epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

IE-NETs: Investigating the Potential for Negative Emissions Technologies (NETs) in Ireland

Authors: Barry McMullin, Michael B. Jones, Paul R. Price, Alwynne McGeever and Paul Rice

www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY
The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing
We regulate the following activities so that they do not endanger human health or harm the environment:
- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement
- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management
- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment
- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions
- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development
- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment
- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection
- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education
- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change
- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA
The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:
- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

IE-NETs: Investigating the Potential for Negative Emissions Technologies (NETs) in Ireland

(2016-CCRP-MS.36)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Dublin City University and Trinity College Dublin

Authors:

Barry McMullin, Michael B. Jones, Paul R. Price, Alwynne McGeever and Paul Rice

ACKNOWLEDGEMENTS

DISCLAIMER

Project Partners

Professor Barry McMullin
School of Electronic Engineering
Dublin City University
Dublin
Ireland
Tel.: +353 1 700 5432
Email: barry.mcmullin@dcu.ie

Professor Michael B. Jones
School of Natural Sciences
Trinity College Dublin
Dublin
Ireland
Tel.: +353 1 896 1769
Email: mike.jones@tcd.ie

Contents

List of Figures

List of Tables

Executive Summary

Human-caused warming of the Earth's climate system is unequivocal. Informed by scientific assessment of severe risks to human welfare, the parties to the Paris Agreement, including Ireland, have committed to goals of limiting warming to well below +2°C over pre-industrial levels and pursuing efforts to limit the increase to +1.5°C. The most significant greenhouse gas emitted from human activities is carbon dioxide (CO_2), arising from fossil fuel use, land use change and particular industrial-scale processes. Once emitted, CO_2 accumulates in the atmosphere for centuries to millennia. For any given temperature rise goal, there is a corresponding limit on net cumulative release of CO_2, termed the global carbon budget (GCB). Net CO_2 emissions must cease ("global net zero") in order to re-stabilise the global atmospheric CO_2 concentration, temperature and climate systems. Ideally, this should happen before the GCB limit for the Paris Agreement temperature goal is reached; however, if there is overshoot of this limit, then sustained negative CO_2 emissions will be needed until the atmospheric concentration is returned to or below a level consistent with the temperature goal.

Effective climate action therefore requires rapid reductions in emissions of CO_2. However, most global scenarios analysed by the Intergovernmental Panel on Climate Change (IPCC) indicate that reduction in gross emissions alone (at currently considered "feasible" rates) will be inadequate to satisfy the Paris Agreement temperature goals. These scenarios therefore additionally assume very large-scale deployment of "negative emissions technologies" (NETs), that is, sustained gross removals of CO_2 from the atmosphere and subsequent secure, long-term storage of this carbon. In this way, net CO_2 emissions may be made to fall to zero and then become global net negative (net removals). This situation of net-negative emissions or net removal of CO_2 from the atmosphere must then be sustained for at least long enough to reverse the accumulated overshoot of the GCB.

The Paris Agreement relies on voluntary, bottom-up actions by the parties, that is, each party formally submits to the United Nations Framework Convention on Climate Change the intended contribution it will make to the global effort to achieve the goals of the agreement. An approach to this bottom-up action that could ensure that the global GCB limit is respected would be for each party to assess its claimed "fair share" of the GCB (here termed a national CO_2 quota or NCQ), formulate future national net CO_2 emissions pathways consistent with this assumed share and determine the role of gross CO_2 removals (NET deployment) that will be committed to in achieving this. Such pathways should include timely reversal of NCQ overshoot if necessary. The IE-NETs project provides a preliminary research basis to inform such an NCQ assessment for Ireland specifically.

The project has found that a prudent, minimally equitable, Paris Agreement-aligned CO_2 quota for Ireland has an upper bound of approximately 400 $MtCO_2$ from 2015. This specific result relies on particular interpretations of prudence, equity and Paris Agreement alignment, and assumptions about the global mitigation of non-CO_2 greenhouse gases, which are elaborated in detail in the body of the report. Based on current emissions rates, the projection is that this national quota would be exceeded by around 2024. Therefore, the analysis presented here indicates an expectation of national CO_2 quota overshoot beginning to accumulate within the next decade. Assessment of the national Climate Action Plan, adopted in 2019, suggests that, under that plan, this NCQ overshoot will keep increasing until at least 2050, reaching an accumulated level of at least 600 $MtCO_2$ by that date.

In principle, deployment of NETs might limit (and then reverse) NCQ overshoot. However, NETs are not a panacea; they vary greatly in maturity, remain uncertain in feasibility (technical, social, political and economic) and all have a very significant lead time to deployment. The IE-NETs project therefore included a first framing assessment of the potential for all those NETs found to be suitable for deployment in Ireland, namely afforestation, enhanced soil carbon sequestration, biochar, bioenergy with carbon capture and storage, direct air carbon capture and storage and enhanced weathering of rock materials. This found the

aggregate technical potential for accumulated gross removals (up to 2100) to be approximately $600\,MtCO_2$. The corresponding practical potential is likely to be substantially less than this estimate. It is proposed that a current, prudent, upper policy assumption for NETs potential in Ireland should be gross removals of no more than $200\,MtCO_2$. The discrepancy between projected net NCQ overshoot (at least $600\,MtCO_2$) and even gross CO_2 removals (at most $200\,MtCO_2$) indicates that much more ambitious, near-term reduction of gross CO_2 emissions remains the most urgent policy priority.

The national Climate Action Plan of 2019 proposes to "adopt a more ambitious commitment of net zero greenhouse gas emissions by 2050" (Action 1) and to introduce a system of statutory 5-year "national carbon budgets" (Action 5). It is recommended that these should now incorporate a statutory NCQ, with statutory limits on both the scale and duration of any CO_2 quota overshoot. This would provide the essential basis for developing broad, society-wide consensus on an equitable and prudential balance between immediate reductions in gross CO_2 emissions and inter-generational commitment to future, sustained and large-scale gross removals of CO_2.

1   Introduction

1.1   Motivation

The central motivation for the IE-NETs project is the need to "ratchet up" the national effort in Ireland and other nations to meet the global climate policy objectives of the Paris Agreement (UNFCCC, 2015), specifically to limit global surface warming to well below +2°C over pre-industrial levels and pursue efforts to limit the increase to less than +1.5°C, in accordance with science and equity.

Of the various greenhouse gases (GHGs) released by human activities that cause global warming, carbon dioxide (CO_2) is the single most significant. Global temperature cannot stabilise until the CO_2 concentration in the atmosphere is stabilised. However, CO_2 is very long-lived once released (thousands to tens of thousands of years) and therefore progressively accumulates in the atmosphere. This means that, to stabilise global temperature and climate, the net annual CO_2 emissions must be brought to zero. Furthermore, the ultimate stabilisation temperature will depend critically on the total net cumulative release of CO_2. In effect, the ability of the atmosphere to safely absorb CO_2 pollution is now almost fully exhausted.

A primary requirement for global climate stabilisation is therefore to reduce annual gross CO_2 emissions to zero as quickly as possible. However, industrialised economies have developed in such a way over many decades that they are now deeply dependent on ("locked in to") such emissions (Tong *et al.*, 2019). Reduction efforts to date have had very limited success; total global annual emissions have risen again in recent years (Jackson *et al.*, 2018). Accordingly, it is now necessary to consider if, in addition to reducing gross emissions as rapidly as possible, it may also be possible to deploy measures or technologies to actively remove CO_2 from the atmosphere and store it in some secure way (for at least hundreds to thousands of years) so as to bring down net emissions (gross emissions less gross removals) more quickly. Such measures are generically referred to as carbon dioxide removal (CDR) or negative emissions technologies (NETs). A large majority of scenarios for effective climate

stabilisation from the Intergovernmental Panel on Climate Change (IPCC) now assume global deployment of such negative emissions measures, starting even before 2030 and achieving not just global net-zero, but global net-negative CO_2 emissions, at a large scale, over the second half of this century (Anderson and Peters, 2016).

Although the deployment of NETs is therefore a global challenge, under the framework of the Paris Agreement it relies on bottom-up, nationally determined actions, voluntarily entered into by each of the participating countries to bring it about effectively. This requires that individual countries assess both the overall scale and the timing of negative emissions that they may need to achieve this (given the Paris temperature goals and assuming good faith commitment to fair and equitable action) and their particular local potential and capabilities for deployment of specific negative emissions measures. Accordingly, the IE-NETs project sets out to make such a preliminary assessment of the need and potential for NETs deployment specifically in Ireland. This final report from the project summarises the results of that assessment and presents relevant recommendations directed both at policymakers and the wider public.

It is important to note that Ireland is a party to the Paris Agreement both in its own right and as a Member State of the European Union (EU). The EU functions as a full party to the agreement and co-ordinates participation in the Paris framework on behalf of all its Member States. Ireland's membership of the EU adds a very significant layer of multi-lateral co-ordination of climate action, including jointly agreed and mutually enforceable mechanisms that go beyond the purely voluntary, bottom-up mechanisms of the Paris Agreement. Nonetheless, for the purposes of the current preliminary investigation, we have chosen to focus primarily on the Irish national perspective and the direct implications of Paris Agreement participation at that level, as these are binding over and above commitments at the EU level. However, it would be beneficial for future work to extend this analysis to consider explicitly the interactions with EU-level policies and the need for NETs assessment to be fully integrated with EU climate measures.

1.2 Review of International Literature on NETs

The first major activity of the IE-NETs project was to undertake an extensive review of the international literature on both the potential need for, and the possible measures and processes for achieving, negative CO_2 emissions. The review focused particularly on the international climate action context following the publication of the IPCC Fifth Assessment Report (IPCC, 2014a) and the adoption of the Paris Agreement (UNFCCC, 2015). The scope included removal of CO_2 from the atmosphere and transfer to secure, long-term storage. It considered both technological and nature-based measures, and interactions between both approaches. The detailed outcome of this review was released as an open-access White Paper, *A Post-Paris Literature Review of Negative Emissions Technology, and Potential for Ireland* (Price *et al.*, 2018). The bibliographic metadata underlying the review, comprising over 1700 separate literature items, were also released as an open-access database.[1] In this section we briefly summarise the conclusions presented in that full White Paper.[2]

To meet the agreed Paris temperature goals, global net CO_2 emissions must fall to zero rapidly, in accordance with the corresponding scientifically determined, remaining cumulative CO_2 global carbon budget (GCB). Although there is significant continuing scientific uncertainty as to the magnitude of the remaining GCB, under the terms of the United Nations Framework Convention on Climate Change (UNFCCC) the following precautionary principle should be applied:

> 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. (UNFCCC, 1992, Article 3.3)

Note that the concept of "cost-effectiveness" here is not concerned with whether or not to take appropriate, prudential action, only with the choices between alternative measures, all of which are commensurate with achieving the identified limits to environmental degradation. Furthermore, the global mitigation effort must be shared on a basis of equity and reflecting the wider United Nations Sustainable Development Goals (SDGs).[3] The rigid physical arithmetic of the global CO_2 budget, and national "fair shares" (quotas) of that budget, mean that mitigation delay translates rapidly to much higher mitigation rates in the near future.

The removal of CO_2 from the atmosphere, coupled with long-term storage, is technically possible by various pathways ("carbon sinks"), both natural and technological. Of currently identified approaches, those most likely to be of material potential for Ireland are:

- Afforestation (AF). Forest plantation is one of the most readily available NETs, with relatively low costs to deliver at scale. However, the key limitation is the need to firstly allocate large (and ever-increasing) areas of land to absorb CO_2 through forest growth (or regrowth) and then to protect and maintain it. Potential problems exist in the release of stored carbon during the disruption of planting or land use change, increased emissions of nitrous oxide (N_2O) resulting from fertilisation, effects on biodiversity, the competition with food crops for land use with a growing global population and the vulnerability of the captured carbon to harvesting (legal and illegal logging) and fires, pests and diseases. Carbon stored in living biomass is thus not secure.
- Soil carbon sequestration (SCS). Modifying agricultural practice, such as reduced tillage, offers potential for increasing carbon storage in soils. In addition, pyrolysis of biomass to form charcoal (biochar – BC) can produce a soil additive that can keep carbon in the soil for many years. Improved management of organic soils, including rewetting of peatlands, can firstly mitigate ongoing soil carbon loss and ultimately re-establish sink activity.
- Bioenergy with carbon capture and storage (BECCS). This involves switching from fossil fuels as a source of energy to biological energy sources

---

1 https://www.zotero.org/groups/2065424/potential_for_negative_emissions_in_ireland/items (accessed 20 July 2020).

2 Although this IE-NETs White Paper has a particular focus on the potential deployment of NETs in Ireland, we note that, since its completion, a global and systematic synthesis of the international literature on NETs has been published (Fuss *et al.*, 2018; Minx *et al.*, 2018).

3 https://sustainabledevelopment.un.org/ (accessed 20 July 2020).

and capturing and storing the CO_2 produced when the energy is used. Bioenergy fuels are produced through plant growth, which involves the absorption of CO_2 from the atmosphere. The return of that carbon to the atmosphere is avoided by associating the combustion process with CCS. BECCS is thus dependent on the combination of large-scale production of bioenergy fuels and efficient and cost-effective CCS technology. BECCS has already featured explicitly in some of the IPCC scenarios consistent with the Paris Agreement temperature goals. However, these typically involve deployment on a scale that would require very large areas of land and this would compete significantly with food production. High water and fertiliser requirements will also be associated with BECCS. Furthermore, the efficiency of biomass in generating electricity is lower than that of fossil fuels owing to the inherent lower energy density and more dispersed and complex supply chains.

- Direct air carbon capture and storage (DACCS). Direct air capture (DAC) of CO_2 involves a system where air from the atmosphere flows over an absorbent material that selectively removes the CO_2, which is then released as a concentrated stream for disposal or reuse, while the absorbent material is regenerated and the CO_2-depleted air is returned to the atmosphere. A range of chemical possibilities exists. The requirements are for rapid and efficient absorption, easy CO_2 release and sorbent regeneration mechanisms, with low energy inputs for air handling and the extraction of CO_2, and the same options for long-term storage or use for the collected CO_2 as are already required for CCS. The main limitations are the size of the equipment and the significant energy cost, which itself has to be derived from a very low CO_2 source.

- Enhanced weathering (EW). EW is where geological processes that naturally absorb CO_2 at slow rates are enhanced by some physical or chemical mechanism. When silicate or carbonate minerals dissolve in rainwater, CO_2 is drawn into the solution from the atmosphere. One technique involves spreading finely ground mineral silicate rocks over large areas of land, as is already done in some cases to reduce the acidity of soils for agriculture. The accelerated weathering concepts that have been explored are the result

of theoretical explorations and limited laboratory testing. Industrial process demonstrations or pilot-scale applications are lacking to date. There are also concerns about the logistical and cost implications of mining, crushing and transporting that material at the scale required. As with DACCS, large inputs of very local CO_2 energy would be required.

These various proposed approaches differ significantly in current maturity, potential scale, storage permanence, estimated financial costs, wider social and environmental impacts, and 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 strong 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 to incur substantially greater societal costs or may not be feasible at all.

Carbon capture and storage is a component technology for two of the proposed CO_2 removal processes with the greatest potential scale and permanence (BECCS and DACCS). Conventional CCS of CO_2 from fossil fuel electricity generation or industrial processes (FFCCS) is more technically mature than either BECCS or DACCS. It could already contribute significantly to mitigation of existing gross CO_2 emissions in Ireland (especially if combined with an 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 national 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 national potential for both BECCS and DACCS. There is therefore a clear Irish national interest in progressing FFCCS proactively, rather than passively relying on increases in carbon pricing (through the EU Emissions Trading

System; ETS) to provide a sufficient external market incentive at some unknown and unpredictable point in the future.

Indigenous natural (biological/biogenic) CO_2 removal capacity (including forestry, soil carbon and bioenergy crop cultivation), being based on land availability, is necessarily a very finite and constrained resource. Furthermore, biogenic carbon stores (particularly forestry and soil carbon) are of variable and uncertain permanence. Accordingly, it may be prudent to progressively prioritise available biogenic capacity for bioenergy production, while prioritising bioenergy use into large-scale conversion/use facilities where CCS (i.e. BECCS) will be feasible. The latter would also have the direct co-benefit of improving local air quality (relative to small-scale and unabated bioenergy use). Absolute increases in indigenous 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 beef or dairy production. Note that there is no inherent conflict here with the requirement (recognised at both national and international levels) to protect and enhance sustainable food production (UNFCCC, 2015, Article 2), although it may involve a systematic shift in local and global dietary balance among food types (Ripple *et al*., 2014).

In Ireland specifically, future research priorities should include:

- further detailing and quantifying the indigenous bioenergy capacity, particularly under the conditions of future climate change;
- developing robust, physically grounded GHG accounting mechanisms through life cycle assessment (LCA) of negative CO_2 emissions measures;
- modelling feasible deep decarbonisation pathways for the Irish energy system with potentially ambitious incorporation of BECCS and/or DACCS;
- assessing the potential for CCS both at the national level (including potential retrofits of existing fossil fuel plants) and/or at the international level, using available CO_2 geo-storage facilities;
- investigating the GHG profile of potential bioenergy imports;

- supporting Irish participation in NETs research internationally, including biogenic carbon stores (forests and soil carbon), and with a particular focus on EU-level policy integration.

1.3   Report Outline

The remainder of the report is structured as follows:

- Chapter 2 provides an assessment of a prudent, Paris Agreement-aligned, national CO_2 quota (NCQ) for Ireland, that is, Ireland's equitable "fair share" of the finite remaining GCB. This is a key parameter, as it provides the overarching quantitative constraint for the net balance between cumulative future gross CO_2 emissions and gross CO_2 removals (NETs) in Ireland. Although there is appropriate scope for societal debate around adopting a precise value for the NCQ, this preliminary assessment provides an articulation of the issues to be considered and proposes a provisional candidate NCQ to support the further analysis in this report. The chapter includes a best-effort projection of the future cumulative net CO_2 emissions that would arise under the current Climate Action Plan (DCCAE, 2019), finding that this would prima facie involve significant overshoot of the provisional NCQ, implying a tacit commitment to future, large-scale NETs deployment to reverse this.
- Chapter 3 presents a preliminary investigation of the potential for deploying a variety of NETs in Ireland. This draws heavily on a similar assessment for the UK by Smith *et al*. (2016), but also goes significantly beyond it, extending the analysis to not just annual CO_2 removal rates (flows) but also the corresponding cumulative CO_2 removals (stocks) that would result, under specific assumptions on deployment timing and rates. There remain very considerable uncertainties and the assessment provides, at best, an indication of the technical NETs potential. The realistic potential under diverse social, political and economic constraints will necessarily be much lower. The chapter concludes with a proposed prudential ceiling, for current policy purposes, on the potential contribution of future NETs to gross cumulative CO_2 removals in Ireland.
- Given the dominant role of fossil fuel energy use in gross national CO_2 emissions, Chapter 4

presents an investigation of modelling approaches to the future evolution of the Irish energy system under a hard NCQ constraint, including potential interactions with specific NETs. It presents a portfolio of coarse-grained scenarios for the future development of the Irish energy system under strict NCQ constraints (with and without overshoot) to better characterise the interactions between supply-side decarbonisation, demand-side constraint and NETs deployment.

- The cultivation of dedicated bioenergy crops can address both mitigation of gross CO_2 emissions from fossil fuel use (by direct displacement) and achievement of long-term gross removals of CO_2 from the atmosphere through BECCS. An additional potential contribution is through displacement of land use from high-GHG-intensity farming systems currently prevalent in Ireland (ruminant livestock systems in particular). Chapter 5 accordingly presents the results of novel, high-resolution modelling incorporating detailed biological mechanisms, to better understand the potential for scaling up indigenous bioenergy production and the possible interaction with local climate change.

- Chapter 6 provides a synthesis of the overall findings from the IE-NETs project. Based on this, it then presents a series of specific recommendations to support public understanding and inform effective policy development in national responses to the global climate emergency, specifically as these involve a limited, but important, potential role for the national deployment of NETs.

2 Assessing a Prudent, "Fair Share" CO_2 Quota for Ireland

Under the Paris Agreement (UNFCCC, 2015), the participating countries have committed to taking action to limit the global temperature increase to "well below 2°C" over pre-industrial levels and, moreover, to "pursue efforts" to hold the increase to a more stringent (lower impact/risk) level of 1.5°C. In planning and assessing policy measures proposed by any individual country to bring this about, and especially any potential role for NETs, it is critically important to identify the quantitative constraints implied by these temperature goals, that is, to determine a basis for understanding whether or not proposed national or regional energy decarbonisation policies are quantitatively commensurate with the global Paris objectives. The relevant policy question is not whether countries are doing what they suggest is feasible, but instead whether they are committed, collectively, to doing what is physically necessary to achieve these global Paris Agreement limits. Within the IE-NETs project, this question was addressed by attempting to assess the prudent remaining "fair share" of the global CO_2 budget that Ireland can reasonably claim. The detailed assessment was published by McMullin *et al*. (2019). This chapter provides a summary of the key results from that assessment.

2.1 The Paris Agreement-aligned Global Carbon Budget

The interpretation of the Paris Agreement temperature goals is complex (Rogelj *et al*., 2017). Nonetheless, referring to the most recent IPCC analysis contained in the *Special Report on the Impacts of Global Warming of 1.5°C* (SR15) (IPCC, 2018), we have estimated the range for the remaining GCB, based on achieving at least a 66% chance of limiting the temperature rise to no more than +2°C, as 610–1780 $GtCO_2$, from 2015. Furthermore, given the SR15 assessment of a significant increase in impact risk between warming of +1.5°C and +2°C, and the consequent importance of the Paris Agreement "efforts towards" respecting the lower temperature goal, we suggest adopting the lower limit of the assessed range (i.e. 610 $GtCO_2$) as a minimally prudent basis for the current assessment and planning of required action at both global and

national levels. Note that this GCB estimate also incorporates assumptions of significant global mitigation of emissions of non-CO_2 GHGs, specifically including methane (CH_4) and N_2O.

2.2 Fair Share Global Carbon Budget Division Principles

Raupach *et al*. (2014) suggest that, at any chosen or agreed reference year, the remaining GCB might be divided into national quotas in direct proportion to the then prevailing national shares of any of the following: annual global CO_2 emissions (which they term inertia division); annual global economic activity (measured by relative gross domestic product – GDP); or global population – an equal per capita division they term as equity and we term population or pop. We make use of this simple blending method by Raupach *et al*. (2014) to straightforwardly examine the range from an equal per capita GCB population allocation, with no inertia or "grandfathering" component, to population–inertia blends and a GCB allocation based on full inertia, the last greatly favouring nations with high current total or per capita emissions. We note, however, that this is an area of much deeper debate (Robiou du Pont *et al*., 2016; Kartha *et al*., 2018; van den Berg *et al*., 2019).

Separately from division of the GCB among nations it can be argued that quotas could or should then be adjusted to take account of at least two kinds of transfers or trade between nations. Firstly, the economic or welfare benefits associated with CO_2 emissions in any given nation may be ultimately enjoyed by citizens in another nation (through trading of goods in which the emissions are effectively embodied). However, such transfers are difficult to measure or verify on a transparent basis. Secondly, it is also possible, in principle, that there could be direct trading of CO_2 quotas, so that a nation might legitimately gain access to a greater quota than would be indicated by any prima facie fair share division. However, given the severe constraint of the remaining GCB at the global level (within which any quota trading would have to take place) and the need to support sustainable development (for nations with poor material welfare and that currently, or historically,

have had relatively more modest CO_2 emission profiles), the practical scope for CO_2 quota trading appears likely to be extremely limited. Finally, although there are some precedents for international trading in aspects of mitigation action (such as under the Clean Development Mechanism of the Kyoto Protocol, the UNFCCC REDD+ programme addressing deforestation and forest degradation and the EU ETS), there are no currently existing, or even proposed, institutional mechanisms to support GCB-based quota allocation and trading per se.

2.3 Estimates of Ireland's CO_2 Quota (from 2015)

All detailed calculations underlying the estimates presented here have been published and archived[4] via the Zenodo open data repository[5] in both spreadsheet (Open Document)[6] and interactive notebook (Jupyter/iPython)[7] formats. The methodology, derived from Raupach *et al.* (2014), is detailed in McMullin *et al.* (2019). On this basis, CO_2 quotas for Ireland, from 2015, for the following three variant cases spanning the full range of both GCB and the Raupach *et al.* (2014) sharing principles (between population and inertia) are estimated as follows:

1. low-GCB-Pop (low GCB: 610 $GtCO_2$; population sharing: $w = 1.0$); quota: 391 $MtCO_2$;

2. mid-GCB-Blend (mid-point GCB: 1190 $GtCO_2$; blended sharing: $w = 0.5$); quota: 996 $MtCO_2$;

3. high-GCB-Inertia (high GCB: 1780 $GtCO_2$; inertia sharing: $w = 0.0$); quota: 1839 $MtCO_2$.

2.4 The Paris Agreement and Good Faith Alignment

The methods used here can provide only indicative values for Ireland's CO_2 quota under the described methods and assumptions. They all embody tacit ethical values and choices that can, and should, be the subject of wide societal discussion and critique. Firstly, the adopted GCB is based on a temperature target of only a 66% probability of limiting the global

temperature rise to no more than +2°C over pre-industrial levels. This is, at best, a questionable interpretation of the Paris Agreement language of limiting the temperature rise to "well below" +2°C and surely falls significantly short of making "efforts" in support of the more stringent Paris Agreement goal of limiting the temperature rise to +1.5°C. As discussed by, for example, Glynn *et al.* (2018), a stronger interpretation of the temperature goal could lead to a GCB that would fall significantly below the minimum of the range used here.

Secondly, existential risks of increasing damage are anticipated for large parts of global human society, as well as pervasive disruption of the biosphere as a whole, as temperatures progressively breach and are sustained above the +2°C level (e.g. Burke *et al.*, 2015). Given the extreme difficulty of reversing the temperature overshoot and the uncertain climate response to the overshoot, the application of the precautionary principle (UNFCCC, 1992) suggests that prudent policy should be based on the lowest end of the assessed GCB range.

Thirdly, although aligning collective global policy with a GCB must include all CO_2 emissions from all sectors, in the current Paris Agreement framework emissions from international aviation and shipping are treated as falling outside the scope of nation state territorial emissions, which introduces significant additional uncertainty into effective governance of mitigation in these sectors (Bows-Larkin, 2015). As a minimum, this implies that the GCB available for sharing among nation state quotas should first be reduced by the amount of current and projected emissions from such international aviation and shipping. However, such a global-level top-slice allocation would implicitly distribute responsibility for such emissions on an equal global per capita basis, despite the highly unequal per capita participation in aviation and shipping between nation states. Accordingly, it may be argued that responsibility should instead be distributed in proportion to relative nation state participation in, or benefits from, international aviation and shipping and thus be counted in a differentiated way against nation state CO_2 quotas. This would mean that

---

4   All resources are available at https://doi.org/10.5281/zenodo.3257409 (accessed 20 July 2020).

5   https://zenodo.org (accessed 20 July 2020).

