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Synthesis of Literature and Preliminary Modelling Relevant to Society-wide Scenarios for Effective Climate Change Mitigation in Ireland

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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.

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- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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EPA RESEARCH PROGRAMME 2014–2020

Synthesis of Literature and Preliminary Modelling Relevant to Society-wide Scenarios for Effective Climate Change Mitigation in Ireland

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EPA Research Report

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Prepared for the Environmental Protection Agency

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DISCLAIMER

This report is based on research carried out/data from March 2019 to May 2020. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

Global climate action is *not* currently aligned with the Paris Agreement goals to limit temperature rise to "well below 2°C" over pre-industrial levels and to pursue efforts to limit it to 1.5°C. Societal well-being and economic stability continue to be highly dependent on climate-polluting inputs – especially fossil fuels for energy and nitrogen fertiliser for agriculture. The research project Society-wide Scenarios for Effective Climate Change Mitigation in Ireland (SSECCM) was a 1-year, preliminary desk study undertaken to inform the implementation of Irish policy on climate mitigation in the context of European Union (EU) and Paris Agreement objectives. It evaluated international studies of society-wide, long-term climate action scenarios, identifying their relevance to the specific situation in Ireland. Although carbon dioxide (CO_2) remains the single most important greenhouse gas (GHG) to consider, emissions of methane (CH_4) and nitrous oxide (N_2O) also make a significant contribution to global climate disruption.[1] The last two are especially important to Ireland because, although CO_2 remains the dominant GHG, we have comparatively high emissions of these other GHGs, primarily from animal agriculture. A new open-source spreadsheet tool, "GHG-WE*",* was developed for the project and has been released under an open licence.[2] This tool incorporates GWP* (modified global warming potential), a metric recently developed to more accurately represent the combined climate effects of different GHGs.

The collected supporting literature is now publicly available in an online bibliographic database to support future research.[3]

Key Literature Review Findings

- **Scenario planning** is essential for exploring the very wide range of possible futures. By developing a limited number of challenging but plausible scenario narratives, the risks of catastrophic outcomes can be properly identified, managed and, ideally, completely avoided. Scenario development should reflect society-wide values and goals.
- **"Effective" scenarios** here are scenarios which are aligned with the Paris Agreement. This requires clear limits on future GHG emissions and commitment to climate justice. "Justice" is taken to encompass equitable treatment of all humanity, i.e. between individuals and socioeconomic groups within countries, and between countries, regions and generations. Reliance on high-risk future technology developments, such as large-scale removal of CO_2 from the atmosphere, should be clearly identified.
- **Scenario assessment** uses *models* to provide insights into real-world outcomes. The research reviewed here identifies significant limitations in the mainstream economic modelling that underpins much climate action policy.

Key Recommendations

- **"Open" data and modelling** with clear documentation is strongly recommended. This can contribute strongly to a common understanding among researchers, citizens and decision-makers.
- **"Simulation" modelling**, in contrast to more usual (largely economic) modelling, attempts to reflect the practical, real-world variety of dynamic interactions among individuals, groups and organisations that underlies the complex aggregate behaviour of human societies. In principle, it can better reflect the complexity of how societies respond to major stresses and the need for transformational change. Simulation modelling is not a replacement for more conventional techno-economic methods – different approaches are complementary, with distinct strengths in

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[1] There are additional human contributions to climate change, including other GHGs and non-GHG factors, such as certain kinds of particulates. However, their overall effect is relatively small compared with the aggregate of CO_2, N_2O and CH_4, and they are not considered in further detail in this report.

[2] https://zenodo.org/record/3974485 (accessed 31 August 2020).

[3] The full SSECCM bibliography is available at https://www.zotero.org/groups/2395490/sseccm-ie-d2b (accessed 31 August 2020).

different contexts. However, simulation modelling is specifically recommended for the study of scenarios of society-wide *transformational* change.

- **“Supply-side” limits on fossil carbon and reactive nitrogen** represent significant climate policy possibilities that have received relatively little emphasis to date. The EU Emissions Trading System does impose some supply-side constraints on fossil fuel use in principle, but it is limited in scope and the constraints are relatively weak. Similarly, the EU Nitrates Directive (EU, 1991) imposes a measure of constraint on reactive nitrogen use, but it is relatively weak, subject to ongoing derogation, and motivated primarily by concerns over localised water pollution rather than globalised climate effects. Measures to directly limit total synthetic nitrogen fertiliser and feed inputs to agricultural production could offer relatively effective, reliable and transparent reductions in N_2O and CH_4 emissions in Ireland. It is recommended that further research be undertaken on the detailed design and potential benefits of and barriers to national supply-side measures that would constrain both fossil carbon and reactive nitrogen flows into the economy.
- **Protecting existing land carbon stocks** from continuing rapid losses by limiting peat extraction, organic soil drainage and forest harvest could be a relatively rapid and effective land use climate action strategy for Ireland. In the immediate term, this should be a much higher policy priority than measures targeting slower, and much less reliable, “enhanced soil carbon sequestration”.
- **Significant reduction in CH_4 emissions** is now critical to effective climate action, both globally and nationally. The spreadsheet tools developed within this project have enabled a preliminary exploration of illustrative GHG emission scenarios for Ireland, constrained within a fair share of the global effort. This has clearly demonstrated the crucial trade-offs between actions affecting different GHGs, with very distinct implications for shared, society-wide transition effort.

Applying the GWP* methodology, a prudent Irish “fair share quota” of the remaining global cumulative GHG budget, within the Paris Agreement temperature rise goals, is estimated at approximately 540 Mt CO_2-we (warming equivalent) from 2015. At current emission levels, aggregated across CO_2, N_2O and CH_4, this would be fully depleted by about 2025. Continuing net positive (CO_2-we) annual emissions beyond that will give rise to progressive national quota overshoot, which will have to be capped as quickly as possible and then reversed, potentially implying very large-scale *removal* of CO_2 from the atmosphere and a transfer to very long-term (geological) storage. Urgency in research delivery and policy application is now required if Ireland is to achieve deep and rapid reductions in CO_2 emissions from fossil fuel use and land carbon losses. Given the lead time in replacing fossil energy infrastructure and the very limited practical potential for actively *removing* CO_2 from the atmosphere once it has been emitted, it is now very important to *also* rapidly reduce emissions of the two other major GHGs – N_2O and CH_4. The coronavirus disease 2019 (COVID-19) research response and rate of policy reaction shows what can be done when an emergency is treated as such. A wider policy and advisory basis of scenario planning and simulation is needed to better inform coherent policy planning and avoid costly unanticipated transition surprises and severe or catastrophic climate damages. This report presents initial, illustrative steps in this direction to inform scoping of a potential future large-scale project.

1 Introduction: Report Outline and Context

1.1 Mandate and Reporting

The project Society-wide Scenarios for Effective Climate Change Mitigation in Ireland (SSECCM)[4] was a 1-year, preliminary desk study undertaken to inform the implementation of policy on climate mitigation in the context of European Union (EU) and Paris Agreement objectives. The research aimed to provide a scoping basis for a future full-scale decarbonisation pathway scenarios study. The project examined the international literature context for the development of robust scenario planning and modelling to assess Irish climate mitigation alternatives in aggregate and by gas for all relevant greenhouse gas (GHG) emissions from all key sources, including Ireland's energy, agriculture, forestry and other land use. This synthesis report presents a synopsis of the literature review and summarises the illustrative findings from the use of a warming-equivalent scenario comparison tool developed for this project. A separate technical report presents a more detailed literature review and an in-depth discussion of implications from the preliminary modelling.

1.2 Context: Global

Global climate action is not currently aligned with staying within the remaining global carbon budgets set out by the Intergovernmental Panel on Climate Change (IPCC), which correspond to the Paris Agreement temperature rise limit of "well below 2°C" and pursuing efforts to limit temperature increase to 1.5°C above pre-industrial levels. The carbon dioxide (CO_2) pathways assessed in the SR1.5 report (Masson-Delmotte *et al*., 2018a) as meeting the Paris Agreement goals critically depend on achieving reductions in the non-CO_2 gases nitrous oxide (N_2O) and methane (CH_4) (Figure SPM.3a in IPCC, 2018). To date, the climate actions of developed nations have been insufficient, despite their acknowledged responsibility for a disproportionate share of historical emissions and capacity for action given their comparative wealth (Matthews, 2015). For developed nations with high per capita emissions, effective policies to achieve deep reductions in whole-economy emissions are now urgently needed to limit the duration and extent of overshoot beyond a nation's "fair share" of the global carbon budget (Obersteiner *et al*., 2018). Climate scenario planning, modelling and frameworks can help guide decision-makers towards a post-carbon societal transition: the achievement – locally and globally – of a situation in which anthropogenic radiative forcing is first stabilised and then progressively reduced, to restore human society to a position in which it can live, and even flourish, within its most critical planetary boundary, namely that of a stable, liveable climate (Rockström and Klum, 2012; Raworth, 2017).

1.3 Context: Ireland

Ireland's location on the Atlantic Ocean margin of north-west Europe determines its regional climate regime and climate variability. Average temperatures are increasing in line with the rapid average rate of global warming (Sweeney *et al*., 2008; Dwyer, 2012; Gleeson *et al.,* 2013), and climate change is contributing to extreme weather events affecting Ireland, particularly increased heavy rainfall (Otto *et al*., 2018). Ireland's 2019 Climate Action Plan (CAP2019) (DCCAE, 2019a) indicates a quantitative target reduction in overall annual GHG emissions of approximately –20% over the period 2021–2030[5] and then potentially to "net-zero" by 2050. Ireland's per capita CO_2 emissions are currently higher than the EU average. Power generation has steadily decarbonised owing to reduced use of coal and peat and increased wind energy. Transport emissions are strongly correlated to the economy and domestic heating emissions are strongly influenced by a large stock of older, poorly insulated buildings. Ireland's per capita CH_4 and N_2O emissions are three times the

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[4] This research project, funded by the Government of Ireland and the Environmental Protection Agency Research Programme 2014–2020, responds to *EPA Research – Climate Research Call 2018 – Project 11: Climate Mitigation Transition Pathway Scenarios*.

[5] "Specifically, Ireland requires a change in its overall emissions trajectory of the order of a 2% decline each year from 2021 to 2030 to meet our EU targets" (DCCAE, 2019a, pp. 26–27).

EU average, primarily because of (expanding) beef and dairy agriculture. Given Ireland's high per capita emissions, an increasing population represents an additional challenge to climate mitigation. Large jumps in Irish gross domestic product (GDP) since 2015 include finance passing through Ireland that is based on activities (and emissions) occurring elsewhere (Box 2.1 in CCAC, 2019), so the Climate Change Advisory Council (CCAC) suggests that, "[a]s a result, the relationship between GDP and emissions in Ireland is no longer straightforward". Energy use (Figure 1.1) is the primary driver of CO_2 emissions through fossil carbon combustion, comprising oil, natural gas, coal and peat, and together accounting for 89% of primary energy in 2017 (SEAI, 2018). Oil alone accounts for 49% of primary energy. Ireland's overall emissions profile has an exceptionally large contribution from non-CO_2 emissions from ruminant (cattle-based) beef and dairy agriculture, which therefore needs to be included in a quantitative comparison of climate change mitigation scenarios. Forestry carbon sequestration rates are decreasing, and carbon losses from land use continue to be substantial and exceed sequestration: drained organic grassland soils are a significant CO_2 source, and peat continues to be extracted for energy and horticulture, losing carbon from wetlands. Effective climate change mitigation needs to address all sectors of energy, industry and land use while ensuring equity for all citizens – a so-called "just transition".

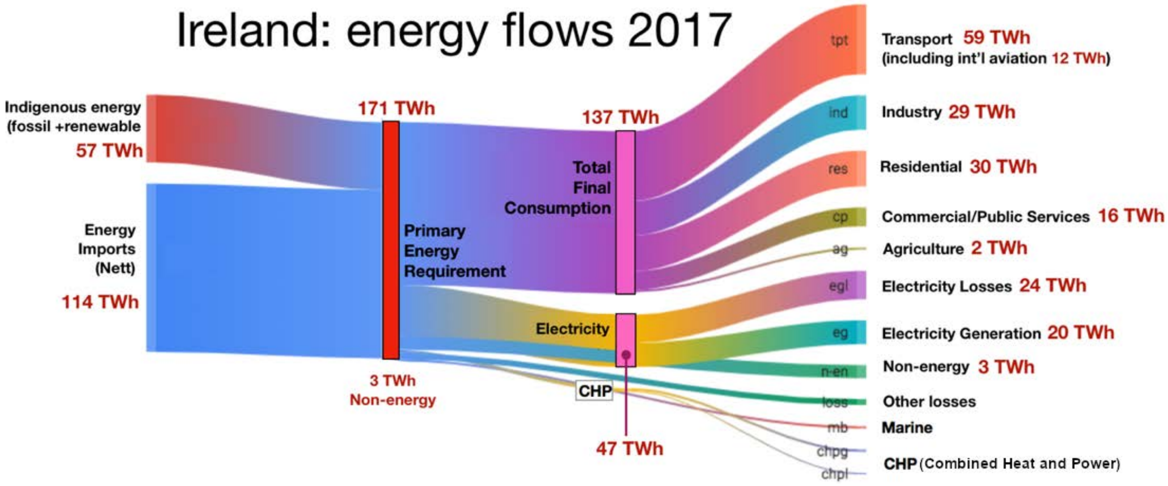

Figure 1.1. Ireland energy flows in 2017. Data from SEAI (2018); chart created for this project.

2 Bibliography: A Reference Database of Mitigation Literature

As a basis for the project literature review, relevant international and Irish literature items were identified and catalogued for inclusion in a searchable open access bibliographic database resource, particularly items relevant to Ireland's low carbon transition and climate mitigation in the context of the Paris Agreement. The bibliographical data collected were stored using Zotero, a free-to-use, non-proprietary reference management database offering open web access. The final, augmented version of the bibliography[6] followed a "funnel" sorting of database items (Barker, 2014), which evolved in parallel with the project report development and organised items into primary topic collections (folders) and secondary sub-collections. Multiple tagging enables cross-reference database searches by subjects across folders. The zero-level folder in the database gives project documentation, including selected detailed notes for users. A short introductory video to using the database is available online.[7]

A low carbon transition for an individual nation requires locally appropriate, place-based approaches that are constrained within national and Paris-aligned emission budget limits (Giest, 2014). A wide knowledge base informed by international literature can ensure that such responses avoid path-dependent "silo" responses in research and governance that risk overlooking or ignoring barriers to achieving deep decarbonisation (Giest, 2014; Seto *et al.*, 2016). Over 25,000 research papers on climate change are published each year (Haunschild *et al.*, 2016); therefore, a systematic bibliometric survey was not attempted for this small-scale project. Google Scholar was used as the primary bibliographic search tool on the basis of its ease of access, comprehensiveness and its suitability as a primary academic search engine (Harzing and Alakangas, 2016; Gusenbauer, 2019). The literature collection aimed to achieve wide coverage of not only peer-reviewed academic literature but also grey literature, such as official and technical documents, if appropriate. A constrained but unstructured snowball method (Lecy and Beatty, 2012) was used to sample mitigation references and related citations using relevant Google Scholar search terms. The initial focus was on references relevant to transition pathways that could be characterised as "radical" rather than "incremental". The initial demarcation criterion was that these should correspond to sustained, multi-decade GHG emission rate reductions of at least –8% per annum. Particular attention was given to references relevant to Ireland's distinctive emissions profile (with its high agricultural contribution of non-CO_2 GHGs), opportunities to ensure deep reductions in fossil fuel usage, assessments of indigenous, very low CO_2-intensity energy resources and consideration of land carbon storage issues.

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[6] https://www.zotero.org/groups/2395490/sseccm-ie-d2b (accessed 1 September 2020)

[7] https://www.youtube.com/watch?v=7Y2ZmMxXlfE (accessed 1 September 2020).

3 Scenario Planning for Effective Climate Mitigation

3.1 Literature Review

The IPCC special report on global warming of 1.5°C (SR1.5) defines a scenario as “an internally consistent, plausible, and integrated description of a possible future of the human–environment system, including a narrative with qualitative trends and quantitative projections” (Kainuma *et al.*, 2018). The term pathway is usually used to describe a particular progression of scenario outcomes through time, depending on the societal choices described in the scenario or scenario variant. Following the Paris Agreement, the IPCC SR1.5 scientific assessments focused on achieving emission pathways limiting temperature rise to 1.5°C by 2100. Rogelj *et al.* (2019) show that the common choice of 2100 as an end year for scenarios can bias modelling towards favouring delayed action pathways that may accept higher mitigation risks and costs. Geden and Löschel (2017) and Rogelj *et al*. (2019) show that, if governments are serious about climate action, they need to provide far greater clarity when stating the essential carbon budget parameters that must underpin coherent national mitigation policy. SR1.5 compares and contrasts “bottom up”, regional and national scenarios and case studies, particularly studies of societal transition towards low carbon energy systems with or without nuclear or large-scale biomass or carbon capture and storage (CCS), and examines sectoral mitigation options (de Coninck *et al.*, 2018). A core basis for the assessment of scenarios in SR1.5 is an ethical framework based on distributive and procedural equity and sustainable development, particularly stressing fair distribution of burdens among and within nations and between generations (Allen *et al.* 2018a; Roy *et al.* 2018).

The stylised Figure 3.1 shows a very large future possibility space of global scenarios, summarising the lack of agreement across international research on a likely future pathway for global society. The figure charts global warming, estimated from cumulative CO_2 emissions, relative to economic activity, measured by gross world product, with time proceeding along the charted line. The historical segment in the lower left part of the figure (data derived from Rogelj *et al.*, 2018; World Bank, 2019) shows two distinct past fossil fuel energy periods, both proceeding roughly linearly: the first period is the steep rise in cumulative emissions (and thus warming) from 1870 to 1950, dominated by coal use; and the second is the shallower trend from 1950 to the present day, with large-scale oil and gas use during the so-called “great acceleration” (Steffen *et al.*, 2015a). The current trajectory continues towards breaching Paris-aligned carbon budget limits within the next 10 to 20 years.

