global electrical power generation and establishing a sustainability indicator for analysis, Farfan and Breyer (2017) estimate that zero GHG emissions may be required to meet a 2ºC target, leading to 300GW of stranded coal-fired electricity generator assets, including those already commissioned from 2014 onwards. Therefore, state-owned and private, existing and planned, electricity generation will need to anticipate asset stranding in their continuing investment decision-making (2017).

The Bank of England is making the need for climate change risk assessment clear, particularly with regard to the insurance industry and in the avoidance of asset stranding to support an orderly market transition to a low carbon economy (Bank of England, 2017).

By integrating global or national committed emissions – from existing and planned infrastructure, other policy commitments affecting heating and transport, timelines for negative emissions delivery, and from extractable known fossil fuel reserves – CO_2 commitment accounting could constitute a powerful policy analysis method enabling comparison of the committed emissions budget with the global carbon budget and national carbon quotas for alternative policy pathways. In particular, it could make explicit, at a much earlier stage of policy adoption, other implicit commitments to asset stranding (premature plant retirement) and/or to required deployment (at uncertain or unknown cost) of negative emissions technologies. This can inform policy and the public as to whether whole-economy choices are scientifically aligned with equitably achieving the Paris temperature targets or not, and thus whether infrastructure should be built or not – requiring significant changes from traditional views of long-term planning. The zero-sum nature of carbon budgets (with or without negative emissions) means that there must inevitably be difficult social and political choices concerning the sectoral shares of committed emissions and the infrastructure in electricity generation, heating and transport that can be built. This may also involve investment and delivery of negative emissions depending on the net emissions pathway chosen by individual nations (Fuss et al., 2013).

Unfortunately, it appears that, in international finance, where capital allocation is still seriously misaligned with Paris Agreement climate action (Diaz-Rainey et al., 2017), institutional investors are currently blind to stranded asset risk because their investment decision chain is benchmarked against market volatility and the behaviour of other major investors (Silver, 2017). From the standpoint of a finance system insider, Silver suggests that significant changes in financial investment theory and finance industry regulation will be needed to avoid stranded asset losses and (correspondingly) to prevent excess emissions (Silver, 2017). Similarly, investment assessment of monopoly regulation and disruptive discontinuity (due to competition, regulatory change or other impacts) shows that significant eventual damage to shareholder wealth, to consumers, and to societal welfare may occur due to stranded assets; and that, even though these losses are very difficult to estimate, asset holders, investors, and insurers should plan ahead to avoid or mitigate asset stranding potential (Simshauser, 2017).

The asset impairment risk implications of exceeding the planetary boundaries, as identified by Rockström *et al.* (2009) and those due to changing technology and social expectations, are discussed by Linnenluecke *et al.* (2015) based on existing international accounting standards for asset impairment. Direct climate change impacts due to weather extremes are found to be an asset impairment problem already for one mineral and mining corporation. Both the production of pollution and consequent pollution impacts have serious potential to cause asset value reductions. Such effects are likely to be increasingly subject to market evaluation, regulatory scrutiny, academic assessment and public judgement, so businesses are advised to plan now for a rapid low-carbon transition or else face potentially serious regulatory and reputational damage (2015).

5.3.3 Decision-making in a 'second-best' policy landscape

Standard modelling approaches commonly used to advise policy-makers typically depend on optimising outcomes assuming a single rational decision-maker with perfect foresight operating in a 'first best' 'policy landscape' that is highly responsive to carbon pricing and without path dependent lock-in effects. These are not the reality for decision-makers so modelling is increasingly being adapted to look at 'second-best' policy landscapes with significant institutional and policy lock-ins and where there are many agents making myopic decisions focused on the short-term with varying degrees of sensitivity to regulation and carbon pricing. Also, as discussed in Chapter 4, small adjustments in economic model or technical inputs, or imposing different constraints, can result in very large differences in pathway recommendations. Global IAM and regional/national ESOM modelling is responding to this challenge by adapting models to incorporate second-best policy landscapes. For the IAMs producing scenarios for IPCC assessment the framework of Shared Socioeconomic Pathways (SSPs) gives a sets of quantified parameters as drivers for model scenarios within ideal and second-best futures.

In national energy modelling, Strachan and Usher (2012) identify issues in the UK energy system, both *internal* (in implementation and in behavioural change) and external (in resource access and technology development) that combine to make current climate goals unfeasible unless these issues are addressed. By performing a sensitivity analysis with UK MED, a MARKAL variant, costs are "manageable" for first-best and second-best 90% CO_2 reduction by 2050 scenarios if there is no delay in implementation starting in 2010, but costs rapidly become "prohibitive" if emission reductions are delayed even to 2018, and occur more quickly in second-best policy cases. Strachan and Usher say modellers should give clear criteria of mitigation scenario failure (that they currently lack), suggesting these include: failure to find an optimal solution; some measure of 'excessive cost'; and dependence on highly uncertain mitigation options such as the second-best issues they identify. Using *BLUE,* a system dynamic simulation model, Li (2017) projects scenarios of second-best climate policy in the UK to assess the robustness of ESOM least-cost modelling. *Market heterogeneity* (with different sectoral actors) is introduced whereby all sectors may be strongly sensitive to high carbon price in the uniform, 'Idealised Policy' landscape, or else actors may act with very different carbon price sensitivities in a 'Dysfunctional Policy" landscape (as is typically seen in reality). 'Non-rational' behaviour is introduced by varying the *hurdle rate* (per cent discount rate) for Government and individual behaviour in decision-making, between a "Cost-Optimal Decisions" case, where individuals as well as Government use the lower social discount rate in their decisions, ranging to the real-world situation where individuals and companies typically evaluate decisions on a much higher discount rate than Government. The results indicate that "[policy] actors behaving badly", and failure to align economic incentives for individuals with the societal climate action imperative, produces a far slower, far more costly and higher cumulative carbon transition that may fall well short of the stated policy goals. The realistic, simple assumption that the policy landscape is messy

– subject to different sectoral interests and individual agents who behave myopically according to current circumstances – is enough to produce ‘least cost’ energy system pathways that are entirely at odds with ESOM outputs assuming a single actor with perfect foresight and idealised decision-making.

As Li concludes, this “second-best policy” energy system modelling shows that pure notional-cost optimising models may have some useful role in informing climate-energy economic policy, but they are far from sufficient. Overcoming policy landscape lock-ins (path dependency involving government, institutions and vested interests) and setting a whole-society investment pathway are likely to be pivotal if anything like an optimal and “least cost” pathway is to be followed while still robustly delivering on stated, long term, goals.

5.3.4 Dependence on economic growth: mitigation strategy or added risk?

Public debate and policy targets often prioritise a need for continued economic growth or *green growth* (based on low carbon energy and energy efficient consumption, and taken to be *therefore* consistent with climate and all other wider sustainability constraints) as essential to social welfare and technological development to achieve climate goals. However, strong coupling between global energy use and economic output (despite continuing increases in energy efficiency) persists, and there is increasing evidence that sustained, progressive, decoupling of energy and carbon emissions from output, as measured by global GDP, is far more difficult than presumed, especially at a global scale. Economics has increasingly focussed on an often highly contested debate between (at least) three distinct groups: proponents of green growth, those advocating a *steady state economy* (at some level of energy use), and an increasing literature suggesting that *degrowth* in wealthier economies (while adequately protecting, or even enhancing, societal well-being), will be necessary at least in the near- to medium-term, to enable the speed and scale of reductions in fossil fuel use and carbon emissions now needed.

Some have argued that use of the specific word “degrowth”, with its potentially negative connotations may itself be unhelpful in advancing a wider debate about economic alternatives to GDP growth, so that focusing on human welfare and, in public communication, on stable prosperity or a “good life” may be more conducive to furthering understanding (Drews and Antal, 2016). Others strongly disagree, proposing that ‘degrowth’ is an essential concept to focus attention on the need for equitable economic contraction by the wealthy nations in response to global limits on climate pollution and resource extraction (D’Alisa et al., 2014). In an evaluation of economic literature, Jakob and Edenhofer (2014) argue that both green growth and degrowth are popular concepts that are often misleading because social welfare (overall societal wellbeing) rather than growth (the “end” rather than the “means”) should be the point of an economic system. As measuring welfare can be difficult, Jakob and Edenhofer recommend a transparent, ‘welfare diagnostic’ process of public deliberation to assess what a society values, with the physical and social sciences contributing to this deliberative democracy by focusing on clear communication of assumptions, uncertainties and carefully describing areas which require value judgments. Similarly, van den Bergh (van den Bergh, 2017) points out that a GDP-focus is not consistent with the welfare emphasis that is the basis of modern micro- and macroeconomics including growth theory. Therefore, van den Bergh suggests nations accept an 'agrowth' strategy that is indifferent to growth, even if zero or negative, and instead prioritises essential distributional welfare including spending on climate policies, which contribute to medium- and long-term welfare. An agrowth strategy does not exclude green growth -- if it proves feasible and welfare maximising, and rebound effects can be adequately controlled (Antal and van den Bergh, 2014).

Limiting global scale, macroeconomic rebound, which leads to more emissions due to the savings from mitigation being spent on additional emissions-generating activities, may require trade tariffs on carbon intensive goods. Bergh (2017) discusses why controlling such rebound is important to meeting the Paris Agreement temperature goals and how implementation of revenue-recycling offsets by 'climate club' groups of cooperating nations (see Stua, 2017) and carbon tariffs on trade could be made politically possible – and thereby increasing pressure on "free-rider" nations who are not decarbonising at an equitable rate. Current trade barriers and trade rules facilitate carbon intensive production and discriminate against needed economic development in current absolutely impoverished nations, requiring trade concessions and consumption reduction by the global North, but the political prospects for such change remain poor (Iqbal and Pierson, 2015). To break this impasse, and stressing the need for fast and effective global decision-making, Grasso and Roberts (2014) propose a political compromise based on a combination of action by the major economies (responsible for 80% of global emissions), consumption-based carbon accounting, burden-sharing based on capacity and responsibility, and integration with the UNFCCC – a proposal only very partially echoed by the Paris Agreement. To enable fairness in this framework each of the major economies would both lose and gain but: "By so doing, all countries will gain a liveable future, the core principle of national and human security" (2014).

5.3.5 Economic costs of inadequate climate mitigation policy

The costs of mitigation inaction are often systematically avoided in benefit cost analysis IAMs by neglecting uncertainties (Butler et al., 2014), non-precautionary damage estimates and strongly present-day biased value judgements embedded in discount rate assumptions (Ackerman et al., 2009; Scrieciu et al., 2013). Similarly, evidence from cost effectiveness IAMs and energy system optimisation modelling compellingly shows that least cost delivery of sufficient decarbonisation to meet Paris levels of ambition requires significant and then ongoing action that starts without delay (Luderer et al., 2013). This is the economic consequence of the physical reality of a limited global carbon budget that is being rapidly exhausted, particularly by nations, corporate entities and individuals with high annual emissions (Gignac and Matthews, 2015; Raupach et al., 2007). National claims to act at 'least cost' in aligning action with the Paris Agreement *by definition* accept the essential cost-effectiveness assumption that the agreement temperature goals *must* be met and actually achieved (See 2.5.4.1 IPCC AR5 WG3, 2014, p. 171).

Comparing past CEA and ESOM modelling with actual data for the time period since that modelling occurred, including emissions, costs and investments, might be an effective method of estimating the costs of recent inaction and enable discussion of the lock-in effects that presumably resulted in a second-best outcome with higher economic costs and reduced societal well-being. A similar method of comparison of modelled versus actual policy outcomes might be possible regarding equitable emissions mitigation modelling.

Existing capital investment in infrastructure represents a financial commitment to future CO_2 emissions that can be represented by the carbon intensity of capital in mass of CO_2 USD^{-1}. In addition to early mitigation effort, AR5 2ºC scenarios require a very low carbon intensity of capital by 2050 of 33 to 77 gCO_2 USD^{-1}, compared to about 360 gCO_2 USD^{-1} today; and due to the lifespan of carbon intensive capital, every year of delay in beginning rapid decarbonisation makes future effort more difficult by decreasing the CO_2 intensity required of new production by 20 to 50 gCO_2 USD^{-1} yr^{-1} (Rozenberg et al., 2015).

The reasons for national and corporate inaction on climate change are not well covered in the literature. In a study of firms, that may well be applicable to institutions generally, Slawinski *et al.* (2017) show that failure to reduce *absolute* greenhouse gas emissions, as needed for sufficient and effective mitigation (see Table 5.1, reproduced below) is due to uncertainty avoidance and short-termism that is mutually reinforcing across individual, organisational and institutional levels.

Table 5.1 Explaining organisational inaction on climate change in terms of corporate mitigation measures and the need of absolute reductions in emissions. Reproduced from Slawinski et al. *(2017).*

	Corporate mitigation measures	
GHG emissions	No	Yes
No reductions	Inaction; climate change not on business agenda	Inaction; symbolic action on climate change
Relative reductions	Inaction; reduction only due to regular efficiency improvements	Inaction; necessary but insufficient condition for effective action on climate change in the case of growth
Absolute reductions	Inaction; reduction due only to organizational downsizing	Sufficient condition for effective action on climate change

Individually, a present-time perspective lowers tolerance for uncertainty and leads to only incremental changes that do not add up to absolute or commensurate emission reductions. Organisationally, standard management practices' emphasis on decision-making leads to a focus on short-term financial returns rather than long-term investments that results in decarbonisation. Institutionally, dependence on 'market logic', ideologically stating that mitigation efforts are only valid if they are profitable, and avoiding (or perhaps increasing) regulatory uncertainty, also enable climate change mitigation inaction (2017). These levels negatively interact to create a "vicious circle of organizational inaction" such that although professing proactive intentions their absolute emissions are increasing (2017).

A stronger understanding of what is required – absolute emissions reduction – needs to be integrated into all of these behavioural levels at all levels of carbon governance; but above all, stringent and stable regulations are needed to set the rules within which behaviours are socially licenced. However, such regulation is opposed to the framework of behaviours in firms identified by Slawinski *et al.,* therefore inertial resistance may be expected that will need to be overcome by a stronger framing of the imperative for absolute emission reductions. Howlett *et al.* (Howlett et al., 2015) examine the persistence of policy failures and ineffective decision-making in governments is due to risk-averse politics, inertia in governance and inadequate understandings of risk and uncertainty in decision-making.

5.4 Climate system uncertainty and mitigation risk

The most immediate climate risk to human systems is in those geographical areas exposed to large changes relative to past experience. Frame *et al.* (2017) identify areas where large fractions of the world's population would benefit greatly, even within the next few decades, from effective mitigation of emissions that will limit global warming and delay climate change enabling cumulative benefits from reduced exposure and improved food security. Without stringent mitigation, hitherto unknown local climates will rapidly emerge in the next decades that might well be avoidable or delayed (Challinor et al., 2017). To at least enable more time for adaptation, climate risks will inevitably have to be addressed by all nations, across borders and governance scales, ideally acting in concert (Challinor et al., 2017).

A core uncertainty in our understanding of climate change, affecting socioeconomic analysis and political opinion on climate mitigation, is the amount and rate of response of the natural system to the human-caused emissions of CO_2 and short-lived climate pollutants. Knutti *et al.* (2017) gives a comprehensive 'state of the art' review of all climate science estimates to date of equilibrium climate sensitivity and transient climate response (TCR), metrics that cannot be measured directly. As observed warming in the recent record constrains TCR estimates this value is more relevant to predicted near-term warming and therefore more informative to near-term policy. Even more policy relevant is the transient climate response to cumulative carbon emissions (TCRE), in the range of 0.8 °C to 2.5 °C per 1,000 GtC (3,670 $GtCO_2$), that describes the approximately linear relation between cumulative CO_2 emissions and global mean surface temperature rise. Knutti *et al.* find there is little evidence from climate system physics or observations to suggest that climate sensitivity is lower than current estimates and "to keep warming to within 2°C, future CO_2 emissions have to remain strongly limited, irrespective of climate sensitivity being at the high or low end." Therefore, Knutti *et al.* (2017) conclude climate sensitivity is of minimal mitigation near-term policy importance compared to the far more important and greater uncertainty relating to actual future emissions resulting from human and political socioeconomic decisions being made now and in the near-term.

Non-CO_2 emissions also need to be reduced but doing so does little to change the urgency of planned CO_2 mitigation (Rogelj et al., 2014b). Knutti *et al.* recommend that economic modelling or impact studies use the overall central range for ECS and TCR combined with an understanding of the physical constraints that are likely to narrow the range estimates (Stevens et al., 2016). From a precautionary perspective though, given the likelihood of escalating and possibly highly damaging impacts using the entire range of estimates equates to a requirement to use a value that is higher than the mean value (Lewandowsky et al., 2014b).

5.5 Socio-political inertia and mitigation risk

'First-best' policies based on uniform carbon prices and optimal notional-cost pathways may ignore the behavioural features of institutions (including government departments and agencies), companies and individuals, therefore Gazheli *et al.* (2015) set out a framework based on literature concerning social interaction, learning and bounded rationality. Recommendations to policy-makers are made toward fostering transition despite likely opposition from vested interest groups and "allied behavioural anomalies such as non-rational resistance to change". Research by Rickards *et al.* (2014) shows that senior decision makers in multi-national corporations and Western governments have a "deep propensity for inaction" on climate policy due to pressure within their narrow perspectives to deliver on near-term concerns, including peer-reputation, financial status and professional relationships. Rickards *et al.* conclude that a multi-frontal approach is vital to enabling change toward supporting essential delivery of climate mitigation. Addressing these behavioural barriers will likely require both sustained, external "outside track" pressure, through pointing out the dangers of inaction (stranded assets, revealed biases, potential loss of social license), and direct, "inside track" persuasion through the generation and communication of legitimate alternatives that are not being considered (Rickards et al., 2014). A "middle out" approach of shareholder activism and voter or public service user feedback can also push change in otherwise recalcitrant institutions. Focusing on the UK, based on documentary analysis and interviews with central political actors, Gillard and Lock (2016) find that the cross-party, high salience support for the Climate Change Act of 2008 has faltered from a focus on climate policy efficacy into contradictory claims stressing economic efficiency but often not delivering it.

Overcoming lock-in effects is difficult. Alcott (2010) finds that *enforcing* a limit to pollution impact, such as through an explicitly defined national carbon quota, ideally equitably aligned with "well below 2ºC", would give investment and societal certainty. This, in turn, could drive effective bottom-up responses from government and other relevant societal actors while confronting lock-ins immediately and limiting rebound. Comparable though to a wartime or other "national emergency" situation, such a policy would require wide societal understanding of the overwhelming imperative to begin and sustain deep decarbonisation; a societal understanding that, moreover, would have to be extraordinarily robust in the face of pro-active (and typically covert) attack from powerful actors vested in the status quo. Particularly in the higher emitting nations, the clear need for such drastic measures, as indicated by climate science and equity assessments, has serious implications for typical government and sectoral activity-based policies aiming to limit consumption on a sufficiency basis or increase energy efficiency. Such efforts are commonly claimed to cut emissions but have been repeatedly found to fall far short of realising the levels of system decarbonisation needed to align with large ongoing cuts in total emissions (Brockway et al., 2017; Herring and Roy, 2007). As Jarvis *et al.* (2012) point out, at the global level, large increases in energy efficiency have not limited emissions, as consumption per capita in particular, and also population, have increased in part at least due to the cost and energy savings from efficiencies that have then become available to be spent on additional activities and investments that ultimately lead to more emissions.

Policies with seemingly very high near-term mitigation costs may be ‘fragile’ in the face of public opinion and adverse political decisions. Otto *et al.* (2015) recommend *anti-fragile policies* for climate mitigation, akin to adaptive management techniques, that could be based on explicitly indexed risks that governments are more likely to respect, are more easily communicated and are more able to evolve over time. However, useful as the Paris-aligned suggestions made by Otto *et al.* maybe – indexed emission reductions, high and rising carbon taxes, or an indexed sequestration mandate on all fossil fuel extractors – all of them seem likely result in the same requirement on high emitters to cut emissions fast, starting without delay, and possibly ramp up negative emissions investment and delivery too. These are sensible suggestions but they are do not appear particularly anti-fragile given the evident political resistance to applying them.

Maier *et al.* (2016) provides a wide-ranging multidisciplinary overview of the use of multiple alternative scenarios of plausible futures in producing assessments given deep uncertainty for which “best guess” or optimal pathways may be inappropriate or misleading. Three types of scenario modelling are: *predictive*, answering ‘what if?’ questions and projecting trends; *exploratory* scenarios, which answer the question, “what will happen” or “what could happen”; and *normative* scenarios, which are directed toward achieving a specific target future, whether transformational or preserving existing features. In exploratory or long time-period scenarios the ability to model rapid responses to shocks and feedbacks between processes becomes more important because understanding overall system behaviour is more valuable to decision-makers than detailed pathway choices (2016). When the degree of uncertainty and the degree of flexibility are low, or a long implementation time is possible relative to the rate of change, then a relatively static approach with a single, fixed strategy is possible (2016). At the other end of the spectrum of solution approaches is *adaptive management* with multiple, flexible strategies when decision time is short, flexibility is possible or uncertainty is high. Maier *et al.* (2016) recommend that modellers use relevant qualitative information, particularly on political, societal and investment decision-making to improve the ‘real world’ applicability of scenarios and narratives.

With multiple references, Trutnevyte (2016) first discusses why the perfect foresight, least-cost, energy system optimisation models (ESOMs) and optimising simulation models that commonly inform IPCC AR5 and national policy-making worldwide have been widely criticised for systematic biases due to assumptions that are value laden, fragile or narrowly based. Trutnevyte uses a specially developed ESOM to produce 'near-optimal' scenarios, meeting a cost threshold a set amount above the optimal scenario result, for *ex-post* modelling of the UK electricity system's transition from 1990 to 2014. Cost optimisation failed to project the real-world outcomes, and costs were 9-23% *lower* than the projected *least*-cost. Trutnevyte concludes that ESOMs gloss over uncertainties such that there is only a very small chance of such modelling selecting a scenario that matches real-world transition and so recommends use of the *bounding analysis* (Casman et al., 1999) and *envelope of predictability* approaches using multiple modelling types and examining different scales of dynamic complexity, creatively tested against and learning from historical data (Cornell et al., 2010).

5.6 Decision-making issues regarding NETs in climate mitigation policy

Aligning national and regional (for example, EU) decarbonisation pathways with the equitable achievement of the Paris temperature goals will be very difficult unless a clear and commensurate plan of action is set out (Rockström et al., 2017). Climate mitigation policy decision-making therefore has to be based on whole-economy action that adds up to a steadily reducing annual net emission totals, by some combination of rapid gross emissions reduction and commitments to carbon dioxide removals. National decisions have global economic consequences from both mitigation action and inaction, affecting energy use, food production and investments in high or low carbon technology (Muratori et al., 2016). As long as the cumulative future emissions commitment of current and projected policies is clearly inadequate to deliver Paris-aligned mitigation then significant delivery of negative emissions is tacitly being assumed (Anderson, 2015). Therefore, the IPCC AR5 model scenario runs, largely based on continued economic growth and increasing, though less carbon intensive, energy use, rely on presumed deployment of substantial amounts of negative emissions, particularly from BECCS (Peters, 2016; Ricci and Selosse, 2013). One survey of expert assessment finds that IAM assumptions for CCS are realistic, but for BECCS the assumptions for biological productivity, technical capability and governance allowing a high rate and large extent of BECCS deployment are unrealistically optimistic (Vaughan and Gough, 2016). The AR5 Database 2ºC scenarios, developed by IAMs reliant on simplified carbon-cycle models calibrated against ESMs, often accept significant radiative forcing and/or temperature overshoot that is anticipated to be later reversed through large-scale deployment of NETs. However, Jones *et al.* (2016) find that the Earth system behaviour is highly pathway-dependent, responding to rates of system change and CO_2 concentration rather than to the timing and amount of NETs deployed. Future overshoot scenarios will need to account for carbon-cycle feedbacks that might limit the effectiveness of NETs in reducing $atmCO_2$, thereby increasing the required amount of negative emissions.

Peters and Geden (2017) examine the output from four integrated assessment models used in the IPCC assessment to project energy use and CO_2 emissions. The 'cost-optimal' pathways show significant amounts of BECCS deployment even before 2050 and much more afterward to 2100. The median outcome for the EU is cumulative BECCS storage of 7.5 $GtCO_2$ by 2050, the equivalent of two years of current emissions, and 50 $GtCO_2$ stored by 2100. This would be in addition to substantial CCS applied to conventional fossil fuel usage. Peters and Geden suggest three key policy areas to push political and national engagement with carbon dioxide removal if it is to be part of Paris-aligned climate policy:

- Update national and regional emission reduction pledges: countries already need to begin negotiating equitable sharing of negative emissions and outlining the amounts of CO_2 removals that might be achieved.
- Enable an internationally coherent system of negative emissions accounting with dependable measurement, reporting and verification, to create trust in and incentives for carbon dioxide removal.
- Ensure national and regional policies push international policy forward in these first two areas and incentivise research aiming for rapid domestic delivery of negative emissions at scale including CCS.

Comparing 'techno-paradigm' S-curves of successful technology development – from early market competition, through rapid uptake by society, and slowing when market saturated – Zheng and Wu (2014) suggest the likely progress of CCS technology requires government backing and policy support. For CCS to be a significant part of a low carbon transition, planning policy needs to target very early CCS delivery at significant scale. If any substantive mitigation contribution is expected from negative emissions technologies, then CCS is likely to be an essential enabling technology without which a very large share of nuclear and variable renewables is likely needed to supply sufficient low carbon energy (Selosse and Ricci, 2014). Nonetheless, mitigation policy still needs to reduce ongoing and substantial whole-economy emissions rapidly to hedge against the possibilities that CCS in particular, and negative emissions in general, may not deliver at scale (Larkin et al., 2017).

Bhave *et al.* (2017) summarise outcomes from the *Techno-Economic Study of Biomass to Power with* CO_2 *capture (TESBiC)* project that performs a technology review, assessing Technology Readiness Level and includes pilot plant visit details and data for the four BECCS plants in operation to date, mostly capturing CO_2 from ethanol production. BECCS is currently uncompetitive compared to unabated (FF or bioenergy) electricity generation due to high capital and operating costs; changing this would require addressing the worldwide lack of specific financial subsidies and/or introducing favourable carbon accounting rules for negative emissions that would incentivise BECCS development. Modelling BECCS technology alternatives for typical 50 MW_e and 250 MW_e plant scales, the most techno-economically beneficial options were co-firing biomass with coal and bio-mass with integrated gasification combined cycle; the least efficient were bio-oxy and bio-amine technologies. Relative to an unabated equivalent, capital investment costs were 45% to 130% higher, maintenance costs increased by 4% to 160%, and a net energy penalty of 6% to 15% (2017). Modelling toward deployment of BECCS at scale by 2050, Bhave *et al.* find that economic cost, feedstock sustainability and regulatory barriers are more significant than generating plant technical infrastructure feasibility. However, Bhave *et al.* are only examining generating plant efficiency and cost including carbon capture, so these conclusions do not extend to the limited progress to date toward large scale geological storage development and the political reality that future deployment will significantly depend on public acceptance of the need for CCS (Aminu et al., 2017).

Sanchez and Callaway (2016) provides one of the few studies of practical BECCS design issues and uses a spatially-explicit model based on data for biomass supply and transportation to look at optimising economies of scale. Bioenergy facilities are likely to be more economically viable the larger they are, but feedstock needs to be delivered from larger distances as facility size grows and near-by feedstock likely increases in price as a result. Modelling biomass supply and transportation costs for the US State of Illinois, Sanchez and Callaway find that larger scale BECCS power plants are favoured and the optimal scale is not sensitive to location in the State. However, this may not be true for areas with limited road infrastructure or where biomass supply is not located near to geologic sites suitable for CO_2 storage. That is, these findings are likely to be highly specific to local and regional circumstances.

The research discussed here illustrates the scale and timeline of investment now required to be devoted to BECCS or other NETs in the near-term if they are to be realistically and practically considered as mitigation measures in the long-term.

5.6.1 Land carbon sequestration decision making

Dooley and Gupta (2017) find that reliance on a balance between sources and sinks in the Paris Agreement (based in part on the assumption of large scale negative emissions in modelled projections) has high potential for serious political conflicts over land, especially as the responsibility for land based sinks and sequestration remains to be negotiated. Equity as well as technical feasibility and reversibility will need to be addressed (Canadell and Schulze, 2014; Hansis et al., 2015). In Europe, forest sequestration efficiency is only likely to be enhanced in 25% of cases and the possibility of forestry turning from a sink into a net carbon source is sufficient to change the merit order of alternatives for decision-makers (Valade et al., 2017).

5.7 Chapter Conclusions: Decision-making in mitigation policy

If taken seriously and considered in the expert context given by the IPCC assessment, the Paris Agreement provides clear guidance to national decision-makers in developed nations: a very rapid reduction in global CO_2 emissions needs to begin now, without delay, reaching net zero soon after 2050; and, developed nations must lead with economy-wide reductions in emissions. The Paris Agreement reiterated the need for precautionary decision-making to face an unambiguous threat due to accumulating CO_2 emissions and increasing flows of non-CO_2 climate pollutants. Local emissions due to human consumption of energy and land are resulting in a 'top-down' Earth climate system response that will last for many centuries and can only escalate unless net CO_2 emissions go to zero quickly. In this physical sense climate change is a 'simple' problem; that is, stopping fossil fuel extraction, sooner or later, is necessary to "solve" the problem. The 'wicked problem' is entirely human and societal, the need to turn around a global techno-economic system that is built around fossil fuel use and the rapidly depleting time in which to do so. The 2x2 matrix of risk, uncertainty, ambiguity, ignorance (Stirling, 2007) gives a useful framework for policy decision-makers to identify types of "incertitude" and the appropriate types of responses and analyses. Adaptive governance responses (reacting to events) as favoured by 'robust decision making' methods to deal with uncertainty and ambiguity can only be successful if decision-makers also work within the precautionary context of the Paris Agreement acceptance of serious and escalating Knightian risk (due to increasing atmCO_2) that is greatly magnified by the plausible existential systemic risks hidden by deep uncertainty, or ignorance, that, nonetheless, cannot be ignored (Convery and Wagner, 2015; Weitzman, 2009).

Decision makers, even, and possibly especially, national and local ones, need to realise that the very long-term and global impact of anthropogenic emissions causing ongoing global energy imbalance and resulting climate change is unlike any other problem faced by humanity. Paris target-aligned collective action at local, national and regional levels demands actions that really do *add up* to *permanent* mitigation at the *global* level and over the very long-term with some high degree of certainty, otherwise the emissions and cost savings are too easily lost (Holz et al., 2017). That can only happen if emissions governance within Paris target aligned carbon budgets restricts rebound effects and free-riding. This means that every governance level needs to be limiting and reducing its own domestic emissions and also using all diplomatic means to ensure that others do not waste efforts (Price, 2015).

In this sense, action by national decision-makers needs to be "middle up", pushing both domestically and internationally to systemically address the overriding top-down effect due to the physics of our climate system, a dual obligation that extends to equity and climate justice in meeting the Paris Agreement (Holz et al., 2017, p. 15). Economic and societal resilience within Paris-aligned pathways requires early action to divert from existing GHG-intensive policies so that potential for employment losses, stranded assets and potential sudden economic shocks is minimised. Climate justice also requires decision-makers to recognise that climate mitigation to meet the WB2C target is a zero sum game within the associated WB2C carbon budget range: every tonne of CO_2 used locally or in the near-term is one that others cannot use in future – unless there is a serious national commitment to definitely achieving substantial negative emissions to extend the budget (Peters et al., 2015).

So far, nations, particularly richer nations, have failed to take difficult decisions even though delay makes future action ever more difficult. Continued GHG intensive economic growth itself threatens climate action unless economy-wide emissions fall year-on-year. The recent apparent levelling off in global CO_2 emissions would need to turn quickly into rapid emissions reduction through the coordinated and collective decisions and governance choices at local, national and regional levels.

Decisions looking toward achieving a nett-zero CO_2 emissions society by 2050 will need a context of public understanding of the level of action needed so that decisions are supported. In nations with high per capita or high total emissions decision-makers will need to make difficult choices (such as demand reduction) without delay (Anderson et al., 2015). The WB2C target means climate mitigation policy is a near-term problem, each year of continued high emissions takes another large bite out of a nation's equitable share of the remaining WB2C global carbon budget. In climate change mitigation policy, the most limited resource is now time. However difficult, effective decisions are needed to take a very different path to ensure a low carbon transition starts immediately to achieve substantial and sustained reduction in gross emissions with very limited dependence on negative emissions.

6 Governance, mechanisms and accounting for low carbon transition, including options for NETs and bioenergy

Summary

- Effective governance is essential to enable sustained climate change mitigation and prevent rebound effects (free riding on past efforts or misreporting CDR).
- Policy dependence on carbon dioxide removal (CDR) by NETs requires policy statements committing to well defined and quantified investment time-steps in research, institutional design, legal enabling, and pilot project delivery.
- Developing NETs at large scales sufficient to prolong fossil fuel use demands near-term global coordination to allocate responsibility, drive investment and enable reliable monitoring, reporting and verification (MRV) of CDR.
- Regulation of absolute carbon emissions and uniform or global carbon taxes continue to be strongly resisted by many actors in global, regional and national governance though they are key mitigation measures in almost all research.
- Carbon markets and market-based carbon pricing (flexible mechanisms) are increasingly used globally, but their effectiveness in achieving verifiable mitigation is strongly contested.
- Carbon accounting is often contested or questionable.
- Unabated BE use is generally being incorrectly accounted as carbon neutral in the energy sector, even though bioenergy may have significant nett CO_2 emissions depending on crop rotation time, land use and combustion efficiency. Strictly enforced sustainability criteria would be needed to ensure carbon neutrality but these are mostly absent.
- In current EU policy only fossil CO_2 capture would be credited in CCS; bioenergy CO_2 is accounted exclusively in the land sector, so capture and storage on use cannot attract additional credit. Policy change is therefore needed to credit (incentivise) BECCS relative to unabated BE use.
- Land carbon storage accounts for 20-25% of Paris NDC decarbonisation pledges to 2030 yet land carbon accounting has very large uncertainties and profound implications for societies, land use and equity.
- If the Paris limit is to be met and NETs are needed then CO_2 storage in geologic formations is an essential backstop technology for CDR, otherwise land carbon storage (subject to reversal) has little long-term value.
- Strong internationally coordinated MRV protocols are essential for NETs. For some NETs such as soil carbon sequestration, the cost of MRV necessary to verify and assure additionality may be excessive.
- Developing effective NETs at the speed and scale necessary for a WB2C carbon budget, even allowing transient overshoot, may have profound social, environmental and economic implications that need to be thoroughly considered in mitigation policy and weighed against the risks of inaction and other mitigation actions.

6.1 Governance issues for climate change mitigation, including NETs

If NETS are to play a significant role in low carbon transitions aligned with “well below 2ºC” (WB2C) decarbonisation and within the associated global carbon budget, then international cooperation and coherent governance will be needed to drive forward agreements, including regulatory, pricing and market instruments that emphasise global mitigation achievement (IPCC AR5 WG3, 2014, p. Ch. 13). Developing NETs to ease mitigation pathways will require global negotiations, international coordination of carbon removal and storage accounting and national commitments to allocate and monitor responsibility for investment and delivery of negative emissions (Peters and Geden, 2017). Mechanisms including border carbon instruments may be needed to account for traded carbon – the emissions embodied in extracted fossil fuel and in goods and services – that accounts for large fractions of global emissions (Peters et al., 2012); although a decarbonised global energy system aligned with the Paris Agreement may, in itself, significantly reduce energy related shipping by 2050 (Sharmina et al., 2017). If climate action is addressed ambitiously and backed up by some level of enforcement, the defined Paris temperature target potentially reduces the incentives for nations to delay action on the basis of less clear targets (Gerlagh and Michielsen, 2015). Large amounts of global finance and investment will need to be scaled up in both developing and developed nations, particularly directed toward overcoming barriers to deploying mitigation measures (IPCC AR5 WG3, 2014, p. Ch. 16). Some international and national mechanisms for meeting greenhouse gas mitigation targets will need to be updated as they currently do not account for negative emissions so financial incentives are lacking for both public and private investment (Bhave et al., 2017, p. 488). Carbon governance is strongly tied to energy planning and the reality of outcomes. Analysing European energy policy, Szulecki and Westphal (2014) describe “five cardinal sins” in EU energy governance primarily due to failing to address tensions between national self-interest and EU solidarity, and inadequate attention to energy security and climate concerns, particularly due to a short-term focus at the expense of long-term effectiveness. Contrary to widespread mainstream economic criticism of the interaction between renewable energy targets and the ETS, del Río (2017) argues that multidisciplinary economic theory favours the combination, particularly to enable long-term policy goals, provided other coordination policies are in place, such as dedicated RES-E support in addition to a carbon price.

The core driver for carbon governance is the level and clarity of carbon quota committed to (and *reliably* achievable) by any particular basket of planned policies. If that commitment is vague then governance is likely to be vague. A CO_2 emission pathway over time to zero nett emissions within a fixed carbon quota needs to add up and show the planned sectoral gross emissions and dependence (if any) on negative emissions. Any dependence on land use carbon sinks or bioenergy requires stringent carbon accounting and strong MMV to ensure additionality. Trans-boundary transfers of emissions (“carbon leakage”) appears to significantly compound the difficulties of MMV, with quite asymmetrical motivations, incentives and interests for the parties to such transfers.

6.2 Governance of land carbon sequestration

Estimates of future bioenergy resource and land carbon sequestration assessments are dependent on data that has large uncertainties and on divergent modelling assumptions of future food and bioenergy demand, land use productivity (based on technology and environmental constraints), residue and waste availability, economic growth, population and diet (Slade et al., 2014). Surveying 90 studies of biomass potential, Slade *et al.* finds they are: systematically biased toward optimistic scenarios by focusing on sustainable pathways and avoiding examination of unsustainable paths; and difficult to compare due to a large range of inconsistent assumptions and the use of poorly defined terms. Effective regulatory governance within defined legal frameworks, with monitoring and verification to give sustainability assurance, and investment in learning by doing to gather evidence (to resolve current bioenergy emissions controversy), are essential to environmentally responsible bioenergy production and energy CO_2 mitigation (Slade et al., 2014). In a systematic literature review, Stechemesser and Guenther (2012) find the term 'carbon accounting' has differing definitions across different disciplines and governance scales, being directed toward different purposes, both monetary and non-monetary. To aid comparability Stechemesser and Guenther (2012) give an operational definition[17] of carbon accounting for use by researchers, policymakers and business, which could be extended to include climate impacts. In social and environmental accounting, particularly as used by business organisations, carbon accounting has been compliance and inventory based but Ascui (2014) advocates a stronger focus on interdisciplinary efforts to extend carbon accounting toward climate responsibility and informing societal choices more widely.

Similarly, Fuss *et al.* (2014a) shows the need for consistency in science and policy narratives toward developing NETs, and identifies risks in mitigation dependence on future negative emissions given large uncertainties in: biomass supply and carbon storage; the Earth system carbon cycle response from land and ocean sinks; cost estimates that vary greatly among NETs and other mitigation options; and the complexity of policy and institutional change requiring global frameworks of monitoring, regulations, instruments and pricing, all of which may meet significant political and cultural resistance. Nonetheless, Lomax *et al.* (2015) argue that the escalating risk of severe climate impacts and the inadequate progress in cutting gross emissions mean that there are also large risks in delaying policy engagement with NETs. Therefore: policy planning and medium-term funding needs to include but not depend on NETs options; negative emissions need to be fully integrated into emissions accounting mechanisms; and explicit policy for near-term investment is needed for pilot projects aimed at rapid scaling up of BECCS and other NETs in order to "learn by doing". Due to their differences in mitigation quality, permanent CO_2 storage in geologic

[17] Carbon accounting definition by Stechemesser and Guenther (2012, p. 36): "carbon accounting comprises the recognition, the non-monetary and monetary evaluation and the monitoring of greenhouse gas emissions on all levels of the value chain and the recognition, evaluation and monitoring of the effects of these emissions on the carbon cycle of ecosystems".

reservoirs, and impermanent CO_2 storage by terrestrial sequestration in forests and soils, which is vulnerable to future disturbance and to climate impacts, are not equivalent (IPCC AR5 WG1, 2013, p. Ch. 6.5). Therefore, permanent and temporary carbon stocks and sinks will need to be carefully distinguished in policy mechanisms to account for the differences in mitigation effectiveness.

Grassi *et al.* (2017) show that land use and especially forests supply a quarter of the decarbonisation pledged by UNFCCC nations in the submitted Paris Agreement NDCs, globally reducing from 1990-2010 gross land use emissions of 1.3 ± 1.1 $GtCO_2e\ yr^{-1}$ by mitigation efforts to a net sink of -1.1 ± 0.5 $GtCO_2e\ yr^{-1}$ by 2030. For such pledges to have any credibility, given a current discrepancy of about 3 $GtCO_2e\ yr^{-1}$ between scientific studies and country estimates, there is an urgent need for far more rigorous monitoring and verification, greater data transparency, and increased common understanding of what actually can be considered an 'anthropogenic sink' (2017).

Another study similarly finds the NDCs expect a 20% contribution from the LULUCF sector (mostly from a small set of countries) despite very significant data uncertainties and "a lack of technical know-how and capacity on issues that will ensure the additionality and environmental integrity of LULUCF measures" (Forsell et al., 2016). Beyond the need for rapid decarbonisation in Paris-aligned pathways, policy and IAM dependence on land sinks and increased biological production for energy has profound political, economic, land use and equity implications for the working of mechanisms developed to deliver negative emissions and BECCS (Dooley and Gupta, 2017).

6.3 Low carbon transition governance: social and civic mechanisms

Following a low carbon transition pathway to zero nett CO_2 emissions within a WB2C global carbon budget will require societal efforts including mechanisms, instruments and behavioural change that add up to the scientific Earth system requirement to ensure "substantial and sustained reductions in GHG emissions" to limit climate change (IPCC AR5 WG1, 2013, p. 19). *Governance*, involving multiple actors and networks across society as well as government, and *political economy* (the societal balance of government, corporate interests and civil society), are "critical determinants" in climate mitigation, equity and sustainable development outcomes (IPCC AR5 WG3, 2014, p. 297). In particular, low carbon transition governance will involve: respecting biophysical planetary limits; assessing complex intergenerational impacts; acknowledging that effective responses *may* require a fundamental restructuring of economic and social systems; and a need for strongly coherent national and international efforts to address multiple issues including climate change (IPCC AR5 WG3, 2014, pp. 297–298). As this WG3 assessment points out, political controversy is inevitable in climate governance because key actors at all scales have different views of burden sharing, and therefore "the pertinent policies are highly contentious given the combination of factors at play, prominent among which are finance, politics, ineffective institutions, and vested interests".

To enable focused discussion of different types of governance, Midttun (2005) gives a simplified model of governance (see Figure 6.1) with three core societal actors -– civil society, government and industry – that relate through broad "exchange arenas": denoted as, political, regulatory and commercial. Viewing different governance forms in this model: a welfare state political economy emphasises political exchange between civil society and government, whereas neo-liberal political economy emphasises commercial exchange between industry and civil society.

