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TECHNICAL REPORT

Society-wide Scenarios for Effective Climate Change Mitigation in Ireland

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EPA Research Report

Prepared for the Environmental Protection Agency by

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DISCLAIMER

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 staying within remaining global cumulative carbon dioxide (CO_2) budgets (GCBs) corresponding to the Paris Agreement temperature limits of "well below 2°C" and making efforts toward a lower limit of 1.5°C over pre-industrial. Moreover, GCB estimates depend critically on also achieving commensurate reductions in emissions of nitrous oxide (N_2O) and in methane (CH_4). Societal well-being and economic growth continue to be highly dependent on climate polluting inputs – fossil fuels for energy, cement and steel for infrastructure, and nitrogen inputs to agriculture. The research project *Society-wide Scenarios for Effective Climate Change Mitigation in Ireland* (SSECCM) was a one-year, preliminary desk study undertaken to inform implementation of Irish policy on climate mitigation in the context of EU and Paris Agreement objectives. It evaluated international studies of society-wide, long-term climate action scenarios, identifying relevance to the specific situation in Ireland. While CO_2 remains the single most important greenhouse gas to consider, emissions of CH_4 and N_2O also make a significant contribution to global climate disruption[1]. The latter two are especially important to Ireland because, though CO_2 remains the dominant GHG, we have comparatively high emissions of these other GHGs, primarily from ruminant livestock agriculture. A new open-source spreadsheet tool, "*GHG-WE",* was developed for the project and has also been made available online[2]. This tool incorporates GWP* (modified Global Warming Potential), a new, recently developed, metric to better represent the combined climate effects of different greenhouse gases. This enables comparative national-level "warming-equivalent" analysis of society-wide and sectoral policy alternatives. An additional tool, a "Methane Warming Calculator" has also been developed and released for simplified, CH_4 only, scenario exploration[3]. The collected supporting literature is now publicly available in an online bibliographic database to support future research[4].

Key literature review findings

- **Scenario planning** is essential to explore 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.
- **The concept of "effective" scenarios** is used here to mean alignment with the Paris Agreement. This requires clear limits on future greenhouse gas emissions, and commitment to climate justice. "Justice" is taken to encompass equitable treatment of all humanity: as 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 in scenario descriptions. As yet, there is a lack of international literature which adequately addresses the alignment between national development scenarios and agreed global mitigation objectives.
- **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.

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[1] There are additional human contributions to climate change, including other greenhouse gases and non-greenhouse gas factors such as certain kinds of particulates. However, their overall effect is relatively small compared to 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
[3] https://zenodo.org/record/3974485
[4] The full SSECCM bibliography is available at https://www.zotero.org/groups/2395490/sseccm-ie-d2b

Key Recommendations

- **Open data and modelling** with clear documentation is strongly recommended. This can contribute strongly to 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 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 (ETS) does impose some supply constraint on fossil fuel use in principle, but it is limited in scope, and the constraints are relatively weak. Similarly, the EU nitrates directive imposes a measure of constraint on reactive nitrogen use, but it is relatively weak, subject to ongoing derogation, and motivated primarily by concerns with 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 of nitrous oxide and methane 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 which act more slowly, and are harder to monitor and verify, such as "enhanced soil carbon sequestration".
- **Methane (**CH_4**) emissions reductions are now critical to Paris aligned climate action, both globally and nationally.** Supplementing the primary requirement for radical CO_2 mitigation, substantial and sustained reductions in total national CH_4 emissions appear to be essential to the feasibility of achieving Paris aligned climate action in Ireland. As noted, two spreadsheet tools, incorporating the newly developed GWP* cumulative GHG aggregation methodology, have been developed for this project. This has enabled preliminary exploration of illustrative GHG emission pathway scenarios for Ireland, constrained within a minimally prudent and equitable quota of a Paris-aligned global cumulative GHG budget range. This has clearly demonstrated the crucial trade-offs between mitigation 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 $MtCO_2$-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 from 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 greenhouse gases, N_2O and CH_4. The coronavirus-2019 (COVID19) 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 Project Mandate

This Technical Report summarises the outputs of the research project *Society-wide Scenarios for Effective Climate Change Mitigation in Ireland* (SSECCM)[5], a one-year, preliminary desk study undertaken to inform national policy on climate mitigation in the context of EU and Paris Agreement objectives. The project examines international literature addressing robust climate action scenario planning and modelling for effective climate action. It applies this in a preliminary, illustrative way, to assess Irish climate mitigation pathways for all relevant greenhouse gas (GHG) emissions from all key sources, including energy, agriculture, forestry and other land-use. The research also provides a basis for scoping a possible future full-scale decarbonisation pathways scenarios study. In addition to this detailed Technical Report, an accompanying Synthesis Report presents a summary, plain language synopsis of the project findings.

1.2 Context: Global

Global climate action is *not* currently aligned with achieving the Paris Agreement temperature limits of "well below 2°C" and making efforts toward a limiting to 1.5°C above pre-industrial. Even prior to Paris, the UNFCCC Structured Expert Dialogue "… established that 2°C cannot be considered safe" (Schleussner and Fyson 2020) and this higher limit approximately doubles global exposure to multi-sector risks compared to the 1.5ºC limit (Byers et al. 2018). The CO_2 pathways assessed in the SR15 report (IPCC 2018) as meeting the Paris temperature limits critically depend on *also* achieving reductions in key non-CO_2 gases, specifically N_2O and CH_4 (Allen et al. 2018a). To date, the climate actions of developed nations in particular have been insufficient despite their acknowledged responsibility for a disproportionate share of historic emissions and their greater capacity for action given their comparative wealth (Matthews 2015). Societal well-being and economic growth continue to be highly dependent on climate polluting inputs – fossil fuels for energy, cement and steel for infrastructure, and nitrogen inputs to agriculture (Hickel 2019a). 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 each nation's 'fair share' of the global carbon budget (Obersteiner et al. 2018). Climate scenarios, modelling and frameworks are needed to guide nations and decision-makers toward an effective *post-carbon transition*, the achievement, locally and globally, of a situation where anthropogenic radiative forcing (human caused global warming) is first stabilised and then progressively reduced, to restore human society to a position where 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. Ireland's average temperatures have increased in line with the rapid average rate of global warming (Sweeney et al. 2008; Dwyer 2012; Gleeson et al. 2013) and climate change appears to be increasing the regional impact of extreme weather events affecting Ireland, particularly increased heavy rainfall (Otto et al. 2018). Ireland's population reached 4.9 million in 2019 (CSO 2019) and is projected to grow by 14-36%, to between 5.6 and 6.7 million, by 2051 (CSO 2018). Given that Ireland's per capita GHG emissions are already higher than the EU average, an increasing population represents an additional challenge to effective climate mitigation. Future Irish trade and politics have been complicated by renewed concerns over the status of the Irish border due to the UK

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

exit from the EU (Laffan 2018; O'Brennan 2019). Large jumps in Irish GDP since 2015 have been the result of cross-border transfers by foreign owned multinational enterprises (Wright and Zucman 2018), including income passing through Ireland that is based on activities (and emissions) occurring elsewhere, particularly Asia (CCAC 2019, Box 2.1). The Climate Change Advisory Council (CCAC) emphasise that, "[a]s a result, the relationship between GDP and emissions in Ireland is no longer straightforward".

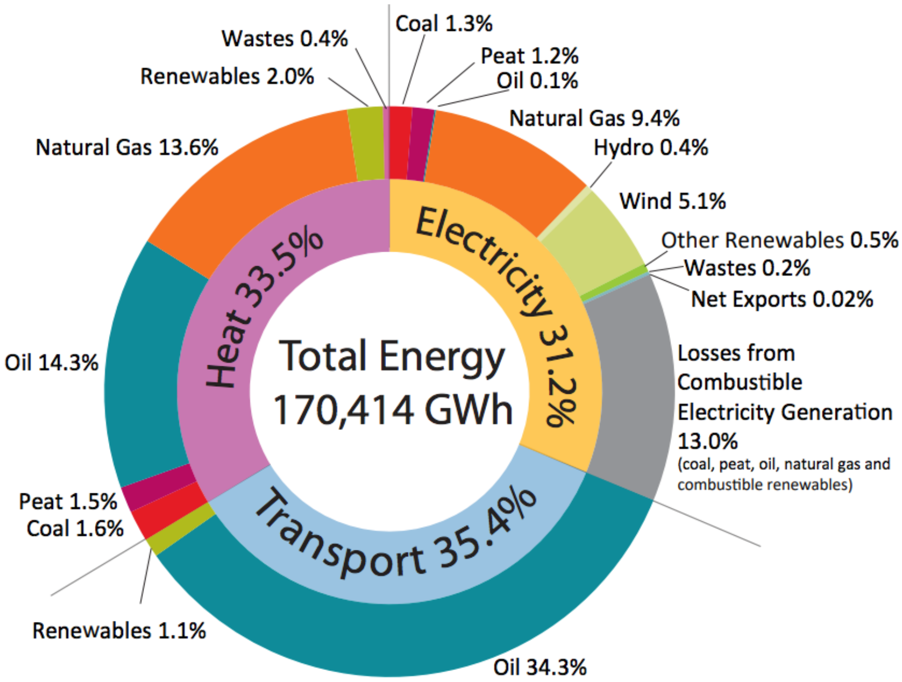


Figure 1.1 Ireland's primary energy by fuel and demand mode (SEAI 2019).

The EPA inventory of Ireland's GHG emissions is based on five sectoral categories: energy (including electricity generation, manufacturing and transport); industry, including cement and mineral production; agriculture; land use, land use change and forestry (LULUCF); and, waste (Duffy et al. 2019). In accordance with current reporting rules, emissions of CO_2 arising due to *bunkers* (international aviation and shipping) and from bioenergy use are reported 'below the line' and are not included in the attributed total territorial emissions, although they are associated to a significant degree with consumption arising in Ireland. This issue of emissions attribution continues to be discussed at international level. Aviation emissions due to international flights *within* the EU have been brought within the scope of the EU-wide emissions trading system (EU-ETS). CO_2 emissions are primarily due to: fossil carbon combustion from peat, coal, oil and gas in energy uses; decarbonisation of carbonates during cement production; and net LULUCF emissions as gross annual removals by forest growth and transfer to harvested wood products are outweighed by gross emissions from grasslands, wetlands and forest harvest (Duffy et al. 2019, Table 6.2). Fossil fuel (oil, coal, natural gas and peat) combustion accounted for 89% of Irish primary energy requirement of 170 TWh in 2018 (SEAI 2019). As shown inFigure 1.1, this was divided into approximately one third each for electricity generation, heat (for industry and buildings) and transport (SEAI 2019). On a final energy basis by sector, percentage shares were: transport 42%, residential heating 23%, industrial heat 21%; services 12%, and agriculture/fisheries 2% (SEAI 2019, Table 2). N_2O emissions are primarily (93%) soil emissions driven by the use of nitrogen fertiliser in agriculture. CH_4 emissions are also predominantly from agriculture (92%) – primarily due to enteric fermentation from cattle digestion of grass and feeds, and from animal manure – with the remainder mostly from the waste sector.

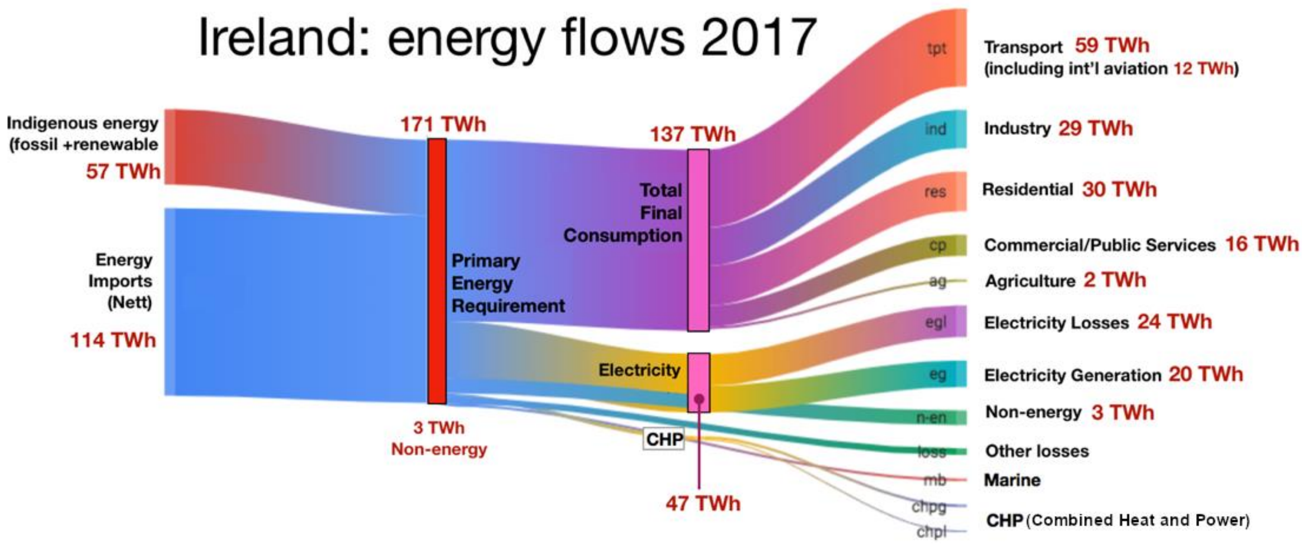


Figure 1.2. Ireland energy flows in 2017. Original chart, based on data from (SEAI 2018).

1.4 Structure of the Report

This report presents the detailed research findings from the project. It is intended to inform national policy by identifying and applying relevant international literature, presenting preliminary, illustrative, national GHG scenario modelling, and indicating potential solution strategies relevant to Ireland, on the basis of identified pressures. The body of the report is structured as follows:

- Chapter 2: Briefly presents the methodology underlying the bibliographic database of relevant literature developed for the project.
- Chapter 3: Summarises findings relevant to overall scenario planning for effective, Paris-aligned, climate action.
- Chapter 4: Summarises findings on societal and modelling issues in comparison of climate change mitigation scenarios, particularly limitations in current modelling.
- Chapter 5: Summarises relevant findings from EU and national climate mitigation research.
- Chapter 6: Focusses in more detail on the key GHGs, their properties, drivers and potential for mitigation.
- Chapter 7: Presents preliminary, illustrative modelling of GHG mitigation pathway scenarios for Ireland.
- Chapter 8: Presents recommendations arising from the project, for overall national climate action policy and specifically for further research on society-wide mitigation scenarios.

2 Bibliography: a reference database of mitigation literature

As a basis for the project literature review, relevant national and international literature was identified and catalogued, for inclusion in a searchable public-access bibliographic database resource with particularly relevance to Ireland's low carbon transition and climate mitigation in the context of the Paris Agreement. Collected bibliographic data is stored using Zotero[6], a free-to-use, non-proprietary reference management database offering public web access. The final Augmented version of the bibliography[7] followed a "funnel" sorting of database items (Barker 2014), which evolved in parallel with the project report development, to organise items into primary topic collections (folders) and secondary sub-collections. Multiple tagging enables cross-reference database search by keywords across folders. The zero-level folder in the database gives project documentation, including detailed notes for users. A short introductory video to use of the database is available online[8].

A low carbon transition for an individual nation requires locally appropriate *place-based approaches* that are constrained within national, Paris-aligned, emission limits (Giest 2014). A wide knowledge base informed by international literature can ensure such responses avoid path-dependent "silo" responses that might 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). Literature collection aimed to achieve wide coverage, primarily of peer-reviewed academic literature, but also well-evidenced grey literature such as official and technical documents where 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". This used a pragmatic demarcation criterion of sustained, multi-decade, GHG (mass flow) emission rate reductions of at least-8% p.a. Particular attention was given to references relevant to Ireland's distinctive emissions profile (high agricultural contribution of non-CO_2 GHGs), opportunities to ensure deep reductions in fossil fuel usage, assessment of indigenous very low CO_2-intensity energy resources, and consideration of land carbon storage issues.

[6] http://www.zotero.org

[7] The Augmented SSECCM bibliography is available at https://www.zotero.org/groups/2395490/sseccm-ie-d2b

[8] User guide video for the SSECCM bibliography database: https://www.youtube.com/watch?v=7Y2ZmMxXlfE

3 Scenario planning for effective climate mitigation

3.1 Introduction: findings relevant to scenario planning for effective climate action

This chapter focuses on the use of scenario planning for the exploration of transition risk and deep uncertainty, including reference to societal goals such as the UN sustainable developments goals (SDGs) and UNFCCC and EU climate goals. Ireland's Climate Act (Oireachtas 2015) aims to provide the statutory basis for the State to achieve its "national transition objective", defined only qualitatively, as a "transition to a climate resilient and environmentally sustainable economy by the end of the year 2050". Ireland's most recent Climate Action Plan (DCCAE 2019) indicates a quantitative target reduction in overall annual GHG emissions of approximately -20% over the period 2021-2030[9] and then potentially to "net zero" by 2050. It also continues to reference the Irish National Policy Position on climate action, or NPP (DECLG 2014), which predates the Act. This specified two separate long term GHG mitigation targets expressed as: "an aggregate reduction in carbon dioxide (CO_2) emissions of at least 80% (compared to 1990 levels) by 2050 across the electricity generation, built environment and transport"; and, "in parallel, an approach to carbon neutrality in the agriculture and land-use sector, including forestry, which does not compromise capacity for sustainable food production". Neither "carbon neutrality" nor "sustainable" were specifically defined. The Act states that achieving the transition objective shall have regard to the UNFCCC Article 2 objective and to climate justice. These commitments to equitable action have subsequently been reinforced by: ratification of the Paris Agreement, requiring mitigation action on the basis of equity; and participation in achieving the SDGs, especially noting the interactions between SDG 5 (gender equality) and SDG 13 (climate action). The CCAC Annual Report (CCAC 2019) notes the centrality of equity in climate, energy and environmental justice, domestically and internationally, and particularly focuses on ensuring a just transition for workers within Ireland.

3.2 National scenario planning in the context of a deeply uncertain global future

3.2.1 Global futures: no consensus on the scenario possibility space

As illustrated in the indicative Figure 3.1, there is a very large future possibility space of global scenarios with no consensus across international research on the likely future pathway for global society. The figure charts global warming, measured by cumulative CO_2 emissions, relative to economic activity, measured by Gross World Product, with time proceeding along the charted line. At lower left, a chart (data from: Rogelj et al. 2018; World Bank 2019) shows that from 1870 to 2017 there were two distinct fossil fuel energy periods, both proceeding more or less linearly: first, a steep rise in cumulative emissions from 1870–1950 dominated by coal use; and a second shallower trend, with the addition of large scale oil and gas use, from 1950, the so-called "great acceleration" (Steffen et al. 2015a), to present, accelerating on a trajectory toward breaching Paris-aligned global cumulative CO_2 budget limits within the period 2030-2040. The stylised alternative future pathways illustrate the widely divergent possible global pathways that are evident across the expert research literature. IPCC-assessed IAM modelling is now using the Shared Socioeconomic Pathways (SSP) framework of five schematic socioeconomic futures that differ in their level of challenges to mitigation and adaptation (O'Neill et al. 2017). All the SSPs appear to posit some form of continuing global economic growth, with sustained per capita economic growth rates of 1.0 to 2.8% per annum, resulting in a global economy that is three to nine times larger in 2100 compared to 2020 (Leimbach et al. 2017). In orthodox climate economics, cost-benefit analysis (CBA) IAMs, exemplified by work extending over the past 30 years using the DICE

[9] "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 2019, pp. 26-27)

climate economics model (Nordhaus 1991, 1993), the "economically optimal" pathway that is calculated by these models generally continues the business-as-usual (BAU) trajectory of recent decades with little apparent effect on aggregate global economic activity even at cumulative CO_2 budgets potentially corresponding to 4°C of average warming (Nordhaus 2019). Such "economically optimal" pathways appear physically irreconcilable with the IPCC's expert assessments of climate science and environmental impacts, which indicate that such a level of warming risks severe, potentially catastrophic, damage to global physical, human and ecological systems, beyond limits to adaptation (Heal et al. 2014; Klein et al. 2014).

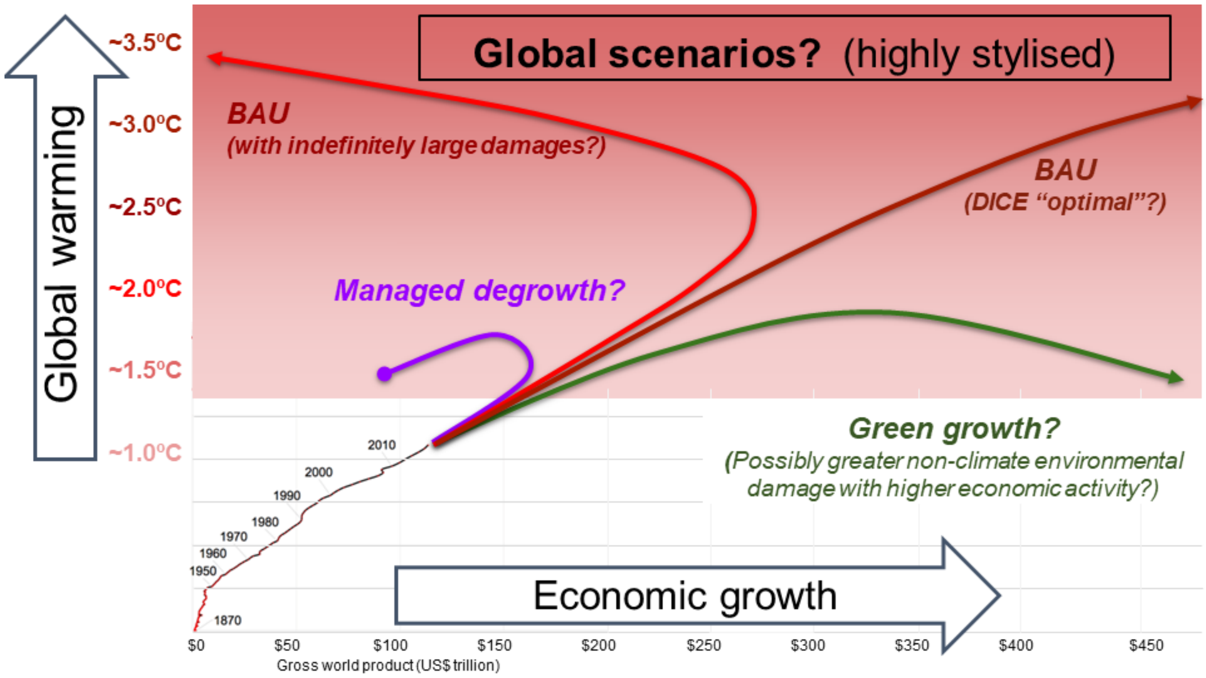


Figure 3.1. Stylised possibility space of future global scenarios for climate change (warming over pre-industrial) interacting with economic activity

In Figure 3.1 the pathway labelled *BAU with damages?* denotes this possibility of global mitigation failure and disorderly socioeconomic collapse due to growth in human economic activity overshooting biophysical limits (Field et al. 2014b, Assessment Box SPM.1). This possibility is discussed in research literature (Ehrlich Paul R. and Ehrlich Anne H. 2013; Martin et al. 2016; Cumming and Peterson 2017; King 2020), particularly dating from the publication of *The Limits to Growth* (Meadows et al. 1972; Turner 2008) and through recent work more precisely delineating possible biogeochemical planetary boundaries (Steffen et al. 2015b). So-called *tipping points* in physical, ecological and societal systems may be crossed well before the triggered dynamics of a self-reinforcing shift to a new system configuration become clearly manifest (Lenton and Ciscar 2013; Steffen et al. 2018; Lenton et al. 2019). Understandably, there is little coherent research assessing such potentially highly disorderly outcomes; but it would be unwise to simply discount or ignore such possibilities. This point is also captured to a certain extent in the IPCC AR5 discussion of "low probability, catastrophic events" (Kunreuther et al. 2014). The final fourth potential category of trajectory shown in Figure 3.1 is characterised as *managed degrowth.* This represents scenarios of urgent, radical transition to enable the continuing viability of global society within ecological limits (Trainer 2012, 2020), based on research indicating that sustained further growth of Gross World Product may be unfeasible given energy and resource depletion, and pollution impacts including climate change (Meadows et al. 1972; Kerschner 2010; D'Alisa et al. 2014). Degrowth studies examine scenarios including coordinated action to achieve globally equitable outcomes, often envisaging a significant *reduction* in energy use, and technology use that is comparatively *less* complex and/or extensive than is typical of current highly industrialised societies (Alexander and Yacoumis 2018) accompanied by large scale ecological restoration (Blignaut and Aronson 2020). Such scenarios would likely require emergency measures, especially by wealthy nations and actors in the near-term, to strongly limit future GHG emissions (Anderson and Bows 2011; Steinberger et al. 2020). It is argued that transition research should therefore focus greater attention on unsustainable trends and their drivers (Antal et al. 2020). Overall, the lack of consensus and deep uncertainty in the research understanding of global socioeconomic pathways poses severe challenges for national climate mitigation scenario development.

3.2.2 Scenario planning: exploring deep uncertainty

Scenario planning has long been used in strategic analysis to investigate uncertainty in future outcomes by systematically defining a limited range of challenging alternative scenarios – each with a plausible narrative of qualitative and quantitative description of variables. Ideally, the number of scenarios developed for policy assessment is limited to no more than six but it needs to be sufficient in number to provide useful insights into developing policies or responses to potentially difficult futures (Coates 2000). Börjeson *et al.* (2006) give a typology of scenarios based on primary futures questions – "*What will happen?, What can happen?* and *How can a specific target be reached?*"– corresponding to predictive, exploratory and normative modes of analysis. Amer *et al.* (2013) describe and compare the characteristics of different scenario development techniques that are commonly used in corporate and government scenario planning, including the Wilson (1998) criteria for scenario inclusion in an analysis: plausibility; logical consistency; relevance to critical decisions; challenges to conventional wisdom; and, clear differentiation from other included scenarios.

Over-confidence is a major problem in scenario planning and modelling, and its interpretation by stakeholders, particularly if risk and uncertainty are not clearly differentiated. According to the original definition by Knight (1921), *risk* can be estimated on the basis of assessed probability, whereas, *uncertainty* cannot be calculated in terms of probability. In addition to *risk* that can be statistically modelled, Stirling (2007) classes possible outcomes in non-linear, complex systems subject to compound events or tipping elements under *uncertainty*; *ambiguity* arises when information is entirely insufficient or highly contested, and, appropriately, groups 'unknown, unknowns' and unanticipated events under *ignorance*. Derbyshire (2017a) points out that the mainstream economics literature often fails to properly distinguish uncertainty from risk by incorrectly assuming that expert-judgment of subjective probabilities can be applied to both. He argues that this is a highly misleading simplification, liable to support flawed recommendations. Moreover, incorporating path-dependent preconceptions into scenarios can bias decision-makers. Derbyshire notes that in scenario planning within Royal Dutch Shell during the 1970s, aimed at limiting exposure to oil supply crises, researchers found that if high impact scenarios were assigned small probabilities then management failed to give these possibilities due attention despite their plausibility and potentially very large negative impacts. Spaniol and Rowland (2018) argue that such issues lead to a paradox in that scenario planning is much used but the huge range of qualitative and quantitative methods, and the unknowable nature of deep uncertainty, mean that it lacks strong support from consistent theory, thereby undermining its credibility. Addressing this, Derbyshire (2017b) posits that a stronger, though still inevitably subjective approach lies in the use of Shackle's 'Potential Surprise Theory' (PST), through which uncertainty is investigated by the unbounded use of scenario descriptions that are deliberately defined to challenge existing thinking by starting from a *basis of implausibility* or *maximum potential surprise*, each scenario arising from particular policy strategies being challenged by potential highly adverse conditions and each then being assessed on the basis of potential gains or losses. Avoiding probabilistic methods, which can imply an unjustified level of confidence, and being highly explicit about such headline assumptions are clear recommendations from the scenario planning literature and in surveys of researchers using energy scenarios (Braunreiter and Blumer 2018). To improve organisational *horizon scanning*, Rowe *et al.* (2017) advocate expert-elicitation focus on the most positive and most negative outcomes of existing or possible policy objectives, and, from these, aiming to identify the possible causal chains resulting in these outcomes.