3.2 Global Context for Scenario Planning

Figure 3.1 shows four indicative future trajectories from *c.*2020 onwards, which are explored in literature and by integrated assessment models (IAMs):

- *“Green growth”* scenarios, as in IPCC-assessed IAM modelling using the shared socioeconomic pathways framework (O’Neill *et al.*, 2017), limit emissions to meet Paris-aligned carbon budgets by 2100, even if accompanied by greatly increased economic activity (Leimbach *et al.*, 2017). Typically, these involve the somewhat counter-intuitive idea that economic growth *itself* can facilitate progressively and absolutely reducing the environmental impact of economic activity via the so-called “Environmental Kuznets Curve” hypothesis. However, such green growth scenarios are questionable, given studies indicating overshoot of planetary boundaries (Steffen *et al.*, 2015b; Martin *et al.*, 2016; Hickel and Kallis, 2019) and concerns that tipping points in physical, ecological and societal systems may well be crossed before a damaging shift towards a new system regime becomes apparent (Lenton and Ciscar, 2013; Steffen *et al.*, 2018; Lenton *et al.*, 2019).
- *“Optimal” business-as-usual (BAU)* pathways from cost–benefit analysis (CBA) IAMs are exemplified by the work of Nordhaus (1991, 1993) over the past 30 years, who used the Dynamic Integrated Climate–Economy (DICE) model. However, these pathways exceeding 3°C warming appear irreconcilable with the IPCC’s expert assessments of climate science and environmental impacts,

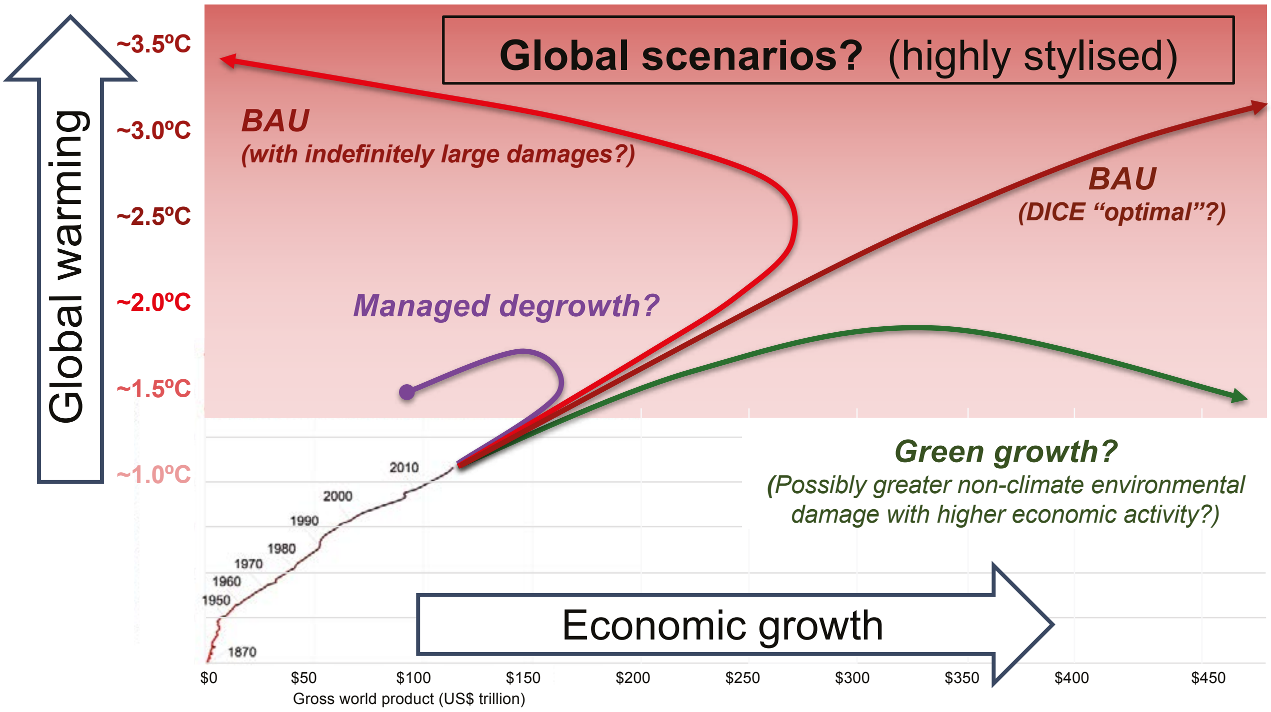

Figure 3.1. Qualitative illustration of diversity in literature on future scenarios for global temperature rise versus economic activity (gross world product). Historical data derived from CDIAC (2017), Bolt *et al.* (2018), Le Quéré *et al.* (2018), Rogelj *et al.* (2018) and World Bank (2019).

which indicate that such warming risks severe, potentially catastrophic, damage to global physical, human and ecological systems, beyond limits to adaptation (Field *et al*., 2014).

- *"Collapse" BAU with damages* scenarios indicate the possibility of mitigation failure and disorderly societal collapse due to growth overshooting biophysical limits (Meadows *et al*., 1972; Ehrlich and Ehrlich, 2013; Cumming and Peterson, 2017). Understandably, there is no coherent research understanding of potentially highly disorderly societal collapse outcomes, but it would be unwise to discount or ignore this possibility in scenario planning.
- *"Managed degrowth"* scenarios represent an urgent, radical transition, particularly in wealthy nations, to ensure the continuing viability of global society within limits (Trainer, 2012, 2020). Degrowth studies (D'Alisa *et al*., 2014; Hanaček *et al*., 2020) examine scenarios including coordinated management of climate action achieving globally equitable outcomes, often envisaging or requiring a significant reduction in energy use, and technology use that is comparatively less complex and/or extensive than that that is typical of current highly industrialised societies (Alexander and Yacoumis, 2018). Research suggests that enabling such a transition likely requires emergency mitigation measures from wealthy nations and stakeholders in the near term (Anderson and Bows, 2011; Oswald *et al*., 2020). Transition research therefore needs to identify and focus greater attention on unsustainable trends and their drivers (Antal *et al*., 2020).

In the face of such deep uncertainty across possible futures, effective scenario planning becomes critical to assess potential societal transition and climate damage risks within the Paris temperature limits, based on equity and best-available science, as well as cost considerations (Wilson, 1998; Amer *et al*., 2013). Ideally, the number of scenarios developed for policy assessment is limited to no more than six, but it needs to be large enough to provide useful insights into developing policies or responses to potential future outcomes (Coates, 2000; Börjeson *et al*., 2006). According to the original definition by Knight (1921), risk can be estimated on the basis of assessed statistical probability, whereas uncertainty cannot, although neoliberal economics literature misleadingly often fails to make this critical conceptual distinction (Derbyshire, 2017a). A key understanding for climate policy scenario assessment is that uncertainty regarding negative societal impacts due to the climate impacts of GHG emissions reduces the cost of precautionary early mitigation and increases the costs of delay (Lewandowsky *et al.*, 2014a,b). Derbyshire (2017b) suggests the use of Shackle's "Potential Surprise Theory", through which uncertainty is investigated by the unbounded use of scenario narratives that are deliberately defined to challenge existing thinking by starting from a basis of implausibility or maximum potential surprise.

The IPCC SR1.5 Chapter 1 framework for mitigation scenarios (Solecki *et al.*, 2018) offers informative guidance but lacks an explicit statement to direct the reasoned development of an evidenced policy strategy motivated by values and goals. Bunch (1983) sets out a practical, straightforward and easily applicable theory outline with four sequential steps: (1) a description of existing reality; (2) an analysis of why this current reality exists; (3) a vision of alternatives based on explicitly stated values and goals, and the range of possible futures; and (4) a strategy – a synthesis outlining alternative plausible scenarios to accomplish the vision. This theory outline foregrounds the deeply political and normative choices underpinning different societal and technical choices relevant to scenario development.

The SSECCM Technical Report details literature on the need for independent institutions to support societal action (Chapter 4 in Edenhofer *et al.*, 2014; de Coninck *et al.*, 2018: 15), commons responses (Jamieson, 2010; Ostrom, 2010), transition delay risks due to path-dependent lock-in (Unruh, 2000; Bertram *et al.*, 2015; Seto *et al.*, 2016) and incumbent vested interests (Dorsch and Flachsland, 2017; Johnsson *et al.*, 2019; Ellis *et al.*, 2019; Galvin, 2020). Lamb and Minx (2020) stress the urgency and importance of taking "a clear-eyed view of these political economic challenges" to motivate the rapid decisions, changes and experimentation needed, given the immense cost of failure. As recognised through the United Nations Sustainable Development Goals (SDGs) and in Irish policy, gender relations, agency and vulnerabilities are fundamental in climate action (Bee *et al.*, 2015; Zoloth, 2017). Hickel argues that the SDGs are contradictory, with Goal 8 – economic growth – being globally incompatible with the sustainability- and resource-oriented SDGs 6, 12, 13, 14 and 15, finding that SDG achievement could require radical near-term reductions in total energy use by high-income nations. Similarly, Hickel suggests that, although it "is theoretically possible to achieve a good life for all within planetary boundaries in poor nations", this would require that "…rich nations dramatically reduce their biophysical footprints by 40–50%". Reviewing gender research and feminist political ecology regarding climate change, Pearse (2017) concludes that women are at greater risk in societies undergoing climate disruption because of existing cultural and socioeconomic biases, and evidence shows that positive climate policy outcomes for women and men are improved by explicitly supporting greater agency and responsibility for women. The Paris Agreement context of urgency is too often left unconsidered in social science research (e.g. D'Alessandro *et al.*, 2020); as Gómez-Baggethu (2019) argues, political ecology and social science often continue to focus on technological change, overlooking the reality of the environmental pollution thresholds and planetary boundaries shown by physical and ecological science, and therefore fail to assess the potential for just and equitable effective policies within limits (Kallis, 2019). A growing body of literature indicates that supply-side measures to limit the total consumption of fossil carbon directly could have economic and political advantages, potentially attracting greater popular support as rationing within carbon limits can be seen by an informed public as inherently more equitable climate action (Green and Denniss, 2018; Erickson *et al.*, 2018; Le Billon and Kristoffersen, 2019).

3.3 Policy Solutions for Improving Transition Scenario Planning

Ireland's transition to a low carbon society, meaning effective climate change mitigation action aligned with the temperature limits of the Paris Agreement, implies an escalating urgency for early, deep and sustained emission reductions (Glynn *et al.*, 2018; McMullin *et al.*, 2019) affecting all of society in the use of energy and land (see also the illustrative GHG scenarios for Ireland described in Chapter 7 below). By contrast, the scenarios currently used in analysis and projection of Irish climate mitigation action tend to be narrowly based on economic policy preferences and aspirational policy targets without a stated Paris carbon budget context. Optimisation modelling in support of national climate mitigation policy tends to outline a single, notionally optimal pathway based on complex and non-transparent modelling, often overly reliant on proprietary data. To avoid costly surprises, including possible catastrophic impacts that could severely damage societal, environmental or ecological systems, Ireland would benefit from a wider basis of scenario planning and model assessment, using open data and transparent modelling to explore and prepare for potentially large societal impacts that could result from both radical mitigation policy action and escalating climate damage risks. If policy and policy outcomes show that such research advice is being ignored or inadequately adopted, as appears to substantially be the case to date, *ex post* research and policy assessment needs to critically assess the governance and research issues causing persistent policy failure (Howlett *et al.*, 2015; Price, 2015; Kenny *et al.*, 2018).

4 Modelling Issues in Transition Scenario Analysis

4.1 Literature Review

Most current Irish economy, emissions and energy modelling feeding into climate mitigation policy through the Technical Research and Modelling (TRAM) Advisory Group (DCCAE, 2019b) is directly reliant on neoclassical assumptions of equilibrium, particularly around projected constant long-term economic growth. This includes the Economic and Social Research Institute (ESRI) I3E model (de Bruin and Yakut, 2019), Sustainable Energy Authority of Ireland energy projections, the Irish TIMES energy system optimisation model[8] and Teagasc's FAPRI-Ireland agricultural policy modelling[9] (Teagasc, 2016). Typically, these models assume a long-term growth rate determined by the ESRI COre Structure MOdel of the Irish economy (COSMO) whereby "the variables do eventually converge to their long-run path as specified by [neoclassical] theory" (Bergin *et al.*, 2017) and assumptions of (national or sectoral) partial equilibrium. In Ireland, this theory basis also underpins the financial modelling feeding into governance (Kirby 2010; Bergin *et al.*, 2016), including policies aiming to achieve effective climate change mitigation. Therefore, it is important to consider recent literature showing major problems relating to such mainstream "neoclassical" economic theory and outlining alternatives. These critiques apply specifically in contexts in which model outputs are interpreted as forecasts. It is important to acknowledge that such use may not have been mandated by those developing or running these models; given this, the critique below is most properly directed towards those applying such model outputs beyond their intended scope.

Hendry (2018) is a seminal reference showing that mainstream (neoclassical) equilibrium economics and dependent model projections are fundamentally flawed by mistakenly assuming *ceteris paribus* stationarity (predictable responses) in system behaviour, whereas the real world is subject to intrinsic variation, lagged feedbacks and surprising outlier occurrences resulting in location shifts (abrupt changes in statistical distributions from previous econometric behaviour) due to a surprise event or unforeseen reactions. Fundamentally, mainstream theory mistakenly assumes static uniformity in distributions across a system and through time and tendency to equilibrium (Peters, 2019). Simplifying assumptions can form the basis of a useful model if they are still "skilful" in the sense of reflecting the actual behaviour of real-world systems; however, the 2008 global economic crisis exemplifies the phenomenon of forecast failure in neoclassical economics (Bezemer, 2010) and the superiority of non-equilibrium, input–output modelling such as Keen (2010) following the theory of Minsky (2016). Summarising the results of 30 years of work by Hendry and co-authors (Hendry and Doornik, 2014; Hendry and Pretis, 2016; Hendry and Muellbauer, 2018), Hendry (2018) provides strong theoretical and econometric evidence to conclude that "all equilibrium-correction models then systematically mis-forecast", which includes all computable general equilibrium (CGE), dynamic stochastic general equilibrium (DSGE) and partial equilibrium models relied on by central banks, economists, integrated assessment modellers and energy system modellers worldwide, including in Ireland. Hendry (2018) makes it clear that modelling based on imposing macroeconomic theory on reality and real data is doomed to general failure in forecasting, but some level of skilfulness can be attained through empirical model discovery, that is, simultaneous testing of theory- and data-driven approaches through a step-wise, "design of experiments" analytical approach of automatic model selection and discovery. Globally, the neoclassical economic growth model used by the DICE CBA climate IAM provides no skill in forecasting future techno-economic change (Millner and McDermott, 2016). Mercure *et al.* (2016) identify serious flaws in equilibrium and optimisation modelling. Trutnevyte (2016) comments that energy system optimisation models "gloss over uncertainty". Moreover, Pollitt and Mercure (2017) show that CBA in CGE models is biased against investments (such as climate

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[8] An Ireland-specific version of the more general TIMES (The Integrated MARKAL-EFOM System) model.

[9] Developed in collaboration with the Food and Agricultural Policy Research Institute (FAPRI) at the University of Missouri.

mitigation policy), because the current “equilibrium” is (questionably) assumed to be an efficient market making optimal use of resources. Similarly to Bezemer (2010), they find non-equilibrium, agent-based models can be far more responsive to policy change, but such models still need to be assessed for their skilfulness in adjusting to events and changed circumstances.

There is an extensive body of literature arguing that both neoclassical and Keynesian economics and their production functions violate basic laws of thermodynamics, failing to include energy (more specifically exergy, useful energy) as a non-substitutable input to production by land, labour or capital, and giving insufficient consideration to losses and waste or pollution (Daly, 2007; Ayres *et al.*, 2013; Keen *et al.*, 2019). Global trends since 1850 reveal an emergent societal efficiency–climate rebound feedback, with growing energy use and emissions at near constant rates of 2.4% per year and 1.8% per year, respectively (Jarvis *et al.*, 2012; see also, Garrett, 2012). This could ultimately reach thermodynamic limits when there is insufficient residual energy from energy efficiency savings to invest in additional infrastructure (Brockway *et al.*, 2019), but Jarvis (2018) suggests it is likely that climate damages to societal infrastructure may well be a much nearer-term threat.

Least-cost, cost–benefit and energy system optimisation modelling claims to find a single equilibrium mitigation pathway to maximise “utility” but typically fails to incorporate system inertia and feedbacks over time, thereby avoiding the high likelihood that there are in fact multiple divergent equilibriums and pathways that are highly dependent on past choices (Grubb and Wieners, 2020). This failure to include path-dependent behaviour – system rebound effects, inertia and mutual feedbacks between measures – likewise impairs the value of marginal abatement cost (MAC) curves (Kesicki and Ekins, 2012). Moreover, MAC analysis has been strongly critiqued for overlooking large early investments with long-term returns (Vogt-Schilb *et al.*, 2018) and for mis-ranking measures, especially those with supposedly negative costs (Taylor, 2012; Ward, 2014; Levihn, 2016). These flaws are often overlooked in policy use of MAC curves.

Nikas *et al*. (2019) provide a neoclassical typology detailing six common types of IAM climate–economy models in the literature. Kriegler *et al.* (2015) describe the type and modelling approach of the foremost energy–economy IAMs, but, notably, the equilibrium type (general or partial) listed for models differs in several cases from that listed in Nikas *et al.* Tavoni and Socolow (2013) contrast simulation models, such as the Global Change Assessment Model (GCAM) and the Integrated Model to Assess the Global Environment (IMAGE), which calculate separate equilibria for every time step, with optimisation models, such as the REgional Model of INvestments and Development (REMIND) and the World Induced Technical Change Hybrid (WITCH) model, which calculate a single, notionally cost-optimal pathway up to 2100, assuming perfect foresight and discount rates based on steady assumed economic growth. Even so, GCAM and IMAGE are still based on equilibrium assumptions subject to the same deficiencies.

In assessing the mitigation pathway outputs of IAMs, IPCC SR1.5 (Rogelj *et al.*, 2018) states that “limitations remain, as climate damages, avoided impacts, or societal co-benefits of the modelled transformations remain largely unaccounted for”; “[m]inimisation of mitigation expenditures, but not climate-related damages or sustainable development impacts, is often the basis for these pathways to the desired climate target”; and “none of the GDP projections in the mitigation pathway literature assessed in this chapter included the feedback of climate damages on economic growth”. Based on such modelling, climate transition policy measures are intrinsically assumed to be a net cost to economic activity, yet these models lack skilful costings of climate damage that could negatively affect the GDP assumptions that govern the costings. These are serious issues, as damages remain poorly defined and are likely to be omitted or underestimated by assuming economically negligible damages relative to discount rates (typically assumed to be 5% per year). Showing the effect of discounting on net-zero and carbon budget overshoot, Emmerling *et al.* (2019) find far lower discount rates of 2% or less to ensure intergenerational equity. This echoes the findings of earlier, overlapping-generations models from the 1990s (Howarth and Norgaard, 1990, 1992) that examined different levels of intergenerational capital transfer – a proxy for sustainable decision-making. Such transfers are ignored in partial equilibrium models and are excluded from general equilibrium models by untenably assuming a single, infinitely long-lived, representative agent. Much of climate economics and policy analysis finds steadily increasing carbon pricing to be optimal, yet economic modelling appropriate to risk assessment demands high upfront societal carbon costs as risk premium insurance, to guarantee early mitigation achievement and low carbon technology uptake and innovation so that carbon costs can fall only after mitigation is achieved, clarifying risk and damage costs (Daniel *et al.*, 2019). Therefore, IAM outputs may well fail to inform policy sufficiently by not reflecting the near-term climate risks indicated by physical science, that is, by underestimating climate damage impacts by extrapolating linear change when non-linear threshold changes are possible (Steffen *et al.*, 2015b); by failing to include tipping points or compound events (Zscheischler *et al.*, 2018); and by using inequitable discount rates or low carbon pricing that is inappropriate for limited carbon budgets (Drouet and Emmerling, 2016). These biases can reflect unfairness in decision-making by wealthier nations and non-state actors, allowing more vulnerable, often poorer, societies to face escalating risks (Knutti *et al.*, 2016).

4.2 Simulation and Non-Equilibrium System Modelling for Climate Policy

Simulation modelling aims to emulate and project the behaviour of real systems, often using input–output stock-flow analysis, including dynamic feedbacks, to examine multiple alternative policy scenarios, to aid decision-making. Moon (2017) reviews literature covering the three main types of simulation modelling: agent-based, discrete-event and system dynamics. Macal (2016) gives an overview of recent developments in the use and vocabulary of agent-based models, and Abar (2017) reviews and assesses a selection of related software. An informative set of articles in a special journal issue (Kunc *et al.*, 2018) surveys developments in system dynamics and multi-method approaches. A notable recent contribution is Minsky, a new system dynamics modelling software package (Standish and Keen, 2020) that has been used at the national level for Portugal. An insightful article by Lund *et al.* (2017) contrasts the very different theoretical approaches of optimisation and simulation, particularly in energy system modelling, noting that both methods involve value judgements in setting parameters. In optimisation, investment or policy decisions for system development are determined endogenously, within a prescriptive analytical model, on the basis of parameters such as least notional cost over time to notionally optimise system design; whereas, in simulation, decisions are determined exogenously to assess a system performance descriptively under certain specified scenario assumptions (Lund *et al.*, 2017). Noting the recent Danish political and policy context, Lund *et al.* (2017) argue that "[w]hereas optimisation modelling may turn the role of politics into administration, the use of simulation models and the model-external evaluation of scenarios leaves more room for the political decision-making processes", concluding that simulation models are superior for the presentation of long-term policy options.