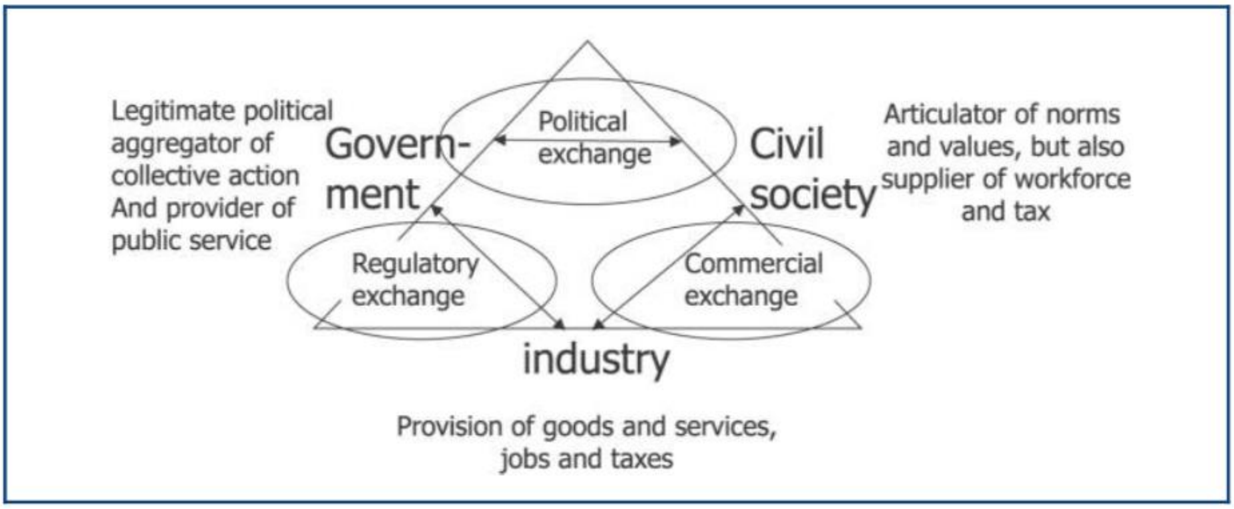

Figure 6.1: A simplified model of societal governance with three core societal actors and exchange 'arenas' between them. Reproduced from Midttun (2005)

Carbon governance can include multi-stakeholder initiatives involving non-government and government actors – industry groups, business entities and environmental and developmental NGOs – creating legal and voluntary frameworks aiming to achieve climate mitigation. However, power and capacity imbalances can limit the effectiveness of such initiatives. For example, Moog *et al.* (2015) present a case study of the Forest Stewardship Council, which established new standards for forest and forest products but has failed to substantially change forestry practices or reduce tropical deforestation.

Without wide political and citizen support for stringent climate policy and/or rising carbon taxes, mitigation mechanisms are unlikely to be durable or effective. In a survey of citizens in British Columbia, Canada, respondents had little awareness of climate policy types but were more likely to express support for regulations (such as energy efficiency or zero-carbon electricity) rather than supporting a carbon tax (Rhodes et al., 2014). Citizen knowledge of climate policy, even with more information on projected policy effectiveness, did not translate into greater support for it. Rhodes *et al.* conclude that regulations may be more acceptable than carbon taxation, and trusted key influencers in a community may well have more impact in advancing carbon mitigation than simply providing "more" information.

6.4 Regulatory mechanisms in a low carbon transition

Dependable policy commitment to decarbonisation regulation lowers required carbon prices in economic models for low carbon transition. Section 2.6.5 in IPCC WG3 gives a full discussion of a range of risks and uncertainties choosing and designing the many types of policy instruments focussing on interventions targeting emissions through carbon taxes and regulation, and on those promoting Research, Development, Deployment and Diffusion, RDD&D (IPCC AR5 WG3, 2014, p. 184). Setting an enforced cap or price floor on emissions can stabilise finance and investment expectations. In stimulating RDD&D in new technologies, the use of a feed-in tariff system to reduce investment risks and give assurances as in Germany has been found to outperform quota-type systems, as used in the UK, based on incentivising investment and limiting rises in energy costs (IPCC AR5 WG3, 2014, p. 184). Uncertainties in policy instruments undermined investor confidence when they are not well designed: allowance trading markets and renewables quotas can dampen investment, in contrast to subsidies and feed-in tariffs that can overheat markets while wasting public money, i.e., tacitly “non-cost-optimal” means toward achieving stated policy targets (IPCC AR5 WG3, 2014, p. 184). However, the IPCC assessment here seems more focused on the effectiveness in increasing the market penetration of low carbon technology as opposed to assessing policy achievement in mitigation aiming to reduce absolute emissions.

Hildén *et al.* (2014) examine formal and independent climate policy evaluation in the EU finding that formal policy and evaluations, even though narrowly focused on aggregate emissions targets, are often in themselves highly political and “many actors in the EU have preferred to keep evaluators on a tight leash” (2014). Barriers to evaluation identified include limited data access and transparency, lack of resources and capacity within governance networks (including NGOs) to carry out mitigation evaluation, and political resistance to systematic monitoring and evaluation that would allow accurate *ex ante* and *ex post* assessments (2014).

Rather than emphasising emission permits or a carbon tax, Allen *et al.* (Allen et al., 2009) suggest a more effective global framework (still based on limiting total future cumulative emissions) would be to make a legally binding obligation on fossil fuel extractors to deliver carbon dioxide removal commensurate with extraction. In this proposal, the fossil fuel industry (including state actors where relevant) is required to be responsible for avoiding all climate pollution resulting from their extraction, a potentially far simpler and enforceable regulatory requirement than global governance of carbon taxes or trade. Nonetheless, as the authors admit, the resistance from extractors would be significant, and regressive inequities within and between nations resulting from increased energy costs would need to be balanced by other distributive economic policy.

Lower national compliance levels under the Kyoto Protocol were strongly correlated with higher consumption per capita suggesting that achieving sufficient GHG mitigation may involve reduced consumption. This finding is prima facie in conflict with the common political (and often citizen) voiced preference for continuing economic growth (as also included in the Sustainable Development Goals) — unless rapid, absolute, decoupling of consumption from climate pollution proves possible (Harris and Lee, 2017).

Climate change policy and governance decisions are often subject to sustained under-reaction by governments (possibly motivated by *blame-avoidance*) due to the relative invisibility – or intermittent visibility – of climate change concerns, coupled with the relative ease of avoiding climate action compared to other public policy priorities (Howlett and Kemmerling, 2017). This means that inaction and limited symbolic measures are possible for governments unless focusing events or sustained political pressure make blame unavoidable, in which case *credit claiming* impulses can prevail (Leong and Howlett, 2017). Leading up to the Climate Change Act (2008) in the UK, a combination of factors – cross-party attention focused on leadership, a long-term agenda set by the public and civic actors, and the publication of the Stern Review – enabled a credit claiming environment that led to adoption of five-yearly, interim carbon budgets overseen by a somewhat independent Committee on Climate Change (Gillard et al., 2017). However, surveying UK policy makers and documents since 2008, Gillard *et al.* find contradictory political pressures shifting between claims of decarbonising efficacy and economic efficiency have led to increasingly incoherent climate change policy, undermining UK climate policy ambition.

Carbon intensity of fuels or GHG intensity of products or sectors are often stated as a basis for standards or targets in climate policy. Examining the LCA methodologies underpinning fuel carbon intensity standards in California, Oregon, British Columbia and the EU, Plevin *et al.* (2017) conclude that such standards are "inevitably subjective and unverifiable" and therefore unreliable in promoting technologies beneficial to emissions reduction. Plevin *et al.* suggest a more effective alternative to intensity drivers are national and regional regulatory caps on total sector GHGs, including biogenic CO_2, particularly in transport and agriculture, and ratcheting caps down over time; or "less desirably", imposing a carbon tax. Given the climate mitigation requirement to limit absolute future emissions, avoiding complex modelling and attributional or consequential LCAs that are ill-suited to enabling reliable mitigation outcomes makes sense. Focusing efforts on policy commitments that add up to meeting whole-economy and sectoral emission caps may well be more reliable climate policy.

6.5 Carbon pricing for climate change mitigation

A universally applied and then escalating global carbon price is a key assumption in the modelled cost effectiveness scenario runs detailed in the AR5 Scenario Database and in the IPCC's assessment (IPCC AR5 WG3, 2014, p. Ch. 7). Despite this assumed significance for climate policy, the IPCC WG3 assessment (2014 see see Ch. 13 to 16) is surprisingly limited in detailing current international mechanisms for coordinated carbon pricing (via a tax or through emissions trading) and international finance measures (redistributing revenues from high emitters to fund mitigation in poorer nations). Assessing national and sub-national policies and instruments, Chapter 15 provides the most detailed sections on economic instruments (taxes, subsidies and emissions trading), regulatory approaches and government provision of public goods. Economic growth theory (assuming ideal conditions of foresight, rapid change and information) indicates that cost effective mitigation requires an economy-wide and market-based focus on cutting absolute emissions. However, the IPCC acknowledges that sector-specific policies are more commonly used, especially due to strong sectoral policy networks within nations that undermine the priority attaching to cost-effective climate policy. Path dependent political feasibility is given as a reason for the loose and non-binding caps in existing cap-and-trade systems that have limited mitigation effectiveness. Carbon taxes have been implemented in some countries enabling some local relative decoupling, but usually differential values are applied between sectors for reasons of political feasibility rather than mitigation efficacy, again reducing mitigation cost-effectiveness (IPCC AR5 WG3, 2014, p. Ch. 7). Government commitments to climate policy, finance mechanisms and regulatory trajectories (such as emission caps and price floors and ceilings) increase investment confidence and ease societal low-carbon behavioural transitions. Civil society stakeholders including independent media and NGOs are seen as having a major role in raising public awareness by using technical and scientific understanding in advocacy and monitoring, thereby enhancing accountability – ideally encouraged by an inclusive approach across climate policy governance (IPCC AR5 WG3, 2014, p. Ch. 7). NGOs have had a significant role in assessing the NDCs up to CoP21 in Paris and this is expected to continue in the Paris Agreement's pledge and review system (Jacquet and Jamieson, 2016, p. 645).

Applying a rising and uniform carbon fee is often advocated in climate economics to maximise social welfare at least cost, by driving adoption of low carbon energy supply and consumption of low carbon goods and services and limit rebound effects, while also raising revenue that may be used to reduce other taxes (Baranzini et al., 2017). Nationally, subsidies are often used to support early-stage mitigation technologies but can be far costlier than a carbon fee to achieve the same mitigation (Baranzini et al., 2017). Contrary to this dominant view, based on evidence from the US, Jenkins (2014) details political economy constraints on economically optimal, "first-best" carbon pricing including: the opposition of incumbent vested interests, holding either principal agent powers or potentially stranded assets; and citizens having a low "willingness-to-pay" for decarbonisation measures. Therefore, a mix of "second-best" regulatory policies may in fact be optimal in practical reality to drive mitigation effectiveness. These may include direct procurement of emissions abatement (as in a clean energy plan), linking long-term climate damages to immediate co-benefits (as in controlling air pollution), and leading, and responding to, changes in public understanding with adaptive policy design to ratchet up decarbonisation measures (2014).

At present carbon prices globally are effectively very low and, in the short term, raising them will bring in revenue. However, if mitigation policy is ultimately successful in reaching near-zero emissions globally then revenues will again reach near-zero so there is a trade-off in future policy between welfare-maximising and revenue-maximising incentives (Wang et al., 2017). Using the DICE BCA IAM, Wang *et al.* therefore conclude that revenue-raising from carbon taxes may be a useful incentive in the short to medium term but climate mitigation policy will also require regulation and policy measures to limit emissions, otherwise in the long-term very high carbon taxes rates will be needed theoretically even as carbon tax revenues go to zero with decreasing and even negative emissions. This conclusion is greatly magnified by inspecting the cumulative emissions under the curves in Wang *et al.* (Wang et al., 2017), see Figure 6.2, indicating about 3000 $GtCO_2$ to be emitted over the next 100 years under the "welfare maximising" curve (until net zero CO_2 emissions by 2120), and more than 10,000 $GtCO_2$ to be emitted under "revenue maximising" policies, with emissions still at an extremely high level thereafter at 50 $GtCO_2$ yr^{-1}. Given the WB2C global carbon budget is likely less than 1000 $GtCO_2$, even the notionally "welfare maximising" curve appears to be incompatible with the Paris temperature goals, and reliant on extraordinary amounts of CDR from NETs of over 40 $GtCO_2$ yr^{-1}. Again, as in other similar analyses, this output seems to point to a wide gulf between the DICE model damage function and the best available science accepted by the UNFCCC Parties in the Paris Agreement. As discussed in Chapter 4.2, the damage functions used in DICE and other BCA IAMs are very poorly defined and highly questionable – when modelled for "revenue maximisation", global climate damage in 2200 is estimated as only 5.2% of GDP, despite using up enough fossil fuel carbon to result in 6ºC warming (based on Fig. SPM.10 IPCC AR5 WG1, 2013), a warming level and velocity of change that many scientists would consider catastrophic in impacts on human and natural systems as well as likely passing numerous known tipping points. Abating trillions of tonnes of CO_2 to avoid the impacts of emitting seems implausible. Therefore, for policy planning and governance decisions, economic analyses based on DICE appear to be of schematic value at best for policy planning. As indicated by the acceptance of the science in the Paris Agreement, a far more precautionary, risk-based approach would seem necessary even within economic analysis (Heal and Millner, 2014).

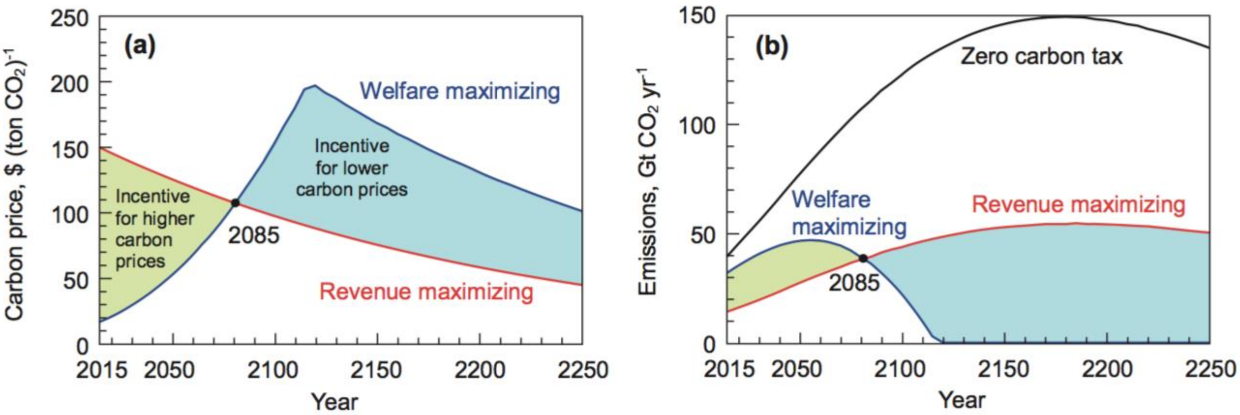

Figure 6.2: Reproduced from Figure 1(a) and (b) of Wang et al. *(2017): "Results as calculated by the DICE-2013R model under the welfare-maximizing, revenue-maximizing and zero-carbon-tax cases: (a) optimized carbon price paths in 2005 US dollars. (The green area illustrates where increased carbon price would increase carbon-tax revenue. The blue area shows where decreasing carbon price would increase carbon-tax revenue.) (b) CO_2-equivalent emissions to the atmosphere,"*

Using WITCH, an unusual IAM with a game-theoretic structure to optimise global, low carbon transitions, minimising future notional cost, Carraro *et al.* (2012) explore investment needs and distribution by region and sector over time. As also shown by Wang *et al.* above, carbon tax revenues peak and then decline (forming a "carbon Laffer" curve), at least for scenarios meeting 460 ppm and 500 ppm atmCO_2 levels by 2100 (approximately equivalent to 2.5ºC warming above pre-industrial, see Figure 12.43 IPCC AR5 WG1, 2013; Zickfeld *et al.*, 2013).

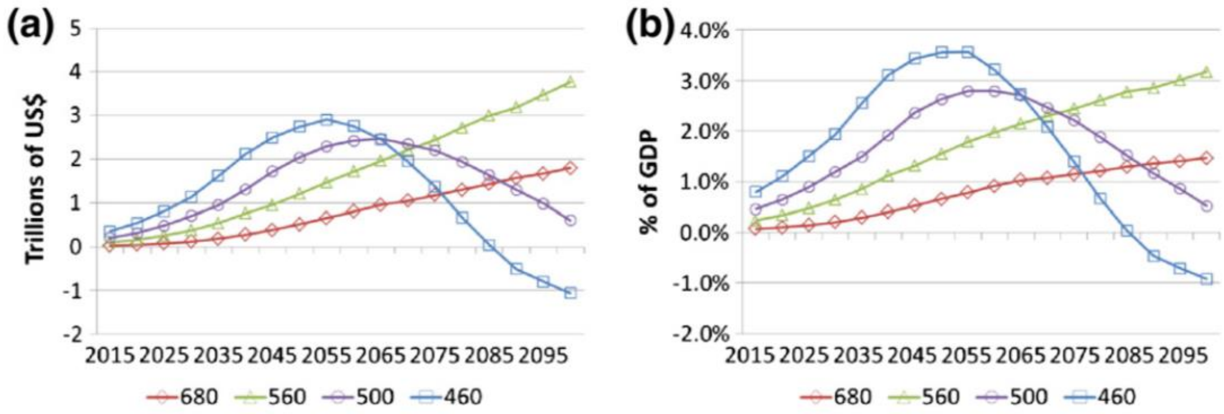

Figure 6.3: Revenues from carbon taxes in OECD economies in absolute value (a) and as a fraction of GDP (b). Reproduced from Figure 10 of Carraro et al. *(2012).*

In the 460 ppm scenario carbon revenues become negative in the developed world regions after 2050 (see Figure 6.3, left, 'Cap-and-Trade') to subsidise negative emissions from facilities combining biomass with integrated gasification combined cycle (IGCC) coal with carbon capture and storage. Carraro *et al.* (2012) makes the important point that, even in a tax-based policy that would usually exclude direct subsidies, subsidised CDR is found to be welfare enhancing because CO_2 is a stock pollutant, therefore a cost effectiveness framework requires that the atmospheric CO_2 stock must be kept below the scenario target limit. However, increases in taxes or reduced public expenditures are needed to fund continuing CDR. In this "riskless environment" cost estimates undervalue the investments and difficulties in managing a real transition to a global power sector involving large amounts of CCS, bioenergy, nuclear and wind power (Carraro *et al.* 2012).

Also using the WITCH IAM, Favero *et al.* (2017) examines the global use of forests to store carbon, including active afforestation and reforestation (AR), and/or to supply woody biomass to BECCS electricity generation. Ignoring potential direct climate change effects (albedo decrease due to conifer planting and fire and beetle losses due to warming), the least notional-cost pathway is to use both forest storage and BECCS, with forest carbon storage dominating while carbon prices are low, tending toward larger trees and mature forest land use, and BECCS takes over as carbon prices rise increasing plantation forestry. Given the 14.5 GtCO_2 yr^{-1} in removals by AR and BECCS over the 2020–2100 period, the RCP2.6 2050 and 2100 carbon prices of US\$200 tCO_2^{-1} seem remarkably low, perhaps implausibly so, compared to other global modelling.

On regional cooperation IPCC (2014, p. 1087) note that, even with its deep integration, the EU has only had very limited success achieving mitigation objectives using market-based carbon pricing. The EU ETS has provided a functioning cap and trade system but has not driven mitigation, because it has yielded only a very modest carbon price to date, below €10

tCO_2^{-1} – explained by excessive free credits to incumbent polluters, the financial crisis and incoherence with energy efficiency and renewable policies. One interpretation then is that the financial crisis "co-incidentally" delivered a lot of unanticipated mitigation, so that the mitigation "left" for the ETS to achieve was relatively trivial. Strictly speaking, the ETS did exactly (and only) what was asked of it, that is, to ensure that a specific level of mitigation is achieved, and do so at the least overall "societal cost". The ETS was not designed to take the opportunity to ratchet up mitigation ambition (by dynamically tightening the emissions cap, in the face of the low realised carbon price), so the deeper questions regarding the ETS are the EU's governance arrangements around it, specifically the collective political will of the EU Member States to deliver additional emission reductions even in adverse economic circumstances. Given the necessity for UNFCCC Parties to ratchet up ambition to meet a WB2C carbon budget, carbon pricing and emission caps likely need to be designed to ensure that "free-riders" do not take advantage of short-term system mitigation gains due to economic downturns or due to the mitigation efforts of others.

6.6 Accounting for differences in carbon sequestration permanence

The AR5 report on mitigation (IPCC AR5 WG3, 2014) briefly mentions the issue of sequestration permanence, noting "[t]he properties of potential carbon storage reservoirs are also critically important, as limits to reservoir capacity and longevity will constrain the quantity and permanence of CO_2 storage" (p. 489), and notes the problems of non-permanence (reversibility) and saturation in land carbon stocks in forestry and soils (Section 11.3.2). Unfortunately, there appears to be insufficient WG3 assessment of past literature relating to the consequent importance of pricing and accounting for carbon sequestration non-permanence in mitigation policy (possibly because relatively few papers on this topic were published after AR4 and up to the AR5 cut-off date). Nonetheless, as the available research does make clear, it is critical for effective mechanisms to provide assurance that mitigation is additional to what would have occurred without the specific intervention, and account for any re-emission of CO_2 from carbon sequestration reservoirs, whether from land sinks or geological storage.

Focusing on soil carbon sequestration (SCS) science and policy, Thamo and Pannell (2016) find potentially perverse outcomes mean that policymakers have three choices:

- ensure extremely rigorous monitoring and verification of additionality and sequestration (necessitating high transaction costs);
- simplify the scheme resulting in lower costs but inefficient and unreliable mitigation;
- Or, as the study concludes, accept the balance of evidence that policy reliance on SCS-attributed mitigation is an ill-advised, cost-ineffective and unreliable approach, especially as there are very strong land management reasons (soil fertility and water retention) to act to store carbon in soil in any case without the need for additional incentives.

Assessing potential adjustment of SCS for permanence, leakage, and additionality Murray *et al.* (2007) find limited empirical evidence of lost sequestration but agree that large sequestration discounts (losses of economic value due to carbon loss) are possible, though the relatively low opportunity cost of SCS may still make the sequestration worthwhile. However, Murray *et al.* (2007) do not seem to consider fully the potentially very high transaction costs of stringent MMV that is likely needed to guarantee reliable sequestration.

Protecting 'set-aside' forest areas from harvest and land-use conversion using incentive payments potentially increases carbon stock permanence (and adds biodiversity and other co-benefits). Based on economic analysis, more flexible programmes, crediting both set-aside areas and additional carbon stock on other lands, are far less susceptible to 'leakage' effects than programmes solely crediting set-aside (Sun and Sohngen, 2009). Using perfect-foresight, optimisation modelling of stylised, future carbon markets in the US, Haim *et al.* (2014) assess the permanence of afforested agricultural land (and its sequestered carbon) assuming 30 USD tCO_2^{-1} and 50 USD tCO_2^{-1} carbon prices, finding that Midwest regions continue largely unharvested through 2060, but large areas of Southern regions, which have shorter forestry rotation times, are harvested and returned to agricultural use.

All carbon mitigation options (even in geological storage) are potentially temporary relative to the millennial scale influence of atmospheric CO_2. Herzog *et al.* (2003) defines 'sequestration effectiveness' as "the ratio of the benefit gained from temporary storage compared to the benefit gained if the storage was [literally] permanent". Using a basic, theoretical economic analysis to examine deep ocean CO_2 sequestration of differing duration, Herzog *et al.* find that excessive use of non-permanent reservoirs is equivalent to burning excess fossil fuels, inequitably passing on the costs to future generations. For low discount rates approaching zero, if carbon prices rise at near the discount rate, then sequestration effectiveness also approaches zero unless an effective 'backstop' technology such as CCS is available – providing CDR at a high but dependable cost (2003). Herzog reject the 'ton-year accounting' approach for temporary storage (based on the 100 year GWP_{100} metric period) as lacking any economic or scientific rationale. A more scientific and economically logical accounting assesses emissions and removals as separate events, and sequestration removals as a permanent liability for the owner, which require a best-estimate of the expected price path given the sequestration effectiveness of the CDR. For a fixed global carbon budget of future cumulative emissions (as in emission pathways aligned with the Paris Agreement), even with a very slow rate of leakage, temporary sequestration options have little value compared to permanent (geological) storage (2003). This theoretical finding would seem to rule out land carbon sequestration (in forest and soils) in particular as a useful mitigation option unless whole-economy mitigation (globally as well as nationally) is achieving deep decarbonisation in line with a WB2C target.

To develop sequestration incentives that account for potential loss of sequestered carbon, Marland *et al.* (2001) reject the asymmetry in emissions and removals in ton-year accounting (like Herzog *et al.*), and develop a liability-based framework of emitters offsetting the debits for their emissions by renting credits from the owner of the sequestered carbon, based on continuous ownership and responsibility for the sequestered carbon (transferrable through sale). An alternative, though again similar proposal is for a system of 5 year 'expiring credits' based on “clear and strict” rules, again dependent on strong MMV, to enable proof of sequestration validity (Maréchal and Hecq, 2006).

For land carbon storage alternatives of forest management and agricultural tillage, Kim *et al.* (2008) find that sequestration payments may require a non-permanence discount of 50% (valued at 50% of the carbon price) – due to the ease of re-emission – and these “offsets” may well be worthless if carbon prices escalate at or near the discount rate because rising price result in rising ‘buyback’ liability costs for the sequestration owner and high payments to carbon stock owners to maintain stored carbon. Agreeing with Herzog *et al.* (2003), only a dependable backstop technology (like CCS) to provide very-near permanent storage enables land-carbon sequestration to be worthwhile even in the near- to medium-term.

In summary, particularly in land-based NETs, carbon pricing needs to account explicitly for non-permanence in sequestration, and define the reliability and costs of backstop technologies including BECCS and DACCS. The IPCC AR5 Working Groups Guidance Note for Lead Authors states:

> *… low-probability outcomes can have significant impacts, particularly when characterized by large magnitude, long persistence, broad prevalence, and/or irreversibility.* (Mastrandrea et al., 2010)

Non-permanence of carbon sequestration is dependent on the type of carbon storage but, particularly in the case of terrestrial carbon stores, can have a high probability of reversibility with significant magnitude of persistent climate effect. Given the policy focus on land sequestration as opposed to geological storage (CCS), the apparent lack of recent attention to this issue for carbon storage of all types is concerning and needs further assessment.

6.7 Market mechanisms for climate mitigation

International carbon markets and international emissions trading theoretically minimise mitigation cost by directing funds to the most efficient and cost-effective interventions. Using a CEA IAM, Hof *et al.* (2017) find that allowing emission trading would be about half as costly for the more sustainable SSP1 assumption than for the SSP3 assumptions of fast expanding population, weak economic growth, and high inequality. In this socioeconomic modelling, emission trading with a uniform carbon price greatly reduces global costs for the NDCs – by more than half for the unconditional NDCs and by less than half for the conditional NDCs (2017). It is much more expensive to meet 1.5ºC or 2ºC pathways by 2030 (twice and 5 to 6 times as high, respectively) than to meet the conditional NDCs but this effort is now required if the Paris temperature goals are to be met (2017). The flexible mechanisms developed under the Kyoto Protocol, including the Clean Development Mechanism, have supported its economic viability but their environmental and decarbonisation effectiveness is contested (IPCC AR5 WG3, 2014, p. Ch. 13.13). Despite sixteen compliance carbon markets in operation around the world, and more planned, Pearse and Böhm (2014) emphatically argue that carbon markets are a very poor climate policy choice. Ten theoretical and empirical criticisms that undermine the standard economic rationale are described including: ineffectiveness, fraudulent credits, lack of additionality, evasion of responsibility by richer nations, acting as a fossil fuel subsidy, supporting regressive carbon taxation, and endorsing a highly contested view that natural capital such as forests can be priced. The EU ETS is given as one example of carbon markets as an obstacle to effective mitigation by forming a political barrier and an evasionary compliance mechanism through buying carbon credits of sometimes dubious value from brokers and speculators in markets that can obstruct and delay other more meaningful domestic action to enable decarbonisation, such as actions to ensure energy transition. Spash (2010) similarly concludes that theoretical claims of the mitigation cost effectiveness of carbon trading are heavily undermined by strong uncertainty and high complexity which perpetuate path dependant control and profit-taking that distract and detract from necessary system and behavioural change in nations.

Futures contracts are a market instrument that could enable polluters to buy units of CDR at a fixed price per tonne of CO_2 and allows trading of such contracts as mitigation prices change, but there may be a large potential for market failure unless the long-term security on CO_2 storage can be guaranteed by sovereign states, perhaps by issuing state-backed futures for land and geological carbon sequestration (Coffman and Lockley, 2017). From a social research perspective, Leijonhufvud and Fitts (2015) suggest an optimistic view that capital markets may be a key in addressing climate change, if pressure from long-term investors and the divestment movement can result in risk management reflecting climate and other long-term risks, reform of investment reporting standards, and much stronger regulatory oversight of the finance and investment industry. However, analysis by Strand (2016) suggests that a nation with future expectation of climate finance payments for mitigation or binding climate treaty regulation then has an economic incentive to deliberately increase near-term emissions and maintain them at a high level, thereby increasing the likely level of future payments and boosting apparent difficulty and cost of mitigation. Shielding high emitters from near-term costs is similarly prone to failure unless very clear baselines and pathways are specified as early as possible (Leijonhufvud and Fitts, 2015). This finding, illustrating the near-term advantages to actors gaming carbon management systems, is clearly at odds with the reality of much climate policy, for example the sector-specific privileges and credits given to sectors and higher polluters in the EU ETS and by rules in individual EU Member States. Furthermore, Leijonhufvud and Fitts (2015) find that economic analysis suggests that likely inertia in the ability to adjust energy emissions downward, due to infrastructural carbon commitment, implies a need for significant national carbon taxation in addition to climate finance to drive sufficient mitigation.

6.8 Accounting for biogenic carbon in bioenergy and negative emissions policy: problems and solutions

Negative emissions make it notionally allowable for cumulative CO_2 emissions to exceed the nett global carbon budget, with a (temporary) overshoot of atmospheric CO_2 concentration targets (Vuuren et al., 2013); but carbon accounting needs to accurately account for the subsequent removals required to correct this overshoot. BECCS is particularly important in AR5 Database 2ºC IAM scenarios as it provides both energy and negative emissions (Fuss et al., 2014a). In IEA-funded research, Zakkour *et al.* (2014) examine the ability of current GHG accounting frameworks to record and incentivise negative emissions from BECCS. Current GHG accounting rules include: UNFCCC inventories for developed Parties, based on the *2006 IPCC Guidelines for National Greenhouse Gas Inventories*; project-based schemes such as those in the Kyoto Protocol's CDM; regional carbon market rules as in the EU ETS; and product-based schemes including market portfolio carbon emission standards. In cap-and-trade schemes where emission rights are 'surrendered', usually on an annual basis, baseline mechanisms do not usually enable credits to be generated for below zero emissions, unlike project-based schemes that can theoretically recognise negative emissions based on actual emissions and removals (Zakkour *et al.* 2014).

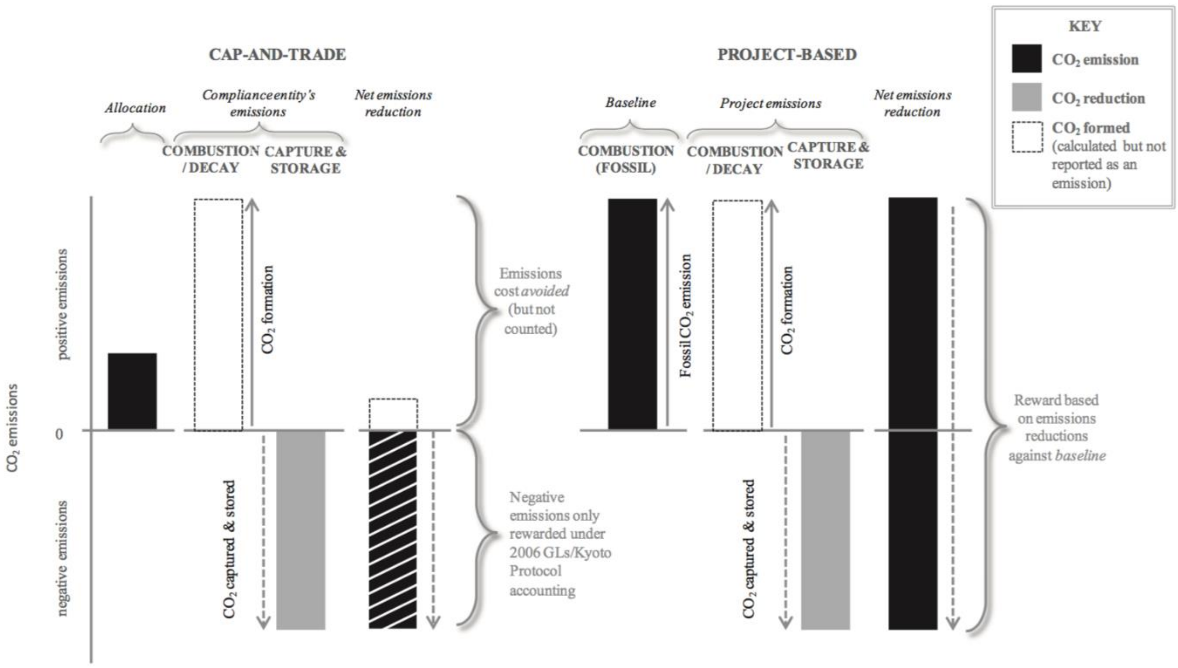

Figure 6.4: Negative emissions accounting in cap-and-trade compared to project-based schemes. Reproduced from Zakkour et al. *2014.*

In the EU ETS and other cap-and-trade schemes, the 'compliance entity' is usually a single facility within the whole international scheme, making this kind of framework unsuitable for pooling negative emissions or CCS removals across multiple facilities or for use in meeting national targets (Zakkour *et al.* 2014). Therefore, in the EU ETS currently, only CO_2 captured from burning fossil fuel in a facility and then permanently (geologically) stored may be deducted from its gross inventory emissions (see Figure 6.4). CO_2 emissions from installations burning biomass exclusively, whether unabated (nett positive) or subject to carbon capture and storage (BECCS, potentially nett negative), are specifically excluded from accounting in the ETS. Even if biomass were co-fired with coal in a single CCS facility, then only a nominal "fossil-fuel-derived" portion of the captured and stored CO_2 could be accounted as deduction from gross inventory emissions (therefore yielding an absolute minimum nett emissions level of zero, rather than negative). This approach in the EU ETS is not accidental, but by design: once a decision was taken that, in principle, all biogenic carbon fluxes should be accounted already, and exclusively, in the LULUCF accounting domain, then any accounting in the energy-combustion-CCS domain would lead inevitably to double counting (whether nett positive or negative within any particular facility or system boundary).

Further demonstrating the effect of current EU rules on BECCS accounting, a report looking a UK policy roadmaps for the UK CCC (Berg et al., 2017) states that:

> *The economics of GGR [Greenhouse Gas Removal] options are typically assessed on the basis of costs per tonne CO_2 removed from the atmosphere. Here it is important to distinguish between costs per tonne of CO_2 mitigated and per tonne of CO_2 removed to account for the carbon-negative properties of GGR options. When discussing remuneration for GGR, this removed CO_2 is often the part that is likely to be financed as it represents the additional benefit compared to traditional carbon abatement measures. This is illustrated in the example of BECCS power co-firing, where one share of the CO_2 removed by CCS is of fossil origin and another is biogenic. Only the latter may count as GGR after supply chain emissions have been accounted for and this should thus also be reflected in the removal costs. (Berg et al., 2017)*

It is notable that both the IEA and UK Climate Change Committee documents implicitly accept the policy-defined carbon neutrality of biomass energy without substantive reference to the abundant literature challenging the reliability of this accounting assumption, specifically the reliance on often weak accounting rules governing carbon monitoring in the extremely complex, and often poorly accounted land use sector, with high uncertainties in sources, sinks and carbon stocks (Colomb et al., 2013).

Forestry modelling assumptions frequently allow inaccurate carbon accounting, failing to include a reference scenario accounting for carbon stock increases in the absence of bioenergy harvest (Searchinger et al., 2009; Ter-Mikaelian et al., 2015). The simplistic carbon neutrality assumption for bioenergy also ignores systemic feedbacks, land use history and feedstock types resulting in potentially major errors in carbon accounting (Haberl, 2013). Searchinger *et al.* (2017) examines studies that estimate large potential for future bioenergy from land use, detailing ways in which they count carbon removals but fail to account for costs including opportunity costs that can appear to overwhelmingly favour solar PV energy production on land rather than bioenergy. However, this generally ignores the fundamental lack of interchangeability between biomass that provides dispatchable energy and variable renewable forms of energy that are not dispatchable. In proper accounting of biomass Searchinger *et al.* state:

> *Like any other offset, an offset by plant growth can only exist if and to the extent the plant growth is "additional" to the growth that would occur anyway. Counting existing plant growth as an offset counts the same*

carbon twice … Bioenergy can only reduce GHGs through plant growth if total plant growth increases globally while also factoring in any releases of stored carbon. (Searchinger et al., 2017, p. 435)

A 2013 European Commission technical report gives a thorough overview of carbon accounting of forest bioenergy (Agostini et al., 2013) pointing out that carbon emissions from bioenergy are treated as carbon neutral in the energy domain, being reported only as 'below the line' memo items in national inventories to avoid double-counting as the emissions are assumed to be already accounted for in reporting of harvest data under the land use domain. However, if longer-rotation stemwood is used then it takes more time for new growth to replenish the lost carbon, which can lead to nett carbon emissions within that period, complexity that may not be fully captured by land use accounting. Woody biomass also emits more CO_2 per unit of energy produced than fossil fuels and greater emissions for biomass also occur due to fuel collection, transport, processing and storage (Agostini et al., 2013). All of these factors have implications for carbon accounting in both climate and energy policy governance. Policy should also note that unless biomass is being reserved for large scale BECCS to enable negative emissions, policy supportive of woody biomass for energy may increase resultant global warming relative to fossil fuel use, reduce carbon stocks and increase energy costs. A key conclusion states:

From the studies analysed it emerges that in order to assess the climate change mitigation potential of forest bioenergy pathways, the assumption of biogenic carbon neutrality is not valid under policy relevant time horizons (in particular for dedicated harvest of stemwood for bioenergy only) if carbon stock changes in the forest are not accounted for. (Agostini et al., 2013, p. 18)

6.9 Mitigation policy additionality in bioenergy production

Bioenergy production may be 'renewable' in the sense of potential regrowth, and also resulting in CO_2 sequestration flows, but that does not necessarily equate to increasing overall carbon stocks to effect climate mitigation, or guarantee stable environmental impacts in avoiding other pollution or land degradation (Searchinger et al., 2017, p. 435). Therefore no assumption of 'sustainability' can be made unless specific accounting is applied to each sustainability claim (Haberl et al., 2012). UNFCCC rules for reporting of land use and energy emissions are only valid at the global scale and can break down when bioenergy resources are traded between nations or if sub-global rules do not treat energy and land-use with equal significance (Searchinger et al., 2017, p. 435). For example, if trees are harvested in the USA and exported as wood pellets to be burned for energy in the EU, the EU ETS assumption of carbon neutrality can only be valid if US land use accounting is sufficiently detailed and dependable, a finding, as in Miner *et al.* (2014), that is strongly contested by US NGOs (NRDC, 2015) and scientists (Agostini et al., 2017).

Moreover, Searchinger *et al.* (2017) examines an intercomparison of 15 IAMs and energy models, finding serious double-counting errors in regard to biomass-related removals and emissions in half of them, and highly optimistic and idealised outcomes in the others. A tonne of CO_2 sequestered by CCS has the same effect on atmospheric concentration regardless of whether the CO_2 is from burning fossil fuel or biomass. Further, biomass has lower energy and is not so easily transported as fossil fuel to a location near geological storage for CO_2, therefore CCS for fossil fuel use should arguably be prioritised over use in BECCS (Searchinger et al., 2017, p. 443). The relevance to governance here is that Searchinger *et al.* conclude that IAM scenarios with large amounts of BECCS necessarily depend on strong (and, by implication, internationally co-ordinated) government regulation of land use to maintain and increase land carbon stocks, and interventions to find "surplus" land for afforestation, often by implicit taxation of ruminant, particularly beef, GHG emissions to free up land at least notional-cost. Contrary to the IEA and CDP[18], Searchinger *et al.* suggest that even if large-scale BECCS may at some point provide aggregate GHG benefits relative to accessing the same energy from fossil fuels (also with CCS), this requires difficult conditions to be met in general: surplus agricultural land (to avoid competition with food production), high yields and prior, or simultaneous, elimination, of all fossil fuel emissions.

One strand of published research suggest that a short-term biogenic carbon pulse of warming due to a permanent increase in bioenergy use is worthwhile based on a longer-term mitigation plan up to 2050 (Lamers and Junginger, 2013), but this appears to be contrary to the current timescale for strong actions (required already up to 2050) to meet the WB2C target. Lamers and Junginger also claim that forest bioenergy, such as that imported as wood pellets from the US, is primarily residue based with a "marginal" (though increasing) role for roundwood. This view appears to be contradicted by photographic evidence submitted to courts and government by scientists and NGOs showing very large amounts of roundwood directed to wood pellet use, and significant deforestation, due to harvesting in the south-east US (Agostini et al., 2017).

Land based NETS including afforestation/reforestation, biochar and soil carbon sequestration depend on land carbon sinks and, like BECCS, depend on biological productivity, therefore integrated land use strategies to achieve increased carbon sequestration require accurate carbon accounting and governance that fully reflect complex sink dynamics and respect the likely need for increased harvesting of net primary production (Canadell and Schulze, 2014). A reliance on land sinks may also be risky as observations, in line with modelling, now suggest the natural land sink may be beginning a long-term weakening, as nutrient limitations reduce the CO_2 fertilisation effect, thereby amplifying global warming itself, and the effects of heat and drought due to warming (Peñuelas et al. 2017).

A literature review by Gren and Aklilu (2016) of economic policy design for support of forest carbon sequestration (capture and permanent storage) compares theoretical policy with practice. The review describes measures to address the uncertainty and differences in forest carbon sequestration due to heterogeneity of land and management conditions, the difficulty in monitoring impermanence over time (due to tree harvesting and natural disturbances such

[18] Carbon Disclosure Project: https://www.cdp.net/

as fires and storms), and the problem of determining *additionality* (ensuring that projects receiving carbon credits for increasing carbon stock, or other carbon-stock-equivalent processes, would not have occurred without the credits). Ideally carbon prices would need to be uniformly applied to address heterogeneity in land types. Stringent mitigation policy ("hard" emission caps) would then drive demand for 'offsets' from polluters, regulators would become responsible for certifying information, and landowners would be responsible for guaranteeing forest carbon permanence. In practice, payments for monitoring and verifying sequestration, and additionality-confirmation costs, are on a per-project basis, and permanence is credited in some countries on the basis of buffer credits to landowners. In the EU ETS there is a relatively low supply of domestically produced traded forest carbon credits because they are reserved by Member States for national allocations (p. 130). In the proposed 2030 EU Effort Sharing Regulation, quantified allowances ("flexibilities") for forest credits may be allowed in LULUCF carbon accounting: a significant change from the practice under the 2020 Effort Sharing Directive, which did not recognise such credits.