6   http://opendocumentformat.org/ (accessed 20 July 2020).

7   http://jupyter.org/ (accessed 20 July 2020).

highly developed countries, such as Ireland, would see a proportionally much greater reduction in their remaining quotas for strictly domestic CO_2 emissions.

Fourthly, as noted, the GCB estimate used here incorporates assumptions of significant global reduction in emissions of non-CO_2 GHGs, specifically including CH_4 and N_2O. Any shortfall in mitigation of these gases will reduce the available GCB and thus the national quotas for all nations. This has a specific salience for Ireland, given its relatively large per capita emissions of both CH_4 and N_2O (discussed further in section 2.6).

Finally, both the UNFCCC and the Paris Agreement imply good faith commitment to equitable action: it may be argued that the pure population division basis, which still omits considerations of historical responsibility and differentiated capacity and vulnerability (Kartha *et al*., 2018), represents an absolutely minimum interpretation of such equity.

Based on all these considerations, we recommend that the minimum quota assessed above, Low-GCB-Pop, 391 $MtCO_2$ (from 2015), should be regarded as an absolute maximum that could still represent properly good faith alignment with the Paris Agreement goals.

2.5 Quota-based Assessment of the Climate Action Plan 2019

The Irish NCQ analysis presented in McMullin *et al*. (2019) includes a summary assessment of the cumulative CO_2 emissions implied by the National Policy Position on Climate Action (DECLG, 2014) and the then-current CO_2 emissions inventory and projections reports (EPA, 2018, 2019a). However, that paper was completed before publication of a new Irish Climate Action Plan in June 2019 (DCCAE, 2019). Accordingly, in this section we provide a brief quota-based assessment of this plan.[8] In particular, we consider the question of whether or not, based on the plan, the fair share CO_2 quota is expected to be exhausted and, if so, assess the timing and scale of such an "overshoot" of the quota (also referred to here as "CO_2 debt").

The national quota estimates presented in section 2.3 above use a pathway baseline year of 2015, as the

year of the adoption of the Paris Agreement text. However, given that the measures in the new plan are unlikely to substantially change emissions for either 2019 or 2020, we will consider a set of pathways that all start by assuming that emissions for 2015–2020 are per the most recent Environmental Protection Agency (EPA) report, using the "with existing measures" data (EPA, 2019b).

Beyond 2020, the Climate Action Plan 2019 does not clearly describe a target pathway for either national GHG emissions as a whole or individual gases (such as CO_2, the specific focus of the current discussion). This is a significant shortcoming in itself. Instead, the plan equivocates between discussion of sectors defined nationally (such as an aggregate of "electricity generation, built environment and transport") and sectors defined relative to EU policy measures (specifically demarcated between the EU ETS and the non-traded national domestic emissions – non-ETS emissions), with potentially different component gases and processes (including removals) in each case. These different sectoral aggregates relate to each other in complex ways that are not explicitly decomposed in the plan, which makes interpretation difficult. Nonetheless, we present a "best effort" attempt to arrive at a coherent definition of future CO_2 emissions pathway(s) that are at least consistent with, if not explicitly mandated by, the plan.

The plan targets what it describes as a "2% per annum" reduction pathway specifically for the non-ETS emissions sector from 2021 to 2030, based on attainment of Ireland's agreed national-level commitment to EU-wide emissions reduction under the Effort Sharing Regulation (ESR) (EU, 2018a). It goes on to state that:

> ... in the period between 2030 and 2050, a much steeper decline of 7% per annum will have to be achieved based on achieving a minimum 80% emissions reduction by 2050, relative to 1990. (DCCAE, 2019, p. 27)

Strictly, compounding year-on-year reductions at any fixed percentage rate would yield pathway segments that are mathematically exponential. However, mathematically linear pathways (characterised

---

8   The analysis was released in spreadsheet form under open licensing. Available online in ODS format: http://ienets.eeng.dcu.ie/ documents/IE-CO2-Quota-CAP-2019.ods (accessed 20 July 2020).

by reduction by a fixed absolute amount in each year, rather than by a compounding year-on-year percentage) are more typical in EU policies (such as the ESR) and for the presentation of indicative CO_2 decarbonisation pathways by the EPA, Climate Change Advisory Council (CCAC) and Sustainable Energy Authority of Ireland (SEAI). Furthermore, the chart presented in the actual plan, illustrating the non-ETS emissions pathway to 2030 (DCCAE, 2019, p. 19), does in fact show a linear rather than exponential form.

Accordingly, we will assume that the action plan is best interpreted as proposing to achieve emissions pathways (across sectors and gases) that are, generally, piecewise linear from 2021 to 2030, and then again from 2031 to 2050, but potentially with different linear reduction rates in those two periods. In addition, we will assume that, for 2021–2030, the rate (linear slope) will be fixed at *c*.2% of the 2020 emissions rate. As already noted, this is stated explicitly in the plan for the non-ETS sector and, in the absence of more precise guidance, we will therefore extrapolate this to all national CO_2 emissions (i.e. across both ETS and non-ETS sectors). Beyond 2030, the reduction rate will be determined relative to a targeted point-in-time level in 2050. This later level is indicated to be (for the time being) an overall reduction of 80% relative to 1990 levels (at least for CO_2, if not other gases) based on long-term targets originally contained in the National Policy Position on Climate Action (DECLG, 2014). Those long-term targets have expressly not been superseded in the new plan, although the plan does also commit (Action 1) that early consideration will be given to a "more ambitious" long-term target of achieving "net-zero" emissions in 2050.

This yields an interpretation of the Climate Action Plan 2019 as envisaging the following possible pathways for total future CO_2 emissions in Ireland:

- From 2021 to 2030, there should be a linear pathway characterised by successive annual reductions of 0.86 $MtCO_2$ per year, each year, representing 2% of projected net 2020 CO_2 emissions (all sectors), for an overall 20% reduction by 2030 relative to 2020.
- From 2031 to 2050, there should be a divergence between two possible pathways, both again linear, and differing only in the "point-in-time" emissions level in 2050, being either:

– an 80% reduction compared with 1990, implying an annual reduction of 1.34 $MtCO_2$ per year, each year, equivalent to 3.1% of the projected 2020 level; or
– net zero in 2050, implying an annual reduction of 1.72 $MtCO_2$ per year, each year, equivalent to 4% of the projected 2020 level.

We note that the 2031–2050 annual reduction rate of "3.1% of the projected 2020 level", cited here as based on achieving an 80% reduction relative to 1990 by 2050, appears substantially less than the 7% cited in the Climate Action Plan. This discrepancy precisely illustrates the difficulties that arise on account of the mixture of different and potentially ambiguous approaches to sectoral divisions, gases, baseline reference years, and percentage and absolute reductions that are used at different points in the plan text, lacking clear cross-referencing, decomposition or transparent mapping to public datasets, calculations or audit trails.

In Figure 2.1 we compare these two Climate Action Plan-based pathways with a reference linear pathway that is constrained to *just* use up (without overshoot) our estimated maximum prudent "fair share" quota of *c*.391 $MtCO_2$ (dating from 2015). Based on the projected accumulated emissions to 2020, this quota-constrained reference pathway would require successive annual reductions of 6.0 $MtCO_2$ per year (representing 14% of the projected 2020 emissions level) each year from 2021 until it reaches net zero, which would occur by about 2028 (and maintaining net-zero emissions thereafter).

In Figure 2.2 we show the corresponding cumulative depletion of the fair share quota (starting at the assessed prudent value of 391 $MtCO_2$ as of 2015, in all cases). By construction, the theoretical Paris Agreement-aligned, no-overshoot linear pathway would exactly exhaust the quota (*c*.2028) and does not enter CO_2 debt (as there are no further net emissions). By contrast, the Climate Action Plan pathways both exhaust the entire quota as early as 2024 and subsequently overshoot into CO_2 debt. The pathway to −80% by 2050 reaches a cumulative CO_2 debt of 615 $MtCO_2$ (which would still continue to deepen even thereafter) and the pathway to net zero by 2050 levels out (but does not yet start reversing) CO_2 debt at 535 $MtCO_2$ at that year.
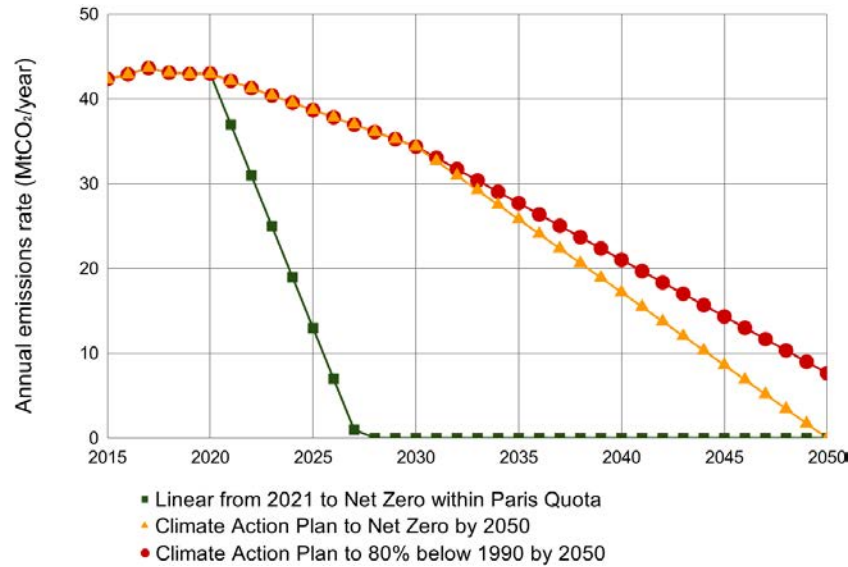
Figure 2.1. Hypothesised annual CO_2 emission rate pathways based on the Climate Action Plan 2019.
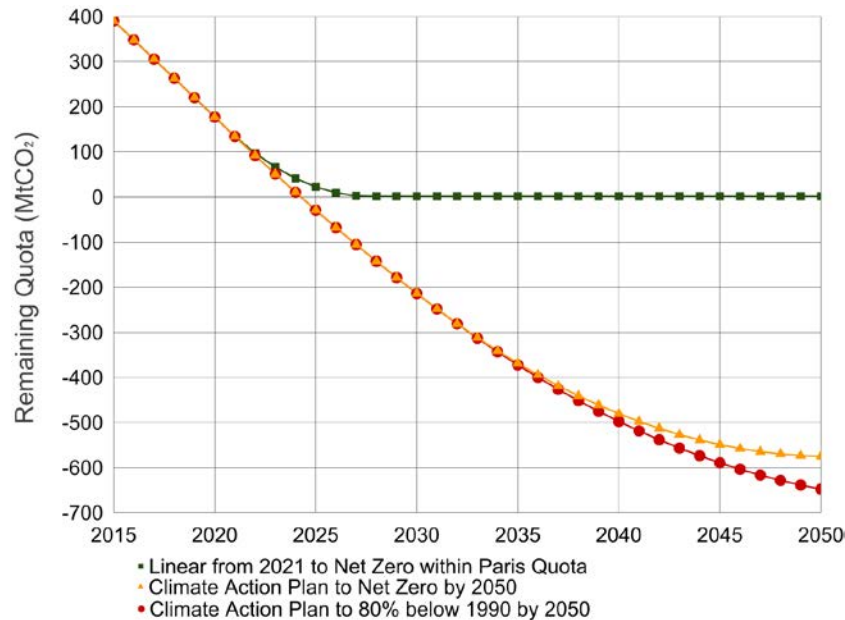
Figure 2.2. Ireland's 2015 remaining quota of 391 MtCO2 is depleted by the net CO_2 emissions in each year for each pathway. CO_2 debt occurs if or when the remaining quota becomes negative, tacitly implying a commitment to subsequent net-negative emissions to "pay back" this debt.

It is notable that an apparently significant potential increase of ambition represented by "net-zero" annual emissions by 2050 actually makes only a modest difference (*c*.13%) to the level of CO_2 debt accumulated by that time (however, it would at least have stopped growing under the net-zero constraint). Thus, the critical criterion in evaluating the effectiveness of CO_2 mitigation is not some nominal "point-in-time" (2050) emissions rate, but the pathway towards such a point. Even for exactly the same "point-in-time" target (the same overall reduction in annual

emissions), early cuts are much more significant than later ones, simply owing to their additional duration (MaREI, 2018). Conversely, procrastination not only implies that the deeper, presumably more politically challenging reductions are delayed, but also that they may then have to be achieved against a background of potentially much more severe climate impacts (nationally and globally).

For comparison, McMullin *et al*. (2019) assessed inter alia the evolution of cumulative CO_2 emissions that

would have arisen if an exponential (consciously front-loaded) pathway towards even the nominally "less ambitious" 80% reduction by 2050 target had been immediately initiated when that point-in-time objective was originally adopted in the National Policy Position on Climate Action in 2014. Although that would have still resulted in significant carbon debt (relative to our assessed prudent quota), it would have reached a level of only about 350 MtCO$_2$ by 2050, substantially less (35–45%) than either of the pathways now suggested by the new 2019 plan. Thus, rather than representing increased ambition, this plan appears rather to retrospectively endorse a de facto erosion of ambition that has occurred since the National Policy Position was formally adopted (where "ambition" is here measured by cumulative CO$_2$, as most properly reflects the underlying physical science).

2.6 Irish Policy Approach to Non-CO$_2$ Greenhouse Gases

The previous analysis has been focused on CO$_2$ emissions only (across all sectors), as this is directly amenable to a cumulative quota assessment. However, the National Policy Position on Climate Action instead adopts a mixed-gas, sector-based objective of "an approach to carbon neutrality in the agriculture and land-use sector, including forestry, which does not compromise capacity for sustainable food production". The overall emissions profile for this agriculture, forestry and other land use (AFOLU) sector is dominated by CH$_4$ and N$_2$O, although also involving significant emissions and removals of CO$_2$ in land use and forestry. The concept of neutrality in AFOLU is therefore not a straightforward one and evidently involves aggregation of the effects of different gases to achieve a neutral or net-zero emissions level. In current Kyoto Protocol-based inventory accounting, this aggregation is done using the so-called global warming potential over 100 years (GWP$_{100}$) equivalence factors to yield CO$_2$-equivalent (CO$_2$e) values (EPA, 2017). On this basis, as of 2017, non-CO$_2$ gases accounted for approximately 35% of total Irish annual CO$_2$e emissions (derived from EPA, 2019a). This is an unusually high proportion compared with most other nation states, driven primarily by the relatively large, grass-fed, ruminant agriculture sector in Ireland, driving high emissions of both CH$_4$ and N$_2$O. However, while GWP$_{100}$ is an established approach to aggregating annual emission rates, it is

well understood that it is not suitable for comparing the effects of different GHGs with the effects of cumulative CO$_2$ in a budget (GCB) or quota framework (Allen *et al.*, 2018). On the contrary, the different physical climate effects of CO$_2$ relative to non-CO$_2$ emissions mean that the shorter lived GHGs (such as CH$_4$ and F-gases) are best treated in a separate policy basket to the longer lived N$_2$O and CO$_2$ (Smith *et al.*, 2012; Solomon *et al.*, 2013). The former might be usefully subjected to an aggregate annual emission rate target, based on GWP$_{100}$ or otherwise, which does not necessarily go to net zero (or negative), whereas the latter should be separately aggregated in a cumulative budget framework, which does imply a net-zero (or potentially negative) requirement. Alternatively, a single, aggregated, cumulative metric may be used but this should be based not on conventional GWP$_{100}$ equivalence, but instead on, for example, the so-called cumulative CO$_2$we (CO$_2$ warming equivalent) methodology proposed by Allen *et al.* (2018). Of course, corresponding fair share, Paris Agreement-aligned, national quota targets, now incorporating non-CO$_2$ pollutants, would have to be recalculated to reflect any such methodology.

Although it is beyond the scope of the current discussion to assess any detailed division of mitigation effort between gases, it is clear that the national Irish CO$_2$ quota estimates presented here do presuppose some fair share level of effective mitigation of non-CO$_2$ pollutants as well, which would necessarily impact primarily on the ruminant agriculture sector. Unfortunately, current trends and projections, and indeed national policy in relation to expansion of agricultural production in Ireland, are leading to increasing rates of emission of key non-CO$_2$ gases, particularly CH$_4$ and N$_2$O (EPA, 2018, 2019a). At the very least this is a further reason to treat the Irish CO$_2$ net quota suggested here as an absolute upper limit to Paris Agreement alignment for CO$_2$ emissions specifically, across all sectors.

2.7 Conclusion

In this chapter we have presented an assessment of the plausible Paris Agreement-aligned, fair share net cumulative CO$_2$ quota remaining for Ireland from 2015 and have compared and contrasted this with CO$_2$ emissions pathways informed by the Climate Action Plan 2019. The mitigation trajectories implied by the

plan, insofar as they can be reasonably inferred, prima facie suggest a very early exhaustion of our assessed prudent "fair share" (Paris Agreement-aligned) CO_2 quota, with consequent emergence of CO_2 debt of the order of 600 $MtCO_2$ by 2050. Good faith contribution to achievement of the Paris Agreement temperature goals therefore suggests a tacit commitment to future "debt repayment" in the form of deployment of negative emissions measures to achieve large-scale net removal of CO_2 from the atmosphere, sustained over an extended period of time. This involves a significant risk that these measures may fail to deliver, as their deployment is currently highly speculative at the relevant required scale and at a feasible cost (Larkin *et al*., 2017).

On the positive side, the action plan does propose very significant strengthening of Irish climate action governance in the immediate future, including the introduction of a system of binding, 5-yearly "emissions budgets", extending at least 15 years into the future and addressing all GHGs. This is a very positive commitment that represents a significant opportunity for a step change in mitigation urgency and effectiveness. However, to realise this opportunity, it is strongly recommended that the governance reforms should also explicitly incorporate some overall binding cumulative CO_2 emissions limit (quota), adopted on a statutory basis. Although such a statutory quota

might, of course, still differ from the specific value identified in the current research, it is essential that it be scientifically and ethically informed on a basis of prudence and global equity, and be accompanied by a transparent articulation of how it is claimed to align with the Paris Agreement goals. Furthermore, to the extent that any proposed sequence of 5-year budgets would subsequently imply overshoot of this statutory quota, there should be a governance requirement to explicitly recognise this anticipated emergence of CO_2 debt, and for that to be coupled with immediate planning for how the extent and duration of such debt will be limited.

From a climate perspective, the core recommendation for both national and global mitigation strategies must be the prioritisation of achieving net-zero CO_2 emissions within a stated overarching net CO_2 cumulative quota constraint, limiting commitment to CO_2 debt and rigorously respecting a net CO_2 emissions rate pathway that is commensurate with satisfying this cumulative constraint. Although the detailed policy situation will clearly differ with respect to different CO_2 removal technologies (Fuss *et al*., 2018; Minx *et al*., 2018) and from country to country (e.g. Smith *et al*., 2016; McGeever *et al*., 2019), we recommend that this methodology and, in particular, the use of CO_2 quota depletion as a policy metric, should be applied as widely as possible.

3 Negative Emissions Technologies Potential in Ireland

In this chapter we summarise the NETs most commonly considered in the international literature and assess their specific suitability and technical potential for deployment in Ireland, both qualitatively and quantitatively (albeit generally with high uncertainty). More extensive analysis and discussion has been separately published in McGeever *et al.* (2019).

3.1 Overview of NET Options for Ireland

One way of classifying potential NET approaches is according to the targeted carbon storage mechanism: either biogenic (soil organic carbon or standing plant biomass) or geological (most typically assumed to be by pumping captured CO_2, under pressure, into suitable porous rock formations sealed below non-porous strata). Although both can contribute in the short (decadal) term, concerns over saturation and permanence of biogenic storage, particularly in the face of ongoing climate impacts, mean that this is best viewed as a transitional measure only. Ultimately, only the 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.

A second, high-level classification is according to the mechanism for initial removal of CO_2 from the 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" – DAC). Table 3.1 presents the particular NETs that will be considered further in this chapter, together with their respective classifications

of both CO_2 removal from the atmosphere and carbon storage. Figure 3.1 shows a separate graphical representation, reproduced from Minx *et al.* (2018).

There is extensive prior experience in Ireland with AF and more limited experience with bioenergy crop cultivation and enhancement of SCS via the use of BC or otherwise. There is no existing experience with either DACCS or BECCS owing primarily to the immaturity and cost (to date) of CCS. BECCS, DACCS and EW would interact significantly with the overall energy system: BECCS could contribute net energy, whereas both DACCS and EW would require additional energy consumption. Note that although BECCS is most commonly conceived as use of bioenergy specifically in electricity generation, it can refer more generally to any bioenergy exploitation pathway where the carbon component of the bioenergy material is captured and consigned to secure geo-storage, so as well as conversion to electricity, this may include conversion to other non-carbon energy carriers, such as hydrogen (H_2) or ammonia (NH_3), to support large-scale energy storage and transport and/or direct decarbonisation of end uses where electrification may be especially difficult (high-temperature heat, heavy transport, etc.). With the exception of DACCS, all the NETs mentioned in Table 3.1 would interact very substantially with domestic land use and agricultural practices, in some cases competing with existing land use (bioenergy crops, AF) and in other cases potentially being complementary to, or co-existing with, existing use (enhanced SCS, EW).

There are many challenges and limitations to deploying and scaling up various NETs options in Ireland. Barriers include technical readiness, cost,

Table 3.1. High-level NET classification

NET	Removal	Storage
SCS	Biogenic	Biogenic
BC	Biogenic	Biogenic
AF	Biogenic	Biogenic
EW	Technological	Geological
BECCS	Biogenic	Geological
DACCS	Technological	Geological
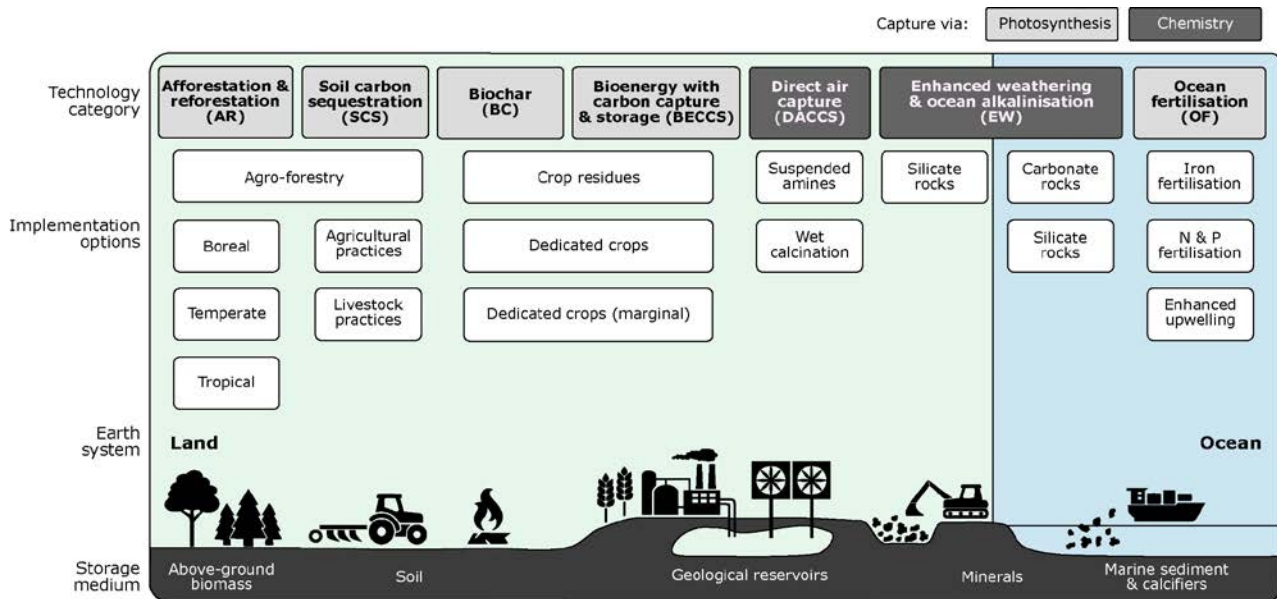
Figure 3.1. A taxonomy of NETs. NETs are distinguished by their approach to carbon capture, earth system and storage medium. Major implementation options are distinguished for each NET. Original figure from Minx *et al*. (2018). Reproduced under the terms of the Creative Commons Attribution 3.0 licence (http://creativecommons.org/licenses/by/3.0).

storage permanence and knowledge gaps in Ireland-specific research. A preliminary qualitative summary of these and other policy considerations for deploying NETs options in Ireland, based on the overall international literature, is presented in Table 3.2.

3.2   Assessing Quantitative National NETs Potential

Smith *et al*. (2016) present a method to estimate the technical CO_2 removal capacity (annual flow, not cumulative/stock) of various NETs options under hypothetical land area availability scenarios for the UK. In this section we will adopt and further develop this methodology to model the potential for such NETs to contribute to effective (CO_2 quota-based) climate change mitigation in Ireland.

The analysis of Smith *et al*. (2016) begins with estimates of the ranges for a number of quantitative parameters for a variety of NETs (under UK conditions). Table 3.3 summarises these parameter ranges, with unit conversions for consistency with the conventions of the current report. In interpreting and applying these data, it is important to bear in mind the following caveats from Smith *et al*. (2016, p. 1401, emphasis added):

Systemic, holistic issues need to be considered for NETs deployment and are probably the most immediate aspects of developing these technologies which need to be addressed. It must be noted that this is a preliminary, technology focussed assessment that takes no account of such socio-political aspects of NETs deployment, which when considered *would be expected to lower considerably the technical potentials estimated here*. Further, whilst the best available data have been used, different technologies are at different stages of development (e.g. AF and SCS widely applied already; DAC yet to be demonstrated at scale), and the quantity and quality of data varies greatly between technologies.

Accordingly, for the remainder of the discussion here, we will focus attention on the "low" estimates for the removal potential shown, noting that even these are probably considerably higher than could be realised under realistic economic, political and social constraints, especially under the expected additional stress of unfolding climate change impacts (nationally, regionally and globally).

Table 3.2. A schematic qualitative summary of the main policy-relevant considerations for utilising NET options in Ireland

Policy consideration	Positive sense	SCS	BC	EW	AF	BECCS	DACCS
CO_2 removal potential	High	Low[a]	Medium	High	Medium	High	High
Readiness	High	Very high	Very high	Medium	Very high	Medium	Very low
Cost	Low	Medium[a]	Medium[a]	High[a]	Low	Medium[a]	Very high
Vulnerability to re-release	Low	High	Medium[a]	Low	Medium[a]	Low	Low
Vulnerability to future climate change	Low	Very high	High	Medium	High	Medium	Very low
Biodiversity risk	Low	Low	Low	Medium	High[a]	High	Low
Land use/conflict	Low	Low	High	Low	High	High	Very low
Energy output/input	High output	Low input	Medium output	High input	Low input[a]	High output[a]	Very high input

Green shades denote a positive rating, yellow shade denotes a medium rating and red shades denote a negative rating. The column "Positive sense" indicates which of "high" or "low" is considered positive for each policy consideration. All options provide opportunities and difficulties for decision-makers, with significant uncertainty ranges in many cases requiring more specific evaluation.