4.3 Policy Solutions: Recognising Model Limitations and Increasing Use of Simulation

Results from all types of modelling should be presented with due caution. The literature evidences major problems with the neoclassical economic theory basis that supports most current modelling feeding into climate mitigation decision-making that require more explicit and prominent recognition, because flawed assumptions and unstated limitations in such models propagate into dependent energy system models and energy and emission projections. ESRI documentation for the neoclassical COSMO and the Ireland Environment, Energy and Economy (I3E) models (ESRI *et al.*, 2019) problematically fails to acknowledge the evidence showing that neoclassical assumptions and equilibrium methods are subject to systematic bias and forecast failure. Despite the serious problems identified in MAC analysis (Ward, 2014; Vogt-Schilb *et al.*, 2018), it continues to be widely used in policy advice in Ireland, as in the Climate Action Plan (DCCAE, 2019a) and Teagasc recommendations (Schulte *et al.*, 2012; Lanigan and Donnellan, 2018), without due cautionary statements of MAC limitations. More precautionary framing and openness would be advisable if MACs are to be used to support policy. Estimated climate damage costs and negative impacts on global growth, and therefore on Ireland's open economy, could well be far higher than has been assessed by IPCC Fifth Assessment Report (AR5) Working Group III (Edenhofer *et al.*, 2014). Best-practice transition modelling could include precautionary estimates in the costs of continued emission-causing activities. These issues imply that scenario planning needs to explore radical mitigation and adaptation futures using a wider basis of non-equilibrium simulation models and integrated model types (Scoones *et al.*, 2017) that can combine interdisciplinary insights and overlapping models to support radical transition. Greater use of simulation modelling, particularly incorporating system dynamic models, can be more appropriate in scenario planning exploration of multiple what-if narrative scenario alternatives within the context of Paris Agreement and SDG commitments.

5 International Climate Mitigation Scenario Literature

5.1 Literature Review

5.1.1 Extending the shared socioeconomic pathway framework

A comparatively small body of literature describes the extension of the global shared socioeconomic pathway (SSP) framework to assess climate impacts, vulnerability and adaptation at regional, national and sub-national levels (Absar and Preston, 2015; Nilsson *et al.*, 2017; Cradock-Henry *et al.*, 2018; Kebede *et al.*, 2018; Reimann *et al.*, 2018), although these approaches do not appear overly useful in designing scenarios to explore mitigation at the national level. Frame *et al.* (2018) describe the downscaling of global SSPs and shared climate policy assumptions as a credible basis and context for national mitigation and adaptation scenario development and robustness testing. They stress the need for multidisciplinary teams and the inclusion of local actors and civil society to build coherent, evidence-based policy action with wide support (see also Lorek and Fuchs, 2013). Kok *et al.* (2019) propose a specific approach to downscaling SSPs, applying this at a continental scale (specifically to Europe) while highlighting continuing methodological challenges.

5.1.2 Deep Decarbonisation Pathways Project

The Deep Decarbonisation Pathways Project (DDPP) was established as a global initiative supporting research to provide a shared research framework for the production of 2°C-consistent national mitigation pathways (Bataille *et al*. 2016). Country teams from 16 nations each developed a set of national deep decarbonisation pathways based on economy-wide analysis with sectoral disaggregation; long-term time frames, initially only to 2050; and a detailed description of the transition pathway of energy supply and demand, including energy efficiency, electricity decarbonisation and switching to low-carbon energy (SDSN and IDDRI, 2015; Bataille *et al*., 2016). Two summary DDPP reports were produced – the 2014 report *Pathways to Deep Decarbonisation* (SDSN and IDDRI, 2014) and the 2015 synthesis report *Pathways to Deep Decarbonisation* (SDSN and IDDRI, 2015). The 2014 report states that “in general, we are interested in global pathways that are ‘likely’ to stay below 2°C” (the use of “likely” here is usually defined as “a probability of two-thirds or higher” by the IPCC). However, the DDPP scenarios are based on the International Energy Agency 2°C scenario (2DS), using global and national emissions pathways that assume only a 50% chance of 2°C – a target with a much higher global carbon budget than for a 66% chance. Waisman *et al*. (2019) acknowledge that the DDPP’s “as likely as not” probability of 2°C was a less ambitious objective than that adopted in the Paris Agreement; nonetheless, they argue that the DDPP framework methodology is important for producing coherent, comparable and useful national scenarios.

5.1.3 COP21-RIPPLES

The COP21-RIPPLES project, a follow-up to the DDPP, is funded by the EU to examine the implications of the Paris Agreement for EU deep decarbonisation. It also examines coherent Paris-aligned scenarios based on country-level teams from Germany, France, the UK, Italy and non-EU nations – Brazil, China and South Africa (DDPP, 2017). Unlike the original DDPP, the multidisciplinary RIPPLES project does not appear to foreground a strong focus on meeting a cumulative carbon budget or equity; instead it focuses on “carbon neutrality” after 2050 and a reduction in the carbon intensity of GDP. These weak objectives do not explicitly target reaching net-zero CO_2 emissions by a specified date or limiting emissions within equitable national carbon quota shares of a Paris-aligned global carbon budget.

5.1.4 PATHWAYS project

The EU-funded PATHWAYS project looked at transition pathways using a framework encompassing three research approaches that aimed to be mutually informative: (1) quantitative system modelling to compare scenarios; (2) socio-technical transition analysis to investigate the potential for niche innovation; and (3) case studies of practice-based action research (Hof *et al*., 2017). Three idealised scenarios were described: (1) the current trajectory, with only incremental change; (2) an incumbent-led trajectory enabling rapid technological change; and (3) a radical transformative system and citizen change trajectory led by government, new entrants and civil society (Turnheim and Berkhout, 2016). Both change scenarios “imply substantial and urgent departure from existing trends”, requiring an explicit statement of options as a basis for sociopolitical choices. A structured societal dialogue between alternative approaches could resolve conflicts and generate local insights (Turnheim *et al*., 2015; Turnheim and Berkhout, 2016).

5.1.5 Dialogue on European decarbonisation strategies

The dialogue on European decarbonisation strategies (DEEDS) project (DEEDS, 2017) coordinates expert sectoral research and innovation groups in support of the High-Level Panel of the European Decarbonisation Pathways Initiative (European Commission, 2018) that assists the European Commission in preparing decarbonisation research, policy and legislative proposals. A DEEDS workshop report, *Decarbonising the Energy Sector Through Research & Innovation* (DEEDS, 2019), notes the four illustrative IPCC SR1.5 model pathways and the EU *Vision for a Clean Planet by 2050* pathway, but it does not suggest or derive any equitable, Paris-aligned aggregate quota or sectoral carbon quotas within which aggregate or by-sector decarbonisation is likely to occur.

5.1.6 MEDEAS: a system dynamics, non-equilibrium model to guide transition

Modelling Energy Development under Environmental And Socioeconomic constraints (MEDEAS) is an EU-funded, multidisciplinary, open-source, energy–economy emissions simulation model, which has been applied to date at global, European and national levels for Austria and Bulgaria (Capellán-Pérez *et al*., 2019, 2020). As outlined in Figure 5.1, this hybrid top-down/bottom-up model applies a system dynamics basis capable of modelling non-linear system change and feedbacks – physical flows of energy, food and material quantities are modelled between and within eight modules. Unlike supply-led optimisation modelling (based on equilibrium substitution between capital, labour and technologies), the MEDEAS

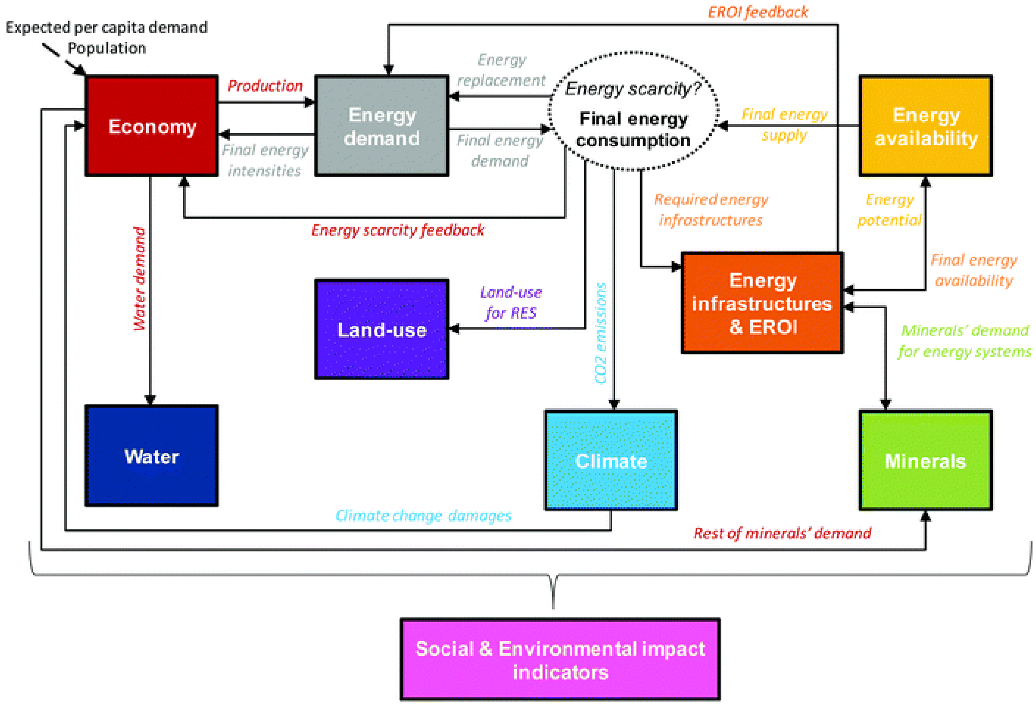

Figure 5.1. Schematic of MEDEAS-World model modules and linkages. EROI denotes energy return on investment; RES denotes renewable energy supply. Source: Capellán-Pérez *et al.* (2020). Published by the Royal Society of Chemistry and reproduced under the terms and conditions of the Creative Commons attribution licence CC BY 3.0 (https://creativecommons.org/licenses/by/3.0/).

system dynamics model is demand-led and supply-constrained, resulting in disequilibrium (post-Keynesian) macroeconomics linked to biophysical input–output analysis of sectors and fuels over time, based on defined flows and stock quantities rather than notional prices (de Blas *et al.*, 2019). MEDEAS is unusual in that it incorporates climate change impacts, energy and material availability, and declining energy return on energy investment, as endogenous system feedbacks that act as limits to growth (Capellán-Pérez *et al.*, 2019, 2020).

5.1.7 UK Committee on Climate Change Net Zero

In 2019, the UK Committee on Climate Change (CCC) published a major policy advisory report entitled *Net Zero: The UK's Contribution to Stopping Global Warming* (CCC, 2019a) with a supporting technical report (CCC, 2019b) that is further evidenced by 2018 CCC reports on hydrogen, land use and biomass. As shown in Figure 5.2, the *Net Zero* report details a core scenario meeting an 80% reduction in emissions (global warming potential over 100 years – GWP_{100} – basis) by 2050, and a further ambition scenario for the UK meeting a reduction of more than 90%. According to the CCC, reaching net-zero annual aggregate GHG emissions (GWP_{100} basis) as early as 2050 is possible, but it would depend on at least some speculative options to achieve additional reductions, such as radical reductions in aviation demand, dietary change away from ruminant meat and dairy, large-scale use of synthetic carbon neutral fuels, and development of so-called "negative emissions technologies" (NETs) at scale, such as direct air capture and removal of CO_2 from atmosphere. This "net zero by 2050" target is said to represent a substantial increase in ambition and urgency from the previous target of an 80% reduction in GHG emissions by 2050 (relative to 1990). The main policy levers for increased ambition are a quadrupling of low-carbon electricity, efficiency improvement, electrification, and increased reliance on the use of CCS and low-carbon hydrogen. Increased ambition is made possible through greater industry CO_2 abatement; more use of syn-fuels and hydrogen for energy storage from variable renewables; all buildings becoming low carbon by 2050; dietary change away from beef and dairy, enabling changes in agricultural practices; and the inclusion of land use, and aviation and shipping in carbon budget pathways. In addition to greater land carbon storage through increased afforestation and soil carbon sequestration, engineered negative emissions utilising CCS have a key role to play in "all currently credible pathways" (CCC, 2019a).

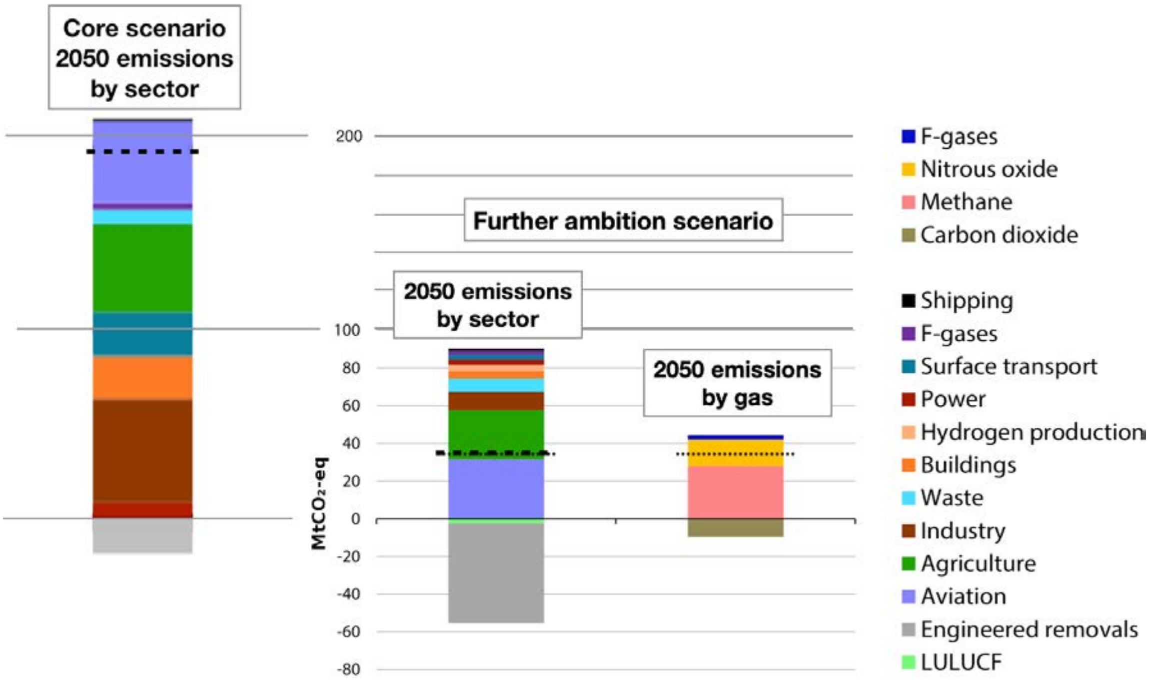

Figure 5.2. Comparison of emissions in the CCC *core* and *further ambition* scenarios. LULUCF denotes land use, land use change and forestry. Source: adapted from: CCC (2019a).

The CCC report states that achieving the net zero by 2050 target “would end the UK’s contribution to rising global temperatures” (CCC, 2019a, p. 16) and that this target “meets fully the requirements of the Paris Agreement, including the stipulation of ‘highest possible ambition’” (CCC, 2019a, p. 8). However, in subsequent grey literature commentary, other researchers have critiqued this assertion (Anderson, 2019; Blakey and Hudson, 2019; Bullock, 2019). The CCC advisory group of external experts concluded that net zero by 2050 is technically achievable, but it was concerned about the political capability to achieve a fundamental change in policy and societal approaches (Watson, 2019).

5.1.8 Zero Carbon Britain

Zero Carbon Britain, developed by a team at the Centre for Alternative Technology, was initially devised as a single narrative scenario in which net-zero CO_2 emissions from the UK are achieved within 20 years by reducing total energy demand and greatly increasing renewables (Helweg-Larsen *et al.* 2007). Societally equitable well-being is given precedence over BAU growth, accepting a possible need for economic degrowth to enable sustainable outcomes. Further publications describe decarbonisation employment benefits (Kemp, 2010), a zero carbon energy model for the UK (Hooker-Stroud *et al.*, 2014), an analysis of low carbon diets (Allen *et al.*, 2013), sectoral change (Toms *et al.*, 2017) and decarbonisation case studies (Allen and Bottoms, 2018).

5.1.9 UK FIRES Absolute Zero

The UK FIRES *Absolute Zero* report (Allwood *et al.,* 2019) examines a pathway to zero emissions via incremental changes starting from today’s technologies through electrification of energy and major reductions in meat consumption. In contrast to the CCC, a near-complete phase out of fossil fuels before 2050 is required, constraining energy use and resulting in serious bottlenecks in aviation and shipping to the point of shutdown until renewable production of synthetic fuels becomes possible. Through dietary change, beef and lamb production and consumption are to be phased out by 2050 to limit CH_4 emissions. Bioenergy production is severely limited by biodiversity and agricultural land limitations. This report sees substantial opportunities for industry and innovation in this transition, with sectors growing once more after 2050 as zero carbon energy availability grows.

5.1.10 Other climate mitigation scenarios and national planning literature

Delina and Diesendorf (2013) conclude that, as in wartime, an executive government including a “ministry for transition”, with separate, independent mitigation-focused institutional oversight to specify limits and timelines, is a strong governance model, provided it has wide public support. They warn that a focus on adaptation is likely to result in “‘quick fix’ antidotal approaches” that are attractive to policymakers but fail on climate mitigation.

A report by Höhne *et al*. (2019) finds that the EU has already exhausted its fair share of cumulative GHG emissions, given the higher level of ambition required by the Paris Agreement. It recommends that the EU reach effective net-zero GHG emissions around 2030 to 2040 (on a GWP_{100} aggregation basis), with net negative emissions of $-2.5\,Gt\,CO_2$-eq (carbon dioxide equivalent) by 2050 and only very limited reliance on carbon “trading” beyond the EU territorial boundaries. Most recently, the European Commission has summarised its climate action strategy in the form of a proposed European Green Deal that includes the adoption of an EU-wide net-zero GHG emissions goal, albeit only by 2050.

New Zealand’s climate act (New Zealand Government, 2019), with input from climate scientists (ICCC-NZ, 2019), provides an important reference for Ireland, given that the country has a similar population and a comparable emissions profile with substantial ruminant agriculture.

5.2 Policy Solutions

The international literature surveyed for this review is surprisingly lacking in scenarios explicitly aligned with producing GHG mitigation pathways corresponding to equitably limiting emissions aligned with the United Nations Framework Convention on Climate Change (UNFCCC) and SDG targets. These commitments provide a crucial context in which good faith stakeholders would need to achieve decarbonisation, yet they often appear to be secondary to economic and energy growth assumptions (Anderson *et al.*, 2020). Therefore, a key recommendation from this literature review is that best-practice climate action-related research and policy advice contextualises scenarios and findings in terms of fair share climate action with regard to both equity and emissions relative to the limited remaining GHG and CO_2 global carbon budget. What constitutes a national fair share of global mitigation action is subject to strong contestation, but research and policy omitting such a context effectively denies the acknowledged importance of intergenerational fairness and climate justice.

Economic modelling uses costs as a proxy for resource scarcity, whereas climate impacts directly depend on actual uses of total fossil carbon and reactive nitrogen (de Blas *et al.,* 2019). Simulation modelling can examine scenario outcomes based on input quantities of direct climate change drivers (amounts of fossil carbon and reactive nitrogen) and resulting emission quantities by gas and aggregate resultant warming. Possible Irish implementation of the MEDEAS and Minsky or similar models is therefore an opportunity for further research into supporting policy choices. It is recommended that this should be actively considered in scoping any potential large-scale research project to explore national, society-wide, Paris-aligned, decarbonisation scenarios.

6 Key Greenhouse Gases: Properties, Drivers and Policy

6.1 Ireland's Greenhouse Gas Emissions Profile

This chapter provides context for the preliminary modelling detailed in Chapter 7. Table 6.1 gives the current UNFCCC- and EU-mandated conversion metrics (GWP_{100}) to yield CO_2-eq values. The table also shows Irish emissions of the main three GHGs, compared on this CO_2-eq basis (EPA, 2019a).

Ireland continues to be heavily reliant on fossil fuel combustion to supply over 90% of its energy used in electricity generation, heating and transport. Together with cement production (which also produces CO_2), this results in emissions of over 38 Mt CO_2/y (SEAI, 2018). Oil is the form of fossil energy used predominantly in transport and domestic heating (especially in rural areas), while natural gas, coal and peat are used in electricity generation and heating. Coal and peat consumption have been declining because of reduced use in electricity generation. However, based on an analysis of the draft National Energy and Climate Plan (NECP), overall fossil fuel CO_2 emissions are still projected to continue at approximately the current annual level, possibly even up to 2040 (McMullin and Price, 2019). According to Ireland's inventory reports to the UNFCCC, the land use and forestry sectors (exclusive of agriculture) also currently contribute significant net CO_2 emissions at a rate of about 4.3 Mt CO_2/y.