Examining the political economy of biofuel policies, mechanisms and governance in the US, Brazil and the EU, Oliveira *et al.* (2017) find that they originate in energy security and economic concerns, driven particularly by larger corporate interests in concert with government, resulting in state subsidies, fuel-blending mandates and tax credits that benefit these producers. As a result, even for second- and third-generation biofuels, these policies tend to "backfire" (in terms of aggregate social, political climate outcomes) by focusing on technical and legal framing, and actually result in negative environmental and social consequences (2017).

Mander *et al.* (2017) gives a full listing of IAMs' use of key BECCS-related assumptions including details regarding bioenergy potential, CCS capability, BECCS cost, policy supports and bioenergy as a percentage of primary energy, making clear the daunting level of system integration needed to deliver effective CO_2 removal through BECCS, linking up the full biomass supply chain with energy transformation (typically, electricity generation) and CCS. As Mander *et al.* also points out, the political and socio-economic (broadly, governance) assumptions are no less challenging for practical BECCS deployment: bioenergy potential is based on land-use estimates, biomass sustainability criteria, population, diet and global energy demand; global participation in decarbonisation is assumed with effective international carbon pricing; and a global governance system is required to enable the BECCS supply chain and enforce reliable carbon accounting and verification of the putative negative emissions.

Including a BAU land use scenario of tropical deforestation that they argue the IPCC underestimates, Mahowald *et al.* (2017) find the climate system response to cumulative land use emissions may be twice that for non-land use processes because of the effect of fossil aerosols (negative forcing) versus methane and nitrous oxide from land use. This results in 1ºC of anthropogenic global warming by 2100 from land use and land cover change alone, even without further fossil fuel emissions, requiring urgent, globally coordinated policies (including dietary change and reversal of deforestation) to reduce emissions if the Paris limit of keeping warming well below 2ºC over pre-industrial is to be avoided.

6.10 Mechanisms addressing emissions embodied in trade

Under UNFCCC accounting rules emissions are inventoried by each party (nation state or regional bloc) on a territorial basis and mitigation targets in Nationally Determined Contributions then relate to reducing such domestic/territorial emissions. As mitigation policies and production costs vary between nations there may be incentives for “carbon leakage”: production of goods and services may migrate to a country with lower production costs (possibly based on weaker regulations, including climate policies) potentially causing emissions to rise overall (the apparent emission reduction in one territory “leaks” into higher emissions from another). Border carbon adjustments (BCAs), levying duties relative to embodied carbon, have been proposed as a possible remedy but Sakai and Barrett (2016) argue that this would be a complicated, ineffective and expensive corrective policy relative to carbon priced ‘offset’ policies such as the Clean Development Mechanism (CDM). That said, the CDM has itself been subject to strong criticism due to non-additionality and over-claiming of emission reductions (Carbon Market Watch, 2013; DG CLIMA, 2017; Pearse and Böhm, 2014). There is no common agreement in research literature on good border carbon adjustment design to ensure effective and enforceable emissions reduction.

Rocchi, *et al.* (2018) undertake an economic analysis using World Input Output Database (WIOD) trade data to examine an alternative carbon border tax (CBT) approach, based on emissions avoided at a product level, taking international prices and differential carbon prices into account in line with current World Trade Organisation practice. A CBT based on product-level emissions is, in principle, simpler than a border carbon adjustment based on embodied carbon as it only needs national data on emission factors by technology. The goods most affected by an avoided emissions CBT would be energy-intensive ones, with high carbon content, and high monetary value electronic products. Rocchi *et al.* conclude that an avoided emissions CBT would allow essential international coordination of carbon pricing between countries that is currently missing from the nationally focussed NDC model of the Paris Agreement. Introducing a CBT might potentially face obstacles under the current WTO legal framework, which is explicitly directed at *lowering* trade barriers and liberalising world trade. However, Weber (2015, p. 417) suggests that in the light of recent WTO cases, which have been based on broader interpretation of the rules, including “exhaustion of natural resources” and health protection, non-retrospective border trade mechanisms such as CBT may be legally achievable within current WTO rules — *if* there were broad international political will to do so.

6.11 Chapter Conclusions on governance and mechanisms:

Governance choices overall are constrained by physical limits first, and political choices second, a fact that can too easily be lost in policy discussions. The physical sciences are pointing to biophysical global boundaries, some of which are already being breached, with societal and economic consequences requiring some combination of governance that enables planning, investment and results to limit future impacts. Carbon (CO_2) governance toward a temperature target requires achievement of a path to zero net emissions within a stated total carbon budget aligned with the target. The Paris Agreement temperature targets scientifically imply ‘total avoidance budget’ ranges for any selected probability of avoiding 1.5ºC or “well below” 2ºC. Although there is no global authority and therefore no integrated approach to global climate governance, we can say that, whatever actual governance coordination does take place, the Paris Agreement implies agreement that international efforts do need to add up “to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity”; and to do so in a manner consistent with the stated temperature goals. Therefore, given the need to meet a zero-sum (and rapidly depleting) global carbon budget, climate action will depend on Parties presenting their understanding of what this means for themselves, how it adds up internationally, and rapidly achieving real results within their own separate jurisdictions; including negative emissions investment and delivery if that is part of any given Party’s plan. Explicit and strengthened accounting mechanisms to address international trade, and emissions from international shipping and aviation (currently excluded from the formal Paris Agreement scope), will be needed in addition to the current focus on single-nation territorial emissions.

This chapter has shown that the large uncertainties in land use carbon accounting, nationally and internationally, undermine generic or simplistic claims of carbon neutrality for bioenergy from biomass, biofuels and biogas. Moreover, science showing that the warming effect of biogenic CO_2 emissions is akin to short-lived climate forcings like methane (Cherubini et al., 2014) implies that, even under a speculative assumption that bioenergy related removals can be made additional to existing biogenic flows, a choice to use increased amounts of unabated bioenergy has significant 20 to 40 year warming effects that are important in a 2ºC climate action context of limited time for action (Allen et al., 2016).

In the EU ETS and other cap-and-trade emissions control mechanisms, the current inability to account accurately and reliably for putative negative emissions is a serious impediment to developing government- or commercially-funded BECCS. One possible remedy, supported by research, is to change the accounting so that all energy CO_2 is accounted at the “smokestack” (wherever the CO_2 is produced). This would allow emission factors (such as those calculated for bioenergy) to be appropriately accounted and all of the combustion/oxidisation emissions (nett of any captured CO_2 delivered to reliable, permanent storage) appropriately accounted for *within* the energy sector. Future land use sequestration to retrieve the same amount of CO_2 is far more uncertain, but potentially could be given certified sequestration factors according to land use and the quality of carbon stewardship but only on the basis of provably containing accurately monitored carbon stocks. In a reformed ETS, revenues from levying the ETS price on all CO_2 emissions, including from bioenergy, could then be used to reward/incentivise landowners and/or providers of geological storage services, according to the sequestration factor, and, crucially, for *maintaining* an increased stock of carbon storage (subject to reliable monitoring, verification and ongoing maintenance of biogenic carbon stocks). Accounting for bioenergy in this way (Haberl *et al.* 2012) could also incentivise negative emissions in BECCS through net energy-biomass accounting to include both biogenic (soil and biomass carbon) and geological carbon storage.

Progressing bioenergy systems towards negative emissions may increase potential savings through replacement of fossil fuels with BECCS in a recast European ETS and Renewable Energy Directive aligned with achieving the Paris Agreement mitigation objectives. Landowners would then have additional economic choices between forms of conventional, but GHG-intensive, agriculture, which might incur GHG taxes, and carbon sequestration and storage in forestry biomass and soils, and/or growing dedicated energy crops enabling lower-carbon energy (if unabated) or carbon-negative energy (with BECCS). In the specific case of Ireland, such choices for land use, combined with sustainability criteria, may offer an opportunity to maintain the viability of the rural economy in an increasingly likely future of market prices that will incur regulations or taxes based on nett GHG emissions.

The striking lack of IPCC assessment and national policies looking at non-permanence of land-based (biomass and soil) carbon sequestration, requires attention. Research literature shows that non-permanent sequestration without a backstop technology like geological storage (CCS) is of limited value. To be of properly effective, stringent Measurement, Monitoring and Verification (MMV) is needed for land use carbon accounting to test additionality and to monitor carbon fluxes, land use change and forestry harvests. Although land use carbon sequestration in soils and trees has relatively low opportunity costs, the level of MMV required is likely to have high transaction costs and the co-requirement for CCS as a backstop technology effectively adds to the actual opportunity cost. For soils in particular, given the clear separate benefits of soil improvement, the effort to ensure additionality for claimed carbon sequestration, the danger of future disturbance leading to carbon losses, and the need to perform the required level of MMV, militates against soil carbon as a reliable or cost-effective element of sequestration planning and policy. For forestry, the necessary increase in MMV might be less costly but costs similarly add up.

If credits are to be allowed for negative emissions (on land or geologically) then sequestration removals need to be treated as a permanent liability for the carbon storage owner with a best-estimate required for expected price path matching the effectiveness of the CDR's sequestration through time. This is essential so that the owners of the liability (including governments) and any potential buyers or insurers have sufficient information for due diligence. The value of the sequestration can then be properly accounted in meeting emissions budgets and in receiving payments from emitters.

7 Ireland's Emission Profile, Projections and Policy

Summary

- Total Irish GHG emissions in 2016 were 61.1 MtCO_2e, of which energy and process emissions were 39.9 MtCO_2. Ireland has a large proportion of non-CO_2 emissions including 18.6 MtCO_2e of methane and nitrous oxide, particularly from a ruminant livestock-dominated agriculture sector.
- Ireland's emission accounting is reported by the EPA in the annual National Inventory Report and Common Reporting Format data tables.
- Recent history shows that Ireland's emissions are strongly correlated with economic trends.
- Based on existing policies, and economic growth outpacing improvements in carbon intensity, emissions are projected to rise to 2035 in both 'With Existing Measures' (WEM) and 'With Additional Measures' (WAM) scenarios.
- Electricity generation, transport, manufacturing and industrial emissions are projected to rise by over 20% to 2035. Agriculture, residential and commercial emissions are projected to flat line at 2015 levels to 2050.
- Assessed nett land use emissions in 2015 for all GHGs were 4.2 MtCO_2e including emissions of 5.9 MtCO_2e from grassland, 2.6 MtCO_2e from wetlands and nett removals of 4.3 MtCO_2e due to forests. Nett CO_2-only emissions from land use were 3.7 MtCO_2.
- Ireland's Kyoto first period target was an allowed increase in whole-economy emissions of 13% relative to 1990 for average 2008 to 2012 emissions. The target was met (largely due to the economic downturn over this period).
- The EU 2020 and proposed 2030 targets, relative to 2005, separately cover aggregate sectors for the Emissions Trading Scheme, ETS (an EU wide target) and non-ETS emissions (legally binding national targets).
- The 2014 National Policy Position (NPP) states mitigation objectives of an 80% reduction relative to 1990 for energy CO_2 emissions and "an approach to carbon neutrality in the agriculture and land-use sector, including forestry". A (tacit) policy of little or no mitigation in the agriculture sector implies an expectation of correspondingly larger reductions in energy and process CO_2 emissions, potentially becoming nett negative.
- Low carbon transitions in modelling or suggested by policy analysis generally use linear or piece-wise linear pathways to meet these end-point targets, thereby tacitly increasing the fractional year-on-year effort over time.
- Ireland participates in the Paris Agreement process via the EU-wide NDC. Current Irish policies, falling short of EU commitments, are not aligned with this NDC; furthermore (and more seriously) the current NDCs collectively fall far short of meeting the Paris temperature goals. Good faith participation in the Paris Agreement process implies radically more stringent reductions in nett emissions (incorporating use of NETs or otherwise) at both EU and member state levels.

7.1 Introduction

Ireland's GHG emissions are higher than the EU28 average with an unusual emissions profile compared to other EU member states. Transport CO_2 emissions are high and overall GHGs are much higher than average per capita non-CO_2 gases particularly due to methane and nitrous oxide emissions from agriculture (including over 7 million beef and dairy cattle). In 2016, total annual GHG emissions of 61.1 $MtCO_2e$ comprised: approximately 39.3 $MtCO_2$ emissions from energy use and industrial processes; 19.6 $MtCO_2e$ from agriculture, particularly due to methane and nitrous oxide emissions from ruminants and fertiliser use; 1.3 $MtCO_2e$ from F-gases; and 0.9 $MtCO_2e$ from waste (EPA, 2017a, pp. 1990–2016). In 2015, nett CO_2-only land use emissions were 3.7 $MtCO_2$. As shown in Figure 7.1 (EU EEA, 2017), per capita emissions by greenhouse gas and compared to the EU28 average were: carbon dioxide 8.26 tCO_2 (EU28: 6.87 tCO_2); methane 2.85 tCO_2e (EU28: 0.90 tCO_2e); nitrous oxide 1.52 tCO_2e (EU28: 0.46 tCO_2e); and fluorinated gases 0.26 (EU28: 0.23 tCO_2e).

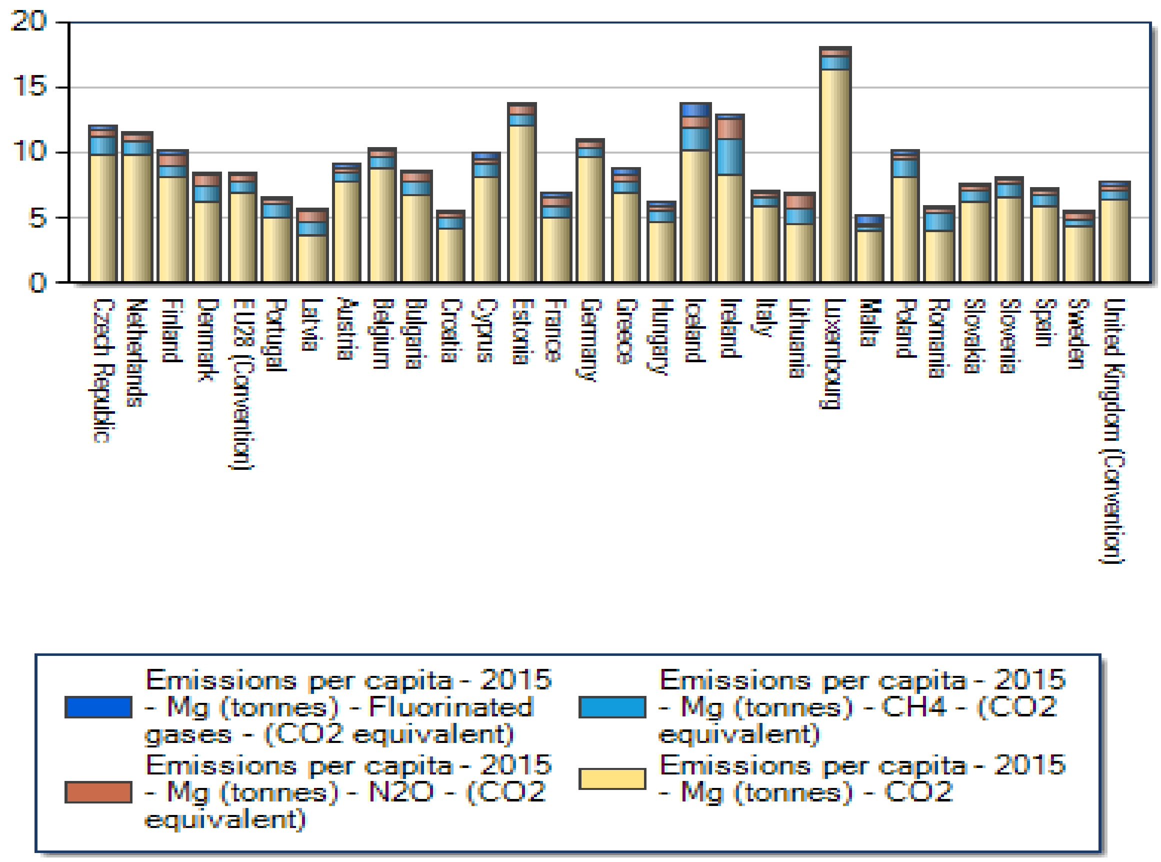

Figure 7.1: EU28 Emissions per capita by country and greenhouse gas. Reproduced from (EU EEA, 2017)

Ireland's recent CO_2 emissions are placed in a global context in Figure 7.2, showing the stronger effect of economic growth and downturn in Ireland compared to other OECD nations. Emissions increased rapidly from 1995 to 2008, and fell dramatically following the global financial crisis. The relatively stable per capita emissions of OECD nations and the recent increase in non-OECD nations, evidences the difficulty for all nations in reaching nett zero CO_2 to meet climate targets, but especially for OECD nations with high existing per capita emissions.

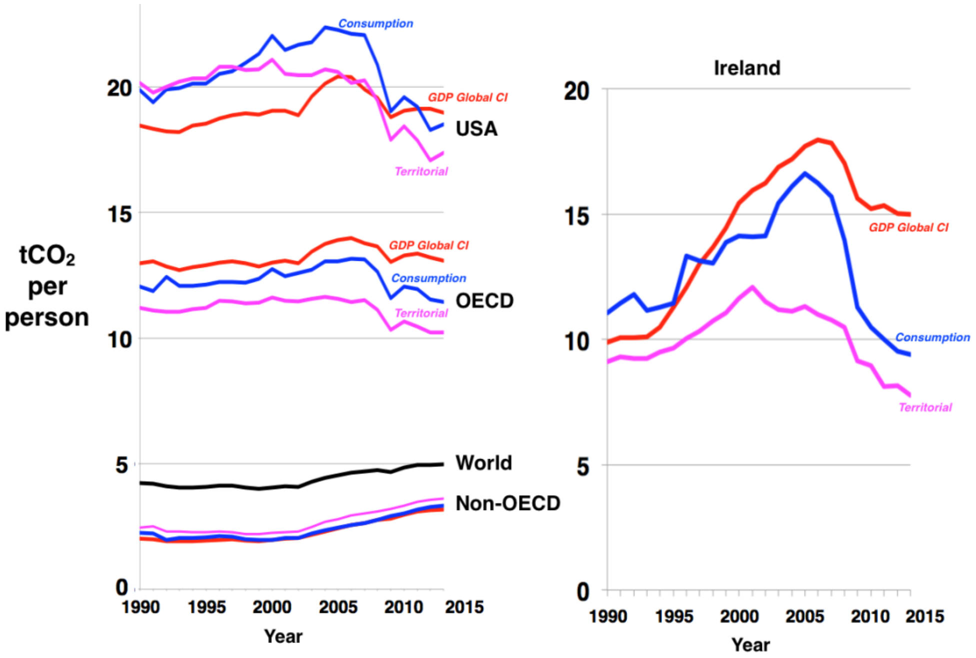

Figure 7.2: Ireland's per capita CO_2-only emissions, 1990 to 2013, compared with global data (sourced from Global Carbon Project, 2016). Territorial emissions are as reported to the UNFCCC; consumption emissions account for total CO_2 nett of imports and exports; and GDP Global CI (carbon intensity) shows group or national per capita in terms of GDP multiplied by the average carbon intensity of global GDP giving an indicative measure for global comparison.

This chapter gives a more detailed description of Ireland's emissions (based on EPA inventories and annual updates); examines Irish and European climate policy to mitigate GHG emissions; summarises published modelling and analysis of the mitigation potential for Ireland and its sectors; and briefly describes Ireland's projected emissions, and planned mitigation policy under the 2017 National Mitigation Plan (DCCAE, 2017a). The concluding focus, on policy goals relative to Ireland's past and projected cumulative emissions, provides a basis for Chapter 8, which estimates carbon quotas that could guide Paris-aligned mitigation policy. Chapter 9 will cover the literature on the potential in Ireland to deliver NETs to assist in closing the mitigation gap that may need to be filled by delivery of CDR by NETs, in addition to achieving other deep decarbonisation measures.

7.2 Ireland's Emissions Profile and Accounting

7.2.1 EPA Emissions Inventory Accounting

The Environmental Protection Agency is responsible for Ireland's emissions accounting by producing an in-depth National Inventory Report (NIR) and Common Reporting Format (CRF) data for the annual monitoring submissions to the UNFCCC and Kyoto Protocol. This accounting also provides the basis for additional reporting to the EU Greenhouse Gas Monitoring Mechanism Regulation (MMR) that is available online from the European Environment Agency[19], along with other environmental data sets (EEA, 2017). The NIR is usually published in May and covers emissions up to the year-but-one prior to publication: so the EPA's 2017 NIR covers emissions from 1990 to 2015 inclusive (EPA, 2017b). All annual NIRs, supporting CRF spreadsheets and summaries are available online from the EPA website[20].

A basic provisional summary is provided earlier than the NIR release, usually in November of the year prior to the final Report's publication, including a comparison of Ireland's emissions and particularly detailing progress relative to applicable EU targets. As discussed further in the next section, EU emissions are assigned between: the EU's Emissions Trading Scheme (ETS), covering facilities such as power plants with large emissions, and non-ETS emissions that are intended to be reduced through member state actions according to national targets set out by EU Directives and Regulations. 1990 is the base year for UNFCCC emissions and the EU's Nationally Determined Contributions. However, the base year for EU ETS and non-ETS policy is 2005 when the ETS system was formally initiated. Both of these base years are therefore referenced in EU targets and in the EPA's provisional summaries.

Each NIR is produced in line with the UNFCCC detailed reporting and quality assurance requirements, and provides complete coverage of domestic GHG emissions (carbon dioxide, methane, nitrous oxide and F-gases) and Ireland's Kyoto Protocol LULUCF inventory. Indirect GHG emissions are recorded in the inventory, including nitrogen oxides (NO_X), carbon monoxide (CO), volatile organic compounds (VOC) and sulphur dioxide (SO_2). As discussed in Chapter 1, UNFCCC reporting continues to use a potentially misleading GHG equivalence factors, with global warming potential values from IPCC AR4 (EPA, 2017c, p. 10). The updated AR5 GWP_{100} factor for one tonne of methane has increased from 25 to 34 tCO_2e. If the updated value is incorporated into future UNFCCC accounting, and GWP_{100} continues to be used, this would raise Ireland's reported recent and projected annual national, and agriculture sector, emissions by 3-5 $MtCO_2e\ yr^{-1}$.

Sectoral overviews and trends are described in detail in the NIR for energy emissions (energy industries including public electricity, manufacturing and transport), industrial

[19] http://www.eionet.europa.eu/

[20] http://www.epa.ie/climate/emissionsinventoriesandprojections/nationalemissionsinventories/

processes (including cement and lime, chemicals and metal production), agriculture (particularly methane from ruminant enteric fermentation and manure; and nitrous oxide from fertiliser use and livestock manures), land-use, land-use change, forestry and waste. Emissions due to international aviation and shipping (collectively known as 'bunkers'), and biomass combustion (mainly due to co-firing in Ireland's three peat burning power plants), are recorded as "memo items" in national reporting. These 'below the line' items do not count toward domestic emissions under current UNFCCC rules, but they are significant when totalled globally and all three are currently projected to rise rapidly in future.

Transport and Energy Industries (mainly electricity generation), each about 12 $MtCO_2\ yr^{-1}$, are the largest CO_2 emitting sectors with other significant energy CO_2 sectors being residential heating (6 $MtCO_2\ yr^{-1}$), manufacturing (4 $MtCO_2\ yr^{-1}$), industry (including cement process emissions) and heating commercial buildings. Ireland's reported emissions profile is unusual relative to other EU countries in having a particularly substantial contribution from non-CO_2 GHGs, especially methane and nitrous oxide due to significant emissions from ruminant agriculture based on rearing cattle and sheep for beef, dairy and sheep meat. Ireland has 5.6 million beef cattle and 1.3 million dairy cattle (Table 3.3A EPA, 2017b, p. 514). This has significant implications for Ireland's climate mitigation options, including non-agricultural emissions within non-ETS accounting, because mitigation options for ruminant emissions are biophysically very limited[21]; therefore it is unlikely that substantial reductions in total emissions will occur unless production of milk, beef and sheep meat is capped or reduced, likely requiring reduced herd numbers (Donnellan *et al.*, 2013).

Consumption emissions (including domestic emissions plus embodied emissions in imports, minus embodied emissions in exports) are not reported in the NIR nor in other EPA reporting, as UNFCCC and Kyoto are designed to depend only on domestic (territorial) emissions. However, consumption emissions estimates for most countries globally, Ireland included, for years since 1990 are available from the Global Carbon Atlas (2016).

Land-use, land-use change and forestry (LULUCF) is reported within six top-level categories of managed land area, each divided between lands still in the same use as before 1990 and lands that have changed use since 1990. This accounting enables changes in land-use since 1990 to be tracked and reported according to UNFCCC and Kyoto Protocol rules. Estimates of annual net source and sink flows (emissions and removals) from land are reported in up to five carbon pools (stocks) for each land category: above-ground biomass, below-ground biomass, dead organic matter (litter and dead wood) and soils (EPA, 2017b, pp. 193–195). Combustion emissions from peat extracted for electricity production and

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[21] An analogous argument ("mitigation options are limited") is used explicitly in the discussion of aviation, in particular; and, somewhat less explicitly, for "heavy", non-rail, surface transport (buses, trucks). In all cases, the view based on physical climate science is that a requirement for reduction in absolute emission levels should be included in the suite of mitigation policy options to be considered – possibly implying a need for modal shift and/or an absolute and sustained contraction in total GHG intensive activities.

residential use is accounted under energy and residential respectively in the NIR. However, emissions due to horticultural peat extraction (EPA, 2017b, p. 315, carbon loss estimated at over 1.7 MtC in 2016, equivalent to 6.2 MtCO2), and arising from peatlands drained prior to 1990, do not have to be reported.

Projected emissions are usually published at about the same time as the NIR. The EPA emission projections to 2035 are estimated based on modelling and data provided by government departments and advisory agencies (including the Economic and Social Research Institute for economic data, SEAI for energy and Teagasc for agriculture). As in other EU Member States, two projections are supplied by the EPA for different levels of policy ambition: "With Existing Measures" (WEM), based on the achievement of current primary mitigation policies, and "With Additional Measures" (WAM), based on the achievement of identified additional mitigation policy measures that could further reduce national emissions (EPA, 2017b, p. 315). Significant interacting assumptions regarding future economic growth, energy mix and sectoral policy inputs (such as mode share in transport and herd size in agriculture) must be made to project future emissions based on current factors and past experience. Actual emissions and achieve mitigation are greatly affected by changes in economic performance and in the effectiveness of policy delivery.

The trends in national and sectoral emissions detailed in the following sub-sections are as reported in *Ireland's National Inventory Report 2017: Greenhouse Gas Emissions 1990-2015* (EPA, 2017b). Data are available on the EPA website from this reporting and from the EPA 2017 GHG Emission Projections Report (EPA, 2017c). The NIR's emissions accounting is based on the IPCC's 2006 Guidelines and the non-CO_2 GHGs are expressed in "CO_2 equivalent" (CO_2e) terms on the basis of the GWP_{100} metrics in IPCC AR4.

7.2.2 Trends in National Emissions

The main trends in Ireland's past, recorded total emissions (shown in Figure 7.3) strongly reflect economic and structural trends. From 1990 to 2002 the economy grew strongly and emissions rose rapidly.

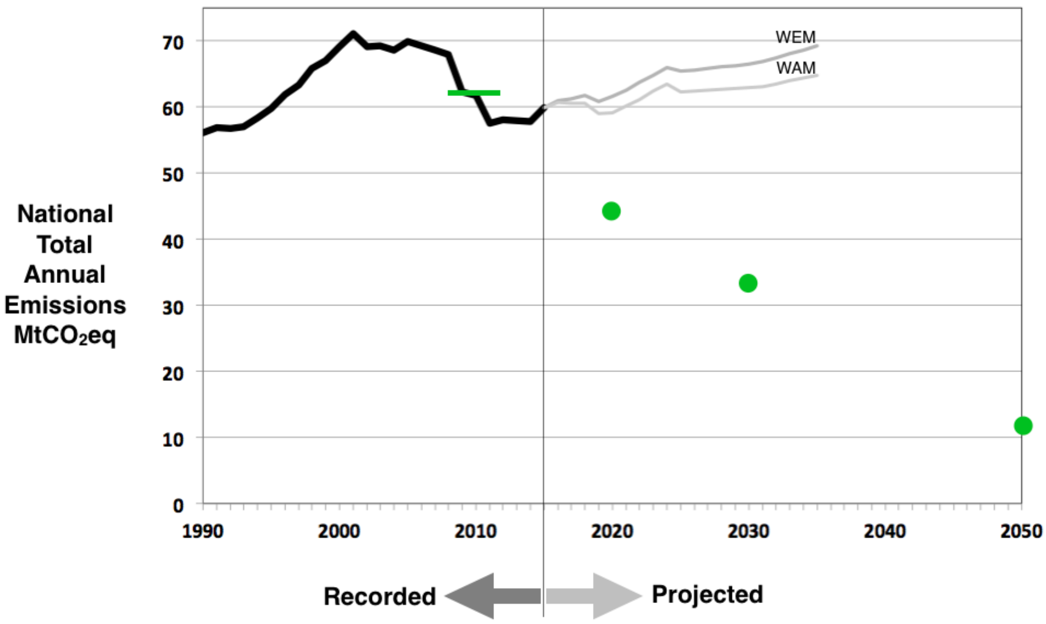

Figure 7.3: EPA data (chart generated from EPA data EPA, 2017a) and in EPA reporting to (EEA, 2017) showing Ireland's total annual emissions (past as recorded and future projected 'With Existing Measures' and 'With Additional Measures'). Green line shows Kyoto first period target level for 2008-2012. Green dots show indicative EU emission targets for Irish emissions of 20%, 40% and 80% below 1990 by 2020, 2030 and 2050 respectively.

From 2002 to 2008, cuts in EU subsidies and the EU milk quota steadily reduced agricultural emissions and a sudden, prolonged flat-lining of exports, see Figure 7.4, stabilised emissions to 2008. Then the Irish banking collapse and global economic downturn caused Ireland's emissions to fall rapidly by an average 5% yr^{-1} to 2011. Emissions then stabilised up to 2014 with emissions beginning to rise again thereafter due to economic recovery and export-focused policy measures, particularly in agri-food production expansion for exports driven by government-backed industry policy. Irish climate policy does not appear to have acted as a determining constraint on overall emissions at any point (as compared to the effect of wider economic conditions). EU policy in constraining farm production after 1998 does appear to have reduced agricultural emissions noticeably. EPA model projections to 2035 (see Figure 7.5) appear to echo historic emissions trends, implying that – absent a significant change in societal/political priorities – national emissions will not be effectively constrained by existing or proposed decarbonisation policies.

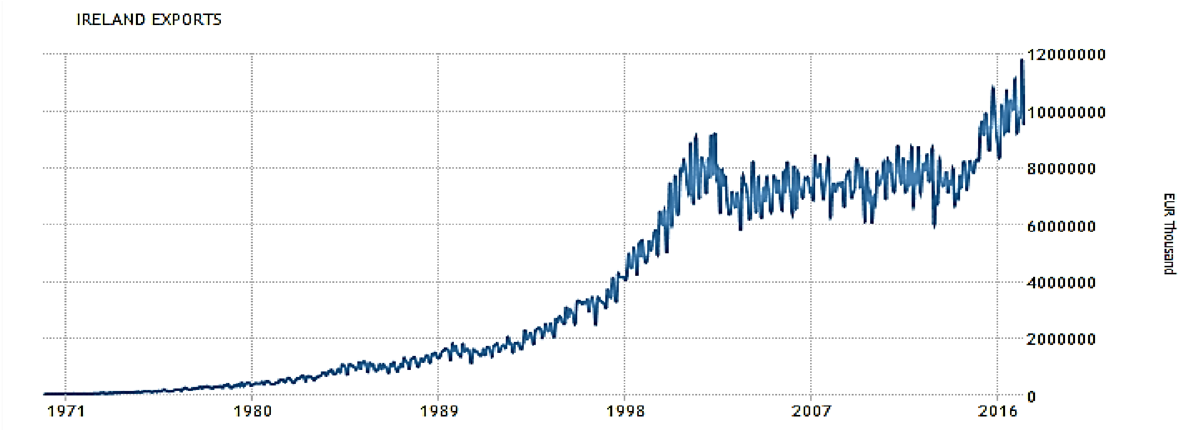

Figure 7.4: Ireland exports in € thousands, CSO data (chart by, Trading Economics, 2017)

In 2015, NIR national emissions were 59.9 $MtCO_2e$, 6.7% greater than 1990 emissions but 15.8% below peak emissions of 71.1 $MtCO_2e$ in 2001 (EPA, 2017b, p. 24). The GHG-specific proportions of CO_2e emissions in 2015 were: CO_2 64%, CH_4 23%, N_2O 12%, and F-gases 2%. Sectoral emissions, as proportions of the national total, were Energy (including electricity, buildings, transport and industry) 61%, Agriculture 32%, Industry 5% and Waste 1.6%. Uncertainty levels are reported in the EPA 2017 Inventory in Table 1.12 with and without LULUCF. The overall uncertainty in the absolute inventory total is estimated to be 10%, mainly due to uncertainties in estimating agricultural and soil emissions; the CO_2 emissions from energy data, being based on fossil fuel consumption data, are generally more accurate and reliable.

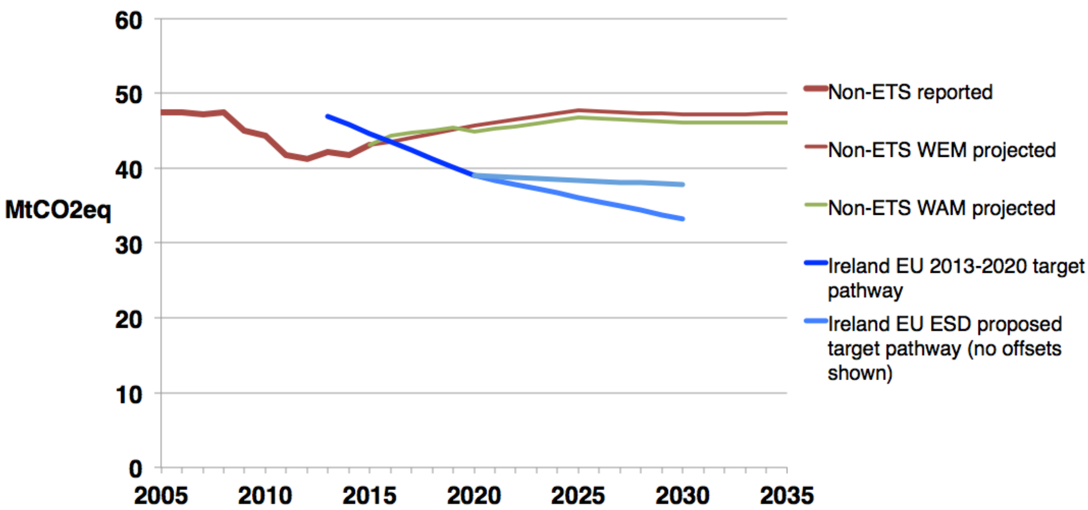

Figure 7.5 Comparison of recorded and projected Non-ETS data with Ireland's 2013-2020 pathway of reductions and with the proposed EU ESD pathway to 2030, with and without the proposed offsets in ETS and land-use (generated from EPA, 2017c). The effect of the economic crisis after 2008 is apparent. As projected emissions are expected to flat-line so no absolute mitigation of emissions is anticipated given current and proposed policies.

As of 2017, the EPA project that Ireland's emissions will increase rapidly with continuing economic growth, and national non-ETS emissions will likely be only 4-6% below 2005 by 2020 (EPA, 2017d), compared to the agreed EU target of a 20% reduction (EU Commission, 2017a). By 2020, transport emissions are projected to grow by 10-12% (1.2-1.4 $MtCO_2e$) and agriculture by a further 4- 5% (0.8-1.0 $MtCO_2e$) relative to 2015. Non-ETS emissions (see Figure 7.5), are expected to do no better than flat-line until 2035 and are likely to grow, thus staying well in excess of EU targets (depending on their final definition). In the ETS sector EU policy targets an EU-wide 21% cut in emissions relative to 2005, and 43% by 2030 (EU Commission, 2017a, 2017b). As shown in Figure 7.6, Ireland's ETS CO_2 emissions fell dramatically following the 2008 economic crisis (25% below 2005 levels in 2015), although ETS emissions are projected to exceed the overall EU-aligned pathway if no additional policies are implemented. Economic and export implications of Brexit do not appear to have been accounted for yet in these projections, and Brexit could impact emissions across some or all sectors.

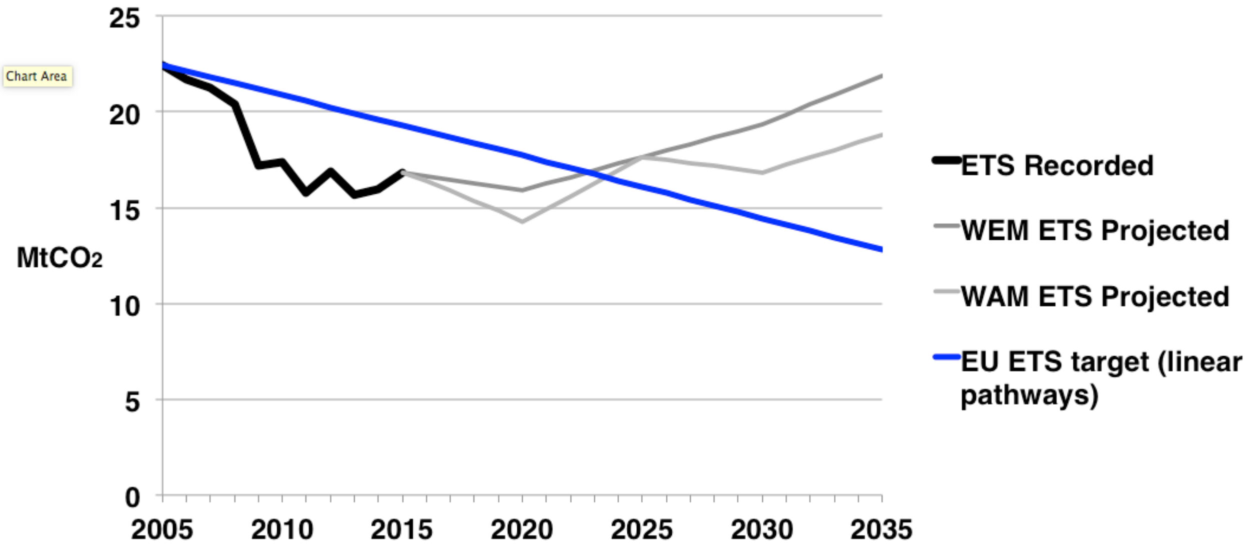

Figure 7.6: Chart generated from EPA data (EPA, 2017c, p. 15) comparing recorded and projected ETS data with the linear EU ETS target decarbonisation pathway (as set for all of Europe collectively).

7.2.3 Trends in Sectoral Emissions

Ireland's past recorded and projected future sectoral emissions are shown in Figure 7.7. Transport emissions increased very rapidly from 5.1 $MtCO_2$ in 1990 to 14.4 $MtCO_2$ in 2007, a rise of 180%. Transport emissions dropped back to 10.8 $MtCO_2$ with the economic recession but are now rising rapidly again. Energy industries emissions are dominated by electricity generation which increased rapidly with economic growth to 2002, thereafter falling similarly rapidly with the increased use of natural gas and renewables, reducing the amount of coal and peat-fuelled electricity generation. Comparing 2015 to 1990 in percentage of generation: gas rose from 27% to 42%, renewables were up from 2% to 17%, while coal use fell from 40% to 25%, and peat from 20% to 12% (see Fig, 17 and Table 7 SEAI, 2016a). Overall, the primary fuel input to electricity generation rose by 71% to a 2001 high of 5,237 ktoe. In 2015, electricity generation consumed 4,500 ktoe of fuel and energy industries emissions jumped 5.4% due to a large (19.4%) rise in coal use for electricity generation at Moneypoint power station.

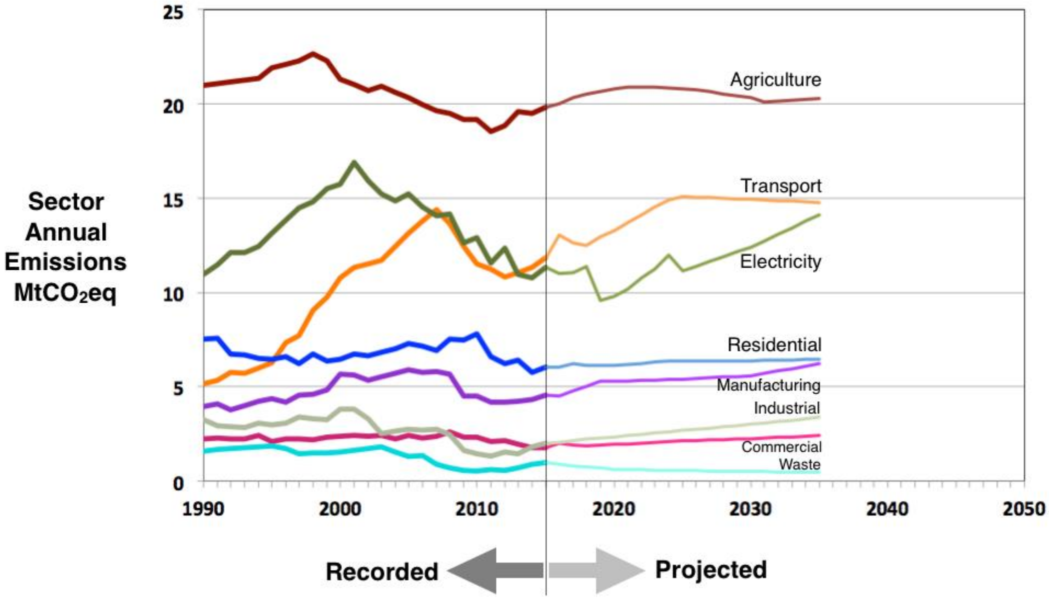

Figure 7.7: Chart generated from EPA data (EPA, 2017a) showing Ireland's sectoral annual emissions (past as recorded and future projected With Existing Measures). For clarity F-gases and non-electricity energy industry are omitted. F-gases: 0.04 MtCO$_2$e in 1990; 1.14 MtCO$_2$e in 2015 and projected to be 0.7 MtCO$_2$e in 2035. Non-electricity energy (petro-refining, solid fuel making and fugitive emissions) averages 0.5 MtCO$_2$e yr-1, steady over the period.

Agriculture has the largest CO$_2$e emissions of any sector (primarily due to methane and nitrous oxide emissions associated with cattle for beef and dairy production). The sector's emissions rose to a peak in 1998 and then fell steadily, apparently as a side-effect of changes in the EU's Common Agricultural Policy breaking the linkage between production and supports, and as a result of the milk quota limit on dairy production. In 2015, agriculture was 33% of total emissions and 44% of non-ETS emissions. Irish dairy production has been particularly targeted for expansion under government-endorsed policies, Food Harvest 2020 and Food Wise 2025, leading to a rapid, ongoing rise in dairy sector methane emissions (Figure 7.8). Nitrous oxide emissions are also rising rapidly with increasing livestock numbers as a result of these policies.