[a]Assessments with low or very low confidence, in the sense defined by the IPCC (Mastrandrea *et al.*, 2010).

Table 3.3. Estimated parameter ranges for specific NETs (under UK/Irish conditions where relevant)

Technology		SCS	EW	AF	BC	BECCS	DACCS
CO_2 removal rate (flow) per land area (tCO_2 ha^{-1} y^{-1})	Low	0.1	3.0	12.5	4.2	11.0	–
	High	3.7	40.0	12.5	27.5	44.0	–
Water use (1000 m^3 $t^{-1}CO_2$)	Low	0.00	0.00	0.32	0.00	0.55	0.02
	High	0.00	0.00	0.64	0.00	0.68	0.03
Energy input (MWh $t^{-1}CO_2$)	Low	0.00	0.23	0.00	−3.79	−2.92	0.20
	High	0.00	3.50	0.00	−1.52	0.66	3.47
N (kg N $t^{-1}CO_2$)	Low	21.82	0.00	0.55	8.18	3.00	0.00
	High	21.82	0.00	1.36	8.18	5.45	0.00
P (kg P $t^{-1}CO_2$)	Low	5.45	0.00	1.09	2.73	0.22	0.00
	High	5.45	0.00	1.36	2.73	5.45	0.00
K (kg K $t^{-1}CO_2$)	Low	4.09	0.00	0.11	19.09	1.55	0.00
	High	4.09	0.00	0.85	19.09	6.00	0.00
Albedo impact (unitless)	Low	0.00	0.00	0.00	0.08	0.00	0.00
	High	0.00	0.00	0.62	0.12	0.04	0.00
Cost (€$tC^{-1}O_2$)	Low	−41	23	16	-205	33	394
	High	10	1450	27	296	33	512

K, potassium; N, nitrogen; P, phosphorus.

Derived from Smith *et al*. (2016), Table 1.

With the exception of DACCS (which will be considered separately in the conclusion), the key limiting factor for indigenous use of all the NETs shown in Table 3.3 is the available land area for their deployment. In the current analysis we are focused on the territorial potential for Ireland, so we must estimate the feasible land use change to facilitate their use. We follow the approach of Smith *et al.* (2016) for the UK as closely as possible. The Irish Council for Forest Research and Development classifies Irish land into four distinct levels (COFORD, 2016). The level most suitable for potential NETs deployment is level 4: "land most likely

to have potential for forest expansion". We assume that SCS could, in principle, be applied to all of this (3.75 Mha) without conflict with existing use.[9] For BECCS, AF and BC, the assessment is informed by the potential land area available for bioenergy crops in Ireland (SEAI, 2012), constraints on land use change arising from the EU Common Agricultural Policy (DAFM, 2015) and the existing national AF target for 2050 (COFORD, 2016). On this basis, two illustrative land use change scenarios (for the aggregate of new AF, BC and/or BECCS) are considered here: a "low" scenario of 0.55 Mha and a "high" (very ambitious/ disruptive) scenario of 1.0 Mha. We assume that EW at an application rate up to 10 t rock ha^{-1} might be applied to all level 4 land (3.75 Mha); however, noting that the most comparable existing practice, liming, is generally applied at rates less than 0.4 t ha^{-1}, this would have to be considered as extremely ambitious in both total area and application rate. Based on these land use scenarios, and using the parameter ranges from Table 3.3, we derive an assessment of the range of annual NETs removal potential, impacts and costs specific to Ireland, as shown in Table 3.4. Note that AF, BC and BECCS are regarded as competing for the same land use, so the values shown here are for each one considered in isolation, that is, these potentials are mutually exclusive and the separate potentials

shown are therefore not additive. Indeed, this caution that assessed potentials for different NETs are not generally additive has also been highlighted in the comprehensive assessment of Fuss *et al.* (2018).

Although this provides a useful insight into the technical range of annual flow of the NETs CO_2 removal potential for a given land use, from the point of view of effective climate change mitigation it is actually the cumulative stock of removed (and stored) CO_2 that is of critical interest. Several additional factors must be accounted for to assess this, namely the feasible deployment start year (varying according to the current maturity of different technologies), the deployment rate in time for any given land use change (ha y^{-1}) up to the specified target land use and any carbon storage saturation effects.

For illustrative purposes, we assume that SCS, BC and AF are already mature and could start deployment from 2021. For BECCS we assume deployment from 2030 and for EW (which requires access to commensurate, effectively zero-carbon, energy) from 2035.

In assessing feasible deployment rates, where this involves significant land use change (AF, BC, BECCS) we note that the existing target AF rate is estimated at 15 kha y^{-1} (from 2020), while recently achieved rates

Table 3.4. Summary of applied CO_2 removal (negative emission) potential, impacts on water use, energy and nutrient (N, P and K) requirements, and bottom-up estimates of cost for Ireland

Technology	SCS	EW (10 t ha^{-1})	AF		BC		BECCS	
LUC scenario			Low	High	Low	High	Low	High
Area applied (Mha)	3.75	3.75	0.55	1.00	0.55	1.00	0.55	1.00
CO_2 removal rate (MtCO$_2$e y^{-1})	0.41	11	7	12	2	4	6	11
Water use (km^3 y^{-1})	0.000	0.005	2.207	4.012	0.000	0.000	3.300	6.000
Energy input (TWh y^{-1})	0.000	2.597	0.000	0.000	−8.785	−15.972	−17.692	−32.167
N (kt N y^{-1})	9.000	0.000	3.740	6.800	18.975	34.500	18.150	33.000
P (kt P y^{-1})	2.250	0.000	7.480	13.600	6.325	11.500	1.320	2.400
K (kt K y^{-1})	1.690	0.000	0.748	1.360	44.275	80.500	9.405	17.100
Cost, low estimate (M€ y^{-1})	−17	259	110	200	−474	−862	197	358
Cost, high estimate (M€ y^{-1})	4	16,572	182	332	686	1247	197	358

AF, BC and BECCS compete for land use, so the potentials shown are not additive.

K, potassium; LUC, land use change; N, nitrogen; P, phosphorus.

---

9 This excludes peatlands. Note that although there is also mitigation potential to reduce existing land use CO_2 emissions, for example by rewetting organic soils, this falls outside the scope of the particular analysis here.

have been less than half this (COFORD, 2016). For the current illustrative purpose, we model a notional deployment rate for AF, BC and/or BECCS (each considered in isolation) of 30 kha y^{-1}, acknowledging that this is probably at the extreme upper end of what might be achievable in practice. For EW (at 10 t rock ha^{-1}), which does not require full land use change but would still involve very considerable changes in land use practice and deployment of large-scale support infrastructure (in rock mining, processing, transport and application), we set a notional deployment rate of 60 kha y^{-1}. For SCS, which, in principle, requires the least changes in existing land use practice, we set a notional deployment rate of 200 kha y^{-1}.

Biogenic carbon storage saturation limits apply specifically to SCS, AF and BC. For illustrative purposes here, and consistent with the discussion of Smith *et al.* (2016), we model saturation after 20 years for SCS and AF, and after 40 years for BC. For AF we note that the most critical question is the harvest regime (if any) and the subsequent processing of harvested material. A specific scenario that would merit more detailed consideration could be intensive AF, without large-scale harvest in the short to medium term (2–20 years), potentially allowing time for BECCS technology to mature and be deployed at scale. Then, as BECCS infrastructure becomes available, AF harvest (and replanting either in forest or short rotation dedicated bioenergy crops)[10] might be used to effectively convert the accumulated AF biogenic carbon store into more secure geological CO_2 storage, while continuing to maintain and expand the land area under AF and/or short rotation bioenergy crop cultivation. On the other hand, it must be noted that such a strategy might inhibit interim substitution of fossil energy use and/or fossil energy-intensive building products (steel, concrete) by a potentially lower impact forest harvest. There is an extensive existing literature on assessment of more conventional alternative pathways for carbon, energy and harvested wood products according to alternative forest use scenarios (e.g. Cowie *et al*., 2013; Cintas *et al*., 2017; Koponen *et al*., 2018). However, detailed modelling

of such integrated multi-NET pathways, potentially interacting with wider mitigation measures, is beyond the scope of the current analysis, so we simply show AF saturation at 20 years (effectively a conservative no-harvest assumption).

Of course, geological storage of CO_2 (BECCS and DACCS) is also subject to potential saturation limits on suitable available geology. The technical storage capacity in the close vicinity of Ireland has been estimated as approximately 1600 MtCO_2 (Farrelly *et al*., 2010), with the practical and economic capacity probably substantially smaller. Nonetheless, for the purposes of the current assessment, we assume that geological CO_2 storage capacity would not be a limiting factor in the deployment of BECCS (or DACCS) within the time frames and deployment scales being considered. In any case, in the event that domestic CO_2 geo-storage capacity was exhausted, there would also be potential for exporting of CO_2 for storage in other jurisdictions.[11]

It should still be noted that the existence of limits on indigenous geological CO_2 storage capacity, even if currently uncertain, means that all CCS deployment, specifically including FFCCS, should be critically assessed in the light of such limits. There may be a case for prioritising such storage for BECCS/DACCS over FFCCS (i.e. favouring direct elimination of fossil fuel use rather than relatively temporary substitution of FFCCS) but detailed assessment of that issue was beyond the scope of the current project. Separately, in the case of EW, where carbon is stored in stable mineral form, and ultimately transported to long-term seabed storage, we assume no saturation or storage capacity limit would apply within the relevant time frames and deployment scale.

With these assumptions, it is then possible to model illustrative pathways for the deployment of the land use-constrained NETs in Ireland and assess the CO_2 removal flow and corresponding cumulative CO_2 stock that might be removed from the atmosphere. These pathways are shown in Figures 3.2 and 3.3, respectively, and summarised in Table 3.5.[12]

---

10 Note that a change of land use from forestry to short rotation bioenergy crops would be classified as deforestation under current Irish legislation and as such is prohibited. New or amending legislation would therefore be required to enable any such policy intervention.

11 See, for example, the proposed "full-scale CCS" project proposed by Norway: https://ccsnorway.com/ (accessed 20 July 2020).

12 The detailed spreadsheet modelling tool to produce these pathways has been separately released for reuse under open licensing. Available online in ODS format: http://ienets.eeng.dcu.ie/documents/IE-NETs-potential-summary.ods (accessed 20 July 2020).
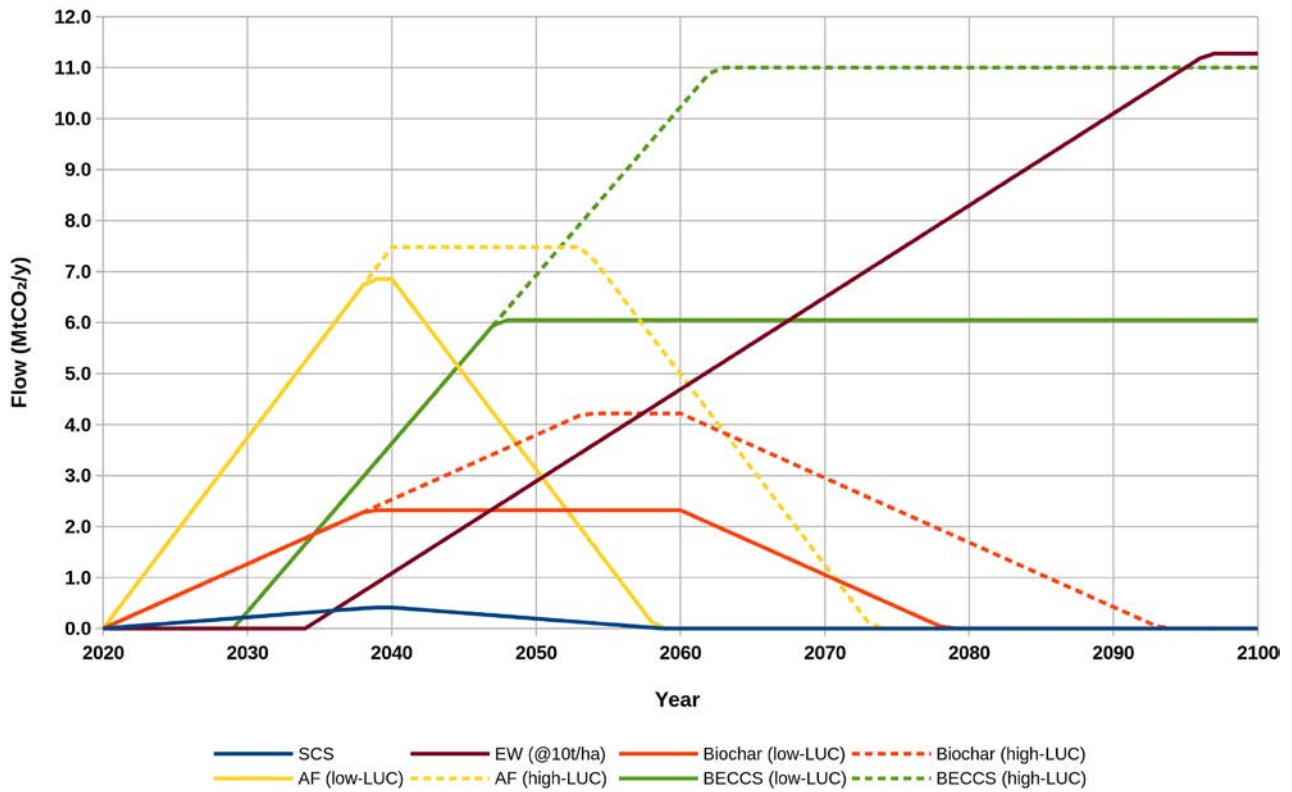
Figure 3.2. Illustrative NETs CO$_2$ removal flow pathways (MtCO$_2$ y^{-1}) for Ireland, 2020–2100. LUC, land use change.
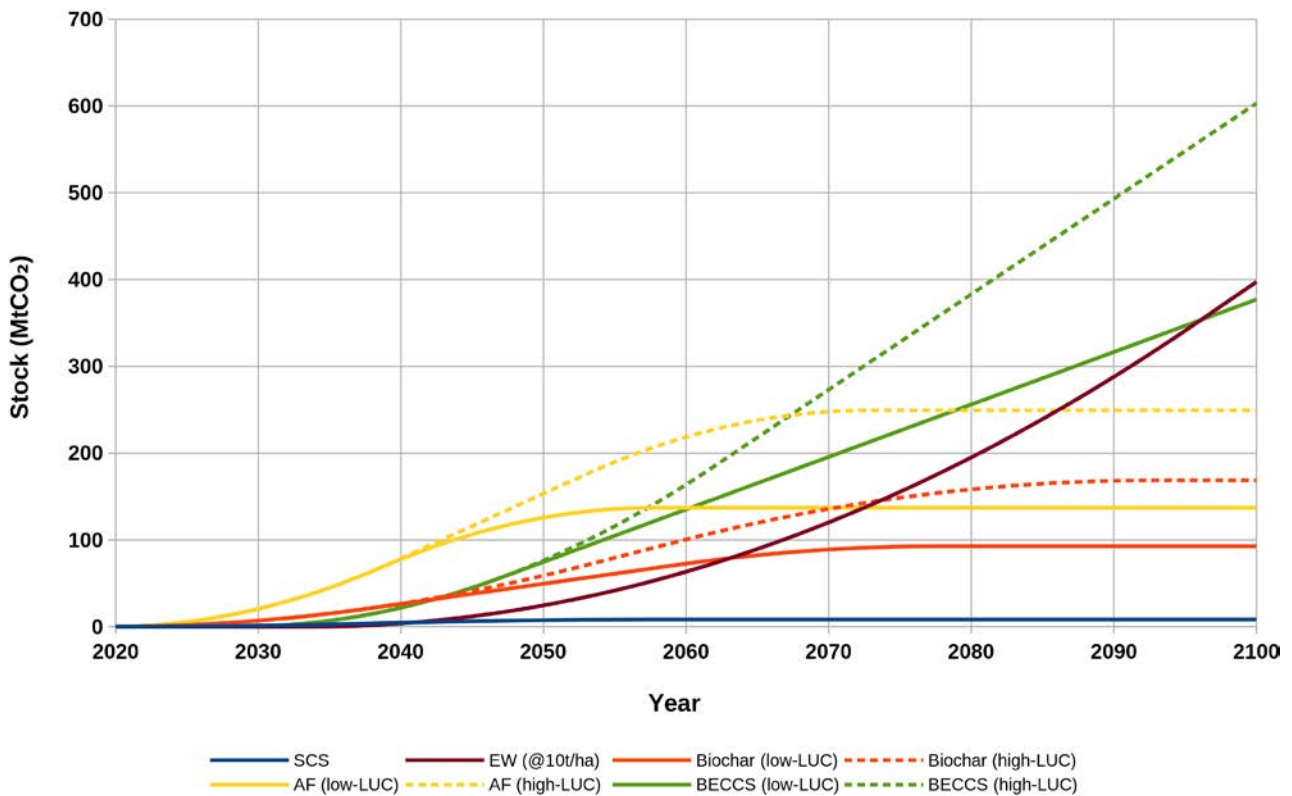

Figure 3.3. Illustrative NETs CO$_2$ removal stock pathways (MtCO$_2$) for Ireland, 2020–2100. LUC, land use change.

Table 3.5. Summary of illustrative NETs cumulative CO_2 (stock) removal pathways

Technology	Start year	Max area (Mha)	Max flow (MtCO$_2$ y^{-1})	Max energy input (TWh y^{-1})		Stock (MtCO$_2$)			
				Low	High	2025	2050	2075	2100
SCS	2021	3.750	0.41			0	8	8	8
EW (at 10 t ha^{-1})	2035	3.750	11.28	2.56	39.46	0	25	155	397
BC (low LUC)	2021	0.550	2.32	−8.78	−3.51	2	49	92	93
BC (high LUC)	2021	1.000	4.22	−15.97	−6.39	2	59	149	169
BECCS (low LUC)	2030	0.550	6.05	−17.69	3.99	0	75	226	377
BECCS (high LUC)	2030	1.000	11.00	−32.17	7.25	0	76	328	603
AF (low LUC)	2021	0.550	6.86			6	126	137	137
AF (high LUC)	2021	1.000	12.47			6	153	249	249

LUC, land use change.

3.3 Discussion

We have presented an assessment and illustrative pathways for the deployment of NETs in Ireland. In the short to medium term (5–15 years), the most promising quantitative option appears to be AF, owing to its simplicity and technical maturity. However, effective CO_2 removal through AF depends critically on actually achieving a steadily increasing forest carbon stock, for example through a moratorium on harvest. As noted, such a moratorium would inhibit interim substitution of fossil energy use and/or fossil energy-intensive building products (steel, concrete) by potentially lower impact forest harvest. Furthermore, existing AF policy assumes economic support from harvest income and would have to be fundamentally re-evaluated under any harvest moratorium. Even under this condition, depending on land use commitment, AF removal is estimated to saturate at the order of 140–250 MtCO$_2$ removed, with saturation reached between 2050 and 2065. Whereas the assumed 20-year AF saturation time is probably an underestimate, the CO_2 removal flow rate of 12 tCO$_2$ ha^{-1} y^{-1} is probably an overestimate (see Bateman and Lovett, 2000; CCAC, 2019). The most critical constraints on AF removals are therefore the feasible deployment rate and maximum total land area that can be afforested within social, political and economic constraints, as well as the resilience of the forest to possible negative impacts of climate change (particularly water stress during droughts), attacks by diseases, storm damage and forest fires. A prudent estimate of practically achievable total indigenous AF removal is therefore probably significantly less than 100 MtCO$_2$. Even this would be very vulnerable to rerelease, either through harvest or natural loss

(particularly under climatic stress). Accordingly, it appears that AF is best viewed as a short-term CO_2 removal "triage" measure with a clear strategic objective for the removed carbon to be transferred to secure, long-term geological storage as soon as possible, most probably through early deployment of BECCS.

In the longer term, BECCS (combined with indigenous bioenergy crop cultivation) currently appears to offer the best prospect of large-scale indigenous CO_2 removal with secure long-term storage. It has the additional possible benefit of providing net energy output, potentially in the form of dispatchable electricity and/or storable non-carbon chemical fuels (H$_2$, NH$_3$), which could substantially complement indigenous variable (non-dispatchable) renewable energy sources (primarily wind and solar). The illustrative pathway indicates a BECCS cumulative removal potential of 400–600 MtCO$_2$ by 2100. However, it should be emphasised that this is an estimated technical potential only. It is premised on extremely ambitious, early, rapid and sustained deployment of BECCS infrastructure (including CO_2 geo-storage), rapid and sustained land use change to bioenergy cultivation and, ultimately, large-scale land use reallocation. Furthermore, the potential interactions of BECCS with other NETs and non-BECCS uses of bioenergy remain complex and difficult to anticipate (Butnar *et al*., 2019). Thus, at this point, although early BECCS deployment may usefully be made a significant policy priority, a prudent estimate of the cumulative removal potential, on relevant policy timescales, is probably significantly less than 200 MtCO$_2$. Note that this is not *in addition* to the AF potential, as AF and (other)

bioenergy cultivation ultimately compete for the same land use and AF carbon storage is impermanent; thus, AF carbon ultimately needs to be transferred to secure geo-storage (via BECCS or otherwise).

Based on the methodology and specific parameter estimates of Smith *et al*. (2016), the potential contributions of SCS and BC (even with very ambitious deployment) appear less promising than those of AF and BECCS; however, given the relative maturity of these techniques, their relatively low estimated costs (indeed, perhaps zero or negative – theoretically requiring no economic incentive) and the potential for other co-benefits (improved soil quality, reduced agricultural inputs), there is clear merit in also including these in the policy mix. A relevant consideration here is the recent advice from the CCAC that agroforestry deployment should be actively considered in Ireland (CCAC, 2019, pp. 119–120). This potentially overcomes some disadvantages of conventional commercial (intensive monocrop) AF. Although the expected CO_2 removal rate of agroforestry cited by the CCAC is significantly less than assumed previously for conventional AF (*c.*$7\,tCO_2\,ha^{-1}y^{-1}$ vs $12\,tCO_2\,ha^{-1}y^{-1}$), unlike AF, it can be effectively combined with other complementary land use. A particular possibility may be to combine it with bioenergy crop cultivation, potentially contributing to both improved SCS and a BC pathway. This might conceivably allow early synergistic combination of agroforestry-based AF, BC and SCS for short- to medium-term CO_2 removal and storage (pending the progressive – and uncertain – deployment of BECCS). This could also have some localised energy supply benefits (primarily heat energy in BC production). Although such integrative possibilities should certainly be the subject of further research and pilot implementation, there is no current basis to suppose that such a combination would significantly increase the overall practical potential for cumulative CO_2 removal and storage as compared with conventional AF alone.

While the technical potential of EW is shown as being approximately comparable with that of BECCS, this again relies on an extremely ambitious deployment rate and scale and, more critically, would require very substantial net energy input – which would have to come from extremely low CO_2 sources and would necessarily compete with other societal energy needs. Although the DACCS potential has not been quantitatively modelled here (as it is not constrained

by indigenous land use as such), it would similarly require large-scale, very low CO_2 energy inputs and would additionally compete with BECCS (and FFCCS, if deployed) for CO_2 geo-storage capacity. Thus, while both EW and DACCS will bear continuing research- and perhaps pilot-scale deployments, it would not be prudent at this time to assume large-scale contributions to cumulative CO_2 removal from either of these.

3.4   Conclusion

In conclusion, we find that a current prudent assessment of cumulative indigenous CO_2 removal potential for Ireland, across the full portfolio of NETs considered, would be significantly less than $200\,MtCO_2$ and even this would require urgent and disruptive new policy measures to bring it about on a timely basis. This assessment is preliminary and it is recommended that a programme of continuing research should be sustained to allow ongoing refinement and updating of estimates of CO_2 removal potential in the light of improvements in both underlying scientific understanding and deployment experience. Nonetheless, in the current state of knowledge, this assessment can be directly compared with the analysis presented in Chapter 2, indicating, on the basis of current plans and policies, a minimum overshoot of Ireland's prudent, Paris Agreement-aligned, "fair share" CO_2 emission quota by as much as $600\,MtCO_2$ as early as 2050. The difference between these (> $400\,MtCO_2$) is a quantitative indication of the gap, in mitigation scale and speed, between even the most ambitious interpretation of current national policy and the internationally agreed temperature goals of the Paris Agreement. This implies that, even assuming "anticipatory reliance" on NETs for future CO_2 removals, it is still the case that much deeper, near-term reductions in gross CO_2 emissions are required than are considered under current policy parameters. In particular, pending successful large-scale deployment of NETs, it is recommended that a prudent ceiling on the accumulation of CO_2 debt would be *c.*$200\,MtCO_2$. Based on the analysis and methodology of Chapter 2, conforming with such a ceiling would imply the achievement of national net-zero territorial CO_2 emissions by about 2035–2040, i.e. much earlier than the currently "most ambitious" net-zero target of about 2050.

4   Negative Emission Technologies and Irish Energy System Decarbonisation

4.1   Introduction

Chapter 2 reported a prudent, "fair share" CO_2 quota for Ireland as *c*.400 MtCO$_2$ from 2015. It identified that, under even an optimistic assessment of current policy objectives, there is likely to be net overshoot of this of *c*.600 MtCO$_2$ before CO_2 net emissions are brought to zero, not earlier than 2050 under the current Climate Action Plan 2019. Chapter 3, conversely, presented a preliminary assessment of the cumulative future potential of territorial NCTs (removal of CO_2 from the atmosphere to some form of storage) as possible measures both to contribute to the achievement of national net-zero CO_2 emissions in the first instance and subsequently net negative to putatively correct the quota overshoot. This found a technical upper limit of cumulative gross removals of *c*.600 MtCO$_2$ to the year 2100 and recommended that, on a prudential basis, the practical (social, political, economic) limit should currently be assumed to be no more than 200 MtCO$_2$. On account of the cumulative nature of CO_2 as a stock pollutant, any policy-system delay in recognising and addressing this mismatch progressively increases the risk of mitigation policy failure. At face value*,* this mismatch between projected CO_2 quota overshoot and removal potential therefore represents a fundamental challenge to effective national climate mitigation action.

Given that, on the one hand, the energy system is a dominant contributor to current territorial CO_2 emissions and that, on the other hand, multiple NETs would interact strongly with the energy system (positively or negatively); this element of the IE-NETS project focused on a more detailed (although still relatively schematic) understanding of these interactions. This involved a small-scale, desk-based study aimed at giving a preliminary view of energy system modelling alternatives that address the potential need for and role of NETs under a Paris Agreement-aligned NCQ constraint. This addresses multiple key interactions with the energy system, including continuing gross emissions of CO_2 from fossil energy use, potential contributions to the energy supply from bioenergy sources with much

lower or even negative CO_2 emissions (via BECCS) and potential additional demand for energy to drive additional technological CO_2 removals at large scale (via DACCS, EW). A fully detailed report of the results has been released as an open-access White Paper (McMullin and Price, 2019). In this chapter we briefly summarise the modelling approaches and the corresponding conclusions presented in that full White Paper.