However, Derbyshire and Wright (2014, 2017) caution against assuming such causal determinacy in horizon scanning because it fails to appreciate the indeterminate nature of uncertainty and therefore an "anti-fragile" approach to scenario definition must necessarily include consideration of plausible surprise events that may be without obvious causes yet carry the potential for substantial systemic socioeconomic disruption. This implies that all theories and models including those used in scenario planning must be agile or simple enough to be easily and quickly adjusted to changed circumstances.

Scenarios can be divided into two main classes: *explorative* and *target* (*backcasting*) methods (Dagnachew et al. 2019). In an explorative scenario, a specific set of socioeconomic, technology and policy assumptions are made, and the resulting scenario outcome over time is described. This may be based on modelling or through other research, such as comparison with case studies or using expert opinion. In a target scenario methodology, a long-term target becomes the base assumption from which a pathway is either backcast from, or optimised toward. An example might be stabilising global temperature rise to the Paris Agreement's "well below 2°C" limit by a certain date. This distinction extends into climate economics integrated assessment models (IAMs): *cost benefit analysis* is typically exploratory, notionally optimising or balancing transition costs against damage cost, whereas *cost effectiveness analysis* is target-based, focused on evaluating the costs of meeting a stated goal without fail.

Policy uncertainty and governance issues are often claimed as a reason to adopt adaptive policies of "wait and see" or incremental change to reduce costs (Olsson et al. 2006; Roelich and Giesekam 2018), even under 'robust decision making' methodologies (Lempert and Schlesinger 2000). To the contrary however, the fact of deep uncertainty in future outcomes including plausible high impact outcomes necessarily results higher policy costs for delayed mitigation (Lewandowsky et al. 2014c). For plausible but (deeply) uncertain catastrophic outcomes from global warming, decision-makers need to be aware that "any appeal to uncertainty implies a stronger, rather than weaker, need to cut greenhouse gas emissions than in the absence of uncertainty" (Lewandowsky et al. 2014a). Therefore, a key finding for climate policy scenario assessment is that uncertainty regarding negative societal impacts due to the climate impacts of GHG emissions logically decreases the cost of precautionary early mitigation and increases the costs of delay (Lewandowsky et al. 2014c, b).

3.2.3 Frameworks and requirement for scenarios to explore effective climate mitigation

The IPCC SR15 report 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. The SR15 report assesses a large range of modelled global scenarios increasingly related to the detailed definitions of five Shared Socioeconomic Pathways (SSPs) that are now being used as no-policy baselines of socio-economic and population development for IPCC-assessed modelling (Riahi et al. 2014; Ebi et al. 2014; Kriegler et al. 2014; O'Neill et al. 2014). The likely emissions for baseline SSPs and SSPs with different levels of Shared climate Policy Assumptions (SPAs) have been determined using differing IAMs and different assumptions (Riahi et al. 2017) as recorded in the open and accessible online SR15 database (Huppmann et al. 2018a) and this research continues toward the forthcoming IPCC Assessment Report 6.

Scientific assessments since the Paris Agreement have focused on achieving emission pathways limiting global temperature rise to 1.5 °C over per-industrial, based on a literature that explored achieving specific climate outcomes by 2100. However, Rogelj *et al.* (2019) show that this common choice of 2100 as an end year for scenarios can bias modelling toward favouring delayed action pathways that may accept higher mitigation risks and costs. Geden and Löschel (2017) argue that if nation states intend, in good faith, to meet the Paris temperature goals, then they need to provide far greater clarity by explicitly stating the essential emission parameters that must underpin coherent national mitigation policy including: a stated start and completion date for effective climate change mitigation; CO_2 annual emission pathways based on stated cumulative emissions budgets, clearly demarcating fossil fuel and land use emissions; explicit commitments to amounts and duration of negative emissions (CO_2 removals from atmosphere); and clarity in interpretation and commitment to climate justice. Rogelj *et al.* (2019) propose three scenario design elements based on physical science and the Paris Agreement text to define and assess mitigation pathways in terms of their alignment with the Paris temperature goals: the timing of net-zero annual CO_2 emissions and stringency of non-CO_2 mitigation until net-zero annual CO_2 emissions, to give a determinate peak warming commitment; specifying total net cumulative CO_2 until net zero annual CO_2 emissions is reached; and stating the total net negative cumulative CO_2 to be achieved *after* net zero annual CO_2, which determines the potential amount of warming reversal from peak warming to be achieved by the scenario or policy.

The SR15 report compares and contrasts 'bottom up', regional and national scenarios and case studies, particularly studies of societal transition toward low carbon energy systems with or without nuclear or large scale biomass or carbon capture and storage, and examining sectoral mitigation options (de Coninck et al. 2018). A core basis for the assessment of scenarios in the SR15 report 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).

3.2.4 A theory framework for mitigation policy development

The IPCC SR15 framework for mitigation scenarios (see Solecki et al. 2018) offers informative but less coherent guidance through detailed tables of checklists within six focus *dimensions* (geophysical, environmental-ecological, technological, economic, socio-cultural, and institutional) in response to systemic, dynamic and spatial climate change *effects*. However, these tables lack an explicit statement of theory production that can direct the reasoned development of an evidenced policy strategy motivated by values and goals. Therefore, the clarity of the values- and goals- based theory framework outlined by Bunch (1983) is worth consideration in the context of Irish climate change research, policy-development and decision-making, as it sets out the need for explicitly stated values and goals in the context of and as context for research and governance. Bunch provides a practical, straightforward and easily applicable theory outline with four sequential steps for examining and assessing scenario options:

1. **Description**: interpreting existing reality using existing and fresh thinking.
2. **Analysis**: analysing why this current reality exists, and the range of possible futures.
3. **Vision**: determining alternatives based on *explicitly stated* values and goals.
4. **Strategy**: outlining alternative plausible actions to accomplish the vision.

This theory outline foregrounds the deeply political and normative choices underpinning different societal and technical choices that are relevant in scenario development. Applied to achieving Ireland's 'low carbon transition' aligned with the Paris Agreement, using such an explicit theory methodology could be particularly helpful in transparent and inclusive development of radical deep decarbonisation scenarios. Doing so could promote a wider and clearer understanding of motivations, aims and pathways among researchers, decision-makers and the wider public, so that challenging decisions can be made from a common basis and in a context of transparent analysis (open data and modelling).

3.2.5 Values and goals in climate change mitigation scenarios

Describing and analysing existing societal path-dependencies in policy and governance, and contrasting them with national values and goals as embodied by Ireland's declared commitment to the Sustainable Development (SDG) goals can inform a more robust basis for scenario development and coherent climate mitigation policy. Governance to enable a sustainable national transition is likely to be most effective if it is procedurally equitable (while recognising the uneven distribution of wealth and power) to garner support, and if independent institutions are supported to provide a basis for societal action (Fleurbaey et al. 2014; de Coninck et al. 2018). As climate action is a global commons issue, its resolution must ultimately rely on commons responses (Jamieson 2010) accomplished through an evolution of global multi-lateral action through some combination of markets, regulation and polycentric governance (Ostrom 2010). Efforts can include enforcing regulation and clear institutional rules to overcome path-dependent research and policies that act as barriers to action and implementation (Anderson and Bows 2011; O'Reilly et al. 2012; Kirby and O'Mahony 2018). To reach a sustainable future will require humanity to achieve social-ecological stewardship of the Earth system we are embedded within (Folke et al. 2016).

Pathways to a high resilience and low risk future are being missed through failures to learn and failures-to-act despite the potential for irreversible and potentially catastrophic damages (Burkett et al. 2014, Figure 1-5). Nation states remain the key governance level for climate action, though they are strongly influenced by powerful "veto players", such as those with interests in continued fossil fuel resource extraction (Dorsch and Flachsland 2017; Johnsson et al. 2019; Galvin 2020). However, nations can use scenario planning and act on evidence, inwardly through policy and outwardly through diplomacy, to contribute to a "Stabilised Earth" pathway from the current socioeconomic system (heavily dependent on fossil fuel energy) to a "post-carbon" global society (Wiseman et al. 2013; Steffen et al. 2018; Farmer et al. 2019). Self-reinforcing lock-ins in societal networks, and cost or acceptance barriers, delay change (Unruh 2000; Seto et al. 2016) even though stringent near-term policies are more likely to avoid more costly pathways for society (Bertram et al. 2015). Ellis *et al.* (2019) note that the issue of incumbent political and vested-interest power has not been adequately addressed in transition studies: a failure to overcome incumbency is noted in the Netherlands, whereas in Germany strong citizen-led support for a renewable energy transition has limited the impact of fossil fuel incumbents and promoted energy democracy; albeit also promoting early closure of (relatively low CO_2-intensity) nuclear power generation. In a political-economic comparison of nations and climate action, Lamb and Minx (2020) find the widespread failure to deliver deep decarbonisation pathways can be due to fossil fuel extraction dependence, corruption, lack of democratic norms, public climate unawareness and low social trust levels. Despite the difficulty of addressing these issues, Lamb and Minx stress the urgency and importance of taking "a clear-eyed view of these political economic challenges" in order to motivate the rapid decisions changes and experimentation needed given the immense cost of failure.

As recognised through the UN SDGs and in Irish policy, gender relations, agency and vulnerabilities are fundamental in existing societies and will continue to be so in societal responses to climate change including design of inclusive scenarios for formulation for society-wide participation and engagement in deep decarbonisation (Bee et al. 2015; Zoloth 2017). Hickel (2019a) suggests that while 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%". Hickel (2019b) argues further that the SDGs are themselves mutually contradictory: Goal 8, economic growth, being globally incompatible with the sustainability- and resource-oriented SDG Goals 6, 12, 13, 14, and 15. Hickel concludes that, *even* with the most rapid plausible deployment of very low emissions energy sources, meaningful achievement of the SDGs could require radical near-term reductions in total energy use by high income nations and an overriding focus on inequality reduction *rather* than economic growth.

Within and between societies, both the physical impacts of climate change and societal impacts due to mitigation and adaptation policy responses, differentially impact individuals, groups and institutions, by amplifying existing negative stressors in social change – poverty, unemployment, food insecurity, land-use change and inequalities – through power and identity differences including gender, age, disability, class, beliefs, education level, race and indigeneity (Tuana and Cuomo 2014; Jerneck 2018). In a wide-ranging literature review of gender research and feminist political ecology regarding climate change, Pearse (2017) concludes that women can be at greater risk in societies undergoing climate disruption due to 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. Jerneck (2018) details evidence for three key findings: synergistic societal responses are required to both mitigate against changes and adapt to impacts; gender-inclusive decision-making, policies and decisions enable more flexible and stronger shared responses; and considering and addressing changes in norms, rules and values of social relations, needs to be taken as seriously to enable effective policy. Inclusive societal action, respecting climate justice and gender equality can therefore be as important in policy-relevant scenario development as techno-economic objectives.

Social science articles generally, and those from ecofeminist and gender-lens viewpoints in particular, offer a necessary critique of existing, often weak, national and international commitments to climate justice and provide compelling observed and theoretical evidence for different approaches. Nonetheless, from a scientific point of view, a common weakness in political ecology literature, feminist and otherwise, appears to be an unjustified promotion of a misleading rhetoric that inaccurately conflates the physical science and its scientists, assessing climate risks, with political economic forces affecting climate risks, such as neoliberalism (see for example: Macgregor 2014; or Ruiz and Vallejo 2019). In particular the physical science context of the Paris Agreement 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 continues to focus on technological change, overlooking the reality of environmental thresholds and boundaries, as shown by physical and ecological science, and therefore fails to assess the potential for just and equitable effective policies *within limits* (Kallis 2019).

3.3 Supply-side climate policy: directly restricting fossil carbon inputs to society

Effective climate action requires limiting total future net CO_2 emissions within a cumulative CO_2 budget, aligned with the Paris temperature goals. Thus, early achievement of net zero anthropogenic carbon transfers between geologically stored, permanent carbon stocks (fossil fuels) and the atmosphere is required (Verkuijl et al. 2018; Erickson et al. 2018). Current policies globally may have proved ineffective because of aggregate global and intertemporal macroeconomic rebound effects (Herring and Roy 2007; Alcott 2010; Brockway et al. 2017) meaning that demand-side efficiency, conservation and sufficiency measures (including renewables energy penetration targets) are not effectively constrained by sustainability limits on carbon use (Lazarus and van Asselt 2018) nor rapid enough even to match emissions growth (Manoli et al. 2016). The EU-ETS, other cap and trade schemes, and carbon markets, including REDD+, are designed to link market pricing to fossil carbon emission quantities, but multiple weaknesses in governance, particularly in allowing freely allocated or poorly evidenced CO_2 emission "credits", severely undermine their effectiveness in radical decarbonisation pathways (Pearse and Böhm 2014; Edstedt and Carton 2018; Corbera and Friedli 2012; Carbon Market Watch 2017; Walters and Martin 2013). A growing literature indicates that supply side measures to *directly* limit or ration the total *quantities* of fossil carbon entering the global economy or national economies, regardless of price could have economic and political advantages, potentially attracting greater popular support as an inherently more equitable and effective form of climate action (Green and Denniss 2018; Erickson et al. 2018; Le Billon and Kristoffersen 2019).

3.4 Policy solutions for improving transition scenario planning

The EU and Ireland's current scenario approach to analysing climate policy in near-term emission projections is relatively narrowly limited to existing and proposed 'measures', generally based on policies that do not meet the parameters described in Section 3.2.3 for clarity, transparency and effectiveness. The EU-mandated National Energy and Climate Plan assessment is based on a similarly limited range of policies and notional prices that have questionable usefulness as these could be strongly impacted by radical decarbonisation transition policies, climate damage impacts or other major events (McMullin et al. 2019b). "Optimisation" modelling in support of national climate mitigation policy tends to outline a single, notionally optimal pathway based on complex and technically opaque modelling, which may itself be reliant on closed or proprietorial data inputs. Analysis by departments and advisory agencies has a tendency to be policy-based rather than fully acknowledging limits on total future fossil carbon usage. This makes it difficult to assess them in terms of equitable and scientifically based statements of national Paris-aligned commitments, or test them within the possibility space of uncertain futures (global and national) with potential high impact outcomes. Therefore, to avoid costly surprises, including possible catastrophic impacts that could severely damage societal, environmental or ecological systems, Irish policy development would arguably benefit from a wider and deeper basis of scenario planning and alternative model assessments, using open datasets 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.

Another issue for scenario planning and modelling occurs if societal policies fail to actually incorporate policy-relevant scenario advice coherently. For example, Irish TIMES modelling (Ó Gallachóir et al. 2012) has produced detailed pathways since 2012 outlining notionally least cost mitigation pathways, but as of 2020, real outcomes since 2010 have in fact tracked close to the "no policy" baseline; and agricultural emissions have actually reversed the tangible GHG mitigation that had been achieved in the prior decade. This suggests that despite the availability of such research evidence, the political governance system failed to successfully integrate this research into actual policy deployment. If policy outcomes show that such research advice is ineffective in guiding policy development, as appears to be substantially the case to date, then *ex post* research and policy assessment needs to critically assess the governance and research issues contributing to such apparent neglect of research inputs (Howlett et al. 2015; Price 2015; Kenny et al. 2018). More recent research has outlined Irish mitigation pathways based on Paris-aligned fair share national CO_2 quotas (Glynn et al. 2018; McMullin et al. 2019a), but national policy coherent with these pathways would require radical near-term decarbonisation at rates far higher than contemplated in the (subsequent) 2019 Climate Action Plan.

4 Modelling issues in transition scenario analysis

4.1 Introduction: model skilfulness and transparency are essential

As described above, scenario planning means identifying a range of scenario narratives to explore the possibility space of policy alternatives for insights into possible futures. Modelling tools are developed to use as simplified representations of a system to derive pathway outcomes related to a scenario, to enable some assessment of potential risks and identification of knowledge gaps. It is important to remember that “all models are wrong, [but] some are useful” (Box 1976), so models do need to be sufficiently skilful or informative to be useful. Even if models are necessarily restricted in representing the future or reality they can be tested against past data or assessed by using them to simulate outcomes based on known relationships or quantities. Both model developers and users have a responsibility to provide clarity through transparent data, and stating assumptions and limitations for research outputs.

4.2 Modelling issues in climate economics and energy system optimisation

4.2.1 Assumptions of constant economic growth are problematic

Consideration of mainstream ‘neoclassical’ economic theory is important because it provides the dominant theory context for the economic models underpinning national finance planning and climate scenarios in IAMs and most national energy system optimisation models (ESOMs). In Ireland, this theory basis underpins the primary financial modelling feeding into governance (Kirby 2010; Bergin et al. 2016), including policies aiming to achieve effective climate change mitigation. Mainstream macroeconomics and integrated assessment is based on neoclassical Ramsay (or similar) growth models that assume continuing long-run economic growth as an exogenous driver for scenario outcomes, and equilibrium modelling, based on assumptions of stationarity, meaning no change over time in outcome distributions relative to inputs (Hendry and Pretis 2016; Strunz et al. 2017). However, as illustrated previously in Figure 3.1, given the continuing strong relationship between global carbon emissions and global economic growth since 1950, there is increasing doubt that global economic growth rates can be sustained as this would either conflict with effective climate mitigation, be forcibly disrupted by climate impacts, or be constrained by some complex interaction of the two (Sorrell 2010; Hickel 2019a). Earlier critique by Daly (1974) and others suggested a need to reach a steady-state economy to enable long term sustainability for human societies; though even this formulation has been critiqued as being fundamentally inconsistent with long term ecological sustainability (Pirgmaier 2017). The growing literature questioning the possibility of green growth (Hickel and Kallis 2019) focuses on the potential need for economic degrowth (Kerschner 2010; Alexander 2015; D’Alisa et al. 2014), particularly in richer countries (Hickel 2019b). Other research suggests a need to prefer growth-agnostic (“a-growth”) scenario development (van den Bergh 2017), or to pursue “post-growth” policies to observe planetary limits and prioritise other societal goals such as sustainability, well-being and equity (Harangozo et al. 2018). It is concerning that, for the moment, mainstream economic and ESOM modelling generally offers little acknowledgement of these critiques, and, even when considered, may resort to probability sensitivity approaches to provide “near-optimal” analyses (e.g. Trutnevyte 2016), which are inappropriate to situations of *uncertainty* (in the technical sense), as discussed in Section 3.2.2.

4.2.2 Equilibrium modelling favours lock-in behaviour and undervalues sustainability

To find a notionally “optimal” outcome, neoclassical general- and partial- equilibrium economics modelling generally adopts a highly problematic simplifying assumption that a socioeconomic system can be represented as if it is an indefinitely long-lived single representative agent, with perfect foresight, such that markets are perfectly efficient, acting on a free flow of information (Hendry 2018). Fundamentally, such theory assumes *ergodicity*, static uniformity in probability distributions across a system and through time and tendency to equilibrium, even though real, dynamic socioeconomic systems are non-ergodic and non-equilibrium with mutual feedbacks, as is well understood outside mainstream economics (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-word systems, but in reality, the 2008 global economic crisis, unforeseen by mainstream equilibrium models and following a long period of apparent stability, exemplifies forecast failure in neoclassical economics (Bezemer 2010). Bezemer shows that Post-Keynesian accounting or flow-of-funds models – following the early work of Minsky (1982), and more recently Keen (2010) – performed far more skilfully in anticipating the financial crisis. In a hindcasting test, comparing models to historic data, the neoclassical economic growth model used by the DICE CBA climate IAM failed to forecast long-run US economic growth and, used globally, provides no skill in forecasting subsequent techno-economic change (Millner and McDermott 2016). Mercure *et al.* (2016) identify five serious flaws in equilibrium and economic optimisation modelling: optimal strategies are unrealistic; economic agents are not ‘rational’; inadequate representation of changing emergent system behaviour due to reinforcing feedbacks (both beneficial and damaging); path-dependency due to societal and technological lock-in (Unruh 2000; Seto et al. 2016) is missing from most economic models and IAMs; and, equilibrium models most often assume a rational “single representative agent” optimised on the basis of notional average “expected utility”, ignoring the reality of extreme heterogeneity among agents and their welfare interests, values and expectations. Moreover, Pollitt and Mercure (2017) show that cost benefit analysis in Computed General Equilibrium (CGE) models is biased against investments (such as climate mitigation policy), because the current “equilibrium” is (questionably) assumed to already be the outcome of an efficient market making optimal use of resources. In contrast, they find non-equilibrium, agent-based models can be far more responsive to policy change, but still need to be assessed for their skilfulness or ease of adjustment to changed circumstances.

4.2.3 Forecast failure: perfect foresight is an invalid assumption

The skilfulness of mainstream (neoclassical) equilibrium economics and dependent model projections is fundamentally flawed by assuming *ceteris paribus* stationarity 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 surprise event or unforeseen reactions. Hendry (2018) is a seminal reference summarising the results of 30 years of work by Hendry and co-authors to provide strong empirical and theoretical support for the conclusion that *“*all *equilibrium-correction* models then systematically mis-forecast”, with outcomes failing from the first location shift onward such that “[s]ystematic forecast failure is a pervasive and pernicious problem affecting all EqCM [equilibrium-correction mechanism] members”. This includes all CGE, Dynamic Stochastic General Equilibrium (DSGE) and partial equilibrium models currently widely relied upon by Central Banks, economists, IAM and energy modellers worldwide, including in Ireland. “Like a fire station that automatically burns down whenever a big fire starts, DSGEs become unreliable when they are most needed*”* is a concerning conclusion that renders long-term economic projections void (Hendry and Mizon 2014). Hendry’s mathematical logic and historic econometric assessment shows that location shifts invalidate the so-called “law of iterated expectation” meaning that core assumptions of mainstream economics are mutually contradictory: economic agents would have to behave “irrationally” after an abrupt location change if they followed the projections from optimisation, which assume “rational expectations” among agents aligned with “perfect foresight” by an imagined central planner (Hendry 2018). Over many publications, Hendry (2009, 2015, 2018), and Hendry with co-authors (Hendry and Doornik 2014; Hendry and Pretis 2016; Hendry and Muellbauer 2018), show that forecast failure is intrinsic to all theory-derived models. 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*, by testing theory- and data-driven approaches simultaneously through a step-wise, “design of experiments” analytical approach of automatic model selection and discovery. This method assumes all possible states of non-stationarity with candidate theory variables exceeding the number of data observations until a best-fit local data generation process to match a 'theory' with existing data is achieved. Usefully this process can reveal hidden location shifts in macroeconomic data that may also uncover important relations between poorly measured variables, providing valuable information to improve model skilfulness.

4.2.4 Omission of energy and pollution outputs in economics

There is an extensive literature arguing that both neoclassical and Keynesian economics and their production functions, risk contradiction with basic laws of thermodynamics in their omission of energy (more specifically exergy, or useful energy) as a non-substitutable input to production by land, labour or capital, as well as insufficient consideration of losses and waste or pollution (Daly 2007; Ayres et al. 2013; Keen et al. 2019). The Stiglitz-Solow attempt in mainstream economics to include natural resources into neoclassical production functions fails because, absurdly, the reformulation allows economic output to occur without energy inputs (Keen 2019). At the aggregate global level and over the long term, since 1900, Jarvis (2018a) finds that rebound reinvestment of energy efficiency savings has enabled marginal increases in total energy use (mostly fossil fuels) and economic growth at an emergent long-run rate of nearly 2.5% per year, thereby enabling investment in technology and infrastructure to feed back into increasing system efficiency savings to consistently overcome infrastructure decay. Since 1850, energy-economy system feedback has enabled an ongoing climate-economy feedback, growing emissions at a near constant rate of 1.8% per year (Jarvis et al. 2012). This emergent (global and decadal) macro-system behaviour showing an efficiency-rebound feedback within the global socioeconomic system could ultimately reach thermodynamic limits when there is insufficient residual energy from energy efficiency savings to invest in additional infrastructure (Jarvis 2018b; Brockway et al. 2019), but Jarvis suggests it is likely that climate damages to societal infrastructure may well be a more near-term threat to growth. Garrett (2012) suggests that aggregate global economic activity measured over time by cumulative GDP (indicating wealth and spent wealth) has exhibited a simple coupled relation to global energy consumption growth, via constant power input, a process that is sustained by energy efficiency gains that *increase* consumption (rather than decreasing consumption as is often assumed). Garrett argues that this simple model outperforms the complexity of IAMs and that increasing environmental impacts, especially from climate change, pollution and resource depletion, will act as an ever-stronger brake on economic growth and energy use, inevitably leading to fragile system behaviour, economic decline and possible collapse (Garrett 2014, 2015). Given the strong linear relation of cumulative CO_2 emissions to global warming, rather than modelling using notional costs based on physically problematic theory, modelling effective climate action can have a *physical* basis, such as meeting a particular global carbon budget (GCB) at global level (Dietz and Venmans 2019), or at national or regional level based on meeting a GCB-derived, "fair share", national CO_2 quota allocation (McMullin et al. 2019a).

4.2.5 Issues in scenario cost analysis and marginal abatement cost (MAC) curves

Climate cost benefit analysis (CBA) and CBA-IAMs such as DICE are predominantly exploratory, claiming to project notionally cost optimal outcomes from climate policy based on economic modelling and path dependent assumptions. A common but largely unrecognised problem in least-cost climate and energy modelling aimed at finding a single equilibrium pathway is a failure to incorporate system inertia and feedbacks over time, thereby avoiding the high likelihood that there are in fact multiple divergent equilibria and pathways that are highly dependent on past choices (Grubb and Wieners 2020), echoing the analysis and social science of human risk assessment reported by Peters (2019). This failure to include path-dependent behaviour and inertia, and mutual feedbacks between measures and system rebounds, also impairs the value of marginal abatement cost, or MAC, curves (Kesicki and Ekins 2012). Moreover, MAC analysis has been strongly critiqued for overlooking large early investments with beneficial long term returns (Vogt-Schilb et al. 2018) and for mis-ranking specific measures, especially those with supposedly negative cost (Taylor 2012; Ward 2014; Levihn 2016).