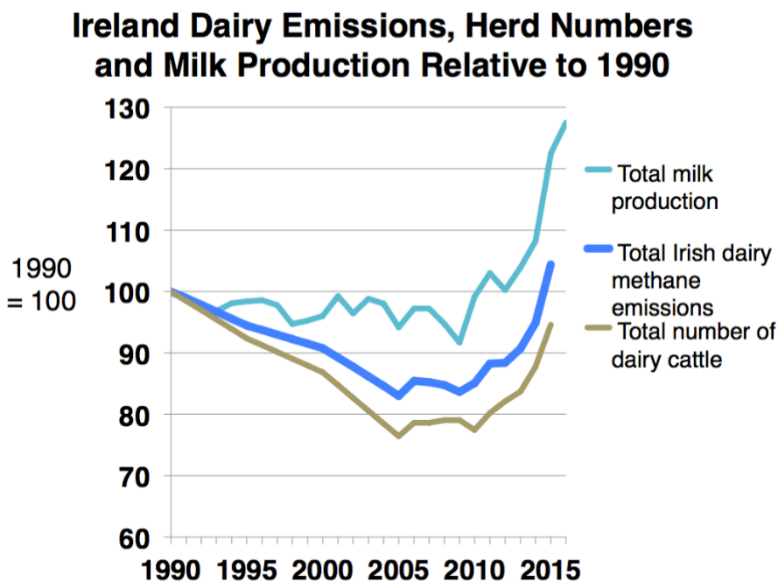

Figure 7.8: Irish dairy industry trends since 1990, indexed to 1990=100. Data from EPA (2017b).

Economic growth and recession appear to have been important drivers of some emission trends in Ireland. Most notably emissions in transport and F-gases continue to be highly correlated with both rising and falling per capita GDP[22]. But other sectors' trends, shown in Figure 7.9, are not so strongly attuned, presumably due to a variety of other factors including: changes in the structure of the economy toward financial and other services, reduced herd numbers in agriculture (until recently) and increased penetration of natural gas[23] and renewables in electricity generation. A further potential confounding factor during this period is the commissioning of the East-West electricity interconnector which has a varying nett emissions effect dependent on the amount of nett electricity imported (or exported) and the associated territorial transfer of emissions reporting.

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[22] Using per capita GDP here attempts to normalise underlying population change.

[23] There is a hard limit to achievable reduction from increased gas: namely, once higher intensity sources (coal, peat) are taken or driven off the system. Beyond that, increased gas consumption will always mean increased emissions (unless gas is then combined with CCS).

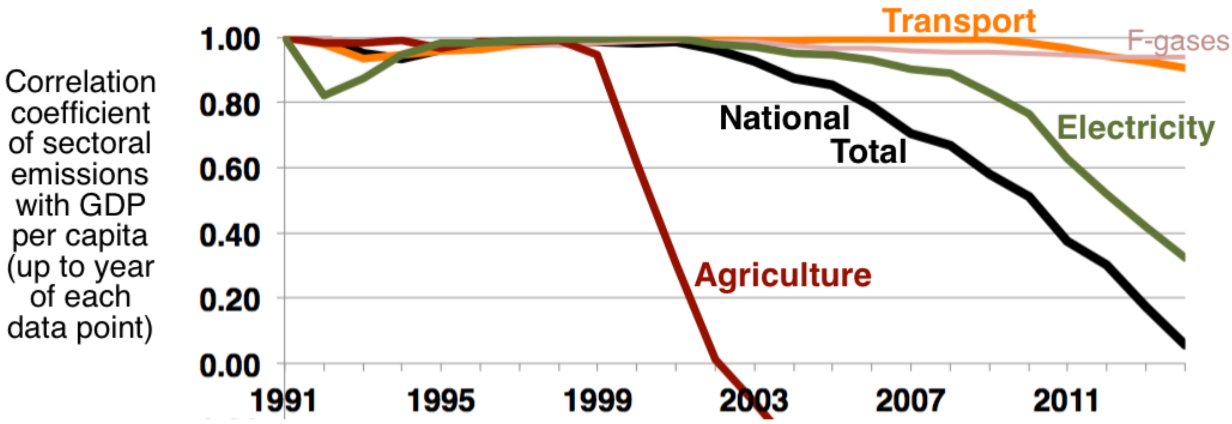

Figure 7.9 Generated correlations of 'Irish sectoral emissions to per capita GDP' showing correlation coefficients from 1990 up to each year to 2014; charted to indicate degree of coupling with economic cycle. Sectors not shown show no strong correlation with GDP per capita over time.

Annual net LULUCF emissions are shown in Figure 7.10, showing that Ireland's LULUCF emissions in 2015 constitute a net source of 4.3 $MtCO_2e$: Grasslands (5.9 $MtCO_2e$) and Wetlands (2.6 $MtCO_2e$) are the significant land-use sources (due to drainage of organic soils); and Forestland (-3.6 $MtCO_2e$) is the significant land-use sink. CO_2 is the major gas in LULUCF emissions and removals, with non-CO_2 gases (methane and nitrous oxide) playing only a small part (see Table 6.2, EPA, 2017b). Trends since 1990 show a reduction in total net LULUCF emissions highly correlate with Forestland planting and timber growth (EPA, 2017b, p. 80). A decrease of 1.2 $MtCO_2e$ in Grassland emissions has been substantially negated by an increase of 1.0 $MtCO_2e$ in emissions from Wetlands.

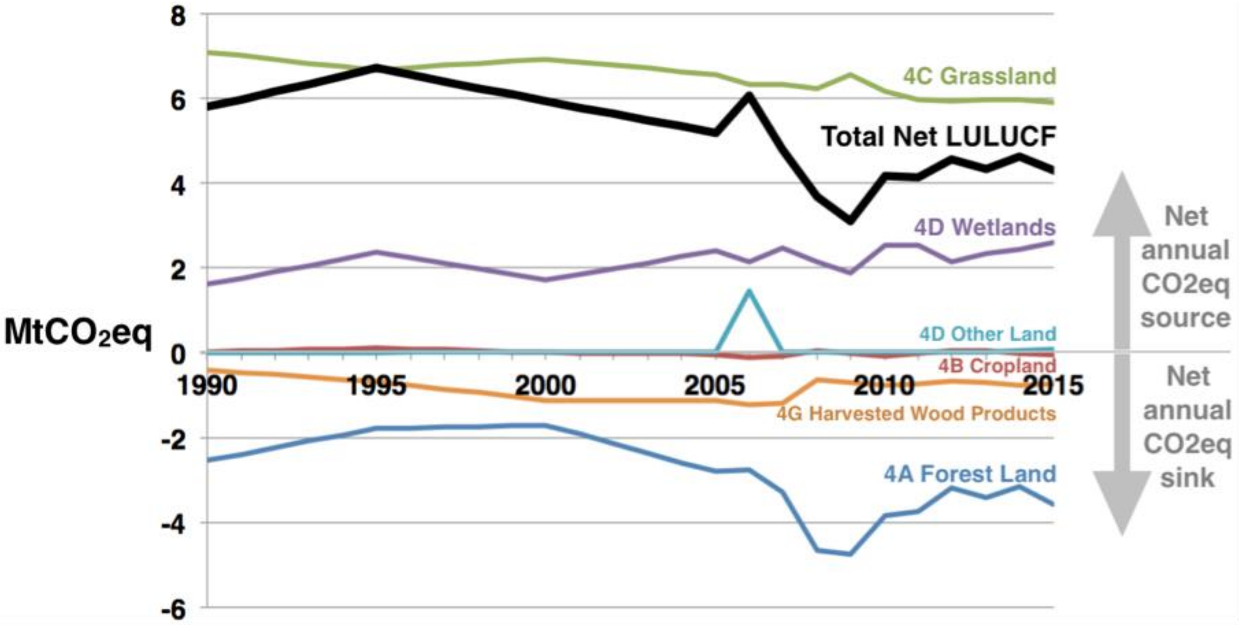

Figure 7.10: Irish LULUCF nett national and sectoral source and sink emissions by land category. (Data from Table 6.2 in EPA, 2017a) Sector codes per UNFCCC accounting.

7.3 Ireland and EU policy for mitigating GHG emissions 1990 to 2020

7.3.1 Ireland and the UN Framework Convention on Climate Change

Ireland signed the UNFCCC on 5 June 1992, ratified it on 20 April 1994 and it entered into force on the 19th July 1994. In 2000, Ireland published a first National Climate Change Strategy (DECLG, 2000) proposing quantified indicative reductions totalling 15.4 $MtCO_2e$ yr^{-1} across all sectors compared to baseline projections to 2010. No binding commitments to emission reduction were made until the Kyoto Protocol to the UNFCCC (adopted in September 1997, entering into force on 16 February 2005) committing developed nations including the EU to achieving specific 'top-down' reductions of domestic emissions (UNFCCC, 1997). The related first commitment period was then set for January 2008 to December 2012. As noted in Chapter 2, the second Kyoto commitment period (identified in the Doha amendment of 2012) never formally entered into force, though the EU 2020 emissions target period is still based on it.

7.3.2 The Kyoto Protocol first period 2008-2012

In participating in the UNFCCC Conference of the Parties, Ireland is both a Party in its own right, and one of the EU member states that form the EU bloc that is also a Party. The global risks and IPCC "reasons for concern", and the EU consideration of the 2ºC limit in 1996 (reaffirmed in 2004/5) as a simplified basis for global and Irish policy to avoid "dangerous anthropogenic interference", are recounted by McElwain and Sweeney (2006). Conducted within the UNFCCC but as a separate agreement among developed nations, the 1997 Kyoto Protocol was the first international commitment made by Ireland and the EU to actually reduce emissions overall. These so-called "Annex-1" Nations were required to limit emissions to below a cumulative target for the period 2008-2012, although 'flexible mechanisms' (international credits for mitigation elsewhere) could be bought to ensure compliance if the target was breached. Within the EU burden sharing to meet the Kyoto targets, Ireland, to support its economic development, was allowed to *increase* annual emissions by 13% for the period 2008 to 2012 relative to 1990, but had already reached this level by 1997 when the Protocol was signed. National emissions continued to rise rapidly until 2002.

In response to Kyoto, Ireland set out the National Climate Change Strategy (DECLG, 2000) detailing cross-sectoral market-based carbon taxation and trading options. It also specified sectoral measures: in energy, an intent to cease coal use at Moneypoint; in transport, modal shift measures supporting public transport and fuel efficiency; in agriculture, a reduction in methane emissions equivalent to 10% reduction in livestock numbers; and in forestry, full achievement of the planting target. Overall reductions of 15.4 $MtCO_2e$ yr^{-1} relative to a reference baseline were targeted. In 2007, the renewed National Climate Change Strategy (DEHLG, 2007) stated that Irish emissions were 25% above 1990 levels (with an economy 150% larger) so it was likely that Ireland would need to buy compliance for exceeding the Kyoto cumulative target 314 $MtCO_2e$ (62.8 Mt yr^{-1}) for 2008-2012. However, due to the banking and financial crisis of 2008 and its aftermath, national emissions dropped rapidly such that Ireland met its cumulative Kyoto target, with the 17.0 $MtCO_2e$ of forest sinks (allowed under Kyoto accounting) cancelling out the 16.2 $MtCO_2$ emissions in excess of the target (Duffy, 2013). Note that this Kyoto accounting carbon sink is for net annual sequestration from Afforestation, Reforestation and Deforestation (Kyoto Protocol Article 3, Paragraph 3, see EPA, 2017b, p. 29), which differs from the net Forestland CO_2e removals shown in Figure 7.10, that also includes forest management of existing woodlands.

7.3.3 The Kyoto Protocol second period: the EU 2020 targets

O'Reilly *et al.* (2012) details the development of the European Union 2020 targets as part of the second commitment period of the Kyoto Protocol, and describes the EU 2050 Roadmap laying out a longer-term European perspective on decarbonisation towards 2050 across different sectors. This research also outlines the Emissions Trading Scheme (ETS), the EU market mechanism to decarbonise major industrial emission sources over time, and the Effort Sharing Decision (ESD) of 2009 (European Union, 2009), the EU policy to reduce non-ETS emissions through individual targets in each Member State. Noting that the EU's 2020 reduction target is not in line with a 2ºC goal, O'Reilly *et al.* (2012) suggest an increase in ambition to a 30% reduction by 2020 would be aligned with achieving a 2ºC pathway though the exact basis for this claimed alignment is not elaborated. The EU's Effort Sharing Decision specifying that "the overall global annual mean surface temperature increase should not exceed 2°C above pre-industrial levels" did include a conditional offer by the EU to reduce emissions by 30% by 2020 relative to 1990, provided that other developed countries commit themselves to comparable emission reductions and that economically more advanced developing countries commit themselves to contributing adequately according to their responsibilities and capabilities (European Union, 2009). However, this offer was not taken up by other relevant countries.

Due to the economic crisis of 2008 and the recession years thereafter, Ireland began the second Kyoto period with national emissions well below its targeted linear pathway of decreasing non-ETS emissions over the 2013 to 2020 period, under the EU's burden-sharing agreement for the Kyoto second period. However, Irish non-ETS emissions have steadily increased again since, due to economic recovery and renewed growth (not differentiated or constrained by relative emissions impact, hence not even relatively decoupled from growth), and also through more specific, policy-directed, growth in agriculture, such that annual emissions will likely exceed the target pathway already for 2017 (EPA, 2017a). Cumulatively Ireland is currently projected to exceed its 2013-2020 ESD target by 12-14 $MtCO_2$e (EPA, 2017e, p. 5).

7.3.4 Ireland and EU Climate Policy Developments Since 2012

7.3.4.1 Ireland's National Policy Position

Announced in April 2014, alongside the heads of a draft climate bill, the Irish government published a Climate Action and Low-Carbon Development National Policy Position (DECLG, 2014). This National Policy Position (NPP) states two separate quantitative mitigation objectives (for 2050) as characterising the intended "low-carbon transition":

The low-carbon road mapping process will be guided by a long-term vision of low-carbon transition based on –

- *an aggregate reduction in carbon dioxide (CO_2) emissions of at least 80% (compared to 1990 levels) by 2050 across the electricity generation, built environment and transport sectors; and*
- *In parallel, an approach to carbon neutrality in the agriculture and land-use sector, including forestry, which does not compromise capacity for sustainable food production. (DECLG, 2014)*

No quantitative indication of a proposed emissions *pathway* toward the 2050 end-point target is given within the NPP (so additional assumptions are needed to infer a specific cumulative carbon quota associated with these objectives). The document does mention the wider context of Irish policy being within the EU objective of reducing GHGs by 80-95% by 2050 compared to 1990, This refers to the EU Roadmap that indicates overall EU emission reductions of 80% or more by 2050, based on significant measures in agriculture (-42% to -49%) and transport (-54% to -58%), and much greater percentage reductions in electricity generation (-93% to -99%), residential (-88% to -91%) and industry (-83% to -88%) (Chiodi et al., 2013b). The NPP outlines a separation between energy and agricultural emissions that cuts across the EU policy target separation between ETS and non-ETS emissions. The NPP's aggregate energy sector, targeting an 80% reduction relative to 1990, includes electricity generation (an ETS sector) as well as 'built environment', presumably emissions due to heating residential and commercial buildings, and transport (both currently almost entirely non-ETS sectors). Electrifying transport and heating sectors would automatically move their accounting into the ETS under current emission accounting rules, so there is a certain logic in the NPP (which extends to 2050) in not distinguishing between ETS and non-ETS.

Apparently omitted from this aggregate NPP energy sector are some non-ETS energy and industry CO_2 emissions from manufacturing, and non-CO_2 from waste and F-gases – possibly representing up to around 4 $MtCO_2e$ of reported emissions in 2015. It is unclear whether this omission has some policy significance, or was merely for simplicity of exposition (with an implication that these other sectors would be subject to comparable reduction targets).

In the NPP, agriculture is given separate status in Irish policy, whereas in EU policy the sector is within the national responsibility to reduce non-ETS emissions in line with the EU's agreed burden sharing for the EU2020 and 2030 targets. This presumably reflects the much larger role of agricultural emissions in Ireland (33% of total emissions) compared to other EU members states. Agriculture's "approach to carbon neutrality" in the NPP appears to assume that forestry sinks, in particular, can be used as an offset to continued agricultural emissions, equated in CO_2e terms: specifically, offsetting methane from ruminants with the CO_2 sink in growing woodland. Other land-use source emissions from Grasslands and Wetlands can be ignored under current UNFCCC and Kyoto accounting if nations opt to do so, as Ireland has done (peatlands cut-away before 1990 are also excluded from land-use change accounting). Despite the agriculture sector's separate treatment within Irish policy, the sector still lies within the non-ETS sector in meeting EU effort-sharing targets, together with the transport and heating sectors, and waste and F-gases. In EU accounting then, any failure to mitigate absolute emissions from agriculture will need to be compensated by correspondingly larger CO_2e reductions in Ireland's other non-ETS sectors, or else compliance costs will become payable for local climate action policy target shortfalls.

7.3.4.2 The EU's (Intended) Nationally Determined Contribution

In March 2015, in advance of the UNFCCC CoP21, the EU submitted its Intended Nationally Determined Contribution (INDC) as its decarbonisation pledge (European Commission, 2015). On the GWP_{100} metric basis, the EU commitment "to a binding target of an at least a collective 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990, to be fulfilled jointly" is declared to be a "significant progression" beyond the EU's 2020 targets and in line with an 80-95% reduction in emissions by 2050 compared to 1990. EU ETS emissions are to decrease by 43% by 2030 compared to 2005, and EU non-ETS by 30%. In the EU's NDC pledge, average per capita emissions in the EU are projected to fall to around 6 tCO_2e by 2050, compared to about 12 tCO_2e per capita in 1990.

7.3.4.3 Climate Action and Low Carbon Development Act (2015)

Ireland's Climate Action and Low Carbon Development Act (Oireachtas, 2015) became law on 10th December 2015 directing the submission of a "National Mitigation Plan (NMP) by 10th June 2017 to be revised at intervals of no longer than 5 years thereafter. The NMP is to specify measures to reduce greenhouse gas emissions toward meeting the National Transition Objective (NTO), which is defined, in Article 3(1), as "the transition to a low carbon, climate resilient and environmentally sustainable economy by the end of the year 2050". No specific quantitative targets are enshrined in the Act. The Government must "endeavour" to meet the objective, ensuring that measures are "cost effective" and can be seen as "having regard to": government climate policy (presumably meaning the NPP in the first instance though, as simply a cabinet decision, this can presumably be arbitrarily modified at any time, as the then Government may determine), mitigation commitments made by the EU or in relation to the UNFCCC, and "climate justice" (no further definition is given). The Act requires the Government to take into account existing State obligations arising from its membership of the EU or under any international climate change agreement ratified by Ireland. The Act also set up an independent Climate Change Advisory Council (CCAC) to review, advise and report periodically on both climate change mitigation and adaptation. The CCAC produced its First Report in December 2015, summarising scientific understanding, global, EU and national policy responses (including the Paris Agreement, EU targets and the National Policy Position) and steps toward mitigation and adaptation (CCAC, 2016). Although not explicitly stated in the Act, the CCAC have equate the NPP's quantitative mitigation targets (quoted above) with what they term the National Mitigation Objective, and take this to be prescriptive for the formulation of the National Mitigation Plan(s), required under the Act.

7.3.4.4 The National Mitigation Plan (July 2017)

The National Mitigation Plan, or NMP (DCCAE, 2017a), states that Ireland's contribution to the Paris Agreement will be through the EU's NDC, committing to an EU-wide 40% reduction in GHG emissions by 2030 relative to 1990, and notes that the EU's NDC will need to increase in ambition over time (p.11). Under the 2009 EU Effort Sharing Decision, Ireland has a non-ETS target of a 20% reduction by 2020 (relative to 2005) but may only achieve 4% to 6% compared to 2005, despite beginning the 2013-2020 period with emissions well below the target pathway due to the economic crisis of 2008-2012. Under the currently proposed 2017 Effort Sharing Regulation Ireland's non-ETS target is -30% but the proposed 'flexibilities' from the land-use sector (5.6%) and potential transfers in credits from the ETS sector (4%) which may possibly reduce Ireland's effective 2030 non-ETS target to just 20.4% below 2005. The NMP is based on the National Policy Position and indicatively shows a linear path of annual reductions of 0.75 $MtCO_2\ yr^{-1}$ from 2015 to 2050 in the NPP aggregate sector of electricity generation, built environment and transport (Figure 2.1 in NMP, 2017). The NMP is based on the Climate Action and Low Carbon Development Act and the 2015 Energy White Paper with an economic objective explicitly stated, though the possible related total emissions in the Plan are not clear:

> *[the NMP] policy will contribute to reductions in Ireland's greenhouse gas emissions and enhancement of sinks in a manner that achieves the optimum benefits at least cost. (DCCAE 2017, 15)*

However, as shown in the projected emissions to 2020 and 2035 (Figures 2.5 and 2.1 in NMP, 2017) Ireland's emissions are on a trajectory of increasing emissions that appears contrary to this declared aim. Toward the 2020 non-ETS target, the likely cumulative shortfall in emissions reductions is 13.7 $MtCO_2$ (Table 2.1 in NMP, 2017), and to between 89 and 113 $MtCO_2e$ in possible shortfall in non-ETS CO_2e quota (Table 2.2 in NMP, 2017)). Two supporting reports for the NMP explore transition pathway scenarios for Ireland, *Low Carbon Energy Roadmaps for Ireland* (ESRI et al., 2013) and *Energy Modelling to Inform the National Mitigation* Plan (Curtin et al., 2017). In an "NMP scenario", non-ETS energy emissions fall 23 $MtCO_2\ yr^{-1}$ in 2020 to 17 $MtCO_2\ yr^{-1}$ in 2030 (Curtin *et al.*, 2017, p. 22) .

A further feasibility study of CO_2 geological storage reservoirs to begin by 2022 is proposed, but CCS is said to be dependent on commercial viability based on a sufficiently high ETS price, which would seem to indicate CCS is only being considered in the longer term beyond 2030 (Curtin *et al.*, 2017, pp. 36, 49, 159). Bioenergy is noted as possibly being "the dominant energy source by 2050, with significant implications for land use and energy security" (p. 22), for heating and transport more than electrical generation (p. 42). BECCS is not mentioned in the NMP. Use of forest based biomass (FBB) bioenergy is projected to double from 15 PJ in 2020 to 29 PJ in 2035 (p. 134) with €132.5 million to be spent on afforestation to bridge a forecast gap in FBB supply by 2020 (p. 146). By 2019 reviews of the future of the coal-fired Moneypoint electricity generating plant and the peat-fired plants are to be completed. Energy storage is referenced as a research subject but no specific projects are mentioned. In transport, which has rapidly escalating emissions, biofuels are advocated as a major part of emissions reduction given the EU RED specification of 10% renewable energy in transport by 2020 (p. 95).

The NMP follows the NPP's "approach to carbon neutrality in the agriculture and land-use sector, including forestry" for Ireland's growing agricultural sector methane and nitrous oxide emissions – particularly due to increased livestock production resulting from industry and government expansion policies. Mitigation in this aggregate sector is anticipated from the forest sector "equivalent to 20-22% of agricultural emissions on an annual basis" (p. 123). Although soil carbon management is mentioned and a long list of other measures for agriculture is given, no other quantified estimate of absolute emissions reductions is mentioned.

7.3.4.5 Literature Critiquing Ireland's Climate Policy

As briefly summarised below, literature relating to Ireland's climate change policy to date generally points to its weak potential for limiting national or sectoral emissions and the EPA finds little sign of decoupling emissions from economic growth[24] and points particularly to concern over future emissions increases in transport, agriculture and electricity generation (EPA, 2016). As described previously, the agricultural sector from 2000-2009 was achieving absolute and relative decoupling of emissions in primarily due to efficiencies being realised, due to the EU milk quota cap, reducing the dairy herd size yet maintaining production, and by the delinking of EU subsidies from food production.

Torney (2017) examines the slow development of Irish climate legislation since the initial National Climate Change Strategy in 2000. Torney finds the progress toward an Irish climate Act to be an example of limited policy diffusion from the UK following the UK Climate Change Act of 2008, affected by limited commitment from political parties and subject to strong counter-lobbying from business and farming groups. Progress was further slowed by the economic and banking crisis and the international political failure to produce a new global climate agreement at the UNFCCC CoP at Copenhagen in 2009. Little (2017), examines climate change policy in the context of Ireland's leading political parties finding that only when the goal of seeking office has aligned with opportunities to progress climate policy have party policies changed. However, intra-party co-operation has been limited, local politics has a considerable role and some topics have typically been ruled out of discussion, for example:

> *Political consensus has also put some climate policy questions – specifically, the question of growing agricultural production and developing new markets for meat and dairy produce – outside the realm of 'reasonable politics' (interview 9). (Little, 2017, p. 215)*

[24] Another relevant policy framing would be to measure the decoupling of domestic emissions from overall economic *activity,* not just economic growth since it is activities (production and consumption) that result in emissions.

Interim and final reports to the Department of the Taoiseach by the Secretariat of the National Economic and Social Council (NESC-Sec, 2012a, 2012b) outlining the "climate change challenge" claim to reframe it as a process of evolutionary institutional learning and bottom-up effort within society, going "beyond compliance". However, Kirby (2013) points out that such 'policy optimism' is strongly at odds with the scientific reality of limits to emissions in line with temperature targets. Limits strongly imply the need for strict targets and monitoring to meet them, as well as strong societal effort both top-down and bottom-up, which challenges the existing political economy of Irish governance that is left uncritiqued by the NESC-Secretariat. Price (2015) also points to the need for governance within carbon limits, without which efficiency savings by local agents (local authorities, businesses, farms or individuals) may be wasted due to rebound effects (more emissions spent on other activities as a result of cash savings being spent by themselves or others free-riding on good efforts). Looking at Ireland climate change mitigation options, O'Reilly *et al.* (2012) suggest a rapid shift to investment in low or zero carbon technologies "is required by 2015" to avoid escalating costs toward a 'GHG neutral Ireland by 2050'. Also recommended are carbon-pricing in non-ETS sectors, private sector engagement and learning projects to better inform policy-makers, arguing that the global demand for climate solutions will create economic opportunities for job creation and 'green growth' (albeit this still arguably understates the scale of the challenge of decoupling even such "green" economic growth from continued emissions growth, given the potential for systemic rebound effects). In contrast, Morgan (2017) is more critical of the existing economic and media barriers to addressing sustainability and climate change, finding that "deep systemic issues" are dominant factors, particularly:

> *The "elephant in the room" of neoliberalism needs to be named as a major obstacle to facilitating individual and societal responses to sustainability. As long as individuals are treated as consumers or commodities, their role in society will reflect this. Likewise, as long as society is treated as a means to an economic end, the behaviours that follow will encourage such arrangements. (Morgan, 2017, p. 42)*

As noted in interviews by Torney (2017, p. 260), and as inferred by the CCAC, the Irish Act's note to "have regard to" "government climate policy" appears to be a reference to the National Policy Position's two driving objectives and is being taken by the CCAC and others to mean Ireland's core mitigation policy. However, McMullin and Price (2017) – noting the problems inherent in assuming negative emissions, accounting differently for different GHG gases, and in the inconsistent treatment of sinks – urge the CCAC to consider the NPP's implicit incoherence, both between the two specified drivers themselves and with the various EU end-date objectives to 2050. The incompatibility of both the NPP and the EU targets with the Paris Agreement's temperature goals (especially the need to increase ambition beyond that undertaken in the pre-Paris INDCS, no later than 2023) is also noted. The scientific and moral need for Irish policy to specify a Paris-aligned cumulative limit on total future CO_2 emissions (as a share of the remaining global carbon budget), or an equivalent CO_2 emissions rate pathway over time, is identified as critical if Irish climate policy is, in good faith, to "have regard to" the Paris Agreement – albeit this legal phrasing has little strength in law (is almost certainly not justiciable).

7.4 Available Modelling and Analysis of Ireland's Mitigation Potential

7.4.1 Mitigation Options Considered in Modelling

O'Reilly *et al.* (2012) mention (citing Resigner *et al.*, 2012) the need for significant levels of net negative emissions globally after 2050 in 450 ppm stabilisation scenarios. As previously noted in Chapter 1.8, scenario analysis indicates that investment in NETs and CCS would need to be followed by actual achievement of negative emissions as soon as 2030 and ramping up annual carbon reduction removal thereafter (van Vuuren et al., 2016). Chiodi *et al.* (2013b) find that an 80% whole-economy emissions reduction by 2050 compared to 1990 is technically achievable in Ireland, provided agriculture can achieve a 50% reduction in its emissions, otherwise negative emissions are also required to achieve that end point. Existing modelling is based on domestic measures to supply low carbon energy and efforts toward achieving demand-side efficiency improvement and achieving demand reduction. Another alternative to local mitigation may be through Irish or EU funding of emission reduction elsewhere (outside the Irish territorial jurisdiction). In principle, given the global mitigation constraint, that may only represent a mechanism for temporary deferral, rather than long term avoidance, of progressively deeper local mitigation (i.e., only while additional, relatively less expensive, mitigation options are still available in other jurisdictions, over and above their own accepted, "equitable", contributions). However, if negative emissions technologies could be deployed at sufficient speed and scale, at sufficiently low cost, and if that service were traded internationally, then that might open a longer-term possibility for continued "purchase" of additional extra-territorial mitigation in preference to deeper local mitigation, according to the differential costs of such technology deployment in different jurisdictions.

7.4.2 The Irish TIMES Model

Based on the widely used MARKAL/TIMES modelling, Irish TIMES is a detailed (partial equilibrium) energy-systems optimisation model specific to Ireland, developed at University College Cork with the assistance of EPA Research funding (Chiodi *et al.*, 2013b). Ó Gallachóir *et al.* (2012) describes the model and its use to optimise energy supply for the Irish economy at least (notional, estimated) cost, under varying assumptions and exogenous constraints (including GHG emissions constraints). Optimising for interactions between all energy system sectors enables assessment of alternative technology choices, energy mix and GHG emissions for different policy scenarios, according to the availability and estimated costs of different technology options. Results are strongly dependent on the assumptions of future economic activities (rates of economic growth or otherwise) and capital and operating costs (including future fuel prices) that drive the model. In general, for UCC's Irish TIMES modelling to 2050, economic growth is assumed to be constant at 1.69% yr^{-1} and total final energy consumption varies between 0.37% yr^{-1} *growth* in a reference scenario and 0.16% and 0.23% yr^{-1} *reduction* in decarbonisation scenarios to show relative decoupling between economic activity and emissions (Chiodi *et al.*, 2013b). Policy and agent 'landscape' effects (the inertia of business-as-usual and entrenched interests, see Li and Strachan, 2016) are not well represented in TIMES modelling so the focus is on technology choices assuming perfect knowledge and rapid response (see Chapter 7 regarding modelling types). As a validity check of the power (electricity) sector results from Irish TIMES the model is 'soft linked'[25] (Martinsen, 2011) to the PLEXOS software, developed by the Commission for Energy Regulation, that models Ireland's gas and electricity system (Deane et al., 2013) with high time resolution. Key model input components to Irish TIMES are energy service demands, fuel and resource supplies and costs, policy scenarios and technologies and their costs (Chiodi *et al.*, 2013b,). There is no elastic demand module so Irish TIMES cannot respond to emission constraints by reducing final demand, only through increasing energy efficiency (reducing primary requirement) or changing technology (Chiodi *et al.*, 2013b).

Initial results based on meeting alternative energy CO_2 reduction targets for 2050 highlighted major challenges for Ireland in meeting the EU's 2050 Roadmap target of an 80-95% reduction in emissions compared to 1990 (Ó Gallachóir et al., 2012). In particular, if agriculture cannot achieve an 80% reduction then even a ~50% reduction in Irish agricultural emissions (as assumed by the EU Roadmap) would require a 95% reduction in energy emissions. Least-cost results for meeting Ireland's 2020 targets (under the EU ESD, the Renewable Energy Directive and longer-term emission targets) suggest a greater emphasis is now needed on investment in renewable heat and transport relative to wind generated electricity[26]. However, this analysis does assume the EU policy position that biomass energy is carbon neutral whereas there is strong scientific critique that makes that position highly questionable.

Papers giving further results from Irish TIMES modelling look at:

- The impact of meeting Ireland's 2020 non-ETS target (Chiodi et al., 2013a). This suggests that the target is "far from cost optimal" for Ireland if a low mitigation potential in the agricultural sector is assumed That is, it suggests that, on the margin, some significant 2020 Irish non-ETS mitigation could be achieved at lower cost in other EU member states (over and above first meeting their own non-ETS mitigation obligations); and that, therefore, it should be cheaper for Ireland to purchase such non-ETS mitigation "credits" from other member states rather than implementing it domestically. It is argued that, as long as the total EU-wide non-ETS target is indeed

[25] Soft-linking or informal linking means that the models are run iteratively and the information transfer between the models is carried out by the user. The soft-link facilitates the use of comprehensive models, as the complexity and running time generally is manageable.

[26] While the 2020 ESD emissions target and the RES renewable penetration target obviously interact in complex ways, from a strict climate point of view – as opposed to a political/economic point of view – achievement of the RES target is not relevant in itself; only the absolute emissions outcome is ultimately relevant.

achieved, then this would be the most "economically efficient" outcome. Note that flexibility for such bi-lateral or multi-lateral transfers, in the interests of maximising EU-wide cost-effectiveness, were explicitly anticipated and indeed encouraged in the provisions of the 2020 Effort Sharing Directive (article 10): but will still represent tangible charges on the Irish exchequer (rather than on the polluting activities themselves).

- Bioenergy's role in least notional cost mitigation scenarios up to 2050 (Chiodi et al., 2015a). This finds that bioenergy could meet half of Ireland's energy needs by 2050; but constraints due to imposition of sustainability criteria and/or reliance on domestic resources would greatly increase energy costs in 2050, the more expensive scenarios then requiring natural gas CCS and variable renewable electricity (wind, solar and ocean) sources to produce hydrogen, and increased end-use efficiency. Constraints on domestic *Miscanthus* production are identified and the difficulty of reconciling beef and dairy industry growth with a low GHG economy is stressed.
- Czyrnek-Delêtre *et al.* (2016) assess the possible impact of direct and indirect land-use change (D/I-LUC) emissions on biofuel usage and costs in Ireland up to 2050. They find a potential decrease of 30% in bioenergy availability and marginal abatement costs increasing by 68% if conservative ILUC emissions are included. Domestic biomass energy crops, such as *Miscanthus*, willow and oilseed rape, are assumed to cause ILUC on the basis that they would displace existing cropland; however, the study apparently did not allow for displacing grassland (and thereby ruminant emissions) on the basis that grassland conversion to arable is restricted to a limited conversion rate under current EU CAP rules.
- Total GHG emission reductions in Ireland of 80-95% by 2050 in line with the EU 2050 Roadmap (Chiodi et al., 2013b). This finds that the Irish energy system would have to deliver a "127%" emission reduction to meet a whole-economy GHG reduction of 80% if agricultural emissions stay at the same level as those likely in 2020; that is, would have to achieve *nett negative emissions* (presumed to be via domestic BECCS or international emissions trading) within the energy sector at 27% of the 1990 level (i.e., c. 8 $MtCO_2\ yr^{-1}$), to be sustained indefinitely. Even with a 50% cut in agricultural emissions by 2050, there would still be a requirement for a 95% cut in energy emissions[27].

7.4.3 Other energy modelling of Irish mitigation pathways

Making numerous substantial assumptions, such as large scale district heating and large scale hydrogen use in transport, Connolly *et al.* (2011) use EnergyPLAN (an energy system analysis tool) to make a preliminary outline of three different 100% "renewable" (not

[27] Though not stated in this study, achieving some level of negative emissions would also go some way to enabling and assisting in policies requiring such nett energy decarbonisation even short of 100%.

necessarily “low-” or zero-emissions) energy systems for Ireland, focused on biomass, hydrogen, or variable renewable electricity. The modelling only looks at resource and technical constraints and does not consider economic cost, business case or other (non-climate) impacts. In another study EnergyPLAN was used to assess the short-term maximum potential wind-energy (annual average) penetration of about 30% in the Irish electricity system up to 2020 (Connolly et al., 2011). For context, the Irish TIMES model (based on Eirgrid analysis) allows an instantaneous maximum of 70% variable renewable energy (Chiodi *et al.*, 2013b,), and Connolly quotes research by Meibom *et al.* that found wind penetration of 42% annual average electricity is feasible in Ireland (Connolly *et al.*, 2011,).

The Sustainable Energy Authority of Ireland (SEAI) undertakes national energy modelling and reporting that also produces inputs to EPA emission projections (see annual “Energy in Ireland” reports SEAI, 2016a). The SEAI energy projection modelling is linked to an ESRI economic model primarily toward assessing future energy supply needs, costs and sources, with emission factors to show energy CO_2. However, analysis showing scenarios and energy projections that would align Ireland’s energy sector and its emissions with Paris-target climate action is missing. Particularly stressing bioenergy development,, recent SEAI modelling publications cover progress toward energy targets on emissions and renewable energy penetration (2016b), a macroeconomic analysis of bioenergy use to 2020 (2015a), achieving Ireland’s EU 2020 renewable heat target (2015b), biogas costs (2017) and energy efficiency (2016c).

7.4.4 FAPRI and MACC Modelling for Agriculture

Teagasc uses Ireland-specific FAPRI-modelling, a partial equilibrium economic model for Ireland’s agricultural sector, to look at agricultural economics, emissions and mitigation costs. Donnellan *et al.* (2013) find that any reduction of Ireland’s national emissions is likely to require agricultural sector emission reductions but Ireland’s Food Harvest 2020 policies do not address this constraint. Eliminating Ireland’s entire suckler herd would still fail to reduce the sector’s emissions by 20%, and a reduction as low as 10% is characterised as “likely to be politically unfeasible” (Donnellan et al., 2014), making the difficult choices in aligning sectoral and climate policy explicit.

Teagasc has also undertaken modelling combining Life Cycle Analysis and the IPCC methodology to assess potential GHG mitigation in Irish agriculture (Teagasc, 2012). These findings show that mitigation of 2.5 $MtCO_2e\ yr^{-1}$ could be feasibly achieved by 2020 relative to their projected reference scenario. Of this, only 1.1 $MtCO_2e\ yr^{-1}$ could be credited to agriculture in EU and UNFCCC reporting; the remainder would arise largely from increases in biofuel and bioenergy crop cultivation, which would be accounted as displacing fuel consumption emissions in electricity generation and transport, rather than as mitigating agriculture sector emissions.

7.5 Ireland's Projected Emissions and proposed decarbonisation pathways

7.5.1 Possible policy emissions pathway from O'Reilly *et al.* 2012

The EPA report by O'Reilly *et al.* (2012) outlines a potential mitigation scenario for Ireland to 2050 based on the EU 2050 Roadmap assumptions and Irish TIMES energy modelling (Ó Gallachóir et al., 2012) as illustrated in Figure 7.11. Energy CO_2 emissions fall to about 5% of 1990 levels and agriculture emissions are assumed to fall by 49%. However, total CO_2e emissions only fall by 78% by 2050, compared to the EU 2050 Roadmap objective of 80 to 95% because of the "limited reduction by agriculture".

The pathway illustrated by O'Reilly *et al.* (2012) suggests an approximate 70% reduction in total annual energy emissions (including electricity generation, transport, residential heating and industry) between 2020 and 2030. Cumulative energy CO_2 emissions shown by the pathway total approximately 600 $MtCO_2$.

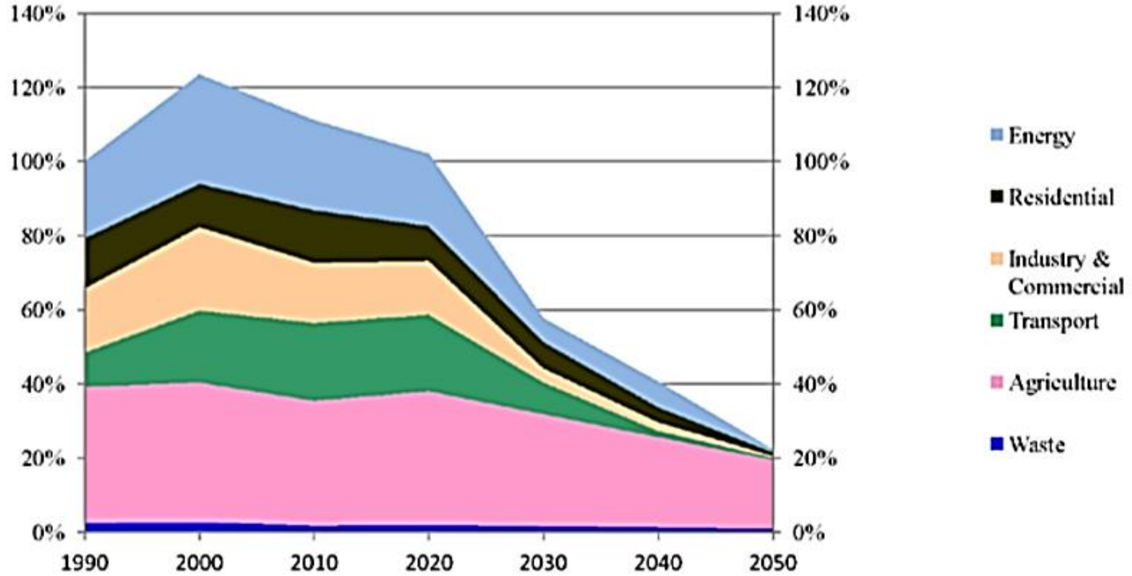

Figure 7.11: Potential emissions in Ireland 1990-2050 (Reproduced from O'Reilly (2012))

7.5.2 Pathways from Ó Gallachóir *et al.* (2012)

Ó Gallachóir *et al.* (2012) use the Irish TIMES Model to develop energy and energy-related CO_2 emissions scenarios to 2050, based on ESRI-generated macro-economic modelling. In addition to a reference scenario, three scenarios are developed (see Figure 7.12), starting in 2015, are based on the policy assumption that agriculture does not meet an 80% reduction by 2050 compared with 1990. The CO_2-127 scenario, assuming that agriculture flatlines emissions at 2020 levels, requires a 127% reduction in energy CO_2 emissions. As previously discussed, based on the equivalent results from (Chiodi et al., 2013b), this would require an energy system that would deliver negative emissions (CO_2 *removal*) of 8 $MtCO_2$ yr^{-1} by 2050, based on BECCS deployment or otherwise. The CO_2-95 scenario, assuming a 50%

reduction in agricultural emissions in line with the EU 2050 Roadmap, still requires a 95% reduction in energy CO_2 by 2050. The third scenario, CO_2-80, assumes an 80% reduction only in the energy sector.

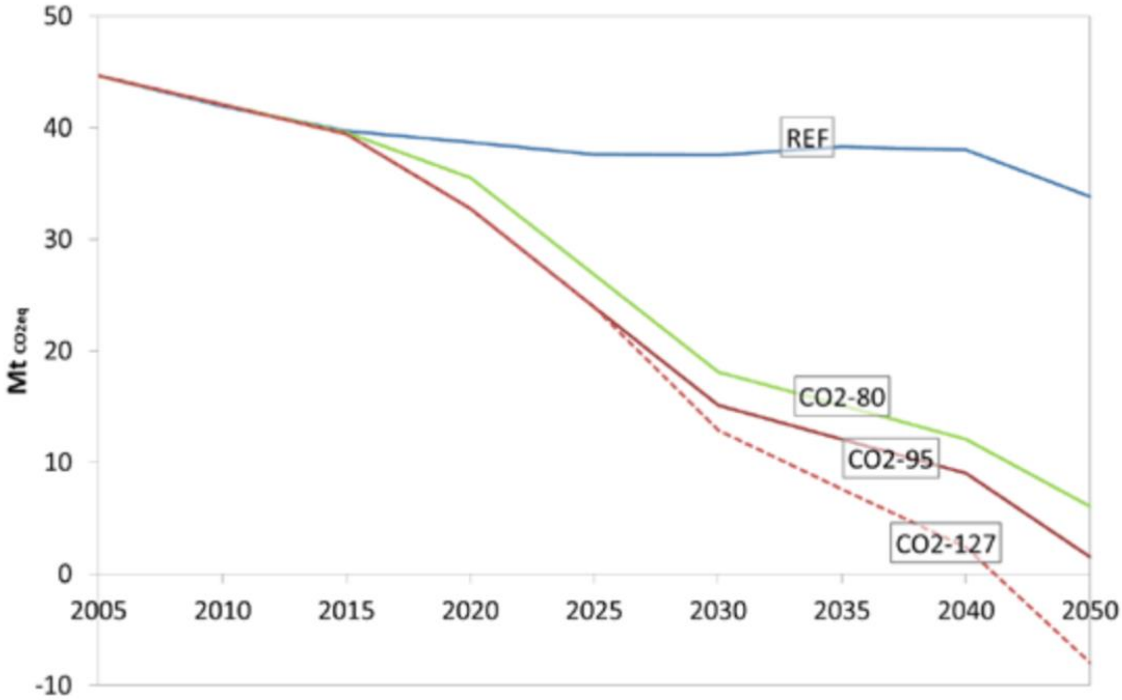

Figure 7.12: Mitigation scenarios to 2050 generated using the Irish TIMES Model to develop energy and energy-related CO_2 emissions scenarios, based on ESRI-generated macro-economic modelling. Reproduced from Ó Gallachóir (2012).