4.2   Irish Energy System Modelling Context

Many diverse modelling approaches and tools are appropriate in different research and policy contexts. Pfenninger *et al.* (2014) provide a helpful taxonomy and classification. The general issues and challenges in applying modelling tools in policy evaluation are critically discussed by Horschig and Thrän (2017).

Previous policy-relevant modelling of energy system change in Ireland has, to date, been primarily based on "top-down" economic cost and growth assumptions and sectoral energy demand projections linked with either prescribed or open (bottom-up) mitigation measures. In short- to medium-term modelling by the SEAI and EPA, exemplified by the Draft National Energy and Climate Plan (DCCAE, 2018), energy supply, demand and emissions projections are framed by macro-economic analysis (including projections of fossil fuel and carbon pricing, and population change) and a portfolio of potential mitigation policy measures. Separately, more general (and typically longer time horizon) modelling, such as that reported by Deane *et al*. (2013), uses the "bottom-up", technology-rich, Irish TIMES proprietary energy system modelling platform (Ó Gallachóir *et al*., 2012). This typically takes long-term economic growth, energy demand and energy technology cost and maturity assumptions as exogenous inputs and imposes other additional constraints such as CO_2 emissions (point in time or pathways over time). With technical assumptions of linearity in the key relationships, this can be framed as a linear programming optimisation problem and algorithmically "solved" to yield least (notional) cost

energy system transition pathways. Although this approach has some undoubted strengths, it also has significant limitations. In particular, energy demand is derived from exogenous inputs of extremely uncertain economic projections (Millner and McDermott, 2016) based on general or partial equilibrium modelling (Pollitt and Mercure, 2017) and often on unrealistic "first best" policy choices (Strachan and Usher, 2012). Furthermore, within such a complex technology-rich model, each technology and fuel projection has itself very large cost and development uncertainties over the time horizons being studied (Stern, 2017).

In the light of these considerations, it became clear that there may be a specific value in complementary, coarse-grained modelling that is just sufficiently detailed to represent energy system transitions meaningfully while still being simple enough to provide useful high-level information on long-term energy and climate strategy to inform policymakers and the public. Tools that are more accessible to a wider range of users, with assumptions that are made as transparent as possible, could be particularly useful for energy and climate assessments by high-level policy advisors, such as the CCAC, in educational settings and in deliberative democracy exercises, as in Ireland's use of the Citizens' Assembly model (CA-IE, 2018). The focus was therefore on using, evaluating and producing coarse-grained energy system modelling that is publicly available and, ideally, open source and useful for informing long-term energy and climate strategy for Ireland relevant to Paris Agreement-aligned climate action. That said, of course, it must be clearly acknowledged that such coarse-grained modelling is subject to its own characteristic limitations. At best, it can provide a heuristic, high-level view of potential policy interactions and constraints, which can be useful to inform avenues for much more detailed analysis; at worst, it may yield simplistic or positively misleading policy prescriptions. It is certainly not a replacement for, and should not be relied upon in isolation from, other modelling approaches.

Note that the detailed work presented in this chapter used a reference NCQ for Ireland of 371 $MtCO_2$ from 2015, whereas Chapter 2 estimated the prudent, "fair share", Paris Agreement-aligned NCQ at *c.*391 $MtCO_2$ from 2015. This difference reflects an update to the

quota estimate during the course of the project, arising from the release of the IPCC SR15 (IPCC, 2018); however, it does not materially alter the conclusions in this chapter.

4.3 Coarse-grained Modelling of Irish Energy System Decarbonisation

4.3.1 EnergyPLAN and the "Green Plan Ireland"

The EnergyPLAN modelling tool was developed at Aalborg University, Denmark. It may be used free of charge and is distributed in executable form for Microsoft Windows platforms only (closed source).[13] It is an "energy balance" tool only. Given an energy system configuration (supply sources, conversions, etc.) and demand profile time series (hourly resolution), it determines a specific dynamic operation of that system, over time, to meet that demand profile. Assuming that that can be done at all then, in general, EnergyPLAN determines an "optimal" solution, accounting for cost, jobs created and national balance of payments. It enables manual development and analysis of a sequence of energy system transition steps generally oriented towards a 100% renewable final energy system. The tool is well documented (Lund, 2017), includes a technology cost database (Connolly, 2015) and is supported by extensive training materials.

EnergyPLAN has been already applied to model one potential 100% renewable energy transition pathway specifically for Ireland (Connolly and Mathiesen, 2014). This is presented as a sequence of seven successive transition "steps" (distinct configurations of the Irish energy system), achieving effectively net-zero annual CO_2 emissions at the final step. Supplementary materials, including the applicable EnergyPLAN input and output data files, have been released via the Green Plan Ireland website.[14]

This transition pathway notionally extends from 2015 to 2050, but, as published, does not stipulate a specific duration for each step, nor the specific annual CO_2 emissions rates associated with each step. Furthermore, EnergyPLAN itself has no in-built support for assessing cumulative CO_2 emissions

---

13 https://www.energyplan.eu/ (accessed 20 July 2020).

14 http://dconnolly.net/greenplanireland/ (accessed 20 July 2020).

across a complete transition pathway. Accordingly, within the scope of the IE-NETs project, additional development work was carried out firstly to reproduce the results of Connolly and Mathiesen (2014) and then to derive pathways of annual CO_2 emission rates and corresponding cumulative emissions, assuming (by default) equal, 5-year durations for each of the transition steps. The outputs are summarised in

Figure 4.1 and Figure 4.2 (including a minor correction accounting for electrofuel import/export effects).[15] Although this clearly represents an ambitious and substantive energy decarbonisation pathway, cumulative emissions still overshoot the estimated NCQ by *c.*500 $MtCO_2$ (exclusive of land use CO_2 emissions). This would be an improvement (of about 100 $MtCO_2$) on the outline assessment of the Climate
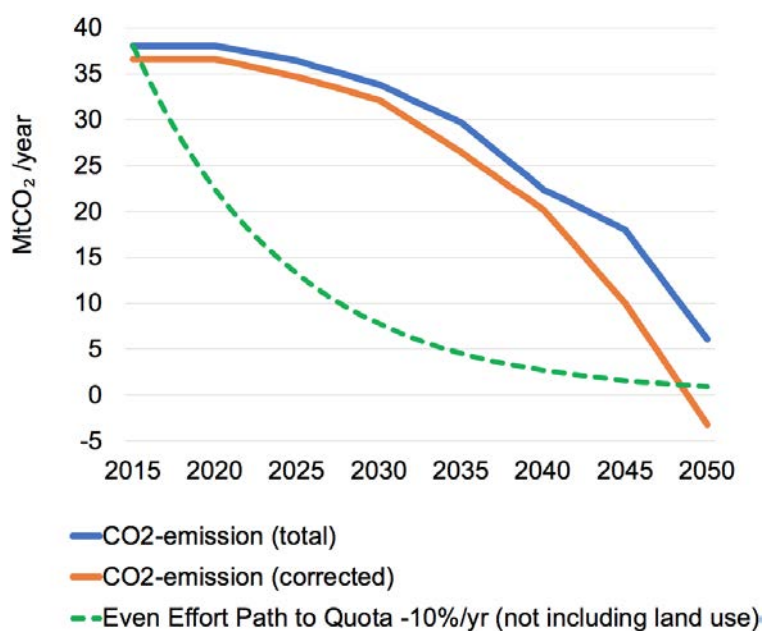

Figure 4.1. Annual CO_2 emissions (derived from Connolly and Mathiesen, 2014).
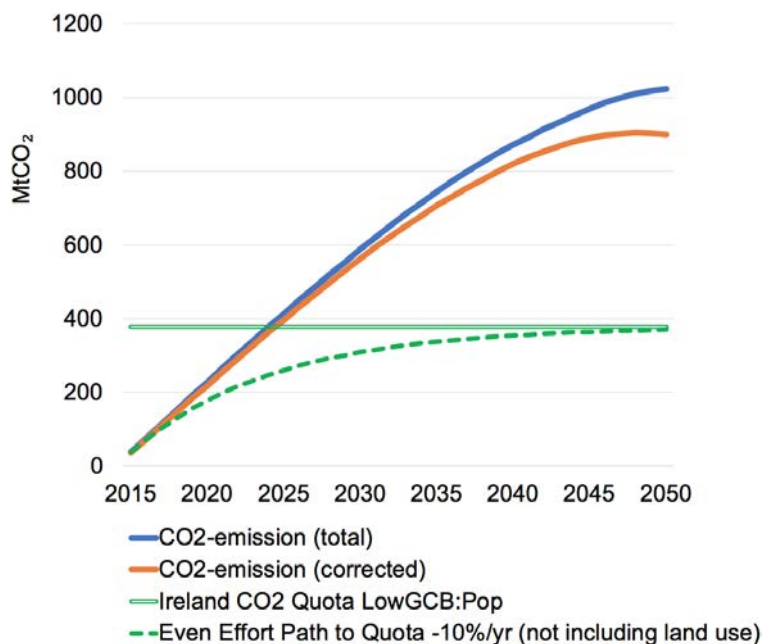

Figure 4.2. Cumulative CO_2 emissions (derived from Connolly and Mathiesen, 2014).

15 Detailed IE-NETs spreadsheet (.xlsx) released under open licence. Available online: http://tinyurl.com/Green-Plan-5yr-Steps-xls-DL (accessed 20 July 2020).

Action Plan 2019 (see Chapter 2) but still represents over twice the scale of CO_2-quota overshoot that might prudently be expected to be subsequently feasible to reverse via indigenous NETs deployment (Chapter 3).

Of course, it is possible that the Green Plan Ireland steps, as defined, could be planned to overlap in time and/or begin much earlier in terms of investment and achievement to yield a decarbonisation pathway that accumulates a significantly smaller quota overshoot. Critically, though, it is the final two pathway steps – relying heavily on synthetic chemical fuel production from variable renewable electricity – that have the largest effect on total energy system emissions. This suggests that, in parallel with complete achievement of the other key steps, early investment in research, development and capacity building for synthetic fuel production and distribution – including planning additional wind and solar electricity generation to provide the required very-low-carbon energy – might need to be a critical focus for mitigation planning. The Green Plan also uses a default assumption of constant energy demand at 2015 levels; near-term measures that achieve early and sustained reductions in absolute energy demand would therefore also greatly assist. Energy efficiency may help here, but only if carbon pricing or supply regulation is sufficient to eliminate rebound effects owing to spending of cost savings. Immediate phase-out of the most carbon-intensive fossil fuels in electricity production (peat and coal) would also provide an important early benefit.

4.3.2   Anthem: a novel fossil-energy supply model

It is clear that the key driver of CO_2 emissions from the energy system is the use of carbon-based chemical fuels (fossil or bioenergy). Although this is incorporated in all practical energy system modelling, it was found within the IE-NETs project that there may be value in a standalone tool that focuses solely on the primary energy requirement for such carbon-based fuels. A dedicated, high-level modelling tool was accordingly developed for this purpose. The tool is called Anthem. It is spreadsheet based and has been released under open licensing as part of the project data products.[16] It is a primary energy supply scenario tool showing net CO_2 emissions to the atmosphere, in terms of

gross emissions minus gross removals, and net CO_2 geological storage requirement for CCS, if any, comprising CO_2 stored from fossil fuel combustion or industrial processes and CO_2 stored from CO_2 removal via NETs such as BECCS or DACCS. It also calculates corresponding cumulative CO_2 emissions. Anthem thus allows rapid development and comparison of alternative primary energy supply scenarios, with or without CCS and NETs. Anthem was specifically applied to assess how much primary energy from unabated fossil fuel (FF) and bioenergy fuel (BE) could be available while meeting Ireland's "fair share" NCQ. This is briefly illustrated here with the outputs from a baseline (minimal mitigation) scenario and four representative decarbonisation scenarios. The decarbonisation scenarios are subject to a common constraint to meet the estimated Paris Agreement-aligned NCQ (cumulative net-zero CO_2, compared with NCQ, no later than 2100). Key output data are shown in Figure 4.3.

All scenarios cover the period 2015–2100, with actual input energy data used for 2015 and 2016 and projected energy input data used for 2017–2019. Scenarios diverge from 2020 onwards. Bioenergy use rises to a maximum indigenous level of about 42 GWh projected for 2050. Bioenergy CO_2 production (pre CCS, if any) is exactly matched by a bioenergy CO_2 removal credit (reflecting the associated removal of CO_2 from the atmosphere in the original growth of the bioenergy feedstock). Any applied CCS is assumed to have a 95% capture rate with an energy penalty of 20%. The scenarios differ as follows:

- Flatline-2020-Oil-Gas: this is a baseline, minimal mitigation scenario. It simply assumes that oil and gas use separately flatline at their projected 2020 levels but that coal and peat are phased out early (by 2020).
- No-Overshoot-No-CCS: no transient overshoot of the NCQ and no CCS deployed. This implies extremely deep and rapid cuts in fossil fuel use and industrial process emissions.
- No-Overshoot-CCS: no transient overshoot of the NCQ but CCS assumed, affecting 50% of fuel use from 2030 and rising to 65% by 2050. Again, extremely deep and rapid cuts in fossil fuel use and industrial process emissions are still inevitably required to avoid overshoot.

---

16 https://tinyurl.com/IENETS-WP4-Anthem-Scenarios (Google Drive link; accessed 20 July 2020).
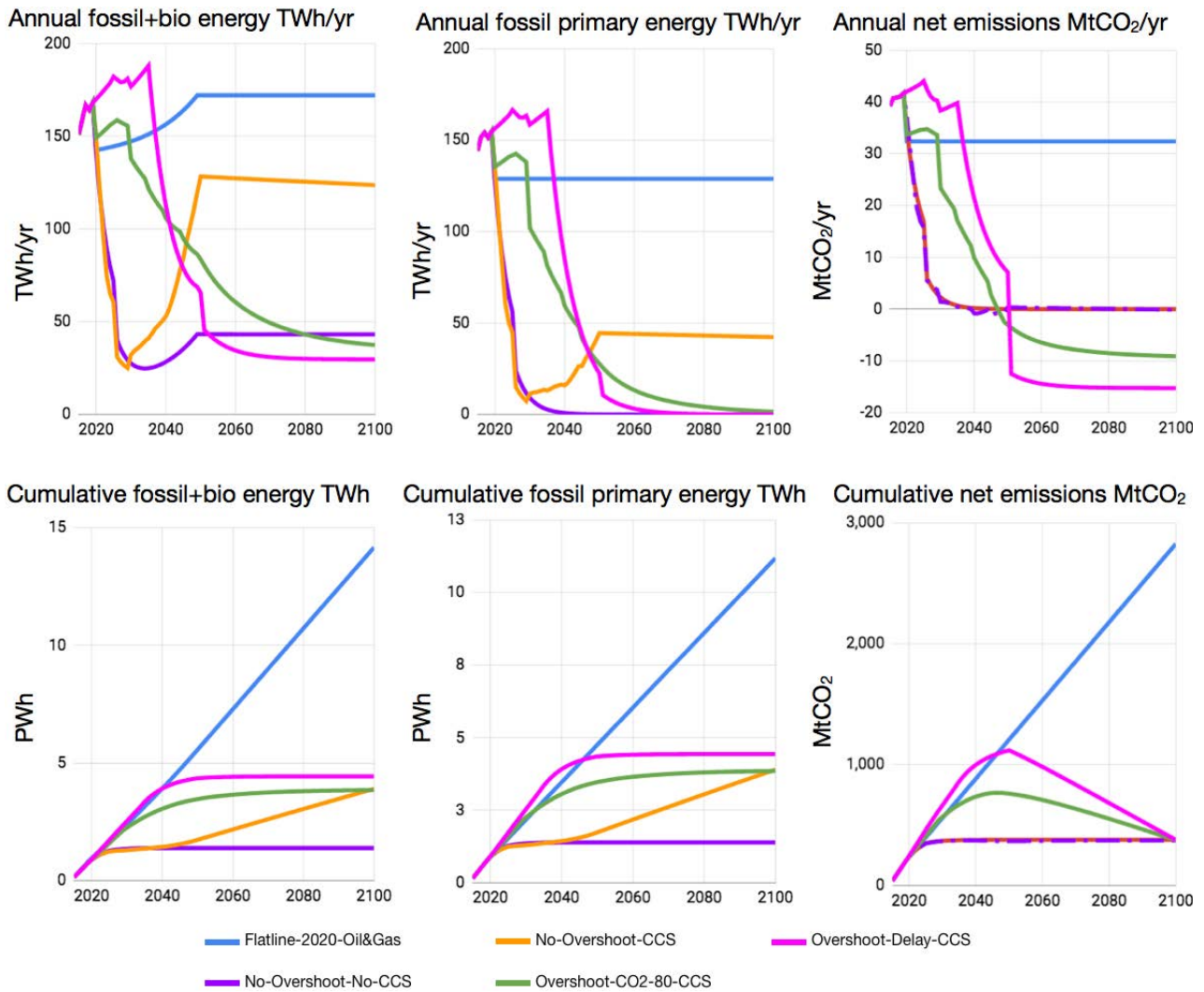
Figure 4.3. Summary output from five example Anthem scenarios.

- Overshoot-CO$_2$-80-CCS: fossil fuel usage and gross emissions are adjusted so that total energy available follows the fossil fuel energy pathway shown (up to 2050) in Ireland's first National Mitigation Plan (Deane *et al.*, 2013). This implies substantial NCQ overshoot, peaking at about 350 MtCO$_2$, that must then be reversed by 2100.
- Overshoot-Delay-CCS: fossil fuel usage and related emissions continue to 2035 in line with EPA "with existing measures" projections and then follow a linear pathway to meet a point-in-time target of an 80% reduction by 2050 relative to 1990. CCS is assumed to be available only from 2050 onwards but is applied to ~100% of all carbon-based fuel use from that time. The delayed action in this case inevitably implies much greater NCQ overshoot, now peaking at about 700 MtCO$_2$, which must still be reversed by 2100.

These example Anthem scenarios starkly illustrate the increasingly difficult near-term carbon-based energy choices now facing Irish society. Anthem usefully allows fast estimation of the carbon-based primary energy (unabated or abated) available to society and the quantity of CO$_2$ removal required for scenarios constrained by an appropriately specified NCQ. This enables exploration of the (highly constrained) range of alternatives that might be considered for more detailed cost-effectiveness analysis. By definition, scenarios that do not fully reverse NCQ overshoot by a specified date, or that do not account for the full cost of CO$_2$ removal to do so, would not meet the "cost-effective" criterion. That said, it is important to emphasise that Anthem itself is neither intended to, nor is capable of, assessing the wider societal implications of specific emissions scenarios.

Note that once the NCQ is exhausted all further fossil fuel energy use (unabated or with CCS) requires corresponding CO_2 removal to remove all of the emitted CO_2. That is, gross removals essentially license a corresponding additional amount of unabated fossil fuel energy or a significantly greater amount of FFCCS energy. The relationship of available FFCCS energy to remaining CO_2 quota is very sensitive to the fraction of combustion CO_2 captured in the specific FFCCS process. If it were possible for the FFCCS capture ratio to reach 100% (while still delivering some net energy output, despite the likely very high energy penalty of such a capture rate) then the specific emissions constraint on FFCCS energy availability would disappear. Of course, other factors, such as extra-territorial upstream emissions in fossil fuel production and transport, fossil fuel resource depletion and pricing and security of supply risk, would then still limit fossil fuel supply differently, but outside the scope of the current analysis. Somewhat more realistically, if the FFCCS capture ratio could be feasibly increased (even while still falling short of 100%), then the FFCCS energy supply "bonus" or "multiplier" for each unit of CO_2 removals achieved would get larger (ultimately tending towards infinity only if the capture ratio could reach 100%). However, even this possibility may be overridden by economic or physical constraints on cumulative CO_2 geo-storage. Therefore, a more critical parameter for distinguishing scenarios might well be the system-wide CO_2 capture ratio, i.e. the extent to which direct fossil fuel use can be limited to circumstances where CCS is technically feasible – essentially large-scale point-source plants: electricity generation, large-scale/high-temperature industrial heating or possibly H_2 production through steam CH_4 reforming (with zero emissions from downstream, distributed/small-scale H_2 use).

As shown by the No-Overshoot-No-CCS scenario, only immediate and severe restrictions on unabated fossil fuel supply and process cement emissions could completely avoid NCQ overshoot at this point. The No-Overshoot-CCS scenario would still require similarly severe restrictions on near-term carbon-based energy availability and assumes an improbable early delivery of CCS at scale, for both BECCS and FFCCS, to forestall overshoot while still allowing later recovery

of a relatively high level of abated carbon-based energy. In these two, now-implausible "no overshoot" scenarios Anthem shows a severe (probably socio-politically intolerable) "trough" in carbon-based primary energy availability. Conversely, more or less delayed action to reduce gross CO_2 emissions, as illustrated in the two overshoot scenarios, allows somewhat greater near-term carbon-based energy availability, avoiding a discrete supply trough, but still implying unprecedentedly rapid and deep reductions in carbon-based energy supply coupled with reliance on future cumulative CO_2 removal, which is then significantly in excess of the prudent indigenous potential assessed in Chapter 3.

4.3.3 *Ireland 2050 energy pathways calculator*

Ireland 2050[17] (IE2050) is an open-source spreadsheet and set of associated web applications developed by the Irish branch of the Energy Institute,[18] derived from the UK-based Department of Energy and Climate Change (DECC) 2050 Pathways Calculator and spreadsheet (DECC, 2010). Its purpose is to allow a diversity of users, from ordinary citizens to energy professionals and policymakers, to explore a wide variety of options for achieving deep decarbonisation of the Irish energy system. The Irish energy balance and mix for 2013 is the reference basis. Modelling is structured through a set of "ambition levers", typically having four discrete levels, with each lever representing a distinct sector or aspect of energy supply or demand. Based on the lever settings, a specific pathway is generated for the evolution of the overall energy system for the period 2015–2050, with distinct configurations at 5-year intervals. The model will attempt to balance supply and demand on an annual basis only. In the electricity sector any excess annual generation (after buffering via energy storage systems with a maximum capacity of 70 GWh) is assumed to be exported; conversely, any shortfall is assumed to be met by additional unabated fossil gas generation. Within the IE-NETs project, the Excel workbook version of IE2050[19] was extended to show annual and cumulative CO_2 emissions outputs for better comparison with the EnergyPLAN and Anthem

---

17 http://ireland2050.ie/ (accessed 20 July 2020).

18 http://www.energyinst.org/ei-near-me/republic-of-ireland (accessed 20 July 2020).

19 http://calculator.ireland2050.ie/assets/excel/model.xlsx (accessed 20 July 2020).

results. Fixed assumptions in IE2050 include growth at fixed rates in GDP, population and building stocks.

On the supply side, IE2050 provides levers for electricity generation and bioenergy. Under electricity generation, the levers are for nuclear power stations, CCS penetration (of fossil fuel or bioenergy combustion plants), wind (offshore, onshore and small-scale), wave, tidal, solar, hydroelectric and bioenergy in electricity generation and electricity imports. For overall bioenergy supply, import choices range from 0 to 24 TWh y^{-1} in 2050. Indigenous bioenergy supply depends on the land area dedicated to bioenergy (relative to livestock), waste availability and potential for producing energy from algae. CCS-enabled electricity generation can be enabled up to a maximum of 15 TWh y^{-1}. The CCS power station fuel mix presents options ranging between 100% solid fuel (coal and biomass) and 100% gas fuel (fossil gas and biomethane), the proportion of fossil and bioenergy fuels being dependent on the amount of indigenous bioenergy fuel available. For use here, a separate data table was created to estimate the CO_2 removal owing to BECCS removals on the basis of available CCS and bioenergy fuel types. Separately, DACCS ("geosequestration" in IE2050) presents ambition levels from zero up to storage of 5.4 MtCO$_2$ y^{-1}.

Demand-side mitigation options in IE2050 are grouped as transport, households and business. In maximum ambition (level 4) for domestic transport by 2050, there is a 1% increase in total passenger km, modal share for passenger cars decreases from 83% to 70% of total passenger km, all cars are electric (battery or fuel cell) and domestic freight increases by 40% (rather than by 89% as for level 1). In international aviation, for level 1 passenger load increases by 150%, with 55% more fuel use by 2050, whereas for level 4 there is a 30% increase in passenger numbers, with a 20% decrease in fuel use overall. Residential heating maximum ambition by 2050 includes smart meter rollout enabling a 9% reduction in electricity demand, 80% of homes with an A–B2 building energy rating (BER), 70% of homes with heat pumps and significant bioenergy and district heating from thermal power stations. A particularly notable maximum ambition demand lever assumes Irish industrial output falls by 30–40% by 2050, combined with 66% supply electrification and significant reductions in process emissions. In commercial energy demand, for highest ambition by 2050, space heating demand reduces by 25%, hot water demand reduces by 10%, cooling

demand reduces by 60%, lighting demand reduces by 25% and commercial cooking energy demand reduces by 25%.

Although nominally open source, extending IE2050 proved very difficult on account of the workbook's complexity and relative opacity in operation. This limits the model's applicability for the current purposes in various ways. IE2050 was designed to target a point-in-time aggregate GHG (CO$_2$e/GWP$_{100}$) reduction (up to 80% by 2050 relative to 1990). By contrast, the IE-NETs project is particularly focused on limiting cumulative future CO_2 emissions within a Paris Agreement-aligned CO_2-only NCQ over the full period of the required decarbonisation transition. This requires reaching at least net-zero annual emissions and potentially net-negative emissions if a temporary NCQ overshoot has to be reversed. Some relative cost calculations are presented in the web application version of IE2050 but are not included in the worksheet version. Accordingly, it did not prove possible to interrogate or analyse these notional cost comparisons in a systematic or robust way. IE2050, as distributed, does not support exploration of pathways extending beyond 2050. The presentation of data and charts by IE2050 is useful but lacks the detail relevant to scenarios with high penetration of variable-renewable and/or BECCS energy sources. In particular, all excess wind, solar or bioenergy is automatically assigned to export without the option of storing the energy in Ireland for near- or medium-term future use to displace continuing higher emissions from fossil fuel use. Separately, Barton *et al.* (2017) find that the requirements of system flexibility and energy storage (including seasonally) to support continuous real-time grid balancing involving increased renewables penetration are considerably underestimated by the UK DECC 2050 Calculator and therefore, presumably, in IE2050 as well.