Ireland's overall GHG emissions profile is unusual in having a comparatively large fraction of non-CO_2 GHG emissions, primarily from the agricultural sector. Agriculture is the source of 93% of N_2O emissions and 93% of CH_4 emissions. Agricultural N_2O and CH_4 emissions are strongly linked through the use of nitrogen fertiliser to increase grass and silage production for ruminant agriculture (Duffy *et al.*, 2019). Figure 6.1 charts historical trends in agricultural GHG emissions and nitrogen fertiliser usage, showing this strong correlation.

6.2 CO_2 Global Context: Emissions from Fossil Fuel, Industry and Land Use

In IPCC SR1.5 (Rogelj *et al.*, 2018), remaining global cumulative CO_2 budgets (GCBs) from the beginning of 2018 that are likely to meet Paris targets are stated in Chapter 2, Table 2.2, as 420 Gt CO_2 for limiting warming to 1.5°C, and 1170 Gt CO_2 for limiting warming to 2°C. Of global annual CO_2 emissions in 2011, about 87% came from fossil fuel and industry and about 12% from land use. Global fossil fuel combustion and industry emissions of CO_2 are the single largest human cause of global temperature rise. The climate-forcing effect of CO_2 emissions is extremely long-lasting: an "approximation of the lifetime of fossil fuel CO_2 for public discussion might be '300 years, plus 25% that lasts forever'" (Archer, 2005). Annual global emissions of the long-lived climate forcers (LLCFs), CO_2 and N_2O, need to reduce to zero to stabilise the level of such gases in the atmosphere and thus limit the level of warming (Allen *et al.*, 2018a). Limiting to a particular temperature requires staying within a directly corresponding total of *cumulative* emissions of CO_2 (the GCB) *as well as* achieving strong reductions in emissions of non-CO_2 GHGs. Global net emissions of CO_2 deplete the remaining GCB. Global net CO_2

Table 6.1. Major climate forcers by class, lifetime and GWP_{100} value

Forcer	Abbreviation	Class	Lifetime (years to reduce by about 63%)	GWP_{100}	Ireland 2017 emissions (Mt CO_2-eq)
Carbon dioxide	CO_2	LLCF	> 300	1	43.6
Nitrous oxide	N_2O	LLCF	114	298	7.2
Methane	CH_4	SLCF	12	25	14.7

LLCF, long-lived climate forcer; SLCF, short-lived climate forcer.

Sources: UNFCCC GHG characteristics from Myhre *et al.* (2013, Appendix 8.A) and Environmental Protection Agency emissions data from Duffy *et al.* (2019).

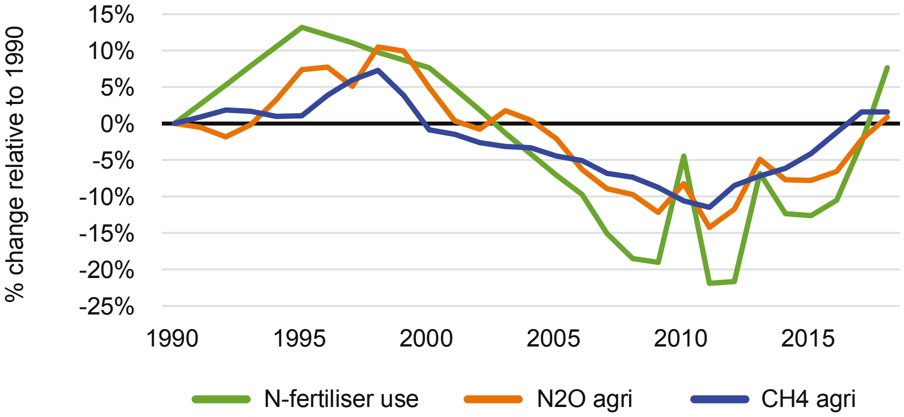

Figure 6.1. Changes in Irish agricultural CH_4 and N_2O emissions, and nitrogen fertiliser use, since 1990. Chart created for this report, using data from the Environmental Protection Agency (EPA, 2019b).

removals from the atmosphere would be needed to return from any overshoot of the GCB. Although this suggests a focus on cumulative *net* CO_2 emissions at both global and sub-global levels, research also strongly indicates that national policy should maintain a clear separation in emissions accounting between gross emissions and gross removals, with projected removals clearly identified as land-based or geological via CCS (Peters and Geden, 2017; Geden *et al.*, 2018; McLaren *et al.*, 2019).

Although land would naturally represent a net sink for CO_2, human-caused land use change results in global net emissions of approximately 5 Gt CO_2/y, from deforestation in particular. Land carbon stocks can be thought of as “slow in, rapid out” (Körner, 2003): soils and plants take up carbon over decades (up to some saturation level), but land carbon is vulnerable to rapid re-release by human interventions (ploughing or forest harvesting) or natural disturbances (drought or fire) – both of which may be exacerbated by human-caused global warming (Valade *et al.*, 2017). The potential impermanence of the land carbon storage relative to the permanence of unextracted fossil carbon greatly limits its mitigation contribution (Mackey *et al.*, 2013; Fuglestvedt *et al.*, 2018; Kim *et al.*, 2008), while the scale of potential indigenous land-based storage in Ireland is also strongly constrained by competing land uses. The EU accounting convention that states that bioenergy is “carbon neutral” (EU, 2018) has been strongly contested on multiple grounds (EASAC, 2017; Alexandrov *et al.*, 2018; Searchinger *et al.*, 2018). Likewise, the “4 per 1000” initiative[10] aiming to greatly increase soil carbon sequestration (Minasny *et al.*, 2017; Smith *et al.*, 2019) has been severely criticised as potentially distracting from the urgent need for rapid fossil fuel CO_2 mitigation (Thamo and Pannell, 2016; Poulton *et al.*, 2017; Amundson and Biardeau, 2018; Baveye *et al.*, 2018).

6.3 N_2O Emissions and Reactive Nitrogen

N_2O is a potent GHG that also causes loss of stratospheric ozone. With an atmospheric half-life of 120 years, it can be counted as an LLCF on a similar basis to CO_2. Pre-industrial N_2O emissions and removals were in balance, but human activity has pushed the global nitrogen cycle beyond a “safe” planetary boundary (Steffen *et al.*, 2015b). Agriculture is the major anthropogenic source of N_2O because of nitrogen fertiliser use and manure production (Reay *et al.*, 2012). Historically, food production was dependent on natural plant fixation of unreactive atmospheric nitrogen into reactive nitrogen (Nr), but the invention of the Haber–Bosch process has resulted in massive disturbance to the nitrogen cycle (Galloway *et al.*, 2014). Global use of synthetic nitrogen fertiliser increased by about 800% from 1961 to 2015 (Davidson, 2009; Lu and Tian, 2017). Over the same period, cereal yields increased by 200% and ruminant livestock numbers increased by 65% (Figure SPM.1 in IPCC, 2019). Top-down global input–output and life cycle analysis shows that about 3–5% of Nr from fertiliser and manure is converted to

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[10] https://www.4p1000.org/ (accessed 3 September 2020).

N_2O (Smith *et al.,* 2012). Synthetic nitrogen fertiliser not only increases both grass and feed production, but also results in increased climate emissions and environmental pollution damages. This can then be further exacerbated by animal agriculture, from feed and grass inputs to digestion and excreta (Thompson *et al.*, 2019). The European Nitrogen Assessment (ENA) provides an extensive and exhaustive review of the regional use of Nr. The ENA reports provide strong, evidence-based policy recommendations to limit Nr impacts (Sutton, 2011). The ENA estimates the overall environmental cost of Nr pollution in Europe at €70–320 billion per year, which is equivalent to €150–750 per capita, outweighing the benefit of its use in cost terms (Brink *et al.*, 2011).

6.4 CH_4 Emissions and Mitigation

CH_4 is the second most important human-mediated GHG in terms of the radiative forcing effect (Myhre *et al.*, 2013). Despite its short atmospheric lifetime, CH_4 atmospheric concentration has increased significantly over pre-industrial level owing to human activity, and it continues to rise. This has been caused by rising annual emissions, including fugitive emissions from coal mining and natural gas extraction, and from agriculture, particularly ruminant livestock and rice production systems (Fletcher and Schaefer, 2019). Reductions in fossil fuel use would *also* result in significant associated reductions in ongoing fossil CH_4 emissions (Rogelj *et al.*, 2015). Sustained CH_4 reductions should be regarded as complementary rather than alternatives to early, deep CO_2 mitigation (Shoemaker and Schrag, 2013; Pierrehumbert, 2014). Nonetheless, the importance of mitigation action to reduce emissions of *all* climate forcers is evident in assessing Paris goals (Fuglestvedt *et al.*, 2018).

Trends in Irish CH_4 emissions echo N_2O trends and reflect nitrogen fertiliser use (Duffy *et al.* 2019). Beef and dairy agriculture is the primary driver, responsible for 93% of Irish CH_4 emissions (Duffy *et al.* 2019). Intensive dairy farming has expanded rapidly since 2011. According to Environmental Protection Agency (EPA) data, dairy cow numbers reached 1.4 million in 2017, an increase of 0.35 million compared with 2011, and beef cattle numbers reached 5.9 million, an increase of 0.5 million compared with 2011 (Tables 3.3.A, B and C in Duffy *et al.*, 2019). Leakage of fossil CH_4 from the natural gas grid is assessed as relatively low in Ireland. However, current Irish policy proposals envisage an expanded CH_4 gas grid, which would likely increase total fugitive losses (Ervia and Gas Networks Ireland, 2019).

Anaerobic digestion (AD) plants enable the conversion of agricultural waste to produce CH_4 (biomethane) and digestate, which can be used as fertiliser with due care (Nkoa, 2014). However, CH_4 losses through leakage and the lifecycle climate effect of Nr inputs to feedstocks can undercut the sustainability of biomethane in terms of EU rules, even at low leakage rates of 2% (Liebetrau *et al.*, 2017). Some other studies of AD plant leakage (Baldé *et al.*, 2016; Liebetrau *et al.*, 2017) conclude that AD is a positive climate mitigation measure, even at higher CH_4 leakage rates of up to 7–12%. These studies generally assume that “negative emissions” credits are due to AD for avoided CH_4 emissions arising from associated changes in manure management. However, this interpretation of “negative emissions” is contrary to and risks confusion with the more usual climate science meaning of requiring GHGs to be physically removed from the atmosphere and secured in some very long-term form of storage (Tanzer and Ramírez, 2019).

6.5 Greenhouse Gas Mitigation Solutions

Aligning climate action with the aggregate GHG pathways (especially including N_2O and CH_4) as assessed by the IPCC for Paris-aligned climate action has major implications for society-wide policies in Ireland. Limiting fossil carbon inputs and land use carbon loss is key to CO_2 mitigation. This equates to achieving radical reductions in unabated (non-CCS) CO_2 emissions from fossil fuel combustion and planning for annual land use CO_2 emissions to reach net zero and become net negative (removals) as soon as possible. For developed nations such as Ireland, respecting climate justice also implies earlier and deeper action to achieve substantial and sustained reductions in emissions across all GHGs than global averages suggest.

The ENA is an essential policy reference to limit and budget reactive agricultural nitrogen usage, to minimise the cascade of adverse effects. Existing nitrogen-limiting policies are incoherent and inadequate. Therefore, further measures are needed as a matter of urgency. Over the period from 1998 to 2011, the milk quota ensured that local efficiency increases in dairy production resulted in reduced national Nr usage (and fewer cattle) and lower agricultural GHG emissions. Irish agri-food policy since 2010 has leveraged increased usage of imported synthetic nitrogen fertiliser and feeds. On-farm carbon efficiency assessments such as the Carbon Navigator (Murphy *et al.,* 2016) have generally resulted not in material reductions in absolute GHG emissions but in cost-savings that are reinvested into increasing total production, and ultimately *increasing* absolute emissions. Therefore, Ireland provides a clear example showing that national policy change can very effectively *either* mitigate *or* exacerbate Ireland's total agricultural emissions by respecting or removing production limits. Regulated, declining inputs of pollution drivers would reduce the current overshoot of prudent nitrogen use while potentially increasing total employment in more labour-intensive, more nitrogen-efficient horticultural food production and tillage. Facilitating a just transition for farmers and rural society to lower GHG agricultural systems, without compromising production of food nutrition, could contribute to global and national food security. It could also enable a lower-cost pathway to energy emissions mitigation by allowing a somewhat longer energy transition period. Conversely, delaying such changes in agricultural practice could significantly compromise society-wide climate action.

7 Preliminary Modelling of Illustrative Greenhouse Gas Scenarios

7.1 Introduction: Basis and Access to the Project GHG-WE Tool

Different transition pathway scenarios are possible for Ireland in the context of a *fair share,* national carbon quota (NCQ) of a GCB aligned with Paris Agreement objectives. Earlier research for the IE-NETS project (McMullin *et al.*, 2020) concluded that Irish overshoot of a CO_2-only, *minimally equitable* NCQ from 2015 is likely to occur as early as 2025. Therefore, in addition to reducing gross CO_2 emissions as quickly as possible, limiting such overshoot implies a tacit commitment to progressively implementing CO_2 removal (CDR) from the atmosphere into secure long-term storage. A practical upper policy limit on the possible future level of achievable CDR was estimated at no more than about 200 Mt CO_2 (McMullin *et al.*, 2020). This poses a very severe challenge for Ireland to now achieve its Paris commitment to a fair share of global mitigation action. However, given Ireland's unusual emissions profile, with comparatively large non-CO_2 emissions, a proper assessment of fair share action requires a methodology that can appropriately reflect and integrate the cumulative warming effects of CH_4 and N_2O, as well as just CO_2.

This chapter describes the use of a spreadsheet tool developed for this project called "GHG-WE", which incorporates the recently developed GWP* metric (Allen *et al.*, 2018b; Cain *et al.*, 2019; Lynch *et al.,* 2020) to aggregate short-lived CH_4 with long-lived CO_2 and N_2O, to enable a cumulative CO_2-we (carbon dioxide warming-equivalent) comparison of policy scenarios. The GWP* metric itself has not yet been adopted for any particular policy use and its methodologies are still in development.[11] However, its use in global scenarios is described and illustrated in IPCC SR1.5 Chapter 1 (Allen *et al.*, 2018a) and recommended by Lynch *et al.* (2020) as a link between reported cumulative CO_2-eq emissions and warming impacts. GWP* enables the net global warming contribution of policy options – by GHG and in aggregate – to be shown in terms of cumulative CO_2-we from a reference date up to a given time horizon, such as peak warming or 2100. Scenarios can then be constructed or adjusted to meet an illustrative all-GHG NCQ share (denoted NCQ*, as it includes CO_2, N_2O and CH_4) of a peak global all-GHG GCB (denoted GCB*) relevant to the agreed Paris Agreement objectives and temperature limits. For the preliminary, nation-level modelling in this chapter, climate forcers other than CO_2, N_2O and CH_4 are omitted from consideration, as they are judged to be less important in absolute terms. In addition, CO_2 is input in net terms, without disaggregation among emissions (fossil fuel, industry or land use CO_2) or removals (land use or technological CO_2). In future, the tool and methodology could be extended to include disaggregated CO_2 sources and sinks as separate inputs, to enable alternative policy mix options for CO_2.

The GHG-WE tool scenarios and results presented here are intended as a coarse-grained "proof of concept" to assess the usefulness of such a tool for policy-relevant scenario analysis and comparison. An open source Excel workbook for the tool has been made publicly available so that users can explore mitigation options and improve and extend its usefulness. A "methane warming calculator" has also been made publicly available to assist users in understanding the effect of CH_4 mitigation policy changes, by specifying an existing source of CH_4 and then making policy changes by specifying per cent per year change rates over a set period of time, and generating output charts showing the resultant change in CH_4 warming.

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[11] The tools developed for the current project incorporate the different but equivalent mathematical formulations of GWP* in Cain *et al.* (2019) and Lynch *et al.* (2020), but use the GWP_{100} value of 34 for CH_4, including climate–carbon feedbacks as per Table 8.7 in Myhre *et al.* (2013).

7.2 The GWP* Metric Enables Policy-relevant Scenario Comparison Including Non-CO_2

Comparing alternative global or national policy scenarios in terms of their aggregate effect on global warming is challenging because both LLCFs and short-lived climate forcers (SLCFs) should ideally be included in scenario assessment. This is most relevant in nations such as Ireland and New Zealand where the emissions profile includes a large fraction of non-CO_2 emissions. GHG equivalence metrics integrating forcing over time (such as GWP) and end-point metrics indicating temperature change after a stated number of years (such as global temperature potential – GTP) are commonly used to equate the effect of pulses (such as a year's emissions) of different GHGs (Balcombe *et al.*, 2018; Collins *et al.*, 2019). Each of these metrics correctly represents those aspects of the climate system response that they are designed to capture. However, this does not imply that cumulative aggregate emissions calculated by using each metric map closely onto global mean temperature increase (in a manner directly comparable to that of cumulative CO_2 emissions), and in general they do not (Allen *et al.*, 2016). A series of papers (Allen *et al.*, 2018b; Cain *et al.*, 2019; Lynch *et al.*, 2020) have progressively developed a new methodology and metric, denoted GWP*, that does approximate global mean temperature increase stemming from cumulative aggregate emissions of both LLCFs and SLCFs. The method enables the calculation of annualised so-called "CO_2-we" emissions for non-CO_2 GHGs for each year in a time series, given at least 20 years of SLCF values prior to the first year of interest. The methodology is designed and calibrated so that the global mean temperature increase that would arise because of such a non-CO_2 emissions time series is well approximated by the temperature increase that would be associated with the same cumulative emissions of CO_2 only. Cumulative CO_2-we emissions calculated by using GWP* represent the strong initial warming *flow* climate forcing effect of *changes* in CH_4 annual emissions and the limited but still important long-term warming due to its cumulative *stock* forcing effect. Note that earlier versions of GWP* did not adequately capture the latter long-term stock effect; thus, it is important to apply the *most* recent method and parameters (Lynch *et al.*, 2020). For any single year, summing the CO_2-we values for CO_2, N_2O and CH_4 indicates that year's additional contribution to global warming. This could be negative if warming reduction due to CH_4 mitigation exceeds warming increase due to CO_2 and N_2O. Cumulatively from a specified date, the aggregate total CO_2-we emissions are proportional to a scenario's aggregate additional GHG warming contribution over that time period. This method can be used to constrain the *warming contribution* of national policy scenarios, to be consistent with a specified national "fair share" of *global* temperature increase, based specifically on the Paris Agreement global temperature goals. In essence, this means constraining the cumulative aggregate CO_2-we emissions of such national policy scenarios to a stated, national, "fair share" quota of the all-GHG *global cumulative GHG (CO_2-we) budget* (GCB*), aligned with a specific Paris Agreement temperature goal.

The GWP* methodology uses GWP_{100} values to calculate CO_2-we emissions. The most recent IPCC-assessed GWP_{100} values, including climate–carbon feedbacks, are 34 for CH_4 and 298 for N_2O (Table 8.7 in Myhre *et al.*, 2013). For CO_2, the CO_2-we value in tonnes for a year equals the CO_2 emissions in tonnes (by definition). For N_2O, the CO_2-we value for a given year is the same as the CO_2-eq value (found by multiplying tonnes of N_2O emissions by 298). For CH_4, annual CO_2-we is calculated by first determining a year's CO_2-eq value (found by multiplying CH_4 emissions in tonnes by the GWP_{100} value of 34) and then applying the following GWP* calculation (Lynch *et al.*, 2020):

$$CO_2\text{-we} = 4 \times CO_2\text{-eq}(t) - 3.75 \times CO_2\text{-eq}(t-20) \qquad (7.1)$$

where CO_2-eq(t) is the CO_2-eq (GWP_{100}) value for the year in question and CO_2-eq($t-20$) is the CO_2-eq value for the year 20 years prior to the current year.