7.5.3 Pathway from EPA representation of the National Policy Position

Figure 7.13 shows an EPA presentation of the Irish National Policy Position aggregate sector of electricity generation, built environment and transport (EGBET) with combined 2015 emissions of 30.4 $MtCO_2$. Without additional policies, the aggregate sector is projected to increase as shown, rising to 32.9 $MtCO_2$ by 2035, rather than showing any decarbonisation.

In Ireland's current National Policy Position only an end-point mitigation target is specified, a reduction of annual energy CO_2 emissions in 2050 by 80% relative to the 1990 level. However, the climate impact (radiative forcing) Ireland is responsible for critically depends on the actual emission *pathway* taken from now until 2050, which determines the cumulative CO_2 emissions over the period. For different (increasingly difficult) theoretical mitigation start points of 1990, 2015 and 2035 the linear pathways presented by the EPA in Figure 7.13 are characterised by quite different cumulative CO_2 emission: ~900 $MtCO_2$, ~1400 $MtCO_2$, and ~1700 $MtCO_2$, respectively for the period from 1990 to 2050. So although these pathways all meet the same end point constraint, they represent very different contributions to climate impacts. Note that, as this aggregate sector does not include some industrial CO_2 emissions, these totals cannot, in any case, be directly compared directly with other possible CO_2-only pathways.

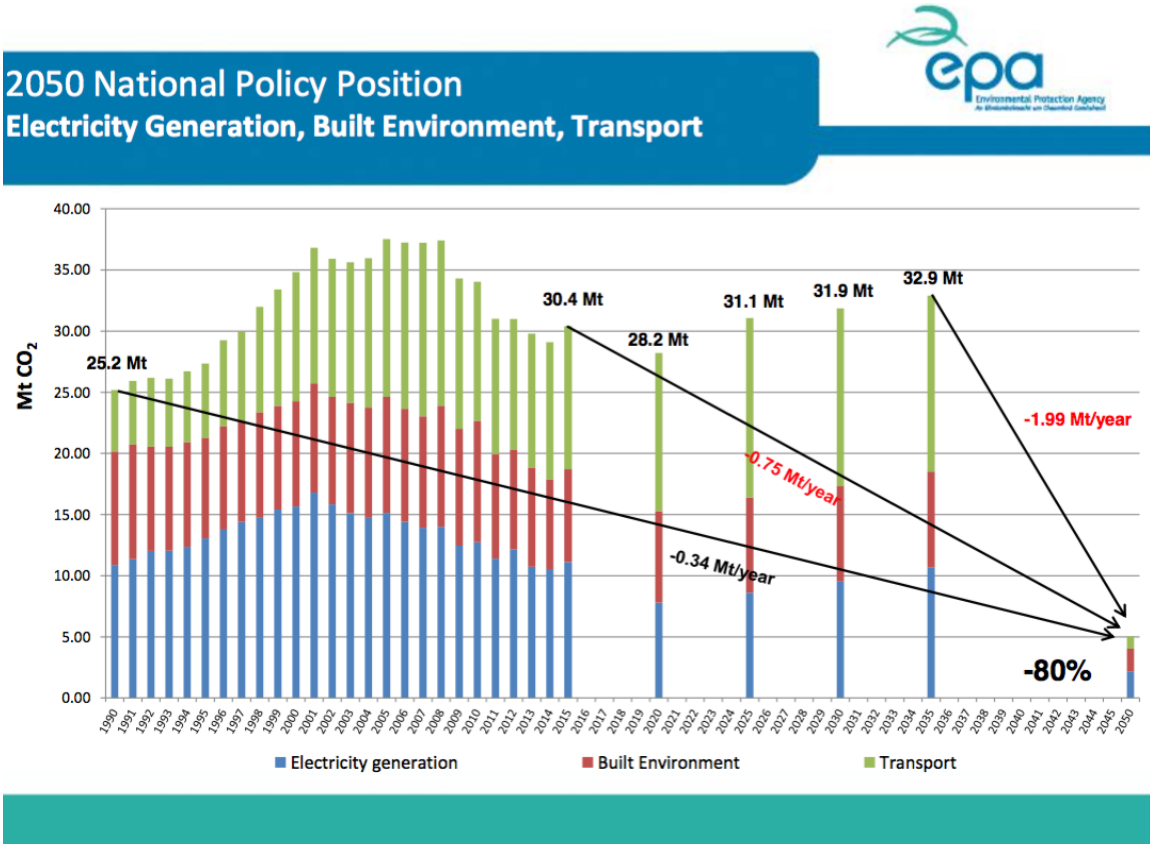

Figure 7.13: Representation of the Irish National Policy Position with annotations of alternative linear pathways shown from 1990, 2015 and 2035 (Reproduced from EPA 2017c).

7.5.4 Pathway and implied Cumulative CO_2 emissions from Climate Change Advisory Council reports 2016 and 2017

Figure 7.14 shows a possible CO_2 decarbonisation pathway from the CCAC First Report (2016) annotated with associated cumulative carbon quotas. Not shown is the quota of 1330 $MtCO_2$ if CO_2 emissions continued at the 2015 level of 38.2 $MtCO_2$. The dark green line is a linear pathway to meet a reduction in CO_2 emissions to 80% below 1990 levels as per the National Policy Position. The light green line is a linear pathway for non-CO_2 emissions from agriculture to about 50% of 1990 levels as per the EU Roadmap.

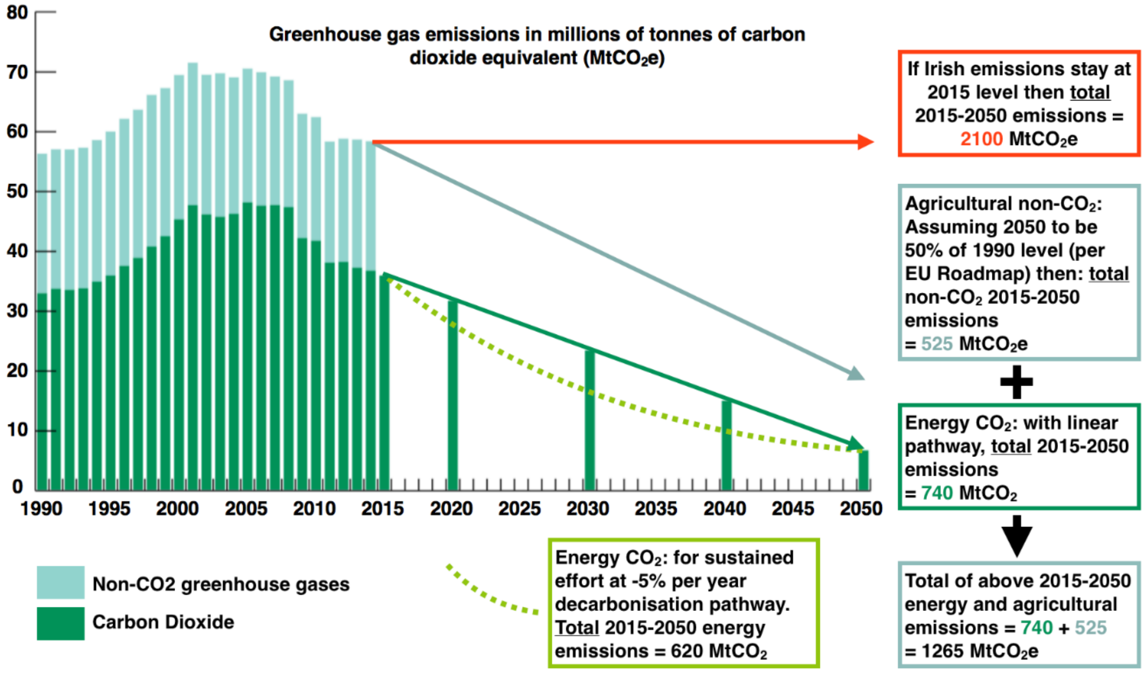

Figure 7.14: Irish GHG emissions 1990 to 2050 (without LULUCF), annotated for this chapter discussion with carbon quotas for the CO_2 pathway indicated with an added non-CO_2 pathway (2016).

The Climate Change Advisory Council Periodic Review 2017 (CCAC, 2017), shows an "illustrative linear pathway" from 38.4 $MtCO_2$ in 2015 toward zero CO_2 emissions in about 2058 (see Figure 7.15). The CCAC state:

> *Future reductions, of over 2% yr^{-1}, similar to the rate experienced during the recession, will be required to achieve the low-carbon transition to 2050. Reductions on this scale will need to come from policy for sustainable economic development in combination with effective national climate policy. (CCAC, 2017, p. 13)*

The pathway shown in Figure 7.15 represents a constant annual absolute reduction rate of ~0.9 $MtCO_2$ yr^{-1}, equating to an annual fractional reduction rate starting at 2.4% yr^{-1}. The cumulative 2015-2058 carbon quota under the "illustrative linear pathway" (red line) to zero nett emissions in 2058 is approximately 810 $MtCO_2$. The cumulative carbon quota commitment of the baseline projections shown 2015-2035 (blue line) is also about 810 $MtCO_2$, exhausting the same quota 15 years earlier. The total implied illustrative future cumulative CO_2-only carbon quota is ~860 $MtCO_2$ based on the pathway being aligned with going to zero by about 2060.

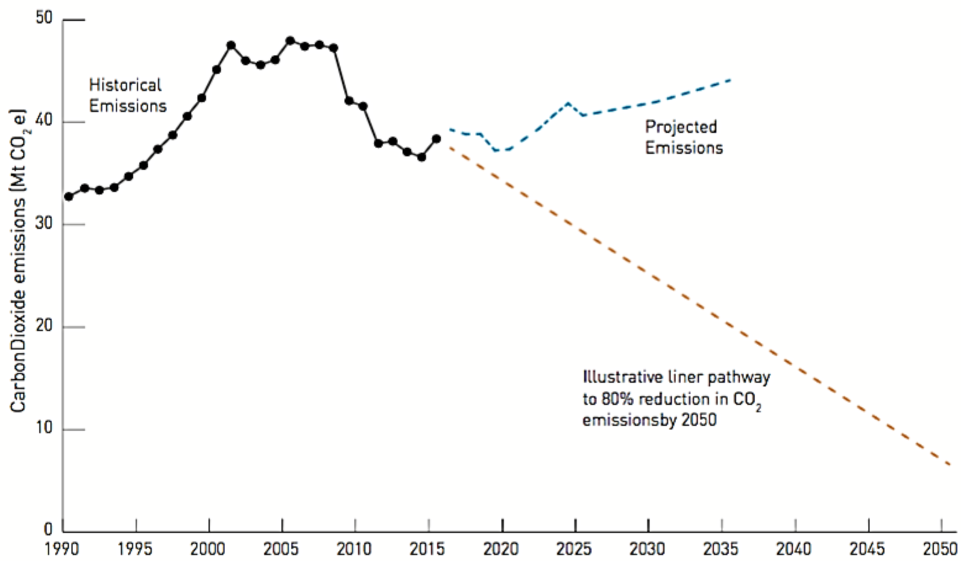

Figure 7.15: Emissions of carbon dioxide in Ireland from 1990 to 2015 and projections from 2016 to 2035 with an illustrative linear pathway for achievement of the low-carbon transition to 2050 (2017). Data source: EPA National Emissions Inventory 2017 and Ireland's GHG Projections 2016-2035.

7.6 Chapter Conclusions: Ireland's Emissions, Projections and Policy

Ireland has higher than average EU per capita CO_2 and per capita GHG emissions with an unusual national emission profile, which includes significant non-CO_2 emissions from agriculture. Irish emission rate changes have been strongly correlated with economic cycles indicating that climate policy to date has not been a strong factor in limiting or reducing emissions. Based on existing and proposed (additional) policies, projected economic growth therefore also results in projections of increasing emissions. In marked contrast, advisory research and policy advisors propose linear and piece-wise linear decarbonisation pathways that would therefore require climate mitigation policies that do in fact realise early, economy-wide, reductions in absolute emissions. Whether sustained decarbonisation in Ireland can be achieved without constraining economic activity will likely depend on the coherence and long-term effectiveness of near-term political decisions, economic policies and forward-looking planning. This would likely require serious emission constraints in public and corporate governance, economic and financial planning, and across Irish society to be rapidly redirected away from fossil fuel use and toward decarbonisation within a limit to future total emissions, possibly assisted by NETs.

The next two chapters aim to assist policy understanding of effective planning for the necessary low-carbon (or, more likely, "negative carbon") transition. By estimating a national cumulative CO_2 quota, Chapter 8 examines the potential cumulative CO_2 emissions constraints of aligning national mitigation policy with Paris Agreement commitments. Finally, Chapter 9 examines NETs and enabling capabilities for NETs that might be most appropriate for Ireland and provides a preliminary, technical estimate of cumulative and annual national NETs capacity.

8 Ireland's carbon quota for the low carbon transition

Summary

- An accepted global carbon budget range for allowable CO_2-only emissions from 2015 onward to limit global warming to "well below 2ºC" is 590-1240 $GtCO_2$ (mid-point 915 $GtCO_2$) based on a 66% chance of success (Rogelj et al., 2016c). For the immediate purposes of this chapter we will generally use the central estimate of 915 $GtCO_2$.
- The average global reduction rate for any carbon budget rises whenever annual emissions fail to meet the required rate. The average, annual reduction rate for the above budget range would have been 3% yr^{-1} to 6% yr^{-1} globally, starting in 2016; but the required rate is rapidly becoming unfeasible on any managed basis, unless peaking and urgent, sustained mitigation begins very quickly; and likely requires negative emissions to also be enabled at scale in any case.
- Four allocation methods are used to estimate Ireland's carbon quota (share of the remaining global carbon budget) using differing weightings of *inertia* and *equity*.
- One additional method, allocating a "fair share" mitigation effort to Ireland by calculating a notional equitable pathway, based on responsibility and capacity, is also included in this chapter to inform a deeper understanding of quota equity.
- As of the end of 2017, a remaining "pure-inertia" CO_2 quota for Ireland (assuming commensurate action on non-CO_2 forcings) is estimated at about 900 $MtCO_2$.
- An Irish "pure-equity" quota is estimated at about 500 $MtCO_2$ as of the end of 2017.
- As "per capita quotas" – dividing by national population for comparison with other nations – these estimates become ~188 tCO_2 per capita for inertia and ~104 tCO_2 per capita for equity.
- In terms of exponential mitigation pathways, which approximate constant fractional additional reduction effort each year and thus minimise the maximum annual fractional reduction over the full pathway, reduction rates are in excess of 4.5% yr^{-1} for inertia and in excess of 8% yr^{-1} for equity.
- Ireland's current projected rises in emission based on current policies indicate an emissions commitment to 2050 in excess of triple the estimated equity quota, implying tacit commitment either to substantial NETs delivered at large scale (domestically or internationally traded) or else inadequate and/or inequitable national mitigation policy relative to the Paris commitments.
- Unless the availability of very large amounts of NETs (and corresponding policy risk) are assumed, plausible stringent mitigation pathways for Ireland aligned with Paris targets now require urgent, substantial and ongoing, near-term reductions in annual emissions.
- At this small nation-state scale, assuming the availability of even moderate levels of negative emissions potential by 2050 is found to significantly ease long-term maintenance of a balance between emissions and removals.

8.1 Introduction

This chapter estimates Ireland's remaining CO_2 carbon quota relevant to aligning climate mitigation policy with the Paris Agreement temperature targets, "in accordance with best available science" and undertaking "rapid reductions" in emissions "on the basis of equity" (Articles 2, 3 and 4, UNFCCC, 2015).

Here we use the term *global carbon budget* to mean the available remaining global CO_2 emissions, accounting for non-CO_2 radiative forcing (RF) that will limit global warming to a specified temperature target with a defined probability. As discussed in Chapter 1, the Paris Agreement target of "well below 2ºC" (WB2C) is widely interpreted as a greater than 66% chance of limiting to 2ºC (though this interpretation is also contested). Based on the modelling values reported in the AR5 Synthesis, Rogelj *et al*. (Rogelj et al., 2016c) recommend UNFCCC policy analysis use a global carbon budget range of 590-1240 $GtCO_2$ (mid-point 915 $GtCO_2$), from 2015 onward, for a greater than 66% chance of limiting global warming to 2ºC[28]. This CO_2 budget range allows for the projected radiative effect of non-CO_2 emissions in WB2C scenarios[29]. Although reducing non-CO_2 emissions limits peak warming, limiting multi-century warming commitment primarily requires urgent, substantial and sustained CO_2 reductions (Pierrehumbert, 2014).

The term carbon *quota* is used here to mean a national or regional share of the global carbon budget, as determined by use of a chosen burden-sharing method[30]. The global carbon budget mid-point of Rogelj *et al.* (2016c) of 915 $GtCO_2$ from 2015 onward is used as the basis for the carbon quota estimates calculated for this chapter; though it is clearly arguable that precaution, as well as the Paris commitment to "pursuing efforts" toward a lower temperature goal of 1.5 ºC, would mandate adopting instead the lower limit of this range

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[28] See Table 2.2 of the IPCC AR5 Synthesis Report. The Rogelj *et al.* (2016) mid-value global carbon budget of 915 $GtCO_2$, from 2015 onward, is based on simple climate models that include non-CO_2 forcings. Also in Table 2.2, more complex models give a budget of 1000 $GtCO_2$ remaining after 2011, which equates to a mid-value of ~840 $GtCO_2$ remaining after 2015 once the ~165 $GtCO_2$ emitted in 2012-2015 is subtracted.

[29] See definitions of three different types of global carbon budget in Rogelj *et al.* (2016b, p. 247). Note that a "CO_2-only" global carbon budget in some climate modelling contexts refers to a theoretical case where CO_2 is the only GHG. This is the most robust metric for committed global warming but, in reality non-CO_2 forcings must be accounted for in limiting to a peak temperature (IPCC AR5 WG1, 2013, p. 1113; Rogelj et al., 2015a). As the Rogelj *et al.* (2016c) budget range does account for an assumed level of future non-CO_2 warming (unlike such "CO_2-only" budgets), the derived national CO_2-only quotas in this chapter's analysis also allows for non-CO_2. Nonetheless, as numerical quotas, they refer strictly to CO_2 and not to a wider basket of climate pollutants.

[30] No such global burden-sharing formula has yet been agreed among the UNFCCC Parties but scientific interpretation of the Paris Agreement implies that some form of burden sharing likely needs to be achieved if global warming is to be limited to "well below 2ºC".

($590GtCO_2$) as a properly prudent basis for planning required action (unless and until more precise prediction becomes possible).

A national carbon quota defines a remaining cumulative *nett* total of CO_2 emissions that could include gross removals as well as total future gross emissions. Burden shares may be based on: *resource sharing* or on *cost-sharing* (Ch. 3, IPCC AR5 WG3, 2014). The remaining 'resource' of the WB2C budget, can be allocated based on the current national share of total global emissions (*inertia*), GDP, or population (*equity*) (Raupach et al., 2014). Equity quotas may be further adjusted by quantifying the 'historical CO_2 emissions debt' of different nations, the amount by which a nation's fossil fuel and cement emissions are in excess of their corresponding per capita share (Matthews, 2015). In effort-sharing assessments, mitigation cost is shared in proportion to allocating the remaining global carbon budget based on *responsibility*, often based on historic emissions, and *capacity*, often related to wealth, especially wealth per capita above a threshold level (Holz et al., 2017).

8.1.1 Using an exponential decarbonisation pathway RR_{exp} as a baseline

Different alternative emission pathways (EPs) are possible to meet the same estimated quota. As a first, useful approximation, a constant fractional reduction rate RR_{exp} can be seen as representing "constant mitigation effort", corresponding to a certain quota of cumulative emissions (see Figure 8.1). This is the basis for the quota and rate estimates in this chapter. For policy analysis and discussion, it is then useful to compare equitable quota-RR_{exp} combinations with those for projected EPs based on current policy, and with mitigation pathways proposed by recent research. Importantly, the shape of an EP, reflecting the annual emissions over a period, determines the cumulative emissions (Price, 2015). Even if an end-period target such as 80% decarbonisation by 2050 is theoretically achieved by notional, rapid reductions late in the mitigation period, cumulative emissions over the period may still be very large due to high emissions early in the mitigation period. Earlier emissions reductions (the "low hanging fruit"), relative to a large base, are likely to be easier to achieve than later reductions relative to an already much contracted base. An exponential mitigation pathway is therefore a useful reference basis for analysis and comparison. Given a "minimum-maximum" fractional reduction rate ("mitigation effort") criterion (for any given starting level and quota constraint), the exponential pathway gives the unique "optimum".

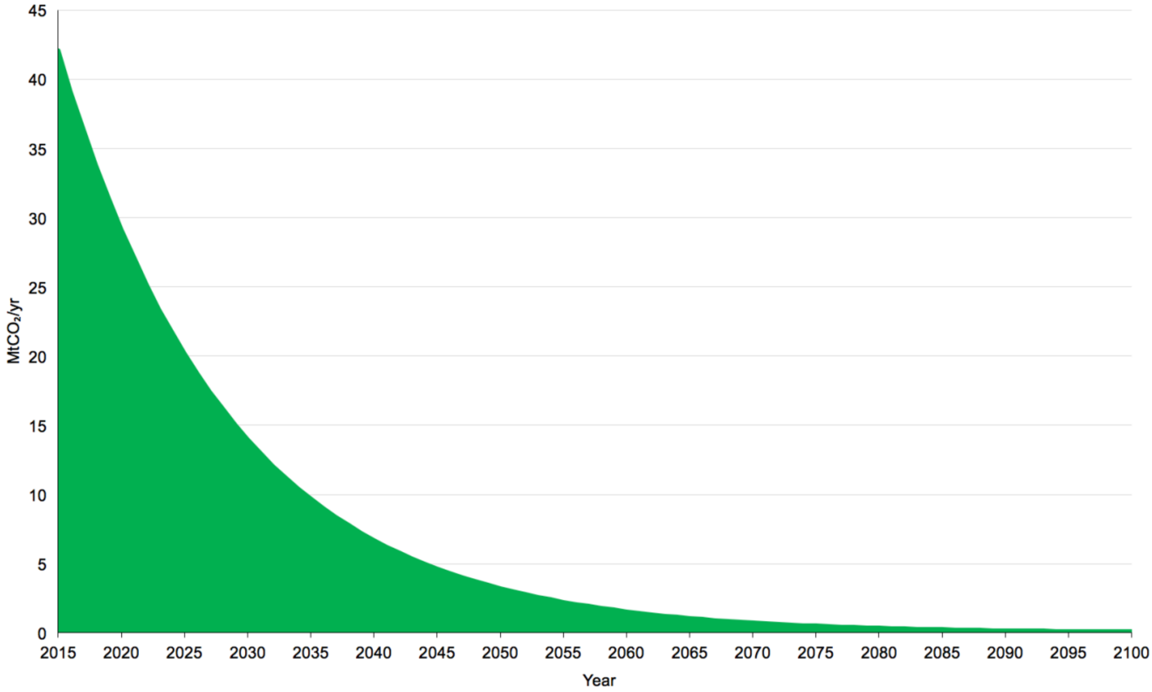

Figure 8.1: Example of an exponential mitigation pathway, reducing at the required rate RR_{exp} corresponding to a finite cumulative CO_2 quota, which is the area under the curve.

8.1.2 Deriving average global RR_{exp} for the WB2C global carbon budget

Based on the IPCC AR5 Synthesis carbon budgets, Rogelj *et al.* (2016b, p. 251) recommend UNFCCC policy analysis use a range of 590-1240 $GtCO_2$ for the remaining CO_2-only global carbon budget quota from 2015. This range has already been used as a basis for national quota policy analysis, for example Pye *et al.* (2017) for the UK.

Global fossil fuel and cement emissions in 2015 were 35.8 $GtCO_2$. Land use emissions vary but average ~4.5 $GtCO_2$ over the past decade. Calculating the average RR_{exp} required as of 2015 is straightforward: dividing the 2015 gross CO_2 emission rate of ~41 $GtCO_2$ yr^{-1} by the low, mid and high values of the Rogelj *et al.* WB2C range of 590 $GtCO_2$, 915 $GtCO_2$, 1240 $GtCO_2$ gives global RR_{exp} of 6.9% yr^{-1}, 4.5% yr^{-1} and 3.3% yr^{-1}, respectively.

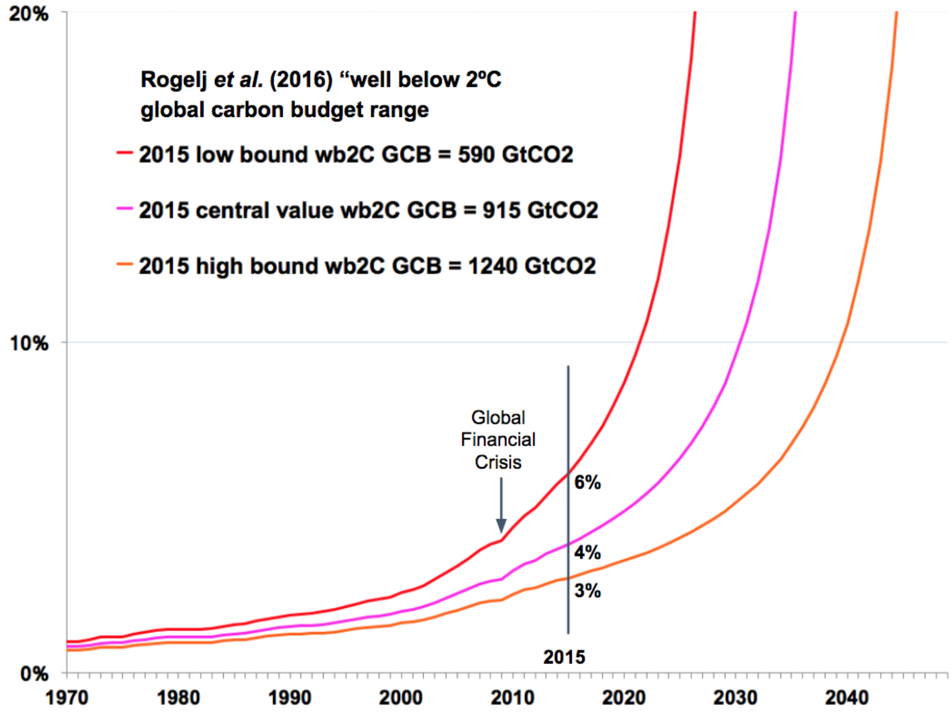

Figure 8.2: Required global average CO_2 fossil fuel and cement emission reduction rates assuming a varying reduction starting point from 1970 to 2040. This is based on the method of Figure 1 in Stocker (2013), but uses the WB2C carbon quota range values from Rogelj et al. *(2016) and actual recorded past emissions. Past year on year variations in global fossil fuel emissions cause unevenness up to 2015. To show a scenario of 'flat-lining emissions', the curves as shown after 2015 result from annual emissions projected to continue at 2015 level until the reduction start year.*

The results of repeating this calculation over time are shown in Figure 8.2 (for fossil fuel and cement emissions only) with required mitigation rates both in the past, based on recorded emissions up to 2015, and in future, as if global emissions 'flat-lined' at 36 $GtCO_2$ yr^{-1} (RRexp = 0% yr^{-1}) in the interim, until exponential mitigation begins. To meet the WB2C carbon budget in 1970 would have only required annual emission reductions of less than 1% yr^{-1} for fossil fuel and cement emissions. As of 2015 the average, global decarbonisation rates required were already 3% yr^{-1} to 6% yr^{-1}. Every year at, or close to, the currently high emissions level very rapidly increases the RR_{exp}. As shown, the 2% yr^{-1} to 5% yr^{-1} decarbonisation rate required around 2008 was briefly met due to the global financial crisis. This figure graphically shows the critical requirement to act with all possible urgency to meet such average global rates if mitigation action is to be aligned with the Paris temperature targets[31]. Relaxing the temperature target decreases the RR_{exp} required now, but delay in

[31] Adding land use emissions to the curves in Figure 8.2 increases the year to year fluctuations and on average reduces the available time on the curves by about two years. The same analysis performed for a 2.5ºC carbon budget (from Table 2.2 in the IPCC, 2014 Synthesis Report) only

achieving the relevant rate rapidly escalates it. Even for the three-times larger, global carbon budget range for a 50% chance of 3ºC (Table 2.2, Synthesis Report IPCC, 2014), the required average global decarbonisation rate is already between 1% yr^{-1} and 2% yr^{-1}. Flatlining emissions in 2016 from 2015, at 36.2 $GtCO_2$, and rising in 2017 to about 36.8 tCO_2 (Quéré et al., 2017), further increased the rate needed and the difficulty of limiting warming to 2ºC.

8.1.3 National carbon quotas as a basis for climate policy

As a nation's contribution to sustained (millennial scale) global warming is directly related to its cumulative CO_2 emissions, estimating a remaining national CO_2 quota assists policy-makers to assess alternative economy-wide emission pathways aligned with a WB2C budget. Inevitably, political and societal decision-making and planning, within and between nations, is needed to allocate a national carbon quota among the different energy, process and land use sectors so that challenging emission pathways can be met. But, aligning near-term societal choices globally and locally with the physics of the climate system response to CO_2 emissions will be required if global warming is to be limited effectively. Of course, achieving an equitable, national decarbonisation pathway in any single country will not be effective in meeting the global temperature goals unless other nations likewise achieve commensurate reductions (Robiou du Pont et al., 2016), possibly based on agreed quota sharing principles beyond carbon markets.

The WB2C global budget constraint implies a need for rapid 'contraction and convergence' (Meyer, 1999) of all nations' emissions to a very low per capita level close to zero nett CO_2 yr^{-1}. For a WB2C budget, the need for all nations to limit future emissions quickly means that the option to buy part of other nations' carbon quotas is likely to be very limited. Sustained and substantial domestic emission reductions and increasing rates of carbon dioxide removal (CDR) using NETs (a service which may, however, be traded internationally, at least in principle) are therefore the major mitigation options.

Analyses to date have generally focused on assumed "top down" multilateral management of the global carbon quota (see Chapter 2). Only a few nation-specific analyses are available showing "bottom up" equitable WB2C carbon quotas or emission pathways. Donner and Zickfield (2016) generate CO_2-only logistic-function emission pathways for Canada's carbon quota for different probabilities of limiting warming to less than 1.5ºC, 2ºC and 3ºC. At its current CO_2 emissions rate, Canada will have exhausted its equity quota for a 50% chance of limiting to 1.5ºC by the end of 2018, and by 2026 for a 66% chance of 2ºC. Pye *et al.* (2017) re-examine UK emission pathways to align UK climate mitigation policy within inertia and equity allocations of the Rogelj *et al.* carbon budget range. Decarbonisation rates for WB2C policy of -11% yr^{-1}, -4% yr^{-1} and -2% yr^{-1} are found for the smallest equity quota to

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allows an additional 17 years of flatlining emissions relative to the wb2C curves before the rates shown are similarly required to meet the higher 2.5ºC target budget.

the largest inertia quota, respectively. However, achieving these nett pathways is argued to require CO_2 removals equivalent to approximately 250%, 100% and 30% of the respective nett quotas. At the sub-national level, Anderson, Stoddard, and Schrage (2017) have recently estimated an equitable WB2C carbon quota for the Swedish Municipality of Järfälla to align local mitigation planning with the Paris Agreement.

8.1.4 Deriving a national carbon quota from the global carbon budget

This chapter focuses on estimating a WB2C CO_2 quota for Ireland, using a variety of proposed allocation principles. The resulting quotas will be put in the context of current and projected Irish emissions and used to discuss implications for Irish climate mitigation policy, and the potential role of CDR/NETs. Possible CO_2 quota estimates are calculated using burden-sharing principles as discussed in Chapter 2 for multilateral management of the WB2C global carbon budget. As detailed further in the next section, the methods used are:

- M1. Global exponential reduction rates
- M2. Raupach *et al.* (2014)
- M3. Regensburg Model (Sargl et al., 2016b)
- M4. Rockström *et al.* (2017)
- M5. Climate Equity Reference Framework, CERF (Athanasiou and Kartha, 2014)

Methods M1-M4 are resource-sharing quotas, aiming to equitably allocate the remaining global carbon budget among all nations based on the current, historic or projected share of emissions, GDP or population. 'Grandfathering' allocations according to current national share of global emissions (termed *inertia*), or by current share of global GDP, are regarded as less equitable than *equity* sharing because they generally give a greater share of the remaining budget to nations that have already benefitted most from fossil fuel use. Method 5 allocates the global carbon budget based on *responsibility* and *capacity* using the "fair share" methodology of Athanasiou and Kartha (2014)

For Ireland, Glynn (2017a, 2017b)[32] has presented a preliminary economic analysis based on the WB2C global carbon budget and an equity quota. The carbon quota given is 766 $MtCO_2$ from 2015, based on the Rogelj *et al.* (2016c) global carbon budget range and Ireland's proportionate population share of the global population. At the current rate of CO_2 emissions from fossil fuel and cement, Ireland would exhaust all of this quota by 2035. Land use CO_2 emissions are omitted from this analysis and equivalent exponential reduction rates are not stated. Glynn clearly illustrates the need for substantial near-term reductions if such a quota is to be met. Delaying mitigation leads to more difficult economic choices, steeper carbon price rises and higher overall mitigation costs.

[32] Presentation at the ESRI and a blogpost, both in 2017, summarising research toward a forthcoming journal article.

Estimates of nett CO_2-only carbon quotas include all gross CO_2 emissions – from fossil fuel use, industrial processes and land use; and all CO_2 removals – into forestry and soils, or potentially into more permanent and less reversible geologic reservoir storage, via other NETs yet to be developed in Ireland (such as BECCS and DACCS). Ireland's nett CO_2 emissions in 2015 were 42.1 $MtCO_2$, including 38.4 $MtCO_2$ from fossil fuel and 3.7 $MtCO_2$ from land use, land use change and forestry (LULUCF)[33] (EPA, 2017b). Current climate mitigation policy in Ireland seeks to offset gross emissions of methane and nitrous oxide, mostly from agriculture, against land use CO_2 removals by forestry and soils. However, the different physical climate effects of CO_2 relative to non-CO_2 emissions mean that the shorter-lived GHGs in particular (such as methane and F-gases) and the intermediate case of N_2O are best treated in a separate policy "basket" to CO_2 (Smith et al., 2012; Solomon et al., 2013a). Also, the Rogelj *et al.* carbon budget range only includes CO_2. Therefore, in this chapter only CO_2 emissions and removals are considered in regard to the carbon quota estimates for Ireland. However, additional radiative forcing due to high or increasing annual non-CO_2 (methane and nitrous oxide) emissions would imply a lower CO_2 quota for Ireland.

The Rogelj *et al.* (2016) mid-point global carbon budget value of 915 $GtCO_2$ remaining nett cumulative emissions is taken as the basis for the headline Irish quota estimates in this chapter, though quota estimates corresponding to the low and high points of the Rogelj range are also reported in some of the results.

8.2 Methods

This section outlines and reviews five methods used to estimate Ireland's remaining CO_2 quota aligned with mitigation action meeting a WB2C nett global carbon budget (with or without a contribution of CDR/negative emissions from NETs).

8.2.1 M1: Average global exponential reduction rates RR_{exp}

As detailed below, an upper limit inertia CO_2 quota range can be obtained directly by allocating the quota based on relative global and Irish emissions in the reference year of 2015. Using the Rogelj *et al.* (2016c) range, these rates can then be applied to Ireland's current emissions to determine inertia quotas. As Ireland's per capita CO_2 emissions are higher than the global average the resulting inertia quota can be expected to be higher than would be equitable. An equity quota estimate can be derived based on a comparative 'what if' assumption of Ireland's population having annual per capita emissions at the average global rate.

Dividing Ireland's current emissions by the average global WB2C RR_{exp} values gives a simple method to estimate a range of inertia quotas for Ireland.

[33] This does not include 1.7 MtC (6.2 $MtCO_2$) in peatland carbon losses due to extraction of horticultural peat (Figure 6.51, EPA, 2017b), which are not accounted in national emissions.

To obtain an equity quota range, an equitable equivalent of total CO_2 for Ireland is calculated by multiplying Ireland's total population by average global per capita emissions. Given 41 $GtCO_2$ yr^{-1} global emissions in 2015 (including the approximate land use CO_2) and dividing by global population of 7.3 billion gives global per capita emissions of 5.6 tCO_2[34]. Multiplying this value by Ireland's population of 4.7 million (2015 UN estimate) gives a measure of Irish 'equitable equivalent' emissions, equal to 26.4 $MtCO_2$ for 2015. Dividing Ireland's actual 2015 CO_2 emissions of 42.1 $MtCO_2$ by the calculated equity quotas then gives the sustained RR_{exp} equity values required by Ireland, corresponding to the low, mid and high values for the Rogelj *et al.* global carbon budget range.

8.2.2 M2: From Raupach *et al.* (2014)

In the methodology adopted by Raupach *et al.*, the global carbon quota is shared according to: *inertia*, based on preserving or locking in the current (inequitable) per capita share of total annual emissions; or *equity*, based on per cent share of global population; or some intermediate blend between the two.

Raupach *et al.* define a linear interpolation or blending between pure equity and pure initial sharing, characterised by a "sharing index" *w.* This then ranges from pure inertia, with w = 0, to pure *equity,* with w =1. Raupach *et al.* suggest that an intermediate blend (such as w = 0.5) gives some balance between decarbonisation feasibility for already developed nations and development needs for developing nations[35].

8.2.3 M3: Regensburg Model

As discussed in Ch. 2.5, the Regensburg model aims to enable contraction and convergence, bringing all countries to an equal per capita emissions level by a stated future year and within a global carbon budget with all nations' annual emissions proceeding nearly linearly toward the target[36]. The detailed Regensburg Model spreadsheet tool has been updated as of December 2016 and good documentation is provided for its use (Sargl et al., 2016b). To enable alternative scenarios, global parameters can be user-defined – such as convergence year, global negative emissions budget, initial reduction rates etc. The

[34] As this equitable equivalent 2015 emissions depends on the global and Irish population numbers, alternative scenarios could also be based on different future population numbers. Raupach *et al.* use a value of 9 billion people as a mid-range future global population value.

[35] This approach can be critically assessed against the rationales of correcting 'equity' even more equitably for historic credits and debits (Gignac and Matthews, 2015), or for historic responsibility for warming and capacity to pay for mitigation (Holz et al., 2017), that would further reduce equity quota estimates.

[36] Ascribing linear pathways to wealthy nations is relatively inequitable but, as with the blended allocation of Raupach *et al.*, this is excused on grounds of political and economic feasibility in effort sharing.

Regensburg Model tool can output alternative emission pathways for any specified nation to compare with existing policy and to assist in suggesting mitigation policy options.

The tool's starting global base data for carbon budget and pathway calculations has a 2020-2100 global carbon quota of 554 $GtCO_2$ (excluding LULUCF), based on the AR5 WG1 >66% 2ºC 1010 $GtCO_2$ budget remaining after 2011, and a convergence level for all nations of 0.25 tCO_2 per cap by 2100. For use of this method here, the calculation was adjusted to use the Rogelj *et al.* global carbon budget range from 2015.

8.2.4 M4: Rockström *et al.* 2017

Rockström *et al.* (2017) state, "alarming inconsistencies remain between science-based targets and national commitments". To make Paris mitigation goals a reality, and to give some leeway in the global carbon budget if negative emissions at scale do not become available, a guideline (exponential) decarbonisation RR_{exp} of halving anthropogenic CO_2 emissions every decade, or about -6.7% yr^{-1}, is proposed for all UNFCCC Parties and all sectors. Land use and agriculture emissions would need to show commensurate mitigation of non-CO_2 GHG emissions, for example, through dietary change (away from intrinsically higher GHG foods, particularly those based on ruminant livestock) and cutting food waste. By 2050, on this decadal halving pathway, annual CO_2 emissions from fossil fuel, industrial processes and land use would fall over three decades to 12.5% (= $1/2^3$ = 1/8) of 2020 emissions. In this method, land use emissions are assumed to fall to zero by 2050.

8.2.5 M5: Climate Equity Reference Framework

In contrast to the resource-sharing methods of M1-M4, using the Climate Equity Reference Framework (CERF) methodology (see earlier discussion in Chapter 2, section 2.6.3), a country's global mitigation requirement (its mitigation *allocation)* based on responsibility and capacity, is then subtracted from a "no policy" baseline of annual emissions (Holz et al., 2017). This gives an allocation emissions pathway for sharing mitigation costs. While the tool output is in the form of pathways (to 2030) rather than cumulative quotas, in general, nations with high responsibility and capacity show pathways quickly going below zero, indicative of large negative quotas that are far greater than their own likely domestic mitigation potential. They would need to somehow fund additional, compensating, mitigation in poorer developing nations by ensuring low carbon development, thereby avoiding their currently-projected equitable shares of future emissions. For poorer nations, the corresponding "dual obligation" would to accept that their development must be low carbon and to implement maximal mitigation efforts to preserve land carbon and/or to facilitate CDR.

The CERF web tool addresses non-CO_2 as well as CO_2 emissions so carbon quotas and emission pathways are in CO_2e, but, as shown in Figure 8.5 below for Ireland, CO_2-only emissions and allocation values can be extracted for regional groups and individual countries allowing limited comparison with CO_2-only approaches. Based on the mitigation and equity user options, the calculator provides global, regional or national reports of fair share emission paths and estimated costs per tCO_2 for mitigation and adaptation up to 2030. Detailed regional reports are produced and summary data for individual countries is shown.

However, the 2030 horizon makes the calculator of limited use for longer term quota comparisons.

8.2.6 An Irish CO_2 quota in the context of possible emission pathways.

The estimated CO_2 quota outputs are compared to six emission pathway scenarios for Ireland, which were previously discussed in Chapter 7.

- WEM assumes the emission commitment of the EPA's "With Existing Measures" pathway for 2015 to 2035, taking its cumulative CO_2 as the basis for an average-exponential rate of increase to and beyond 2035.
- WAM likewise assumes the emission commitment of the EPA's "With Additional Measures" pathway for 2015 to 2035.
- FLAT assumes CO_2 fossil fuel, process and land use emissions are immediately flat-lined at the 2015 level (strictly already superseded, based on provisional inventory for 2016).
- CCAC assumes the 'illustrative linear pathway' presented by CACC (2017).
- CO_2-80 emissions pathway to meet an 80% reduction by 2050 compared to 1990 as detailed in Ó Gallachóir *et al.* (2012).
- CO_2-95 emissions pathway to meet a 95% reduction by 2050 compared to 1990, also as detailed in Ó Gallachóir *et al.* (2012).