Regarding high-ambition trajectories, the IE2050 guidance notes remark that "it is also important to bear in mind that the 'level 4' (L4) trajectories represent heroic levels of effort or change" (Energy Institute, 2014, p. 2). However, this appears questionable in several L4 cases. Compared with published estimates, wind energy potential appears to be underestimated and bioenergy potential appears to be overestimated. Maximum ambition wind energy capacity by 2050 is given as 45 TWh y^{-1} (onshore and offshore). This falls well below the SEAI (2011) estimate of at least 140 TWh y^{-1}. This may be

because large-scale electro-fuel production is not included in IE2050 options, thereby likely discounting this potential synergy, so that an underestimate of maximum wind energy potential does not materially change the degree of indigenous energy system decarbonisation. In contrast, bioenergy is effectively favoured by assuming an indigenous bioenergy resource of 63 TWh y^{-1}, in addition to 17 TWh y^{-1} from waste biomass, which is substantially larger than the 44 TWh y^{-1} projected by Deane *et al.* (2013). Moreover, large-scale bioenergy imports, up to 24 TWh y^{-1} for L4, are allowed in IE2050, compared with the EnergyPLAN outlook and IE-NETs literature review conclusion that bioenergy availability in deep decarbonisation scenarios (unlike wind and solar energy) should be assessed on a precautionary basis and generally limited to lower estimates of indigenous potential, given sustainability and land use issues, and international factors including climate justice. For these reasons, in the work reported here, L4 wind energy was adjusted to the SEAI level and bioenergy levers were reduced to L3 for land dedicated to indigenous bioenergy production and to L1 for bioenergy imports.

We briefly summarise here two specific high-ambition mitigation scenarios investigated with IE2050:

- As-Supplied: predominantly using the L4 trajectories as supplied;
- Enhanced-Action: some L4 trajectories modified internally to increase ambition by specifying earlier or deeper actions.

The resulting annual and cumulative emissions for both scenarios are shown in Figure 4.4. Both scenarios overshoot the target NCQ but the earlier and deeper mitigation action in Enhanced-Action accumulates about 85 MtCO$_2$ lower emissions to 2050 than As-Supplied. Both scenarios achieve net-negative annual CO$_2$ emissions shortly before 2050, enabling the cumulative emissions curves to flatten out and begin to reverse the NCQ overshoot. The peak overshoot of 100–200 MtCO$_2$ is comparable to the recommended prudent ceiling, based on assessed Irish NETs potential presented in Chapter 3. This suggests that, of the various modelling approaches and modelled scenarios investigated in the IE-NETs project, these IE2050-based scenarios probably provide the most promising immediate basis for further Paris Agreement-aligned, coarse-grained energy system policy research.
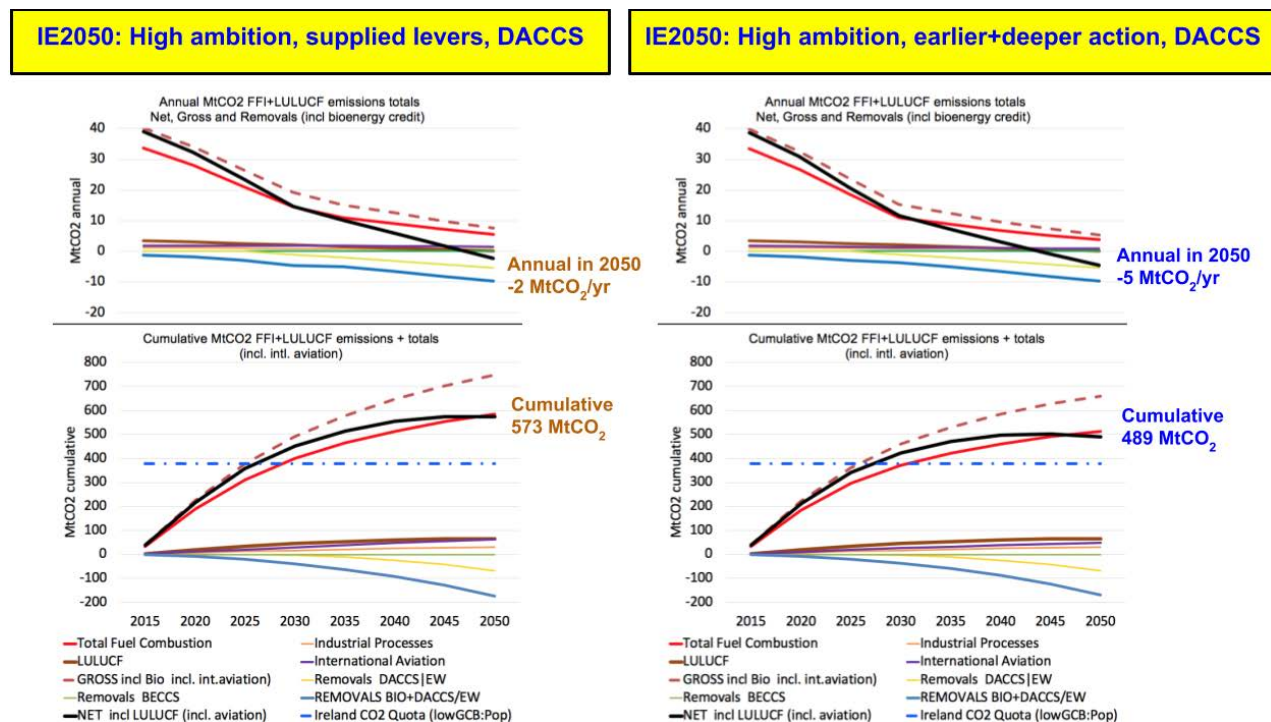

Figure 4.4. CO$_2$ trajectory comparison between the selected high-ambition scenarios: As-Supplied (left) and Enhanced-Action (right). For each scenario, annual CO$_2$ emissions are shown above and cumulative CO$_2$ below.

4.4   Conclusion

Given the near certainty that CO_2 emissions from Ireland's energy usage will now lead to overshoot of the estimated prudent "fair share" Paris Agreement-aligned NCQ, development of future Irish energy system emission pathways will need to include an assessment of the costs and risks due to dependence on negative emissions to return to the NCQ level of cumulative emissions within a very few decades. This is taken here to be by 2100 at the latest, although such an extended duration of quota overshoot would probably represent an unacceptably high risk if replicated at a global level. It is arguable that limiting and assessing the likely level and duration of national quota overshoot, and the consequent amount of new, quasi-permanent carbon storage that may be required, is now essential for effective preparation of EU Member State National Energy and Climate Plans that "contribute to fulfilling the [temperature] objective of the Paris Agreement" (EU, 2018b, Article 15.3b).

This chapter summarised the IE-NETs investigation of coarse-grained modelling options for Paris Agreement-aligned energy system decarbonisation, including the potential roles of CO_2 quota overshoot and NETs. The outputs from such coarse-grained modelling are not comprehensive and all quantified results presented should be treated with due caution as outputs that are indicative only of the overall mitigation outcomes of the particular scenarios. Furthermore, it must be borne in mind that there are smaller, but still significant, additional emissions of CO_2 from processes outside the immediate boundary of the energy system (particularly land use, including drainage of peatlands, and cement manufacture). Nonetheless, the modelling outputs clearly indicate serious CO_2 commitment concerns and critical risks related to alternative scenarios and sketched the possibility space of energy system change constrained by a Paris Agreement-aligned carbon quota, with or without the use of CCS or NETs.

The strong effect of CCS on primary energy options is evident – both in limiting fossil carbon combustion emissions and in enabling permanent CO_2 removal via BECCS and DACCS to limit and potentially reverse NCQ overshoot – as are the associated trade-offs in CCS energy penalty and requirements for large-scale infrastructure investment to capture and store such large amounts of CO_2. Incorporating the potential backstop economic costs of CCS options into decarbonisation analysis may well militate in favour of other mitigation options, such as near-term supply-side constraint (rationing, in effect) of fossil fuel energy to drive more rapid deployment of very low-carbon energy sources and active reductions in societal energy demand and/or early deployment of other NETs, including land carbon storage and EW. In conclusion, although feasibility, costs and trade-offs of NETs deployment remain very uncertain, in a context of de facto policy commitment to substantial NCQ overshoot, these issues are already critically important for effective evidence-based energy system policymaking.

Finally, although not part of the previous scenario analysis, it can be noted that, in principle, some additional mechanisms for meeting carbon quota constraints might be enabled through forms of international "emissions trading", ultimately including "quota trading" or trading of CO_2 removal services. In the case of Ireland, this potentially includes trading within the EU (such as currently codified via the EU ETS and/or the ESR for different categories of emissions) and possible future global arrangements that may be established under the terms of the Paris Agreement. However, as already outlined in section 2.2, given the severe constraint of the remaining GCB at a global level and the need to support global sustainable development, the practical scope for CO_2 quota trading appears likely to be extremely limited.

5 Modelled Yields, Life Cycle Assessment and Techno-economic Assessment of Bioenergy Crops in Ireland

5.1 Introduction

McGeever *et al*. (2019) concluded that a possible strategy for building CO_2 removal capacity in Ireland may be to maximise AR, with limited harvesting in the immediate term (perhaps until 2035), while supporting the parallel development of BECCS. This must be balanced carefully against interim substitution of direct fossil energy use and/or fossil energy-intensive building products (steel, concrete) by potentially lower impact forest harvest, and needs to be considered in a context of very significant overall forestry expansion. BECCS is already recognised at a global scale as one of the more plausible potential technological pathways to achieve net-negative emissions this century (IPCC, 2014b). Furthermore, BECCS is particularly relevant to Ireland given the potential to substitute indigenous bioenergy for imported fossil fuel energy, thus potentially enhancing energy security, balance of trade and employment in the green economy (assuming internationally competitive biomass production costs). However, it is unclear whether or not the possible indigenous bioenergy production capacity could be sufficient to achieve net-negative emissions after economically preferred allocation to displacement of direct fossil fuel use in heating and transport. Importation of bioenergy fuel to support BECCS operations in Ireland can also be considered, although this would forfeit the economic co-benefits of indigenous bioenergy production (security, employment, etc.). International trade and emission accounting rules (to reflect the implied territorial separation of atmospheric drawdown and long-term storage) are also currently unclear and potentially raise concerns about robust monitoring and verification of the emissions profile of bioenergy fuels, particularly including the potential effects of indirect land use change. Accordingly, assessment of maximum feasible indigenous bioenergy production and the environmental costs of this production is an essential component of assessing the potential for effective BECCS deployment in Ireland.

The three distinct goals associated with development of bioenergy feedstocks are (1) maximising the total amount of biomass produced per hectare per year, (2) maintaining sustainability while minimising inputs and (3) maximising the amount of fuel that can be produced per unit of biomass. The grand challenge for biomass production is to develop the so-called "second-generation" energy crops that have a suite of desirable physical and chemical traits that enable them to meet these goals. Furthermore, in order to reduce competition with food crops for land use it is likely that these crops will be grown on marginal land (Jones *et al*., 2015), defined as "an area where a cost-effective agricultural production is not possible, under given site conditions (e.g. soil productivity), cultivation techniques, agricultural policies as well as macro-economic and legal conditions".

The two second-generation crops found to be most suitable for Irish climatic conditions are the perennial rhizomatous grass *Miscanthus* and willow, managed as a short-rotation crop. Compared with long-established food crops, productivity trials of *Miscanthus* and willow are limited in number and extent. In introducing dedicated energy crops it is important to be able to forecast their productivity and stability under a wide range of different environments including changing climate. There is therefore a need to develop and parameterise crop models that can provide reliable predictions of carbon assimilation, growth and yield of second-generation energy crops in Ireland. Our aim was to use state-of-the-art mechanistic modelling to estimate realistic yields of *Miscanthus* and short-rotation forestry (willow) for Ireland.

Nair *et al*. (2012) carried out a survey of the literature and identified 14 models that have been used to simulate bioenergy crops. All of them simulate biomass production but only a small number simulate soil water, nutrient and carbon cycle dynamics and could be classified as ecosystem models. Robertson *et al*. (2015) identified a number of ecosystem models incorporating carbon cycle dynamics and in particular the soil carbon dynamics, parameterised for *Miscanthus* and/or willow. These were WIMOVAC (Miguez *et al*., 2009), BioCro (Miguez *et al*., 2012),

Agro-IBIS (Vanloocke *et al*., 2010), DayCent (Davis *et al*., 2009), DNDC (Gopalakrishnan *et al*., 2012) and MISCANMOD (Stampfl *et al*., 2007). Of these models, WIMOVAC, BioCro, Agro-IBIS and MISCANMOD were originally created to simulate biomass production but subsequently had soil carbon transformations incorporated in their simulations. Conversely, DayCent and DNDC were originally designed to simulate below-ground nutrient cycling but subsequently more complex plant growth routines were incorporated. The justification for the requirement of the models to simulate carbon dynamics was because assuring the commercial viability of a bioenergy plantation and assessing its impacts on GHG emissions are essential before a landowner can decide whether or not to establish them at the expense of other income-generating land uses. A review of the six process-based crop models found that they differed in their design, computational power and spatial scale but none was vastly superior and the main differences were their ability to deal with the specific research questions they were designed for.

Bioenergy technologies are diverse and span a wide range of options and technological pathways. However, the most favoured options and technologies will be those with the lowest life cycle emissions. Evidence suggests that options with low life cycle emissions are site specific and rely on efficient integrated "biomass to bioenergy" systems with sustainable land use management and governances. LCAs are aimed at minimising the environmental impacts of emissions and resource depletion associated with the process of bioenergy production (Davis *et al*., 2009). Conducting a full LCA for bioenergy production is therefore important for determining the authentic environmental benefits of cultivating bioenergy crops.

Life cycle assessment is a complex tool that lies at the interface between science, engineering and policy. Transparent and accountable LCAs provide a scientific foundation for evaluating the ecological and economic sustainability of bioenergy fuels. This holistic view of bioenergy fuels is necessary to accurately assess the costs and benefits of alternative fuel systems. Bioenergy fuel policies adopted by most countries typically require GHG reduction targets to be met, which are measured through LCA. A full LCA includes cradle-to-grave emissions flows (and/or environmental impacts) starting with biomass cultivation and ending with fuel consumption.

5.2   Methods

5.2.1   *Yield modelling*

Models are being continuously improved to increase their applicability in a wider range of environmental and management scenarios. For example, Hastings *et al*. (2009) developed a new model of *Miscanthus* production called MISCANFOR, which is based on the same processes as MISCANMOD but which has improved descriptions of light interception by the canopy and the impact of temperature and water stress on the radiation use efficiency in photosynthesis. When predictions made with MISCANFOR were compared with those from MISCANMOD for 36 experimental data sets for a wide variety of soil and climate conditions in Europe, MISCANFOR matched field experiments with an r^2 of 0.84 compared with 0.64 for MISCANMOD.

Through collaboration with Dr Astley Hastings (University of Aberdeen) we employed the MISCANFOR productivity model, first published in 2009 (Hastings *et al*., 2009). Figure 5.1 shows the major data inputs, calculation stages and outputs.

The model was designed to create data to be converted to rasters for visualisation as maps. The model was calibrated across Europe using daily growth measurements in Ireland, Denmark, Germany and the Netherlands, with monthly measurements of yields and meteorological data from crop experiments in Sweden, Portugal, Greece, Italy and England. To validate the model, the outputs were compared with field experiments using the site-specific meteorological data and the measured soil parameters, and the daily incremental crop yield was compared with incremental harvests made during the growing season. The MISCANFOR model was run using the 0.5-degree grid of future climate scenario data, which provides climate projections for the four IPCC emission scenarios for the period 2000–2100, and yield maps are compared for time slices at 2020, 2050 and 2080.

MISCANFOR, now parameterised for both *Miscanthus* and willow, was used to project Irish-specific *Miscanthus* and willow dry matter yields at a resolution of 1 km^2. The model was run using
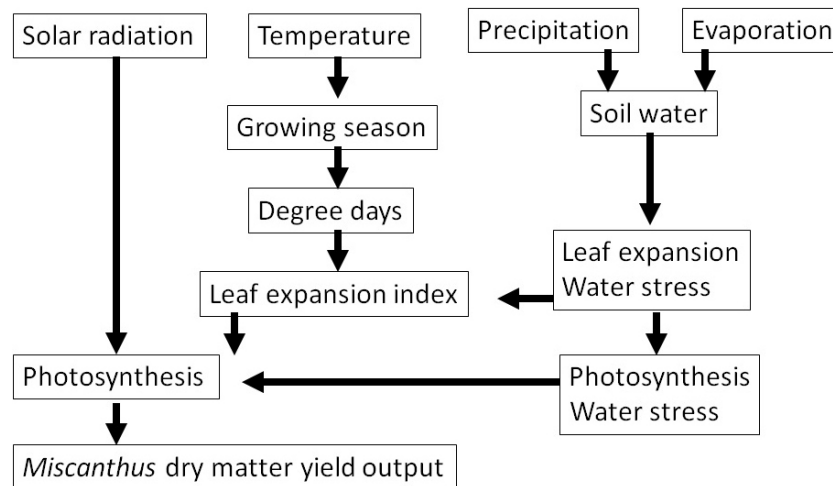
Figure 5.1. Block diagram of MISCANFOR plant growth model showing the major data inputs, calculation stages and outputs.

climate data for current climatic conditions using the University of East Anglia Climate Research Unit 4.2 scenario (Hastings *et al*., 2009). Data for the soil parameter input to MISCANFOR were obtained from the Food and Agriculture Organization of the United Nations Harmonised World Soil Database (HWSD version 1.2).[20] Change in *Miscanthus* yield in Mg ha^{-1} y^{-1} from the current (2019) to the future (2050) projected climate was run with the Representative Concentration Pathway (RCP) 2.6 scenario climate from the Hadley Centre Global Environment Model (HadGEM).[21]

5.2.2 *Life cycle assessment and techno-economic assessment of bioenergy crops in Ireland*

Life cycle assessment has four basic steps: (1) a goal, scope and boundary definition; (2) a life cycle inventory (LCI) analysis; (3) a life cycle impact assessment; and (4) interpretation of results. LCA was developed as a method to compare the environmental profiles of products and services on a "per unit" basis (functional unit) and is, in most applications, a static approach. However, the choice of efficiency terms, life cycle inventories and systems boundaries determines the outcomes of an LCA. Consequently, LCA must be

carried out with awareness of how each component could influence the outcome. The LCA methodology is regulated by the International Organization for Standardization (ISO) 14040:2006 and ISO 14044:2006 standards, which provide the principles, framework, requirements and guidelines for conducting a LCA study, but, fundamentally, it is a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. Despite this standardised approach the published outputs from LCA studies show a very wide range of uncertainties that currently make it impossible to provide an exact quantification of the environmental impacts of bioenergy crops and energy production. This is largely because of the many variables that can be incorporated into any analysis and also because some of the key parameters (such as indirect effects) are not well known and strongly depend on local and climate conditions (Cherubini and Strømman, 2011).

The aim was to develop a comprehensive LCA of the GHG emissions profile of target bioenergy crop cultivation in Ireland with a focus on short-rotation willow and *Miscanthus*. In this work we update the results of Styles and Jones (2008) to calculate GHG emissions from dominant agricultural land uses with a focus on the use of marginal or less productive land for *Miscanthus* and willow.

---

20 http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/ (accessed 20 July 2020).

21 https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/climate-models/hadgem3 (accessed 20 July 2020).

We use a LCI modelling package up to the point of the farm gate to assess net GHG emissions. The inventory considers all inputs and processes involving a net emission or sink of the major GHGs (CO_2, CH_4 and N_2O).

We also apply techno-economic analysis (TEA) to bioenergy production systems to provide a more detailed understanding of their likely economic and technical impacts, including parameters for cost–benefit assessment and evaluation of risk. This has built on and complements previous near-term (up to 2035) supply and economic analysis of bioenergy in Ireland by SEAI (2012), as well as longer term general equilibrium modelling of bioenergy development using the Irish TIMES platform (Chiodi *et al*., 2015).

For both *Miscanthus* and willow production systems, a separate individual attributional LCA model was created in Microsoft Excel. Each model represents a set of site-specific locations (1 km² resolution), varying in soil type and climate, across Ireland. In the case of *Miscanthus*, three cropping scenarios are analysed: (1) SB, the baseline scenario, which includes organic and inorganic fertiliser input; (2) S1, organic fertiliser input only; and (3) S2, inorganic fertiliser input only. The scenario with the highest environmental burden was to be determined. As this study focuses on the

production of energy (GJ⁻¹) from biomass available to the end user, i.e. end user gate, it is thus considered a "cradle-to-gate" LCA. For both production systems, the functional unit (FU) is "1 GJ of energy available to the end user", thus enabling comparison with other energy production systems (Styles and Jones, 2008; Monti *et al*., 2009; Murphy *et al*., 2014).

A delimitation of the system boundary and the processes included for LCA *Miscanthus* production is illustrated in Figure 5.2. The system encompasses the following elements: raw material acquisition (crop cultivation and harvesting), biomass processing (pelleting) and transport to the end user. The *Miscanthus* production model uses yield data obtained from the MISCANFOR model on varying soil types across Ireland, under current climate conditions. *Miscanthus* crops are grown as a perennial with multiple harvest cycles (or rotations).

The first stage of land preparation prior to seeding involves application of herbicide to control actively growing weeds. This is followed by subsoiling and ploughing, all of which is carried out in the autumn of year 0. In spring of year 1, prior to planting, lime is spread. The land is harrowed using a power harrow in order to ensure an adequate soil tilth (Caslin *et al*., 2015). *Miscanthus* rhizomes are then planted
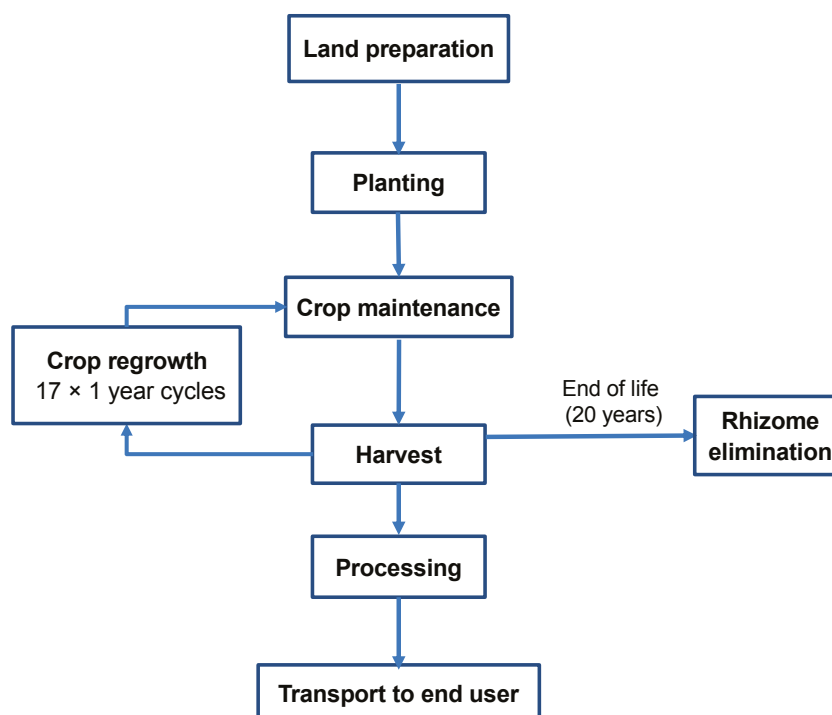

Figure 5.2. Production system boundary delimitation for LCA.

at a density of 15,500 ha^{-1} using a modified potato planter. The site is consolidated by rolling and a residual herbicide applied. During the first two growing seasons fertiliser is not applied. Fertiliser is then applied 17 times over the life of the *Miscanthus* plantation, post harvest. The first harvest of the *Miscanthus* takes place after the third growing season, in year 4 (February/March), with successive harvests carried out on an annual basis thereafter as part of the 20-year cropping cycle. The crop is mown and left in the field to dry before baling. The bales are subsequently transported 5 km to the farmyard. It is chopped and further dried using a modified grain dryer. The *Miscanthus* is then pelleted. The elimination of the *Miscanthus* rhizomes is carried out at the end of the cropping cycle, in year 21. The life cycle model allocates resource demands and associated emissions for all operations evenly across the total biomass harvested over a 21-year timeline.

Land preparation prior to planting willow was assumed to be identical to that for *Miscanthus*. The willow crop is planted with a modified potato planter to a density of approximately 16,500 cuttings ha^{-1} (Murphy *et al*., 2013). The site is consolidated by rolling and a residual herbicide applied. The crop is coppiced/ cut back during the first growing season and further herbicide applied (Caslin *et al*., 2015). Inorganic fertiliser was applied in the first year of each 3-year rotation (Murphy *et al*., 2014). Nitrogen (N) was applied to the crop in the spring so as to minimise the amount of fertiliser taken up by competing plants (weeds) or lost through run-off (Volk *et al*., 2004).

Leaf litter from the willow crop is an additional source of nutrients that can be re-utilised by the growing plant (Ericsson, 1994; Baum *et al*., 2009). Annual leaf fall in this situation is assumed to be 3800 kg ha^{-1} y^{-1} and a leaf N content of 1.5% was assumed according to Heller *et al*. (2004).

As part of willow's cropping cycle it is harvested every 3 years (Murphy *et al*., 2013). In this study willow is harvested by way of "direct chipping", i.e. using a self-propelled forage harvester equipped with a fitment for harvesting willow (Caslin *et al*., 2015). It is assumed that upon harvest, the willow biomass is transported 5 km to the farmyard. The willow chip is then transferred to trucks and transported to the "end user"; the end user is assumed, in this instance, to be located 50 km from the farm.

5.3 Results and Discussion

5.3.1 Yield modelling

Yield maps for the island of Ireland derived from the MISCANFOR outputs are shown in Figures 5.3 and 5.4. The maps show that under the current climate the maximum projected yields of *Miscanthus* are 24 t ha^{-1} y^{-1}, whereas the maximum yields of willow are 16 t ha^{-1} y^{-1}. The areas where maximum yields of both *Miscanthus* and willow occur are in the south and south-east of Ireland. For *Miscanthus*, 37% of the land would produce very low or no viable yields of less than 8 t ha^{-1} y^{-1}. Of the remaining 63% of land cover, 33.4% is in the range of 12–16 t ha^{-1} y^{-1}. Table 5.1 shows the proportion of land cover producing yields in yield categories in increments of 4 t ha^{-1} y^{-1} for *Miscanthus* and Table 5.2 shows the same analysis for willow.

When Hastings *et al*. (2008) ran MISCANFOR for the entire EU27 the mean peak yield was 16.3 t ha^{-1} y^{-1} with a standard deviation of 2 t ha^{-1} y^{-1} as a result of interannual variation in climate. Yields in Ireland are therefore somewhat lower than the average across Europe, as anticipated by the lower mean summer-time temperatures. The distribution of the highest willow yields reflects its greater tolerance of cool and moist conditions in Ireland. Despite model predictions that show that *Miscanthus* can, in suitable locations, significantly outyield willow, it is likely that willow will be the preferred energy crop in cooler and wetter parts of the country. Areas with an annual rainfall of 900–1000 mm appear to be optimal for willow production, as well as areas where the crop has access to ground water (Caslin *et al*., 2015).