Cost benefit analysis (CBA) and CBA-IAMs claims to balance the costs and benefits of climate mitigation, suggesting an "optimal" level of warming for each, based on various scenario assumptions (Edenhofer et al. 2014, Ch. 3). In contrast, cost effectiveness analysis (CEA) and CEA-IAMs are goal or performance constrained, examining only alternative sociopolitical and technology -policy pathways and notionally cost-effective outcomes that all *achieve* a specified objective (Ackerman et al. 2009; Koomey 2013). Ireland's Public Spending Code (DPER 2019) also makes this crucial distinction between "optimisation" in CBA, which may or may not meet any specified goal, and guaranteed (but optimal) *achievement* of a policy goal in CEA.

4.2.6 Climate impacts and damage costs are very likely underestimated in IAMs

Many types of IAM are used to inform understanding of the possible effects of different socioeconomic futures and policy choices on future global climate and environmental outcomes. Including a table of 61 reviewed and described models, Nikas *et al.* (2019) provides a predominantly neoclassical typology detailing six common types of climate-economy models in the literature. Kriegler *et al.* (2015) describe the type and modelling approach of the foremost energy-economy IAMs, though it is notable that the equilibrium type (general or partial) listed for several models differs markedly from that by specified in Nikas *et al.* Tavoni and Socolow (2013) summarise the role of CO_2 removal and negative emissions technologies up to 2100 in different global IAMs intended to assess cost-effective climate mitigation. They contrast *simulation* models such as GCAM and IMAGE, which calculate economic equilibria for every time-step, with *optimisation* models, such as REMIND and WITCH, which calculate a single, notionally cost-optimal pathway up to 2100 assuming perfect foresight and discount rates based on continuous economic growth. Even so, the fact that GCAM and IMAGE are still based on economic equilibrium assumptions indicates that they are subject to the same issues as discussed in Section 4.2.2.

4.2.7 Issues with damages and discounting IAM assumptions

In assessing the mitigation pathway outputs of IAMs the IPCC SR15 report (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]inimization 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". The global IAM community has developed shared socioeconomic pathway (SSP) baseline scenarios, and Shared (climate-)Policy Assumptions (SPAs) are now guiding CEA-IAM exploration of mitigation scenarios. Climate transition policy measures are intrinsically assumed to represent a net societal *cost*, lacking skilful assessment of the counterfactual climate damage that might negatively impact on the assumptions that govern the costings. These are serious issues if damages remain poorly defined or likely to be omitted or underestimated. These standard assumptions of IAM transition modelling, of continued steady economic growth and economically negligible damages relative to discount rates (typically assumed to be of the order of 5%/yr), appear to be in direct conflict with physical science assessment showing high additional risk from 'reasons for concern' (Field et al. 2014a). Given the effect of discounting on the timing of net zero annual emissions and cumulative CO_2 budget overshoot, Emmerling *et al.* (2019) argue that IAMs should use significantly lower discount rates, of 2% or less, to better reflect the needs of inter-generational equity; though it should also be noted that this intergenerational tradeoff effect in IAMs has been at least partly due to focussing on a specific climate outcome at a fixed (arbitrary) horizon time, typically 2100. Intergenerational effects were more explicitly studied in the earlier *overlapping generations* economic models, developed in the 1990s (Howarth and Norgaard 1990, 1992), which examined different levels of intergenerational capital transfer as a proxy for sustainable decision-making. However, these appear to have been largely neglected in mainstream neoclassical economics through an axiomatic stipulation of efficient and optimal transfer through time by a single, tacitly *immortal* representative agent. Climate action policy advice in climate economic modelling of CBA-IAMs such as DICE (Nordhaus 2017) suggests "optimal" temperature pathways to well above 3°C warming, with mitigation measures limited largely to incremental and relatively slow increases in carbon pricing. This appears to be deeply at odds with: the global political acceptance of the Paris ‘guardrail’ temperature limit to acceptable risk (Schellnhuber et al. 2016); the physical science understanding of known tipping points and cascades with resultant, though weakly characterised, non-linear increases in damages (Lenton et al. 2008), thereby greatly escalating costs (Lemoine and Traeger 2016); and economic modelling, more appropriate to risk assessment, requiring high *upfront* carbon pricing as “risk premium insurance” to *require* mitigation achievement, low carbon technology uptake and innovation, such that carbon price premiums can fall only *after* effective mitigation is achieved and damage costs are limited or clearer (Daniel et al. 2019).

While there are some examples of CBA-IAM studies that do incorporate tipping point risks (e.g., Lontzek et al. 2015), it appears that a significant range of IAM outputs may be failing to inform policy sufficiently by: not reflecting the near-term climate risks indicated by physical science; under-estimating climate damage impacts through extrapolating linear change when non-linear threshold changes are possible (Steffen et al. 2015b); failing to include tipping points or compound events (Zscheischler et al. 2018); and using inequitable discount rates or low carbon pricing inappropriate to limited cumulative CO_2 budgets (Drouet and Emmerling 2016). These biases also fail to reflect unfairness in decision lock-ins and trade-offs between the transition risks for wealthier nations and climate risks faced by more vulnerable, often poorer societies (Knutti et al. 2016). These issues suggest a need for a more robust and transparent engagement between modellers and decision-makers, at national level as well as in global modelling, so that government, citizens and media can develop a shared understanding of assumptions and uncertainties in discussing scenarios and pathways, with due attention to equity and climate justice issues. Estimated climate damage costs and negative impacts on economic activity (both global and national) could well be far higher than has been assessed by IPCC AR5 WG3 (Edenhofer et al. 2014). This implies that scenario planning needs to support exploration of significantly more radical change and more appropriate modelling is needed to assess both mitigation and adaptation.

4.3 Simulation and non-equilibrium system modelling for climate policy

Simulation modelling aims to emulate and project the behaviour of real systems to enable the analysis of multiple alternative policy scenarios as an aid to decision-making. Moon (2017) reviews literature covering the three main types of simulation modelling: Agent-Based Modelling and Simulation (ABMS), a ‘bottom up’ approach in which agents interact within in a defined environment; Discrete-Event Modelling and Simulation (DEMS), allowing statistical analysis of an ordered sequence of discrete events affecting a complex system through stochastically defined processes; and System Dynamics Modelling and Simulation (SDMS), a ‘top down’ approach involving high-level, aggregate, dynamic stock-flow analysis of deterministically defined complex systems. Macal (2016) gives an overview of recent developments in the use and vocabulary of ABMS models, and Abar (2017) reviews and assesses a selection of ABMS support software. An informative set of articles in a special journal issue (Kunc et al. 2018) surveys developments in SDMS and multi-method approaches. Relevant to economic and climate policy, a notable recent contribution is a new system dynamics modelling software package called *Minsky* (Standish and Keen 2020) that has been used at 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.* 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 an the [*sic*] political decision-making processes”, concluding that simulation models are generally superior for the presentation of policy options in long-term decision-making for democratic societies.

4.4 Policy solutions: recognising model limitations and increasing the use of simulation

In summary, four major issues with the base assumptions of current modelling generally used in Irish and European policy support are: (1) the exclusion of physical energy and pollution constraints from mainstream neoclassical economics modelling; (2) the inherent flaws in projections that assume or prescribe that medium and long -term exponential economic growth rates will continue on the basis of past averages; (3) assuming structural constancy in an economy, despite the inherent inconstancy of economies due to observed and inevitable political and market *location break events* resulting in dislocations and forecast failure; and (4) treating political commitments to environmental limits and development goals as though they are secondary to optimisation assuming economic growth, when they are best included or simulated as explicit requirements that must be met without fail, e.g. commitments to align climate action with temperature limits, or to achieving the SDGs. Energy system notional-cost-optimisation models "gloss over uncertainty" (Trutnevyte 2016) and are reliant on simplifying economic assumptions that are strongly questioned by the presented literature findings, including problems with: perfect foresight, equilibrium dependence, constant growth, notional costs, lack of feedback effects, complexity, opacity due to use of proprietary data and model software, and single scenario outcomes. If these issues are not articulated sufficiently clearly by modellers then policy-makers, energy modellers and others are, in turn, likely to fail to explain or account for these limitations and their implications, thereby compromising conclusions and policy recommendations.

Most current Irish economy, emissions and energy modelling (such as the ESRI I3E, SEAI projections and Irish TIMES), feeding into climate mitigation policy through the Technical Research and advisory group Modelling (TRAM)[10], is directly reliant on mainstream neoclassical assumptions of constant long-term economic growth at the rate determined by the ESRI COSMO model whereby "the variables do eventually converge to their long-run path as specified by theory" (Bergin et al. 2017). In COSMO the composite of capital is stated in terms of a sum of capital and fossil fuel energy (Bergin et al. 2017), as though energy is only fossil-based and as if capital can exist without energy, see Section 4.2.4. Problematically, the ESRI documentation for the neoclassical COSMO and I3E (de Bruin and Yakut 2019) models fails to set out the cogent econometric and non-neoclassical evidence indicating that these methods may be subject to systematic bias and forecast failure. The evident limitations of such modelling 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. To better inform policy decisions that need to be made despite deep uncertainty, greater use of simulation modelling, particularly incorporating system dynamic models, can be more appropriate in scenario planning exploration of multiple *what-if* narrative alternatives within the context of Paris Agreement and SDG commitments. Despite the serious problems identified in Section 4.2.5, marginal abatement cost (MAC) curve methodology continues to be widely used in policy advice in Ireland. It features in Ireland's Climate Action Plan (DCCAE 2019) and Teagasc recommendations (Schulte et al. 2012; Lanigan and Donnellan 2018) for the agriculture sector, without due cautionary statements of its systematic limitations. Its use appears to have lacked transparency and its effectiveness as a basis for policy achievement has been strongly questioned (An Taisce 2019). More precautionary framing and openness would be advisable if MACs are used directly in support of policy decisions.

[10] https://tinyurl.com/DCCAE-TRAM

5 International climate mitigation scenario literature

5.1 Introduction: assessing international scenario literature relevant to Ireland

This chapter focuses on regional and national climate mitigation scenario literature that could be most relevant to EU and Irish climate action and societal transition. A critical lens for this review is the Paris Agreement (UNFCCC 2015), particularly the requirement for equitable action and the temperature goals, with their associated implications for CO_2 and non-CO_2 emissions. Global integrated assessment models are only covered in terms of application or extension to regional and national or sub-national scenario planning. This overview briefly describes global, regional and national scenario and modelling literature, particularly research projects developed in the EU and relevant to Ireland.

5.2 Extending the global SSP model framework to sub-global assessment

A comparatively small literature describes the extension of the SSP framework to assess climate impacts, vulnerability and adaptation at regional, national and sub-national levels (Absar and Preston 2015; Nilsson et al. 2017; Reimann et al. 2018; Kebede et al. 2018; Cradock-Henry et al. 2018). These approaches do not seem overly useful in designing scenarios to explore mitigation at national level, nonetheless SSP extension to national level does provide context for adaptation risks, regional health risks (Rohat 2018), and detailed population projections (Samir and Lutz 2017). This gives valuable scenario planning information for the potential different contexts for mitigation and transition scenarios according to alternative 'worlds' set out by the SSPs. Frame *et al.* (2018) describe the downscaling of global SSPs and SPAs as a credible basis and context for national mitigation and adaptation scenario development and robustness testing. They stress the need for multi-disciplinary teams and the inclusion of local actors and civil society to enable 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 also highlighting continuing methodological challenges.

5.3 EU deep decarbonisation scenario and modelling literature

5.3.1 Deep Decarbonisation Pathways Project (DDPP)

The Deep Decarbonisation Pathways Project was established as a global initiative supporting research to provide a shared research framework for production of relatively ambitious national mitigation pathways (Bataille et al. 2016). Country teams from 16 nations each developed a set of national DDPs based on: economy-wide analysis with sectoral disaggregation; "long term" time frames, initially to 2050; and detailed description of the transition pathway of energy supply and demand, including energy efficiency, electricity decarbonisation and general switching to low-carbon energy sources (SDSN and IDDRI 2015; Bataille et al. 2016). The defining requirement for ambition of the national DDPs is that they should add up collectively to a share of the global cumulative CO_2 budget aligned with limiting global temperature rise to less than 2°C over pre-industrial levels. It was therefore essential to cross-reference national results with global models, including trade in GHG-intensive products such as iron, steel and fertiliser whose production can use up a significant fraction of the remaining global cumulative GHG budget (Bataille et al. 2016). Two summary DDPP reports were produced (SDSN and IDDRI 2014, 2015). The 2014 report backcasts from an assumed global convergence to 1.6 tonnes in annual CO_2-energy emissions per capita in 2050, with a 2050 global population of 9.5 billion.

The 2014 report states: "In general, we are interested in global pathways that are 'likely' to stay below 2°C. Likely is usually defined as 'a probability of two-thirds or higher.'" However, in practice, these DDPP scenarios are based on the IEA 2DS global and national pathways (IEA 2012), which the DDPP report describes as yielding only a 50% chance of meeting the $\lesssim$2°C goal – nominally allowing a much higher global cumulative CO_2 budget than for a 66% chance. Summarising the DDPP pathway design framework and the contributing national-level assessments, Waisman *et al.* (2019) acknowledge that the DDPP's 'as likely as not' probability of ≲2°C was a less ambitious goal than subsequently agreed at Paris but argues that the DDPP framework is nonetheless important to produce coherent, comparable and useful national scenarios. This is because bottom up national studies usually fail to ensure consistent boundary conditions for collective achievement of climate goals, and global IAMs fail to give sufficient decarbonisation detail appropriate for individual nations. Notably, the strong involvement of the IEA as "a key DDPP Partner Organization" with its 2DS pathway as a core basis for nation DDPs is evident in multiple text and footnote references to the IEA and its publications in the 2014 report, although there are only four footnote references in the 2015 report and no references at all to the IEA basis in (Waisman et al. 2019).

The major elements in all national DDP plans are: greatly increased low-carbon electricity supply (generally from solar, wind and nuclear sources), allowing decarbonisation of existing electricity use and electrification of much current energy demand in heat and transport and reduced total energy use through efficiency improvement (through electrification and otherwise). Moreover, the 2DS scenario assumes: 125 GtCO_2 is captured globally from continuing fossil fuel combustion by 2050 and that CCS is available at scale for mitigating industry non-energy CO_2 sources by 2025. As a corollary, many of the country-level DDPs similarly assume large scale CCS, despite minimal current deployment. The 2014 report committed to consideration of deeper decarbonisation, socioeconomic policy frameworks, and issues of global equity and the UNFCCC (1992) acknowledgement of "common but differentiated responsibilities and respective capabilities" (CBDR-RC). Notably however, the 2015 report failed to consider any of these. Further, despite the well-known, if contested, importance of rebound effects in negating emissions savings due to efficiency measures, only the DDP for Germany detailed in the earlier 2014 report mentions rebound effects. Aggregate energy-CO_2 emissions of the DDPP countries only show a small decrease to the 2010 level by 2030 with the rates of decarbonisation only increasing markedly after 2030 and there are no detailed projections beyond 2050 at all (SDSN and IDDRI 2015). Finally, the DDPP methodology generally does not address significant measures for non-CO_2 mitigation.

5.3.2 COP21-RIPPLES

The COP21-RIPPLES project is a follow-up DDPP that has been funded by the EU to examine the implications of the Paris Agreement for EU deep decarbonisation. It aims to examine explicitly Paris-aligned scenarios based on country-level teams from Germany, France, UK, and Italy, with additional non-EU nations Brazil, China and South Africa (DDPP 2017). Six transition scenario narratives have been developed for technology-driven and behaviour driven transformation toward a ≲1.5°C limit to inform a "long-term perspective to inform the short-term action" and to investigate different ambition levels. Unlike the original DDPP, the multidisciplinary RIPPLES project does not appear to foreground a strong focus on meeting a cumulative CO_2budget or on equity; instead it focuses on "carbon neutrality" after 2050 and reduction in the GHG emissions intensity of GDP. These are comparatively weak objectives because they do not explicitly target reaching net zero CO_2 emissions by a specified date or limiting emissions within an equitable fair share quota of a Paris-aligned cumulative CO_2 budget.

5.3.3 PATHWAYS project

As summarised by Hof *et al.* (2017), the EU-funded PATHWAYS project looked at transition pathways by utilising a framework encompassing three research approaches that aim to be mutually informative: *quantitative system modelling* to enable systematic comparison of scenarios (though with simplified social change); *socio-technical transition analysis* to investigate the potential for niche innovations within existing political economic and path dependent, socio-technical regimes; and case studies of *practice-based action research* to examine exemplar local transition projects in detail. Three idealised scenarios were described: the established BAU trajectory with only incremental change; an incumbent-led trajectory enabling rapid technological change; and a radical transformative system and citizen change trajectory led by government, new entrants and civil society (Turnheim and Berkhout 2016). Both of the change scenarios "imply substantial and urgent departure from existing trends", show that transition governance requires explicit statements of the socio-political basis for choices, and indicate that a structured dialogue between alternative approaches to resolve conflicts and generate local insights could to expand the scope of potential opportunities and co-beneficial linkages (Turnheim et al. 2015; Turnheim and Berkhout 2016). These findings are aligned with the theory set out by Bunch (1983), noted in Section 3.2.4.

5.3.4 DEEDS: 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). This assists the EU Commission in preparing decarbonisation research, policy and legislative proposals. An example is the DEEDS workshop report on "Decarbonising the energy sector through Research & Innovation" (DEEDS 2019) that notes the four illustrative IPCC SR15 model pathways (IPCC 2018) and the EU *Vision for a Clean Planet by 2050* pathway. However, it does not suggest or derive any equitable, Paris-aligned aggregate CO_2 quota or sectoral CO_2 quotas within which decarbonisation is to occur.

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

Modelling Energy Development under Environmental And Socioeconomic constraints (MEDEAS) is an EU-funded, open-source, energy-economy-emissions simulation model. To date, it has been applied at World, European and selected nation levels (Austria and Bulgaria). The model has been created by a multidisciplinary team to assess appropriate decision-making across sectors in a transition to renewable energy use (Capellán-Pérez et al. 2020). As shown in the schematic 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, materials and pollution are modelled across society, environment, ecology and land use. The dynamic relations reflect economic and population consumption of energy and materials, infrastructure, and pollution damages including climate change impacts. Unlike supply-led optimisation modelling (based on equilibrium substitution between capital, labour and technologies), the MEDEAS system dynamics model is demand-led and supply-constrained, resulting in disequilibrium (post-Keynesian) macroeconomic behaviour 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). Moreover, MEDEAS is unusual in incorporating climate change impacts, energy and materials availability, and declining energy return on energy invested (EROI), as endogenous system feedbacks that act as brakes on growth in dependent activities (Capellán-Pérez et al. 2019, 2020).

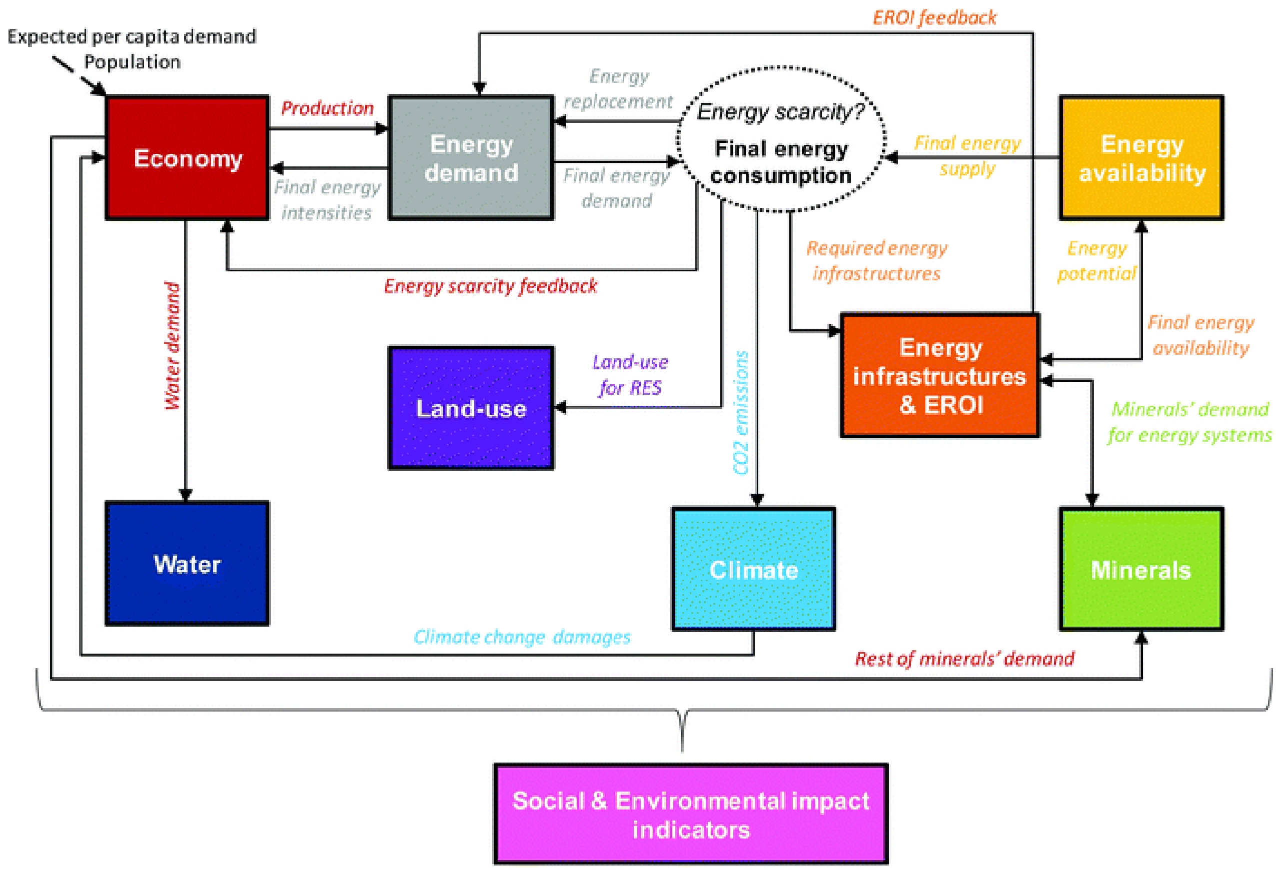


Figure 5.1. Overview of MEDEAS-World model modules and linkages. EROI denotes *Energy Return on (energy-)Invested*; RES denotes *Renewable Energy Supply*. Source: (Capellán-Pérez et al. 2020). Published by the Royal Society of Chemistry and reproduced under the terms and conditions of the Creative Commons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

5.3.6 The Vision Scenario for the European Union (an EU Green/EFA project)

A report funded by the EU Green/EFA group gives a single transition "Vision Scenario" contrasted with a Reference Scenario (Matthes et al. 2018). Economic (GDP) growth of 1.5%/yr is assumed from 2015 up to 2050 (an overall increase in GDP of 68%). Only a small (3%) total increase in the EU population is assumed. The modelling notes that coherent short-, medium- and long-term targets require a cumulative CO_2 emissions basis to ensure consistency with IPCC-assessed physical science. On the basis of a per capita share of a total “well below 2°C” global budget of 890 $GtCO_2$ from 2015 onwards, the project calculated a Paris-aligned EU cumulative quota of 61.5 $GtCO_2$ from 2015 onward. Early and deep reductions in emissions are recognised as essential to avoid the need for much more highly disruptive measures after 2030 if such early action is delayed (see

Figure 5.2). The Vision scenario cumulative CO_2 still slightly exceeded the assessed CO_2 quota for the EU, so the report notes the need for also achieving additional mitigation of non-CO_2 greenhouse gases.

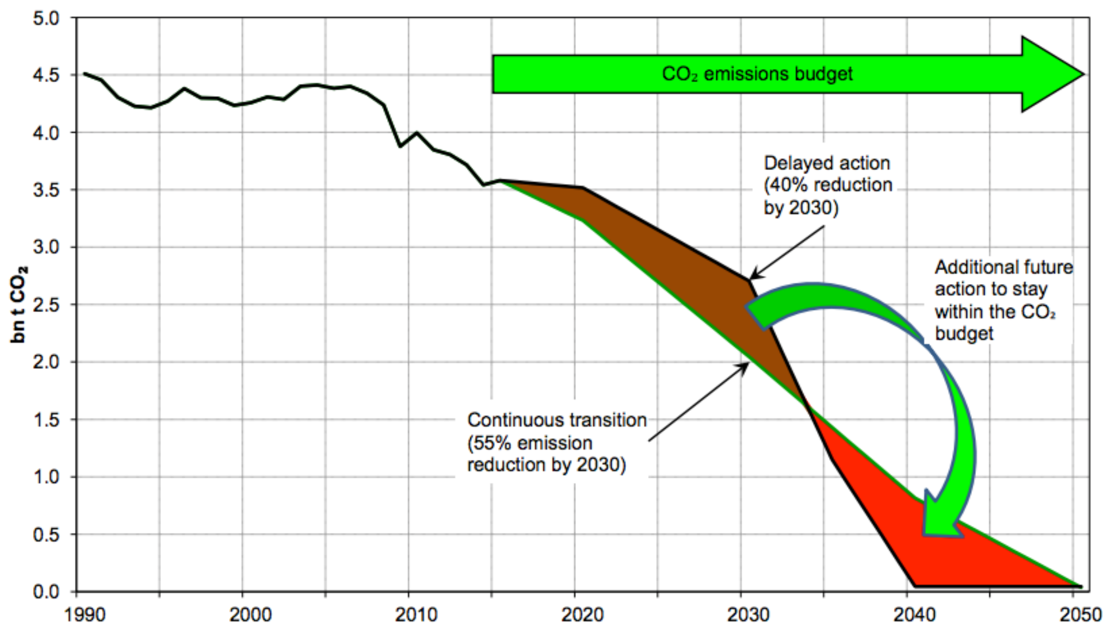


Figure 5.2 CO_2 emissions in the Vision Scenario and a delayed action scenario arriving at the same CO_2 budget, 1990-2050. Reproduced from Figure 8-1 in (Matthes et al. 2018).

5.4 UK deep decarbonisation literature

5.4.1 UK-CCC ‘Net Zero’

In 2019, the UK Committee on Climate Change (UK-CCC) published a major policy advisory report entitled *Net Zero: The UK's contribution to stopping global warming* (UK-CCC 2019a) with a supporting technical report (UK-CCC 2019b) that is further evidenced by earlier UK-CCC reports on hydrogen, land use and biomass. As shown in Figure 5.3, the Net-Zero report details a *Core Scenario*, meeting an 80% reduction in emissions (GWP_{100} basis) by 2050, and a *Further Ambition* scenario for the UK meeting a more than 90% reduction. According to the UK-CCC reaching net-zero annual aggregate GHG emissions (GWP_{100} basis) as early as 2050 is possible, but 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 NETs at scale such as direct air capture. Therefore a ‘net zero by 2050’ target represents a substantial increase in ambition and urgency from the previous target of 80% reduction in annual aggregate GHG emissions by 2050 (relative to 1990). In the Net Zero report, the main levers defined for increased ambition under *Further Ambition* are a quadrupling of low carbon electricity; further energy efficiency improvement;

significant electrification of heat and transport energy use; deployment of low carbon hydrogen both for energy storage and as an additional energy carrier for end use; and large scale CCS. Specifically, increased ambition would be enabled by: greater industry CO_2 abatement; use of synthetic chemical fuels for large scale energy storage from variable renewables; all buildings to be low carbon by 2050; significant dietary shift away from beef and dairy, enabling changes in domestic agricultural practices; and the explicit inclusion of land use, and applicable international aviation and shipping in the assessed emission pathways. In addition to land carbon storage through increased afforestation and enhanced soil carbon sequestration, engineered negative emissions (technological CO_2 removal from atmosphere), utilising CCS, have a key role in "all currently credible pathways". In the *Further Ambition* scenario, total CCS deployment reaches 175 $MtCO_2$ per year by 2050, captured and stored from power generation, industry and hydrogen production (UK-CCC 2019a).