7.3 Estimating a Paris-aligned National Carbon Warming Equivalent Quota (NCQ*)

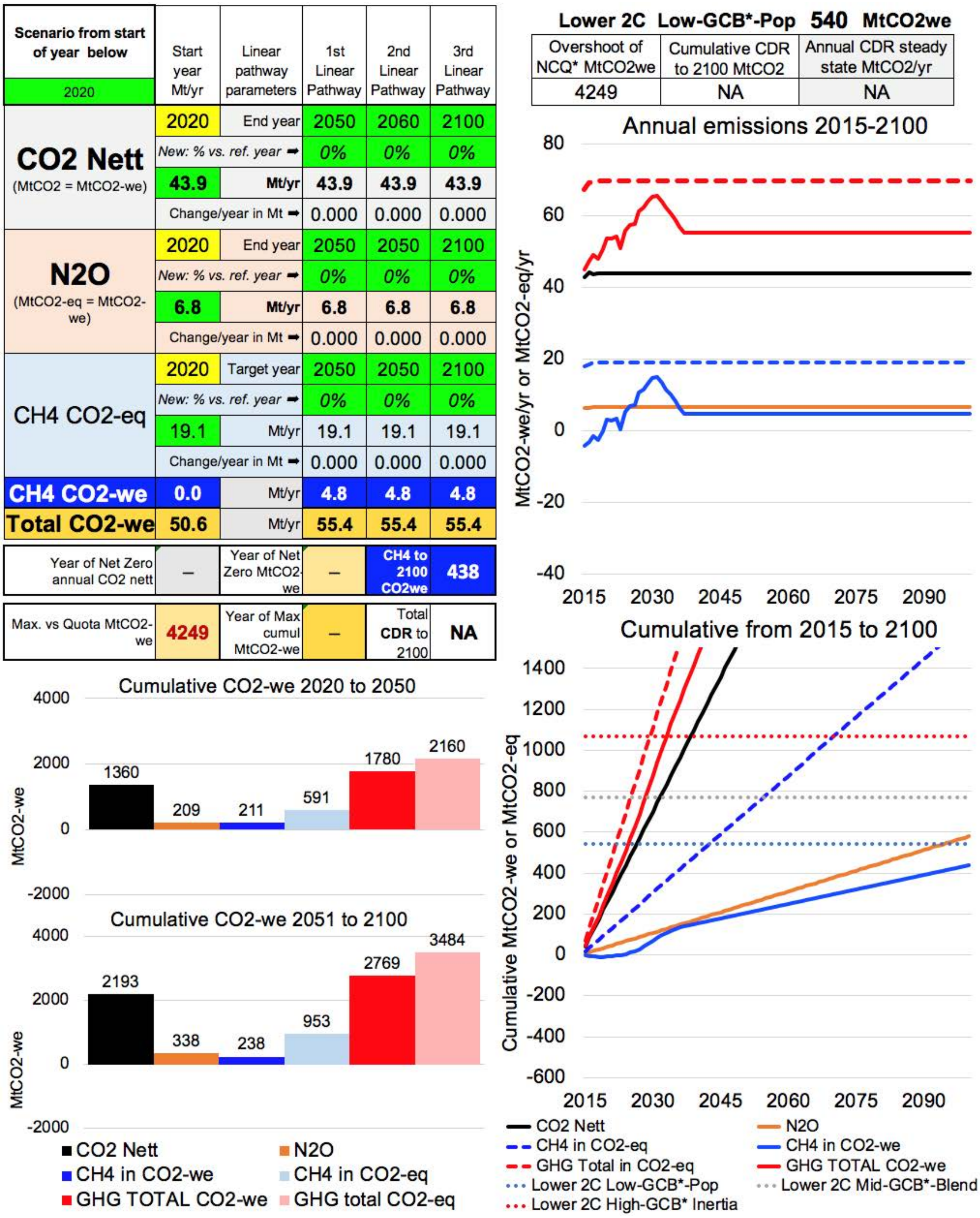
Equitable achievement of the Paris Agreement temperature objectives – holding global warming to "well below 2°C" above pre-industrial levels and pursuing efforts to limit it to 1.5°C – provides the primary internationally agreed context for Ireland's climate change mitigation transition pathway scenarios. Therefore, estimating a range for Ireland's emissions *fair share* quota is important for providing a national transition objective range for alternative scenarios. McMullin *et al.* (2019) made such an estimate for CO_2-only based on the SR1.5 report GCB value (Table 2.2 in Rogelj *et al.*, 2018), combined with use of GCB allocation definitions by Raupach *et al.* (2014) for "equity", "blend" and "inertia" Irish percentage shares of 2015 global population and emissions. However, note that, as in McMullin *et al.* (2019), we will replace the term "equity" with *population* or *pop* to reflect the fact that, even though this denotes the relatively most equitable of the three classes of allocation share defined by Raupach *et al.* (2014), it still falls significantly short of satisfying more comprehensive definitions of equity in the climate justice literature (e.g. Kartha *et al.*, 2018). Progressing from McMullin *et al.*, for this project an assessment was made on the 10th, 50th, and 90th percentiles (subsequently denoted as "low", "mid" and "high" values) of the aggregate range of peak cumulative CO_2-we (GCB*) from 2015 for the IPCC-assessed scenario ensembles corresponding to 1.5°C and "well below 2°C".

It is important to emphasise here that neither the estimation of the GCB* nor the allocation of this among nation-state quotas is exclusively or even primarily a matter of scientific calculation. There is ultimately no unique "scientifically correct" value for either a "Paris-aligned" GCB* or any given nation-state NCQ*. Rather, there exists a variety of methodological approaches, very significant uncertainties, and major value judgements both in the interpretation of "prudence" (at a global level) and of "equity" in allocating, or annexing, down to a national level for the NCQ*. In this light, McMullin *et al.* (2019) suggested that even the *low* end of their estimated CO_2-only NCQ range should be regarded as a benchmark *maximum* CO_2 quota for Ireland. This is described as still being only *minimally equitable*, because stronger interpretations of "equity" would additionally reflect relative historical responsibility, capacity to act, responsibility for international aviation and shipping emissions, and the Paris requirement to pursue efforts to align action with the more prudent 1.5°C (rather than "well below 2°C") temperature goal. However, despite these important caveats, adopting *some* evidence-based NCQ and/or NCQ* estimate, based on transparently articulated principles and value judgements, seems essential to a meaningful and transparent assessment of the Paris alignment of alternative mitigation scenarios for any nation (Geden and Löschel, 2017). Indeed, this may be usefully contrasted with the current typical practice that focuses on point-in-time annual emissions targets or, worse, "renewable" energy penetration targets, having opaque or indeterminate relationships with either equity or the reliable achievement of the global temperature goals.

Full details of the methodology applied to establish an Irish NCQ* range for the illustrative scenarios are given in the SSECCM project Technical Report (McMullin and Price, 2020). The GCB* range assessment was based on the "Lower 2C" scenario class, met by 67 scenarios in the database of scenarios assessed in SR1.5 (Huppmann *et al.*, 2018a,b). The percentile range of GCB* values (in cumulative CO_2-we from 2015) from this analysis were combined with the Raupach *et al.* (2014) allocation methodology, to produce the following range of NCQ* values as targets for illustrative mitigation scenarios: Low-GCB*-Pop, 540 Mt CO_2-we; Mid-GCB*-Blend, 770 Mt CO_2-we; and High-GCB*-Inertia, 1069 Mt CO_2-we.

7.4 Using the GHG-WE Tool: Illustrative Society-Wide Scenarios

Six illustrative society-wide scenarios are presented to examine the use of the GHG-WE tool in assessing critical trade-offs between gases in Irish mitigation scenario development relative to the identified three NCQs* setting out possible (maximum) quota levels for climate mitigation action aligned with "well below 2°C". One scenario, All_FLAT (see Figure 7.1), provides a no mitigation case in which net CO_2, CH_4 and N_2O emissions remain at their 2019 level until 2100. As a narrative basis for mitigation scenarios, two key observations from Irish climate policy and emissions are identified. First, although CAP2019 (DCCAE, 2019a) does not detail proposed emissions reductions broken down by separate gases, it presents aggregate GHG pathways that suggest a linear reduction of at least –20% in CO_2 emissions by 2030 (relative to the then projected level for 2020), followed by a potential reduction to net-zero CO_2 by 2050. This piecewise linear trajectory will be loosely referred to here as a "CAP2019" CO_2 pathway to 2050. Second, N_2O and CH_4 emissions are tightly coupled because of the use of Nr in driving production



Scenario from start of year below 2020	Start year Mt/yr	Linear pathway parameters	1st Linear Pathway	2nd Linear Pathway	3rd Linear Pathway
CO2 Nett (MtCO2 = MtCO2-we)	2020	End year	2050	2060	2100
		New: % vs. ref. year ➡	*0%*	*0%*	*0%*
	43.9	Mt/yr	43.9	43.9	43.9
		Change/year in Mt ➡	0.000	0.000	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2050	2050	2100
		New: % vs. ref. year ➡	*0%*	*0%*	*0%*
	6.8	Mt/yr	6.8	6.8	6.8
		Change/year in Mt ➡	0.000	0.000	0.000
CH4 CO2-eq	2020	Target year	2050	2050	2100
		New: % vs. ref. year ➡	*0%*	*0%*	*0%*
	19.1	Mt/yr	19.1	19.1	19.1
		Change/year in Mt ➡	0.000	0.000	0.000
CH4 CO2-we	0.0	Mt/yr	4.8	4.8	4.8
Total CO2-we	50.6	Mt/yr	55.4	55.4	55.4

Year of Net Zero annual CO2 nett	–	Year of Net Zero MtCO2-we	–	CH4 to 2100 CO2we	438
Max. vs Quota MtCO2-we	4249	Year of Max cumul MtCO2-we	–	Total CDR to 2100	NA

Lower 2C Low-GCB*-Pop 540 MtCO2we

Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual CDR steady state MtCO2/yr
4249	NA	NA

Figure 7.1. *All_FLAT scenario*. No mitigation. Annual emissions: CO_2 net, CH_4 and N_2O are all assumed to remain constant at the 2020 level from 2021 onwards.

from ruminant agriculture. For all scenarios, the CO_2 reduction pathway will be assumed to apply to the aggregate of *all* national CO_2 emissions and removals, specifically including those in the land use sector. In itself, this assumption arguably represents a strengthening of mitigation ambition relative to the climate action plan, because Irish land use is currently reported as a significant net emitter of CO_2.

Since Irish N_2O and CH_4 are strongly correlated, the scenarios assume, for simplicity, that these emissions are reduced or stabilised at the same rates and times. To shorten scenario names, the abbreviation “MN” is used simply to indicate the initial letters of “Methane” and “Nitrous oxide”, and Cn in scenario names denotes “CO_2-neutral”, which is followed by the year of annual net-zero CO_2 emissions.

In the following three Cn2050 scenarios, net CO_2 emissions follow the CAP2019 CO_2 pathway to 2050, and different non-CO_2 pathways are explored, each with N_2O rates held identical to CH_4 rates. Per the CAP2019 pathway, net CO_2 is first cut by –20% from 2020 to 2030, then reduced linearly to pass through net-zero CO_2 at 2050, and, thereafter (2050–2100), is extrapolated to stabilise at a sufficient constant net negative emissions (net removals) level to return the scenario to the specified aggregate CO_2-we quota level by 2100.

- **MN_FLAT_Cn2050** (Figure 7.2): CH_4 and N_2O are kept flat at their 2019 rates up to 2100.
- **MN-25%_Cn2050** (Figure 7.3)**:** CH_4 and N_2O annual emissions are each cut linearly by –25% from 2020 to 2050; thereafter, they remain flat at this new level.
- **MN-50%_Cn2050** (Figure 7.4)**:** CH_4 and N_2O annual emissions are each cut linearly by –50% from 2020 to 2050; thereafter, they remain flat at this new level.

In two Cn2040 scenarios, net-CO_2 emissions are cut linearly from 2020 through net zero by the earlier date of 2040, proceeding to the sustained net negative level required to return to quota by 2100:

- **MN-25%_Cn2040** (Figure 7.5);
- **MN-50%_Cn2040** (Figure 7.6).

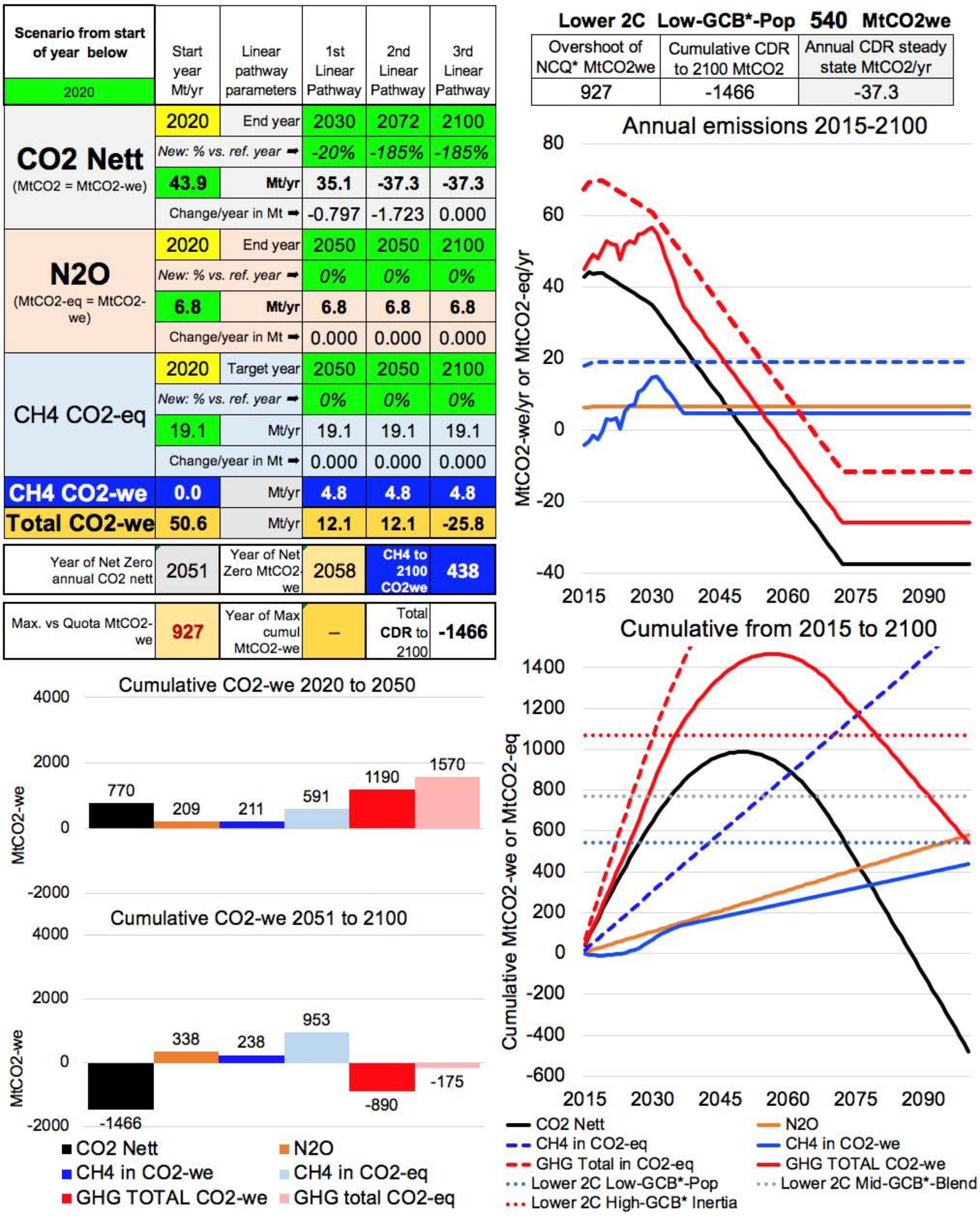
CO_2 is presented in all scenarios as CO_2 net, the value for each year being an aggregate of the CO_2 emissions from fossil fuel and industry, and the CO_2 emissions and CDR from land use, land use change and forestry (LULUCF). CDR could also be achieved if negative emissions technologies (NETs) such as bioenergy with CCS (BECCS), direct air CCS (DACCS) or enhanced weathering (EW) were developed at scale to remove CO_2 from the atmosphere and store it geologically or fix it in mineral form. In these illustrative scenarios, however, no assumptions are made about the mix of gross CO_2 emissions and removals adding up to CO_2 net values in any year.

As a basis for Irish GHG scenario pathways using the SSECCM GHG-WE model, historical values for CO_2, N_2O and CH_4 are available from different sources. The Irish EPA GHG inventory tables provide data for 1990 to 2018; Community Emissions Data System (CEDS) datasets in the supplementary information in Hoesly *et al.* (2018) give annual values for individual nations from 1970 to 2014, with longer-run (decadal) estimates for global regions from 1820 to 1970; and the updated Potsdam Realtime Integrated Model for probabilistic Assessment of emissions Paths (PRIMAP) time series now gives detailed datasets for GHGs by country, sector and sub-sector (Gütschow *et al.*, 2019). The GHG-WE tool gives the user the option of which dataset to use.

7.4.1 Comparison of the illustrative scenarios

Figures 7.1–7.6 show the GHG-WE input table and output charts for each of the illustrative scenarios targeting the Low-GCB*-Pop NCQ* level by 2100. The results for each scenario are detailed in the SSECCM Technical Report (McMullin and Price, 2020). The cumulative CO_2-we emissions pathways (solid red lines) show Ireland on a trajectory to early overshoot of the Paris-aligned NCQ*, even under the most stringent MN50%_Cn2040 scenario, exceeding a Low-GCB*-Pop quota by 2029, compared with overshoot by 2025 in the ALL_FLAT scenario. The ALL_FLAT scenario aggregate CO_2-we exceeds the highest (Inertia) NCQ* by 2035 with no limit to overshoot. Given imminent overshoot in all cases, all mitigation scenarios require CDR or CH_4 reduction, or both, to return to a Paris-aligned quota by 2100 at the latest. Cumulative CDR from peak CO_2 is –1470 Mt CO_2 in Mn_FLAT_Cn2040, requiring annual CDR of –37 Mt CO_2, the equivalent of current fossil and cement emissions. Owing to CH_4 reduction up to 2050 (with CH_4 flow remaining stable thereafter), MN-25% scenarios require 440 Mt CO_2-we less CDR, and MN-50% scenarios require 770 Mt CO_2-we less CDR than the MN_FLAT scenario. Cutting to net-zero CO_2 by 2040 emits positive 660 Mt CO_2 net up to 2040, instead of 990 Mt CO_2 to 2050 in the CAP2019-derived pathway. Mitigation cuts in N_2O emissions by –25% or –50% by 2050 and stable thereafter result in cumulative CO_2-we reductions of 110 Mt CO_2-we or 220 Mt CO_2-we, compared with the no mitigation FLAT scenarios. Figures 7.7 and 7.8 compare key characteristics of all scenarios meeting the Low-GCB*-Pop quota.