Although, in the current exercise, willow yields in Ireland have been projected using MISCANFOR, the model has not, so far, been run for the whole of Europe. Consequently, comparisons of the differences in productivity between *Miscanthus* and willow across the European continent are difficult to make. Mola-Yudego and Aronsson (2008) have developed a willow productivity model for biomass plantations in Sweden and have shown that, for the best growers, they are able to achieve from 5.4 to 7.1 t ha^{-1} y^{-1} in 4-year rotations of the second cutting cycle. These yields are close to those predicted for most of Ireland. Mola-Yudego and Aronsson (2008) point out that numerous studies have shown higher rates of production of willow, up to as much as 30 t ha^{-1} y^{-1}, but these were
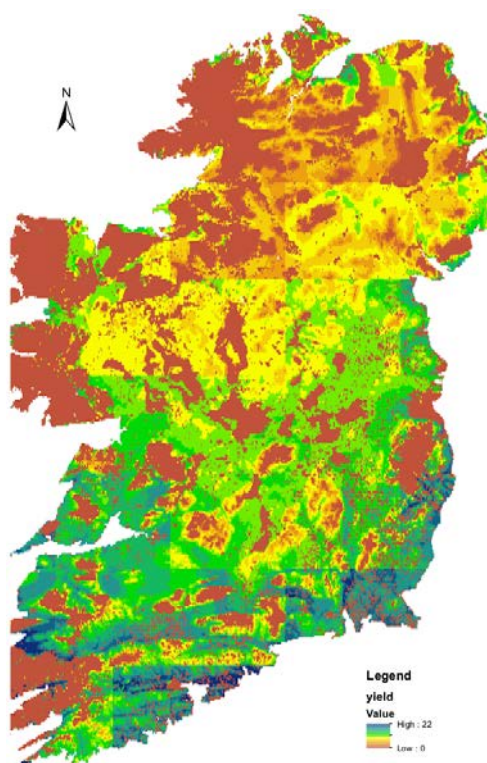
Figure 5.3. Map of potential yield for *Miscanthus* (t ha⁻¹ y⁻¹) under current climate using the MISCANFOR model.
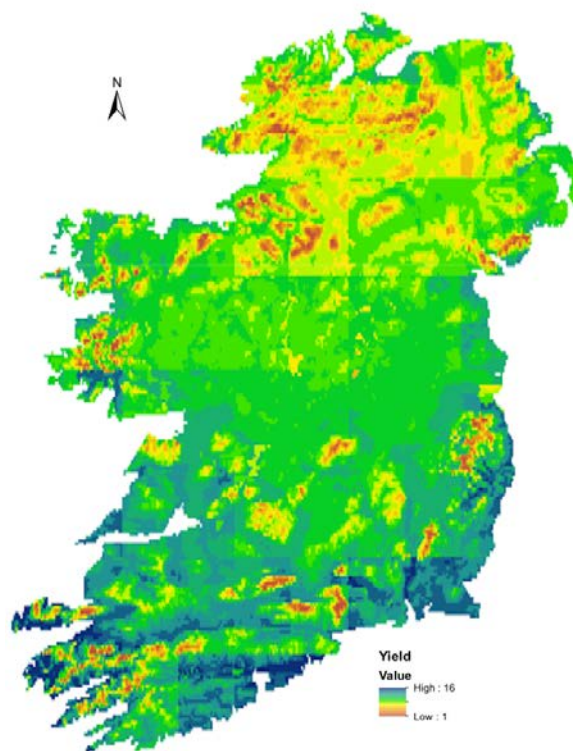
Figure 5.4. Map of potential yield for willow (t ha⁻¹ y⁻¹) under current climate using the MISCANFOR model.

Table 5.1. *Miscanthus* yield categories and proportion of total land area

	Yield category (t ha⁻¹ y⁻¹)					
	0–4	4–8	8–12	12–16	16–20	20–24
Total land area (%)	36.76	<1	26.78	33.41	2.50	<1

Table 5.2. Willow yield categories and proportion of total land area

	Yield category (t ha⁻¹ y⁻¹)					
	0–4	4–8	8–12	12–16	16–20	20–24
Total land area (%)	0.77	13.27	71.65	14.3	–	–

for intensively irrigated and fertilised research plots in southern Sweden. They suggest that such findings may have contributed to over-optimistic predictions of the yield in willow plantations.

High-resolution mapping of the potential productivity of *Miscanthus* and willow shows that large areas of the island can produce economically viable yields given appropriate incentives (see Augustenborg *et al*., 2012). The threshold for economic viability is difficult to determine, but yields of at least 8 t ha⁻¹ y⁻¹ could offer

sufficient income for landowners. Physiological studies show that *Miscanthus* and willow have different optimal temperatures for growth and it would be expected that willow would be better suited than *Miscanthus* to a cooler and wetter climate. The yield maps support this, with *Miscanthus* producing maximum yields 50% higher than willow.

The high-resolution mapping possible with MISCANFOR has shown for the first time details of the potential yield distribution of second-generation

biomass crops across Ireland. Previous yield predictions have been at much coarser spatial scales (e.g. Stampfl *et al*., 2007) and in many cases they have assumed a single average yield across the whole of Ireland. Using this information, we are now in a position to identify the most suitable areas for growing *Miscanthus* and willow and make more reliable predictions about potential yields. This analysis will require knowledge of current land use for agriculture in order to identify those areas that may be of more "marginal" value for food production while excluding those areas that are protected in order to meet sustainability requirements. This information is crucial for life cycle and economic assessments. Nevertheless, it should be recognised that the model output is a potential yield that is very likely to exceed the realised yield on a farm. The model assumes that the land is managed optimally to achieve a potential yield but the realised outputs will be lower and dependent on any deficiencies in less than optimal management.

Crop yields are strongly dependent on prevailing weather conditions so the interannual variations in climate will inevitably result in variations in yield from year to year. One of the important uses of dynamic models such as MISCANFOR is to examine the impacts of these year-to-year variations in climate. This has been beyond the scope of the model runs reported here but it will be important to assess these impacts in the future. However, we have examined the longer term impacts of predicted climate change on *Miscanthus* and simulated yields using the RCP 2.6 scenario climate from HadGEM. Figure 5.5 shows the projected changes in yield between today and 2050 for *Miscanthus*. In general, it shows a projected increase in yields of up to $6\,t\,ha^{-1}\,y^{-1}$ by 2050. This presumably reflects the temperature-driven increase in length of the growing season as the climate warms but it also shows that the predicted changes in average rainfall have a limited impact on yield. However, access to land for harvesting after heavy and/or prolonged rainfall may impact on harvests that need to be carried out before the growing season starts. The map of the distribution in yield changes also indicates that in the south-east of Ireland there will be less of an increase and in some limited regions a decrease in yield. This is likely to reflect the possibility of increasing drought in this region as a result of lower summer rainfall by 2050.
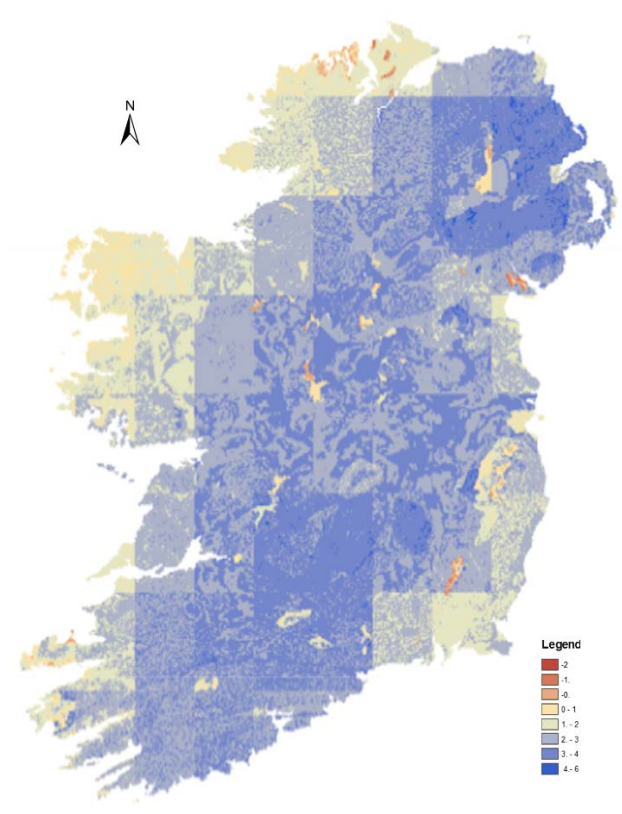
Figure 5.5. Change in *Miscanthus* yield in $t\,ha^{-1}\,y^{-1}$ from today to 2050 with the RCP 2.6 scenario climate change from HadGEM.

5.3.2   Life cycle assessment

The impact categories used were climate change, eutrophication (EP) and acidification (AP). For climate change impact, emissions of CH_4, N_2O and CO_2 were calculated following the approach outlined by Rice *et al*. (2017), which was based on that from the carbon footprint model of O'Brien *et al*. (2014), certified by the Carbon Trust according to PAS 2050 for LCA (BSI, 2011). GHG emissions were expressed in CO_2e using the following global warming potential values from the IPCC (2007, Chapter 2): 1 for CO_2, 28 for CH_4 and 298 for N_2O, assuming a 100-year time horizon (GWP_{100}).

Eutrophication includes contributions from air and water emissions of NH_3 and phosphorus (P), air emissions of nitrogen oxides (NO_x) and water emissions of nitrates and phosphates. The EP impact was calculated using the following generic EP factors as per van der Werf *et al*. (2009) in $kg\,PO_4$-equivalents: NH_3 – 0.35, nitrate (NO_3) – 0.10, NO_2 – 0.13, NO_x – 0.13 and P – 3.06. AP includes air emissions of NH_3, sulfur oxides (SO_2) and NO_x. The AP impact was calculated also using the following generic AP factors

as per van der Werf *et al*. (2009) in kg SO_2-equivalents: NH_3– 1.6, NO_2 – 0.5, NO_x – 0.5 and SO_2 – 1.2.

With regard to N input and associated nitrogenous emissions, firstly NH_3 is released to the atmosphere through volatilisation. After NH_3 volatilisation, N_2O formation was estimated from the remaining available N from synthetic and organic sources. Although nitrate leaching under willow and *Miscanthus* plantations is low when compared with conventional agricultural crops (Murphy *et al*., 2013, 2014), with regard to *Miscanthus*, NO_3 leaching was estimated using the IPCC (2006) emission rate of 30% of applied N from both organic and inorganic fertilisers under conventional cropping systems. Based on findings from Jørgensen *et al*. (2013), the rate of NO_3 leaching for willow in this study was assumed to be 90% lower than that for *Miscanthus*. Additionally, regarding both cropping systems, 0.75% of N leached is converted to N_2O, while N_2O from NH_3 redeposition was estimated at 1%. In this assessment, for *Miscanthus*, three LCA modelling scenarios are compared: (1) organic N fertiliser from leaf litter only, (2) inorganic fertiliser (N, P and potassium – K) only and (3) organic plus inorganic fertiliser. It was assumed that there was no carbon sequestration to the soil (IPCC, 2006; O'Brien *et al*., 2014).

The aim of this analysis was to identify hotspots in the production chains of *Miscanthus* and willow in GHG emissions and environmental impacts. As in previous studies by Styles and Jones (2008) and Murphy *et al*. (2013), maintenance and processing of both crops were the stages of the life cycle that contributed most to the impact categories (global warming potential, AP potential, EP potential and energy demand). The pelleting of the harvested *Miscanthus* contributed most to the life cycle GHG emissions, as this process requires a large quantity of energy in the form of electricity. However, there are large variations in the reported energy requirements for alternative processes for compressing *Miscanthus* such as briquetting (Murphy *et al*., 2013), suggesting that alternative methods for processing *Miscanthus* before transport need to be investigated.

Another significant contributor to each of the impact categories for both crops is their maintenance and, in particular, the production and application of synthetic fertilisers. The production of synthetic fertilisers is an energy-intensive process utilising non-renewable fossil

fuels. In relation to *Miscanthus* production, this raises an important issue about the requirements that its cultivation has for fertiliser inputs. A characteristic of perennial herbaceous rhizomatous grasses, such as *Miscanthus*, is their ability to continuously remobilise nutrients between various organs of the plant as the growing season progresses. Although the lifespan of the plant can be more than 20 years, its stems and leaves function for only one season. The only permanent organ is the rhizome, which functions in vegetative propagation and the storage of nutrients. The internal recycling of nutrients between above- and below-ground organs allows the harvesting of biomass with a low nutrient content, but also reduces the demand for nutrients for renewed growth, which is normally met through application of fertilisers.

The nutrient normally applied in greatest abundance to crops is N, but another feature reducing the demand for N in *Miscanthus* is the C_4 photosynthetic mechanism, which relies on a very effective photosynthetic enzyme, PEP-carboxylase, for assimilating CO_2 (Jones, 2011). The presence of PEP-carboxylase means that for the same amount of photosynthesis as non-C_4 plants, *Miscanthus* has to allocate far less N to producing the enzyme required for CO_2 fixation. As a result of utilising C_4 photosynthesis and achieving an efficient recycling of nutrients, *Miscanthus* has very low N requirements and limited need for fertiliser applications. Indeed, in some agronomic trials there is evidence that *Miscanthus* can be cropped for several years before there is a requirement for added N fertiliser. For example, Christian *et al.* (2008) grew *Miscanthus* x *giganteus* for 14 successive harvests in the south of England and found that fertiliser N application had little influence on yields, which reached 17.7 t ha^{-1} at their peak. It was suggested, however, that other nutrients such as P and K should be added at low levels to avoid depletion of soil reserves. In contrast to this evidence for little or no requirement for N, other trials, particularly in the USA but also in Mediterranean Europe (Cosentino *et al.*, 2007), have shown a significant increase in yields of stands of *Miscanthus* when N fertiliser was added. For example, in a trial in Illinois, Arundale *et al.* (2014) found that *Miscanthus* × *giganteus* yield increased significantly from 23.4 t ha^{-1} with zero fertiliser to 28.9 t ha^{-1} (+25%) at an annual application rate of 202 kg N ha^{-1}. However, the proportional increase in yield per unit of added N is small in *Miscanthus*

compared with other C_4 crops, such as maize and switchgrass (Heaton *et al*., 2004), and, consequently, it is suggested that this response to added fertiliser is unlikely to be economically worthwhile. In conclusion, it appears that there are requirements for low levels of fertiliser to maintain yields of *Miscanthus* but there are very large site-to-site variations, which make generalisations and advice on optimum fertiliser rates extremely difficult to make. In Ireland, Murphy *et al*. (2013) suggest that inputs of N are required for a reasonable yield (*c*.11 t ha^{-1} y^{-1}), although the amounts required are uncertain. Clearly, further research is required to determine more precisely the level of fertiliser required and what the spatial variation is in this requirement. An additional factor is that biosolid fertiliser may have beneficial effects in substituting for synthetic fertiliser although its use will increase AP and EP potential.

Willow is less efficient in its use of N than *Miscanthus* and thus requires significant nitrogen fertiliser applications, which result in N_2O emissions; however, biosolids can be used as an alternative fertiliser. Although there are still emissions associated with biosolid applications, the high energy use in production of artificial fertiliser is avoided. However, using biosolids in the place of synthetic fertiliser increases both AP and EP potential significantly. In essence, the use of biological fertiliser in place of synthetic fertiliser improves the energy performance of the system while negatively affecting each of the environmental impacts (Murphy *et al*., 2013).

As outlined, the economic features of the biomass supply chain and conversion technologies can be reflected through a TEA, where the production cost of the process is summarised to allow comparisons of different biomass sources and their conversion processes to produce energy.

Biomass is the only renewable source of energy that can be directly processed to high-value end products in liquid, solid or gas form using thermochemical conversion technologies. The thermochemical conversion of biomass to useful end products can occur through the processes of pyrolysis, gasification, liquefaction, combustion, carbonisation and co-firing. The implementation of any of these processes depends mainly on the cost-competitiveness of biomass-based fuels and chemicals compared with those produced from conventional fossil sources.

A TEA of biomass thermochemical conversion technologies is important for their development and commercialisation and one of the key outcomes of a TEA is the cost of producing fuels and chemicals. Production costs can be estimated by developing discounted cash-flow sheet models for a biorefinery (Patel *et al*., 2016). The production costs are specific to the chosen thermochemical conversion technologies and their products. This complex analysis is beyond the scope of the current review. Therefore, the TEA we have carried out is a preliminary exercise based on a review of the literature that is relevant to the scenarios we have adopted for the bioenergy production chain and the utilisation of the biomass for energy production linked with CCS. We consider two potential bioenergy production pathways for BECCS in Ireland: (1) a centralised energy system (CES) of large-scale biomass power stations (probably located where existing power plants are currently found) and (2) a distributed energy system of combined heat and power (CHP) stations distributed to meet the heat and power demands in the future. On a transitional basis, the centralised power stations may co-fire biomass with peat or coal. Albanito *et al*. (2019) assessed the mitigation potential and environmental impact of both centralised and distributed BECCS in Great Britain and found that the technical mitigation potentials from BECCS lead to projected CO_2 reductions of approximately 18 and 23 MtCO$_2$ y^{-1} from the centralised and distributed energy systems, respectively.

Centralised power stations in Ireland currently combust fossil fuels or peat for production of electricity. Several boiler types can be used for biomass combustion for power generation. Generally, pulverised coal-fired boilers with a biomass feedstock co-fired with coal gives a lower cost of electricity than fluidised bed boilers. A solely biomass-fuelled power plant normally has a higher cost of electricity than a coal-fired plant when the price of biomass is higher than coal (Patel *et al*., 2016). However, it is important in any emissions impact analysis to consider the expected interactions with the wider energy system, such as potential displacement of high-efficiency combined cycle gas turbine generation (Clancy *et al*., 2018). De and Assadi (2009) report on the results from a number of pilot plant tests that have assessed the technical and economic feasibility of biomass co-firing in existing coal boilers. They have developed a techno-economic model on the basis of the experiences of these pilot

plants to assess the economics of biomass co-firing. The model estimates the total additional costs as well as additional specific costs. A sensitivity analysis was then carried out to find the effects of different operating and logistic parameters on additional costs. The most significant conclusion from this sensitivity analysis was that the CO_2 emission decreases and additional costs of retrofitting for biomass co-firing increase with increasing capacity of the plant, but, again, this specific finding does not reflect analysis of interactions in the Irish energy system, where natural gas is the marginal fuel (Clancy *et al.*, 2018). Furthermore, although the prices of coal and biomass will have some effects on the economics of biomass co-firing, the effects were found not to be that significant for additional specific costs; this is not in line with the levelised cost of electricity (LCOE) modelling completed elsewhere, where fuel prices are found to be the most significant short-run cost contributor, while, for long-run cost, the capital expenditure (CAPEX) and load factor are also important (IEA-ETSAP, IRENA, 2013). In addition, it was found that increasing the mass of biomass co-fired with the coal gives greater reductions in CO_2 emissions but this is accompanied by an increase in total as well as specific costs.

For the case of distributed energy supply, CHP systems involve the simultaneous production of electrical power and thermal energy, such as hot water and space heating. Making efficient use of fuel energy by producing electricity and heat, biomass CHP designs could reach overall efficiencies of over 80%, providing an opportunity to make significant cost savings and CO_2 emission reductions compared with traditional electricity-only systems. The basic biomass CHP system consists of four major components: (1) biomass receiving and preparation, (2) biomass conversion, (3) power generation and (4) heat recovery. Huang *et al.* (2013) compared two CHP systems for generating heat and electricity: organic Rankine cycle (ORC) and biomass gasification based. It was found that the overall efficiencies of the ORC-based CHP systems are 76% when willow chip is used and 81% when *Miscanthus* is used. For the biomass gasification-based CHP system the overall efficiencies were 58% with willow chip and 64% with *Miscanthus*. The differences between feedstocks were found to

be due to the moisture content. The main conclusions from Huang *et al.* (2013) were that it is technically and economically feasible to use willow chips and *Miscanthus* in both types of CHP plants but that the capital costs of the ORC-based CHP systems are much higher than those of the biomass gasification CHP systems. Furthermore, the willow and *Miscanthus* CHP-generated CO_2 emissions were between 421 and 562 g kWh^{-1} compared with advanced coal-fired electricity power station CO_2 emissions of 782 g kWh^{-1}.

Our literature review of assessments of the consequences of the deployment of the biomass supply chain and the conversion technologies in terms of their environmental, technical and economic impacts has highlighted the complexity of the issues relating particularly to the management of the biomass supply chain. In a whole-systems analysis of the BECCS value chain associated with cultivation, harvesting, transport and conversion in dedicated biomass power stations in conjunction with CCS of a range of biomass sources, including *Miscanthus* and willow, Fajardy and Mac Dowell (2017) found that the effects of direct and indirect land use change were the key determinants of the viability of a BECCS project. This meant that the effectiveness of a BECCS plant, in terms of its lifetime removal of CO_2 from the atmosphere, was observed to be highly case specific and the viability of BECCS as a NET option depends entirely on the choices made throughout the supply chain. Fajardy and Mac Dowell (2017) concluded that improvements in the sustainability of BECCS could be achieved, in particular by measuring and limiting the impacts of direct and indirect land use change, minimising biomass transport and maximising the use of carbon-neutral-negative fuels.

The LCA and TEA of bioenergy production from energy crops reviewed here can be used to assess the level of sustainability of the supply chain, taking into account the criteria set out in the recast Renewable Energy Directive (RED II)[22] and other environmental, economic and social indicators. In Ireland, for bioenergy fuels to be eligible to count towards the national 2020 renewable energy targets, they must meet the sustainability criteria as defined in the RED Articles. In essence, they must meet minimum life cycle GHG savings and feedstocks cannot be grown on peatlands or on land with a high biodiversity value

22 https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii (accessed 20 July 2020).

or with high carbon stocks. In the SEAI (2019) report *Sustainability Criteria Options and Impacts for Irish Bioenergy Resources*, typical GHG emission values were calculated for a representative range of supply chains in the Irish context, including values for both *Miscanthus* and willow, neither of which has default values in RED II. They conclude that these perennial energy crops used as feedstocks for bioenergy supply chains have emission values better than the RED II default values.

5.4   Conclusion

Using high-resolution, state-of-the-art mechanistic modelling of potential yields of the dedicated bioenergy crops *Miscanthus* and willow, we have shown that both crops have the potential to produce economically viable yields across large areas of the country. *Miscanthus* achieves significantly higher yields than willow under the most favourable climates in the south-east of Ireland but willow can outyield *Miscanthus* under cooler (and wetter) conditions. The maps of yield distribution should be a useful aid in making recommendations to farmers on the choice of bioenergy crop to plant. The modelling exercise has also predicted effects of future climate change on crop production. The predicted warming by the middle of

the century could result in an excess of 20% higher yields for *Miscanthus*. LCA has highlighted the most important features of the GHG emissions profiles of these crops and has shown that the high N use efficiency of *Miscanthus*, and its consequential lower demand for nitrogenous fertiliser, significantly reduce GHG emissions associated with its cultivation. The LCA and TEA of bioenergy production from energy crops reviewed here can be used to assess the level of sustainability of the supply chain as detailed in *Sustainability Criteria Options and Impacts for Irish Bioenergy Resources*, published by SEAI (2019). In relation to the effectiveness of these bioenergy crops in BECCS plants, in terms of the lifetime removal of CO_2 from the atmosphere, it is highly case specific and the viability of BECCS as a NET option depends entirely on the range of choices made throughout the supply chain. Furthermore, our analysis has assumed that the availability of bioenergy is not a limitation on the implementation of BECCS. However, in reality there are likely to be a number of alternative enabling technologies available that can process biomass into a spectrum of bio-based products as well as bioenergy (Lindorfer *et al*., 2019). Under these circumstances it could well be that there is a limitation on the availability of biomass, which could limit the scale of development of BECCS.

6   Conclusion: Informing Public Policy

This preliminary study of both the need and potential for deployment of NETs in Ireland has found the following:

- A prudent, equitable, Paris Agreement-aligned remaining CO_2 quota for Ireland is assessed as approximately 400 $MtCO_2$ from 2015 or 180 $MtCO_2$ from 2020. This is likely to be exhausted around 2024 on the basis of current policy measures and projections.

- This is strictly an assessment at the Irish national territorial level, under the voluntary, bottom-up framework for global co-operation established by the Paris Agreement. In this study we have not explored the specific implications of this analysis at the regional EU level. However, given the role of the EU in co-ordinating participation in the Paris framework on behalf of all its Member States, it follows that unilateral strengthening of mitigation action at the level of individual Member States may have the perverse consequence of weakening ambition in others. Accordingly, a Member State CO_2 quota analysis should be co-ordinated to ensure consistent commitment and ambition at the EU level and effective integration in EU-wide policy measures. This is an important issue to address in future NETs policy research at both national and EU levels.

- Similarly, this assessment has not incorporated a more general examination of the scope for Ireland to commission either gross CO_2 emissions reduction or gross CO_2 removals outside the national jurisdiction. Such extra-territorial measures might, in principle, ease the domestic mitigation challenge. However, experience to date of such actions, particularly the Clean Development Mechanism of the Kyoto Protocol, is not encouraging (Cames *et al.*, 2016). Furthermore, the now severe constraint of the remaining global CO_2 budget, combined with the continuing need to support sustainable development, suggests that the practical scope for such exchanges or trading of mitigation action is extremely limited. Nonetheless, the possibilities for additional, robustly monitored and verified extra-territorial mitigation might usefully be analysed further in future research.

- The most recent Irish Climate Action Plan (DCCAE, 2019) suggests a current national (territorial) policy envelope that would commit to continued net positive CO_2 emissions out to 2050 (at least). We estimate that this would result in net emissions of approximately 1000 $MtCO_2$ before achieving net-zero annual flow (*c.*2050 at the earliest), that is, overshoot of the assessed quota by about 600 $MtCO_2$. There would be significant risk that eventual overshoot could, in fact, be substantially higher if policy measures are delayed, fall short or are not sustained.

- At face value, quota overshoot represents a tacit commitment to subsequent net CO_2 removal from the atmosphere and long (millennial)-term storage of the same amount. On a global basis, collective overshoot implies heightened risks of both severe direct climate impacts and triggering of potentially irreversible, cascading, feedback effects. The duration of any such overshoot (nationally and globally) must therefore be absolutely minimised (IPCC, 2018).

- A preliminary assessment of the potential for indigenous, land use-constrained CO_2 removal and storage (AF, SCS, BC, BECCS) indicates a technical upper limit, within the Irish territorial boundary, of about 600 $MtCO_2$. DACCS and EW might theoretically add to this but they are subject to very high uncertainty over cost and availability of required very-low-CO_2 energy (over and above wider societal energy requirements). We conclude that a prudent practical (social, political, economic) upper limit on gross cumulative indigenous CO_2 removals for policy purposes should therefore currently be taken as no more than about 200 $MtCO_2$. Even this would rely on a suite of additional, near-term policy interventions to bring such removals about on an effective timescale.