Unlike Ireland's CCAC, the UK-CCC recommendations of quantified cumulative emissions budgets, and measures commensurate with a long term decarbonisation goal, have a significant degree of legal force. The UK government must explicitly respond to them, either by accepting in full, or formally specifying their reasons for not doing so. As in Ireland, a major driver of emission reduction to date in the UK's domestic emissions has been a transition in power generation away from coal to natural gas and wind (facilitated in the UK case via a CO_2 floor price for ETS sector emissions). This has substantially reduced the CO_2 emissions intensity of final energy in electricity (Gambhir et al. 2019).

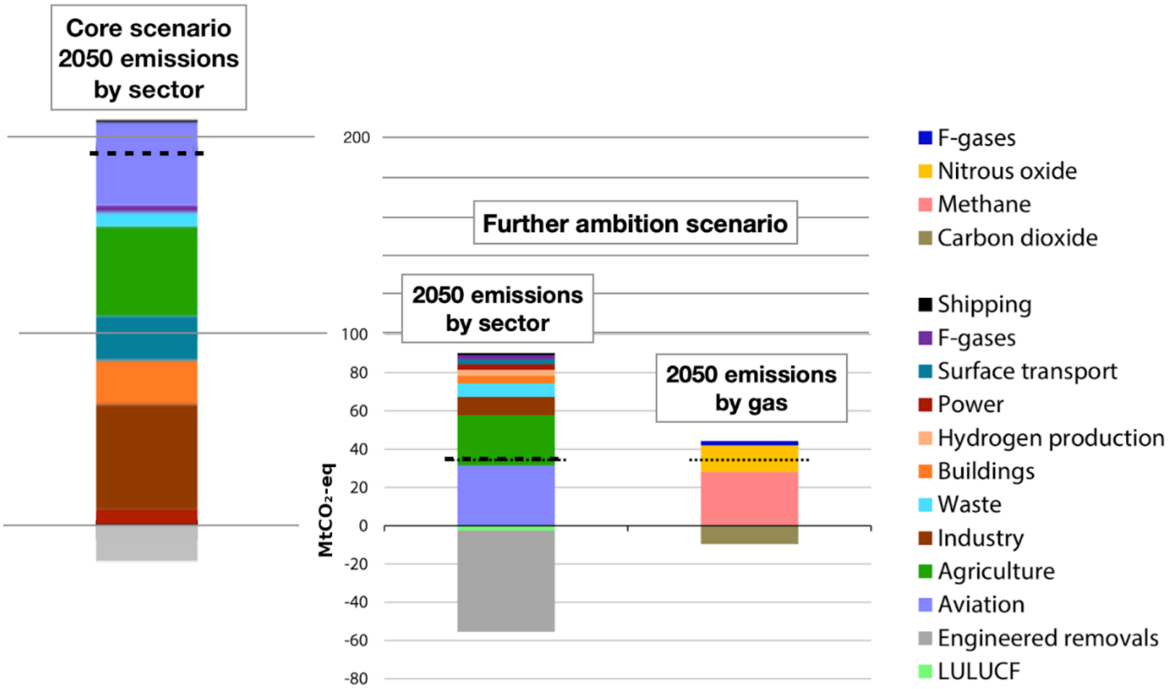


Figure 5.3 Comparison of emissions in the UK-CCC *Core* and *Further ambition* scenarios, adapted from the relevant figures in UK-CCC (2019a). LULUCF denotes Land Use, Land Use Change and Forestry.

The report asserts that meeting its defined 'net-zero by 2050' target "would end the UK's contribution to rising global temperatures", that the combination of its assessed cumulative aggregate national emissions budget and the 'net-zero target' "meets fully the requirements of the Paris Agreement, including the stipulation of 'highest possible ambition'", on the basis of capability and equity. However, in subsequent grey literature commentary, other researchers have strongly critiqued this assertion, pointing out that: the UK-CCC's own analysis guidelines show that it primarily paid attention to capability and feasibility, thereby delaying net zero relative to what might be more equitable (Bullock 2019); the implied share of the remaining global emissions budget is inequitable, and the proposed pathway to achieving it is over-reliant on negative CO_2 emissions (Anderson 2019); and the target inequitably understates responsibility for extra-territorial emissions due to UK consumption, including relevant international aviation and shipping – delaying inclusion of these in budgeted cumulative emissions accounting until 2033 (Blakey and Hudson 2019). Separately, the UK-CCC advisory group of external experts reviewing the Net Zero report concluded that net zero by 2050 is technically achievable but was concerned about the political capability to achieve such a relatively fundamental change in policy and societal commitment (Watson 2019).

5.4.2 Zero Carbon Britain

Zero Carbon Britain (ZCB), developed by a team at the Centre for Alternative Technology[11], was initially developed as a single narrative scenario to achieve net zero annual CO_2, from the UK, within 20 years from c. 2008, by reducing total energy demand and greatly increasing use of renewable energy sources (Helweg-Larsen and Bull 2007). Societally equitable well-being is given precedence over business-as-usual growth, accepting a possible need for managed economic contraction (degrowth) to enable sustainable outcomes. Further iterations of this work have emphasised economic and employment decarbonisation benefits (Kemp 2010), and evidenced ZCB with an online, open source, zero-carbon energy model for the UK and analysis of low-GHG dietary shift (Allen et al. 2013; Hooker-Stroud et al. 2014). More recent reports examine sectoral actions (Toms et al. 2017), barriers to change, and provide decarbonisation case studies from global to sub-national scale (Allen and Bottoms 2018).

5.4.3 UK-FIRES Absolute Zero

The UK FIRES Absolute Zero report (Allwood et al. 2019) examines a pathway to zero annual GHG emissions for the UK, via incremental changes starting from today's technologies, through electrification of energy use, transformation of energy sources, and major reductions in meat consumption. However, in contrast to the UK-CCC, a near-complete phase out of fossil fuels before 2050 is proposed. This results in serious bottlenecks in decarbonising aviation and shipping to the point of effective shutdown until renewable production of synthetic fuels becomes possible on a large scale. Through dietary change, UK beef and lamb production and consumption are phased out by 2050 to limit methane emissions. Bioenergy production is severely limited by biodiversity and agricultural land limitations. Nonetheless, despite the need for urgent, radical, near-term cuts in total energy supply and demand to 2050 due to exiting fossil fuels, this report sees substantial opportunities for industry and innovation in this transition with many sectors enabled to grow once more after 2050 as zero carbon energy availability continues to expand.

5.5 Other climate change mitigation scenarios and national planning literature

Research outlining the conditions for rapid and radical transitions stresses the need for well-informed, inclusive governance to maintain core societal functions and the need for societal support through unifying narratives within a justice framework (Bushell et al. 2017; Delina and Sovacool 2018). The analogy of wartime mobilisation as in World War II has been offered as a model for climate action urgency (Delina and Diesendorf 2013), although Kester and Sovacool (2017) caution that polarised politics and vested interests can leverage such rhetoric to stress insular, polarising security concerns rather than inclusive and peaceful societal transition. Nonetheless, Delina and Diesendorf (2013) conclude that, as in wartime, executive government including a 'ministry for transition', with separate, independent mitigation-focused institutional oversight to specify limits and timelines, is a strong model, *provided* it has wide public support. They suggest that a 10 year societal transition is impossible, but that a 30 to 40 year timeframe should be feasible. They warn that a focus on adaptation is likely to result in "'quick fix' antidotal approaches", which are always likely to be more attractive to policy-makers and the public but which risk diverting attention and effort from the overriding need for sufficient mitigation to make effective, long-term adaptation feasible.

[11] https://www.cat.org.uk/

A report by Höhne *et al.* (2019) finds that the EU has already exhausted its assessed fair share of cumulative GHG emissions given the higher ambition required by the Paris Agreement temperature goals. It concludes that the EU Roadmap (EC 2011) is seriously outdated due to relative inaction in the interim, and the significantly more ambitious Paris goal of $\lesssim$1.5°C. It recommends that the EU reach net-zero annual GHG emissions around 2030 to 2040 (CO_2-eq, on a GWP_{100} aggregation basis) with net negative emissions (net removals) of -2.5 $GtCO_2$-eq by 2050, and incorporating only very limited reliance on emissions "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* which does include adoption of an EU-wide net zero GHG emissions goal, albeit only by 2050 (EC 2019).

New Zealand's climate act (New Zealand Government 2019) and associated input from climate scientists (ICCC-NZ 2019) provides an important reference for Ireland, given a similar population and comparable emissions profile, including CH_4 from a substantial ruminant agriculture sector.

A Norwegian advisory report (Aamaas et al. 2019) plainly digests national implications of the IPCC-assessed global IAM scenarios in terms of GHG emission pathways, equity, carbon pricing, negative emissions technology deployment, land use change and investment timing.

5.6 Policy solutions: explicit emission and removal pathways based on quantities

5.6.1 Policy requires stated, explicit and equitable, emission and removal quotas or pathways

The international literature surveyed for this review is surprisingly lacking in scenarios explicitly aligned with either specified fair share cumulative CO_2 quotas, or specified annual GHG emission pathways, that are clearly and quantitatively constrained to meet the Paris Agreement temperature goals. Despite national commitments under the UNFCCC and to the SDGs, it appears that many EU or national scenario studies fail even to refer to the demands of international equity or the need to limit cumulative CO_2 emissions, or these issues are mentioned only peripherally or aspirationally. Decarbonisation studies relating to energy frequently fail to reference the cumulative climate impact of carbon emissions or inequitable distribution impacts (Zimmermann and Pye 2018). Studies relating to agricultural mitigation frequently fail to mention the key role of limiting inputs of reactive nitrogen. The general use of GWP_{100} for GHG aggregation can fail acknowledge the role of methane warming reduction in early and deep mitigation (see Chapter 7). These apparent weaknesses are notable, given key commitments that nations made to climate action "based on equity" and "best-available science" in ratifying the Paris Agreement. These commitments *should* provide crucial context within which good faith actors would need to achieve decarbonisation, yet they often appear to be secondary to an overriding prioritisation of continuing growth in economic activity and absolute energy consumption (Anderson et al. 2020). Therefore, a key recommendation from this review is that best-practice climate-action-related research and policy advice *should* contextualise scenarios and findings with regard to both equity (national and international) and quantitative emissions constraints demonstrably commensurate with a fair share of the action required by the Paris temperature goals. There are uncertainties and limitations with regard to such statements and these issues can be made clear; but it is concerning that these critical, quantitative mitigation constraints do not appear to be clearly, consistently and unequivocally incorporated in all relevant conclusions and recommendations to enable transparent assessment.

5.6.2 Scenario analysis based on absolute quantities rather than prices, intensity or penetration

A common weakness of both demand-side (efficiency) and renewables-penetration mitigation policy measures is their failure to achieve declining caps on the absolute quantity of emissions effectively. Absent such caps, direct, indirect and macro rebound effects may cancel out some or all of the supposed climate mitigation benefit. The globalised mobility and fungibility of capital means that energy cost savings resulting from mitigation measures directed at a sector or nation can be reinvested in that sector to enable more activity or spent on or invested toward other emission-causing activities elsewhere or in future. Despite these issues, policy and modelling assessments continue to be highly reliant on questionable efficiency benefits, or highly uncertain future fuel or technology cost projections, as seen, for example, in Ireland's Draft NECP energy projections (DCCAE 2018). Projections of notional costs are commonly used in economic modelling as a proxy for resource scarcity but costs are also affected by many near-term human influences and contingent events, whereas climate impacts directly depends on actual changes in quantities of system energy inputs, including total fossil carbon and reactive nitrogen, which drive system outputs, including economic output but also GHGs and other pollution (de Blas et al. 2019). Therefore, it would generally be useful to complement such analyses with simulation modelling of society-wide scenarios for effective mitigation, based on *input quantities* of direct climate change drivers (amounts of fossil carbon and reactive nitrogen), and resulting *output quantities* of emissions by gas and aggregate resultant warming. Possible Irish implementation of the MEDEAS and Minsky models is one possible opportunity for such further research. 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 GHGs by gas: properties, drivers and policy

6.1 Introduction: GHGs, sources and forcings in climate action scenario assessment

In this chapter, the properties, sources and drivers of the main greenhouse gases released by human activities are discussed in the specific context of Ireland's particular emissions profile and potential climate mitigation strategies. This chapter also provides context for the preliminary GHG pathway modelling detailed in Chapter 7.

Table 6.1 gives the "carbon dioxide equivalent" (CO_2-eq) amounts of each GHG emitted in Ireland for 2017 (Duffy et al. 2019), based on the IPCC AR4 GWP_{100} GHG equivalence metrics for non-CO_2 GHGs, as is current in UNFCCC accounting.

Table 6.1. Climate forcers by type, lifetime and GWP_{100} value, with corresponding annual emissions for Ireland in 2017. Based on data from (Duffy et al. 2019) and (Myhre et al. 2013, Appendix 8.A).

Name	Symbol	Class	Lifetime	GWP_{100}	Ireland 2017 emissions	
			Years to decease by c. 63%	Global Warming Potential over 100 years	$MtCO_2$-eq	%
Carbon dioxide	CO_2	Long-lived climate forcer (LLCFs)	>300	1	43.6	65%
Nitrous oxide	N_2O		114	298	7.2	11%
Methane	CH_4	Short-lived climate forcer (SLCFs)	12	25	14.7	22%
Hydroflurocarbons (HFCs)	HFC-125		29	3,500	1.1	2%
	HFC-134a		14	1,430		
	HFC-143a		52	4,470		

Ireland continues to be heavily reliant on fossil fuel combustion to supply approximately 90% of all energy, used in electricity generation, heat and transport. Energy use, together with some additional industrial process emissions (particularly cement production) accounts for the release of over 38 $MtCO_2$/yr (SEAI 2018). Shares of total primary energy requirement (TPER) for each fossil fuel in 2017 were: oil 48%; natural gas 38%; coal 8%; peat 5% (SEAI 2018, Table 2). Oil is used predominantly in transport and in domestic heating (especially in rural areas), while natural gas, coal, and peat are used in both electricity generation and heat. Natural gas is used for high temperature industrial heat as well as low temperature space and water. Absolute coal and peat consumption have been declining due to reduced use in electricity generation. In the draft NECP (DCCAE 2018), use of natural gas has been projected to increase up to 2040, while coal and peat combustion for electricity are anticipated to cease by 2025 and 2030 respectively. However, overall fossil fuel CO_2 emissions were still projected to continue at approximately the current level to 2040 (McMullin and Price 2019), particularly driven by projected increases in total energy use. Such a GHG pathway fails to set any determinate limit to future cumulative CO_2 emissions or resultant contribution to warming. The 2019 Climate Action Plan (DCCAE 2019) outlines a new piece-wise linear reduction trajectory for annual CO_2 emissions from energy and industry, targeting a decline of approximately 20% between 2020 and 2030 and proposing a net zero target by 2050.

According to Ireland's EPA emissions inventory report to the UNFCCC (Duffy et al. 2019), for the year 2017 the Land-use, Land-use-change, and Forestry (LULUCF) sectors in aggregate emitted a net total of about 6.0 $MtCO_2$-eq (mostly CO_2). This net total is made up of gross emissions of about 6.9 $MtCO_2$-eq from grasslands and 3.6 $MtCO_2$-eq from wetlands and gross removals of about -3.7 $MtCO_2$-eq into forestland and -0.9 $MtCO_2$-eq into Harvested Wood Products (HWP).

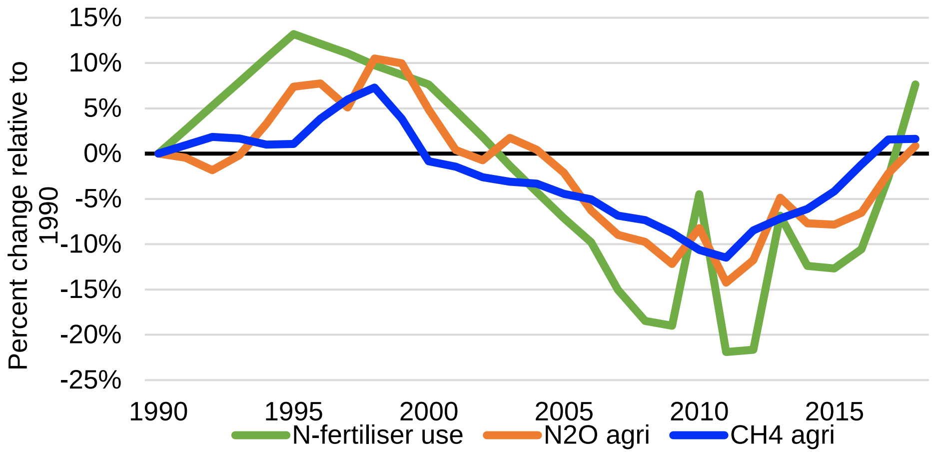


Figure 6.1 Percent changes in Irish nitrogen fertilizer use and agricultural non-CO_2 emissions since 1990. Charted from data in (EPA 2019). Excludes land use (LULUCF) emissions.

Ireland's national emission profile is unusual in having a comparatively large fraction of non-CO_2 GHG emissions, primarily from the agricultural sector, which is responsible for 93% of annual N_2O emissions and 93% of annual CH_4 emissions. In Ireland N_2O and CH_4 emissions are strongly linked, through nitrogen fertiliser use on grass and pasture-grazed ruminant agriculture (Duffy et al. 2019). N_2O and CH_4 together account for 34% of Irish total annual GHG emissions (EPA 2019), as measured by the UNFCCC-mandated GWP_{100} GHG aggregation metrics (CO_2-eq). In other nations CH_4 emission typically also includes a large component strongly related to fossil fuel extraction and leakage of fugitive CH_4 from natural gas infrastructure and facilities. Figure 6.1 charts annual percentage changes in Ireland's non-CO_2 agriculture emissions and nitrogen fertiliser usage from 1990 to 2018, corroborating their relatively tight linkage.

6.2 CO_2 emissions from fossil fuel, industry and land use

The climate forcing effect of CO_2 emissions is extremely long-lasting such that an "approximation of the lifetime of fossil fuel CO_2 for public discussion might be '*300 years, plus 25% that lasts forever*'" (Archer 2005). In the SR15 report, remaining cumulative global CO_2 budgets (GCBs) from the beginning of 2018 corresponding to the Paris temperature goals are stated in Ch. 2 Table 2.2 (Rogelj et al. 2018) as 420 $GtCO_2$ to limit to 1.5°C, and 1170 $GtCO_2$ to limit to 2°C. Of global annual CO_2 emissions in 2011 totalling 42 $GtCO_2$/yr, about 87% or 36.7 $GtCO_2$, come from fossil fuel and industry (FFI, due to fossil fuel combustion and industrial production of cement and steel) and about 12%, 5 $GtCO_2$/yr are from land use. Cumulative global fossil fuel combustion and industry (FFI) emissions of CO_2 are the primary cause of anthropogenic global average temperature rise. The annual emission rate rose from 9 to 37 $GtCO_2$/yr from 1959 to 2018, and in 2018 comprised: coal 40%, oil 34%, gas 20%, cement 4%, and flaring 1% (Friedlingstein et al. 2019).

To effectively limit further global warming, annual aggregate global emissions of long lived climate forcers (LLCFs), primarily CO_2, but also N_2O (discussed in the following section), need to go to net zero in order to stabilise atmospheric concentrations of these gases (Allen et al. 2018a). Limiting to a particular global temperature increase above pre-industrial with a stated probability requires staying within a linearly related cumulative LLCF emissions total (the GCB, as already introduced above, generalised to the aggregate of all LLCFs). Any such GCB limit is dependent on climate sensitivity (the temperature response to given LLCF concentration) and climate system feedbacks – which could reduce land sink effectiveness in future (Goodwin 2018) – as well as achieving complementary mitigation of the emission rate of SLCFs. If there is overshoot of the GCB, then corresponding removals of CO_2 from atmosphere (and/or deeper, sustained SLCF rate reduction) would be needed to return aggregate forcing (and thus temperature) to the required, tolerable, level. While this suggests a focus on cumulative *net* CO_2 emissions at both global and sub-global levels, research strongly indicates that national policy should maintain a strong emission accounting separation between gross CO_2 emissions and gross removals, with removals clearly identified as either purely "nature-based" (biogenic removal and storage) or "technology-based" (biogenic and/or technological removal, with geologic storage) (Peters and Geden 2017; Geden et al. 2018; McLaren et al. 2019).

6.3 Informing policy: Land reservoir carbon stocks are easily lost and only slowly regained

Although global land use is a *net* sink for CO_2, human-caused land use change does give rise to *gross* emissions of CO_2 at approximately 5 $GtCO_2$/yr, especially from deforestation. Limiting GHG emissions from agriculture, forestry and land use is a critical mitigation measure given FAO-projected agriculture emission increases of up to 30% by 2050 (Tubiello et al. 2015). Net increases in biomass through photosynthesis *can* remove carbon from the atmosphere into land carbon reservoir stocks (soils and trees) thereby achieving negative emissions by increasing land carbon storage. However, land carbon stocks should be properly thought of as "slow in, rapid out" (Körner 2003): soils and plants take up carbon over decades, up to a saturation level, but this carbon is vulnerable to rapid re-release by human interventions (ploughing or forest harvest) or natural disturbance (drought or fire). The mitigation value of CO_2 removals from atmosphere to land carbon depends on the permanence of its carbon storage relative to the permanence of unextracted fossil carbon. This significantly limits the relative climate mitigation value of land carbon (Mackey et al. 2013; Fuglestvedt et al. 2018; Kim et al. 2008; see discussion in Price et al. 2018); while the scale of potential indigenous land-based storage in Ireland is also strongly constrained by competing land uses (McGeever et al. 2019). The related EU accounting convention that bioenergy is "carbon neutral" (EP 2018) has been strongly contested on multiple grounds (EASAC 2017; Alexandrov et al. 2018; Searchinger et al. 2018). Research indicates that past and potential climate benefits of forest management over the past 250 years have been minimal because warming, due to carbon loss (by wood extraction exceeding growth uptake) and albedo change due to the lower reflectivity of conifer forest, has exceeded the cooling due a 10% increase in forest area through afforestation (Naudts et al. 2016; Luyssaert et al. 2018; Nabuurs et al. 2018; Mykleby et al. 2017). Climate change impacts could further decrease sequestration and reduce forest stocks (Valade et al. 2017). The per hectare carbon sequestration value of plantation forestry which is subject to thinning and clearcutting is significantly lower than un-thinned and unharvested mixed forest (Bateman and Lovett 2000, Fig. 1). Measuring carbon stocks and source-sink flows in soils is subject to even greater uncertainty than for forests, which significantly and additionally undermines the actual mitigation benefit of soil carbon sequestration. The "4 per mille" initiative[12] aiming to greatly increase global soil carbon sequestration has been partially supported by some research (Minasny et al. 2017; Smith et al. 2019) but has also been severely criticised as a distraction from the overriding priority of fossil fuel CO_2

[12] 4 pour 1000: https://www.4p1000.org/ (Accessed: 30 July 2020)

mitigation, and is strongly argued to be at risk of wasting scarce public resources without sufficient justification (Thamo and Pannell 2016; Poulton et al. 2017; Baveye et al. 2018; Amundson and Biardeau 2018).

6.4 N_2O emissions and reactive nitrogen

N_2O is a potent greenhouse gas with an atmospheric lifetime (to 63% decay) of about 114 years. It also causes loss of stratospheric ozone. Therefore, in the limited time to meet the Paris Agreement's stringent temperature goals, it is best accounted as a long-lived climate forcer on a similar basis to CO_2. Preindustrial 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 arising in fertiliser use and management of manure (Reay et al. 2012). Historically, food production was dependent on natural fixation of unreactive atmospheric nitrogen to reactive nitrogen N_r via by plants, but the invention of the Haber-Bosch process, enabled with fossil fuel energy inputs, has resulted in human production of N_r at a rate three times greater than natural terrestrial processes (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% (IPCC 2019, Figure SPM.1). Recent research is confirming "a nonlinear response at global and regional scales with high levels of N-input" due to global agricultural expansion (Thompson et al. 2019). Overall globally, input-output and life cycle analysis (LCA) shows that about 3–5% of reactive N, from fertiliser and manure, is converted to N_2O (Smith et al. 2012). Synthetic N-fertiliser increases both grass and feed production, but also results in increased GHG emissions and other environmental pollution damages, that can then be exacerbated by animal agriculture through feed and grass inputs to animal digestion and excreta (Thompson et al. 2019).

In general, the land, protein, and nutrient use efficiency of plant-based foods is far greater than for animal derived foods (Nijdam et al. 2012; Cassidy et al. 2013; Alexander et al. 2017). It is misleading, and ethically questionable (Shue 2013), to categorically assume that near-term human preferences based on current dietary trends *must* be met, as literature shows that other dietary pathways are possible (Billen et al. 2013). Without radical change from the current trajectory the livestock sector alone could overshoot humanity's "safe operating space" by 2050 (Pelletier and Tyedmers 2010). Due to the use of N-fertiliser and applying an average 4% N-N_2O conversion the CO_2 saving calculated for crop biofuels compared to fossil fuels can be entirely negated by the associated increase in N_2O emissions (Crutzen et al. 2008).

The European Nitrogen Assessment (Sutton et al. 2011), or ENA, provides an extensive and exhaustive review in 26 multi-author chapters covering the use of reactive nitrogen. In sum, the ENA report and synthesis supports strong, evidence-based policy recommendations to limit N_r impacts. Echoing the findings of climate science requiring limits on fossil carbon usage, the ENA Summary for Policymakers (Sutton and van Grisven 2011) concludes that overuse of N_r, primarily in agriculture, is harming the environment and its contained human subsystem termed "the economy". Conversely, N_r limits and budgets in agriculture have the potential to minimise and limit this cascade of adverse effects. Existing policies such as the EU Nitrates Directive appear to be incoherent and ineffective (failing to directly limit and reduce total synthetic N_r), suggesting that coordinated, well communicated alternative measures are needed as matter of urgency. The ENA estimates the overall environmental cost of Nr pollution in Europe at €70 to €320 billion per year, equivalent to 150–750 euro per capita, outweighing the supposed benefit of its use in conventional economic terms (Brink et al. 2011).