For comparison with the quotas, land use emissions are assumed to remain at the 2015 level of 3.7 $MtCO_2\ yr^{-1}$ for the WEM, WAM and FLAT scenarios, which have growing or flatlining emissions. In the three mitigation scenarios, land use emissions are assumed to reduce at the same rate as the average exponential rate for the scenarios.

8.3 Results: Estimating an Irish CO_2 quota

The Rogelj *et al.* (2016) WB2C global carbon budget is as remaining from 2015 onward, so the estimated quotas given below are also as remaining from this date. Therefore, for quota from subsequent years, the results from each method need to be adjusted for global and national CO_2 emissions since 2015. Since Ireland's share of global emissions is unlikely to change significantly over a short period, subtracting emissions for years following 2015 can give an estimate of the remaining quota values for more recent years.

Quota values and RR_{exp} corresponding to the mid-range WB2C global carbon budget are shown in the Table 8.2 summary and in Figure 8.6 to compare with other results and EP cumulative emissions. Quota and pathway fractions for 2015-2050 and 2050-2100 are also reported in Table 8.2 to inform the policy outlook for nett emissions for each method up to and after 2050.

8.3.1 M1

Ireland's inertia CO_2 quota from this method is 940 $MtCO_2$ corresponding to an RR_{exp} of 4.5% yr^{-1}. Ireland's equity CO_2 quota from this method is 590 $MtCO_2$ corresponding to an

RR_{exp} of 7.1% yr^{-1}. Table 8.1 details the calculated inertia and equity WB2C quota and RR_{exp} values.

Table 8.1 Quota and RR_{exp} results derived from the WB2C global carbon budget and from current global and national emissions.

Quota Type	Annual global CO_2 emissions incl average LULUCF	Remaining global carbon budget for wb2C	Global Sustained reduction rate RRexp	Ireland Sustained reduction rate RRexp	Global per capita CO_2	Ireland pop.	Current annual Irish CO_2 for inertia. / Ireland 'equitable equivalent' CO_2 for equity	**Estimated CO_2 quota for Ireland** 2015-2050	2015-2100	Limit
	$GtCO_2$	$GtCO_2$	%	%	tCO_2	millions	$MtCO_2$	$MtCO_2$	$MtCO_2$	$MtCO_2$
Inertia	41	1240	3.3%	3.3%	NA	NA	42.1	850	1160	1270
		915	4.5%	4.5%				720	880	940
		590	6.9%	6.9%				230	230	270
Equity	41	1240	3.3%	5.3%	5.6	4.7	26.4	530	730	800
		915	4.5%	7.1%				450	550	590
		590	6.9%	11.1%				330	350	380

8.3.2 M2 (Raupach *et al.* method)

Ireland's inertia CO_2 quota from this method is 980 $MtCO_2$ corresponding to an RR_{exp} of 4.3% yr^{-1}. Ireland's equity CO_2 quota from this method is 560 $MtCO_2$ corresponding to an RR_{exp} of 7.5% yr^{-1}. Ireland's blended CO_2 quota from this method is 770 $MtCO_2$ corresponding to an RR_{exp} of 5.5% yr^{-1}.

8.3.3 M3 (Regensburg method)

The Irish CO_2 quota from this method is 610 $MtCO_2$ (see Figure 8.6), corresponding to an RR_{exp} of 6.7% yr^{-1}.

The Figure 8.3 charts and tables show the Regensburg model output for Ireland for four scenarios: one with a constant annual reduction rate (here shown to be 6.0% yr^{-1} after 2019) and three with a starting annual reduction rate of 3.5%, escalating thereafter in slightly differing ways. The continuous annual RR_{exp} of 6.0% does not include land use emissions, but it does not require negative emissions. However the latter three scenarios do require negative emissions from 2055 onwards, with 2020-2100 cumulative gross emission quotas about 8% larger than the 427 $MtCO_2$ for the exponentially declining 6% constant RR scenario. Cumulative emissions are added for 2016-2019 emissions and land-use to give the nett quota from 2015.

Figure 8.3: Regensburg model output for Ireland: CO_2-only pathways for different emission scenarios. Bottom bar chart shows relative percent change in 2030 (blue) and in 2050 (red) compared to 1990 (left) and 2010 (right).

8.3.4 M4 (from Rockström *et al.*)

Ireland's CO_2 nett quota from this method is 700 $MtCO_2$ (Figure 8.4, right), but this includes 330 $MtCO_2$ in removals by NETs, so total gross emissions are 1030 $MtCO_2$ (see Figure 1.7). Land use emissions decline to near-zero by 2050 and are offset by negative emissions increasing to about 5 $MtCO_2$ yr^{-1} by 2050. From 2050 onward, continuing gross emissions of 5 $MtCO_2$ are balanced by CO_2 removals, implying zero additional quota after 2050. Although the Rockström exponential decarbonisation rate is 6.7% for fossil fuel and process emissions, the assumed contribution of NETs reduces the RR_{exp} needed to 6.0% for comparison with other methods.

A direct application of this pathway formulation to Ireland is shown in Figure 8.4, left (tacitly assuming a "pure inertia" sharing principle). This assumes constant annual (nett) CO_2 emissions at the 2015 level up to 2020 (to smooth the transition from increasing to decreasing emissions) and then exponential reduction, halving every decade (6.7% yr^{-1}). On this pathway, annual gross fossil and process emissions decrease from 38.4 $MtCO_2$ to about 5 $MtCO_2$ by 2050, and land use emissions decline to near zero. In the meantime, additional negative emissions ramp up to 5 $MtCO_2$ by 2050, so that removals equal gross emissions.

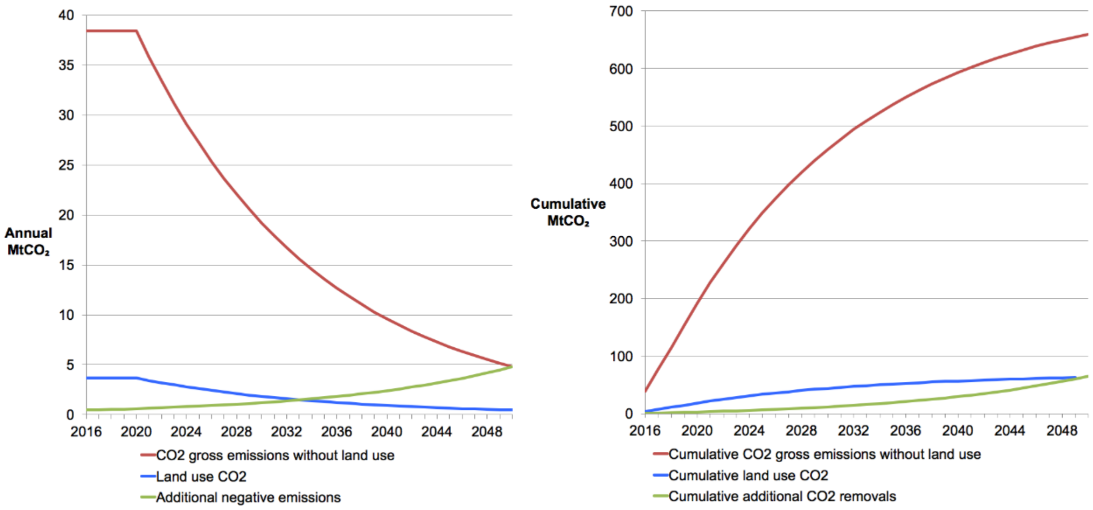

Figure 8.4: illustrating a CO_2-only emissions pathway for Ireland as per the method of Rockström et al. *Chart to left shows Ireland's annual fossil fuel and land use emissions to 2050, assuming flatline from 2015 to 2020, and then reducing by 50% every decade thereafter (annual RR = 6.7%). Negative emissions technologies (gross removals) ramp up to exactly equal gross emissions by 2050. Chart to right shows the corresponding cumulative emissions.*

8.3.5 M5 Climate Equity Reference Framework

In Figure 8.5, the CERF "no policy" baseline projection corresponds closely to the 2017 EPA "With Existing Measures" projections of Ireland's emissions. The CERF calculated annual allocation for Ireland reduces by 3.6 $MtCO_2$ yr^{-1} reaching zero by 2027 and becoming negative thereafter. The difference between the no policy baseline projection and CERF mitigation allocation gives an indication of the responsibility and capacity level of Ireland for global mitigation cost. The increasing divergence between Ireland's "no policy" and mitigation allocation equates to a cumulative mitigation deficit for Ireland of 47 $MtCO_2$ by 2020 and 430 $MtCO_2$ by 2030, the latter being equivalent to over 11 years of current annual CO_2 emissions from fossil fuels and cement.

In Figure 8.5, the gross CO_2 emissions for Ireland's CERF allocation is about 270 $MtCO_2$ until the mitigation the pathway goes below zero in 2027. As the CERF data does not extend after 2030 and though strongly negative, no ultimate, finite, nett emissions quota can be determined using this method. Therefore, as recorded in Table 8.2, this method cannot give a CO_2 quota directly comparable with the M1-4 quota estimates.

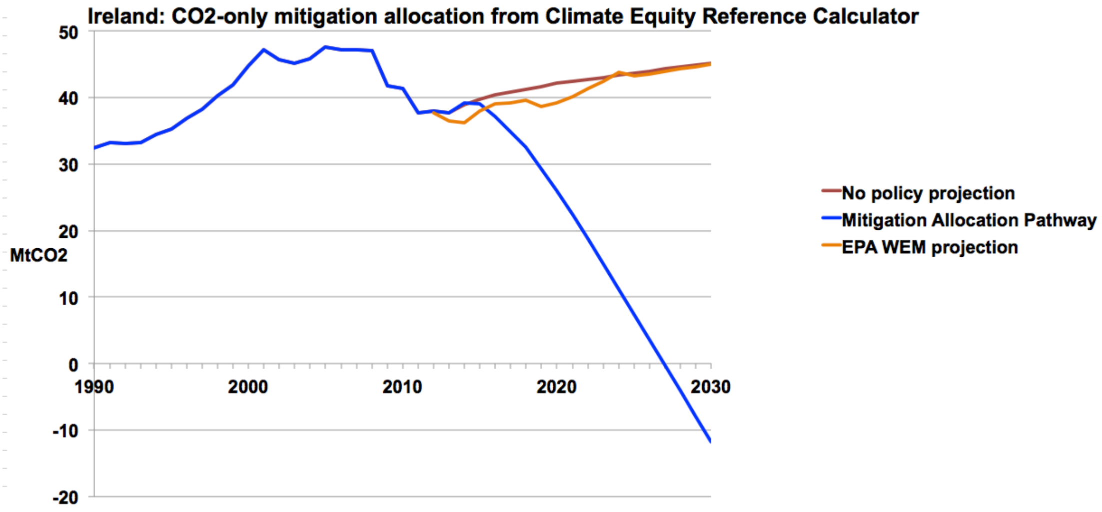

Figure 8.5: Ireland CO_2-only (without LULUCF CO_2) mitigation allocation (extracted from CERF country report data) excluding emissions based on trade, based on responsibility for cumulative emissions since 1990 and with capacity threshold at 7500 USD per capita.

8.4 Comparison of Ireland's national CO_2 quota estimates

The indicative values for Ireland's remaining CO_2 carbon quota from the various methods are collated in Table 8.1 and compared in Figure 8.6. The corresponding RR_{exp} values are charted in Figure 8.7.

Inertia estimates from M1 and M2 are 940 and 980 $MtCO_2$, from 2015, with RR_{exp} of about 4.5% and 4.3%. The nett inertia estimate from M4 is only 700 $MtCO_2$ but this requires ramping up negative emissions to 5 $MtCO_2$ by 2050 and sustaining this level of removals thereafter. Gross emissions for M4 are 1030 $MtCO_2$. At current emissions rates of about 44 $MtCO_2$ including LULUCF, Ireland would exhaust even the largest estimated inertia quota by about 2038.

Equity estimates range from 560 to 590 $MtCO_2$ with RR_{exp} of about 7% yr^{-1}. At current emissions rates of about 44 $MtCO_2$, including LULUCF, Ireland would exhaust such an equity quota by about 2028. Based on the average equity estimate, Figure 8.8 indicatively shows the CO_2 exponential-average pathways proceeding until the average equity quota is exhausted after which the plotted pathways drop immediately to zero.

The M5 quota value of gross emissions 270 $MtCO_2$ is not directly comparable to the other nett estimates as the CERF data only extends to 2030 and the cumulative total of future CO_2 removals is not clear. Nonetheless, the CERF method indicates how a regard for responsibility and capacity can be formulated and would substantially reduce (or eliminate) any "remaining" positive quota for wealthier nations with high past and present per capita emissions.

Even up to 2050 only, the cumulative emissions of 1430-1760 $MtCO_2$ for the WEM, WAM and FLAT EPs are much larger than the entire nett inertia and equity quotas, by over 500 $MtCO_2$ and 1000 $MtCO_2$ respectively. The proposed mitigation pathway carbon quota values implied by the CCAC, CO_2-80 and CO_2-95 pathways lie between the values for the inertia and equity estimates.

Table 8.2: Collated estimates of Ireland's remaining nett carbon quota and cumulative emissions under different pathway scenarios, with equivalent exponential reduction rate. All estimates based on mid-value WB2C 915 $GtCO_2e$ global carbon budget from 2015 onward. For pathways, emissions before and after 2050 are stated as per the source.

Quota/Pathway used for given estimate		RR_{exp}	2015 to 2050	2050 to 2100
Quota	M1 (Inertia)	4.5%	720	160
	M1 (Equity)	7.1%	450	100
	M2 (Inertia)	4.3%	780	190
	M2 (Equity)	7.5%	530	30
	M2 (Blend)	5.5%	670	100
	Glynn (2017)	5.5%	670	100
	M3	6.7%	520	50
	M3 (NETs)	7.0%	555	-45
	M4 (-5 $MtCO_2$ yr^{-1} NETS by 2050)	6.0%	700	0
	M5	Not Comparable	–	–
Pathway	WEM	1.1% [growth]	1760	3500
	WAM	0.6% [growth]	1620	2860
	FLAT (flat line at 42.1 $MtCO_2$)	0%	1430	2110
	CCAC	4.5%	780	30
	CO_2-80	4.6%	600	60
	CO_2-95	6.3%	670	0

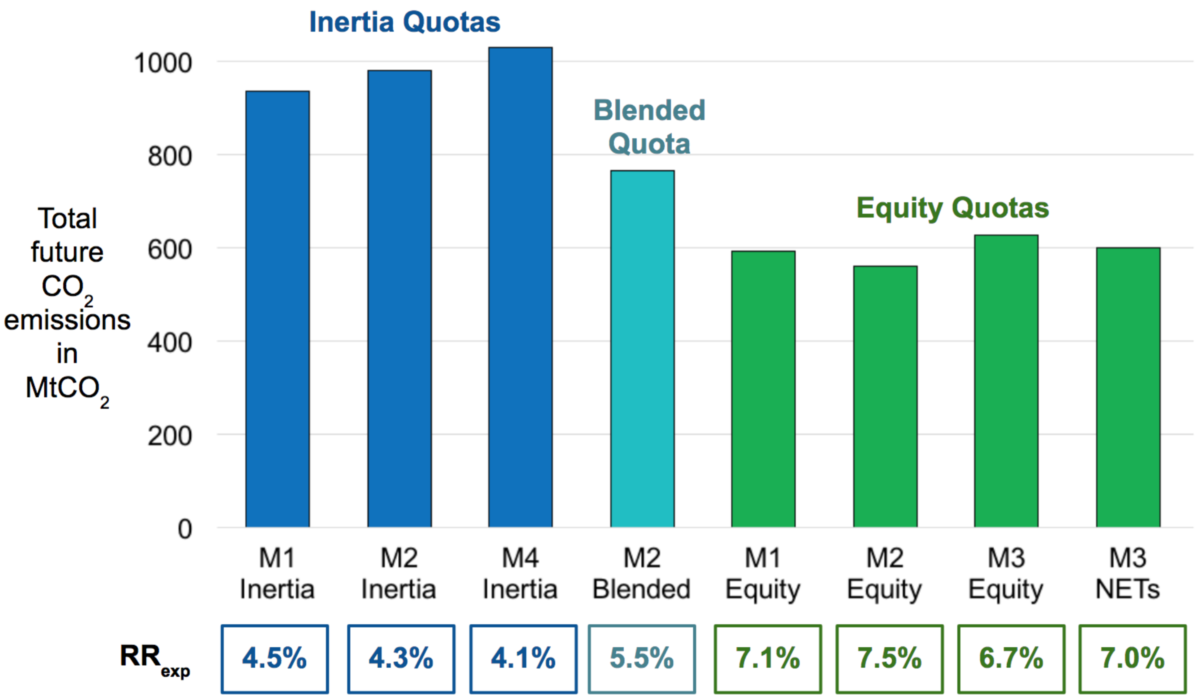

Figure 8.6 Comparison of Irish CO_2 nett quota estimates, methods M1-M4.

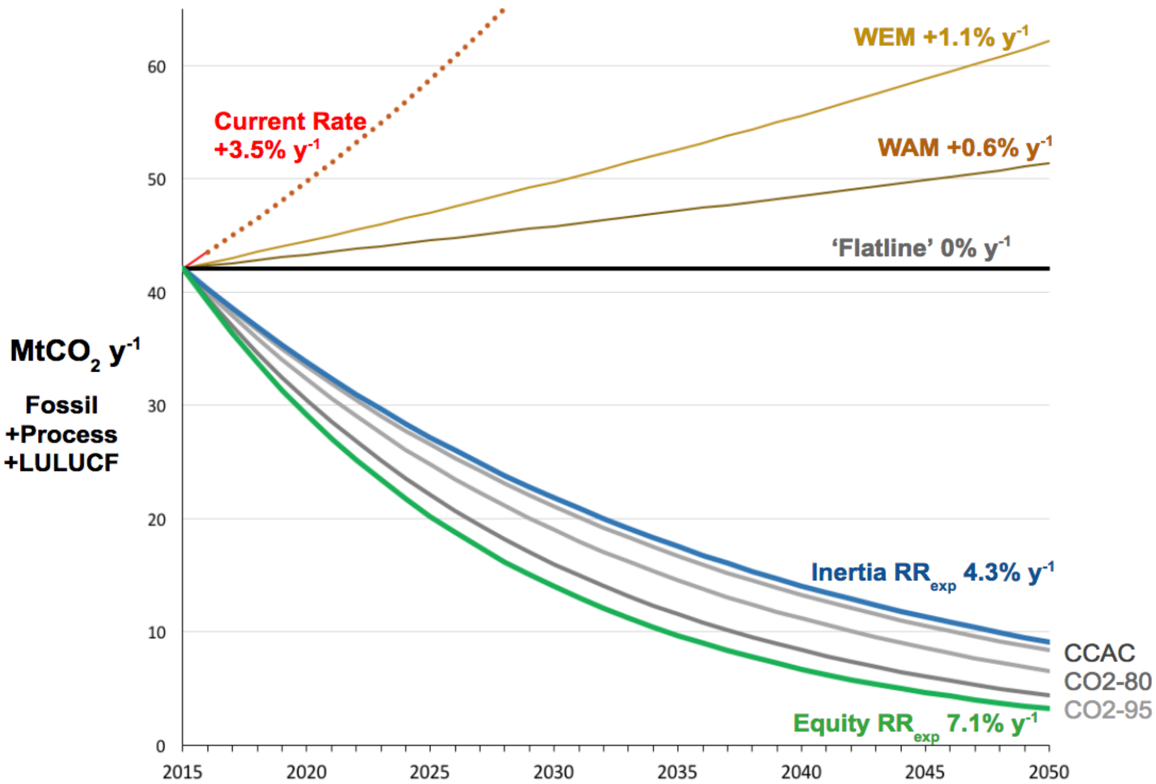

Figure 8.7: Average annual reduction rates required for Irish carbon quota estimates, EPA projections and proposed decarbonisation pathway scenarios. Grey: Reduction rates required for Irish CO_2 quota estimates.

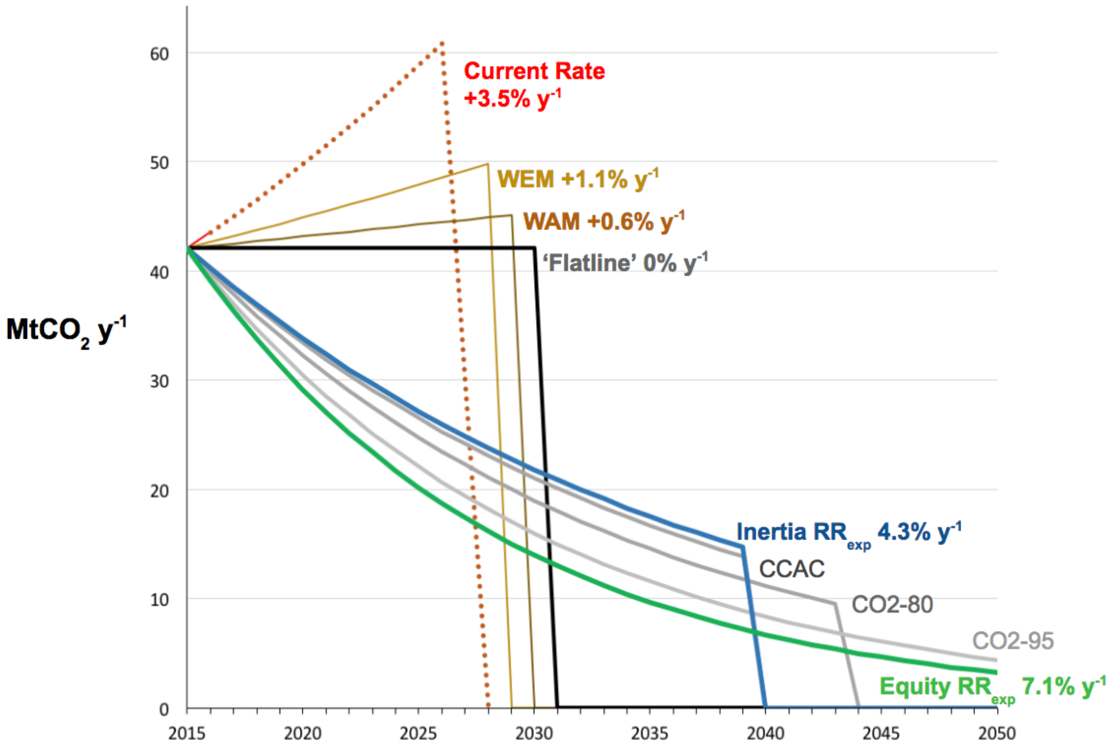

Figure 8.8: Ireland CO_2 exponential-average pathways until the average equity quota is exhausted.

8.5 Limitations of methods and results

All of the methods used here can provide only indicative values for Ireland's carbon quota. They are all based on burden-sharing principles that embody ethical values and choices. Meeting the quotas would rely on national and international political and societal action to limit future global emissions within the remaining WB2C global carbon budget.

The large (±35%) range for the Rogelj *et al.* (2016) WB2C global carbon budget also applies to all of the given national quota estimates. Assuming the global carbon budget is higher than the mid-value given (and therefore that the national carbon quota is larger than estimated above), would not be prudent, given the inherent additional risks (and implied costs) of such an assumption; indeed, both the precautionary principle and the Paris Agreement commitment to "pursuing efforts" toward a lower temperature goal of 1.5 ºC would rather mandate adopting the *lowest* limit of the global budget range as the basis for Paris-aligned action.

8.6 Discussion

8.6.1 Discussion of results and relevant literature

The Paris Agreement embodies a commitment to aligning national climate mitigation policy with limiting future emissions within a WB2C global carbon budget (Schleussner et al., 2016). The results derived for this chapter are only approximate estimates, and are necessarily value-laden. Nonetheless comparing these quota values with the current projected and proposed pathways can point toward the scale and urgency of policy ambition now required to align mitigation action with Paris Agreement commitments. The nett quota estimates in Figure 8.6 suggest that Ireland's remaining mid-range equity quota from 2015 onward is about 590 $MtCO_2$, corresponding to a reduction rate of about 7% yr^{-1}. In fact, Irish CO_2 emissions *increased* by 3.8% in 2016, relative to 2015, to 39.9 $MtCO_2$, reducing Ireland's estimated carbon quota and increasing the corresponding required decarbonisation rate. Accounting for the likely global and national emissions in 2016 and 2017, the remaining mid-value equity quota as of the end of 2017 is likely reduced by about 85-90 $MtCO_2$ to about 500 $MtCO_2$, with the RR_{exp} already increasing from about 7.1% yr^{-1} to 8.5% yr^{-1}. Even the estimated inertia quotas for Ireland are less than 1000 $MtCO_2$, far less than the 1430 $MtCO_2$ to 2050 (and far more being emitted cumulatively beyond 2050) for a scenario flatlining CO_2 emissions at the 2015 level.

The EPA's WEM and WAM pathways to 2035, based on sustained economic growth, with limited emissions decoupling from that growth, project annual energy and process emissions continuing to rise above current levels and, extended to 2050, exceed a likely equity quota by more than 1000 $MtCO_2$. In contrast, all of the equity quota and RR_{exp} combinations indicate that nett Irish CO_2 emissions need to be close to zero by 2050. If substantive removals can be achieved by NETs in Ireland then ongoing gross emissions after 2050 level might be balanced to give nett zero emissions, especially if energy emissions have been brought as near as possible to zero carbon by sustained mitigation action.

Using M5 (Climate Equity Reference Framework), which takes responsibility and capacity into account, does not provide a nett quota to compare with other methods, as the large amount of indicated negative emissions after 2030 is not quantified. Nevertheless, it is included in this chapter to note that this methodology arrives at a very different view of an *equitable* allocation to the 'equity' quotas arrived at on the basis of global population share. In the CERF example examined, Ireland's "fair share" pathway reduces at 3.6 $MtCO_2$ yr^{-1} from current levels, falls below zero in 2027, and continues at this rate into deeply negative allocation values through and beyond 2030. In this methodology, the gap opening between the actual and allocated emission gauges a nation's immediate and escalating responsibility for the global climate mitigation effort to meet a temperature target.

The high decarbonisation rates required for the estimated equity quotas agree with the 5% to 14% range given by Larkin (2017, p. Table 1) for the maximum sustained annual rate needed for nations and regions with high per capita emissions. Policy dependence on negative emissions technologies to deliver the high levels of CDR postulated in many of the AR5 IAM global mitigation scenarios inequitably risks a failure to deliver negative emissions at significant scale in future (Larkin, 2017). Although Larkin *et al.* (2017) focus on groupings of the largest national emitters (the 25 nations responsible for over 80% of global CO_2 emissions), Ireland has higher per capita CO_2 and CO_2e emissions than many of the nations included. IAM modelled global energy decarbonisation scenarios for the WB2C budget range are also high, indicating *average* nett decarbonisation rates of 4.5% yr^{-1} to 8% yr^{-1}. Any easing of the challenge of simply reducing *gross* emissions at such a rate would depend on the scale and timing of negative emissions that are actually successfully deployed (van

Vuuren et al., 2016). Mitigation policy falling short of such challenging nett decarbonisation rates, corresponding to the CO_2 quota estimates for Ireland, is (explicitly or implicitly) incorporating a rising reliance on NETs deployment that implies a tacit commitment to deliver large cumulative amounts of CDR in the future with very high confidence, thereby potentially accepting moral hazard by inequitably transferring significant risk of failure to future decades and populations (Anderson and Peters, 2016). The economic analysis for Ireland outlined by Glynn (2017), based on a WB2C equity quota, and suggests that delaying substantive near-term decarbonisation becomes progressively less cost-effective by increasingly limiting options to less cost-efficient pathways. *Immediate* policy measures to reach and sustain the already required RR_{exp} would evidently be far more cost-effective. The urgency and scale of WB2C mitigation action demanded by physical reality, risk assessment and economic logic contrast strongly with the commonly preferred policy approach of only gradually increasing effort over time (Luderer et al., 2016; Robiou du Pont et al., 2016).

8.6.2 Policy relevance of results

Ireland's current National Policy Position, the basis for the National Mitigation Plan, only explicitly specifies an end-point target, of 80% reduction relative to 1990 levels in 2050, for energy CO_2 emissions among the aggregate sector of electricity generation, built environment and transport (EGBET). An exponential path of sustained fractional effort to meet this target would already require annual reductions of 5% yr^{-1}. However, no pathway or quota to 2050 is specified by the NPP and near-term emissions are increasing rapidly, especially in transport and electricity generation, suggesting that only limited reductions in cumulative CO_2 emissions might be achieved (even if the end point target could still be met) unless strong management of climate pollution is enabled in the near-term. Globally, very early peaking in total emissions is the common factor in stringent mitigation scenarios and IAM scenarios "require a massive scale up of low carbon technologies" by 2050, which can be reduced in scale by reductions in energy demand (van Vuuren et al., 2016).

The increased radiative forcing due to increasing agricultural emissions (increasing by 10.2% from 2011 to 2016) suggest the Irish CO_2 quota should properly be assessed as *lower* than the estimates given here due to the additional warming effect of higher annual rates of methane emission – as non-CO_2 emissions significantly affect the relation of resultant warming to cumulative CO_2 emissions (van Vuuren et al., 2016). The NMP indicates that forestry might only enable CO_2 removals amounting to a fifth of agricultural CO_2e emissions in 2050, assuming UNFCCC equivalence factors (DCCAE, 2017a, p. 123). Within the EU accounting (separating ETS and non-ETS emissions), limited reductions in agricultural emissions by 2050 imply that energy and process emissions may need to be reduced by more than 100%, requiring negative emissions (domestically or on some currently hypothetical basis of future CDR trading) to compensate for ongoing gross agriculture CO_2-equivalent emissions (Chiodi et al., 2015a, 2007).

Following the logic of Peters, Andrew, and Friedlingstein (2015), Ireland's projected emissions based on current policy could be seen as an implicit, highly inequitable claim on the WB2C global carbon budget. This may be arguably be in conflict with the legally specified “regard” for climate justice (Climate Action and Low Carbon Development Act, Art. 3(2c), Oireachtas, 2015). A continuing divergence between emissions and target commitments may be seen as a lack of ambition unless there is a plausible commitment to achieving capacity or responsibility for carbon capture and storage and negative emissions to remove the excess emitted CO_2 in future (Peters et al., 2017; Peters and Geden, 2017). Even on average, emissions need to peak globally by 2020 and fall thereafter, or commit to ensuring negative emissions at large scale, starting well before 2040, for plausible WB2C pathways with stringent mitigation (van Vuuren et al., 2016).

In the immediate term (for at least the next decade) climate mitigation needs to be achieved almost entirely by substantial reductions in annual gross CO_2 emissions, prioritising reductions in fossil fuel use, to align policy with even a small chance of limiting to 2ºC (Bauer et al., 2016). Only as and when scalable CO_2 removals with high storage permanence (i.e., geological storage), are progressively demonstrated, with reliable performance verification and cost projections, could prospective further contributions of such removals be realistically incorporated in ongoing assessment of conformance to any individual county’s nett WB2C CO_2 quota (Larkin et al., 2017). In any case, any policy reliant on NETs needs to realistically assess the risks of non-delivery of negative emissions in future due to technical and biophysical limits, ecological and societal impacts, or ultimately ineffective mitigation if land-stored carbon becomes subject to reversal (Dooley and Kartha, 2017). Risk management within a WB2C carbon quota requires precautionary planning to achieve early and deep decarbonisation while making clear assessments of potential for and limits to national policy dependence on negative emissions (Geden and Löschel, 2017).

As well as indicating an equitable quota to guide future economy-wide policy, a revised National Mitigation Plan would usefully supply a timeline for when initial estimates of negative emissions at significant scale could be integrated into policy, enabling investment and delivery timelines for ongoing negative emissions technology research and development. As the climate impact of Ireland critically depends on the emission pathway taken from now until 2050, the (currently non-statutory) National Policy Position might best be revised to explicitly specify a maximum CO_2 quota as the “National Mitigation Objective” (NMO), identified by the CCAC (2016). Equivalently, the NMO could specify a reference functional form for a nett emissions decarbonisation pathway (linear, exponential or otherwise) which, together with start and end/horizon points, allows effective determination of the intended CO_2 quota commitment. In effect, this would represent Ireland’s explicit policy quota claim on the WB2C global carbon budget.

8.7 Conclusion

- A range of possible Irish carbon quotas (from 2015) aligned with meeting a WB2C target are estimated using four different methods. From the start of 2018, the remaining equity quota for Ireland (subtracting estimated 2016 and 2017 emissions) is about 500 $MtCO_2$ for energy, cement and land use emissions. Comparable inertia quotas are of the order of 900 $MtCO_2$.
- Current emission projections average *growth* of 0.6% yr^{-1} to 1.1% yr^{-1}, and in 2016, Ireland's CO_2 emissions (excluding LULUCF) rose by about 3.8%. In contrast, an equivalent exponential *emissions* reduction rate of about 8% yr^{-1} would be needed from 2018 to stay within the estimated WB2C equity quota.
- The indicative CCAC linear emission path, proposed by the Climate Change Advisory Council (2017), and the CO_2-80 and CO_2-95 pathways (Ó Gallachóir et al., 2012) imply nett CO_2 quotas and decarbonisation rates between the estimated inertia and equity pathways.
- In Ireland, the growing gap between the reality of rising CO_2 (and non-CO_2) emissions and the Paris Agreement implied requirement for plausible, decarbonisation pathway aligned with a WB2C global carbon budget, already suggests a tacit, potentially high-risk, policy reliance on negative emissions.

9 Potential for NETs Deployment in Ireland: A Preliminary Assessment

Summary

- Few national-scale assessments of NETs are available to apply global research to assess negative emissions potential in meeting decarbonisation targets.
- NETs experience to date in Ireland has focused on afforestation (AF), with limited dedicated bioenergy (BE) crop cultivation or enhanced soil carbon sequestration.
- While BE crop cultivation with unabated combustion/oxidation and fossil fuel carbon capture and storage (FFCCS) cannot achieve nett CDR in themselves, they do provide *critical enabling capabilities* for potential future CDR processes.
- *Miscanthus* and willow coppice planting for BE have high potential in Ireland, and have been subsidised, but lack clear long term commitment, reducing confidence.
- Indirect land use change (ILUC) can have a significant emissions impact on the lifecycle assessment of BE, potentially negating much or all supposed climate benefit; especially without CCS (i.e. outside currently theoretical BECCS pathways).
- Currently assessed practical offshore capacity for geological carbon storage in Irish national territory is ~455 $MtCO_2$. Most is in the nearly-exhausted Kinsale natural gas field, with a capacity of ~330 $MtCO_2$ (if suitable, and kept available for CCS).
- Irish soils hold a large standing stock of carbon but soil carbon sequestration (SCS) appears unlikely to achieve nett negative emissions even within the land use sector. Existing soil carbon is currently being lost, requiring arrest by ecological restoration. Relying on large scale enhancement of SCS as a key climate mitigation tool may be ill-advised given accounting (MMV) difficulties and inherent SCS reversibility.
- Ideally (from a climate mitigation perspective), indigenous bioenergy resources might best feed BECCS pathways; but current policy incentivises investment in smaller scale BE heating plants conflicting with future BECCS integration (and risking early stranding of subsidised assets).
- NETs options in Ireland have very different potentials, limitations, benefits and costs (see Table 9.2). Long term strategic commitment, but with flexible response to demonstrated performance, is therefore needed for strategic NETs development.
- Applying the simple NETs model of Smith *et al.* (2016) to Ireland, a preliminary technical assessment indicates potential cumulative CDR of c. 400 $MtCO_2$ to 2100.
- A possible initial NETs strategy is: maximise AF in the near-term while supporting the development of BECCS infrastructure so that AF harvest biomass can be allocated to this pathway as biogenic carbon stocks saturate.
- Direct Air Carbon with CCS (DACCS) and Enhanced Weathering (EW) will be feasible only when (or if) sufficiently low carbon input energy supplies become available.
- In the immediate term, mitigation policy should continue to focus on rapid, deep, reductions in gross GHG emissions, at rates well above current stated policy ambition (and far in excess of current Irish policy delivery). This will be most effective through mutually reinforcing actions at national, EU and global levels.

9.1 Introduction

As presented in the previous chapters, the international research on NETs has been growing rapidly, especially since 2005. For example, Minx *et al.* (2017) found 2900 studies published on NETs from 1991 to 2016, with the rate of publications increasing dramatically. They found the research to be characterised by a focus on particular candidate technologies with few integrated analyses. Publications range in scope from reviewing potential, assessing feasibility and technological maturity and discussing deployment opportunities. Some of the literature addresses the deployment of specific, relatively mature, NET options at a local case study scale, where opportunities are being actively realised (Gale et al., 2011; Mathisen et al., 2011; Matter et al., 2016).

It has been argued that ungrounded optimism in NETs potential could result in delayed reductions in gross CO_2 emissions, with consequent high-risk of overshoot of global temperature targets (Vaughan and Gough, 2016). Hence it is important that the realistic potential of NETs be carefully assessed in every context where it is considered. The literature has identified a gap between general assessments of feasibility and potential and the specific local case studies (Fuss et al., 2016). The downscaling of NETs research to a nationally relevant context is a vital next step in progressing its deployment. An outline study of this sort has recently been presented for the UK (Smith et al., 2016). This chapter will similarly present a preliminary assessment of NETs potential in Ireland, as an example of a small developed island nation at the very early stages of considering scalable NETs deployment. The chapter aims to integrate the global NETs literature with the relevant national research to provide an assessment that reflects the specific national context of practical, social and economic opportunities and constraints.

Ireland has undertaken multiple interacting commitments to greenhouse gas emissions reduction, through its National Policy Position (DECLG, 2014), its participation in EU co-ordinated climate action directives, regulations and decisions, and its ratification of the Paris Agreement (UNFCCC, 2015). Of these, the Paris Agreement temperature goals now represent the overarching constraints that all parties have committed to respect. Parties submitted statements of their separate, voluntary, Intended Nationally Determined Contributions (INDCs) in advance of the adoption of the Paris Agreement. Now formalised as NDCs under the Agreement, these have been assessed for their collective mitigation adequacy. Multiple assessments find that they are currently inadequate to the achievement of the temperature goals (Anderson *et al.* 2015; Schleussner *et al.* 2016, Rogelj, den Elzen *et al.* 2016; Knopf *et al.* 2017). It is in this context that national commitments must now be reassessed. In particular, as discussed in Chapter 8 above, based on the Agreement, Ireland now has a finite remaining quota of further nett CO_2 that it can emit (on the basis of science and equity). It is the possibility that gross emissions of CO_2 either already have, or shortly will, exceed Ireland's remaining quota that raises the question of how much gross CO_2 *removals* Ireland can feasibly achieve, quickly enough, to "re-balance" its nett quota (i.e. clear its tacit "sovereign carbon debt"). Within the spirit of the Agreement, any remaining shortfall will have to be made up either by purchasing unused carbon quota from other parties, or purchasing the required CO_2 removal services.

A first, high level, way of classifying potential NETs approaches is according to the targeted carbon storage mechanism: either biogenic (soil organic carbon or standing biomass) or geological (most typically assumed to be by pumping CO_2, under pressure, into suitable porous rock formations, sealed below non-porous strata). While both can contribute in the short (decadal) term, concerns over saturation and permanence of biogenic storage (particularly in the face of ongoing climate disruption) mean that it is best viewed as only a temporary or transitional measure. Ultimately, only return of carbon to secure geological storage can be relied on to adequately counteract the accumulated effects of transferring carbon from geological stocks of fossil fuels to the atmosphere. Thus, any programme of carbon dioxide removal targeting biogenic storage must also be accompanied by a "backstop" of carbon transfer to geological storage, though this is not explicitly reflected in current UNFCCC mechanisms or accounting.

A second, high level classification is according to the mechanism for initial removal of CO_2 from atmosphere. Again, there are two main possibilities: either biogenic (via photosynthesis in plants) or technological (primarily in the form of what is called "direct air capture" or DAC).

Table 9.1 below presents the particular NETs technologies that will be considered further in this chapter, together with their respective classifications of both CO_2 removal from atmosphere, and carbon storage (whether as CO_2 or in some other form).

Table 9.1: NETs classification

NET	Removal	Storage
Enhanced Soil Carbon Sequestration (SCS)	Biogenic	Biogenic
Biochar	Biogenic	Biogenic
Afforestation	Biogenic	Biogenic
Enhanced weathering	Technological	Geological
Bioenergy with Carbon Capture and Storage (BECCS)	Biogenic	Geological
Direct Air (Carbon) Capture with Storage (DACCS)	Technological	Geological

There is extensive prior experience in Ireland with afforestation, and more limited experience with bioenergy crop cultivation, and with enhancement of soil carbon sequestration (via the use of biochar or otherwise). There is no existing experience with either Direct Air Capture (DAC) of CO_2 or Carbon Capture and Storage (whether in mitigating emissions from conventional fossil fuel combustion – FFCCS – or in conjunction with bioenergy, BECCS, direct air capture, DACCS). BECCS and DACCS would interact directly with the overall energy system: BECCS could contribute nett energy, whereas DACCS would require additional energy consumption. With the exception of DACCS, all the NETs mentioned in Table 9.1 would interact very substantially with domestic land use and agricultural practices; in some cases competing with existing land use (bioenergy crops, afforestation) and in other cases potentially being complementary to, or co-existing with, existing use (enhanced soil carbon sequestration, enhanced weathering).

The following sections will draw from international and national research to provide an account of soil carbon storage and the potential for enhanced soil sequestration in Ireland, discuss the Irish context for biochar applications and for enhanced weathering, detail the GHG profiles and socioeconomic context for afforestation and bioenergy crops in Ireland and assess the status and potential of CCS in Ireland, including FFCCS, BECCS and DACCS.

9.2 Enabling Capabilities

We first consider the status of two *enabling* capabilities: while, in themselves, neither of these can achieve nett removal of CO_2 from atmosphere, there are essential components for certain NET approaches considered subsequently.

9.2.1 Dedicated Bioenergy Crop Cultivation (BE)

In general, cultivation of plants and use for bioenergy production may contribute to overall GHG mitigation in several distinct ways:

- Displacement of higher GHG land use practices (e.g., ruminant animal farming)
- Contribution to enhancement of soil carbon sequestration
- Displacement of fossil fuel energy sources (presumed to be of higher CO_2 emissions intensity)
- Combination with CO_2 capture (pre- or post-combustion) and geological storage to achieve a CO_2 nett negative energy pathway (BECCS)

In this section we specifically consider issues involved in the cultivation of “dedicated” bioenergy crops in Ireland. By this we mean perennial or short rotation crops, cultivated and harvested solely for bioenergy use. On a lifecycle assessment basis such cultivation may have comparatively low emissions intensity, i.e., low nett GHG emissions per unit of useful energy output, but will certainly not achieve zero or negative nett emissions in itself. The combination of BE with CCS (BECCS) to achieve nett negative emissions will be considered subsequently. Note that while forestry can also be harvested for bioenergy use, it has multiple other uses, and, in certain circumstances, can achieve nett negative emissions in its own right. Afforestation will therefore be considered separately, both as a potential NET in itself, and as a potential alternative bioenergy component in BECCS deployment.