- This quantitative mismatch between projected overshoot of the prudent, Paris Agreement-aligned CO_2 quota and prudent potential for compensating CO_2 removal and storage, amounting to at least 400 $MtCO_2$ (on this preliminary assessment),

indicates the need for a fundamental, society-wide re-assessment of the scale and urgency of national CO_2 mitigation action now required.

- Given the global collective action nature of the challenge, this should also involve a prioritisation of Ireland's diplomatic effort in catalysing co-ordinated, just and equitable international mitigation of commensurate scale and urgency. In this, those parties with the highest existing per capita CO_2 emissions have a clear obligation to lead. In the case of Ireland, its potential role in contributing to ambitious policy development at the EU level may be especially relevant here.

On this basis, we make the following summary recommendations directed both at informing immediate national policy interventions and identifying priorities for further national-level research:

- In the context of the measures in the Climate Action Plan (DCCAE, 2019) to "adopt a more ambitious commitment of net zero GHG emissions by 2050" (Action 1), and to introduce a system of statutory 5-year "national carbon budgets" (Action 5), it is recommended that these national-level objectives should incorporate a statutory NCQ, with statutory limits on both the scale and duration of any CO_2 quota overshoot to be tolerated in future national mitigation pathway policy. As already noted, to be properly effective, such national-level commitment must also be aligned and integrated with EU-level policy measures, which will probably require prioritised EU diplomatic effort in parallel with national action.
- Given the challenges and uncertainties around CO_2 removal and secure long-term storage, near-term policy should consider significantly more radical constraints on gross CO_2 emissions in order to strongly limit the potential NETs burden and risk for future citizens (van Vuuren *et al*., 2018); in particular, this would imply an accelerated timescale for the phasing out of all unabated fossil fuel energy use (*c*.2035 at the latest). Given the known risks of system-level rebound, and the continuing strong coupling of CO_2 emissions and economic growth, effective reductions in absolute fossil fuel use will probably require enforced, declining limits on the flow of such fuels into the economy (Chamberlin *et al*., 2014; Jackson *et al*., 2018).

- Rapid fossil fuel phase-out will necessarily be disruptive and raise serious and substantive issues of the absolute level of ongoing economic activity (income and wealth) and of its equitable distribution. These potentially pose high social, political and economic barriers to effective realisation. Society-wide engagement and deliberation must be central to addressing this. The experience of the Irish Citizens' Assembly, specifically in its module on climate action, provides a strong model for such informed, deliberative engagement (CA-IE, 2018). It is recommended that this should be considered as a basis for a greatly scaled-up "national climate dialogue" process, which should extend to evaluation of appropriate metrics of national prosperity and well-being under conditions of global ecological emergency. This should specifically go beyond a narrow focus on GDP (Jackson, 2011; Alexander, 2015; Hickel and Kallis, 2019). Such deliberations should use the cumulative framing of the CO_2 mitigation challenge and thus contribute directly to society-wide understanding and citizen commitment to a binding NCQ and limits on the extent and duration of quota overshoot on a basis of a just and equitable distribution of efforts, burdens and opportunities.
- National policy analysis commonly relies, inter alia, on cost-effectiveness comparisons of alternative measures relative to specified policy objectives. It is recommended that all such cost-effectiveness analyses of climate policy should apply CO_2 quota-based objectives (this would ensure that such analyses explicitly model the costs of reversing quota overshoot, i.e. NETs).
- The Climate Action Plan has already committed to "the establishment of a Steering Group to examine and oversee the feasibility of the utilisation of CCS in Ireland, and report to the Standing Committee on Climate Action" (DCCAE, 2019, Action 33). We recommend that the mandate for this group explicitly includes not just FFCCS, but also BECCS and DACCS, and that its work be accelerated as much as possible. Given the intrinsic thermodynamic/energetic penalty in separating CO_2 from the atmosphere and compressing and transporting it for storage, the group should address all existing and potential high-concentration point sources

of CO_2, whether of fossil or of biogenic origin (specifically including CO_2 arising from biogas upgrade for grid injection). Noting that current policy incentivises the construction of unabated, bioenergy-based heating plants, with support extending for a period up to 15 years (within which period CCS use pathways may plausibly become available), the group should critically review whether there is a case for bioenergy to be strategically prioritised for use in facilities with CCS capability at the earliest feasible time and whether an early statutory ban should be introduced on the licensing of any new fixed facility, of significant scale, that would involve the unabated point release of CO_2 to the atmosphere. Taking account of the capital cost, lead time and constrained ultimate capacity of indigenous CO_2 geo-storage sites, it is recommended that the group critically assesses the case for more rapid CCS deployment (specifically including potential retrofitting of existing unabated point sources), facilitated by exporting of CO_2 for geo-storage in other jurisdictions.[23]

- Given the scale of Ireland's immediate climate mitigation challenge, its deteriorating fossil energy security (especially in respect of natural gas) and its relatively very large indigenous variable renewable energy resource (especially wind – offshore and onshore), there is a clear national opportunity for the rapid demonstration and deployment of electrofuel (power to fuel technology – P2X) technology for very large-scale (multi-TWh) energy buffering, inter-seasonal storage and early migration of particularly challenging end-use sectors (high-temperature heat, heavy transport) to zero-CO_2 chemical fuels such as H_2 or NH_3 (McMullin *et al*., 2018). It is recommended that, as with CCS, this should also be addressed via a high-level national steering group with a mandate to advise on the most effective interventions to promote such strategic developments, including accessing relevant EU funding programmes.
- In addition to such ambitious measures to accelerate the phasing out of unabated fossil fuel use, demand-side constraints should also be actively considered (Chamberlin *et al*., 2014; Creutzig *et al*., 2018). As demand-side measures

(by definition) need not rely heavily on build-out of new large-scale infrastructure, they are particularly relevant to limiting the CO_2 quota overshoot in the short and medium term. This can also particularly facilitate the promotion of "low-regret decarbonisation options" including energy efficiency and overall reductions in energy demand. Conversely, it is recommended that policies that could have the contrary effect of increasing energy demand (for example, in relation to promotion of energy-intensive activities such as data centres, roads infrastructure or international aviation services) should be subject to critical, CO_2-quota-based climate mitigation assessment.

- Nonetheless, assuming that, even with the most ambitious and rapid reductions in gross CO_2 emissions, Ireland will significantly overshoot its prudent CO_2 quota limit and that deployment of significant gross CO_2 removal will be a key and essential policy measure, then the differentiated maturities of different NETs do suggest different timelines for intervention. In particular, we recommend an early focus on reducing and minimising existing land use emissions and enhancement of land use sinks, including peatland restoration, enhanced SCS and AF. AF policy should be carefully assessed to balance multiple objectives, specifically including biodiversity and rural economic development. Limiting forest harvest can significantly enhance the ongoing sink activity. A particular potential strategy is delaying forestry harvest unless and until it can be directed for use in BECCS (thus initially capturing carbon from the atmosphere for relatively insecure, short-term biogenic storage but then transferring to secure, long-term geo-storage). It would be essential to ensure that any such constraint on harvest would not adversely affect forest expansion. In the case of private (commercial) AF this would require interventions to ensure an appropriate economic return on the carbon storage service in standing forest (with rigorous monitoring and verification). Alternatively, it may be appropriate to focus on direct state investment in a new publicly owned and managed forest, with a prescribed objective of increasing carbon storage. Separately, any such overall

---

23 See, for example, the proposed "full-scale CCS" project proposed by Norway: https://ccsnorway.com/ (accessed 20 July 2020).

management regime to systematically increase the national forest carbon stock (pending possible availability of BECCS) must also consider possible unintended effects on substitution of fossil energy use and/or fossil energy-intensive building products (steel, concrete) by potentially lower impact forest harvest. Improved SCS should also be encouraged through sustainable management of agricultural soils, particularly grassland. The very extensive areas of grassland soils in Ireland are known to be currently storing large amounts of carbon but management strategies need to be put in place to protect the current stocks and increase them in future. Promotion of indigenous dedicated bioenergy crops (primarily *Miscanthus* and willow) should also be prioritised. In the short to medium term, the carbon removal and storage impact may be maximised by directing to BC use, but, again, as BECCS plants become available, they would provide for secure, long-term CO_2 storage from such crops. The overall (territorial) climate mitigation benefit of all such agricultural land use change will evidently be maximised where it displaces current high-emissions-intensity agriculture (beef and dairy production). Further targeted national research on all these issues is strongly recommended.

- Although this project has focused on CO_2, there is a clear interaction between the available CO_2 quota and complementary actions on non-CO_2 climate forcing. This is of special relevance to Irish mitigation policy owing to the relatively high contributions to national emissions of CH_4 and N_2O from agricultural activity, especially ruminant livestock farming. Although somewhat shorter lived in the atmosphere than CO_2, N_2O is still properly treated as a cumulative or stock pollutant and, in principle, could be directly incorporated into a "cumulative carbon quota" policy framework on a straightforward basis using the GWP_{100} equivalence factor. CH_4, on the other hand, is more properly treated as a flow pollutant, for example using the GWP* methodology of Allen

et al. (2018). Despite the ongoing debate at the UNFCCC level on approaches to aggregating stock and flow pollutants, it is recommended that, for national policy purposes, CH_4 should be incorporated (via GWP*) with N_2O and CO_2 into a single integrated cumulative GHG quota policy framework based on CO_2we, specifically using GWP* in place of the more conventional GWP_{100} CO_2 equivalence metric. This should replace the structure of distinct sectoral (and non-cumulative) mitigation objectives previously adopted in the Irish National Policy Position on Climate Action (DECLG, 2014) (which has not been formally superseded). This would require further research to inform the quantitative value for such a (prudent, Paris Agreement-aligned) CO_2we-based quota but would have the key advantage of then allowing a properly integrated understanding of how action on mitigating CH_4 and N_2O emissions can effectively contribute to easing the NCQ overshoot and the ultimate future requirement for net CO_2 removal (NETs).

In conclusion, the IE-NETs project has served to clarify, on a preliminary basis, a number of implications for Irish climate policy of the relatively recent understanding that it is the cumulative release of CO_2 that will determine the peak of anthropogenic warming. In particular, this has allowed an initial assessment of a prudent, equitable, Paris Agreement-aligned, remaining CO_2 quota for Ireland and a critical examination of the limited prudent potential to rely on future deployment of NETs to correct the impending overshoot of this quota. This has served to identify, prima facie, a very stark mismatch between current national mitigation ambition and the shared international temperature goals of the Paris Agreement.

Although challenging, we hope that this additional clarity can provide a context and stimulus to inform urgent, society-wide deliberation on how Ireland can best play its fair share, equitable role in addressing this unfolding global emergency.

References

Albanito, F., Hastings, A., Fitton, N., Richards, M., Martin, M., Dowell, N.M., Bell, D., Taylor, S.C., Butnar, I., Li, P.-H., Slade, R. and Smith, P., 2019. Mitigation potential and environmental impact of centralised versus distributed BECCS with domestic biomass production in Great Britain. *Global Change Biology Bioenergy* 11(10): 1234–1252. https://doi.org/10.1111/gcbb.12630

Alexander, S., 2015. *Prosperous Descent: Crisis as Opportunity in an Age of Limits*. Simplicity Institute Publishing, Melbourne, Australia. Available online: https://tinyurl.com/ProsperousDescentPDF (accessed 23 July 2020).

Allen, M.R., Shine, K.P., Fuglestvedt, J.S., Millar, R.J., Cain, M., Frame, D.J. and Macey, A.H., 2018. A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Climate and Atmospheric Science* 1: 16. https://doi.org/10.1038/s41612-018-0026-8

Anderson, K. and Peters, G., 2016. The trouble with negative emissions. *Science* 354: 182–183. https://doi.org/10.1126/science.aah4567

Arundale, R.A., Dohleman, F.G., Voigt, T.B. and Long, S.P., 2014. Nitrogen fertilisation does significantly increase yields of stands of *Miscanthus × giganteus* and *Panicum virgatum* in multiyear trials in Illinois. *BioEnergy Research* 7: 408–416. https://doi.org/10.1007/s12155-013-9385-5

Augustenborg, C.A., Finnan, J., McBennett, L., Connolly, V., Priegnitz, U. and Müller, C., 2012. Farmers' perspectives for the development of a bioenergy industry in Ireland. *GCB Bioenergy* 4: 597–610. https://doi.org/10.1111/j.1757-1707.2011.01151.x

Barton, J., McKenna, E. and Thomson, M., 2017. Time-step analysis of the DECC 2050 Calculator pathways. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 231: 551–579. https://doi.org/10.1177/0957650917704993

Bateman, I.J. and Lovett, A.A., 2000. Estimating and valuing the carbon sequestered in softwood and hardwood trees, timber products and forest soils in Wales. *Journal of Environmental Management* 60: 301–323. https://doi.org/10.1006/jema.2000.0388

Baum, C., Leinweber, P., Weih, M., Lamersdorf, N. and Dimitriou, I., 2009. Effects of short rotation coppice with willows and poplar on soil ecology. *Agriculture and Forestry Research* 59: 183–196.

Bows-Larkin, A., 2015. All adrift: aviation, shipping, and climate change policy. *Climate Policy* 15: 681–702. https://doi.org/10.1080/14693062.2014.965125

BSI (British Standards Institution), 2011. PAS 2050:2011. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI, London. Available online: https://tinyurl.com/PAS2050-2011 (accessed 29 August 2019).

Burke, M., Hsiang, S.M. and Miguel, E., 2015. Global non-linear effect of temperature on economic production. *Nature* 527: 235–239. https://doi.org/10.1038/nature15725

Butnar, I., Broad, O., Rodriguez, B.S. and Dodds, P.E., 2019. The role of bioenergy for global deep decarbonization: CO_2 removal or low-carbon energy? *Global Change Biology Bioenergy* 12: 198–212. https://doi.org/10.1111/gcbb.12666

CA-IE (The Citizens' Assembly, Ireland), 2018. How the state can make Ireland a leader in tackling climate change. CA-IE, Dublin. Available online: http://tinyurl.com/ybhs6867 (accessed 31 January 2019).

Cames, M., Harthan, R.O., Füssler, J., Lazarus, M., Lee, C.M., Erickson, P. and Spalding-Fecher, R., 2016. *How Additional is the Clean Development Mechanism?* Öko-Institut. Study prepared for the European Commission, DG CLIMA. Available online: https://ec.europa.eu/clima/sites/clima/files/ets/docs/clean_dev_mechanism_en.pdf (accessed 22 July 2020).

Caslin, B., Finnan, J., Johnston, C., McCracken, A. and Walsh, L., 2015. *Short Rotation Coppice Willow: Best Practice Guidelines*. Teagasc, Dublin. https://tinyurl.com/TeagascSRC2015 (accessed 29 August 2019).

CCAC (Climate Change Advisory Council), 2019. *Annual Review 2019*. CCAC, Dublin. Available online: https://tinyurl.com/CCAC-IE-Review-2019 (accessed 23 July 2020).

Chamberlin, S., Maxey, L. and Hurth, V., 2014. Reconciling scientific reality with realpolitik: moving beyond carbon pricing to TEQs – an integrated, economy-wide emissions cap. *Carbon Management* 5: 411–427. https://doi.org/10.1080/17583004.2015.1021563

Cherubini, F. and Strømman, A.H., 2011. Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresource Technology* 102: 437–451. https://doi.org/10.1016/j.biortech.2010.08.010

Chiodi, A., Deane, P., Gargiulo, M. and Gallachóir, B.Ó., 2015. The role of bioenergy in Ireland's low carbon future – is it sustainable? *Journal of Sustainable Development of Energy, Water and Environment Systems* 3: 196–216. https://doi.org/10.13044/j.sdewes.2015.03.0016

Christian, D.G., Riche, A.B. and Yates, N.E., 2008. Growth, yield and mineral content of *Miscanthus × giganteus* grown as a biofuel for 14 successive harvests. *Industrial Crops and Products* 28: 320–327. https://doi.org/10.1016/j.indcrop.2008.02.009

Cintas, O., Berndes, G., Cowie, A.L., Egnell, G., Holmström, H., Marland, G. and Ågren, G.I., 2017. Carbon balances of bioenergy systems using biomass from forests managed with long rotations: bridging the gap between stand and landscape assessments. *GCB Bioenergy* 9: 1238–1251. https://doi.org/10.1111/gcbb.12425

Clancy, J.M., Curtis, J. and Ó'Gallachóir, B., 2018. Modelling national policy making to promote bioenergy in heat, transport and electricity to 2030 – interactions, impacts and conflicts. *Energy Policy* 123: 579–593. https://doi.org/10.1016/j.enpol.2018.08.012

COFORD (Council for Forest Research and Development), 2016. *Land Availability for Afforestation: Exploring Opportunities for Expanding Ireland's Forest Resource*. COFORD, Department of Agriculture, Food and the Marine, Dublin. Available online: https://tinyurl.com/COford-LUF-2016 (accessed 23 July 2020).

Connolly, D., 2015. EnergyPLAN Cost Database 3.0. Aalborg University, Aalborg, Denmark. Available online: http://tinyurl.com/yyv6mdcc (accessed 23 July 2020).

Connolly, D. and Mathiesen, B.V., 2014. A technical and economic analysis of one potential pathway to a 100% renewable energy system. *International Journal of Sustainable Energy Planning and Management* 1: 7–28. https://doi.org/10.5278/ijsepm.2014.1.2

Cosentino, S.L., Patanè, C., Sanzone, E., Copani, V. and Foti, S., 2007. Effects of soil water content and nitrogen supply on the productivity of *Miscanthus × giganteus* Greef et Deu. in a Mediterranean environment. *Industrial Crops and Products* 25: 75–88. https://doi.org/10.1016/j.indcrop.2006.07.006

Cowie, A., Berndes, G. and Smith, T., 2013. *On the Timing of Greenhouse Gas Mitigation Benefits of Forest-based Bioenergy*. Available online: https://www.ieabioenergy.com/wp-content/uploads/2013/10/On-the-Timing-of-Greenhouse-Gas-Mitigation-Benefits-of-Forest-Based-Bioenergy.pdf (accessed 7 February 2020).

Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., de Bruin, W.B., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., Hertwich, E.G., Khosla, R., Mattauch, L., Minx, J.C., Ramakrishnan, A., Rao, N.D., Steinberger, J.K., Tavoni, M., Ürge-Vorsatz, D. and Weber, E.U., 2018. Towards demand-side solutions for mitigating climate change. *Nature Climate Change* 8: 260–263. https://doi.org/10.1038/s41558-018-0121-1

DAFM (Department of Agriculture, Food and the Marine), 2015. *A Guide to Greening: 2015*. DAFM, Dublin. Available online: https://tinyurl.com/DAFM-Greening-2015 (accessed 27 November 2017).

Davis, S.C., Anderson-Teixeira, K.J. and DeLucia, E.H., 2009. Life-cycle analysis and the ecology of biofuels. *Trends in Plant Science* 14: 140–146. https://doi.org/10.1016/j.tplants.2008.12.006

DCCAE (Department of Communications, Climate Action and Environment), 2018. *Draft National Energy and Climate Plan (NECP) 2021–2030*. DCCAE, Dublin. Available online: http://tinyurl.com/y4zfpt9t (accessed 23 July 2020).

DCCAE (Department of Communications, Climate Action and Environment), 2019. *Climate Action Plan 2019: To Tackle Climate Breakdown*. DCCAE, Dublin. Available online: https://assets.gov.ie/10206/d042e174c1654c6ca14f39242fb07d22.pdf (accessed 18 July 2019).

De, S. and Assadi, M., 2009. Impact of cofiring biomass with coal in power plants – a techno-economic assessment. *Biomass and Bioenergy* 33: 283–293. https://doi.org/10.1016/j.biombioe.2008.07.005

Deane, P., Curtis, J., Chiodi, A., Gargiulo, M., Regan, F., Dineen, D., Glynn, J., FitzGerald, J. and Ó Gallachóir, B.P., 2013. Technical support on developing low carbon sector roadmaps for Ireland: Low Carbon Energy Roadmap for Ireland. Economic and Social Research Institute, Dublin; E4sma, Turin, Italy; University College Cork, Cork, Ireland. Available online: https://www.esri.ie/pubs/BKMNEXT292.pdf (accessed 22 June 2016).

DECC (Department of Energy and Climate Change), 2010. *2050 Pathways Analysis*. Available online: http://tinyurl.com/y4qmx89c (accessed 6 July 2020).

DECLG (Department of the Environment, Community and Local Government), 2014. Climate action and low-carbon development: national policy position Ireland. DECLG. Dublin. Available online: http://tinyurl.com/y7fxla7b (accessed 23 July 2020).

Energy Institute, 2014. *2050 Pathways Calculator for Ireland*. Available online: http://calculator.ireland2050.ie/assets/onepage/Trajectory-Description.pdf (accessed 22 July 2020).

EPA (Environmental Protection Agency), 2017. *Ireland's National Inventory Report 2017: Greenhouse Gas Emissions 1990–2015*. EPA, Johnstown Castle, Ireland. Available online: http://tinyurl.com/yb8x3pdn (accessed 23 July 2020).

EPA (Environmental Protection Agency), 2018. *Ireland's Greenhouse Gas Emissions Projections 2017–2035*. EPA, Johnstown Castle, Ireland. Available online: http://tinyurl.com/yxb9ew69 (accessed 26 June 2018).

EPA (Environmental Protection Agency), 2019a. *Ireland's National Greenhouse Gas Emissions Projections 2019*. EPA, Johnstown Castle, Ireland. Available online: https://tinyurl.com/y2xecslc (accessed 18 July 2019).

EPA (Environmental Protection Agency), 2019b. *Ireland's Final Greenhouse Gas Emissions 1990–2017*. EPA, Johnstown Castle, Ireland. Available online: https://www.epa.ie/pubs/reports/air/airemissions/ghgemissions2017/ (accessed 23 July 2020).

Ericsson, T., 1994. Nutrient cycling in energy forest plantations. *Biomass and Bioenergy* 6: 115–121. https://doi.org/10.1016/0961-9534(94)90090-6

EU (European Union), 2018a. Regulation (EU) 2018/842 of the European Parliament and of the Council of 30 May 2018 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013. OJ L 156, 19.6.2018, p. 26–42. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32018R0842 (accessed 23 July 2020).

EU (European Union), 2018b. Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action, amending Regulations (EC) No 663/2009 and (EC) No 715/2009 of the European Parliament and of the Council, Directives 94/22/EC, 98/70/EC, 2009/31/EC, 2009/73/EC, 2010/31/EU, 2012/27/EU and 2013/30/EU of the European Parliament and of the Council, Council Directives 2009/119/EC and (EU) 2015/652 and repealing Regulation (EU) No 525/2013 of the European Parliament and of the Council. OJ L 328, 21.12.2018, p. 1–77. Available online: https://tinyurl.com/y7xmcuh9 (accessed 23 July 2020).

Fajardy, M. and Mac Dowell, N., 2017. Can BECCS deliver sustainable and resource efficient negative emissions? *Energy and Environmental Science* 10: 1389. https://doi.org/10.1039/C7EE00465F

Farrelly, I.J., Loske, B., Neele, F.P. and Holdstock, M.P., 2010. An assessment of the potential for geological storage of CO_2 in the vicinity of Moneypoint, Co. Clare. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: http://www.epa.ie/pubs/reports/research/climate/ccrpreport4.html (accessed 11 December 2017).

Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J., del Mar Zamora Dominguez, M. and Minx, J.C., 2018. Negative emissions – part 2: costs, potentials and side effects. *Environmental Research Letters* 13: 063002. https://doi.org/10.1088/1748-9326/aabf9f

Glynn, J., Gargiulo, M., Chiodi, A., Deane, P., Rogan, F. and Ó Gallachóir, B., 2018. Zero carbon energy system pathways for Ireland consistent with the Paris Agreement. *Climate Policy* 19.1: 30–42. https://doi.org/10.1080/14693062.2018.1464893

Gopalakrishnan, G., Negri, M.C. and Salas, W., 2012. Modelling biogeochemical impacts of bioenergy buffers with perennial grasses for a row-crop field in Illinois. *Global Change Biology Bioenergy* 4: 739–750. https://doi.org/10.1111/j.1757-1707.2011.01145.x

Hastings, A., Clifton-Brown, J., Wattenbach, M., Stampfl, P., Mitchell, C.P. and Smith, P., 2008. Potential of *Miscanthus* grasses to provide energy and hence reduce greenhouse gas emissions. *Agronomy for Sustainable Development* 28: 465–472. https://doi.org/10.1051/agro:2008030

Hastings, A., Clifton-Brown, J., Wattenbach, M., Mitchell, C.P. and Smith, P., 2009. The development of MISCANFOR, a new *Miscanthus* crop growth model: towards more robust yield predictions under different climatic and soil conditions. *Global Change Biology Bioenergy* 1: 154–170. https://doi.org/10.1111/j.1757-1707.2009.01007.x

Heaton, E., Voigt, T. and Long, S.P., 2004. A quantitative review comparing the yields of two candidate C_4 perennial biomass crops in relation to nitrogen, temperature and water. *Biomass and Bioenergy* 27: 21–30. https://doi.org/10.1016/j.biombioe.2003.10.005

Heller, M.C., Keoleian, G.A., Mann, M.K. and Volk T.A., 2004. Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renewable Energy* 29: 1023–1042. https://doi.org/10.1016/j.renene.2003.11.018

Hickel, J. and Kallis, G., 2019. Is green growth possible? *New Political Economy* 25: 469–486. https://doi.org/10.1080/13563467.2019.1598964

Horschig, T. and Thrän, D., 2017. Are decisions well supported for the energy transition? A review on modelling approaches for renewable energy policy evaluation. *Energy, Sustainability and Society* 7: 5. https://doi.org/10.1186/s13705-017-0107-2

Huang, Y., McIlveen-Wright, D.R., Rezvani, S., Huang, M.J., Wang, Y.D., Roskilly, A.P. and Hewitt, N.J., 2013. Comparative techno-economic analysis of biomass fuelled combined heat and power for commercial buildings. *Applied Energy* 112: 518–525. https://doi.org/10.1016/j.apenergy.2013.03.078

IEA-ETSAP (International Energy Agency Energy Technology Systems Analysis Programme) and IRENA (International Renewable Energy Agency), 2013. *Biomass Co-firing*. IRENA, Abu Dhabi, United Arab Emirates. Available online: https://irena.org/-/media/Files/IRENA/Agency/Publication/2013/IRENA-ETSAP-Tech-Brief-E21-Biomass-Co-firing.pdf (accessed 29 October 2020).

IPCC (Intergovernmental Panel on Climate Change), 2006. *IPCC Guidelines for National Greenhouse Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use*. Institute for Global Environmental Strategies, Japan. Available online: https://www.ipcc-nggip.iges.or.jp/public/2006gl/vol4.html (accessed 29 August 2019).

IPCC (Intergovernmental Panel on Climate Change), 2007. *AR4 Climate Change 2007: The Physical Science Basis*. Cambridge University Press, Cambridge, UK. Available online: https://www.ipcc.ch/report/ar4/wg1/ (accessed 29 August 2019).