6.5 CH_4 emissions and mitigation

6.5.1 CH_4 emission: global

CH_4 is the second most important greenhouse gas in terms of overall radiative forcing effect (Myhre et al. 2013). Major global sectoral sources of anthropogenic CH_4 emissions arise from: fossil fuel extraction and its transportation, particularly due to leakage from coal mines and from natural gas wells and distribution networks; and from agriculture, particularly from ruminant livestock and from rice production (Fletcher and Schaefer 2019). The Global Carbon Project[13] also provides extensive data on global CH_4 sources. Plant growth boosted by fertilisers results in N_2O soil emissions but also acts as a primary enabler of CH_4 emitted by livestock due to digestion of the additional plant growth and the resultant increase in ruminant enteric fermentation and animal manure management. Globally, substantial reductions in fossil fuel use would necessarily result in significant associated reductions in the warming due to CH_4 and black carbon (Rogelj et al. 2015). SLCFs such as CH_4 influence climate primarily through their flow, that is *changes* in their annual emissions *rate* (flow) determine whether their atmospheric concentration is maintained, increased or decreased. For CH_4 this has an effect on concentration (and thus eventual warming) that lags changes in emissions rate by about 20 years. Although some sources argue that a near-term focus on SLCF reductions could be worthwhile (Shindell et al. 2012), in general this can only offer a one-off reduction in forcing that also risks relatively easy reversal. This means that sustained, permanent SLCF flow rate reductions should be regarded as complementary rather than alternatives to early, deep CO_2 mitigation (Shoemaker and Schrag 2013; Pierrehumbert 2014). More generally, the importance of mitigation action to reduce emissions of *all* climate forcers is evident in assessing Paris goals (Fuglestvedt et al. 2018).

6.5.2 CH_4 emissions: Ireland

Trends in Irish CH_4 emissions echo N_2O trends and fertiliser use, peaking in 1998 at 15.4 $MtCO_2$-eq (based on the AR4 GWP_{100} value of 25 for methane), declining to 12.0 $MtCO_2$-eq in 2011, but then rising again to just over 14 $MtCO_2$-eq in 2018 (Duffy et al. 2019). Agriculture is the primary driver, responsible for 93% of Irish CH_4 emissions, primarily from cattle-based beef and dairy for export; 11.5 $MtCO_2$-eq/yr is from enteric fermentation produced in digestion of grass and feeds and 1.5 $MtCO_2$-eq/yr from manure management (Duffy et al. 2019). Intensive dairy farming has expanded rapidly since 2011. According to EPA data, dairy cow numbers reached 1.4 million in 2017, an increase of 0.35 million from 2011, and beef cattle numbers reached 5.9 million, an increase of 0.5 million from 2011 (Duffy et al. 2019, Tables 3.3.A, B and C). Fugitive CH_4 leakage from the natural gas grid is assessed as being relatively low in Ireland compared with nations with older infrastructure such as the USA. However, some current Irish policy proposals envisage an expanded CH_4 gas grid. Increased use of CH_4 as a fuel (whether from fossil and biological sources) could potentially increase total fugitive CH_4 emissions (Ervia and Gas Networks Ireland 2019). Proposals for increasing biomethane production aim to deliver 11 TWh/yr by 2030 and a possible 22 TWh/yr by 2050 (Ervia and Gas Networks Ireland 2019). This is based on projected installation of hundreds of farm-based anaerobic digestion plants using livestock slurry, grass, silage, and agricultural wastes as feedstock. These proposals appear to be predicated on increasing fertiliser usage to the maximum per hectare level allowed under EU regulations, over and above livestock requirements under existing expansionary agri-food policies (McEniry et al. 2013). This is despite the resultant reduction in system nutrient use efficiency evident in this research, due to diminishing returns from increasing N-fertiliser usage, particularly on marginal land.

[13] See: https://www.globalcarbonproject.org/ (Accessed: 28 July 2020)

6.6 Policy solutions: modelling and policy directed at limiting climate pollution drivers

6.6.1 Limiting fossil carbon inputs and land use carbon extraction are key to CO_2 mitigation

Aligning climate action with the aggregate GHG pathways (especially including N_2O and CH_4), based on an equitable national contribution to meeting the Paris Agreement goals, has major implications for society-wide policies in Ireland. The primary requirement for good faith alignment is a need for radical reductions in gross CO_2 emissions – from fossil fuel, industrial processes and land use (FFI+LU CO_2), to reach net zero annual CO_2 quickly. Gross fossil CO_2 emissions cannot simply be assumed to be avoided if renewable energy penetration rates increase: effective climate action requires that the total quantity of society-wide fossil carbon inputs must decrease very rapidly. Current actual and policy trajectories in Ireland and across the developed nations also tacitly assume substantial future negative CO_2 emissions by as-yet undeveloped NETs capacity. In the specific case of Ireland, it has been proposed that a prudent upper limit to projection of such gross removals would be 200 $MtCO_2$ up to 2100 (McMullin et al. 2019a). Research also points to a moral hazard risk associated with tacit incorporation of large scale future NETs in near-term policy, due to the risk of very high costs or damages if NETs subsequently prove unachievable at the assumed scale (Anderson and Peters 2016; Larkin et al. 2017). Given these issues and Ireland's responsibility and capacity as a developed nation, respecting climate justice therefore implies earlier and deeper action to achieve substantial and sustained reductions in emissions across all GHGs than global average mitigation rates might suggest.

6.6.2 Limiting reactive nitrogen inputs is a key non-CO_2 mitigation lever for Ireland

To supplement effort on CO_2, limited carbon budgets for Paris goals indicate that emissions of N_2O and CH_4 (in Ireland primarily from agriculture) also need to be reduced steadily and permanently. Energy and industry CO_2 trends have been strongly related to national economic trends (especially for transport and cement production), and to partial decarbonisation in electricity (shifting from coal and oil to natural gas and wind). Ireland's agricultural emissions of N_2O and CH_4 are strongly correlated with each other, and, causally, to system inputs of reactive nitrogen through the use of synthetic nitrogen fertiliser and animal feed (Figure 6.1). Fertiliser inputs drive N_2O emissions from soil and from animal excreted nitrogen. Increased use of fertiliser to boost grass growth results in increased grass for enteric fermentation, supplemented by other feeds, resulting in increased CH_4 emissions. Despite these evident considerations, Irish agri-food policy since 2010 has leveraged increased usage of reactive nitrogen in synthetic nitrogen fertiliser (all imported) and feeds (substantial amounts imported) to achieve increased animal production, particularly of beef and milk powder, primarily for export. This has driven steady and substantial increases in the associated sectoral, non-CO_2 absolute annual emission flows, reversing prior climate mitigation.

Two trends emerge from recent Irish experience that echo findings from the presented literature review: (1) over the period from 1998 to 2010, the supply-side milk quota limit ensured that local efficiency increases in dairy production resulted in *reduced* national Nr usage (and fewer cattle) and consequent reduction in emissions of both N_2O and CH_4, thereby avoiding rebound effects by not rewarding reinvestment of cost-savings to increase production and emissions; and (2) following the milk quota removal, and – in the absence of any other quota, regulation or tax on production or pollution – production has increased at relatively low increased fertiliser and feed cost to producers, and this has significantly increased emissions of both N_2O and CH_4. By counting GHG emissions intensity due to farm inputs, but not capping absolute emissions, the Carbon Navigator programme (Murphy et al. 2013) acts as a cost-saving, efficiency tool that can result in increased absolute emissions, as has indeed occurred (Lanigan and Donnellan 2018). Therefore, Ireland provides a clear example showing that national policy change can very effectively *either* mitigate *or* exacerbate total agricultural GHG emissions by respectively imposing or removing production limits, and thereby reducing or expanding ruminant-derived food production in particular. Current policy trends and statements by special interests now indicate plans to increase agricultural biomethane production substantially by assuming continued high cattle numbers and maximising nitrogen fertiliser usage on all land (McEniry et al. 2013). Anaerobic digestion (AD) plants enable conversion of agricultural waste to produce CH_4 and digestate, which can be used as fertiliser with due care (Nkoa 2014). However, CH_4 emissions through leakage and the lifecycle climate effect of reactive nitrogen inputs to feedstocks may undermine biomethane sustainability in terms of EU rules, even at low leakage rates of 2% (Liebetrau et al. 2017). Plant-scale studies of CH_4 leakage from AD systems (Baldé et al. 2016; Liebetrau et al. 2017) have argued that AD remains a positive climate mitigation measure even at higher CH_4 leakage rates (of up to 7–12%). However, these studies typically incorporate a "negative emissions" credit on the basis of AD deployment being associated with *avoided* CH_4 emissions from existing manure storage. This obscures the fact that the emissions from manure storage could, in principle, be effectively mitigated without necessarily deploying an AD system. This usage of "negative emissions" terminology for "avoided emissions" also incidentally risks significant confusion with the now widely established concept of "negative emissions" as *removals* from atmosphere (Tanzer and Ramírez 2019). Such potentially misleading AD plant-level conclusions are possible through LCA boundary choices and so may fail to consider the wider global sustainability of the source agricultural production that may be dependent on inputs that result from and drive significant negative impacts. Conversely, the findings of the European Nitrogen Assessment, and the literature evidencing a requirement for changes away from animal agriculture to return food production within ecological boundaries, suggest that large scale expansion of AD for biomethane production should be contingent on overall reduction in reactive nitrogen inputs; that is, it should happen only if it involves *displacement* of existing nitrogen fertilizer use, rather than presenting a new, additional use.

More useful scenario modelling and effective policy could be based on quantity limits and assessment of supply-side regulation on the national inputs that act as pollution drivers, or else on limiting total ruminant (beef and dairy) production. This would address rebound effects that can otherwise result from cost savings made as result of on-farm carbon assessments such as the Carbon Navigator (Murphy et al. 2013) being spent on increasing total production. A declining supply-side cap on total quantities of nitrogen fertiliser use (combined with fertiliser budgeting by farm production type, catchment parameters and soils) could both limit rebound effects, increase overall *food* production GHG efficiency, and result in effective climate and other pollution mitigation. National agri-food strategies could also examine the most efficient uses of a limited nutrient budget relative to the nutritional value across *all* food types. This budget could reduce over time, which would result in a planned level of absolute reductions in climate and environmental pollution. Regulated, declining inputs of pollution drivers would reduce the current overshoot of the nitrogen planetary boundary and, in the Irish case, could increase total employment in more labour intensive, more N-efficient horticultural food production and tillage. Facilitating a just transition for farmers and rural society to lower GHG agriculture (reducing N_2O and CH_4 emissions while increasing the net nutritional value of food output) within these limits could contribute to global and national food security and assist in a lower-cost whole-societal pathway by also keeping energy system decarbonisation within feasible mitigation rates.

7 Preliminary modelling of illustrative GHG 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 co-ordinated EU action and within a *fair share,* national carbon quota (NCQ) of a global carbon budget aligned with the Paris Agreement temperature goals. Earlier research, for the IE-NETS project (McMullin et al. 2020, forthcoming EPA report), concluded that Irish overshoot of a CO_2-only, *minimally equitable* NCQ of 391 $MtCO_2$ from 2015 is likely by 2025. Therefore, in addition to reducing emissions as quickly as is socio-politically feasible, such overshoot implies a tacit commitment to additional investment in achieving action to reduce the national contribution to warming, by some combination of CDR measures, to remove CO_2 permanently from the atmosphere into long term storage, and sustained CH_4 emissions flow reduction. A practical upper policy limit on the possible future level of achievable cumulative CDR (up to 2100) has been proposed as no more than about -200 $MtCO_2$ (McMullin et al. 2020). Therefore, given Ireland's unusual emission profile, with comparatively large non-CO_2 emissions, and the potential importance of CH_4 mitigation, there is significant policy value in developing a methodology that can properly assess the cumulative warming impacts of all three main anthropogenic GHGs (CO_2, CH_4 and N_2O) by gas and in aggregate under different proposed emissions pathway scenarios.

This chapter describes use of a new spreadsheet tool called "*GHG-WE*" developed for this project, 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 cumulative CO_2-*warming equivalent (*CO_2-*we)* 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. However, its potential use in global scenarios has been described and illustrated in IPCC SR15 Chapter 1 (Allen et al. 2018a) and actively recommended by Lynch *et al.* (2020) as a link between annual emissions of CH_4 (historical and/or projected), *reported* in either CH_4 mass or CO_2-eq terms, and the associated warming impacts. GWP* enables the net global warming contribution of policy options – by GHG gas and in aggregate – to be shown in terms of cumulative CO_2-we from a reference date up to a specified time horizon, typically chosen as its time of global peaking as this implies a corresponding peak in global temperature rise. Given a specific temperature rise goal (aligned with the Paris Agreement) this allows determination of a specific, "global cumulative-forcing GHG budget" (here denoted "GCB*" to distinguish it from a CO_2-only "GCB"). National scenarios can then be constructed or adjusted to meet an illustrative, all-GHG, Paris-aligned national cumulative-forcing quota share (here denoted "NCQ*", again to distinguish from a CO_2-only "NCQ"). For the preliminary, nation-level modelling in this chapter, climate forcers other than CO_2, N_2O and CH_4 are omitted from consideration. The tool, as currently developed, considers pathways for *net* emissions of each gas only. However, in the case of CO_2 in particular, it may be beneficial for future development of the tool to allow disaggregation of this net emission pathway between pathways of gross *emissions* (via fossil fuel, industry or land use) and gross *removals* (via so-called "negative emissions technologies").

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 is made publicly available under an open licence for users to explore mitigation options and to improve and extend its usefulness. An additional Excel tool, a "Methane Warming Calculator" for simple scenarios, assists users to understand the relatively non-intuitive effects of CH_4 mitigation policy changes in isolation.

7.2 Improved GHG equivalence metrics enable effective scenario comparison

Comparing alternative global or national policy scenarios in terms of their aggregate effect on global warming is challenging because long-lived climate forcers (LLCFs) and short-lived ones (SLCFs) should ideally be included in an integrated scenario assessment. This could be particularly useful in nations such as Ireland and New Zealand where the emissions profile includes a relatively large contribution from non-CO_2 emissions. GHG equivalence metrics integrating forcing over time (such as GWP, global warming potential) and end-point metrics indicating temperature change after a stated number of years (such as GTP, global temperature potential) have been commonly used to equate the effect of pulses or of a single year's emissions of different GHGs (Balcombe et al. 2018; Collins et al. 2019). Each of these metrics correctly represents the specific aspects of the climate system response they are designed to capture. However, this does not imply that cumulative CO_2-equivalent emissions calculated with each metric maps closely onto global mean temperature increase. A series of papers (Allen et al. 2016, 2018c; Cain et al. 2019; Lynch et al. 2020) have recently set out a new GHG equivalence metric and methodology, denoted GWP*, that attempts to approximate the global mean temperature increase from accumulated CO_2-equivalent emissions of a mix of both long- and short-lived climate forcers, while still having relatively very low computational overhead. It uses a new method to calculate tonnes of CO_2-we 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 the global mean temperature increase that would arise due to such a non-CO_2 emission timeseries is well approximated by the temperature increase that would be associated with the same cumulative emission of CO_2.

For any single year, the aggregate of annual CO_2-we emissions, summing the values for CO_2, N_2O and CH_4, indicates that year's incremental contribution to global warming. Cumulatively from a specified date, the total CO_2-we then provides a simple estimate of the aggregate GHG warming contribution for an emissions pathway comprising an arbitrary mix of CO_2, N_2O and CH_4. At a national level, this method can be used to assess the aggregate contribution to warming for national emission pathway scenarios, relative to a claimed "fair share" of *global* warming, within the constraint of the Paris temperature goals. The GWP* metric uses GWP_{100} values as parameters in its CO_2-we calculation. These are currently configured with the most recent IPCC-assessed GWP_{100} values, including climate-carbon feedbacks, being 34 for CH_4 and 298 for N_2O. For CO_2, the GWP_{100} value is 1 by definition, and its CO_2-we value is simply equal to the CO_2 emissions in tonnes. For N_2O, because it also functions as a long lived climate forcer (LLCF) the CO_2-we value is identical with the CO_2-eq value: i.e. calculated by multiplying N_2O emissions in tonnes by the applicable GWP_{100} value of 298. For CH_4, the CO_2-eq value is calculated similarly (found by multiplying CH_4 emissions in tonnes by the applicable GWP_{100} value). This is then converted to a CO_2-we value for a given year t by the following formula (Lynch et al. 2020):

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

where CO_2-we(t) and CO_2-eq(t) denote the respective values for the year in question, and CO_2-eq(t-20) denotes the CO_2-eq value for the year 20 years previously. This can also be re-written as:

$$CO_2\text{-we}(t) = 3.75 \times \Delta_{20}CO_2\text{-eq}(t) + 0.25 \times CO_2\text{-eq}(t),$$

where $\Delta_{20}CO_2$-eq(t) is defined as: CO_2-eq(t) - CO_2-eq(t-20)

The 3.75 x $\Delta_{20}CO_2$-eq(t) term approximates the change in warming due to any change averaged over the previous 20 years in the ongoing CH_4 *flow* (it will be zero if the CH_4 emissions flow rate is held constant). The 0.25 × CO_2-eq(t) approximates an incremental increase in the *stock* warming due to a long-term forcing effect of CH_4 emissions on the deep ocean (Zickfeld et al. 2017) – it approximates the longer term increase in warming as long as there is *any* net-positive annual anthropogenic emission of CH_4 (i.e., further warming that would occur as the climate system equilibrates to a stable, but higher, atmospheric concentration of CH_4).

7.3 Estimating a Paris-aligned national carbon warming equivalent quota (NCQ*)

Equitable achievement of the Paris Agreement (PA) temperature objectives – holding global warming to "well below 2°C" above pre-industrial and pursuing efforts to limit to a 1.5°C increase – provides the primary internationally agreed context for Ireland's climate change mitigation transition pathway scenarios. Therefore, estimating a range for Ireland's emissions quota *fair share* of this global effort is important to provide a national transition objective range for alternative scenarios. McMullin et al. (2019a) assessed an Irish fair share quota of the remaining global cumulative CO_2-only budget (GCB) for the PA "well below 2°C" target, from 2015 onward, based on the SR15 report GCB value (Rogelj et al. 2018, Table 2.2), assuming the stated 1.5°C GCB uncertainty of approximately ±50% to determine a GCB range. Progressing from McMullin et al., in this section this is generalised, using the GWP* methodology, to assess a corresponding global cumulative GHG budget (termed GCB*) which aggregates the effects of CO_2, N_2O and CH_4 and this then provides a basis for assessing a Paris-aligned, fair share national cumulative-GHG quota (termed NCQ*) for Ireland. As in McMullin et al. (2019a), an NCB* range is calculated using the GCB allocation mechanism defined by Raupach et al. (2014) applied to the assessed, global, GCB* range. Also as in McMullin et al., the year of the Paris Agreement, 2015, is used as the starting date for assessing Paris-aligned GCB* shares. Note that there is ultimately no single "correct" value for a "Paris aligned" GCB* or NCQ*, with a variety of methodological approaches, very significant uncertainties, and major value judgements involved both in the interpretation of "prudence" (at a global level) and then "equity" (in allocating, or annexing, down to a national level for the NCQ*, including provision for differentiated historical responsibility). It is important to emphasise 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. However, making *some* evidence-based estimate is essential to meaningful assessment of the Paris alignment of alternative mitigation scenarios for any nation (Geden and Löschel 2017).

Multiple *global* level scenarios consistent with the PA objectives have been explored through the use of global IAMs, which represent the interaction of societal and geophysical systems, especially in energy and land use. The ensemble of scenario integrated pathway outputs have been compared and assessed in the SR15 report (Rogelj et al. 2018, Section 2.3) and they are classified in the source database (Huppmann et al. 2018a, b) by *scenario class* according to their likelihood of limiting long-term warming to a specified temperature goal, and the extent of any temporary projected overshoot of such a goal. The CO_2-only warming related to a scenario pathway is here assumed to be determined by its maximum cumulative CO_2 emissions over the period 2010 to 2100, and the corresponding CO_2-only GCB stated below is the cumulative value specifically from the chosen baseline year of 2015. Similarly, for the analysis using GWP*, the GCB* value was determined on the basis of maximum cumulative CO_2-we (aggregate CO_2+N_2O+CH_4) over the period 2010 to 2100, and stated relative to the baseline year of 2015. The 37 scenarios in the database classed as "1.5C low overshoot" were used to assess the 1.5°C GCB and GCB* range and the 67 scenarios classed as "Lower 2C" were used to assess the "well below 2C" GCB and GCB* range. For each scenario, the database provides annual emissions, by gas, in 5-year or 10-year intervals from 2010 to 2100. Interpolating between these values gave emissions by gas for each year, and the cumulative CO_2-we emissions, from 2015-2100, were then calculated for each gas and in aggregate, for each scenario. Both GCB (CO_2-only) and GCB* (CO_2+N_2O+CH_4) were calculated. The distribution of peak values for each of the two scenario ensembles was then summarised by central tendency (50% percentile) and variability (10%-90% percentile). The results are shown in Table 7.1. On this basis for the GCB* range, the 10th percentile, P_{10}, is defined as *Low-GCB**, P_{50} as *Mid-GCB**, and P_{90} as *High-GCB**. As noted by Rogelj et al. (2018, Section 2.3), the scenario ensemble for a scenario class is not necessarily a statistically representative sample of pathways that *could* physically meet the related temperature goal because the selection arises from diverse study designs and parameter choices. Nonetheless, these pathways do give an indication of the scenario range actively explored by IAM modelling, which has been informed by expert judgement, and the range of resultant warming has been projected using simple but well-validated global climate models. In that sense, they may be interpreted as a reasonable representation of the current range of expert views of plausible future global emission scenarios that would still satisfy the given temperature constraints (aligned with the Paris Agreement).

Table 7.1. Estimating Low, Mid, and High values of the global cumulative CO_2-only budget (GCB) and the global cumulative aggregate-GHG ($CO_2+N_2O+CH_4$) budget (GCB*), from 2015 until the time of maximum forcing, for "1.5C low overshoot" and "Lower 2C" scenario classes assessed in the IPCC SR15 report (Rogelj et al. 2018, Section 2.3).

Scenario class: 1.5C Low Overshoot [37 scenarios]		**Percentile**		
	unit	**P_{10}**	**P_{50}**	**P_{90}**
GCB (CO_2 only)	$GtCO_2$	601	675	779
GCB* ($CO_2+N_2O+CH_4$)	***$GtCO_2$-we***	***562***	***641***	***768***
Scenario class: Lower 2C [67 scenarios]		**Percentile**		
	unit	**P_{10}**	**P_{50}**	**P_{90}**
GCB (CO_2 only)	$GtCO_2$	859	1040	1285
GCB* ($CO_2+N_2O+CH_4$)	***$GtCO_2$-we***	***844***	***1030***	***1250***

Ireland's percentage shares of the remaining emission budget as per the Raupach (2014) allocation mechanism is given in Table 7.2, showing Ireland with an "*equity*" (equal per capita) 0.064% share and a 0.086% *"inertia"* share, based on 2015 population data and annual CO_2-we emissions (data sources: Duffy et al. 2019; Gütschow et al. 2019). As per Raupach et al., a 50% *"blend"* value is defined as the mid-value between *equity* and *inertia*. Here, as in McMullin et al. (2019a) the Raupach term "equity" is replaced by *population* or *pop* to reflect the fact that even the lower equal per capita allocation may still be argued to be inherently *in*equitable (Kartha et al. 2018). Note that, by definition, neither of these allocation methods make any allowance for differentiated historical responsibility for climate forcing accumulated *prior* to the chosen baseline year (2015 in the current case); however, that would be a useful direction for additional future research, using GWP* to explore the effect of adopting alternative (earlier) baseline years on relative NCQ* quota allocations.

Table 7.2. Calculation of Ireland's 2015 percentage population and inertia shares of global values.

Ireland 2015 population	4.74	million	Ireland 2015 CO2-we emissions	45.1	MtCO2-we
World 2015 population	7400	million	World 2015 CO2-we emissions	52772	MtCO2-we
Ireland **Population** share	0.064	%	Ireland **Inertia** share	0.086%	%

Multiplying the Low, Mid and High GCB* CO2-we values by the Pop, Blend and Inertia allocation share factors, gives the Irish NCQ* values shown in Table 7.3 for “1.5C low overshoot” and “Lower 2C”. The 1.5°C values are presented, for the purposes of estimating an *illustrative* national NCQ* range across both the less prudent (“well below 2°C”) and more prudent (“efforts toward” a 1.5°C limit) PA temperature goals. Nonetheless, from here onward, we shall present more detailed national scenario exploration based only on the GCB* range associated with the “Lower 2C” scenario set as representing the “well below 2°C” goal; while still emphasising that meaningful “efforts toward” a 1.5°C limit would require focussing on the low end of this range, or, better, targeting the “1.5C Low Overshoot” range. Additional factors may further argue for even smaller allowances from this for the national NCQ*. These factors would particularly include stronger versions of “equity”, reflecting historical responsibility, vulnerability and capacity to act; while, in constructing the illustrative national scenarios, there should properly be an additional incorporation of appropriate responsibility for international aviation and shipping. For Ireland in particular, it appears likely that its relative historical (pre-2015) contribution to current global forcing specifically from CH_4 would be significantly higher than the global per capita average. Taking all these issues into consideration, and following McMullin et al. (2019a), we suggest that the *low* end of the “Lower 2C” GCB* range should be regarded as indicating a benchmark *maximum* NCQ* quota for Ireland, which should still be described as only being *minimally equitable*.

Table 7.3. Ireland NCQ* values for combinations of Low, Mid, and High with Pop, Blend and Inertia shares of GCB* as of the start of 2015 (from Table 7.1).

1.5C low overshoot (37 scenarios) Max 2015–2100 values		"1.5C low overshoot" scenario class		
		Low	**Mid**	**High**
GCB* (GtCO₂-we)		***562***	***641***	***768***
NCQ* ($MtCO_2$-we)	Pop	**360**	410	492
	Blend	420	**479**	574
	Inertia	481	548	**657**

Lower 2C scenarios (67 scenarios) 2015–2100		"Lower 2C" scenario class		
		Low	**Mid**	**High**
GCB* ($GtCO_2$-we)		***844***	***1030***	***1250***
NCQ* ($MtCO_2$-we)	Pop	**540**	659	800
	Blend	631	**770**	935
	Inertia	722	881	**1069**

7.4 Using the GHG-WE tool: Six 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 meeting Ireland's Paris-aligned climate forcing quota of "Lower 2C" CO_2-we NCQ* values corresponding to *Low-GCB*-Pop*, *Mid-GCB*-Blend*, and *High-GCB*-Inertia*, as given in Table 7.3. All scenarios are based on piecewise linear pathways for net annual territorial emissions (by mass) of each of CO_2, CH_4 and N_2O.

One scenario, **All_FLAT** (see Figure 7.1), provides a "no mitigation", baseline or reference case, where net annual CO_2, CH_4 and N_2O emissions remain at their 2019 levels until 2100. In contrast to this baseline, a small set of illustrative, effective, Paris aligned, mitigation scenarios are then defined.