As noted, practical cumulative Irish CDR may be limited to 200 Mt CO_2 (McMullin *et al.*, 2020), with a technical limit estimated at 600 Mt CO_2. However, as shown by the values in Table 7.1, only the most stringent scenario, MN-50%_Cn2040 (CDR



Scenario from start of year below 2020	Start year Mt/yr	Linear pathway parameters	1st Linear Pathway	2nd Linear Pathway	3rd Linear Pathway
CO2 Nett (MtCO2 = MtCO2-we)	2020	End year	2030	2072	2100
		New: % vs. ref. year ➡	*-20%*	*-185%*	*-185%*
	43.9	**Mt/yr**	**35.1**	**-37.3**	**-37.3**
		Change/year in Mt ➡	-0.797	-1.723	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2050	2050	2100
		New: % vs. ref. year ➡	*0%*	*0%*	*0%*
	6.8	**Mt/yr**	**6.8**	**6.8**	**6.8**
		Change/year in Mt ➡	0.000	0.000	0.000
CH4 CO2-eq	2020	Target year	2050	2050	2100
		New: % vs. ref. year ➡	*0%*	*0%*	*0%*
	19.1	Mt/yr	19.1	19.1	19.1
		Change/year in Mt ➡	0.000	0.000	0.000
CH4 CO2-we	**0.0**	Mt/yr	**4.8**	**4.8**	**4.8**
Total CO2-we	**50.6**	Mt/yr	**12.1**	**12.1**	**-25.8**

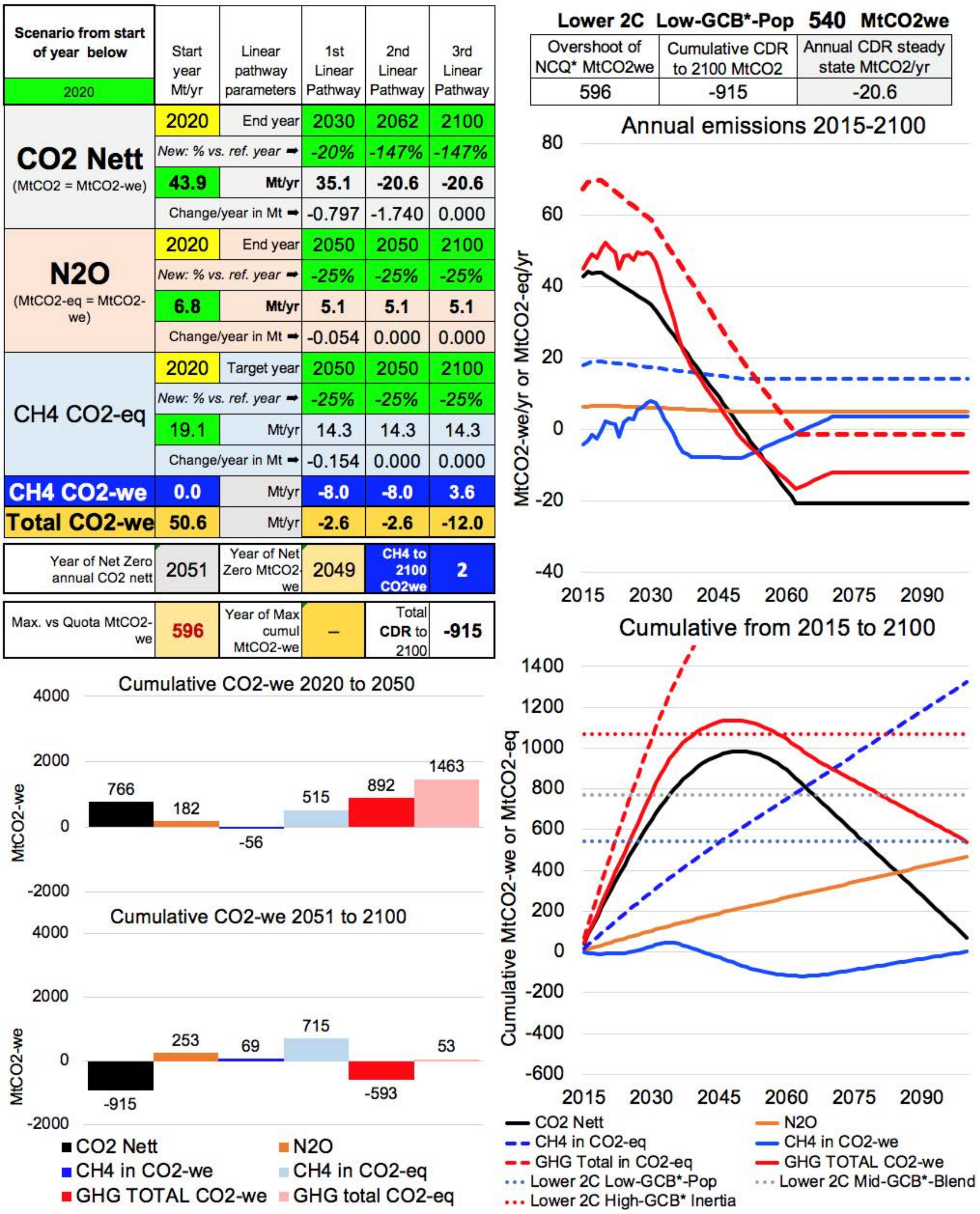
Year of Net Zero annual CO2 nett	2051	Year of Net Zero MtCO2-we	2058	**CH4 to 2100 CO2we**	**438**
Max. vs Quota MtCO2-we	**927**	Year of Max cumul MtCO2-we	–	Total **CDR** to 2100	**-1466**

Lower 2C Low-GCB*-Pop 540 MtCO2we

Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual CDR steady state MtCO2/yr
927	-1466	-37.3

Figure 7.2. *MN_FLAT_Cn2050 scenario* meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O stay at 2019 level to 2100. CO_2 net cut by –20% by 2030, then through annual net-zero CO_2 emissions in 2050.

–35 Mt CO_2), can meet a Low-GCB*-Pop quota without exceeding the practical CDR limit, whereas the MN-50%_Cn2050 (CDR 128 Mt CO_2-we) scenario can meet the Mid-GCB*-Blend quota and the MN-25%_Cn2040 (CDR 50 Mt CO_2) scenario can only meet a High-GCB*-Inertia quota with low enough CDR. All other illustrative mitigation scenarios require CDR in excess of 200 Mt CO_2. CDR exceeds the likely unachievable *technical* limit of 600 Mt CO_2 for MN_FLAT scenarios meeting any NCQ* target, and for the MN-25%_Cn2050 scenario meeting the Low-GCB*-Pop and Mid-GCB*-Blend targets.



Scenario from start of year below 2020	Start year Mt/yr	Linear pathway parameters	1st Linear Pathway	2nd Linear Pathway	3rd Linear Pathway
CO2 Nett (MtCO2 = MtCO2-we)	2020	End year	2030	2062	2100
		New: % vs. ref. year ➡	*-20%*	*-147%*	*-147%*
	43.9	**Mt/yr**	**35.1**	**-20.6**	**-20.6**
		Change/year in Mt ➡	-0.797	-1.740	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2050	2050	2100
		New: % vs. ref. year ➡	*-25%*	*-25%*	*-25%*
	6.8	**Mt/yr**	**5.1**	**5.1**	**5.1**
		Change/year in Mt ➡	-0.054	0.000	0.000
CH4 CO2-eq	2020	Target year	2050	2050	2100
		New: % vs. ref. year ➡	*-25%*	*-25%*	*-25%*
	19.1	Mt/yr	14.3	14.3	14.3
		Change/year in Mt ➡	-0.154	0.000	0.000
CH4 CO2-we	**0.0**	Mt/yr	**-8.0**	**-8.0**	**3.6**
Total CO2-we	**50.6**	Mt/yr	**-2.6**	**-2.6**	**-12.0**

Year of Net Zero annual CO2 nett	2051	Year of Net Zero MtCO2-we	2049	**CH4 to 2100 CO2we**	**2**
Max. vs Quota MtCO2-we	**596**	Year of Max cumul MtCO2-we	–	Total **CDR** to 2100	**-915**

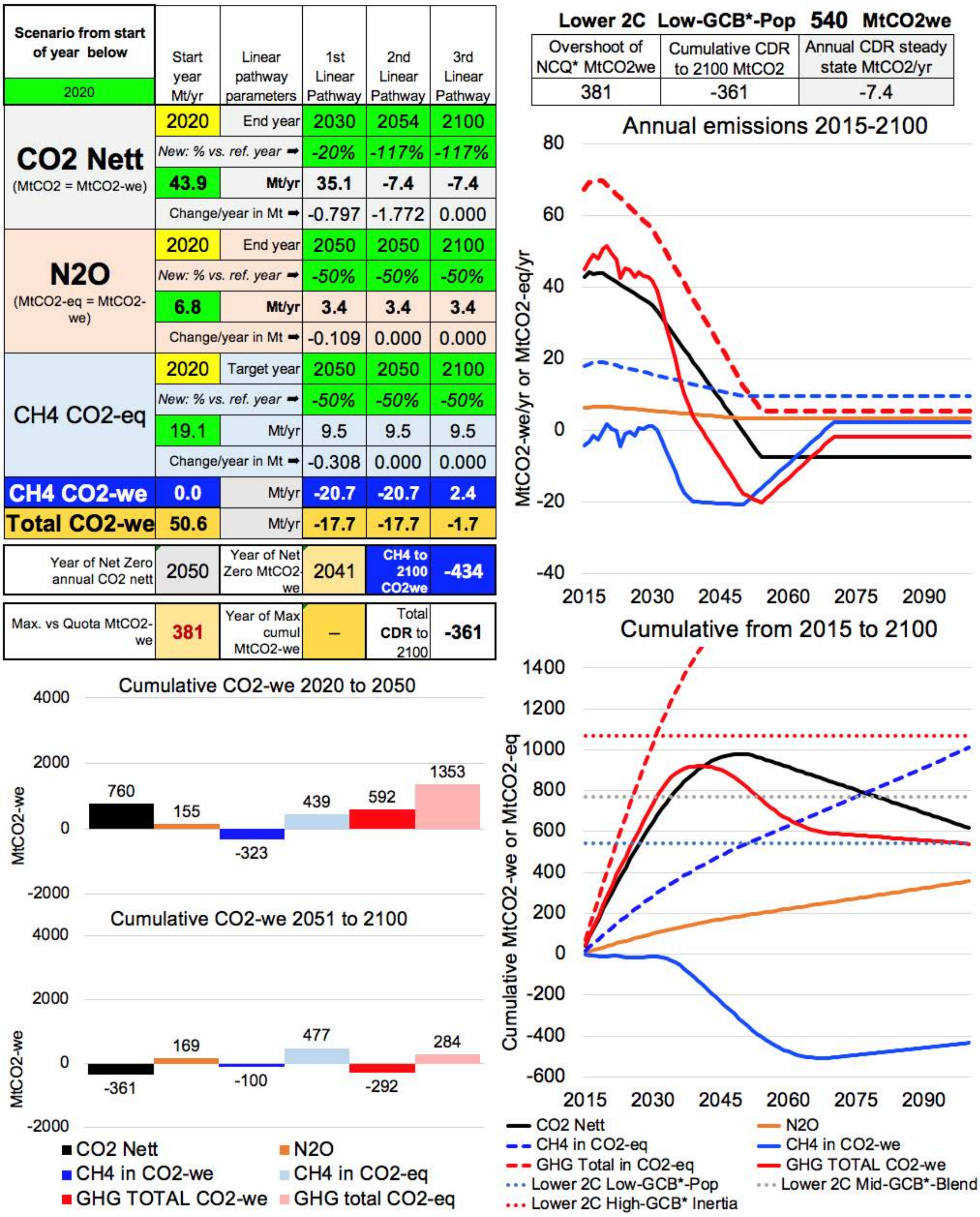
Lower 2C Low-GCB*-Pop 540 MtCO2we

Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual CDR steady state MtCO2/yr
596	-915	-20.6

Figure 7.3. ***MN-25%_Cn2050 scenario*** **meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O cut by –25% from 2020 to 2050. CO_2 net cut by –20% by 2030, then through annual net-zero CO_2 emissions in 2050.**

7.5 Policy Solutions

To satisfy any Paris-aligned, warming-equivalent NCQ (NCQ*), even with allowance of some temporary overshoot, the overall speed and depth of society-wide mitigation required across all GHG gases is now extremely challenging. A radical (early and deep) reduction in annual emissions of net CO_2 only, reaching annual net zero significantly before 2050, and limited, sustainable net CDR now appear to be unavoidable, necessary conditions for such effective climate action to limit long-term warming; however, to limit the ultimate reliance on CDR to plausibly prudent levels would appear to *also* require steady



Scenario from start of year below 2020	Start year Mt/yr	Linear pathway parameters	1st Linear Pathway	2nd Linear Pathway	3rd Linear Pathway
CO2 Nett (MtCO2 = MtCO2-we)	2020	End year	2030	2054	2100
		New: % vs. ref. year ➡	-20%	-117%	-117%
	43.9	Mt/yr	35.1	-7.4	-7.4
		Change/year in Mt ➡	-0.797	-1.772	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2050	2050	2100
		New: % vs. ref. year ➡	-50%	-50%	-50%
	6.8	Mt/yr	3.4	3.4	3.4
		Change/year in Mt ➡	-0.109	0.000	0.000
CH4 CO2-eq	2020	Target year	2050	2050	2100
		New: % vs. ref. year ➡	-50%	-50%	-50%
	19.1	Mt/yr	9.5	9.5	9.5
		Change/year in Mt ➡	-0.308	0.000	0.000
CH4 CO2-we	0.0	Mt/yr	-20.7	-20.7	2.4
Total CO2-we	50.6	Mt/yr	-17.7	-17.7	-1.7

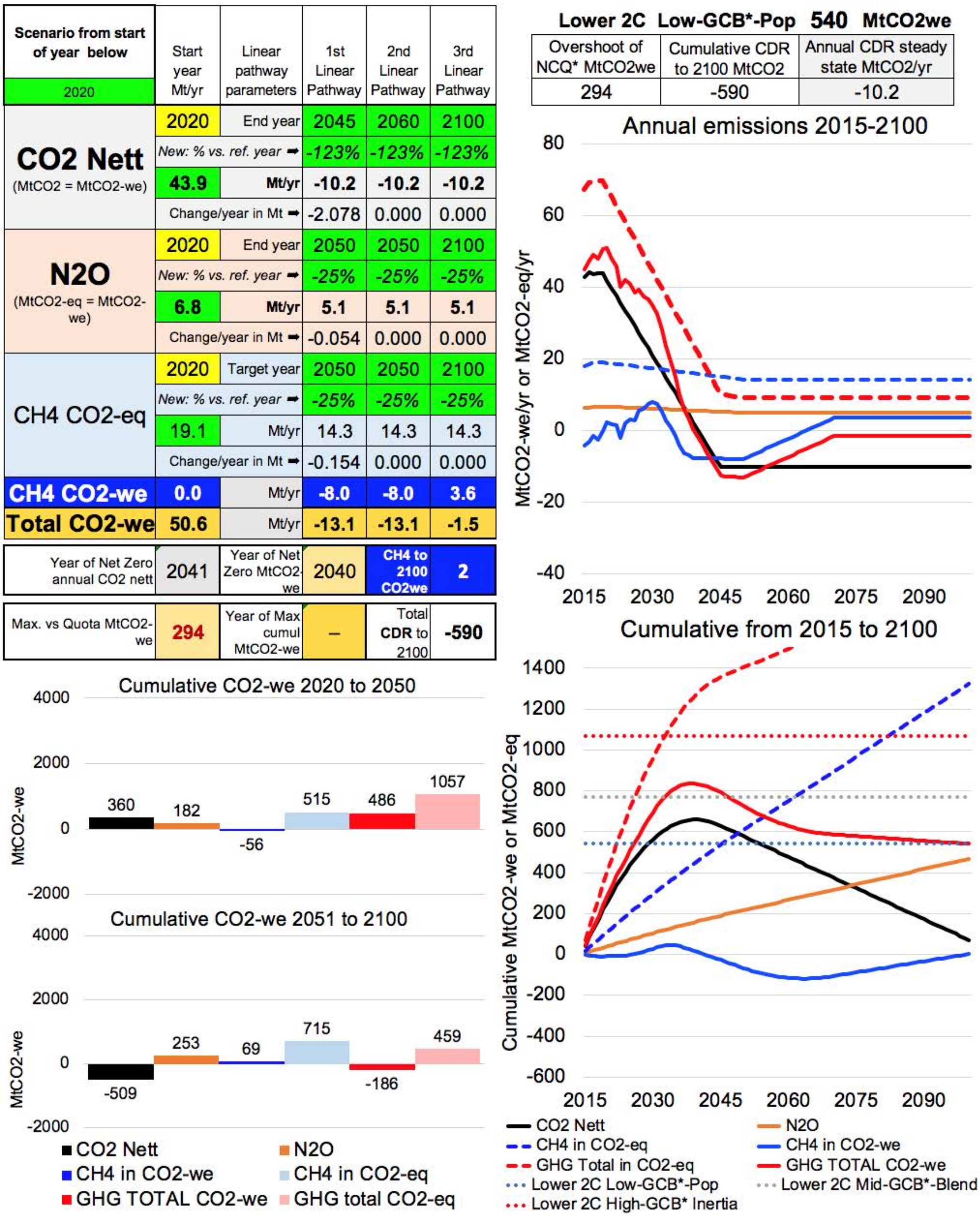
Year of Net Zero annual CO2 nett	2050	Year of Net Zero MtCO2-we	2041	CH4 to 2100 CO2we	-434
Max. vs Quota MtCO2-we	381	Year of Max cumul MtCO2-we	–	Total CDR to 2100	-361

Lower 2C Low-GCB*-Pop 540 MtCO2we

Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual CDR steady state MtCO2/yr
381	-361	-7.4

Figure 7.4. ***MN-50%_Cn2050 scenario*** **meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O cut by –50% from 2020 to 2050. CO_2 net cut by –20% by 2030, then through annual net-zero CO_2 emissions in 2050.**

and permanent annual CH_4 mass flow reductions of approximately 50%, ideally achieved within the next three decades (to substantially limit peak NCQ* quota *overshoot*). A no-mitigation trajectory, based on stable 2019 GHG emissions to 2100 (approximating no mitigation, as provisionally implied by Ireland's draft NECP to 2040), would imply extremely serious, and potentially irreversible, overshoot beyond the estimated Irish fair share emissions quota range. Use of the GHG-WE tool shows that *both* separating the different GHGs (CO_2, N_2O and CH_4) *and* aggregating them is important for assessment and comparison of effective society-wide mitigation policy strategies. Of most importance for Ireland, the GHG-WE tool indicates that the "feasible" CO_2 mitigation policy space appears significantly wider *if* potential reduction



Scenario from start of year below 2020	Start year Mt/yr	Linear pathway parameters	1st Linear Pathway	2nd Linear Pathway	3rd Linear Pathway
CO2 Nett (MtCO2 = MtCO2-we)	2020	End year	2045	2060	2100
		New: % vs. ref. year ➡	*-123%*	*-123%*	*-123%*
	43.9	**Mt/yr**	**-10.2**	**-10.2**	**-10.2**
		Change/year in Mt ➡	-2.078	0.000	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2050	2050	2100
		New: % vs. ref. year ➡	*-25%*	*-25%*	*-25%*
	6.8	**Mt/yr**	**5.1**	**5.1**	**5.1**
		Change/year in Mt ➡	-0.054	0.000	0.000
CH4 CO2-eq	2020	Target year	2050	2050	2100
		New: % vs. ref. year ➡	*-25%*	*-25%*	*-25%*
	19.1	Mt/yr	14.3	14.3	14.3
		Change/year in Mt ➡	-0.154	0.000	0.000
CH4 CO2-we	**0.0**	Mt/yr	**-8.0**	**-8.0**	**3.6**
Total CO2-we	**50.6**	Mt/yr	**-13.1**	**-13.1**	**-1.5**

Year of Net Zero annual CO2 nett	2041	Year of Net Zero MtCO2-we	2040	**CH4 to 2100 CO2we**	**2**
Max. vs Quota MtCO2-we	**294**	Year of Max cumul MtCO2-we	–	Total **CDR** to 2100	**-590**

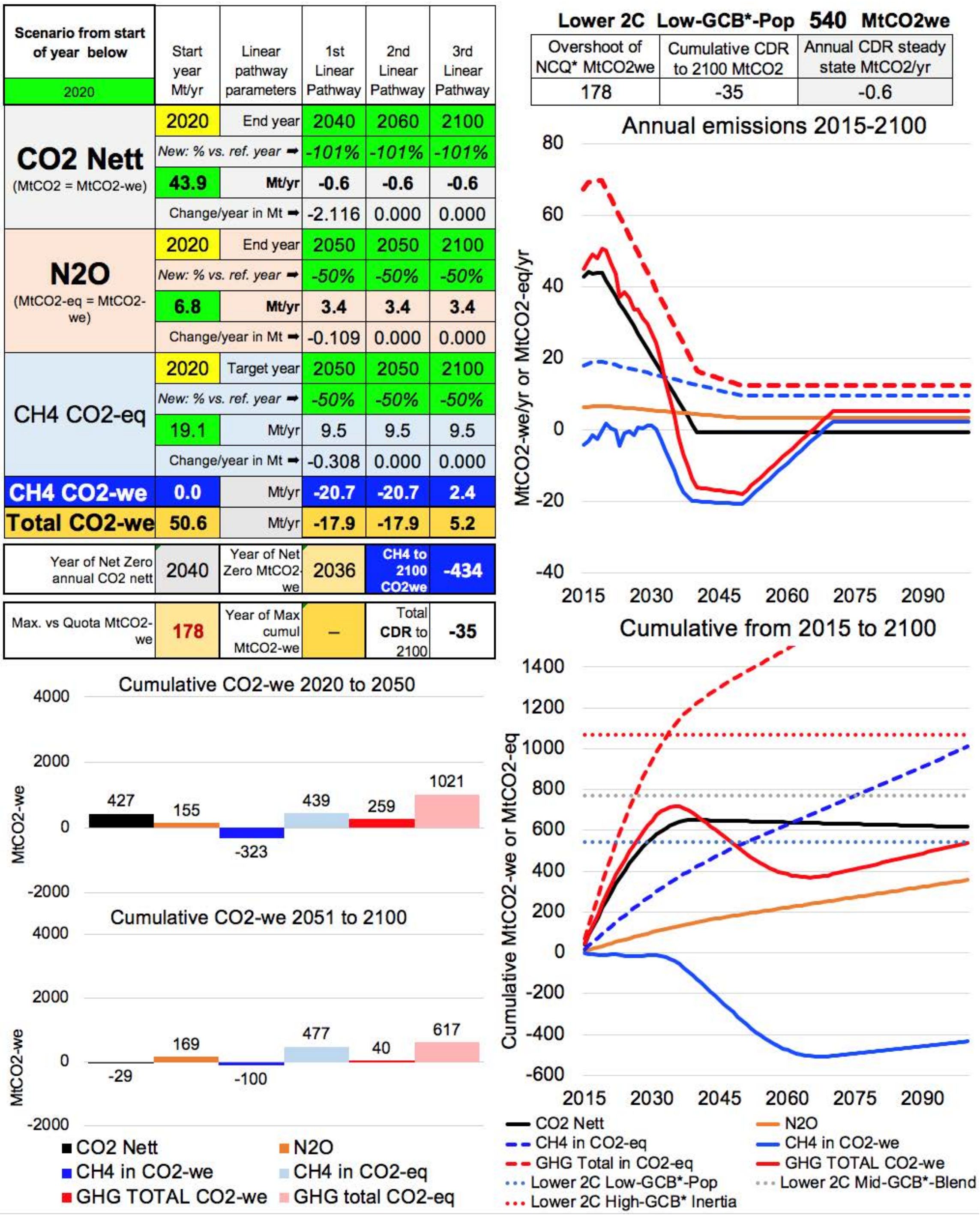
Lower 2C Low-GCB*-Pop 540 MtCO2we

Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual CDR steady state MtCO2/yr
294	-590	-10.2

Figure 7.5. *MN-25%_Cn2040 scenario* meeting Low-GCB*-Pop by 2100. CH_4 and N_2O cut by –25% from 2020 to 2050. CO_2 net cut linearly from 2020 through annual net-zero CO_2 emissions in 2040.

in cumulative warming (comparable in regard to physical effect to CDR) via reduction in annual CH_4 mass flow rate is *appropriately* represented (using the GWP* methodology and *cumulative CO_2-we* scenario trade-offs).