IPCC (Intergovernmental Panel on Climate Change), 2014a. *Fifth Assessment Report (AR5)*. Cambridge University Press, Cambridge, UK. Available online: https://archive.ipcc.ch/report/ar5/ (accessed 23 July 2020).

IPCC (Intergovernmental Panel on Climate Change), 2014b. *Climate Change 2014: Mitigation of Climate Change (Working Group III Contribution to AR5)*. IPCC. Available online: https://www.ipcc.ch/report/ar5/wg3/ (accessed 29 August 2020).

IPCC (Intergovernmental Panel on Climate Change), 2018. *Global Warming of 1.5°C. An IPCC Special Report on the Impacts of Global Warming of 1.5°C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., *et al.* (eds). IPCC, Geneva. Available online: https://www.ipcc.ch/sr15/ (accessed 23 July 2020).

Jackson, R.B., Quéré, C.L., Andrew, R.M., Canadell, J.G., Korsbakken, J.I., Liu, Z., Peters, G.P. and Zheng, B., 2018. Global energy growth is outpacing decarbonization. *Environmental Research Letters* 13: 120401. https://doi.org/10.1088/1748-9326/aaf303

Jackson, T., 2011. *Prosperity without Growth*. Routledge, London.

Jones, M.B., 2011. C_4 species as energy crops. In Raghavendra, A.S. and Sage, R.F. (eds), C_4 *Photosynthesis and Related CO_2 Concentrating Mechanisms*. Springer, Dordrecht, the Netherlands, pp. 379–397. Available online: https://link.springer.com/chapter/10.1007/978-90-481-9407-0_19 (accessed 23 July 2020).

Jones, M.B., Finnan, J. and Hodkinson, T.R., 2015. Morphological and physiological traits for higher biomass production in perennial rhizomatous grasses grown on marginal land. *Global Change Biology Bioenergy* 7: 375–385. https://doi.org/10.1111/gcbb.12203

Jørgensen, U., Pugesgaard, S., Schelde, K., Lærke, P.E. and Larsen, S.U., 2013. Nitrate leaching was 90% lower from willow than from a traditional grain crop even when intensively fertilised. Aarhus University, Copenhagen. Available online: https://tinyurl.com/Jorgensen-N-Leaching (accessed 29 August 2019).

Kartha, S., Athanasiou, T., Caney, S., Cripps, E., Dooley, K., Dubash, N.K., Fei, T., Harris, P.G., Holz, C., Lahn, B., Moellendorf, D., Müller, B., Roberts, J.T., Sagar, A., Shue, H., Singer, P. and Winkler, H., 2018. Cascading biases against poorer countries. *Nature Climate Change* 8: 348–349. https://doi.org/10.1038/s41558-018-0152-7

Koponen, K., Soimakallio, S., Kline, K.L., Cowie, A. and Brandão, M., 2018. Quantifying the climate effects of bioenergy – choice of reference system. *Renewable and Sustainable Energy Reviews* 81: 2271–2280. https://doi.org/10.1016/j.rser.2017.05.292

Larkin, A., Kuriakose, J., Sharmina, M. and Anderson, K., 2017. What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Climate Policy* 18: 690–714. https://doi.org/10.1080/14693062.2017.1346498

Lindorfer, J., Lettner, M., Fazeni, K., Rosenfeld, D., Annevelink, B. and Mandl, M., 2019. *Technical, Economic and Environmental Assessment of Biorefinery Concepts.* IEA Bioenergy. Available online: https://www.ieabioenergy.com/wp-content/uploads/2019/07/TEE_assessment_report_final_20190704-1.pdf (accessed: 22 July 2020).

Lund, H., 2017. EnergyPLAN: advanced energy systems analysis computer model (documentation version 13). Aalborg University, Aalborg, Denmark. Available online: http://tinyurl.com/yxr7nx3l (accessed 23 July 2020).

McGeever, A.H., Price, P., McMullin, B. and Jones, M.B., 2019. Assessing the terrestrial capacity for negative emission technologies in Ireland. *Carbon Management* 10: 1–10. https://doi.org/10.1080/17583004.2018.153 7516

McMullin, B. and Price, P., 2019. *Investigating the Role of Negative Emissions Technologies in Deep Decarbonisation Pathways for the Irish Energy System*. Dublin City University, Dublin. Available online: http://tinyurl.com/IENETs-WP4-Report-PDF (accessed 23 July 2020).

McMullin, B., Price, P., Carton, J. and Anderson, K., 2018. *Is Natural Gas "Essential for Ireland's Future Energy Security"? A Critical Response to the Irish Academy of Engineering*. Stop Climate Chaos, Dublin. Available online: http://tinyurl.com/y99ftz65 (accessed 23 July 2020).

McMullin, B., Price, P., Jones, M.B. and McGeever, A.H., 2019. Assessing negative carbon dioxide emissions from the perspective of a national "fair share" of the remaining global carbon budget. *Mitigation and Adaptation Strategies for Global Change* 25: 579–602. https://doi.org/10.1007/s11027-019-09881-6

MaREI, 2018. *Note to Joint Oireachtas Committee on Climate Action*. Available online: https://tinyurl.com/MaRei-JOCCA-2018 (accessed 18 July 2019).

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W. and Zwiers, F.W., 2010. *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Intergovernmental Panel on Climate Change. Available online: https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf (accessed 26 September 2017).

Miguez, F.E., Zhu, X., Humphries, S., Bollero, G.A. and Long, S.P., 2009. A semimechanistic model predicting the growth and production of the bioenergy crop *Miscanthus × giganteus*: description, parameterisation and validation. *Global Change Biology Bioenergy* 1: 282–296. https://doi.org/10.1111/j.1757-1707.2009.01019.x

Miguez, F.E., Maughan, M., Bollero, G.A. and Long, S.P., 2012. Modelling spatial and dynamic variation in growth, yield, and yield stability of the bioenergy crops *Miscanthus × giganteus* and *Panicum virgatum* across the conterminous United States. *Global Change Biology Bioenergy* 4: 509–520. https://doi.org/10.1111/j.1757-1707.2011.01150.x

Millner, A. and McDermott, T.K.J., 2016. Model confirmation in climate economics. *Proceedings of the National Academy of Sciences* 113: 8675–8680. https://doi.org/10.1073/pnas.1604121113

Minx, J.C., Lamb, W.F., Callaghan, M.W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G.F., Rogelj, J., Smith, P., Vicente, J.L.V., Wilcox, J. and del Mar Zamora Dominguez, M., 2018. Negative emissions – part 1: research landscape and synthesis. *Environmental Research Letters* 13: 063001. https://doi.org/10.1088/1748-9326/aabf9b

Mola-Yudego, B. and Aronsson, P., 2008. Yield models for commercial willow biomass plantations in Sweden. *Biomass and Bioenergy* 32: 829–837. https://doi.org/10.1016/j.biombioe.2008.01.002

Monti, A., Fazio, S. and Venturi, G., 2009. Cradle-to-farm gate life cycle assessment in perennial energy crops. *European Journal of Agronomy* 31: 77–84. https://doi.org/10.1016/j.eja.2009.04.001

Murphy, F., Devlin, G. and McDonnell, K., 2013. *Miscanthus* production and processing in Ireland: an analysis of energy requirements and environmental impacts. *Renewable and Sustainable Energy Reviews* 23: 412–420. https://doi.org/10.1016/j.rser.2013.01.058

Murphy, F., Devlin, G. and McDonnell, K., 2014. Energy requirements and environmental impacts associated with the production of short rotation willow (*Salix* sp.) chip in Ireland. *Global Change Biology Bioenergy* 6: 727–739. https://doi.org/10.1111/gcbb.12111

Nair, S.S., Kang, S., Zhang, X., Miguez, F.E., Izaurralde, R.C., Post, W.M., Dietze, M.C., Lynd, L.R. and Wullschleger, S.D., 2012. Bioenergy crop models: descriptions, data requirements, and future challenges. *Global Change Biology Bioenergy* 4: 620–633. https://doi.org/10.1111/j.1757-1707.2012.01166.x

O'Brien, D., Brennan, P., Humphreys, J., Ruane, E. and Shalloo, L., 2014. An appraisal of carbon footprint of milk from commercial grass-based dairy farms in Ireland according to a certified life cycle assessment methodology. *International Journal of Life Cycle Assessment* 19: 1469–1481. https://doi.org/10.1007/s11367-014-0755-9

Ó Gallachóir, B., Chiodi, A., Gargiulo, M., Deane, P., Lavigne, D. and Rout, U.K., 2012. *Irish TIMES Energy Systems Model*. Environmental Protection Agency, Johnstown Castle, Ireland. Available online: http://tinyurl.com/yay8jlea (accessed 10 August 2014).

Patel, M., Zhang, X. and Kumar, A., 2016. Techno-economic and life cycle assessment on lignocellulosic biomass thermochemical conversion technologies: a review. *Renewable and Sustainable Energy Reviews* 53: 1486–1499. https://doi.org/10.1016/j.rser.2015.09.070

Pfenninger, S., Hawkes, A. and Keirstead, J., 2014. Energy systems modelling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews* 33: 74–86. https://doi.org/10.1016/j.rser.2014.02.003

Pollitt, H. and Mercure, J-F., 2017. The role of money and the financial sector in energy-economy models used for assessing climate and energy policy. *Climate Policy* 18: 1–14. https://doi.org/10.1080/14693062.2016.1277685

Price, P., McGeever, A., Jones, M. and McMullin, B., 2018. *A Post-Paris Literature Review of Negative Emissions Technology, and Potential for Ireland*. Dublin City University and Trinity College Dublin, Dublin. Available online: http://ienets.eeng.dcu.ie/documents/Lit-Review-2018-01.pdf (accessed 23 July 2020).

Raupach, M.R., Davis, S.J., Peters, G.P., Andrew, R.M., Canadell, J.G., Ciais, P., Friedlingstein, P., Jotzo, F., van Vuuren, D.P. and Le Quéré, C., 2014. Sharing a quota on cumulative carbon emissions. *Nature Climate Change* 4: 873–879. https://doi.org/10.1038/nclimate2384

Rice, P., O'Brien, D., Shalloo, L. and Holden, N.M., 2017. Evaluation of allocation methods for calculation of carbon footprint of grass-based dairy production. *Journal of Environmental Management* 202: 311–319. https://doi.org/10.1016/j.jenvman.2017.06.071

Ripple, W.J., Smith, P., Haberl, H., Montzka, S.A., McAlpine, C. and Boucher, D.H., 2014. Ruminants, climate change and climate policy. *Nature Climate Change* 4: 2–5. https://doi.org/10.1038/nclimate2081

Robertson, A.D., Davies, C.A., Smith, P., Dondini, M. and McNamara, N.P., 2015. Modelling the carbon cycle of *Miscanthus* plantations: existing models and the potential for their improvement. *Global Change Biology Bioenergy* 7: 405–421. https://doi.org/10.1111/gcbb.12144

Robiou du Pont, Y., Jeffery, M.L., Gütschow, J., Rogelj, J., Christoff, P. and Meinshausen, M., 2016. Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change* 7: 38–43. https://doi.org/10.1038/nclimate3186

Rogelj, J., Schleussner, C-F. and Hare, W., 2017. Getting it right matters: temperature goal interpretations in geoscience research. *Geophysical Research Letters* 44: 10,662–10,665. https://doi.org/10.1002/2017GL075612

SEAI (Sustainable Energy Authority of Ireland), 2011. *Wind Energy Roadmap 2011–2050*. SEAI, Dublin. Available online: https://tinyurl.com/waojqrk (accessed 23 July 2020).

SEAI (Sustainable Energy Authority of Ireland), 2012. *BioEnergy Supply Curves for Ireland: 2010–2030*. SEAI, Dublin. Available online: https://tinyurl.com/SEAI-BE-Supply-archived (accessed 23 July 2020).

SEAI (Sustainable Energy Authority Ireland), 2019. *Sustainability Criteria Options and Impacts for Irish Bioenergy Resources*. SEAI, Dublin. Available online: https://tinyurl.com/SEAI-Sustainability-Criteria (accessed 29 August 2019).

Smith, P., Haszeldine, R.S. and Smith, S.M., 2016. Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK. *Environmental Science: Processes & Impacts* 18: 1400–1405. https://doi.org/10.1039/C6EM00386A

Smith, S.M., Lowe, J.A., Bowerman, N.H.A., Gohar, L.K., Huntingford, C. and Allen, M.R., 2012. Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Climate Change* 2: 535–538. https://doi.org/10.1038/nclimate1496

Solomon, S., Pierrehumbert, R.T., Matthews, D., Daniel, J.S. and Friedlingstein, P., 2013. Atmospheric composition, irreversible climate change, and mitigation policy: introduction. In Asrar, G.R. and Hurrell, J.W. (eds), *Climate Science for Serving Society*. Springer Netherlands, Dordrecht, the Netherlands, pp. 415–436. Available online: http://link.springer.com/chapter/10.1007/978-94-007-6692-1_15 (accessed 5 March 2017).

Stampfl, P.F., Clifton-Brown, J.C. and Jones, M.B., 2007. European-wide GIS-based modelling system for quantifying the feedstock from *Miscanthus* and the potential contribution to renewable energy targets. *Global Change Biology* 13: 2283–2295. https://doi.org/10.1111/j.1365-2486.2007.01419.x

Stern, D.I., 2017. How accurate are energy intensity projections? *Climatic Change* 143: 537–545. https://doi.org/10.1007/s10584-017-2003-3

Strachan, N. and Usher, W., 2012. Failure to achieve stringent carbon reduction targets in a second-best policy world. *Climatic Change* 113: 121–139. https://doi.org/10.1007/s10584-011-0267-6

Styles, D. and Jones, M.B., 2008. *Miscanthus* and willow heat production – an effective land-use strategy for greenhouse gas emission avoidance in Ireland? *Energy Policy* 36: 97–107. https://doi.org/10.1016/j.enpol.2007.08.030

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y. and Davis, S.J., 2019. Committed emissions from existing energy infrastructure jeopardise 1.5°C climate target. *Nature* 572: 373–377. https://doi.org/10.1038/s41586-019-1364-3

UNFCCC (United Nations Framework Convention on Climate Change), 1992. *United Nations Framework Convention On Climate Change*. United Nations, New York, NY. Available online: http://tinyurl.com/od8tdn6 (accessed 24 July 2020).

UNFCCC (United Nations Framework Convention on Climate Change), 2015. *Decision 1/CP.21: Adoption of the Paris Agreement*. United Nations, Paris. Available online: http://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf (accessed 29 June 2016).

van den Berg, N.J., van Soest, H.L., Hof, A.F., den Elzen, M.G.J., van Vuuren, D.P., Chen, W., Drouet, L., Emmerling, J., Fujimori, S., Höhne, N., Kõberle, A.C., McCollum, D., Schaeffer, R., Shekhar, S., Vishwanathan, S.S., Vrontisi, Z. and Blok, K., 2019. Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change*. https://doi.org/10.1007/s10584-019-02368-y

van der Werf, H.M.G., Kanyarushoki, C. and Corson, M.S., 2009. An operational method for the evaluation of resource use and environmental impacts of dairy farms by life cycle assessment. *Journal of Environmental Management* 90: 3643–3652. https://doi.org/10.1016/j.jenvman.2009.07.003

Vanloocke, A., Bernacchi, C.J. and Twine, T.E., 2010. The impacts of *Miscanthus × giganteus* production on the Midwest US hydrologic cycle. *Global Change Biology Bioenergy* 2: 180–191. https://doi.org/10.1111/j.1757-1707.2010.01053.x

van Vuuren, D.P., Stehfest, E., Gernaat, D.E.H.J., van den Berg, M., Bijl, D.L., de Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F. and van Sluisveld, M.A.E., 2018. Alternative pathways to the 1.5°C target reduce the need for negative emission technologies. *Nature Climate Change* 8: 391–397. https://doi.org/10.1038/s41558-018-0119-8

Volk, T.A., Verwijst, T., Tharakan, P.J., Abrahamson, L.P. and White, E.H., 2004. Growing fuel: a sustainability assessment of willow biomass crops. *Frontiers in Ecology and the Environment* 2: 411–418. https://doi.org/10.1890/1540-9295(2004)002[0411:GFASAO]2.0.CO;2

Abbreviations[24]

AF	**Afforestation**
AFOLU	Agriculture, forestry and other land use
AP	Acidification
BC	**Biochar**
BECCS	**Bioenergy with carbon capture and storage**
CCAC	Climate Change Advisory Council
CCS	Carbon capture and storage
CH_4	Methane
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CO_2we	CO_2 warming equivalent
DAC	Direct air capture
DACCS	**Direct air carbon capture and storage** (also termed **DAC**)
DECC	Department of Energy and Climate Change (UK)
EP	Eutrophication
EPA	Environmental Protection Agency
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
EU	European Union
EW	**Enhanced weathering**
FFCCS	Fossil fuel electricity generation with carbon capture and storage
GCB	Global carbon budget
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
GWP_{100}	Global warming potential over 100 years
GWP*	Modified global warming potential
H_2	Hydrogen
IE2050	Ireland 2050
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
K	Potassium
LCA	Life cycle assessment
LCI	Life cycle inventory
N	Nitrogen
N_2O	Nitrous oxide
NCQ	National CO_2 quota
NET	Negative emissions technology
NH_3	Ammonia
NO_3	Nitrate
Non-ETS	Non-traded national domestic emissions
NO_x	Nitrogen oxides

---

24 Individual NETs are denoted by bold type.

ORC	Organic Rankine cycle
P	Phosphorus
RCP	Representative Concentration Pathway
RED II	Recast Renewable Energy Directive
SCS	**Soil carbon sequestration**
SEAI	Sustainable Energy Authority of Ireland
SO$_2$	Sulfur dioxide
SR15	*Special Report on Global Warming of 1.5°C*
tC	Metric tonnes (1000 kg) of carbon (1 tC corresponds to 3.67 tCO$_2$ on combustion)
tCO$_2$	Metric tonnes (1000 kg) of carbon dioxide
TEA	Techno-economic analysis
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

Afforestation (AF)	A NET whereby the total carbon stock of forestland (as per the UNFCCC definition) is intentionally increased by planting trees on *previously unforested* land
Afforestation and reforestation	A NET whereby the total carbon stock of forestland (as per the UNFCCC definition) is intentionally increased by planting trees on previously unforested land (afforestation) *or* replanting trees on previously forested land (reforestation). It is possible that increased AR may not increase the national forest carbon stock if the harvest cancels or exceeds AR
Assessment report	As in AR5 by the IPCC, published in 2013–2014 and composed of three working group reports and a synthesis report, with summaries for policymakers agreed by governments (IPCC, 2014a)
Biochar (BC)	A NET competing for the same indigenous bioenergy fuel land resource as AR and BECCS
Bioenergy with carbon capture and storage (BECCS)	Usually describing point-source CO_2 abatement at power stations fuelled by biomass or biogas combustion with on-site CO_2 capture from the flue gases, followed by transport by pipeline or ship for injection into geologically secure storage. More generally, BECCS can refer to any bioenergy pathway where the carbon component of the bioenergy material is separated and consigned to secure geo-storage. As well as conversion to electricity, this may include conversion to other non-carbon energy carriers, such as H_2 or NH_3, to support large-scale energy storage and transport, and/or direct decarbonisation of end uses where electrification is especially difficult (high-temperature heat, heavy transport, etc.)
Carbon capture and storage (CCS)	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
Carbon commitment analysis (CCA)	Charting the projected pathway of cumulative CO_2 emissions (net and gross) for an energy–cement–land use scenario
Carbon dioxide (CO_2)	The main greenhouse gas and very long-lived climate pollutant, targeted by climate mitigation policy in energy and land use
Carbon dioxide equivalent (CO_2e)	Used to include CO_2 and all greenhouse gases (including CH_4 and nitrous oxide) in emissions totals. GWP_{100} is generally the conversion metric
Carbon dioxide removal (CDR)	Planned and managed removal of CO_2, using NETs, from the atmosphere into land, ocean or geo-storage (via CCS)
Carbon dioxide warming equivalent (CO_2we)	Used to include CO_2 and all greenhouse gases (including CH_4 and N_2O) in cumulative emissions totals, applying the GWP* conversion metric
Clean development mechanism (CDM)	The largest system of carbon permit emissions trading defined by the Kyoto Protocol, aiming to enable global mitigation at lower cost

Climate Action and Low-carbon Development National Policy Position (Ireland)	The Irish government's current (as of 2019) mitigation policy outline guiding the National Mitigation Plan
Climate Change Advisory Committee (CCAC)	An expert advisory group set up under Ireland's Climate Action and Low Carbon Development Act (2015)
Direct air carbon capture and storage (DACCS)	A NET whereby large volumes of ambient air (with very low CO_2 concentration) are moved through chemical collectors to absorb CO_2, which is then concentrated and transported for injection into geologically secure storage
Enhanced weathering (EW)	A NET whereby ultrabasic or basic rock is mined and powdered (requiring a large energy input) and transported to be diffusely spread over large areas of land so that CO_2 is absorbed from ambient air to produce mineralised carbonates
Fossil fuel electricity generation with carbon capture and storage (FFCCS)	Usually describing a fossil fuel (coal or gas)-burning power station with CCS abatement
Greenhouse gas (GHG)	A trace gas in the atmosphere that reduces reradiation of incident solar energy, keeping the Earth's surface warmer than it would otherwise be (the "greenhouse effect")
Greenhouse gas removal (GGR)	A process or system that removes some greenhouse gas from the atmosphere (either consigning it directly to long-term storage or transforming it to some stable, benign form). Generally synonymous with NET
LowGCB:Pop	A national carbon quota based on a (prudential) low-end estimate of the global carbon budget and shared on a (minimally) equitable equal per capita basis (as of 2015)
Methane (CH_4)	A potent greenhouse gas. Classified as a short-lived climate pollutant, its warming effect depends on the total ongoing flow of emissions. A permanent increase in CH_4 emissions substantially increases net forcing but sustained decrease in CH_4 emissions has an equivalent effect to achieving negative emissions
MidGCB:Pop	A national carbon quota based on a mid-range estimate of the global carbon budget and shared on a (minimally) equitable equal per capita basis (as of 2015)
National carbon quota (NCQ)	A "fair share" national share of the global carbon budget for a defined temperature target on the basis of a defined allocation method such as population, meaning equal per capita sharing
National Mitigation Plan (Ireland)	Produced on a statutory basis under the terms of the Climate Action and Low Carbon Development Act (2015), based on the National Policy Position
Negative emissions technologies (NETs)	Methods that on a life-cycle basis achieve greenhouse gas removal or, more specifically, CO_2 removal from the atmosphere within some specified collection of processes (system boundary)
Net emissions	For greenhouse gases, describes total emissions to the atmosphere minus total removals from the atmosphere to long-term storage (sequestration)

Nitrous oxide (N$_2$O)	A potent greenhouse gas. Classified with CO_2 as a long-lived climate pollutant, it has a GWP_{100} of 265. N$_2$O is particularly related to the use of N fertiliser in agriculture and bioenergy, as emissions from soil and animal manure
Non-ETS	Non-traded national domestic emissions (transport, agriculture and buildings), with Member State mitigation targets agreed under the EU Effort Sharing Directive. For Ireland, the 2020 target is a 20% reduction relative to 1990
Pathway	The time series outputs from an energy system model, particularly as shown over the full period of decarbonisation transition, for example showing primary energy or greenhouse gas emissions/removals on an annual or cumulative basis
Power to fuel technologies (P2X)	Excess grid electricity, predominantly owing to oversupply from variable renewables, used to produce chemical fuels (denoted by X) for longer term energy storage and/or direct end use. The initial synthesis step is typically production of H$_2$ by electrolysis. H$_2$ may itself be the target fuel, or it may be used as a feedstock for the production of alternative fuels (NH$_3$, CH$_4$, methanol, etc.). These fuels may then be used to sustain the grid during under-supply from variable renewable energy or for other direct end uses (e.g. H$_2$ used for heating or in fuel cell transport vehicles)
Scenario	An input set of data and parameters to an energy systems model; may include time series inputs over a proposed decarbonisation transition
Scenario stage	The period between two specified steps in a scenario
Scenario step	A major change point in time in a scenario at which some significant input parameters change
Soil carbon sequestration (SCS)	A NET whereby soil carbon content is intentionally increased over time, although the sequestration rate will reach saturation within decades and this type of carbon storage is always vulnerable to re-release
Variable renewable energy (VRE)	Usually in the form of electricity, typically generated from wind, solar, tidal, etc., sources

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL

Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíocha.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

IE-NETs: Investigating the Potential for Negative Emissions Technologies (NETs) in Ireland

Authors: Barry McMullin, Michael B. Jones, Paul R. Price, Alwynne McGeever and Paul Rice

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying Pressures

The IE-NETs project applies the most recent scientific understanding that effective climate action requires setting a finite limit on total future net emissions of carbon dioxide (CO_2) due to human activities. This is true at the global level, but it also translates directly to local and national levels for climate action in Ireland, as it relates to CO_2, the single largest contributor to human-caused global warming. The analysis reveals the acute pressure to fundamentally alter all those activities in our society that currently release CO_2 to the atmosphere. These activities are dominated by the use of fossil fuels, which is both pervasive in our ongoing activities (transport, heating, electricity) and embodied in our infrastructure and virtually all of the products that we currently produce and consume.

Informing Policy

This framing of climate action in the context of cumulative net CO_2 emissions provides a powerful new lens through which to understand and assess the interactions between short-, medium- and long-term climate mitigation policies. In particular, it allows an integrated assessment of actions that would reduce direct, gross emissions of CO_2 to the atmosphere and complementary actions that might actively remove CO_2 from the atmosphere – so-called negative emissions technologies or NETs. This project has provided the first preliminary assessment of the technical potential for NETs deployment in Ireland. It also provides assessments of Ireland's prudent, minimally equitable, Paris-aligned national CO_2 quota and expected cumulative CO_2 emissions on the basis of existing policy approaches. This has identified a significant gap between mitigation that is currently regarded as feasible, and what appears to be required to discharge even our minimal "fair share" international contribution in responding to the global climate emergency.

Developing Solutions

This project has reviewed the approaches to NETs that currently appear to have most potential for deployment in Ireland: afforestation, enhanced soil carbon sequestration, biochar, bioenergy with carbon capture and storage, direct air carbon capture and storage and enhanced weathering of rock materials. It has developed an assessment of technical potential for the scale, timing and security of long-term carbon storage that each might offer. It has applied novel, high-resolution, modelling, incorporating detailed biological mechanisms, to better understand the potential for scaling up indigenous bioenergy production, and the possible interaction with local climate change. It has also developed a portfolio of coarse-grained scenarios for the future development of the Irish energy system, under strict national CO_2 quota constraints (with and without overshoot), to better characterise the interactions between supply-side decarbonisation, demand-side constraint and NETs deployment. Taken together, these results provide the basis for a set of recommendations to inform public understanding and support a national policy response that is commensurate to the scale of the climate challenge.

www.epa.ie