As a narrative basis for mitigation scenarios aligned with the Paris Agreement, two key observations from Irish climate policy and emissions are identified: the 2019 Climate Action Plan (DCCAE 2019) indicates a cut of about -20% in "overall" GHG emissions over the period 2020 to 2030, followed by a potential reduction to net zero by 2050; and N_2O and CH_4 emissions are tightly coupled due to the use of reactive nitrogen in enabling production from ruminant agriculture. On this basis, for CO_2 specifically, these scenarios adopt a linear reduction pathway of 20% over the period 2020-2030, followed by linear reduction to zero by either 2050 or, more ambitiously, by 2040. This is applied to *net* CO_2, aggregating emissions and removals in all sectors, specifically including land use and forestry. In itself this assumption would represent an increase in mitigation ambition because Irish land use is currently a significant net CO_2 emitter. **Cn** in scenario names denotes "net CO_2", followed by the year of annual net zero CO_2 emissions. Separately from CO_2, and as Irish N_2O and CH_4 are strongly correlated, the scenarios assume that these non-CO_2 emissions are first linearly reduced to reach a common target percentage reduction over the period 2020-2050, and then stabilised at that reduced level. **MN** in scenario names is used to indicate the initial letters of "**M**ethane" and "**N**itrous oxide", and is followed by the aggregate percentage reduction (to be achieved in 2050 relative to 2020).

In the following three illustrative scenarios, net CO_2 emissions follow the CAP2019-indicated CO_2 pathway to 2050. Variations are then explored in target 2050 reduction for the non-CO_2 emissions pathways, and in the CO_2 pathway beyond 2050. In each case, the CO_2 emissions pathway is first extended linearly beyond net zero in 2050 to become net *negative* (net national carbon dioxide removal, or CDR), and then stabilised at some constant net negative level, through to 2100. The exact net negative CO_2 pathway parameters are manually adjusted to achieve sufficient cumulative net negative emissions level to ensure that *cumulative* net emissions across *all* GHGs are constrained within the specified cumulative CO_2-we quota (NCQ*) by no later than 2100. Effectively, net national net CDR is relied on over the period 2050-2100 to reverse any temporary quota overshoot and to compensate for continuing incremental increases in climate forcing due to continuing positive non-CO_2 emissions.

The three distinct scenarios are:

- **MN_FLAT_Cn2050** (Figure 7.2): CH_4 and N_2O are kept flat (at their 2019 annual emission rates) up to 2100.
- **MN-25%_Cn2050** (Figure 7.3)**:** CH_4 and N_2O annual emission rates are each cut linearly by -25% (relative to 2019) from 2020 to 2050; thereafter they remain flat at these lower levels.
- **MN-50%_Cn2050** (Figure 7.4)**:** CH_4 and N_2O annual emission rates are each cut linearly by -50% (relative to 2019) from 2020 to 2050; thereafter they remain flat at these lower levels.

In two further scenarios, net-CO_2 emissions are cut linearly from 2020 through net zero by the earlier date of 2040, and then again proceeding to the sustained net negative (net removals) level required to return to quota by 2100:

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

As already noted, CO_2 is presented in these scenarios on a net basis across all sectors. The value for each year is an aggregate of the CO_2 emissions from fossil fuel and industry (FFI) and the CO_2 emissions and CO_2 removals from land use, land use change and forestry (LULUCF or more simply LU). CDR could also be achieved if negative emissions technologies (NETs), such as BECCS, DACCS or EW were to be developed at large scale to remove CO_2 from atmosphere and store it geologically or fix it in mineral form. In these illustrative scenarios, no assumptions are made about the mix of gross emissions and gross removals adding up to CO_2 net values in any year, or the specific CDR approaches or technologies that may have to be deployed. However, in any case where *annual net negative* emissions (net removals) are shown in a given year, it follows arithmetically that this also represents an absolute minimum of achieved *gross removals* in that year; and similarly, where *cumulative net emissions* over the scenario period (2020-2020) are negative (cumulative net removals) then that indicates an absolute minimum of achieved *cumulative gross removals* over that period.

As a basis for Irish GHG scenario pathways using the SSECCM *GHG-WE* model, historic values for CO_2, N_2O and CH_4 are made available from different sources. The Irish EPA GHG inventory tables provide data for 1990 to 2018 (Duffy et al. 2019); CEDS data sets in Hoesly *et al.* (2018, supplementary information) gives annual values for individual nations from 1970 to 2014, with longer-run (decadal) estimates for global regions from 1820 to 1970; and the updated PRIMAP timeseries gives detailed datasets for GHGs by country, sector and sub-sector (Gütschow et al. 2019). The SSECCM *GHG-WE* tool gives the user the option of which of these data sources to use.

7.4.1 Results from the GHG-WE model for the five illustrative mitigation scenarios

Figures 7.1 to 7.6 show detailed data and output charts for the baseline, no-mitigation, **ALL_FLAT** scenario and then for the five mitigation scenarios that are aligned with the Paris Agreement temperature goal of "well below 2°C"), on the basis of satisfying the Low-GCB*-Pop NCQ* quota of 540 $MtCO_2$-we, no later than 2100. Separately, to illustrate the *sensitivity* of key scenario variables to NCQ*, **Table 7.4** presents summary values for peak NCQ* overshoot, cumulative CDR, and steady state annual CDR per year for the range of assessed NCQ* quota allocations (Low-GCB*-Pop NCQ*, Mid-GCB*-Blend and High-GCB*-Inertia). A bar chart comparison of the mitigation scenarios by key GHG variables is shown in Figure 7.7. The following is a digest of the scenario results meeting the Low-GCB*-Pop NCQ* (with cumulative emissions and CDR values rounded to the nearest 10 $MtCO_2$-we):

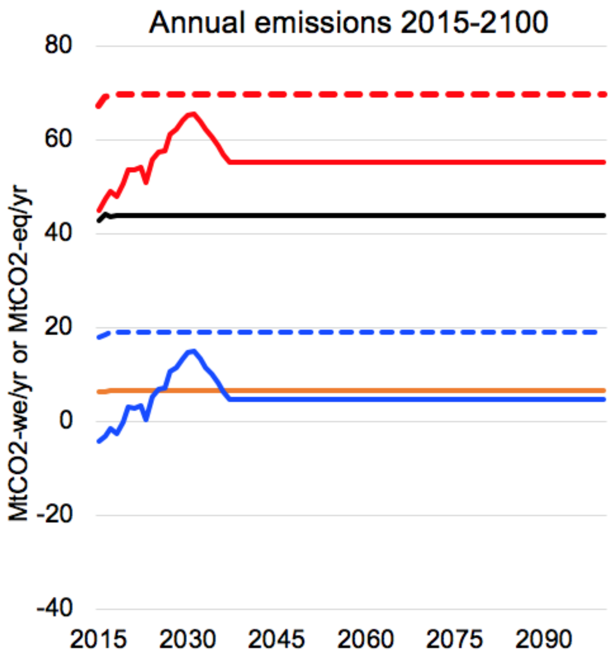
- **All_FLAT** (Figure 7.1): In this baseline, no-mitigation, scenario there is no reduction in annual GHG emissions, resulting in rapidly escalating quota overshoot, reaching 4050 $MtCO_2$-we by 2100. Cumulative net CO_2-only emissions to 2050 are 990 $MtCO_2$. *Increasing* CH_4 forcing (as estimated by CO_2-we) contributes to even earlier breaching of the NCQ*: by 2025 with CH_4, rather than 2027 for LLCFs (CO_2 + N_2O) alone. This flat CH_4 pathway contributes a cumulative warming effect of +440 $MtCO_2$-we by 2100 compared to 2015. The chart also shows the annual **CO_2-eq** level for CH_4 (effectively representing the annual emissions by mass, rather than the incremental increase in warming represented by annual CO_2-we) as this is important to gauge any changes in annual mass flow that would be the proximate target of policy measures under the alternative, strong mitigation, scenarios.
- **MN_FLAT_Cn2050** (Figure 7.2): By definition, this has the same cumulative contribution from N_2O+CH_4 emissions, over 2015-2100, as in the **All_FLAT** scenario. This amounts to 1,020 $MtCO_2$-we, which, in itself already represents substantial overshoot of the overall NCQ* quota. Thus, this scenario requires using CDR to reverse both this underlying NCQ* overshoot due to non-CO_2, *and* any cumulative net emissions of CO_2 up to the time of annual net CO_2 zero. This is specified as 2050 in this case, and amounts to 990 $MtCO_2$. To achieve this, the linear CO_2 net pathway from 2030 through net zero CO_2 in 2050 is continued to a level of -35 $MtCO_2$/yr by 2070, and then maintained constant at that level to 2100. This is just sufficient to allow cumulative aggregate net GHG emissions (CO_2-we) to return to the NCQ* quota by 2100. This ultimately requires cumulative CO_2 removals of -1470 $MtCO_2$ from 2050 to 2100, to cancel the *carbon debt* at the peak quota overshoot (930 $MtCO_2$) and to compensate for the further ongoing N_2O and CH_4 warming contributions.
- **MN-25%_Cn2050** (Figure 7.3)**:** As for all Cn2050 pathways, cumulative CO_2 emissions from 2015-2050 (up to annual net zero CO_2) are 990 $MtCO_2$. However, linearly reducing annual emissions of both CH_4 and N_2O by -25% (measured by mass or CO_2-eq) over the period 2020 to 2050, and stabilising at that new level to 2100, reduces the cumulative contribution from N_2O+CH_4 emissions, over 2015-2100, to 470 $MtCO_2$-we. This scenario still leads to significant temporary overshoot of the NCQ* limit. However, limiting the negative extrapolation of the linear CO_2 net pathway beyond 2050 to reach -20.6 $MtCO_2$/yr by 2060, and then maintaining constant at this level, is now sufficient to return to the NCQ* quota by 2100. Peak quota overshoot is 600 $MtCO_2$-we and cumulative CO_2 removal over 2050 to 2100 falls to -920 $MtCO_2$. The reduction in (still positive) CH_4 mass flow means that CH_4 annual CO_2-we becomes negative for 30 years from 2035 to 2065, effectively substituting for some of the net negative CO_2 (CDR) in the **MN_Flat_Cn2050** scenario. Annual aggregate GHG CO_2-we emissions reach net zero just before net zero CO_2 in 2050. Despite the -25% reduction in CH_4 emissions by 2050, the stock effect warming of stable CH_4 emissions after 2050 cumulatively results in a warming contribution due to CH_4 which ultimately returns to the same cumulative contribution in 2100 as it was in 2015.

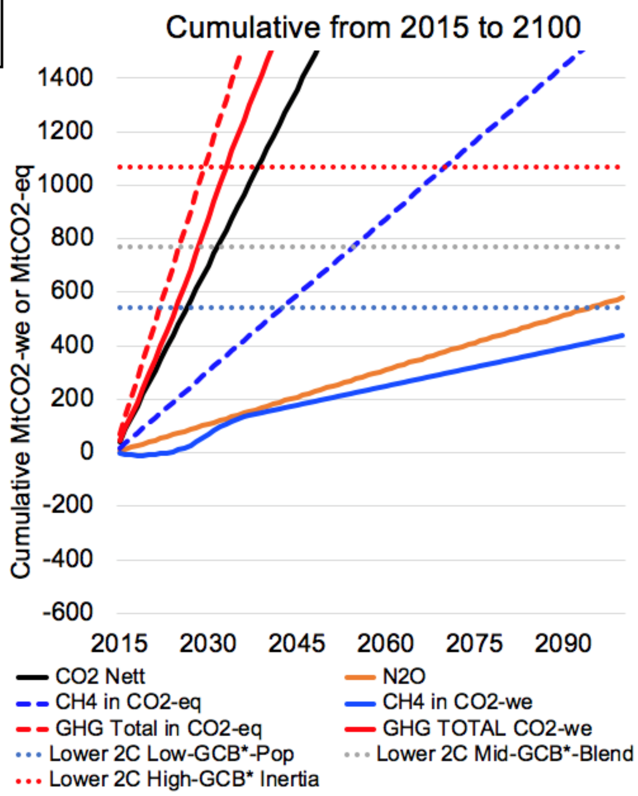
- **MN-50%_Cn2050** (Figure 7.4)**:** Still given the same CO_2 pathway to 2050, cumulative CO_2 emissions from 2015-2050 (up to annual net CO_2 zero) are 990 $MtCO_2$. In this case, annual emissions of both CH_4 and N_2O are again reduced linearly over the period 2020 to 2050, but now by -50% (measured by mass/CO_2-eq), and then again stabilised at this lower level to 2100. This further reduces the cumulative contribution from N_2O+CH_4 emissions, over 2015-2100, and it becomes marginally negative overall at -70 $MtCO_2$-we. While this scenario still involves significant temporary NCQ* overshoot, it does allow limiting the negative extrapolation of the linear CO_2 net pathway beyond 2050 to stabilise at the significantly less demanding level of -7.4 $MtCO_2$/yr by 2054. Peak quota overshoot falls to 380 $MtCO_2$-we and cumulative CO_2 removal over 2050 to 2100 falls to -360 $MtCO_2$. Annual CH_4 CO_2-we emissions are again negative for an extended period (now about 36 years from 2032 to 2068). Annual aggregate GHG CO_2-we emissions reach net zero in 2041, noticeably in advance of net zero CO_2 in 2050. Overall, the deeper reduction in annual mass flow of CH_4, in particular, now substantially eases the CDR burden, and strongly reduces both the extent and effective duration of NCQ* overshoot.
- **MN-25%_Cn2040** (Figure 7.5): As an alternative to the deeper reductions in N_2O and CH_4 flow represented by **MN-50%_Cn2050**, this scenario instead considers even more ambitious CO_2 mitigation (compared to the adopted interpretation of CAP 2019) by bringing forward the date of annual net zero CO_2 from 2050 to 2040, and commencing the linear descent to that immediately from 2020 (rather than having a lesser rate of descent from 2020-2030). As for **MN-25%_Cn2050**, the cumulative contribution from N_2O+CH_4 emissions, over 2015-2100, returns to 470 $MtCO_2$-we. However cumulative CO_2 emissions up to the point of annual net CO_2 zero (now 2040) are reduced from 990 $MtCO_2$ to 660 $MtCO_2$. In this scenario the required negative extrapolation of the linear CO_2 net pathway (beyond 2040) is to a level of -10.2 $MtCO_2$/yr by 2045, and then maintaining constant at this level, to still return to the NCQ* quota by 2100. Peak quota overshoot is somewhat lower than **MN-50%_Cn2050** at 290 $MtCO_2$-we, but the required cumulative CO_2 removal (now over 2040 to 2100) is significantly higher at -590 $MtCO_2$. Annual aggregate GHG CO_2-we emissions reach net zero in 2040, at essentially the same time as net zero CO_2.
- **MN-50%_Cn2040** (Figure 7.6) Finally, to illustrate the most stringent combination of the various mitigation pathways for the different gases, we *combine* the accelerated CO_2 mitigation of the **MN-25%_Cn2040** scenario with the deeper (-50%) annual mass flow reductions of N_2O and CH_4 flow represented by the **MN-50%_Cn2050** scenario. As for **MN-50%_Cn2050**, the cumulative contribution from N_2O+CH_4 emissions, over 2015-2100, becomes marginally negative at -70 $MtCO_2$-we, and cumulative CO_2 emissions up to the point of annual net CO_2 zero (2040) are limited to the 660 $MtCO_2$ of the **MN-25%_Cn2040** scenario. In this case, the requirement for (net) CDR in Ireland would be almost eliminated. The required extrapolation of the linear annual CO_2 net pathway (beyond 2040) is to a level of just -0.6 $MtCO_2$/yr (in 2041), and then maintaining constant at this level. Peak quota overshoot is limited to 180 $MtCO_2$-we, and the required cumulative CO_2 removal (over 2040 to 2100) is just -35 $MtCO_2$. Annual aggregate GHG CO_2-we emissions reach net zero already in 2036, again noticeably in advance of annual net zero CO_2.

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





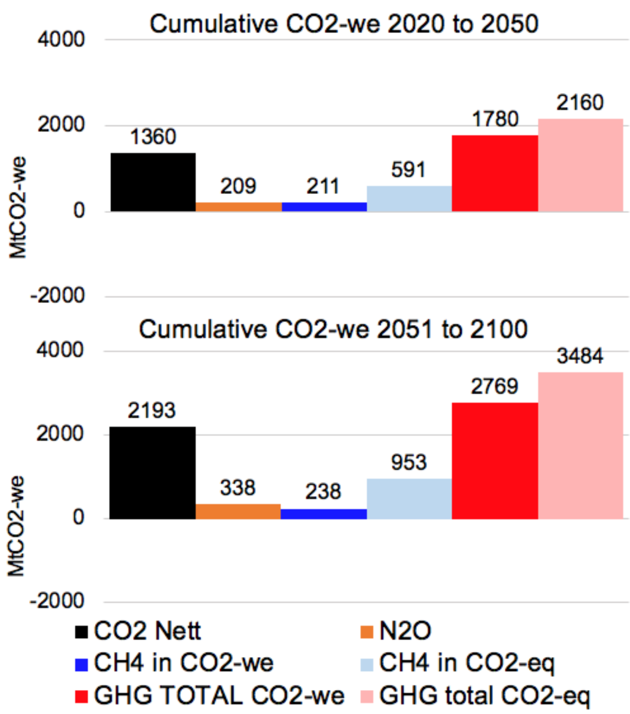
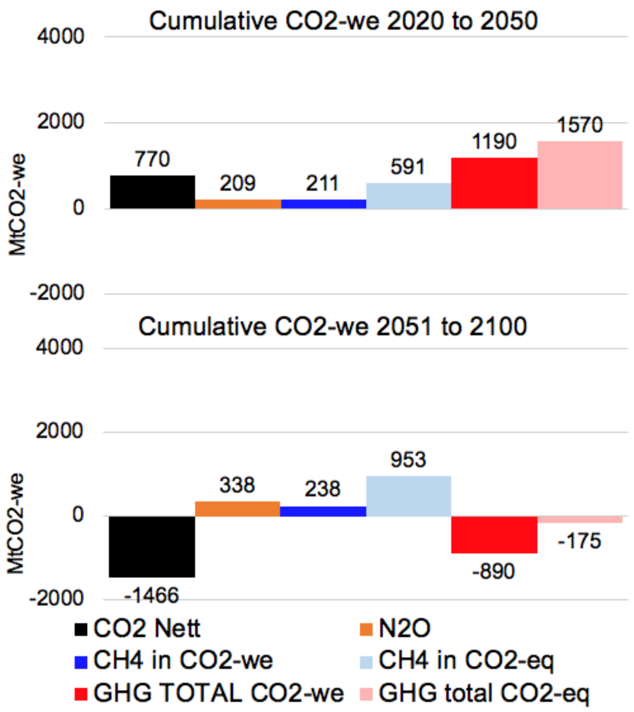


Figure 7.1. ***All_FLAT scenario*** **(no mitigation). Annual emissions: CO_2 net, CH_4 and N_2O are all assumed to remain constant at the 2020 level from 2021 onward.**

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

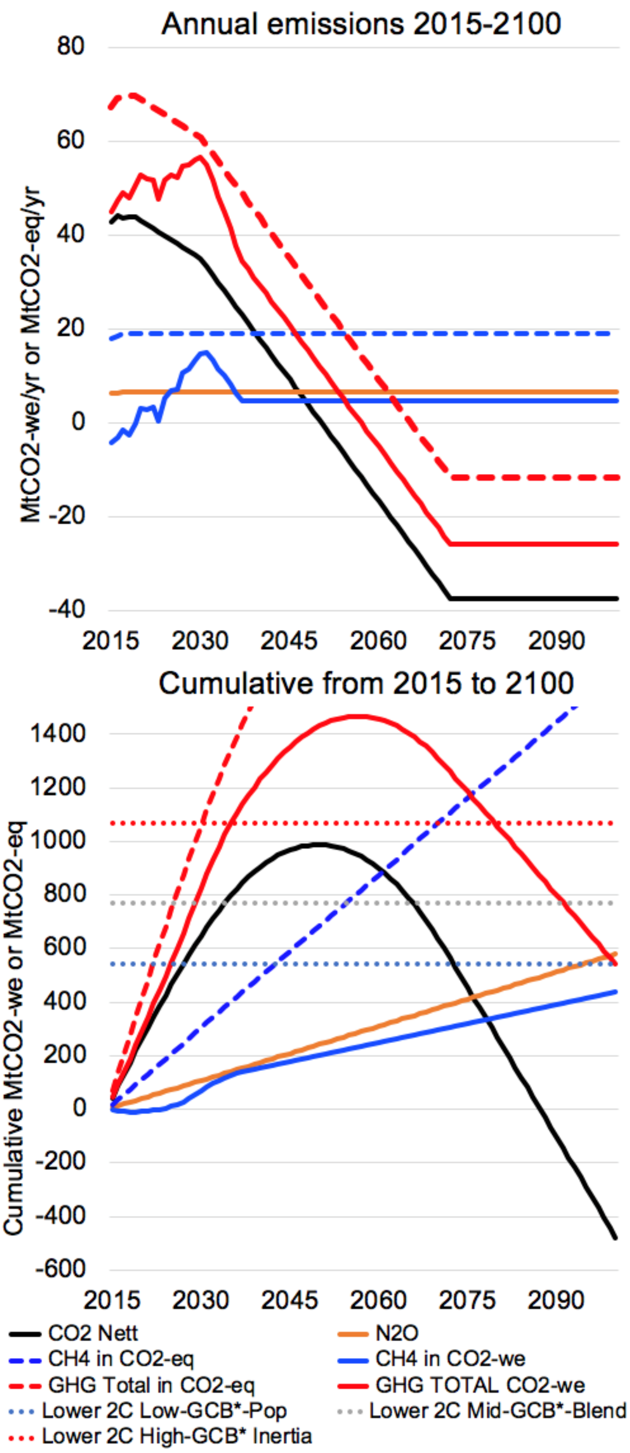
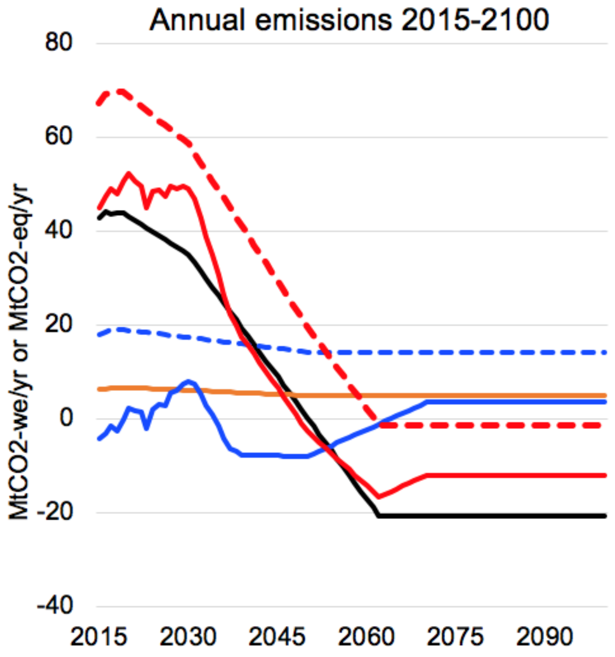


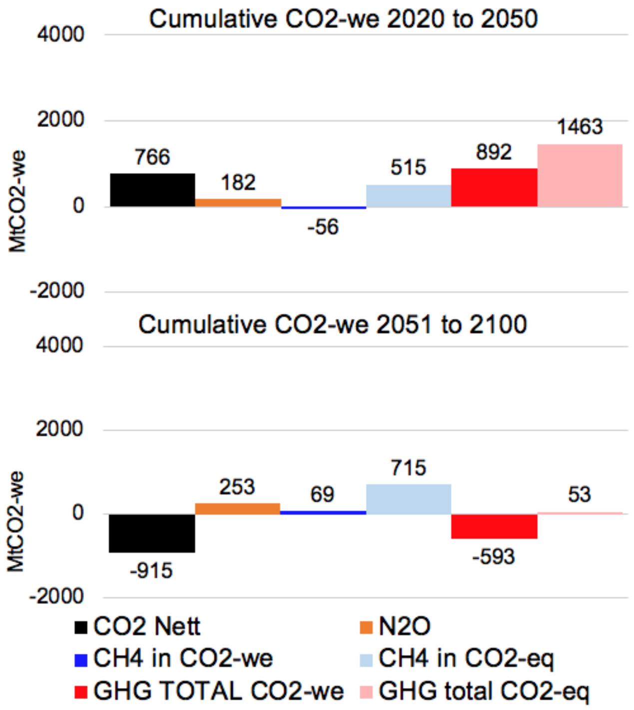
Figure 7.2. ***MN_FLAT_Cn2050 scenario*** **meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O stay at 2019 level to 2100. Net CO_2 cut by -20% by 2030, then through net zero CO_2 emissions in 2050.**

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





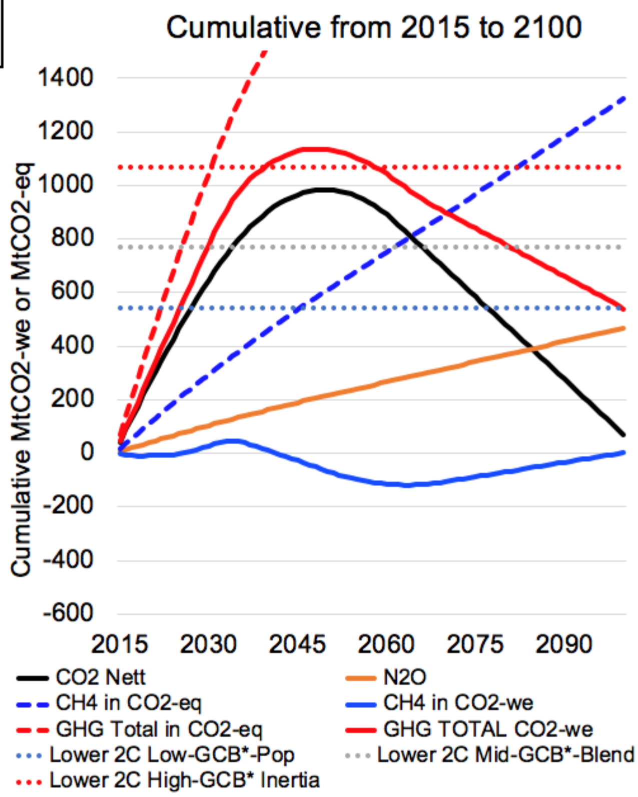
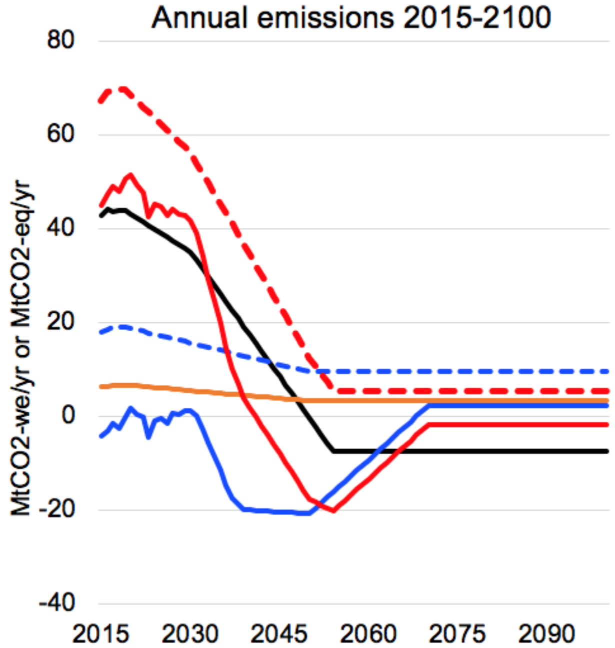