By definition, substantial net CDR (negative net CO_2 emissions) can occur only after net-zero CO_2 is reached (by 2050 or in 2040 in the illustrative scenarios), and then only if large-scale investment can be mobilised to support it, whereas actions to achieve incremental, sustained and ultimately permanent reductions in annual CH_4 mass flow rates could, in principle, start without delay. Such immediate, incremental CH_4 emission mitigation could permit a very early and material contribution to overall national mitigation; therefore, reflecting the IPCC-assessed



Scenario from start of year below 2020	Start year Mt/yr	Linear pathway parameters	1st Linear Pathway	2nd Linear Pathway	3rd Linear Pathway
CO2 Nett (MtCO2 = MtCO2-we)	2020	End year	2040	2060	2100
		New: % vs. ref. year ➡	*-101%*	*-101%*	*-101%*
	43.9	**Mt/yr**	**-0.6**	**-0.6**	**-0.6**
		Change/year in Mt ➡	-2.116	0.000	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2050	2050	2100
		New: % vs. ref. year ➡	*-50%*	*-50%*	*-50%*
	6.8	**Mt/yr**	**3.4**	**3.4**	**3.4**
		Change/year in Mt ➡	-0.109	0.000	0.000
CH4 CO2-eq	2020	Target year	2050	2050	2100
		New: % vs. ref. year ➡	*-50%*	*-50%*	*-50%*
	19.1	Mt/yr	9.5	9.5	9.5
		Change/year in Mt ➡	-0.308	0.000	0.000
CH4 CO2-we	**0.0**	Mt/yr	**-20.7**	**-20.7**	**2.4**
Total CO2-we	**50.6**	Mt/yr	**-17.9**	**-17.9**	**5.2**

Year of Net Zero annual CO2 nett	2040	Year of Net Zero MtCO2-we	2036	**CH4 to 2100 CO2we**	**-434**
Max. vs Quota MtCO2-we	**178**	Year of Max cumul MtCO2-we	–	Total **CDR** to 2100	**-35**

Lower 2C Low-GCB*-Pop 540 MtCO2we

Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual CDR steady state MtCO2/yr
178	-35	-0.6

Figure 7.6. *MN-50%_Cn2040 scenario* meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O cut by –50% from 2020 to 2050. CO_2 net cut linearly from 2020 through annual net-zero CO_2 emissions in 2040.

SR1.5 scenario pathways, use of the GHG-WE tool now strongly suggests that meaningful Paris-aligned climate mitigation action in Ireland cannot now depend on radical CO_2 mitigation and CDR development *alone* – supplemental warming reduction, targeting non-CO_2, particularly CH_4, is also required, otherwise limits on Ireland's estimated practical CDR (~200 Mt CO_2) will be exceeded. Of course, it remains the case that achieving *any* of the illustrative Paris-aligned mitigation pathway scenarios would likely require extraordinary societal change led by a society-wide mitigation strategy to guide transition and investment. This arguably suggests that effective policy would target early, deep and sustained mitigation action, across all GHGs, to limit overall societal transition risk and cost.

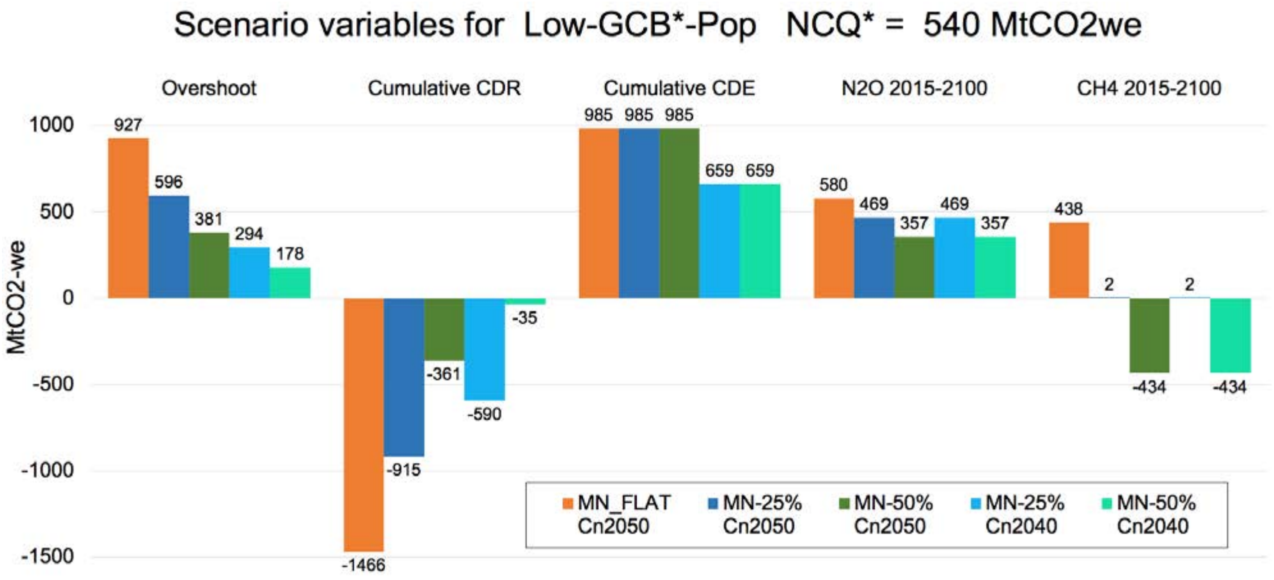


Figure 7.7. Low-GCB*-Pop scenarios: NCQ* overshoot and scenario GHG totals for 2015–2100. CDE, net CO_2 emissions up to net zero in 2050 or 2040.

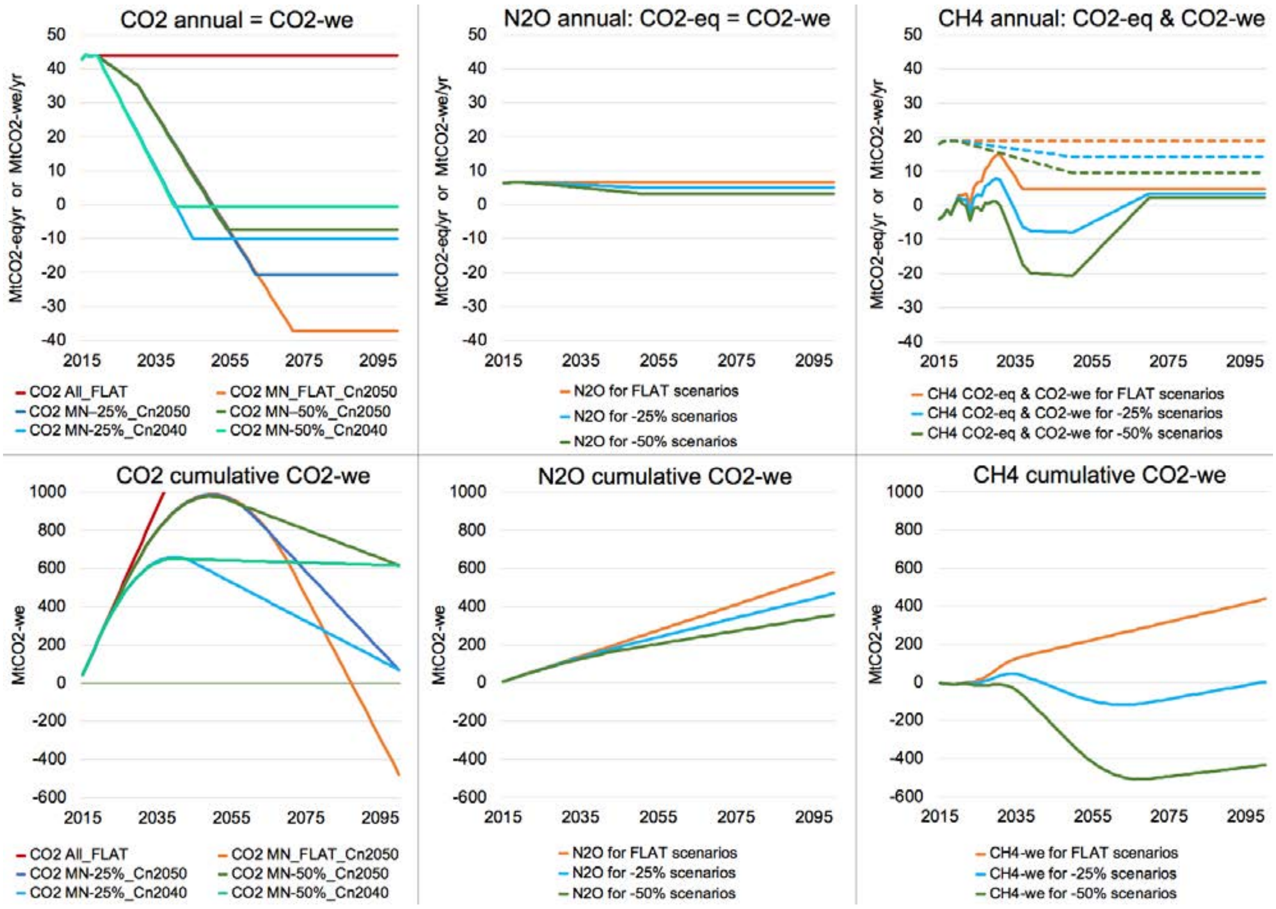


Figure 7.8. Annual and cumulative 2015–2100 comparison of illustrative scenarios. Given a joint CH_4 and N_2O pathway, CO_2 net adjusted to enable Low-GCB*-Pop (NCQ* = 540 Mt CO_2-we by 2100).

Table 7.1. Overshoot, cumulative CDR, and steady state annual CDR per year for no mitigation (ALL_FLAT) and in illustrative scenarios meeting Low-GCB*-Pop (NCQ* = 540 Mt CO_2-we by 2100)

Scenario	Variable	Units	Low-GCB*-Pop (NCQ* = 540 Mt CO_2we)	Mid-GCB*-Blend (NCQ* = 770 Mt CO_2we)	High-GCB*-Inertia (NCQ* = 1069 Mt CO_2we)
ALL_FLAT	Overshoot	Mt CO_2we	4249	4019	3720
	Sum cumulative CDR	Mt CO_2we	NA	NA	NA
	Annual steady state CDR	Mt CO_2we/y	NA	NA	NA
MN_FLAT Cn2050	Overshoot	Mt CO_2we	927	690	388
	Sum cumulative CDR	Mt CO_2we	–1466	–1232	–931
	Annual steady state CDR	Mt CO_2we/y	–37.3	–29.4	–20.9
MN-25% Cn2050	Overshoot	Mt CO_2we	596	368	59
	Sum cumulative CDR	Mt CO_2we	–915	–688	–377
	Annual steady state CDR	Mt CO_2we/y	–20.6	–15.0	–7.7
MN-50% Cn2050	Overshoot	Mt CO_2we	381	149	NA
	Sum cumulative CDR	Mt CO_2we	–361	–128	NA
	Annual steady state CDR	Mt CO_2we/y	–7.4	–2.5	NA
MN-25% Cn2040	Overshoot	Mt CO_2we	294	63	1
	Sum cumulative CDR	Mt CO_2we	–590	–360	–50
	Annual steady state CDR	Mt CO_2we/y	–10.2	–6.1	–0.8
MN-50% Cn2040	Overshoot	Mt CO_2we	178	NA	NA
	Sum cumulative CDR	Mt CO_2we	–35	NA	NA
	Annual steady state CDR	Mt CO_2we/y	–0.6	NA	NA

NA, not applicable.

As Ireland has comparatively very high CH_4 emissions because of ruminant agriculture, reducing these emissions is a significant mitigation policy lever to achieve aggregate society-wide mitigation. GWP* analysis shows that such substantial CO_2-we mitigation occurred as a result of agricultural emissions reductions from 1998 to 2011 related to subsidy reductions and the milk quota, but the expansionary agri-strategy that has been in place since 2010 is now nullifying this earlier mitigation, compromising effective climate action. The scenarios show the importance of limiting CH_4 source emissions in the near term, otherwise CO_2 mitigation effort can easily be cancelled out by increased CH_4 warming that can take 10 to 20 years to reverse. Beginning sustained reductions in total national CH_4 emissions sooner rather than later would ease transition in the agricultural sector. Beyond net-zero CO_2, any net positive forcing due to continued N_2O emissions and CH_4 (including its long-term stock effect on warming) would have to be matched by net negative forcing from net annual CDR.

All drivers and sources of CH_4 emissions should be included in policy assessments. System inputs of Nr from synthetic fertiliser and animal feeds are a key driver of Irish N_2O and CH_4 emissions. Therefore, limiting Nr usage at national system level and limiting inefficient and polluting Nr use on grass (for ruminant and biogas agricultural production) present potentially important policy levers for climate measures. The proposed development of hundreds of AD plants in Ireland to supply biomethane for injection into the Gas (CH_4) Grid by 2030 and 2050 (Ervia and Gas Networks Ireland, 2019) presents significant risk of adding a substantial number of fugitive CH_4 sources. If reported Danish rates of CH_4 leakage of about 2.4% from agricultural biogas AD plants (Scheutz and Fredenslund, 2019) applied to Irish AD, the resulting CH_4 leakage could significantly add to total CH_4-contributed warming. Indeed, reported AD CH_4 leakage rates can be much higher (Baldé *et al.*, 2016), and it is conceivable that ongoing CH_4 leakage from a single AD plant could be equivalent to CH_4 emissions from a herd of hundreds of cattle. If independent regulatory oversight of installation and maintenance of AD plant farms were to be inadequate, then leakage could be still larger (Ebner *et al.*, 2015).

It has been explicitly argued that the Paris Agreement tacitly assumes the UNFCCC usage of the GWP_{100} metric and its associated value judgements, so any widespread change in the UNFCCC base metric from GWP_{100} to GWP* would require very careful consideration of the potential changes in fair share action and the risk of weakening the climate mitigation ambition of the Paris Agreement, because the use of a different metric could affect the original basis of the agreement (Rogelj and Schleussner, 2019; Schleussner *et al.*, 2019). This issue has been partially addressed in the illustrative scenarios by requiring a national NCQ* to be met that was aligned with the Paris *temperature goals.* Even the lowest Irish NCQ* fair share could be considered only a benchmark maximum or *minimally equitable* value, given developed nation responsibility to act first and fastest in cutting absolute emissions. Therefore, the GHG-WE tool is useful in comparing society-wide mitigation scenarios at national level on a defined basis, but care should still be taken in equating GWP* results with adequate compliance with the Paris Agreement.

Using GWP* to show cumulative CO_2-we in a Paris-aligned carbon budget context means that at least some perverse or counterproductive policy choices *might* be avoided and that one particular major flaw regarding CH_4 can be removed from policy analysis. However, narrow annual or single sector GWP* analysis may risk misinforming long-term, society-wide decision-making and value judgements (Reisinger and Leahy, 2019). As the LLCF budget to stay within a stringent temperature limit is exhausted, achieving sufficiently rapid reductions in net CO_2 emissions, and/or scaling up to sufficiently large-scale net removals of CO_2, quickly becomes unfeasible. Near-term policy measures that can reduce CH_4 emissions *in addition to* CO_2 reduction are now becoming ever more critical to good faith climate action – in terms of actual climate forcing over time and in climate action more aligned with Paris limits.

The scenarios and results presented here represent only an initial “proof of concept” for the potential use of GWP* warming-equivalent emissions for national climate policy analysis. We stress that the indicative charts presented are based on a preliminary GWP*-based model and that the results would require further critical testing and independent replication before they could be considered robust. Nonetheless, it is clear that use of the GHG-WE tool, aggregating global warming contributions of CO_2, N_2O, and CH_4, offers an insightful method to navigate complex but critical trade-offs between gases and sectors on a society-wide basis.

8 Recommendations

8.1 Key Project Findings and Recommendations

The GHG-WE spreadsheet tool developed for this project, incorporating the GWP* metric, provided a successful "proof-of-principle" test of a policy-relevant method to compare warming-equivalent outcomes (CO_2-we) of alternative possible mitigation scenarios. The GWP* metric enables SLCFs, particularly CH_4, to be included in aggregate cumulative emission budgets.

- **Recommendation**: Use of GWP* is *only* recommended for nation-level comparisons of society-wide scenarios on the basis of *cumulative* CO_2-we from a *specified reference year* (no later than 2015 – the date of the adoption of the Paris Agreement text) in aggregation of net CO_2, N_2O and CH_4. Use of GWP* is *not* recommended for annual or single sector analyses that may be counter to society-wide, long-term options. Support for the use of GWP* at UNFCCC level (for example in the formulation and updating of statements of nationally determined contribution of mitigation effort) would need to assess fairness and global alignment with meeting the Paris targets.
- **Recommendation**: Further research should be undertaken to critically review wider aspects of the application of GWP* to the formulation of a national "fair share" mitigation quota (NCQ*), specifically including prudence, historical responsibility, the role of "internationalised" emissions (in aviation and shipping) and intergenerational equity.

Use of the GHG-WE tool graphically shows the radical mitigation now required for Ireland to limit overshoot of even a minimally equitable, prudent national carbon budget aligned with meeting the less stringent Paris Agreement temperature goal of keeping global warming "well below 2°C" above pre-industrial levels.