9.2.1.1 GHG LCA for BE Displacement of Fossil Fuels

The direct GHG mitigation potential of bioenergy crops, by fossil fuel displacement, is a contentious issue. There are many components of bioenergy cultivation and processing systems that emit GHGs. Life Cycle Assessments (LCA) seek to measure the net emissions of bioenergy crops by identifying all the sources and sink components in the full life cycle of a crop within a single-farm or national system. In general this may necessarily include non-CO_2 GHGs. While overall effects are commonly aggregated using a "CO_2-equivalence" methodology (GWP-100 or otherwise), in the context of assessing potential for nett negative CO_2 it would arguably be better to maintain separate accounting of each GHG. In any case, CO_2, in particular, released from the supply chain should be fully quantified and must not exceed the amount captured and stored in the original plant cultivation if there is to be any CO_2 mitigation benefit to fossil fuel substitution (Mac Dowell and Fajardy, 2017).

(Mohan, 2016) highlights the general need for life cycle accounting assessment of all proposed bioenergy production systems. However, it also important to note that LCA analysis can be problematic in detailed interpretation and application. For example, (Plevin et al., 2014) argue that "because of several simplifications inherent in ALCA [Attributional LCA], the method, in fact, is not predictive of real-world impacts on climate change, and hence the usual quantitative interpretation of ALCA results is not valid".

A particular challenge in LCA assessment of bioenergy systems is the characterisation of indirect land use change (ILUC), which may represent a significant emissions impact. If indirect land use change emissions are judged to be high, e.g., 130gCO_2 MJ^{-1} (468 g kWh^{-1}) for LUC emission factors of Irish Miscanthus or Willow biomass, based on estimates by (Tonini et al., 2012), then the nett CO_2 mitigation by direct fossil fuel displacement may be modest at best; or at worst, may actually *increase* total CO_2 emissions. (Czyrnek-Delêtre et al., 2016) evaluate potential evolution of the Irish energy system to 2050, under specific CO_2 mitigation constraint and minimisation of overall notional-cost. They find that, if LUC emissions are assessed as relatively high (but still less overall than from fossil fuel use), then the projected bioenergy share might fall by 30%, and would be accompanied by an increase in notional marginal CO_2 abatement cost of 68%.

Apart from LUC, additional sources of local non-CO_2 GHG emissions in bioenergy production come from fertiliser inputs (Dieterich et al., 2008). *Miscanthus* and SRWC cultivation in Ireland are estimated to respectively emit 1.9 kg ha^{-1} yr^{-1} and 1.2 kg ha^{-1} yr^{-1} of N_2O, accounting for 68% of *Miscanthus'* net emissions (Styles and Jones, 2007a). Cultivation and harvest (Styles and Jones, 2007a), processing – pelleting Miscanthus requires much more energy than briquetting (Murphy et al., 2013) – and transport also emit significant GHGs. Nonetheless, (Dondini et al., 2009) suggest that heat energy production from *Miscanthus* and SRWC systems could achieve 'better than carbon neutral' emissions, in the long term, when grown on tillage land.

Overall then, net GHG emission reductions from bioenergy crop cultivation varies in general, dependant on the chosen crop, the displaced land use and displaced fuel. *Miscanthus* and SRWC systems generally have significantly lower GHG emissions than sugar beet or grass systems. LCAs have found that fuel-chain emissions (exclusive of indirect land use effects) for willow and *Miscanthus* are significantly lower than conventional use of gas, oil and electric heat (Styles and Jones, 2008a), and of peat and coal (Styles and Jones, 2008b). Fuel-chain emission reductions range from c. 7.7 tCO_2 $ha^{-1}y^{-1}$ (willow displaced grassland and gas) to c. 34 tCO_2 $ha^{-1}y^{-1}$ (*Miscanthus* displaced set-aside and electric heat) (Styles and Jones, 2008a).

Continued work to refine and improve lifecycle analysis of bioenergy systems in Ireland remains an important research priority to inform future BE policy.

9.2.1.2 BE Enhancement of Soil Carbon Sequestration (SCS)

In Ireland, bioenergy crops could play an additional role in climate mitigation by enhancing soil carbon sequestration (SCS) on cultivated lands. While disturbance and vegetation removal when land use is changed to bioenergy crops initially releases CO_2 from the soil, this may be counterbalanced by the sequestration of CO_2 if the bioenergy crop is allowed to mature. In Ireland 90% of agricultural land is currently in grassland (generally supporting ruminant livestock farming systems) and *Miscanthus,* a perennial rhizomatous grass (PRG), is a leading candidate bioenergy crop. Donnelly *et al.* (2011) found that immediate land use change emissions from grassland to *Miscanthus* are indeed progressively counterbalanced by soil carbon sequestration, with environmental co-benefits of improved water, air, soil fertility and biodiversity, provided that the crop is allowed to become established and mature. Zimmermann, Dondini, & Jones (2013) emphasise the need for long-term commitment to bioenergy systems, calculating that it takes over 14 years for the labile soil carbon initially sequestered by *Miscanthus* in Ireland to stabilise into a more permanent form. Dondini *et al.* (2009) found that converting arable land to *Miscanthus* plantations could store up to c. 11 tCO_2 $ha^{-1}yr^{-1}$. However, soil carbon does generally saturate in time, and the potential contribution of bioenergy crops to Ireland's soil carbon stock depends on the crop yield and initial soil carbon level (relative to saturation). Careful restrictions in management and agricultural practices would help establish bioenergy systems with annual sequestration and long-term mitigation potential (to maximize soil carbon permanence). In principle, the climate mitigation benefit of maintaining enhanced soil carbon stocks in this way could be explicitly incentivised. However any such incentivisation would have to accommodate the (likely substantial) costs of detailed monitoring and verification; with continuing monitoring required indefinitely even after soil carbon reaches saturation.

9.2.1.3 Current Irish Bioenergy Policy Framework

Policies for bioenergy crops in Ireland are characterised by 'a complex mix of incentives and restrictions' (Smyth *et al.* 2010). Prior to a National "Food Harvest 2020" policy and removal of the EU milk quota, EU Common Agricultural Policy (CAP) reforms decoupling production and support had resulted in destocking across Irish livestock agriculture, which created opportunities for introducing new bioenergy crops (Styles and Jones, 2008a). EU supports also provide €45 ha^{-1} of set aside land used for industry, which can be claimed by growing bioenergy crops. However, the CAP has also placed limits on the conversion of permanent grasslands to other uses. Most recently, the 2013 CAP reform imposed a maximum change of 5% in the ratio of permanent grassland to other uses, relative to the situation prior to this reform (DAFM, 2015, p. 42). Such restrictions have been motivated explicitly by a presumed relative carbon sequestration benefit of permanent grassland (EU, 2013 preamble, p 42); though this appears to pre-empt detailed analysis of specific use changes. With 90% of Irish agriculture land being classified as permanent grassland, such limits have been identified as significantly constraining the land potentially available for dedicated bioenergy crops (Smyth et al., 2010).

Separately, the EU has also introduced sustainability criteria that require that biofuel used in transport, and bioliquids more generally, must effect progressively higher CO_2 emissions reduction compared to the fossil fuel displaced. This must reach at least a 60% reduction by 2020 (albeit, exclusive of ILUC effects). EU rules also require that BE production does not use land of high biodiversity value (including peatland) and that “due consideration” is given to any impacts on food production.

A national policy target to replace 30% of peat consumption in electricity generation with biomass from 2007-2015 was published in March 2007, but appears to have been substantially achieved in only one of the three peat-fired plants (Egan, 2015; Moran, 2015). The expectation appears to be that the same total cumulative amount of peat will ultimately be extracted and burned (just over a somewhat longer period); thus, the direct cumulative nett transfer of carbon from the (territorial) peat stock to atmospheric CO_2 will be unchanged. Indeed, it may be argued that this co-firing, by providing access to additional subsidies for such plants (in support of the EU Renewable Energy Directive), actually extended their economic life in a manner contrary to the intentions of the EU Emissions Trading Scheme. Just over 1.7 MtC was also lost due to extraction of peat in 2016 (EPA 2017c).

In any case, establishment grants through a national Bioenergy Scheme were made available for growing bioenergy crops, resulting in 2414 ha of *Miscanthus* and 939 ha of willow (Walsh et al., 2017). For the 30% co-firing target to be met entirely by indigenous biomass, it was estimated that 45,000ha (~1.2% of total land potentially available for all agricultural purposes) would have been required (Clancy et al., 2008). In practice, importing biomass in pursuit of the national co-firing targets is reported as having resulted in significant carbon “leakage” in Ireland’s emissions profile (Murphy and McDonnell, 2017); that is, while reported annual territorial emissions were indeed reduced, nett global emissions directly attributable to this territorial energy use likely remained the same or potentially increased. With annual yields, earlier returns, competitive profit margins and the establishment grant, familiarity and confidence in *Miscanthus* did progressively increase and it became the favoured option for those farmers who chose to plant bioenergy crops (Augustenborg et al., 2012a; Clancy et al., 2012). Then, in 2015, the Bioenergy Scheme stopped supporting *Miscanthus* and only provided support for willow (Walsh et al., 2017). This was reported as being due to the lower chloride content in willow, causing less corrosion on power plant hardware. Nonetheless it is evident that this relatively sudden cessation of support had a negative effect on stakeholder confidence in long term bioenergy crop cultivation. It would be essential that future policies explicitly address issues of coherence and confidence in stable long-term strategy.

Achieving as much as half of Ireland's total energy demand from bioenergy by 2050 has been reported as emerging from least notional-cost modelling of even relatively modest CO_2 mitigation scenarios, but, as already noted, constraints on imports and sustainability criteria (based on LCA-type analysis of actual, global, emissions impacts from substitution for fossil fuels) would greatly reduce this supposed potential (Chiodi et al., 2015a). Ireland's bioenergy industry representative association estimated that a €1.5 billion investment in biomass infrastructure and equipment would have been needed from 2011-2020 for bioenergy to have contributed as required to meeting the 2020 EU renewable energy penetration targets for Ireland (IRBEA, 2012).

Achieving the recent target of indigenous biomass replacing 30% of peat-firing in electricity generation in 2015 was estimated to require prices of €70 and €65 per tonne of willow and *Miscanthus* respectively (Clancy et al., 2012). (SEAI, 2012) bioenergy-supply curves suggest that bioenergy crops of *Miscanthus* and SRWC have the most potential for expansion of bioenergy production in Ireland, but would require progressively higher market prices (up to 250% increase) to achieve a scenario of maximised energy yields from 2010-2030 (see Figure 9.1).

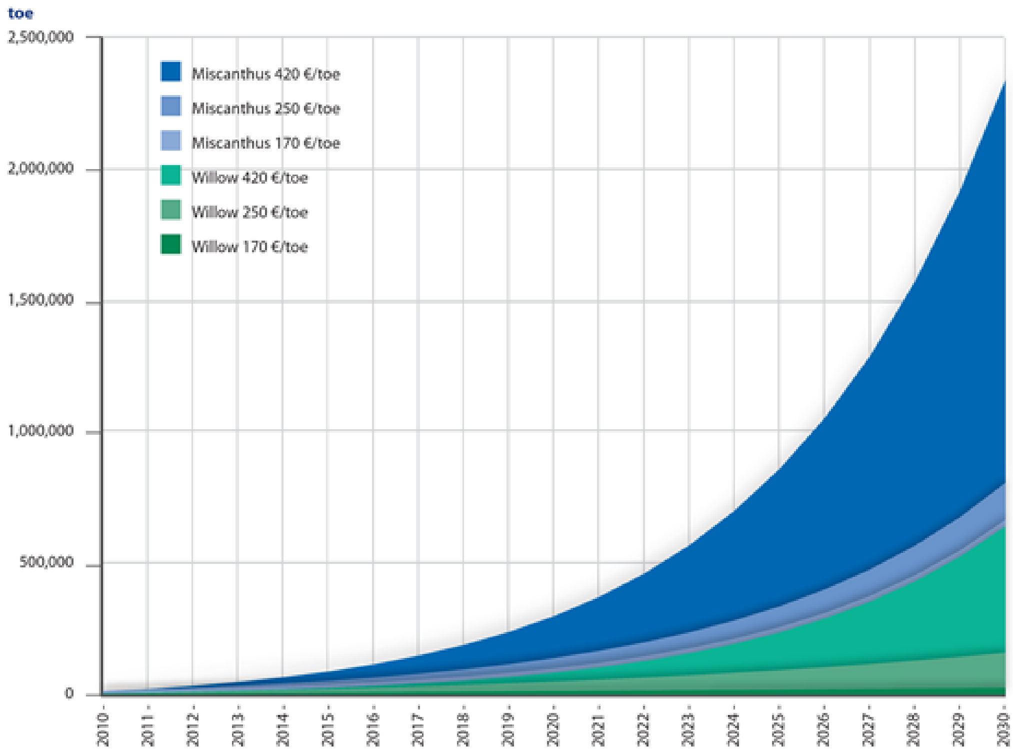

Figure 9.1 Estimate of Potential Perennial Energy crop resource 2010-2030 for different price scenarios (reproduced from SEAI, 2012)

While low fossil fuel prices have generally rendered bioenergy uncompetitive in the past (Rourke et al., 2009), bioenergy production systems are now becoming increasingly attractive relative to conventional agriculture in Ireland. According to (SEAI, 2012) SRWC and *Miscanthus* were then offered higher profits than beef production, were similar to renting grassland, but less profitable than cereal production. This corroborates the earlier findings by (Styles et al., 2008) that, with appropriate supports, bioenergy crops can become increasingly viable options. In 2008 *Miscanthus* had higher gross margins ($ha^{-1} yr^{-1}$) than willow and was considered competitive with all conventional agriculture except dairy (Styles et al., 2008). However the market for Miscanthus is now reduced due to its withdrawal from the national Bioenergy Support scheme.

Trade-offs also exist in Ireland between GHG emissions and energy demand, acidification, eutrophication and biodiversity (Bourke et al., 2014; Murphy et al., 2013, 2014a; Stanley and Stout, 2013). Future policies should endeavour not to undermine existing policies in these areas (Burrascano et al., 2016).

There are several additional barriers to producing bioenergy crops in Ireland. These include:

- Cultural attitudes in the agricultural community. Agriculture in Ireland is traditionally focused on food production (Doran, 2012). Education level, existence of successors (Clancy et al., 2008), farm system and size (Clancy et al., 2011) all influence a farmer’s decisions to adopt energy crops.
- *Miscanthus* takes two years to establish and willow takes four (Styles and Jones, 2007b). The longevity of the bioenergy system must be incorporated into policy incentives for the mitigation potential and all co-benefits to be achieved. The long term commitment required with uncertain market and policy is off-putting (Clancy et al., 2009).
- There is uncertainty for Irish-specific yields and reliability of production (Clancy et al., 2012, 2009) and uncertain financial benefit, high initial capital investment with long payback period and reliance on coordination with the agriculture sector’s long term planning to meet demand (Styles and Jones, 2007b).

Healion (2016) found that successful bioenergy production systems in Ireland were characterised by a strong focus (commercial or philosophical), international network sharing of expertise and technology and financial support.

9.2.2 Fossil Fuel Carbon Capture and Storage (FFCCS)

As with dedicated bioenergy cultivation and use, conventional (fossil fuel) carbon capture and storage (FFCCS) has the potential to provide energy with CO_2 emissions intensity that is substantially lower than existing (unabated) fossil fuel use; but certainly cannot achieve zero or nett negative emissions in itself. However, both the capture and storage components of FFCCS are potentially applicable in multiple nett negative emissions approaches, and so will be presented here in their conventional form first.

A detailed report in 2008 assesses the potential for FFCCS deployment in Ireland (CSA Group, 2008). The maximum potential capacity (total of practical, effective and theoretical capacity) estimated for long term geological storage of carbon in Ireland (including territorial waters/undersea) is 93 $GtCO_2$, but there is a large uncertainty range for this figure due to the paucity of geological data. The more meaningful figure for practical policy use at this time (pending much more extensive and detailed geological investigation) is the estimate of *practical* capacity only, given as 1505 $MtCO_2$. However, the great bulk of this (1050 $MtCO_2$) is in the East Irish Sea, in UK territorial waters; accordingly, only ~455 $MtCO_2$ of practical capacity is identified in Irish territory. To put this in context: given 2015 Irish total energy system emissions of ~38 $MtCO_2$ (SEAI, 2016d) this could theoretically accommodate a maximum of ~12 years of additional gross fossil energy use (neglecting any growth or contraction in primary energy use, supposing that 100% of such additional CO_2 could be captured, directly or indirectly, and ignoring upstream, non-territorial, emissions associated with fossil fuel extraction, processing and transport).

Further assessments have been made of the potential for storage in the Clare Basin, directly adjacent to the existing large coal-fired electricity generating station at Moneypoint, Co. Clare (Farrelly et al., 2010) and in the central Irish Sea (Bentham, 2015). In both cases, the conclusions have been discouraging: due to low permeability in the case of the Clare Basin, and fragmentation of storage closures and high risk of leakage in the case of the central Irish Sea.

Of the originally identified practical capacity within Irish territory, the Kinsale natural gas field is the single largest candidate, with an estimated possible capacity of 330 $MtCO_2$ (90 MtC), and appears as the most likely first suitable storage site, after existing gas extraction is exhausted (c. 2020). However, even this site would require an initial commitment of c. €80 million to be assessed and validated with confidence.

In Irish policy terms, the current position as articulated in the most recent National Mitigation Plan (DCCAE, 2017a) is that CCS deployment in Ireland will be "driven by appropriate carbon price signals of a reformed ETS" (EU Emissions Trading System): which suggests that, beyond limited "feasibility" studies, development would be largely left to commercial market responses rather than direct state support or intervention. Somewhat in contrast, a report from Ireland's Academy of Engineering (IAE, 2016) cautioned that it would be important to properly assess the existing (gas extraction) infrastructure at the Kinsale Head site to ensure that it remains suitable for future CCS use "before any final decision is made on the decommissioning of the Kinsale facilities".

If Ireland does not pursue its indigenous geological carbon storage potential, or if that potential proves to be extremely limited, then, in principle, consideration could also be given to transport (most likely by shipping) of captured CO_2 to a storage facility offered in another jurisdiction. However, detailed legal and business models for such international trading in CO_2 storage services have yet to be demonstrated; and full lifecycle accounting (including the potential for significant additional transport emissions) would be required to assess the overall mitigation effectiveness of such an approach.

Even with CCS, FF energy and various industrial processes (such as cement production) would still be net sources of CO_2, albeit at much lower emission intensity per unit of production. As Ireland's finite CO_2 quota becomes exhausted it will be necessary *either* to discontinue these processes entirely or to fully recapture the ongoing residual (post conventional CCS) atmospheric emissions and commit this to permanent storage i.e., negative emissions technologies of some form. Similarly, if mitigation of gross CO_2 emission is insufficiently rapid, so that the national CO_2 quota is actually exceeded, then it will become necessary to subsequently achieve nett negative CO_2 emission on a complete territorial basis, and sustain this sufficiently long, to fully remove this excess.

9.3 Negative Emission Technology Options

9.3.1 Enhanced Soil Carbon Sequestration (SCS)

(Khalil et al., 2013) estimate the national carbon stock currently in Irish soils as approximately 2.8GtC (equivalent to c. 10GtCO_2 in atmosphere[37]). The highest soil carbon densities are found in the raised bogs. However, in itself, this gives no indication of the potential for enhancing this total stock, or the rate at which such enhancement might be achieved (the flow, or sink, potential). Conversely, Tomlinson (2005) highlights the importance of protecting this existing soil carbon stock in Ireland, as it is currently either being actively being released to atmosphere, or under significant risk of being emitted into the atmosphere, due to disturbance by practices such as peatland drainage, peat extraction, and wider land use change. But if the existing stock can be stabilised, there may then be further potential to add to this stock over time. That said, in general, the carbon stock in any given soil is subject to saturation. Accordingly, the potential for increasing the stock depends on the current carbon deficit in Irish soils, relative to saturation. Unfortunately, there is a paucity of data regarding the maximum stock (saturation) capacity, and corresponding existing carbon deficit, of Irish soils. However the grey literature report (RIA, 2016) suggests that most Irish soils have a significant carbon deficit. This is based on international findings in Europe and other regions with similar climate and soils to Ireland (e.g. New Zealand), where (Feng, 2012; Feng et al., 2013) have found most soils to have a saturation deficit. It is unclear whether this report correctly summarised (Soussana et al., 2007) or adequately addressed the saturation issues noted by (Smith, 2014). A case study for estimating soil saturation deficits at a national level has been presented by (McNally et al., 2017) for New Zealand, where they modelled the saturation deficit for different soil types under use in agriculture. This work might facilitate a similar analysis in Ireland. In principle, such analysis could allow targeting of soils with the highest saturation deficit to achieve the most effective increases in soil carbon stock.

However, as against all this, (Thamo and Pannell, 2016) have argued that soil carbon stock changes should, in general, be excluded from consideration in overall CO_2 mitigation accounting and policies, on the basis of the associated "... challenges, risks and potential for perverse outcomes and high transaction costs". They are not arguing against enhancement of soil carbon per se; but, especially in cases where such enhancement may already have sufficient motivation for reasons not directly related to climate mitigation, its

[37] For comparison and clarity, CO_2 and carbon units are provided where possible, on the basis of one mass unit of carbon corresponding (on oxidation) to 3.67 units of CO_2.

inclusion in climate policy measures "... seems particularly ill-advised." Similarly, Mackey et al (2013) argue strongly against equating enhancement of soil carbon with long-term climate mitigation actions.

Minasny *et al.* (2017) highlight that relying on soil organic carbon to retain carbon removed from the atmosphere should be considered as, at most, only a temporary strategy to buy time until other more secure, long-term, (geological) storage technologies are deployed at sufficient scale. More generally, Smith (in Banwart et al., 2014, p. 240) makes the important point is that:

> *The carbon that humans are currently releasing through fossil fuel use has been locked up in the geosphere for hundreds of millions of years, and was accumulated over many millions of years. Using the biosphere to capture this geospheric carbon does not add up — the geospheric carbon released is too large for the biosphere to store effectively.*

Notwithstanding these legitimate concerns and limitations, to the extent that there is merit in promoting enhancement of soil organic carbon stock this can be achieved through the growth of vegetation and resultant addition of carbon to soil through roots and harvest residues. How the soil and vegetation are managed and how the harvest is used will determine whether that agricultural process is a net source or sink of carbon, to or from the atmosphere.

Several components of conventional agriculture have been identified as having potential to add directly to the soil carbon stocks in Ireland. (Minasny et al., 2017), advocating the so-called "four per mille" ambition for global SCS enhancement (increasing soil carbon stocks by 0.4% yr^{-1} on a sustained basis), suggest that, in the specific case of Ireland, associated soil carbon sequestration rates of 0.6, 0.4 and 0.6 $tCha^{-1}yr^{-1}$ should be "possible" for grassland, arable land and forested land, respectively. Based on current land areas in each of these categories, that would imply potential target aggregate sequestration rates of c. 2.6 MtC yr^{-1} (9.6 $MtCO_2yr^{-1}$) for grassland (4.3 million ha), c. 0.16 MtC yr^{-1} (0.59 $MtCO_2yr^{-1}$) for arable land (0.4 million ha) and c. 0.45 MtC yr^{-1} (1.67 $MtCO_2yr^{-1}$) for forested land (0.75 million ha). However, there is little detail on what specific interventions might be necessary to achieve these rates, nor how long these rates might be sustained before saturation limits are reached. Moreover, there are, of course, also many processes that lead to *loss* of soil organic carbon (for example, peat land drainage), which would be equally important to characterise.

As well as saturation limits, and the potential for soil carbon sequestration to be outweighed by gross emissions from other land use practices, other key concerns for any long-term reliance on soil carbon storage are the issues of permanence and potential reversibility. This is somewhat dependant on the site specific processes of organic carbon stabilisation, i.e., soil carbon becoming less susceptible to decomposition through occulation in aggregates or formation of organo-mineral complexes (Lawrence-Smith et al., 2015). However, more general processes of land use change, soil disturbance, and direct climate change impacts (extreme weather, fire etc.), mean that all soil organic carbon must be considered vulnerable to unpredictable and relatively rapid loss back to atmospheric CO_2 at any time, and should not be equated with geologically stable carbon stocks (natural fossil fuel deposits, and engineered geological CO_2 storage).

Much further data and research would be required to estimate a full soil organic carbon balance (annual change in soil organic carbon stock, positive or negative) for Irish soils. On current evidence, it appears that while enhanced soil carbon sequestration might contribute significantly to *reduce* net land use CO_2 emissions, it is unlikely to be sufficient to achieve *net negative* emissions even just within that land use sector (never mind contribute substantially to compensating for gross emissions in the energy sector).

9.3.2 Biochar (BC)

International literature suggests that biochar (suitably prepared charcoal applied as a soil amendment) may have significant negative emissions potential with fewer adverse side-effects than at least some other NETs due to having a lower impact on land, water use, nutrients, albedo, energy requirements and cost (Smith, 2016). In the global context of research literature, Minx *et al.* (2017) identified biochar as one of the largest reported subject areas of NETs research; though examination of indices such as Web of Science or Google Scholar suggests significantly more focus (to date) on BECCS than biochar. Some constraints identified in using biochar include concerns about saturation (relative to agricultural use and productivity of soils) and reversibility, reduced air quality, heavy metal pollution and site-specific effects (Lorenz and Lal, 2014; Ravi et al., 2016; Verheijen et al., 2013). The international literature also highlights many potential co-benefits of biochar including increased yields (Agegnehu *et al.*, 2016), improved soil quality (Lorenz and Lal 2014; Subedi *et al.* 2017; Rasul *et al.*, 2016) and reduced soil emissions of other GHGs (Nelissen *et al.* 2014; Fidel, Laird, & Parkin, 2017; Mukherjee, Lal, & Zimmerman, 2014; Nelissen, Saha, Ruysschaert, & Boeckx, 2014; Shen *et al.*, 2014).

There is little Ireland-specific biochar research, but much of the international research is transferable to an Irish context. Biochar has recently been introduced to market in Ireland for its fertilisation, disease protection and water retention benefits[38] but it does not feature strongly in current Irish climate mitigation policy and research. The limited Irish-specific research on biochar focuses on its potential to suppress other GHG emissions from soils (Augustenborg et al., 2012b; W Kwapinski et al., 2010; Troy et al., 2013) and improving soil quality and yields (Troy et al., 2014).

Improving geographically explicit data of local soil biochar amendment capacity and strategically targeting soils with the largest capacity would be the most appropriate way to deploy biochar applications in Ireland. This would depend on costs (including monitoring,

[38]See, for example: http://www.biocharireland.com/

verification and ongoing maintenance of the biochar soil carbon stock[39]) relative to other available mitigation and negative emission strategies.

Kwapinski, Byrne, *et al.* (2010) identify multiple potential feedstocks suitable for biochar production in Ireland and suggest that the best resources may be manure (dairy, poultry, pig) and waste. However, care must be taken to assess and manage alternative feedstock uses (e.g., anaerobic digestion), and the risk of incentivisation or lock-in of intrinsically high GHG agriculture systems (particularly based on ruminant livestock). Full lifecycle analysis should include GHGs emitted during biochar production and any inputs during production that may have released GHGs (e.g. fertiliser). Biomass from bioenergy crops can also be used to make biochar. This could reduce the life-cycle emissions of bioenergy crop production by increasing the amount of carbon transfer to soil sequestration, reduce fertiliser and land requirements and suppress soil GHG emissions (Kauffman et al., 2014; Koide et al., 2015; Ubando et al., 2014; Z. Wang et al., 2014; Woolf et al., 2014). Conversely, however, producing biochar from the bioenergy crop biomass will of course reduce the energy output of the yield, creating a trade-off between net GHG emissions and bioenergy availability (essentially partitioning the bioenergy yield between CO_2 removal and other energy services). Perhaps more importantly, if the target bioenergy use is (or can be) integrated with CCS (i.e., a BECCS pathway) then that would appear to displace the role for biochar carbon storage per se (given the much greater capacity and permanence of geological storage). Biochar may still have a role for its other soil amendment benefits, of course, which further complicates this assessment.

9.3.3 Afforestation (AF)

The deployment of afforestation in Ireland is already well established and features heavily in existing climate change mitigation policy. Ireland currently has the lowest proportion of forested land in the EU, but has been expanding its forested area since the foundation of the state in 1922 (see Figure 9.2). The following sections will discuss the potential role of afforestation as a NET option for Ireland, taking into consideration its GHG profile and specific socioeconomic constraints.

[39]Note that continuing maintenance and monitoring costs must be sustained indefinitely, even after soil biochar saturation.

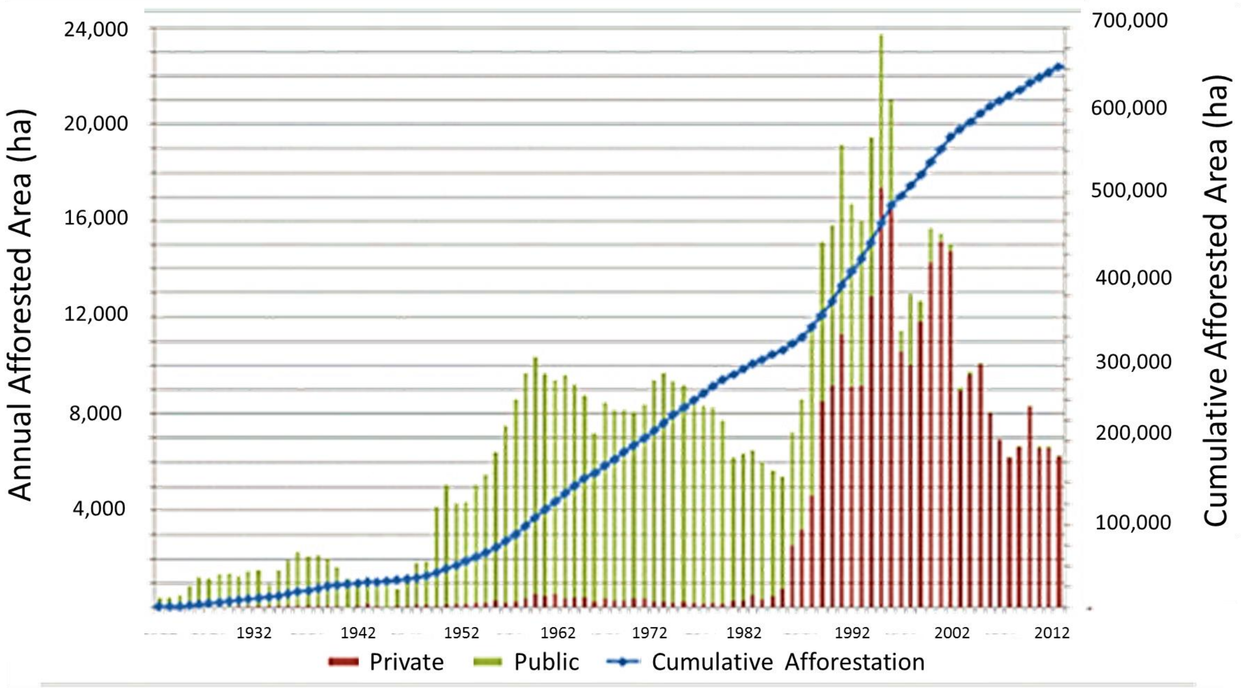

Figure 9.2 Public and Private Afforestation in Ireland (reproduced from Curtin & Arnold, 2016)

Afforestation potentially contributes to carbon storage in two distinct stocks: the tree biomass itself and enhanced soil carbon over the afforested land area. The impact of afforestation on soil carbon stock depends on many factors, including climate, former land-use, forest age, forest type, soil type (clay content), nitrogen deposition and management practices (Bárcena et al., 2014; Han et al., 2017). While the soil stock is initially depleted during afforestation due to disturbance and root respiration, it then subsequently increases again as the forest develops and matures, resulting in a net uptake of carbon into the soil carbon stock from afforestation over time (Byrne and Farrell, 2005; Wellock, 2011). The stability of soil carbon added by forestry depends on land management, and the amount of CO_2 sequestered is subject to the soil carbon saturation limit, with carbon rich soils such as peatlands having much lower additional soil carbon potential (Byrne and Black, 2003). Management should focus on minimal disturbance of the soil and stand to minimise soil carbon decomposition rates. (Jandl et al., 2007) find that mixed species stands stabilise soil carbon better than monoculture stands by reducing decomposition. Future research could usefully investigate what combinations of tree species or overall forest ecologies are best at enhancing and stabilising soil carbon stocks of afforested lands in specific Irish soil and climate conditions.

The direct loss of biomass carbon from harvest, and soil carbon from disturbance during harvesting, must be fully accounted for in the net GHG profile of afforestation and forestry management in Ireland and implications for achieving net negative emissions (for the sector, or nationally) considered. (Naudts et al., 2016) caution that restrictions are needed regarding minimum stand age, to ensure a net gain of carbon, and harvesting protocols to protect stored carbon and ensure its permanence. The full impact of harvesting method (clear-felling, staggered felling, thinning, etc.) on soil carbon specifically should also be measured in an Irish context, and then managed to optimise the soil carbon stock. Hence complete GHG LCAs may be helpful for Irish forestry practices to fully ascertain the net emissions of wood production in Ireland.

(Black and Farrell, 2006) estimate rates of carbon removal from atmosphere by Irish forests at c. 1.6-2.4 $MtCO_2yr^{-1}$ (0.42-0.65 $MtCyr^{-1}$). However, note that this represents net ecosystem productivity only, i.e., excluding harvest. With target afforestation rates of 8000ha from 2015-2020, (Muldowney, 2016) reports that forests could remove 3.4-4.4 $MtCO_2yr^{-1}$ (0.93-1.2 $MtCyr^{-1}$). (Black, 2007) estimates that (under current harvest practices) ongoing afforestation rates need to be above 10,000ha yr^{-1} to prevent forestry in Ireland moving from a net sink to net source of CO_2 emissions. (COFORD, 2014) and (Byrne, 2010) found afforestation needs to be maintained at 15,000 ha yr^{-1} to maintain a stand age class suitable for effective mitigation.

(Teagasc, 2013) projected that afforestation could achieve a nett sequestration rate of 4.2 $MtCO_2$ yr^{-1} (1.14 MtC^{-1}) in 2030, but, with increased harvest (inter alia due to increasing demand for wood fuel) and decreasing afforestation rates, this would fall to 1.6 $MtCO_2yr^{-1}$ (0.44 $MtCyr^{-1}$) by 2050 (see Figure 9.3). (Teagasc, 2017) increased the afforestation target to 20,000 ha yr^{-1} to achieve a proposed nett sink of 5.5 $MtCO_2$ by 2050 (suggested as a potential offset for one quarter of mainly non-CO_2 agricultural emissions).

Per Figure 9.3, as demand for bioenergy fuel increases (due to policy incentives), timber harvest is projected to increase (especially soon after 2030) disrupting the flow of forest emissions/removals. The age profile of trees changes due to increased clearfell and replanting and reducing afforestation rates. Additional harvesting of residues and stumps can also be used to increase yields available for woody biomass energy (Murphy et al., 2014b) however a trade-off exists here as that would remove the residues that would have otherwise become at least partially incorporated into the soil carbon, reducing the sequestration potential of that forest. Currently the heaviest CO_2 emissions source (apart from actual combustion) is in transport and therefore localised production and use may be an important future policy consideration (Murphy et al., 2014b). A complementary strategy may be local gasification, upgrade to biomethane and relatively more efficient pipeline transport (via the existing natural gas grid). In principle this might also integrate well with distributed production of biomethane via anaerobic digestion of non-woody bioenergy feedstocks (SEAI, 2017). However, it should be noted that, for maximum mitigation benefit, bioenergy use should arguably be combined with CCS (i.e., a form of BECCS) and that generally implies use (combustion, gasification or anaerobic digestion) in relatively large, centralised plant. This might be facilitated by such a biomethane pathway. As against this, it appears that the forthcoming Irish Renewable Heat Incentive may primarily incentivise direct biomass combustion in smaller scale heating plants that are unsuitable for CCS (DCCAE, 2017b). This would be expected to effectively “lock out” some of Ireland’s negative emissions potential, at least for the lifetime of such installations (McMullin, 2017).

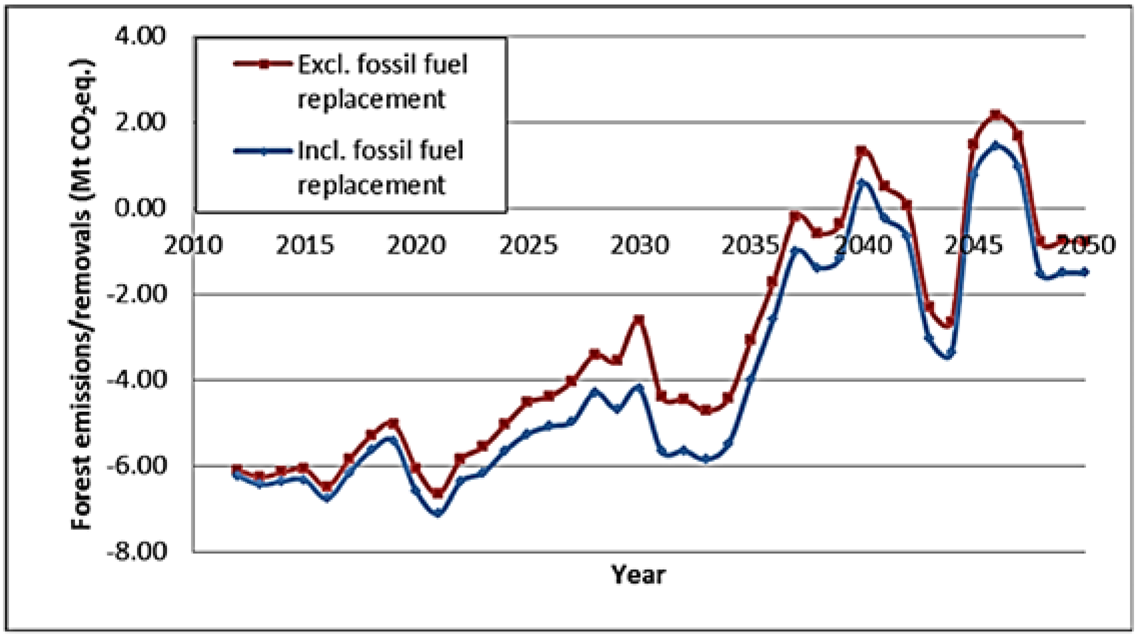

Figure 9.3 Projected GHG emissions for forest land (reproduced from Teagasc, 2013).

However, current afforestation rates are falling significantly short of meeting the policy targets in any case. (Curtin and Amold, 2016) found that then current plantings were 30% below the target for 2016. Ongoing failure to meet afforestation targets (both annual rate and cumulatively) will thus result in a significant reduction in the contribution of forests to Irish CO_2 removals, as older forests will (at best) approach an equilibrium carbon stock (biomass+soil carbon), with new growth balanced by harvesting, after 2030 (Curtin and Amold, 2016). Indeed, there is a concern that Ireland's forest carbon stocks may, in fact, decrease overall, particularly if harvest rates for fuelwood increase as projected from 7% of roundwood production to the 21% projected for 2030 to 2050 (Teagasc, 2013, p. 39). Such increased use of roundwood for fuel may in itself have significant carbon-climate response implications, especially depending on rotation time, relative to the timescale urgency of Paris target aligned mitigation (Cherubini et al., 2014).

The reasons for the decline in afforestation rates (despite continuing state funding support) are complex. Issues such as the permanent nature of compulsory re-plant forestry, the lack of land control and management required, as well as the replacement of traditional practices are all relevant to reduced uptake by farmers (IFA, 2016). A debate has also emerged over competition for land between conventional farmers and afforestation-incentivised private investors (Hubert, 2017). There are additional concerns about the impacts of afforestation on biodiversity, especially bird species, and on the environment generally from the mono-culture blanket forestry currently being deployed under the Afforestation Grant and Premium Scheme (Kelly, 2015).

Agroforestry might be offer a more effective balance in the competition for land between livestock, crops and forestry. Practices such as silvopasture could simultaneously share the land for grazing and tree planting. While this practice is more favourable for biodiversity and the environment than blanket forestry, there is not enough data to accurately assess its climate mitigation potential in an Irish context (Curtin and Amold, 2016).

Notwithstanding these ongoing challenges, Irish forestry is heavily relied upon in future policy scenarios to provide nominally ‘carbon neutral’ (or at least ‘relatively lower carbon’) bioenergy to reduce emissions from the Irish energy sector through direct fossil fuel displacement (Byrne, 2010; Fitzpatrick, 2016), and/or to compensate for continuing heavy non-CO_2 emissions (particularly N_2O and CH_4) from ruminant agriculture. The latter appears to be a specific motivation for a proposed 5.6% flexibility in Ireland’s 2030 non-ETS emission targets in the EU Commission effort sharing regulation. Currently, ruminant livestock numbers are increasing in Ireland, arising from specific policy goals of increasing dairy production following the removal of EU milk quotas (Muldowney, 2016). Based on current EU accounting (including the GWP-100 CO_2-equivalence methodology), (Curtin and Amold, 2016) find the afforestation targets in Ireland could be used to either avoid or offset 25% of projected overall agricultural sector emissions due to a combination of directly sequestering carbon, land use change (from ruminant livestock agriculture to forestry), and displacing fossil fuel.

Some initial barriers in using woody bioenergy in Ireland have been encountered, such as increased prices from supply shortages due to increased utilisation incentives, technical and chemistry issues with combustion (Walker et al., 2009), and increased air pollution (Fitzpatrick, 2016). Despite these issues, demand for bioenergy fuel from wood is growing in Ireland and expected to almost double to 3 million m^3yr^{-1} by 2020 (Murphy et al., 2014a). This represents c. $11MtCO_2yr^{-1}$ ($3MtCyr^{-1}$) released back to atmosphere from the forest biomass stock, based on an assumption of c. $1tCm^{-3}$ for woody biomass (Khatib, 2016).

It is possible that future accounting of energy system emissions will no longer simply count woody biomass as carbon neutral at the point of combustion/oxidation, but rather take account of some or all of its associated upstream emissions. According to (EC et al., 2014): ‘Ideally, a model is needed capable of simulating the temporal dynamics of GHG emissions and removals for carbon stock changes in the forest (i.e. increase in carbon stock); carbon stock changes outside the forest (i.e. increase of the harvested wood products pool), material substitution effects and energy substitution effects’. While it still appears possible that, with appropriate management, monitoring and verification, bioenergy from indigenous EU woody biomass might emit less nett CO_2 on a lifecycle basis (for given energy yield) than unabated burning of fossil fuels, the emissions savings in the energy sector for meeting EU and UNFCCC targets may be considerably over-estimated in the current ‘carbon neutral bioenergy’ calculations. This is particularly so when comparing to the alternative of leaving forest standing to preserve the carbon stock rather than returning it to the atmosphere (Burrascano et al., 2016; Hudiburg et al., 2011; Kreidenweis et al., 2016).

At an EU level, the recent report (EASAC, 2017) draws attention to the diverse roles of forestry in Europe and highlights the key considerations that need to be addressed for effective climate change mitigation. This report discusses the climate impact of forest management, the payback time risks in the current bias towards use of forestry products for bioenergy and advises careful consideration by the European Commission regarding the role woody biomass can play in meeting the Paris Agreement temperature goals. EASAC call for accounting procedures founded in objective science that incentivise maximum climate change mitigation, with renewable energy subsidies designed to reflect the true *nett* impact of biomass energy use on atmospheric CO_2 levels (in place of the current, simplistic, "carbon neutral" or "zero CO_2 on combustion" methodology). It may be argued that policy analysis accounting should also take fully into account the potential adverse impacts of woody biomass combustion on air quality, land use conflict etc.