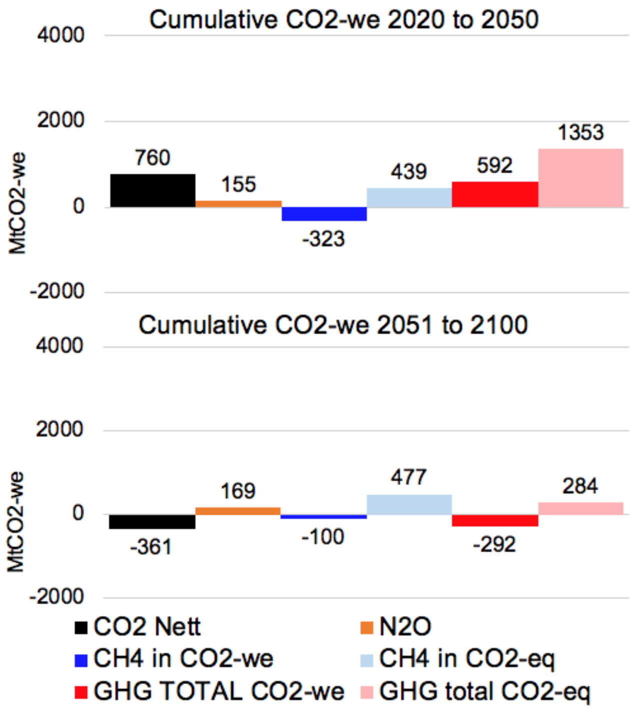
Figure 7.3. ***MN-25%_Cn2050 scenario*** **meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O cut by -25% from 2020 2050. CO_2 net cut by -20% by 2030, then through annual net zero CO_2 emissions in 2050.**

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





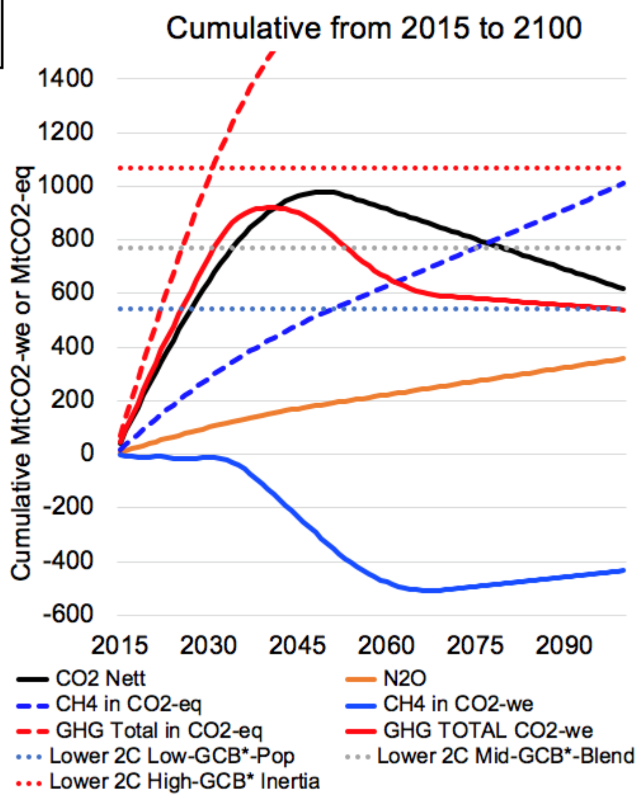
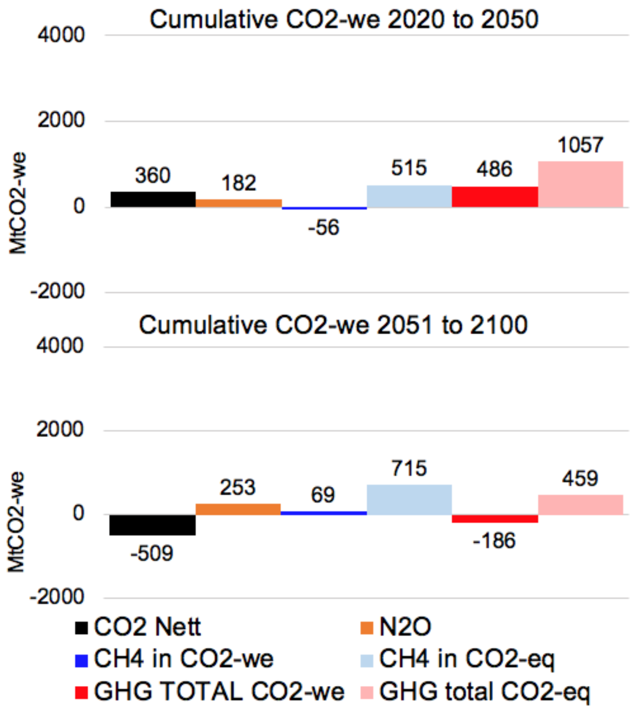


Figure 7.4. ***MN-50%_Cn2050 scenario*** **meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O cut by -50% from 2020 2050. CO_2 net cut by -20% by 2030, then through annual net zero CO_2 emissions in 2050.**

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



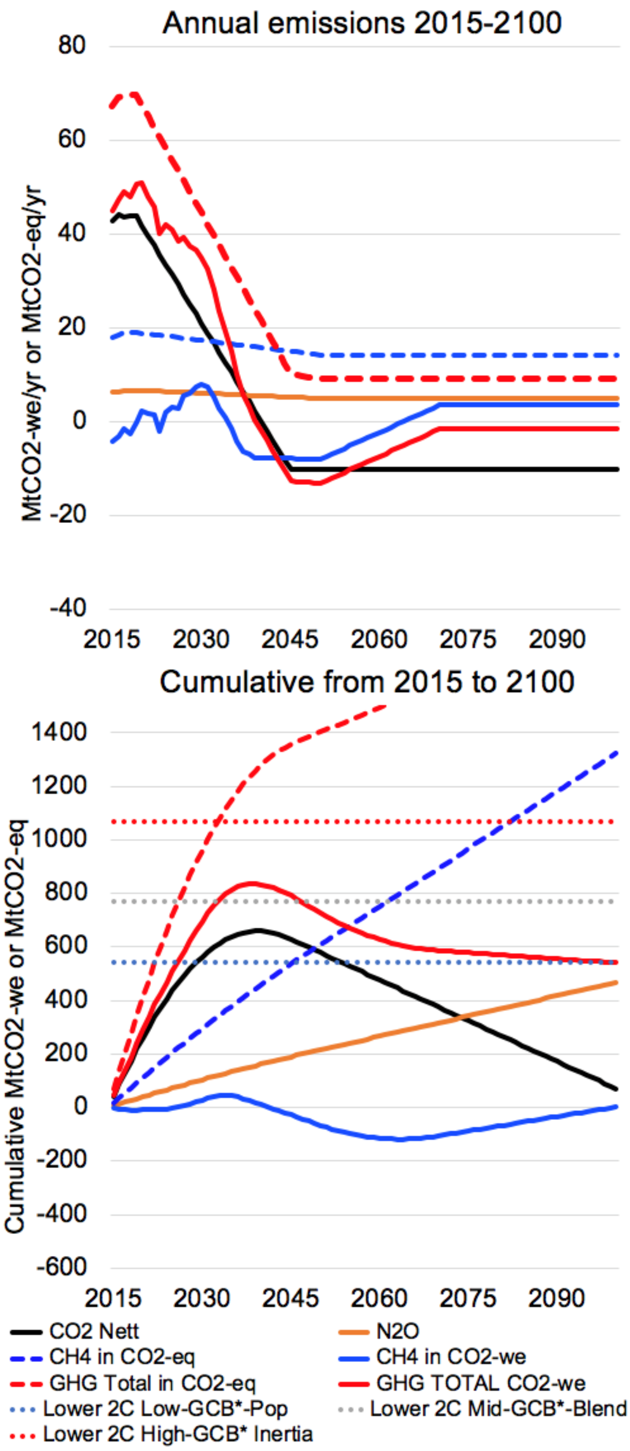
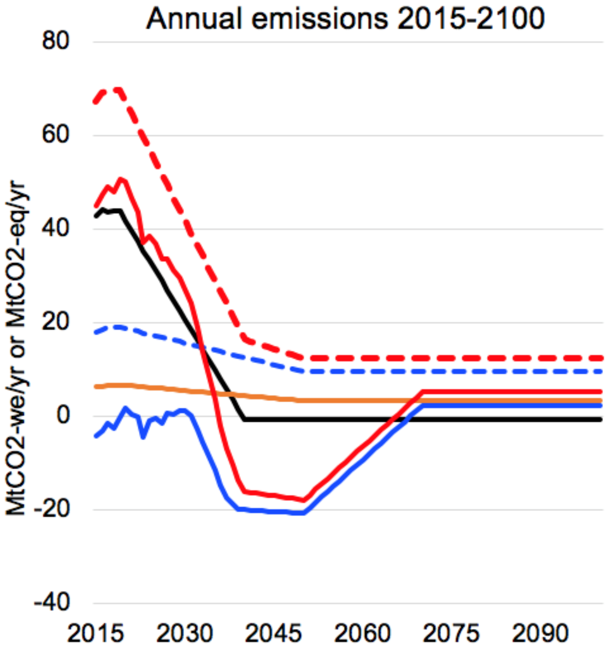


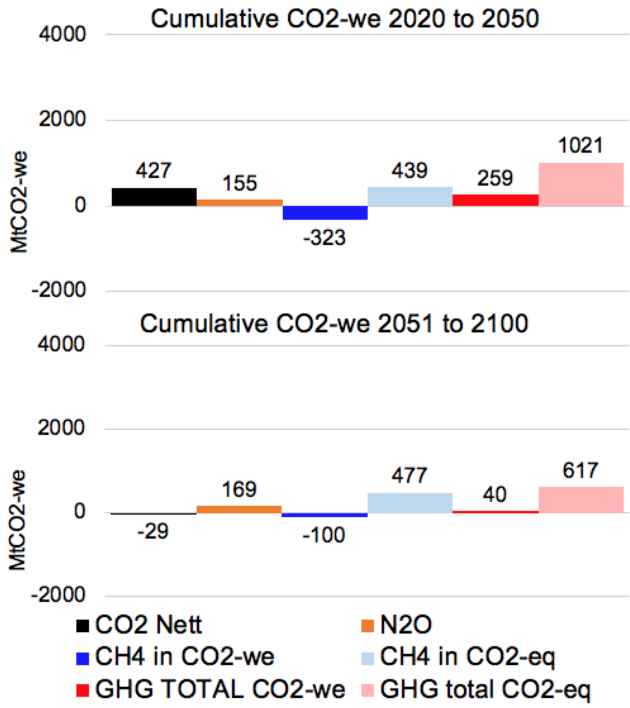
Figure 7.5. ***MN-25%_Cn2040 scenario*** **meeting Low-GCB*-Pop by 2100. CH_4 and N_2O cut by -25% from 2020 to 2050. CO_2 net cut linearly from 2020 through annual net zero CO_2 emissions in 2040.**

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





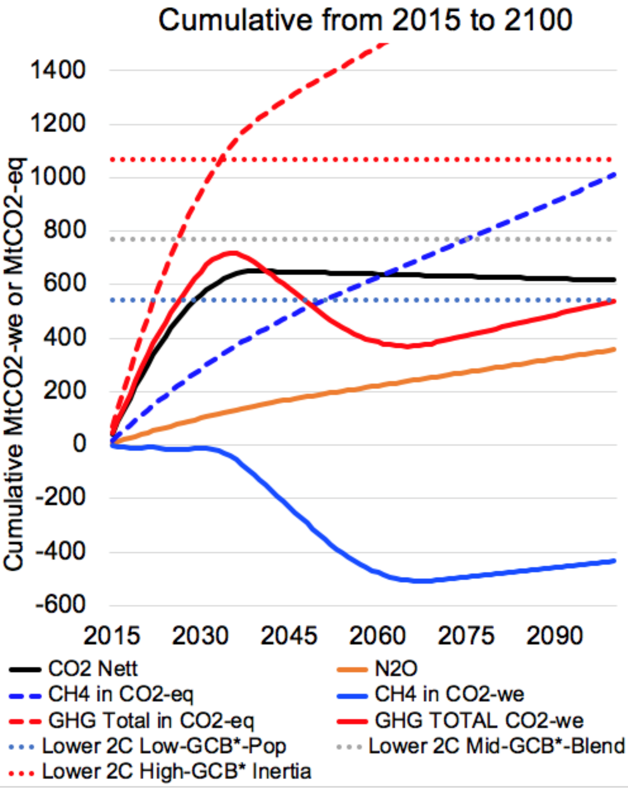


Figure 7.6. ***MN-50%_Cn2040 scenario*** **meeting Low-GCB*-Pop NCQ* by 2100. CH_4 and N_2O cut by -50% from 2020 to 2050. CO_2 net cut linearly from 2020 through annual net zero CO_2 emissions in 2040.**

Table 7.4. Sensitivity of overshoot, cumulative CDR, and steady state annual CDR for all illustrative scenarios, under varying NCQ* constraints. Note that fully detailed pathways have been presented in Figures 7.1 to 7.6 under the Low-GCB*-Pop NCQ* constraint only.

Scenario	**Variable** (all MtCO2-we)	**Low-GCB*-Pop** NCQ* = 540 $MtCO_2$-we	**Mid-GCB*-Blend** NCQ* = 770 $MtCO_2$-we	**High-GCB*-Inertia** NCQ* = 1069 $MtCO_2$-we
ALL_FLAT	Overshoot	4249	4019	3720
	Sum cumulative CDR	NA	NA	NA
	Annual steady state CDR	*NA*	*NA*	*NA*
MN_FLAT Cn2050	Overshoot	927	690	388
	Sum cumulative CDR	-1466	-1232	-931
	Annual steady state CDR	*-37.3*	*-29.4*	*-20.9*
MN-25% Cn2050	Overshoot	596	368	59
	Sum cumulative CDR	-915	-688	-377
	Annual steady state CDR	*-20.6*	*-15.0*	*-7.7*
MN-50% Cn2050	Overshoot	381	149	**NA**
	Sum cumulative CDR	-361	-128	**NA**
	Annual steady state CDR	*-7.4*	*-2.5*	**NA**
MN-25% Cn2040	Overshoot	294	63	1
	Sum cumulative CDR	-590	-360	-50
	Annual steady state CDR	*-10.2*	*-6.1*	*-0.8*
MN-50% Cn2040	Overshoot	178	NA	NA
	Sum cumulative CDR	-35	NA	NA
	Annual steady state CDR	*-0.6*	*NA*	*NA*

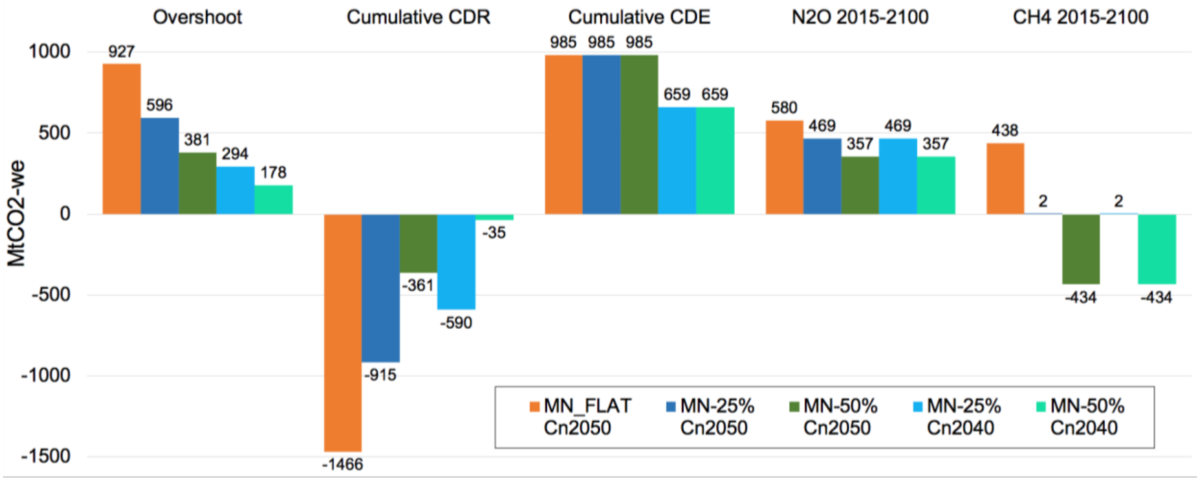


Figure 7.7. NCQ* overshoot and disaggregated cumulative GHG for 2015–2100. CDE = net Carbon Dioxide Emissions up to net zero (in 2050 or 2040 as appropriate). All values in CO_2-we. Low-GCB*-Pop scenario constraint only.

7.4.2 Comparison of the illustrative scenarios

Cumulative CO_2-we emissions pathways for the illustrative scenarios suggest that Ireland is on a trajectory to early overshoot of the (minimally prudent and equitable, Low-GCB*-Pop) Paris-aligned NCQ*. Even under the most stringent MN-50%_Cn2040 scenario, cumulative net CO_2-we emissions exceed the quota as early as 2029 (compared to overshoot by 2025 in the baseline, no mitigation, ALL_FLAT scenario). The ALL_FLAT scenario cumulative CO_2-we exceeds even the highest considered NCQ* (High-GCB*-Inertia) by 2035. Given imminent overshoot in all cases, all effective mitigation scenarios now imply significant and sustained CDR, or significant and sustained CH_4 flow reduction, or both, to return to any meaningfully “Paris-aligned” NCQ* quota within any relevant policy time horizon (here taken as 2100 at the latest). Figure 7.7 and Figure 7.8 compares key characteristics of the scenarios meeting the Low-GCB*-Pop quota. Cumulative CDR from peak CO_2-we is -1470 $MtCO_2$ in Mn_FLAT_Cn2050, requiring annual CDR of -37 $MtCO_2$, which is comparable in scale to continuously removing total current annual fossil and cement emissions to permanent storage, but with no proximal societal benefits. Due to CH_4 reduction up to 2050 (with CH_4 mass flow remaining stable thereafter), MN-25% scenarios imply 440 $MtCO_2$ less CDR, and MN-50% scenarios imply 770 $MtCO_2$ less CDR, compared to the MN_FLAT scenario. Cutting CO_2 to net zero by 2040 emits net positive 660 $MtCO_2$, compared to 990 $MtCO_2$ if net zero is delayed to 2050. Again, this reduces the implied burden of subsequent CDR by essentially the same amount. Reductions in N_2O emissions by -25% or -50% by 2050 and stabilising thereafter, result in cumulative CO_2-we reductions of 110 $MtCO_2$-we or 220 $MtCO_2$-we respectively, compared to the no-mitigation FLAT scenarios. While these are quantitatively much smaller differences than implied by comparable fractional changes in CH_4 annual emissions, nonetheless, they would again substantially reduce the implied future CDR burden.

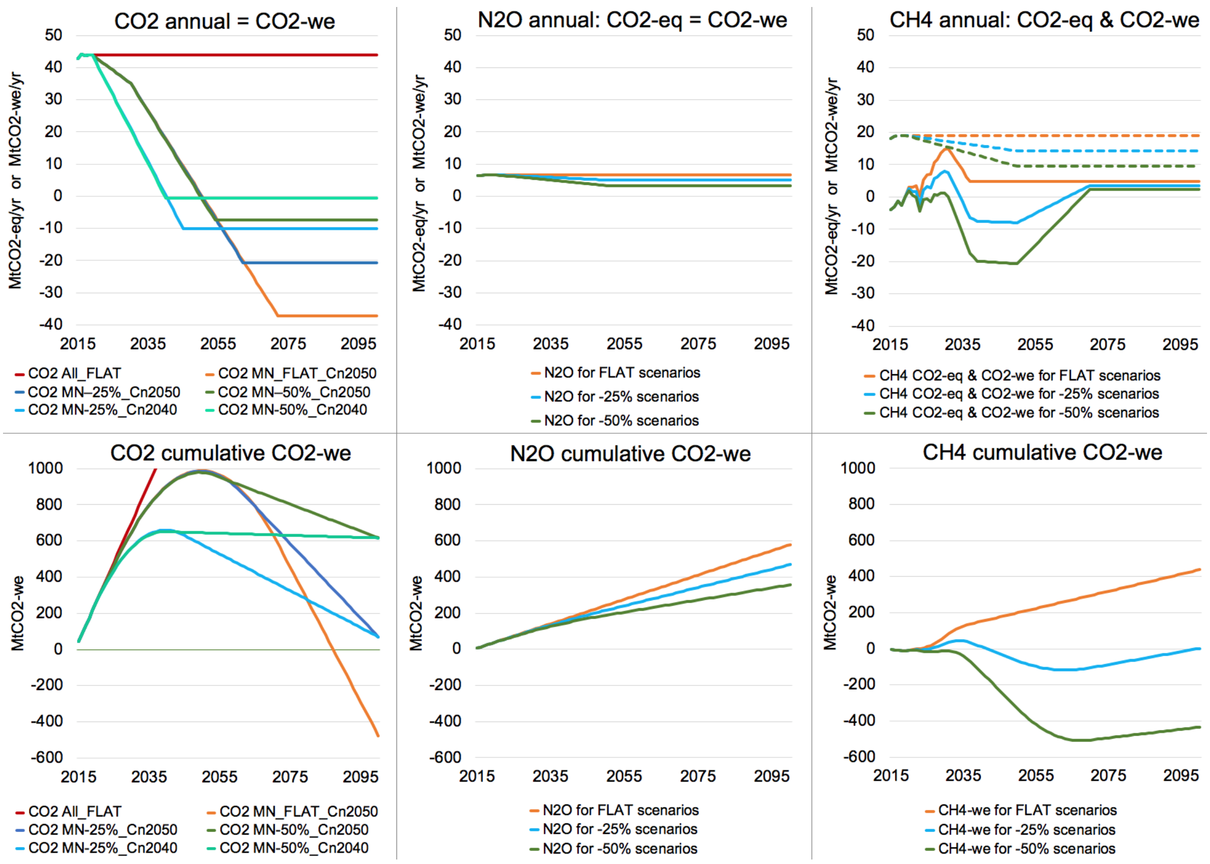


Figure 7.8. Annual and cumulative 2015–2100 comparison of illustrative scenarios. Given a joint CH_4 and N_2O pathway, CO_2 net adjusted to satisfy Low-GCB*-Pop NCQ* by 2100.

As noted earlier, a practical upper policy limit on the possible future level of achievable *gross* cumulative CDR (up to 2100) has been proposed as no more than about -200 $MtCO_2$ (McMullin et al. 2020). Given such a CDR limit, **Table 7.4** shows that only scenarios with *at least* a 50% mass flow reduction in CH_4 and N_2O (MN-50%_Cn2050 and MN-50%_Cn2040) could plausibly satisfy the Low-GCB*-Pop NCQ* quota. Even the MN-50%_Cn2050 scenario would require *some* acceleration in achieving CO_2 net zero and/or deeper flow rate reductions for CH_4 and N_2O; while all other illustrative mitigation scenarios imply *net* CDR far in excess of 200 $MtCO_2$.

7.5 Policy solutions

To satisfy any Paris-aligned, warming-equivalent national carbon quota (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. Radical (early and deep) reduction in annual net CO_2-only emissions, reaching annual net zero significantly before 2050, combined with limited, sustainable net CDR, appear now to be unavoidable necessary conditions for such effective climate action to limit long-term warming; but to limit the ultimate reliance on CDR to plausibly prudent levels would appear to *also* require steady 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*). Severely delayed mitigation, such as continuing GHG emissions approximately at 2019 levels up to 2040 or beyond, as seemingly implied by Ireland's draft NECP (DCCAE 2018), would risk 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" mitigation policy space specifically for CO_2 appears significantly wider *if* potential reduction in cumulative warming via reduction in annual CH_4 mass flow rate (comparable in physical effect to CDR) is *appropriately* represented. This analysis can evidently be done relatively quickly and effectively using the GWP* methodology and **cumulative CO_2-we** scenario trade-offs.

By definition, substantial net CDR (negative net CO_2 emissions) can only occur 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. That is, reflecting the IPCC-assessed SR15 scenario pathways, use of the *GHG-WE* tool now strongly suggests that meaningfully 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. Failing that, limits on Ireland's estimated practical CDR (~200 $MtCO_2$) will almost certainly be tacitly 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 greenhouse gases, to limit overall societal transition risk and cost.

As Ireland has comparatively very high CH_4 emissions due to ruminant agriculture, this is a significant mitigation policy lever, in terms of capacity and responsibility, in achieving aggregate society-wide mitigation. GWP* analysis shows that such substantial CO_2-we mitigation was, in fact, already occurring as a result of agricultural emissions reduction from 1998 to 2011 related to subsidy reductions and the EU milk quota policy. However, expansionary national agrifood strategies since 2010, which appear not to have adequately considered the long term climate implications, are progressively nullifying this earlier mitigation. The illustrative scenarios show the importance of limiting CH_4 source emissions in the near-term, otherwise even strong CO_2 mitigation effort can easily be cancelled out by continuing CH_4 contribution to warming. Beginning sustained reductions in total national CH_4 emissions sooner rather than later would ease transition in the agricultural sector and assist in limiting near-term NCQ* quota overshoot. Beyond reaching annual net zero CO_2-only, any net positive forcing due to continued N_2O and CH_4 emissions would still 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 reactive nitrogen from synthetic fertiliser and animal feeds are a key enabler of Irish N_2O and CH_4 emissions. Therefore, limiting N_r usage at national system level and limiting inefficient and polluting N_r use on grass (such as for ruminant and biogas agricultural production), present potentially important policy levers for climate change mitigation. The proposed development of hundreds of anaerobic digester (AD) plants in Ireland to supply biomethane (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 already add significantly to total CH_4 contributed warming. Some sources suggest that AD CH_4 leakage rates can be much higher (Baldé et al. 2016), particularly if independent regulatory oversight of installation and maintenance of AD plants were to be inadequate (Ebner et al. 2015). It is conceivable that CH_4 leakage from a single AD plant could be equivalent to the warming effect of a herd of hundreds of cattle.

It has been explicitly argued that the Paris Agreement 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 of 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, and the specific possibility that Ireland may bear a disproportionate historical responsibility for accumulated forcing due to CH_4. 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 directly to adequate, equitable, contribution to meeting the Paris Agreement goals.

Applying GWP* in Irish mitigation pathway assessment does mean that at least some perverse or counterproductive policy choices *might* be avoided and that one particular major flaw regarding evaluation of the contribution from CH_4 can be removed from policy analysis. As the LLCF budget to stay within a stringent temperature limit is exhausted, achieving sufficiently rapid reductions of 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 national climate action – in terms of contribution to actual climate forcing over time and in achieving climate action more aligned with staying within the Paris Agreement temperature 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 the results would require further critical testing and independent replication before they could be considered robust. A specific open issue is the appropriate choice of GWP_{100} value for CH_4 in GWP* analysis: the existing GWP* literature is not yet fully clear or consistent on this. Nonetheless, the illustrative scenarios show that use of the *GHG-WE* tool, aggregating the 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 Conclusions and 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 quantitatively compare warming-equivalent outcomes (CO_2-we) of alternative possible mitigation scenarios at a national level. The GWP* metric enables short-lived climate forcers, particularly CH_4, to be included into aggregate cumulative emission budget or quotas. However, UNFCCC accounting (underpinning the Paris Agreement) relies on the use of the GWP_{100} metric. Inconsistent adoption of different aggregation metrics may risk unfair and/or misleading assessment and comparison of mitigation effort (Rogelj and Schleussner 2019).