- **Recommendation:** Best-practice national policy, research and modelling identifies a "fair share", Paris-aligned NCQ (NCQ*) stated in cumulative CO_2-we up to explicit time horizon dates. Within this limit, alternative scenarios of CO_2, N_2O and CH_4 can be explored using the GHG-WE tool or a similar analysis to compare national mitigation policy options.

Owing to CH_4's strong forcing effect, CH_4 mitigation or emission increase is non-linearly related to CO_2 mitigation, meaning that relatively small sustained change rates in annual CH_4 emissions have significant impacts on the rate of CO_2 reduction needed to meet a target. As the GHG-WE model shows, stable or increasing levels of CH_4 emissions can make it impossible to meet prudent Paris-aligned targets.

- **Recommendation:** Owing to high warming-equivalent sensitivity of society-wide mitigation in Ireland to CH_4 emissions, CH_4 emissions could be targeted to fall by at least –1% per year to avoid the still steadily increasing impact of stable emissions. Scenarios with higher sustained CH_4 reduction rates would greatly ease the required net CO_2 mitigation rate and limit overshoot of near-term climate targets.

There is a strong link between CH_4 and N_2O emissions from Irish agriculture. The total input of Nr (fertiliser and feed) to Ireland's combined animal agriculture and bioenergy sector (including grass silage and animal-derived feedstocks) is a primary driver of N_2O and CH_4 emissions.

- **Recommendation:** Applying the European Nitrogen Assessment recommendations, and modelling alternative agricultural pathways, could bring about more coherent transition policy to limit the total use of fertiliser and feed within declining nitrogen total usage limits. Supply-side limits on total national use of Nr in fertiliser and feed would motivate nitrogen budgets.

Current policies fail to protect the carbon stocks in land reservoirs adequately; therefore, substantial land carbon emission losses continue from organic soils and peat extraction. Aiming to reach net-zero annual LULUCF emissions as soon as possible and enabling net negative land use emissions from then on would greatly assist in meeting a national CO_2 carbon quota, otherwise more rapid reductions in energy or agriculture emissions, combined with CDR, would be needed.

- **Recommendation:** Immediate land use policy could best prioritise much increased protection of carbon reservoirs (in peatlands, organic grassland soils and forests) by limiting peat extraction, preventing drainage of organic soils and potentially limiting future timber harvests (subject to careful assessment of downstream implications, including interactions with the use of high emissions intensity construction materials and fossil fuel energy sources). A lower immediate priority on soil sequestration and afforestation is advised, as these are of uncertain value by comparison; however, they can and should be actively pursued as longer-term measures, *in addition* to an immediate, primary protection of existing carbon reservoirs.

Standard economic and energy system optimisation modelling, as typically used in Ireland and internationally, relies on the simplifying assumptions of mainstream neoclassical economics. However, the literature, notably Hendry (2018), provides compelling evidence that these assumptions are flawed.

- **Recommendation:** Neoclassical equilibrium modelling is often misused (as forecasting, especially) in a policy context. Therefore, the model design and its intended use need to be made more explicit to critical users in the policy community, and policymakers need to respect model limitations. Alternative modelling methods, such as simulation and participatory modelling, particularly based on open data, open software, and simpler models for rapid and transparent analysis, can complement existing models and enable wider societal engagement. The recent EU-funded MEDEAS project (Capellán-Pérez *et al.,* 2020) is a notable simulation model example that has been used at national level and could be adapted for Ireland.

The available alternative policy pathways to align climate mitigation action with the Paris Agreement temperature goals are becoming very limited. Both transition costs and climate damage costs are increasing, whereas Paris-aligned required mitigation rates are increasing non-linearly. These factors will affect the global and local outcomes of Irish efforts to achieve the sustainability aims of the SDGs and the Paris Agreement temperature goals.

- **Recommendation:** Gender, equity and climate justice consequences of all policies are relevant to the societal values required for effective climate change mitigation and need to be deeply considered in national and EU scenarios and modelling. Policy and research for an effective society-wide climate mitigation strategy need to explore scenarios that are coherent with achieving these explicit societal values, based on a description and analysis of existing path dependencies.

The literature agrees on three main transition drivers – (1) maximising energy efficiency, (2) decarbonising power generation as fast as possible and (3) greatly increased electrification of transport and domestic heating. However, rebound effects that can negate gains are often omitted from consideration. The literature offers widely differing recommendations on low carbon energy (nuclear, biomass, wind and solar, combined with energy storage) and also differs on the timing, required scale and delivery duration of CCS and NETs. There is also wide agreement that large-scale dietary change away from animal-based food is likely to be crucial in feeding a larger global population and to limit emissions.

- **Recommendation:** Greater use of scenario planning, using alternative scenarios and appropriate simulation models to examine adverse futures to mitigate costly surprises would provide a wider basis for policy to minimise the potential cost of plausible high-impact events.

Demand-side mitigation measures (energy efficiency, low carbon energy penetration, carbon markets and carbon taxes) aim to reduce the absolute supply of fossil carbon and Nr, but they have been ineffective. In the absence of stated and enforced declining limits on fossil carbon and Nr, it is not clear how these measures will add up to a Paris-aligned pathway. Policy-based emission projections indicate that they will not.

- **Recommendations:** Supply-side measures – directly regulating system input quantities of fossil carbon and nitrogen in the EU or Ireland – have a potential to drive more rapid change if they are carefully planned and communicated to prioritise clarity and equity.

8.2 Specific Recommendations for Further Research

The GHG-WE spreadsheet tool proved to be insightful in supporting a rapid comparison of Paris-aligned national scenarios. Possible future enhancements could enable a finer grained, policy-relevant assessment of sources/sinks and sectors/sub-sectors. Using the recently updated PRIMAP dataset (Gütschow *et al.*, 2019), the model could be extended to enable users to choose combinations of any specific regions or nations, and specific emissions sectors and sub-sectors, as well as a global analysis.

Climate mitigation policy to limit CO_2 emissions from energy, cement and land use has failed to follow past "policy-relevant" modelling recommendations. *Ex post* research could investigate the reasons for this failure to better examine the policy relevance of scenarios and their use in effective policy.

It has been noted in the findings above that there is a significant potential role for new and/or strengthened *supply-side* measures to limit the flows of fossil carbon and Nr into the economy at both national and EU levels. However, this raises substantive questions in relation to the detailed design of specific measures, mitigation effectiveness, fairness, impacts on wider societal well-being and overall societal support. It is recommended that specific further research be undertaken on these issues, including substantial engagement with society-wide stakeholders.

In summary, very urgent and deep mitigation is needed to adequately address the declared climate emergency. Research will need to match the pace of rapid, large-scale transformational changes likely to be needed in society. The coronavirus disease 2019 (COVID-19) research response and rate of policy reaction shows what can be done when an emergency is treated as such. An ongoing large-scale, multidisciplinary mitigation research effort is warranted to navigate transition uncertainty and continually update the findings to assist the public, political leaders, government and other decision-makers to enable society-wide achievement of effective climate change mitigation.

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Abbreviations

AD	Anaerobic digestion
BAU	Business as usual
CAP2019	2019 Climate Action Plan
CBA	Cost–benefit analysis
CCAC	Climate Change Advisory Council (Ireland)
CCC	Committee on Climate Change (UK)
CCS	Carbon capture and storage
CDR	Carbon dioxide removal(s)
CGE	Computable general equilibrium
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
CO_2-we	Carbon dioxide warming-equivalent
COSMO	COre Structure MOdel of the Irish economy
DDPP	Deep Decarbonisation Pathways Project
DEEDS	Dialogue on European decarbonisation strategies
DICE	Dynamic Integrated Climate Economy
ENA	European Nitrogen Assessment
EPA	Environmental Protection Agency
ESRI	Economic and Social Research Institute
EU	European Union
GCAM	Global Change Assessment Model
GCB	Global cumulative CO_2 budget
GCB*	Global cumulative GHG budget
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
GWP_{100}	Global warming potential over 100 years
IAM	Integrated assessment models
IMAGE	Integrated Model to Assess the Global Environment
IPCC	Intergovernmental Panel on Climate Change
LLCF	Long-lived climate forcer
LULUCF	Land use, land use change and forestry
MAC	Marginal abatement cost
MEDEAS	Modelling Energy Development under Environmental And Socioeconomic constraints
NCQ	National carbon quota
NCQ*	National cumulative-GHG quota
NECP	National Energy and Climate Plan
NET	Negative emissions technology
Nr	Reactive nitrogen
N_2O	Nitrous oxide
PRIMAP	Potsdam Realtime Integrated Model for probabilistic Assessment of emissions Paths
SDG	Sustainable Development Goal
SLCF	Short-lived climate forcer
SPM	Summary for Policymakers

SR1.5	IPCC Special report on global warming of 1.5°C
SSECCM	Society-wide Scenarios for Effective Climate Change Mitigation in Ireland (project)
SSP	Shared socioeconomic pathway
tC	Metric tonnes (1000 kg) of carbon (1 tC corresponds to 3.67 t CO_2 on combustion)
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

Afforestation and reafforestation	A negative emissions technology whereby the total carbon stock of forested land (as per the United Nations Framework Convention on Climate Change definition) is intentionally increased by planting trees on previously unforested land (afforestation) or replanting trees on previously forested land (reafforestation). It is possible that increased afforestation and reafforestation may not increase national forest carbon stock if harvest cancels or exceeds afforestation and reafforestation.
Biochar	A negative emissions technology competing for the same indigenous bioenergy fuel land resource as afforestation and reafforestation and bioenergy with carbon capture and storage.
Bioenergy with carbon capture and storage	Usually describes point-source CO_2 abatement at power stations fuelled by biomass or biogas combustion with on-site CO_2 capture from the flue gases, which is then transported by pipeline or ship for injection into geologically secure storage.
Black carbon	Fine carbon soot pollutant particles that act as a very short-lifetime climate forcer.
CAP2019	The 2019 Climate Action Plan is Ireland's current climate plan.
Carbon capture and storage	Methods that achieve the capture of CO_2 from flue gases or the atmosphere, followed by transport by pipeline and then injection into geologically secure storage.
Carbon commitment analysis	This charts the projected pathway of cumulative CO_2 emissions (net and gross) for an energy–cement–land use scenario.
Carbon dioxide	CO_2 is the main greenhouse gas and very long-lived climate forcer, targeted by climate mitigation policy in energy and land use.
Carbon dioxide equivalent	Denotes the amount of CO_2 emissions that is equivalent, according to the applicable GWP_{100} metric, to a given amount of non-CO_2 GHG emissions. Note that for short-lived climate forcers (such as CH_4), this may yield a very poor estimate of the *cumulative* warming effect of such emissions.
Carbon dioxide removal(s)	Planned and managed removal of CO_2, using negative emissions technologies, from the atmosphere to land, ocean or geo-storage (via carbon capture and storage). Generally synonymous with greenhouse gas removal.
Carbon dioxide warming equivalent	Denotes the amount of CO_2 emissions that is equivalent, according to the GWP* metric formula, to a given amount of non-CO_2 GHG emissions. For long-lived climate forcers (e.g. N_2O) this is identical to conventional carbon dioxide equivalent (using GWP_{100}). However, for short-lived climate forcers (e.g. CH_4), this provides a different, and significantly improved, estimate of the *cumulative* warming effect of such emissions.

Clean Development Mechanism	The largest system of carbon permit emissions trading defined by the Kyoto Protocol, aiming to enable global mitigation at a lower cost.
Climate Action and Low-Carbon Development National Policy Position (Ireland)	This is the Irish Government's current (as of 2019) mitigation policy outline guiding the National Mitigation Plan.
Direct air carbon capture and storage	A net emissions technology 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	A net emissions technology whereby ultrabasic or basic rock is mined and powdered (requiring 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.
Fifth Assessment Report	AR5, published by the IPCC from 2013 to 2014, is composed of three working group reports and a synthesis report, with summaries for policymakers agreed by governments.
Fossil fuel and industry energy generation or industrial production with carbon capture and storage	This usually describes a fossil fuel (coal or gas) burning power station with carbon capture and storage abatement.
Fossil fuel and industry sources of greenhouse gases	This is primarily CO_2 from unabated fossil fuel combustion, but also from cement and steel production.
Global cumulative CO_2 budget	An estimated cumulative limit on CO_2 (only) that can be released to atmosphere based on a specific limit on global temperature increase. GCB estimates are referenced to a specified start year, and necessarily incorporate assumptions about warming due to other (non-CO_2) climate forcers.
Global cumulative GHG budget	A modified version of global cumulative CO_2 budget that reflects the combined effect of multiple, long- and short-lived greenhouse gases using the GWP* metric. Thus, it is an estimated cumulative limit on a mix of greenhouse gases that can be released to atmosphere based on a specific limit on global temperature increase. Global cumulative GHG budget estimates are referenced to a specified start year.
Global warming potential	A metric for comparing the global warming effects of different greenhouse gases. It is defined as the time-integrated radiative forcing due to a pulse emission of a given gas, relative to a pulse emission of an equal mass of CO_2, over some specified time period. Note that, in general, the GWP metric provides a relatively poor estimate for the combined warming effect of cumulative emissions of a mix of both short- and long-lived greenhouse gases. GWP* is a modified version of the GWP metric for comparing the global warming effects of different greenhouse gases. It is specifically designed and calibrated to provide an improved estimate for the combined warming effect of cumulative emissions of both short- and long-lived greenhouse gases compared to the direct use of GWP.

Greenhouse gas	A trace gas in the atmosphere that reduces re-radiation of incident solar energy, keeping the Earth's surface warmer than it would otherwise be (the "greenhouse effect").
Greenhouse gas removal	A process that removes some greenhouse gases from the atmosphere (and either consigns them directly to long-term storage or transforms them to some stable, benign form). Generally synonymous with NET and with CDR.
HighGCB_Pop	A national carbon quota defined by McMullin *et al.* (2019), based on a high-end estimate of the global carbon budget and shared on a (minimally) equitable equal-per-capita basis (as of 2015).
Integrated assessment models	Analytical models combining climate models with global, regional or national models' economic growth, energy use and technologies. Used to advise on policy options.
LowGCB_Pop	A national carbon quota defined by McMullin *et al.* (2019), 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 is a potent greenhouse gas. Classified as a short-lived climate forcer, its warming effect depends on the total ongoing flow of emissions. A permanent increase in CH_4 emissions substantially increases net forcing, but a sustained decrease in CH_4 emissions has an equivalent effect to achieving negative emissions.
MidGCB_Pop	A national carbon quota, defined by McMullin *et al.* (2019), 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 cumulative CO_2 quota	An assessed national "fair share" of the global cumulative-CO_2-only budget (GCB) for a defined temperature limit goal, from a given reference year, on the basis of some defined allocation method.
National cumulative GHG quota	A modified version of NCQ that reflects the combined effect of multiple, long- and short-lived, greenhouse gases using the GWP* metric. Thus, it is an assessed national "fair share" of the global cumulative-GHG budget (GCB*) for a defined temperature limit goal, from a given reference year, on the basis of a defined allocation method, such as *population*, meaning equal-per-capita sharing.
National Energy and Climate Plan	This is produced by an EU Member State as part of aggregate EU planning.
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 technology	A method that, on a lifecycle basis, achieves greenhouse gas removal, or, more specifically, CO_2 removal, from the atmosphere within some specified collection of processes (system boundary).
Net	This describes total emissions to the atmosphere minus total removals from the atmosphere to long-term storage (sequestration).

Nitrous oxide	This is a potent greenhouse gas. Classified with CO_2 as a long-lived climate forcer, it has a GWP_{100} of 265. N_2O is particularly related to the use of nitrogen fertiliser in agriculture and bioenergy, as emissions from soil and animal manure.
Non-traded national domestic emissions	This includes emissions from transport, agriculture and buildings, with Member State mitigation targets agreed under the European Union Effort Sharing Directive. For Ireland, the 2020 target is a 20% reduction relative to 1990.
Nutrient use efficiency	This is a measure of the amount of nutrient (such as nitrogen) contained in outputs (at farm gate or in final food) relative to the system nutrient input.
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 methane	Variable renewable electricity (usually solar or wind), in excess of instantaneous demand, directed to production of synthetic CH_4. See also power to fuel technologies.
Power to fuel technologies	Variable renewable electricity (usually solar or wind), in excess of instantaneous demand, directed to production of chemical fuels (denoted by X) for longer-term energy storage and/or direct end use. The initial synthesis step is typically production of hydrogen by electrolysis. Hydrogen may itself be the target fuel, or it may be used as a feedstock for the production of alternative fuels (ammonia, CH_4, methanol, etc.). These fuels may then be used to sustain the grid during under-supply from VRE or for other direct end uses (e.g. hydrogen used for heating or in fuel cell transport vehicles).
Reactive nitrogen	This is used in agriculture, primarily in synthetic fertiliser for uptake by plants, to increase productivity, and is essential for proteins.
Scenario	An *input* set of data and narrative parameters in a socioeconomic system with energy emissions as outputs from a simulation model, which 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	A net emissions technology 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.
Summary for Policymakers	This particularly refers to the SPMs from the Intergovernmental Panel on Climate Change Assessment Reports.

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 raideolaíochta.
- 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.

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Synthesis of Literature and Preliminary Modelling Relevant to Society-wide Scenarios for Effective Climate Change Mitigation in Ireland

Authors: Barry McMullin and Paul Price

Identifying Pressures

Rapid global warming due to emissions of greenhouse gases (GHGs) caused by human activities is negatively affecting global climate and ecological systems. Rapid reduction of GHG emissions to meet the goals of the Paris Agreement will require transformational changes in society while maintaining and supporting society's resilience. Ireland's energy supply is already moving away from the use of coal and peat, but it will also need to rapidly stop using oil and natural gas. Ireland's electricity grid is world leading in integrating variable wind energy. However, even greater flexibility, including very large-scale energy storage, will be required in future, as well as substantially electrifying heat and transport energy use. Transport emissions continue to be strongly coupled to national economic activity. Agricultural emissions decreased in the 2000s but, since 2010, policy to encourage expansion has greatly increased imports of nitrogen fertiliser and feed inputs, resulting in rapidly rising emissions of nitrous oxide from soils and methane emissions from animals. International aviation and other consumption emissions arising outside Ireland' borders are projected to grow. Projected Irish population growth substantially increases the required rate of decarbonisation.

Informing Policy

This research assesses the international literature to inform climate mitigation policy in Ireland. It provides a preliminary tool for comparing policy within the Paris Agreement commitments. This requires explicit national "fair share" cumulative GHG emission budgets, equitably aligned with the Paris goals to limit global temperature increases, with very limited reliance on high-risk carbon dioxide (CO_2) removal from the atmosphere. Current policy-relevant scenarios and related analyses are too narrowly based, so exploring "radical" scenarios would give a stronger risk assessment basis for climate action to avoid costly surprises. The likely damage caused by climate is being underestimated. Robust climate planning incorporates just transition, social equity (including gender equality), and economic distribution effects. Current national economic and energy modelling is reliant on highly contested simplifying assumptions. Greater use of dynamic simulation modelling to evaluate policy resilience under system change or sudden crisis could better inform societal change and achieve mitigation rates more aligned with the escalating climate and biodiversity emergencies. The use of reactive nitrogen, imported in fertiliser and indirectly via feed, and already effectively reduced in other EU nations, is a primary driver of increasing Irish methane emissions from cattle.

Developing Solutions

Delayed climate action to date now means achieving GHG emission reduction very rapidly. Further research must occur in parallel with rapid near-term decarbonisation. To drive innovation, overcome carbon lock-in effects and increase social acceptance, existing demand measures (efficiency and carbon pricing) could be complemented by equitable supply-side regulation of imported fossil fuel and reactive nitrogen. Modelling for global climate and sustainable development goals could be improved if it were based on allowable future quantities of fossil fuel and reactive nitrogen use within equitable national budgets, rather than on notional costs. The GHG-WE tool developed in this project provides preliminary modelling of alternative national policy scenarios. For effective climate change mitigation, steadily reducing Ireland's relatively high non-CO_2 emissions from agriculture could greatly ease otherwise increasingly unachievable reductions solely in CO_2. Recent policy developments in New Zealand, which has similar population and agricultural emissions profiles to Ireland, provides useful guidance for Irish policy development. Protecting existing carbon stocks (in peat and managed forest) should be the strongest priority for near-term mitigation of CO_2 emissions arising from land use.

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