9.3.4 Bioenergy with CCS (BECCS)

The basic concept of BECCS is straightforward, as previously explained (Chapter 3, section 3.4). CO_2 is removed from air during plant growth, with the input of direct solar energy, via photosynthesis (whether in bioenergy crops or forestry, and whether the harvest is dedicated exclusively for bioenergy production or the energy use is secondary to some other "primary" crop use, perhaps only via plant residues or "waste"). While there are many potential pathways for exploitation of the consequent bioenergy content with different suitabilities for particular bioenergy feedstocks and applications, they all involve re-oxidation of the captured carbon and the production of CO_2. However, this regenerated CO_2 stream is potentially accessible at relatively high concentration (compared to the very dilute concentration in atmosphere) so there is the *possibility* of relatively efficient capture and then long-term sequestration in suitable geological storage. In this way, the process as a whole can move CO_2 from atmosphere to geological storage; with the added advantage of yielding usable energy output. Capture and storage do, of course, impose energy demands in their own right, so the usable nett energy yield will be lower than from unabated use of bioenergy; and there are generally other emissions (CO_2 and potentially other GHGs) associated with the full BECCS processing chain. So rigorous lifecycle assessment is required of any particular proposed BECCS system to establish the quantitative impact on overall GHG loading (and corresponding radiative forcing) in the atmosphere. While the details are complex, unless there is an unambiguous nett climate benefit (involving sufficient CO_2 removal to outweigh all CO_2 re-release and also any associated release of other GHGs) BECCS deployment will not constitute an effective negative emissions technology.

The major potential pathways for indigenous bioenergy feedstock production in Ireland have already been reviewed in this chapter (sections 9.2.1, 9.3.3 above) and also the current status of (fossil fuel) CCS investigation (section 9.2.2). There appear to be two immediately conceivable paths toward early combination of these for BECCS deployment in Ireland:

- Application of CCS to electricity generation from direct combustion of solid biomass. There is some (mixed) experience of such biomass combustion through co-firing with peat at one existing electricity station (Edenderry); however, there are significant technical limits to the proportion of biomass co-firing, the current indigenous supply of suitable (woody) biomass is very limited, and in any case this plant is not suitably geographically located with respect to any currently identified geological storage site (even if it were technically feasible to retrofit post-combustion CO_2 capture). A somewhat more plausible suggestion relates to the potential replacement of a large coal-fired electricity plant (Moneypoint) which will reach end of life in its current configuration by c. 2025. This could conceivably be repowered with a direct biomass combustion plant (e.g., on the model of the Drax power station in the UK) but with integrated carbon capture. However this would be technically challenging on many levels: there is no existing example of such a direct biomass fired CCS plant; it would necessarily rely (at least initially) primarily on imported biomass fuel, with significant transport emissions, and complex (at best) production emissions profile; and again the site is not well geographically located relative to any currently identified geological storage site (CSA Group, 2008).

- Production of biomethane, injected into the natural gas grid which could be used directly in existing, high efficiency, combined cycle gas turbine (CCGT) electricity generating plant, retrofitted with post combustion CO_2 capture. Pipeline transport might substantially reduce the energy (and emissions) overhead, compared to transport of solid biomass. There are two candidate CCGT plants already suitably located relatively close to the proposed Kinsale Head geological storage site. Preliminary indications[40] suggest that, in the first instance, injection into this site may be possible at relatively moderate pressure which could make the initial deployment technically simpler and significantly lower cost. While this low-pressure injection would likely only be effective for perhaps 30% of the site storage capacity (after which much higher-pressure injection would become necessary), such an initial development could facilitate an early build-up of strategic national expertise and capability. A key attraction of this strategic approach would be that it largely decouples the CCS deployment from the BE availability: even while the power plants are still burning natural gas, such (FF) CCS would deliver up to 90% end-point emissions intensity reduction[41]; if or when the natural gas can be displaced by biomethane, the emissions intensity could be made progressively lower, and potentially become negative. However, this overall CO_2 balance would still depend critically on the biomethane supply chain. There appears to be significant technical scope for indigenous production via Anaerobic Digestion (AD) of feedstocks including animal slurries, food waste and conventional grass silage. Dedicated Miscanthus use would also be possible, and would likely offer significantly lower overall lifecycle GHG emissions than grass (Styles and Jones, 2008b). It would, of course, be critically important to avoid perverse incentification or lock-in either of food waste supply or slurry production (especially from intrinsically high GHG ruminant food production). And while storage and transport of (bio) methane can be relatively energetically efficient, it is intrinsically vulnerable to leakage ("fugitive emissions"). Because of the comparatively very high warming potential of methane, relatively

[40] Gas Networks Ireland, informal briefing, November 2017.

[41] Albeit such FFCCS would, of course, provide no effective mitigation of the *upstream* emissions associated with extraction, processing or transport of the fuel (Anderson and Broderick, 2017).

small absolutely amounts of leakage could fundamentally undermine the overall climate benefit achieved. Separately, a significant amount of the CO_2 production in an AD based pathway arises at the AD stage: the raw biogas from the digester must, in fact, be "upgraded" to biomethane (by separation of CO_2) before injection into the natural gas grid. While this separation means there is a relatively pure CO_2 stream available at the AD site, these sites are typically anticipated to be relatively small scale and geographically distributed (down to the level of a modest cluster of farms). While this distributed AD arrangement would minimise energy (and emissions) in transport of bulk feedstock, and return of digestate (for on-farm fertilizer use), it also means that full integration in a BECCS system would require transport of CO_2 from these distributed sites to a central location for incorporation into geological storage. The full energy and emissions implications of such CO_2 transport must again be included in any assessment of the overall emissions balance.

While there are, therefore, identifiable potential pathways toward BECCS deployment in Ireland, it must be emphasised that they remain very uncertain in technical feasibility, overall GHG benefit, and cost. Nonetheless, there is a clear argument that policy should seek at the very least to avoid closing off pathways toward such BECCS deployment, and progress detailed understanding of the key enabling capabilities, namely verifiably low emissions indigenous bioenergy production, and geological CO_2 storage.

By contrast, much Irish-specific bioenergy policy literature to date has tended instead to focus on the potential to "directly" decarbonise heating and/or transport energy use (Browne et al., 2011; Goulding and Power, 2013; Murphy, 2015; Murphy and Power, 2009; Singh et al., 2010; Smyth et al., 2009; Thamsiriroj and Murphy, 2010). However, in the context of achieving negative emissions through BECCS, it is essential that any CO_2 producing step in continuing energy use pathways be progressively restricted to contexts where it is practical to efficiently capture (and then transport and store). As already mentioned above, this would be a specific challenge in AD-biomethane BECCS systems, but might conceivably still be feasible, as CO_2 separation is already an intrinsic part of the pathway; whereas such capture seems unlikely to ever be at all compatible with direct (end-point) bioenergy use either in transport or small to medium scale heating applications. Accordingly, prudent policy development, even in the near term, should arguably re-focus on energy system interventions in both heating and transport that would avoid continued lock-in of end-point CO_2 emissions: this would firstly prioritise efficiency and other demand reduction measures (which amplify the impact of *all* other decarbonisation interventions), and either electrification or, in some circumstances, use of hydrogen as an end-point energy carrier (assuming CO_2 capture at the site of upstream hydrogen production, where applicable).

9.3.5 Direct Air Carbon Capture and Storage (DACCS)

The general principles of DACCS as a negative emissions technology have been presented in Chapter 3 (section 3.7). In general, the key attraction of DACCS over other NETs options is its minimal intrinsic requirement for dedicated land area; conversely, its key disadvantage is the requirement for potentially large energy inputs; inputs which must themselves be extremely low carbon if the system as a whole is to achieve nett CO_2 removal from atmosphere.

In the Irish context, a preliminary requirement for any consideration of DACCS would be availability of suitable geological storage. As already discussed, while there is, in principle, significant indigenous storage capacity (CSA Group, 2008), none of this has been developed to date; and such development is most likely to be in the context of FFCCS initially, with possible migration toward BECCS subsequently (provided genuinely nett negative BECCS pathways can be developed). But if or when access to geological storage, at significant scale, can be proven (either indigenously or through the development of internationally traded CO_2 storage services) then the potential for DACCS deployment in Ireland could be seriously considered, in parallel with BECCS evaluation.

In terms of low carbon energy supply, one theoretical scenario would be to integrate DACCS with very high penetration of renewable energy sources in the Irish electricity system. In principle, this could align well with the relatively abundant indigenous wind energy resource in Ireland, both onshore and offshore (SEAI, 2011). If DACCS plant could be designed in such a way as to be highly dispatchable, then they might function to stabilise overall grid operation, at very high variable renewable penetration, even while consuming primarily, or exclusively, very low carbon renewable electricity that would otherwise be curtailed (discarded). This does involve large scale over-provisioning of variable renewable generation (compared to conventional demand); but (absent radical technical advances in electricity storage) that may be implicit in the integration of progressively greater amounts of variable renewable generation anyway, and at least it provides a potential material co-benefit to such over-provision. However: the logical implication is that the DACCS plant itself, similar to the renewable generation assets, would run at significantly reduced capacity factor (because contingent on variable renewable energy availability) – as compared, for example, to supply from a (low carbon) nuclear energy source, where the composite system could run at very high capacity factor. But as indigenous nuclear generation is currently prohibited in Ireland, the latter is not an accessible scenario here at this time.

Supplying the energy required by a DACCS plant primarily or exclusively via electricity has a technical advantage in that the plant can be flexibly located geographically, and, in particular, could be located close to available geological storage sites (to minimise transport energy/emissions). Again, because such a (theoretically) dispatchable DACCS plant would vary consumption to balance overall renewable supply and demand, it would not necessarily impose excessive requirements for additional transmission line capacity (peak load would not necessarily increase). However, much detailed investigation would be necessary to assess these in-principle possibilities further.

Of course, suitable business models would be required to enable significant DACCS deployment – that would actually provide revenue for CO_2 removal services – though this is primarily a socio-political rather than a technical barrier. One obvious early possibility would be to target levies or charges on otherwise very difficult to decarbonise activities. Aviation, in particular, has few technical options for direct decarbonisation and current proposed measures rely heavily on “offsetting” (ICAO, 2016). While such offsetting has been conceived to date in terms of "avoided emissions" in other sectors, this approach has been heavily contested (Hyams and Fawcett, 2013). Many of these objections could be overcome via the provision of fully dedicated and verified CO_2 removal and storage as a service, such as would be theoretically possible via DACCS. Ireland has significant existing economic activity arising from international aviation (particularly through financial services for aircraft leasing); and thus arguably has a particular interest in seeing the development of commensurate decarbonisation actions for aviation. Given this, and given the potential availability of relatively cheap, low carbon intensity (but variable) wind energy, there is clearly a case for support of pilot scale DACCS development and deployment in Ireland. Offsetting, of course, by definition does not achieve nett negative emissions: thus, while it might function as a mechanism for early investment in DACCS deployment, full CDR via DACCS would ultimately require dedicated economic arrangements that explicitly fund CO_2 removal.

9.3.6 Enhanced Weathering (EW)

The general principles of EW as a negative emissions technology have been presented in Chapter 3 (section 3.8). While EW does involve extensive land use, this does not conflict with conventional agriculture (excluding forestry). Accordingly, EW shares with DACCS the key attraction of a minimal requirement for *dedicated* land area. Conversely, its key disadvantage is also similar to DACCS, namely the requirement for potentially large energy inputs (for rock mining and extraction, transport, and application and spreading); inputs which must themselves be extremely low carbon if the system as a whole is to achieve nett CO_2 removal from atmosphere. On the other hand, unlike DACCS, EW sequesters carbon in an intrinsically stable form (bicarbonate) and so is not contingent on the availability of geological storage for CO_2. This distinction also means that EW may involve higher transaction overheads in monitoring and verification of ongoing carbon storage compared to DACCS.

Geological surveys have identified outcrops of ultra-basic rock in various locations in the Republic of Ireland (Leake, 1986). Additionally, a UK study specifically for EW has identified large potential resources in Northern Ireland that may be readily accessible (Renforth, 2012). Accordingly, the critical barriers to early deployment of EW in Ireland are very low carbon energy (in forms suitable for use in EW: primarily in machinery for extraction, processing and application, and in transport), and, of course, suitable supports or business models to explicitly fund extraction and storage. As with DACCS, the most immediately plausible pathway toward very low carbon energy supply in Ireland is in the form of variable renewable (wind) electricity: accordingly there is certainly scope to investigate the detailed energy requirements in EW processes to demonstrate how they might be addressed from such sources. The single most energy intensive step appears to be rock crushing; and again, if this could be done in large, fixed, plant, and engineered to be highly dispatchable, it is possible that it could positively facilitate high variable renewable electricity penetration; but with the corollary that the capacity factor on such plant would be constrained by variable energy availability, with correspondingly increased capital and financing costs.

In summary, while there is certainly merit in assessing the potential capacity for EW in Ireland, and possibly engaging in pilot scale deployment to properly characterise the required processes and likely costs, its potential contribution to effective climate mitigation remains highly speculative.

9.4 Modelling the technical capacity of NET options in Ireland

Previous discussions outline the challenges and limitations of deploying and scaling up various NET options in Ireland. Barriers include technical readiness, cost, storage permanence, and knowledge gaps in Ireland-specific research. A preliminary qualitative summary of these and other considerations for deploying NET options in Ireland is presented in Table 9.2.

*Table 9.2: A schematic qualitative summary of the main policy relevant considerations for utilising NET options in Ireland. * denotes relatively high equivocation and uncertainty in the assessment.*

	SCS	Biochar	EW	Afforestation	BECCS	CCS	DACCS
Carbon removal	Medium *	Medium	Medium	Medium	High	High	Very High
Readiness	Very High	Very High	Medium	Very High	Medium	Low	Very Low
Cost	Medium *	Medium *	Medium	Low	Medium	High	Very High
Vulnerability to re-release	High	High	Medium	Medium *	Low	Low	Low
Vulnerability to future climate change	Very High	High	Medium	High	Medium	Very Low	Very Low
Biodiversity Risk	Low	Low	Medium	High *	High	Low	Low
Energy Penalty	Low	Medium	High	Low *	Very Low *	Medium *	Very High
Land Pressure	Low	Medium	Low	High	High	Very Low	Very Low

The following presents a simplified model that makes an *approximate* quantitative estimation of the technical potential carbon removal and storage capacity of NETs in Ireland, under the assumption that the aforementioned limitations, discussed in detail in previous sections, can be fully overcome and options then deployed at scale in Ireland (i.e., this analysis does not attempt to quantitatively assess the many additional economic, political and social barriers to deployment).

9.4.1 The Model

(Smith et al., 2016) present a method to estimate the technical carbon removal capacity of various NET options (BECCS, AF, SCS, Biochar, DACCS and EW) under hypothetical land area availability scenarios for the UK.

To apply this model to Ireland, suitable land areas potentially available for relevant NET option deployment had to be determined. In choosing an appropriate land area, two main resources were considered; the COFORD land classification scheme (COFORD, 2016), and the discussions on land area availability for bioenergy by SEAI bioenergy supply curves (SEAI, 2012).

(COFORD, 2016) classifies Irish land into 4 levels. The level most suitable for potential NET deployment is level 4: 'Land most likely to have potential for forest expansion'. This is currently made up of farmland (occupied by dairy, cattle, sheep, mixed livestock and tillage) with wide and limited usage, not farmed grassland and unenclosed land. For estimating the capacity of SCS and EW the same assumption as (Smith et al., 2016) was made, namely that these options could be applied to all of the level 4 land (3,750,000 ha). For BECCS, AF and Biochar, the chosen maximum value for land area availability was 550,000ha, representing 16% of level 4 land in the (COFORD, 2016) classification scheme. This choice is informed by the discussion of (SEAI, 2012) on the potential land area available for bioenergy crops in Ireland. This identifies that the EU Common Agricultural Policy (CAP) limits conversion of existing permanent grassland to arable (including bioenergy) crops to 10% (350,000ha) up to 2020. Further, (DAFM, 2015, p. 42) indicates an even more restrictive CAP conversion limit of 5%. Beyond 2020, (SEAI, 2012) identify 200,000ha of additional pastureland that may be eligible for conversion, subject to CAP reform. We therefore adopt the relatively ambitious assumption that 350,000ha of permanent grassland could be converted and attributed to a relevant NET option (BECCS, Biochar or AF) up until 2020, and that post 2020 the additional 200,000ha may become accessible, creating a total land area estimate in Ireland of 550,000ha. This land area is also in a similar range to that required to achieve an 18% afforestation target by 2050 (510,000ha) according to (COFORD, 2016). We suggest that this area therefore represents a realistic baseline land use scenario for assessing the NET capacity in Ireland up until 2100.

Two additional, even more ambitious, 'high end' scenarios were also tested to inform the current Irish policy direction of pursuing "carbon neutrality" within the agriculture sector. These two scenarios allocate 30% of level 4 agricultural land (total of 970,273 ha; 'high-end-1') and 75% of level 4 land that is classified of 'limited agricultural use' and 'not farmed' (total of 1,007,407ha; 'high-end-2').

A final "edge case" scenario was modelled which assumed that bioenergy supply was not limited by indigenous capacity (i.e. an unlimited amount could be imported), to estimate how much carbon sequestration could hypothetically be achieved via BECCS if the entirety of Ireland's primary energy was electrified and provided by bioenergy. (SEAI, 2016a). Reports Irish total primary energy requirement (TPER) in 2015 as 13,889 ktoe (162 TWh). (SEAI, 2012) estimates that 203,000ha of Miscanthus and SRC will produce c. 1,167 ktoe (16.6 TWh). On this basis, a hypothetical land area of 2,415,996ha (the majority of which, by definition, would be outside the national territory) was entered into the (Smith et al., 2016) model to estimate corresponding carbon removal capacity for this scenario.

9.4.2 Land use emissions displacement

Additional calculations, not present in the original model of (Smith et al., 2016), were carried out to estimate the reduction of Irish emissions (largely non-CO_2) resulting from the displacement of current agricultural practices by deploying NET. The purpose of this exercise was to more specifically inform the current policy directive of pursuing efforts towards "carbon neutrality" in the agricultural sector, as outlined in the National Mitigation Plan (DCCAE, 2017a). To estimate this displacement value, GHG emission values for Irish agricultural practices were taken from (Styles and Jones, 2007a). For the three land area scenarios it was assumed the NET option was applied equally between all level 4 land use categories except tillage for the baseline and high-end-1 scenarios, and 75% of all 'limited agricultural use' and 'not farmed' land for the high-end-2 scenario.

9.4.3 Cumulative technical capacity of NETs in Ireland to 2050 and 2100

Additional work was carried out to consider the cumulative amount of carbon removed by each NET option if deployed in Ireland first up until 2050, and then extended to 2100. The purpose of this exercise was to provide insight on the effect of saturation on time limitations for NET options such as SCS, biochar and AF, in contrast to the much higher storage (and therefore longer term sustained removal) capacities of BECCS and DACCS (see previous sections with discussions on soil saturation limits and geological storage capacity for CCS in Ireland). This addresses the issue of NET options like AF, Biochar and SCS being technically available to scale up to full potential now, but as an emissions management strategy is time limited and subject to saturation effects. Whereas NET options such as BECCS and DACCS are not yet ready to deploy at scale, but are expected to be less limited by saturation due to much larger (and more secure) storage capacity. This work estimates the cumulative removals achieved by Biochar, SCS and AF under the assumption that Irish soils will saturate after c. 20 years. A paucity of data on Irish soil carbon deficits means the actual time to saturation cannot currently be estimated with any precision. This value of 20 years is taken on the basis of guidelines by (IPCC, 2006). This work also assumes that CCS storage capacity is not constraining within the given time horizons (i.e., national CCS storage capacity will not be fully used by 2100, or if it is, that there will be options to export Irish captured CO_2 to be permanently stored elsewhere). It was assumed that all NET options were deployed to the full baseline scenario land areas by 2020, with the exception of BECCS and DACCS for which the assumed start year was 2035 (anticipating full technological readiness by then, implying much earlier full-scale FFCCS deployment, and progressive BECCS and DACCS capability build-up through at least pilot and demonstration scale deployments well in advance of 2035).

9.4.4 Results

The key results can be seen in Table 9.3. Due to the simple nature and limitations of the model each NET option is considered individually rather than in combination. In the hypothetical edge case scenario where Ireland's entire primary energy is supplied by BECCS, c. 7.25 MtC (26.6MtCO_2) might be removed annually. As with discussions by (Smith et al., 2016), we consider the 'low' values of the model output. Of the low NET capacity estimates, AF has the highest capacity, followed by BECCS and DACCS, and lowest capacities are from SCS, Biochar and EW (Table 9.3, Figure 9.4). Compared to total Irish emissions, under the baseline land area scenario, up to 11% of the 2015 emissions might be offset by a NET option. If additional land area became available, this proportion could technically be as high as 21% (high-end-2 AF scenario, Table 9.3). Biochar and SCS are the most economically viable options, with DAC currently estimated as the most expensive by several orders of magnitude (Table 9.3). 1-1.7MtC could be displaced per year in Ireland's land use sector by converting existing agricultural land to BECCS, AF or Biochar land use (Figure 9.4), equivalent to up to 32% of current Irish annual agricultural emissions (high-end-1 scenario, Table 9.3). In both high-end scenarios, the combination of the carbon removals possible from AF and the emissions displaced would result in net negative emissions in Irish agriculture and land use. For the baseline scenario, maximising AF and displacing 16% of current agriculture lowers net emissions by 52% in this sector, still making a significant contribution towards the expressed policy goal of "carbon neutrality". Further reductions could be achieved by combining SCS and EW on the remaining agricultural land.

The cumulative carbon removal capacity of NET options in Ireland, under the baseline land area scenario, can be seen in Figure 9.6. These results show the limit on carbon removal capacity of AF and Biochar due to soil carbon saturation. Hence, while AF showed the highest carbon removal capacity per year (Table 9.2), this annual removal capacity will not be available long term to 2100.

In Chapter 8 a detailed review of the Irish carbon quota and the important considerations needed for its estimation and implementation are discussed. Taking the carbon quota for Ireland of 770 MtCO_2 from (Glynn, 2017a) provides a context for the cumulative capacities of different NET options in Ireland shown in Figure 9.6. The cumulative capacities of NET options in Ireland up until 2100 are as high as 400 MtCO_2 (BECCS and DACCS), indicating the technical potential to significantly contribute to Ireland's achievability of a net carbon quota of 770MtCO_2 by effectively increasing the gross carbon quota by 52%. Up until 2050, 550,000 ha of AF could cumulatively remove 137 MtCO_2, increasing Glynn (2017)'s gross carbon quota for Ireland by 17%. However, Chapter 8 finds an emissions gap between Irish carbon quota estimates and projected cumulative Irish emissions to 2100 in the range of 2570-4990 MtCO_2. And as seen in Figure 9.6, under a baseline land area scenario NET options in Ireland are likely to fall well short of this required capacity implied by current emission projections: demonstrating that, *even* with "anticipatory reliance" on (unproven) NETs, deep, near term, reductions in gross emissions are still required.

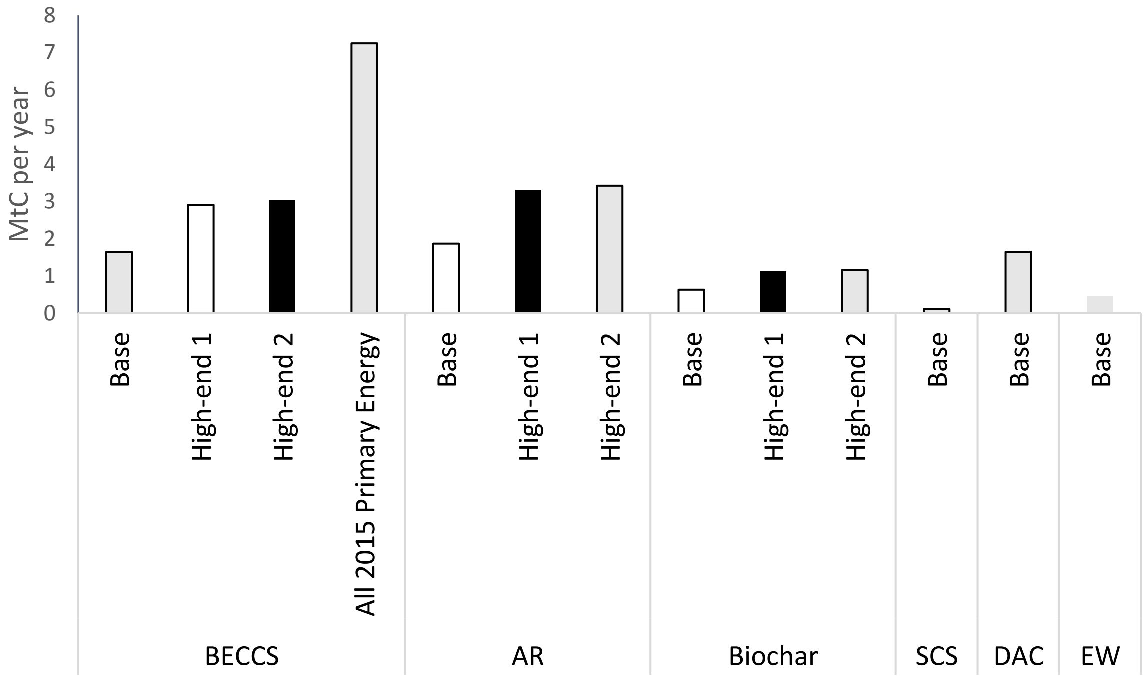

Figure 9.4 Estimates of carbon removal per year in Ireland under different land use scenarios: grey: baseline scenario, white: high-end-1, black: high-end-2.

*Table 9.3: Capacity of NET options in Ireland, based on the model by (Smith et al., 2016), under three land area scenarios for BECCS, AF and Biochar (Baseline scenario; 16% of level-4 land, High-end-1; 30% of level 4 agricultural land and High-end-2; 75% of level 4 land that was of 'limited agricultural use' and 'not farmed') and the assumption of all level-4 agricultural land is available for SCS and EW. An additional scenario was calculated for BECCS whereby the 2015 primary energy requirement in Ireland was supplied by BECCS. *DACCS potential is not constrained by area so impacts assessed at same level of implementation as BECCS.*

Technology	Area applied		Carbon Removal				Cost		Displaced Emissions	
			Low	High	Low	High	Low	High		
	Scenario	Mha	Mt Ce yr-1		% of 2015 Irish Emissions		€ per tCe yr-1		MtCe yr-1	% of 2015 Agri emissions
BECCS	Base	0.55	1.65	6.6	10.1	40.4	187	749	0.97	17.9
	High-end-1	0.97	2.911	11.643	17.8	71.3	330	1,322	1.7	31.6
	High-end-2	1.01	3.022	12.089	18.5	74.0	343	1,372	1.5	28.4
	All Irish Energy	2.42	7.25	29			823	3291		
AF	Base	0.55	1.87	1.87	11.4	11.4	105	174	0.97	17.9
	High-end-1	0.97	3.299	3.299	20.2	20.2	184	306	1.7	31.6
	High-end-2	1.01	3.425	3.425	21.0	21.0	191	318	1.5	28.4
Biochar	Base	0.55	0.633	4.125	3.9	25.2	-451	4,257	0.97	17.9
	High-end-1	0.97	1.116	7.277	6.8	44.5	-796	7,510	1.7	31.6
	High-end-2	1.01	1.159	7.556	7.1	46.2	-827	7,797	1.5	28.4
SCS	Base	3.75	0.112	3.749	0.7	22.9	-16	129		
DACCS	Base	*	1.65	6.6	10.1	40.4	2,270	11,806		
EW	Base	3.75	0.451	40.9	2.8	250.3	36	207,068		

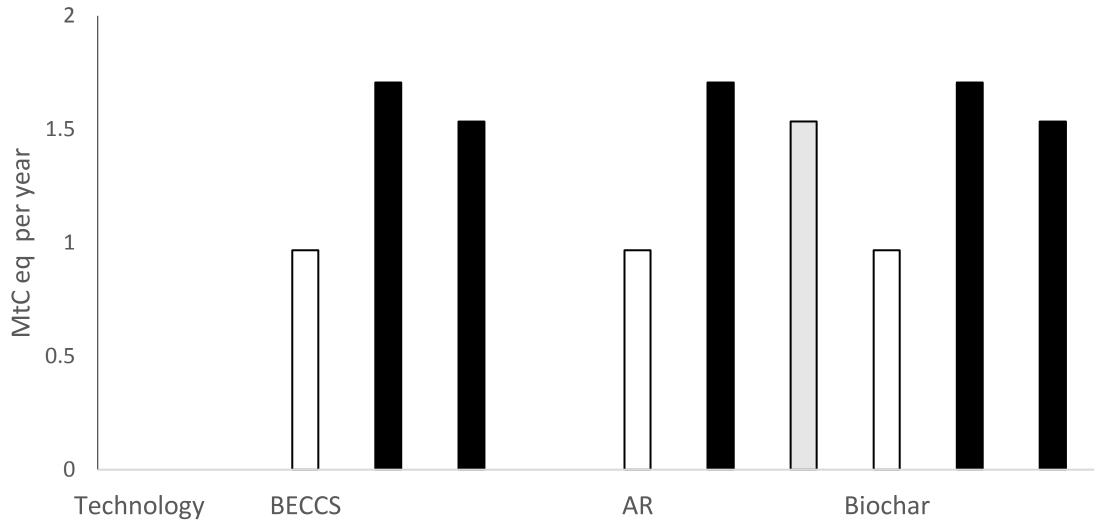

Figure 9.5: Carbon equivalent emissions displaced by conversion of agricultural land to NET options under three land use scenarios: grey: baseline scenario, white: high-end-1, black: high-end-2.

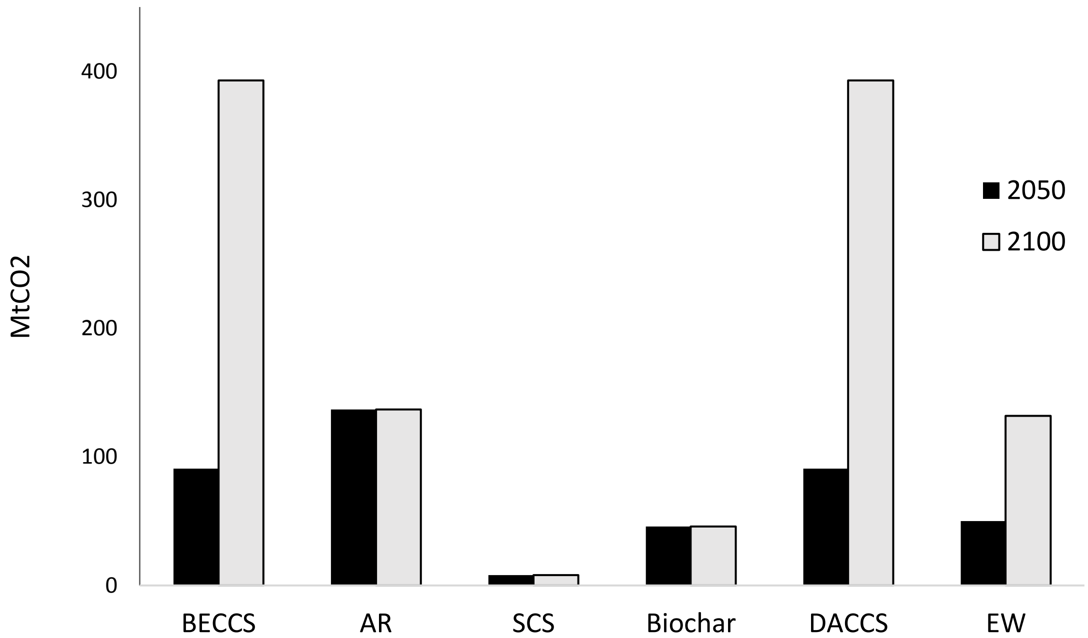

Figure 9.6: Estimated total cumulative CO_2 removal capacity of NET options in Ireland, based on the (Smith et al., 2016) model under the land area assumptions of the baseline scenario.

9.4.5 Discussion

These preliminary findings suggest that Ireland may have potential capacity to remove a significant amount of carbon from the atmosphere, even under a baseline land allocation scenario of 16% of suitable agricultural land, through deployment of various NET options. On a cumulative scale, NET capacity in Ireland up until 2050 and 2100 may have the potential to significantly increase the achievability of an equitable nett Irish carbon quota. Each NET option is considered individually for Ireland. While, in principle, a portfolio of multiple NET options could be deployed together, they would interact in complex ways, and significantly more sophisticated land allocation modelling, compared to the relatively simplistic scenarios presented here, would be required to assess this.

Presently, AF, Biochar and SCS are the most immediately suitable and ready to deploy NET options in Ireland (see discussions in previous sections and Table 9.3). Our results find that these options might remove 1.87,0.63 and 0.11 MtC yr^{-1} respectively, offsetting up to 11% of Ireland's current annual emissions. However each of these options rely on biogenic and soil storage of the removed carbon, which is subject to a saturation limit and vulnerable to re-release (see previous discussions in Chapters 3 and 9). So while these results demonstrate significant annual removal capacity in Ireland, cumulatively these NET capacities are estimated to be limited to 137, 46 and 8 $MtCO_2$ respectively (Figure 9.6). If deployed fully by 2020, this maximum capacity could be reached as early as 2050. Despite offering no further capacity, protection and management of this vulnerable captured carbon would still require significant resources into the indefinite future.

While technological maturity, cost and national capacity knowledge gaps render BECCS and DACCS difficult to deploy in Ireland in the very short term (less than 5 years), our results find they may also have significant capacity to remove atmospheric carbon, up to the equivalent of ~10% of current annual national emissions. These options are not limited by the biogenic saturation concerns previously discussed, and in principle therefore might allow significant carbon removals post-2050, potentially increasing the gross carbon quota for Ireland by 52%. However, the current state of readiness and high costs warrant caution and prudence in *relying* on future availability of these technologies.

In Irish policy terms NETs can be framed as aiding the proposed progression of Irish agriculture towards "carbon neutrality" in the first instance; and displacement of current high emissions intensity ruminant food production with bioenergy cultivation would further support this. Displacing 16% of available agricultural land with AF may achieve additional emissions saving, relative to current agriculture, of 1MtC (19% of 2015 agricultural emissions, if equated on an approximate GWP-100 equivalence basis). Two additional 'high-end' scenarios indicate a technical potential to go beyond "carbon neutrality" and achieve net negative emission within Irish agriculture and land use sector, albeit this would also depend on a significant change in future policy direction to remove current restrictions and incentivise much more extensive land conversion to forestry and/or bioenergy cultivation for use in BECCS.

Based on these results, a preferred strategy that emerges for deploying NETs in Ireland appears to be to maximise AF, with minimal harvesting, in the immediate term (perhaps up until 2035) while supporting the development of BECCS, with the view of allocating AF harvest biomass to BECCS when CCS costs are lowered and/or AF stocks (land, biomass and soil) have saturated. However, it must be emphasised that this would rely on little or no harvest of the accumulating forest biomass during this period (for any purpose that could not guarantee the continued long term preservation of the captured carbon stock), which would imply fundamental changes in current AF support policies. However, if BECCS does not become ready or remains infeasibly expensive, the use of AF becomes limited by saturation and unavailability of further additional land, after which no further removals can be achieved. Additionally, carbon removed by AF is stored biogenically (biomass and soil carbon) which is all vulnerable to re-release and will require continued maintenance, monitoring and protection (see discussion in previous sections and Chapter 3). Hence, while this work may inform policy discussions about the potential capacity for NETs in Ireland, the limitations imposed by permanence and saturation render NET options that are immediately available (AF, Biochar and SCS) high risk; while technological uncertainty and high costs render alternative options (BECCS and DACCS) presently unavailable and high risk to depend on future availability. Additionally, Irish NET capacities estimated herein fall well short of the implied requirements of the current gap between estimated Irish CO_2 quotas and current projected cumulative Irish emissions (see Chapter 8). Therefore, while our results indicate that NETs in Ireland may have material carbon removal capacity and contribute towards achieving future net emission targets, *the highest priority and emphasis of Irish climate mitigation actions should be immediate, significant, and sustained reductions in gross emissions*.

9.5 Chapter Conclusions: NETs potential in Irish mitigation policy

This review applies the growing material on the use of negative emissions in a global context to meet specific targets and conditions of a small developed island nation, Ireland. It finds the following key conclusions:

- BECCS and biochar are heavily represented in the global NET literature, but both are currently limited in their application in an Irish context particularly due to cost and technological immaturity for CCS, and lack of promotion and uptake in Ireland for Biochar
- Bioenergy crops are largely discussed in relation to BECCS in the NETs context. In contrast to CCS in Ireland, bioenergy crop production has been substantially proven from a technical perspective and is ready for significant potential scaling up. But early BECCS deployment is difficult under the aforementioned cost and technical maturity limitations of CCS. Accordingly, early, rapid deployment of FFCCS (i.e., on conventional fossil fuel electricity generation and on other industrial scale CO_2 sources) is arguably a critical step in clarifying the longer term potential for BECCS in Ireland.
- Afforestation is also relatively mature and already deployed in Ireland. Similar concerns to those raised in the international NETs literature are relevant to Ireland. Issues to be addressed include carbon leakage from importing woody biomass, debate over harvest or preservation of carbon in biomass, and competition between different land uses. Pending practical availability of BECCS pathways for bioenergy, it is arguable that afforestation should be prioritised as a land use over dedicated bioenergy crop cultivation, *provided the carbon stock is allowed to accumulate, rather than be harvested, for energy or other purposes*. Fossil fuel use would still, of course, have to be displaced from the energy system: but the immediate priority there (in advance of BECCS availability) may be absolute demand reduction, through efficiency measures and otherwise, and deployment of the lowest emissions intensity alternatives that are available, *exclusive of bioenergy*. In the Irish case this would suggest rapid electrification of heating and transport, accompanied by further expansion of indigenous wind energy production (onshore and offshore), early deployment of FFCCS, and potentially some nuclear energy use (though under current Irish legislation that can only be accessed by import over electricity interconnectors from other jurisdictions). All of these would require *radically* stronger policy measures to achieve the required scale within the very limited time window remaining for effective achievement of the Paris Agreement temperature goals.
- For both bioenergy crops and afforestation, issues of accurate GHG LCAs and long term protection of both biomass and soil carbon stocks, should be a priority in relation to their Irish use; this must extend to accurate assessment and reporting of processes leading to potential soil carbon loss equally with reporting of processes leading to gains. Policy needs to realistically allow for the potentially very high, very long term, costs associated with such detailed

monitoring, verification, and maintenance of biogenic carbon stocks.

- Potential for DACCS, while significant in principle, is reliant on significant technology advance and cost reduction, large scale geological storage development, and perhaps most critically, large scale availability of extremely low carbon energy. There may be some medium to long term possibility of integration of “dispatchable” DACCS with variable renewable energy sources (essentially exploiting wind energy that would otherwise be curtailed, if very high wind energy penetrations are pursued); but overall uncertainty over both technical feasibility and cost remains very high, and certainly does not provide any basis for speculative early overshoot of the national nett carbon quota.
- Potential for EW currently remains largely theoretical unless and until very low carbon energy sources can be identified to dramatically reduce the emissions associated with quarrying, processing, transport and application of the required rock materials. Potential transaction costs in monitoring, verifying and preserving resultant carbon stocks would also have to be carefully considered.
- In general, we note the need for ambitious short term action, within coherent long term policy constraints that are demonstrably commensurate with the scale of the climate challenge. In the case of CO_2, this can only prudently be anchored in the rigid arithmetic of the remaining, finite and rapidly depleting, national nett CO_2 quota. In the case of bioenergy production and use, supply chain obstacles arising from existing policies need to be addressed.

10. Literature Review: Summary Conclusions

To meet the agreed Paris temperature goals, global nett CO_2 emissions *must* fall to zero rapidly, in accordance with the scientifically determined remaining cumulative CO_2 global carbon budget (and subjecting continuing scientific uncertainty to the precautionary principle). This global mitigation effort must be shared on a basis of equity and reflecting the wider UN sustainable development goals (SDGs).

The remaining nett CO_2 equity quota (share of the global budget) for Ireland is small; with a reference starting year of 2015, it was likely no more than c. 590MtCO_2 on an equity basis, implying a (nett) CO_2 emission pathway *rapidly* reaching a sustained reduction rate of over 7% yr^{-1}. (The rigid physical arithmetic of the CO_2 quota means that mitigation delay translates rapidly to much higher mitigation *rates* in the near future.)

Carbon dioxide removal from atmosphere, coupled with long term storage, is technically possible by various pathways ("carbon sinks"), both natural and technological: to the extent that existing natural sinks can be strengthened, and new (technological) sinks can be created, the quota for remaining *gross* CO_2 emissions *might* legitimately be increased (and thus the mitigation rate for gross emissions might be somewhat eased or delayed relative to the nett rate just cited).

Of currently identified CO_2 removal and storage approaches, those most likely to be of material potential for Ireland are: forestry, soil carbon management (including peatlands and biochar), BECCS and DACCS. These vary very significantly in current maturity, potential scale, storage permanence, estimated financial costs, wider social and environmental impacts, and in degree of confidence in any of these parameters.

While continuing research and development can be expected to progressively improve our understanding of the potential for such CO_2 removal and storage, it would be an extremely high-risk policy to base *current* mitigation action on particular assumptions of *future* gross removals (at significant scale). *There is no current basis for assuming that large scale future removals will be possible at significantly less cost than for directly mitigating gross emissions now*; on the contrary, there is significant risk that future removals (at scale) will prove either to incur substantially *greater* societal costs or *may not prove feasible at all*.

CCS is a component technology for two of the proposed CO_2 removal processes with greatest potential scale and permanence (BECCS and DACCS). Conventional CCS of fossil fuelled electricity generation or industrial process CO_2 (FFCCS) is much more technically mature than either BECCS or DACCS. It could already contribute significantly to mitigation of existing *gross* CO_2 emissions (most especially if combined with absolute contraction in energy demand, aggressive complementary exploitation of wind energy, and rapid electrification of heating and transport). Absolute reductions in fossil fuel use, and diversification of primary energy sources for heat and transport (via electrification) would also contribute significantly to energy security and resilience.

Accordingly, there would appear to be multiple potential co-benefits to the *earliest feasible* FFCCS deployment. This in turn would fundamentally clarify the potential for both BECCS and DACCS. There is therefore a clear Irish national interest in progressing FFCCS proactively (rather than passively relying on ETS market prices to provide sufficient exogenous market incentive at some unknown and unpredictable point in the future).

To the extent that the indigenous biogenic CO_2 removal capacity (including forestry, soil carbon, bioenergy fuels or all types) is necessarily a very constrained resource, and that biogenic carbon *stores* (particularly forestry and soil carbon) are of variable and uncertain permanence, it may be prudent to progressively prioritise available biogenic capacity for bioenergy production, while prioritising bioenergy use in large scale facilities (CHP where practical, otherwise electricity only), where CCS (i.e., BECCS) will be feasible. The latter would also have a direct co-benefit in improving air quality (relative to small scale and unabated bioenergy use). Absolute increases in bioenergy production could potentially also contribute to mitigation of non-CO_2 emissions, to the extent that, in at least some situations, such production could displace current intrinsically high-GHG agricultural systems, such as dairy and beef production.

Specifically in Ireland, future research priorities include quantifying the indigenous bioenergy capacity, particularly under the conditions of future climate change, developing robust, physically-grounded, GHG accounting mechanisms through LCAs of NETs relevant systems, and modelling feasible deep decarbonisation pathways for the Irish energy system with potentially ambitious incorporation of BECCS and/or DACCS.

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