Recommendation: At this point, GWP* is recommended for use *only* in nation-level comparison of society-wide scenarios on the basis of cumulative CO_2-we from a specified reference year in the aggregation of emissions from diverse long- and short-lived climate forcers. In particular, this is the recommended use of the GHG-WE tool in the context of an explicitly stated national cumulative CO_2-we quota share of a Paris-aligned global cumulative GHG budget. The use of GWP* is *not* recommended for isolated annual or single sector analysis, especially when a reference year is not given, as such use could lead to misleading or perverse policy advice. Support for potential use of GWP* at UNFCCC level (for example, in the formulation and updating of the 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 formulation of a national "fair share" mitigation quota (NCQ*), specifically including prudence, historical responsibility, the role of "internationalised" emissions (in aviation and shipping), and inter-generational equity. The reference year for such quota analysis should certainly be no later than the date of the adoption of the Paris Agreement text (2015); but use of a significantly earlier reference year could go some way to acknowledging differentiated historical responsibility for warming to date. Given its distinctive GHG profile, it is possible that Ireland may bear a disproportionate historical responsibility for accumulated forcing due to CH_4. This question should be subject to further specific research.

Use of the *GHG-WE* tool graphically shows the radical mitigation now required for Ireland to limit overshoot of even a minimally prudent and equitable national cumulative GHG quota aligned with meeting the (minimal) Paris Agreement temperature goal of "well below 2°C" global warming above pre-industrial. For good faith actors, substantial near term quota overshoot appears to imply a tacit commitment to significant future deployment of CO_2 removal (CDR) measures. Such measures are likely to be practically limited by capacity and sustainability, would require large scale investment and would likely take decades to deliver at substantive scale. Accordingly, they present a significant and serious risk of policy failure. The precautionary principal would imply that such reliance should be absolutely minimised. In the specific case of Ireland, there is an additional policy option available, complementary to CDR: namely, significant and sustained reductions in the annual (mass) flow rate of CH_4. While this complementary policy option is also extremely challenging, it seems essential that it should be properly considered within any society-wide assessment of climate risks, costs, and impacts.

- **Recommendation:** Best practice national policy, research and modelling can identify a 'fair share', Paris-aligned national cumulative GHG quota (NCQ*) stated in cumulative CO_2-we from a reference year up to explicit time horizon dates. This is the national claim on the global budget that provides the crucial aggregate GHG context for scenario options and policy-relevant modelling. Within this limit, alternative emission scenarios can be explored across all relevant GHGs (using the GHG-WE tool or otherwise). This should include open and careful assessment of differentiated historical responsibility for accumulated forcing. In the case of Ireland, potentially disproportionate historical contribution to global CH_4 forcing is especially relevant.

As use of the GHG-WE tool shows, given its comparatively large CH_4 emissions, Ireland has a larger climate action 'lever' for CH_4 reduction than other nations. CH_4 mitigation or emission increase is non-linearly related to CO_2 mitigation. That is, relatively small but sustained rates of reduction in annual CH_4 (mass flow) emissions can have very significant impacts on the required CO_2 mitigation action needed to meet a given goal. Conversely, stable or increasing CH_4 emissions can make it impossible to meet prudent Paris-aligned cumulative GHG quota limits. Using the GHG-WE tool in illustrative scenarios shows that a rapid cessation of net CO_2 emissions (to net-zero, before 2050) supplemented by deep CH_4 reduction (of the order of -50% by 2050, which is in line with IPCC-assessed global illustrative scenarios in the SR15 SPM report) can combine to significantly limit quota overshoot and achieve rapid reversal. Reducing Irish annual CH_4 emissions by a fixed fractional rate of -2.2% per year from 2020 to 2050 would be sufficient to achieve and aggregate reduction of -50% by 2050 (albeit this technically yields an exponential rather than linear decline pathway).

There is a strong link between CH_4 and N_2O emissions in Irish agriculture. The total input of reactive nitrogen (fertiliser and feed) to Ireland to the combined animal agriculture and bioenergy (including grass silage and animal derived feedstocks) is an essential physical driver for N_2O and CH_4 emissions.

- **Recommendation:** The full recommendations of the European Nitrogen Assessment should be applied to ensure more coherent policy toward limiting the total use of reactive nitrogen as far as possible. Modelling of alternative agricultural pathways *within a declining nitrogen budget* should inform all strategic agricultural policy planning. Supply-side limits on total reactive nitrogen (N_r) in fertiliser and feed imports (e.g. returning to the 2011 level as soon as possible and declining at a stated reduction rate from there) could be an effective policy measure to catalyse required changes.

Current policies fail to protect the carbon stocks in land reservoirs adequately. As a result, there are substantial ongoing land use CO_2 emissions from organic soils and peat extraction. The current policy trend is toward supports for sequestration measures through afforestation, increasing soil carbon uptake and rewetting. However, such measures are relatively slow in effect and often subject to large uncertainty compared to the more definite benefit of protecting *existing* land carbon stocks. Carbon pricing mechanisms used in modelling or policy should reflect the reality that land carbon storage should be heavily discounted for non-permanence (Kim et al. 2008) compared to reservoirs of unextracted fossil carbon. Aiming to reach net zero annual LULUCF emissions as soon as possible and enabling net negative land use CO_2 emissions (net CO_2 removals) from then on could nonetheless contribute significantly in society-wide policy to meet any Paris-aligned NCQ* constraint.

- **Recommendation:** In addition to early and deep reductions in aggregate fossil fuel use and cement production, CO_2 emissions 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 harvest (subject to careful assessment of downstream implications, including interactions with 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, due to the costs of proving sequestration (effective independent monitoring and verification), and vulnerability to re-release; 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 equilibrium assumptions of mainstream neoclassical economics. However, the literature, particularly as distilled by Hendry (2018), provides compelling evidence that these assumptions are deeply problematic and exhibit repeated forecast failure at structural location shifts in historic timeseries. These flaws severely limit the policy-relevance of their projected notional costs for technology and fuels. Simulation modelling, by contrast, can incorporate non-equilibrium dynamics, and incorporate system feedbacks to assess or contain rebound effects. Simulation models can be based on known biophysical *quantities* relating to societal energy and food inputs (fossil carbon and reactive nitrogen) and pollution outputs (carbon and air pollution budgets) rather than notional *costs*. If sufficiently skilful, such simulation modelling can provide insights that complement and question existing economic and energy-emissions modelling.

- **Recommendation:** Neoclassical equilibrium modelling (including the ESRI's DSGE economic models and the Irish TIMES energy system modelling) appears to have significant intrinsic limitations in relation to informing rapid, large scale, society-wide, transformation. It would be helpful for such limitations to be made more explicit to users, stakeholders and wider society. 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 potentially enable wider and deeper societal engagement. The recent EU-funded MEDEAS project (Capellán-Pérez et al. 2017) 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 now severely constrained. Both transition costs and climate damage costs are increasing, while required mitigation and/or CDR rates (for any given global temperature goal) are increasing non-linearly. These factors will affect the global and local outcomes of Irish efforts to achieve the sustainability aims of the Sustainable Development Goals and the Paris Agreement temperature goals. Existing research and policies appear not to foreground such established, society-wide aims and goals; and tend to focus relatively narrowly on a continued preference for economic growth. While this objective falls within the suite of SDGs, its role is highly contested, and an excessive emphasis on it may well be incompatible with achieving other SDGs.

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

In the literature, current policy recommendations for energy system scenarios under effective climate mitigation widely agree on three main transition drivers – maximising energy efficiency, increasing low carbon share of electricity and 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 sources, including nuclear, biomass, and variable renewables (wind and solar) combined with large-scale storage of this energy via hydrogen and other synthetic chemical fuels. The literature also differs on the timing, required scale and duration of CCS and NETs. The literature generally agrees that decarbonising existing electricity generation as fast as possible is essential to decarbonising other sectors. Separately, there is also wide agreement that dietary change away from animal-based food is likely to be crucial both to adequately feed a higher global population and to limit GHG emissions from soils, manure and ruminants.

- **Recommendation:** Scenario planning for effective climate action should aim to anticipate and avoid costly surprises by setting out a set of scenarios to examine radical changes, including societal impacts from possible deep decarbonisation measures (e.g. reduction in total energy availability, dietary change, limits on non-essential activities), and impacts from possible compound climate damages.

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 reactive nitrogen, but have been largely ineffective to date. In the absence of stated and enforced declining limits on fossil carbon and reactive nitrogen inputs, it is not clear how such measures can add up to a Paris-aligned pathway. Current policy-based emission projections indicate they will not.

- **Recommendations:** Supply-side measures – directly regulating system inputs quantities of carbon and nitrogen into the EU or Ireland –should be more fully considered by decision-makers and advisory bodies as they 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 model proved useful in comparing national scenarios by diverse long- and short- lived GHGs, both separately and in aggregate. Possible future enhancements could enable 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-sector, as well as global analysis. Developing open data and open, lower complexity modelling is likely to be more transparent for wider understanding and more amenable to rapid adjustment to react to changing circumstances. The model can also facilitate further research on differentiated national responsibility for accumulated climate forcing, especially in relation to SLCFs, specifically CH_4.

Climate mitigation policy to limit CO_2 emissions from energy, cement and land use to date has generally failed to fully or effectively follow past "policy-relevant" modelling recommendations. *Ex post* research could investigate reasons for this failure, and could critically examine the policy relevance of scenarios and their use in effective policy. Similarly, significant progress toward climate mitigation has been recently reversed in agriculture as a result of policy changes from 2010. Again more research such as Kenny (2018) could establish the drivers for such mitigation failure.

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 reactive nitrogen into the economy at both national and EU levels. However, this raises substantive questions in relation to 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, given the urgency of early and deep emissions reductions to constrain cumulative emissions within a Paris-Agreement aligned cumulative emissions budget, while minimising reliance on negative emissions from relatively speculative and uncertain future deployment of CDR, research will also need to deliver evidence-based insights more quickly, to better inform the large-scale changes likely to be needed in energy system and land use policies. Due to delayed mitigation action to date, research and governance will need to look at how to limit the disruptive effects of a fundamental restructuring of society likely needed to enable radical mitigation and adaptation, and to deliver on climate justice commitments. Research will now need to match the pace of the rapid, large-scale, transformational changes likely to be needed in society. The recent COVID19 research response and rate of policy reaction shows what can be done when an emergency is treated as such. We conclude that a further, ongoing, national, large scale, multidisciplinary research effort is indeed warranted to assist the public, political leaders, government and business decision-makers to enable society-wide achievement of effective climate change mitigation.

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Abbreviations

AR	Afforestation and Reafforestation. A NET whereby the total carbon stock of Forestland (as per UNFCCC 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 AR may not increase national forest carbon stock if harvest cancels or exceeds AR.
AR5	IPCC Fifth Assessment Report (https://www.ipcc.ch/assessment-report/ar5/). Composed of three working group reports and a synthesis report, published between March 2013 and October 2014, with additional summaries for policymakers (SPMs) agreed by governments.
BAU	Business-As-Usual. Commonly used to refer to a reference scenario of continuing socioeconomic processes in the absence of new policy interventions.
BC	Biochar. A NET competing for the same indigenous bioenergy fuel land resource as AR and BECCS.
BC	Black carbon: fine carbon soot pollutant particles that act as a warming very short-lifetime climate pollutant.
BE	Bioenergy fuel or unabated (non-CCS) bioenergy use.
BECCS	Bioenergy with Carbon Capture and Storage, usually describing point-source CO_2 abatement at power stations fuelled by biomass or biogas combustion with on-site CO_2 capture from the flue gases, followed by transport by pipeline or ship for injection into geologically secure storage.
CAP19	2019 Climate Action Plan. Ireland's current climate plan (DCCAE 2019).
CCA	Carbon Commitment Analysis, charting the projected pathway of cumulative CO_2 emissions (net and gross) for an energy-cement-land-use scenario
CCAC	Climate Change Advisory Committee, an expert advisory group set up under Ireland's Climate Action and Low Carbon Development Act (2015).
CCS	Carbon Capture and Storage. Methods that achieve capture of CO_2 from flue gases or from the atmosphere, followed by transportation by pipeline and then injection into geologically secure storage.
CDM	Clean Development Mechanism. The largest system of carbon emissions trading defined by the Kyoto Protocol, aiming to enable global mitigation at lower cost.
CDR	Carbon Dioxide Removal. Planned and managed removal of CO_2, using negative emissions technologies, from the atmosphere into land, ocean or geo-storage (via CCS technologies).
CH_4	Methane, a potent greenhouse gas. Classified as a short-lived climate pollutant, it's warming effect depends importantly on the total ongoing flow of emissions. A permanent increase in CH_4 emissions substantially increases net forcing; conversely a sustained decrease in CH_4 emissions substantially reduces net forcing, thus having an equivalent effect to achieving negative emissions (removal) of CO_2.
CO_2	Carbon dioxide, the single most significant anthropogenic greenhouse gas. It is a very long-lived climate pollutant, targeted by climate mitigation policy affecting energy and land use.

CO_2-eq	Carbon dioxide equivalent. Used to aggregate non-CO_2 (including methane and nitrous oxide) with CO_2 in emissions totals. GWP_{100} is the standard GHG equivalence metric used as a scalar factor multiplied by the tonnes of the GHG emitted.
CO_2-we	Carbon dioxide warming-equivalent, derived from annual CO_2-eq emissions via the GWP* metric formula for SLCFs such as CH_4 to enable aggregation into cumulative emissions proportional to its global warming contribution.
DACCS	Direct Air Carbon Capture and Storage (also termed DAC). A negative emissions technology (NET) whereby large volumes of ambient air (with very low CO_2 concentration) are moved through chemical collectors to absorb CO_2, which is then concentrated and transported for injection into geologically secure storage.
DAFM	Department of Agriculture, Food and the Marine (Ireland).
DCCAE	Department of Communication, Climate Action and Environment (Ireland).
DECLG	Department of Environment, Community and Local Government (Ireland), now DCCAE.
DECC	Department of Energy and Climate Change (UK).
DPER	Department of Public Expenditure and Reform (Ireland).
EU	European Union.
EW	Enhanced Weathering. A negative emissions technology (NET) whereby ultrabasic or basic rock is mined and powdered (requiring large energy input), transported to be diffusely spread over large areas of land so that CO_2 is absorbed from ambient air to produce mineralised carbonates.
FFI	Fossil Fuel and Industry sources of GHGs, primarily CO_2 from unabated fossil fuel combustion, and from non-energy CO_2 associated with cement and steel production.
FFI CCS	The application of CCS (Carbon Capture and Storage) to substantially reduce emissions of CO_2 from fossil fuel energy sources and/or relevant non-energy industrial processes (such as cement manufacture). Most commonly refers to a fossil fuel (coal or gas) burning power station with CCS abatement of CO_2 emissions.
GHG	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").
GGR	Greenhouse Gas removal: a process of system that removes some greenhouse gas from atmosphere (and either consigning it directly to long term storage, or transforming it to some stable, benign, form). Generally synonymous with negative emission technology (NET) and carbon dioxide removal (CDR).
HighGCB_Pop	A national carbon quota defined by McMullin *et al.* (2019a), based on a *high-end* estimate of the global carbon budget and shared on a (minimally) equitable equal-per-capita basis (as of 2015).
IAM	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.
IPCC	Intergovernmental Panel on Climate Change.
LCA	Life Cycle Analysis.

LowGCB_Pop	A national carbon quota defined by McMullin *et al.* (2019a), 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).
MidGCB_Pop	A national carbon quota defined by McMullin *et al.* (2019a), based on a *mid-range* estimate of the global carbon budget and shared on a (minimally) equitable equal-per-capita basis (as of 2015).
MS	Member State of the EU
NCQ	National Carbon Quota defined by McMullin *et al.* (2019a) as a "fair share" national allocation of the global carbon budget for a defined temperature target on the basis of some defined "equitable sharing" method, such as *population*, meaning equal per capita sharing.
Net emissions	For GHGs, describes total emissions to atmosphere minus total removals from atmosphere to long term storage (sequestration).
NECP	National Energy and Climate Plan, produced by EU member states toward aggregate EU climate action planning and governance (European Parliament 2018).
NETs	Negative Emissions Technologies. Methods that on a lifecycle basis achieve greenhouse gas removal (GGR), or, more specifically, carbon dioxide removal (CDR), from the atmosphere within some specified collection of processes (system boundary).
NMP	National Mitigation Plan (Ireland) (DCCAE 2017). Produced on a statutory basis under the terms of the Climate Action and Low Carbon Development Act, 2015, based on the National Policy Position (NPP).
NPP	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 NMP (DECLG 2014).
Non-ETS	Non-traded national domestic emissions (transport, agriculture and buildings), with member state mitigation targets agreed under the EU Effort Sharing Directive. For Ireland, the 2020 target is a 20% reduction relative to 1990.
N_r	Reactive nitrogen, used in agriculture, primarily via synthetic fertiliser, for uptake by plants, increasing productivity and essential for protein synthesis.
NUE	Nutrient use efficiency, a measure of the amount of nutrient (such as nitrogen) contained in outputs (at farm gate or in final food a) relative to the system nutrient input.
N_2O	Nitrous oxide, a potent greenhouse gas. Classified with CO_2 as a long-lived climate pollutant. It has a GWP_{100} of 265. N_2O is particularly related to the use of nitrogen fertiliser in agriculture and bioenergy production, giving rise to emissions from soil and from animal manure.
PA	The Paris Climate Agreement (UNFCCC 2015).
Pathway	The timeseries *outputs* from an energy system model, particularly as shown over the full period of decarbonisation transition, for example showing primary energy or GHG emissions/removals on an annual or cumulative basis.
P2M	Power to Methane. VRE excess energy going into production of synthetic methane.
P2X	Power to fuel technologies. Chemical fuels (denoted by X) produced from "power" (electricity), for purposes of very large scale energy storage (to buffer interseasonal

	intermittency of variable renewable soures) and/or for 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, methane, 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).
PBA	Place-based approaches to mitigation and adaptation.
Scenario	A *input* set of data and narrative parameters into a socio-economic system with energy-emissions as outputs from a simulation model; may include timeseries inputs over a proposed decarbonisation transition.
Scenario step	A major change point in time in a scenario at which some significant input parameters change.
Scenario stage	The period between two specified steps in a scenario.
SCS	Soil Carbon Sequestration. A NET whereby soil carbon content is intentionally increased over time, although the sequestration rate will reach saturation within decades and this type of carbon storage is always vulnerable to re-release.
SD	System dynamics modelling.
SEAI	Sustainable Energy Authority of Ireland.
SPM	Summary for Policymakers, particularly the SPMs from the IPCC Assessment Reports.
SR15	The IPCC Special Report on Global Warming of 1.5°C (Masson-Delmotte et al. 2018).
tCH_4	Metric tonnes (1000 kg) of methane.
tCO_2	Metric tonnes (1000 kg) of carbon dioxide.
tC	Metric tonnes (1000 kg) of carbon. 1 tC corresponds to 3.67 tCO_2 on combustion.
tN_2O	Metric tonnes (1000 kg) of nitrous oxide.
VRE	Variable Renewable Energy: energy from sources that are intrinsically variable in time, predominantly solar and wind, but also including wave, tidal, etc.

Appendix: Using the GHG-WE scenario tool (v.1)

The GHG-WE tool is an Excel spreadsheet made freely available for public use[14] to enable coarse-grained comparison of alternative society-wide or sectoral climate mitigation scenarios. As is typical of climate policy and advisory analysis the tool is used to create 'piece-wise' linear pathways, in this case meaning a series of up to three linear segments for a time period from the previous period up to an end date. Based on alternative illustrative mitigation pathways developed from a scenario narrative, the user sets out scenario annual emission pathways for each major greenhouse gas (net CO_2, N_2O and CH_4) for each emission pathway segment. From these inputs the tool calculates the annual and cumulative aggregated CO_2 warming-equivalent (in MtCO_2-we). The cumulative CO_2-we value indicates the global warming-equivalent contribution of the scenario, which can be compared with other scenarios and with an estimate of a nation's minimally equitable 'fair share' of the remaining global GHG budget based on the IPCC SR15 scenario assessment.

SSECCM *GHG-WE* scenario tool v.1

Input	Input value	Unit
Scenario start year =	2020	GHG data for the year previous to this entered year used as GHG data starting pt
Methane (CH4) GWP100 =	34	none
Nitrous oxide	298	none
Nation of interest	Ireland	none
National population in 2015	4.74	millions
Choose historic CH4 data	PRIMAP	EPA with estimates, or CEDS with estimates or PRIMAP
Basis of all-GHG National Carbon Quota =	50th percentile	
Scenario class in SR15 scenario explorer	Lower 2C	

Scenario from start of year stated 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	2053	2090
		New: % vs. ref. year ➡	*-20%*	*-108%*	*-108%*
	43.9	**Mt/yr**	**35.1**	**-3.5**	**-3.5**
		Change/year in Mt ➡	-0.797	-1.678	0.000
N2O (MtCO2-eq = MtCO2-we)	2020	End year	2030	2040	2060
		New: % vs. ref. year ➡	*-25%*	*-35%*	*-60%*
	6.8	**Mt/yr**	**5.1**	**4.4**	**2.7**
		Change/year in Mt ➡	-0.153	-0.068	-0.084
CH4 CO2-eq	2020	Target year	2030	2040	2060
		New: % vs. ref. year ➡	*-25%*	*-35%*	*-60%*
	19.1	Mt/yr	14.3	12.4	7.6
		Change/year in Mt ➡	-0.433	-0.191	-0.238
CH4 CO2-we	**0.0**	Mt/yr	**-4.4**	**-20.3**	**-16.0**
Total CO2-we	**50.6**	Mt/yr	**35.8**	**2.4**	**-16.8**
Year of Net Zero annual CO2 nett	2051	Year of Net Zero GWP* all-GHG CO2-we			2043
Max. vs Quota MtCO2-we	**150**	Year of Max cumulative GWP* all-GHG CO2-we			2042

Figure A-1: Screenshot of the GHG-WE tool input cells and table.

Figure A-1 shows a screenshot of the tool. User specified inputs cells are coloured green. All other cells in the table are outputs. The scenario start year is currently set at 2020. The AR5 values of GWP_{100}, including carbon cycle feedbacks, are 34 for CH_4 and 298 for N_2O, but other values are used in the literature and can be entered instead. The nation of interest can be set with the national population in 2015, to enable GHG quota allocation based on a nation's share of the remaining global GHG emissions budget from 2015 to 2100 (denoted GCB*). The basis of GCB* is set by choosing the 10th, 50th or 90th percentile of the aggregate GHG cumulative CO_2-we values in 2100 of the "Lower 2C" scenario class (Huppmann et al. 2018a) and this choice is shown on the cumulative CO_2-we output chart. In the main table, the annual emissions in CO_2-eq are entered for net CO_2, N_2O and CH_4 for the year prior to the first linear pathway segment. In the "1st Linear Pathway" column the end year and the percent reduction compared to the start of the initial year is entered for each gas. The same is done for the succeeding "2nd Linear Pathway" and the following "3rd Linear Pathway". The end date of each pathway segment should be later than the previous one. The charts will automatically adjust according to the inputs. Output charts include annual emissions, cumulative emissions and bar charts for cumulative CO_2-we for 2020–2050 and for 2051–2100.

[14] https://zenodo.org/record/3974485

In the Figure A-1 example, policy begins from the start of 2020 using 2019 annual emissions as the starting level for each gas. For net CO_2, the "1st Linear Pathway" segment has been given a 2030 endpoint that is -20% below the 2020 start value; the "2nd Linear Pathway" segment ends in 2053 at - 108% below the starting point (having been experimentally adjusted so that net CO_2 passes through net zero annual emissions in 2050); and the "3rd Linear Pathway" has the same end level as the second pathway segment so the year set does not affect the result. The CH_4 pathways are set as for CO_2, but they cannot be negative. As supplied, N_2O pathways exactly follow the corresponding CH_4 pathway, but this could be changed in the N_2O input cells to enable separately specified pathways for N_2O end year and percent change.

In the inputs, net CO_2 is assumed to represent gross CO_2 *emissions* (from fossil fuel, cement and land use) minus CO_2 *removals* (by land use and to geological or mineral storage), so more detailed analysis prior to or after using this tool is needed to disaggregate the net CO_2 pathway over time. Further development of the tool could show these CO_2 sources and sinks separately.

Users can aim to meet a chosen NCQ* level by a certain date, by adjusting each gas separately. In Ireland, as N_2O and CH_4 are strongly linked through ruminant agriculture and the use of nitrogen fertiliser, each illustrative scenario shown in Chapter 7 is based on using chosen piece-wise linear pathways for both gases.

As presented, the IE-WE tool is intended to be used with the inputs described above. By copying the workbook and with due care based on a knowledge of Excel, recent and projected annual emissions data can be pasted into the source sheet to update the starting year or to include updated or alternative emission projections.

Identifying Pressures

Rapid global warming due to human-caused emissions of greenhouse gases (GHGs) is negatively impacting global climate and ecological systems in the earth's biosphere. Rapid reduction of GHG emissions, aligned with the Paris Agreement goals, will require effective policies to sustain rapid socioeconomic changes while maintaining and supporting societal resilience. Ireland's energy supply is moving away from use of coal and peat, but will need to rapidly move beyond oil and natural gas also. The 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 performance. Agricultural emissions decreased in the 2000s but, since 2010, expansionary policy has greatly increased imports of nitrogen fertiliser and feed inputs, resulting in rapidly rising emissions of nitrous oxide from soils and methane from animals. International aviation and other extra-territorial consumption emissions are projected to grow. Projected Irish population growth substantially increases the required rate of decarbonisation.

Informing Policy

This research assesses international literature to inform effective society-wide climate mitigation policy in Ireland, and provides a preliminary tool to enable coarse-grained policy comparison within Paris Agreement commitments. This requires explicit national 'fair share' cumulative GHG emission budgets, equitably aligned with meeting the Paris temperature goals targets, with very limited reliance on high-risk carbon dioxide removal from 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 anticipate potentially costly surprises. Likely climate damages and cost are 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. Usage 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 effectively complemented by equitable supply-side regulation of imported fossil fuel and reactive nitrogen. Modelling for global climate and overall sustainable development goals could be improved if based on allowable future *quantities* of fossil fuel and reactive nitrogen usage within equitable national budgets, rather than on *notional* costs. The GHG-WE tool, developed by the project and made freely available online, provides preliminary, coarse-grained modelling comparison of alternative national policy scenarios. For effective mitigation, steadily reducing Ireland's relatively high non-CO_2 emissions from agriculture (e.g. by reducing reactive nitrogen usage) could greatly ease otherwise increasingly unfeasible reductions solely in CO_2. Recent policy development in New Zealand, which has a similar population to Ireland, and similarly high agricultural emissions, provides informative guidance for Irish policy development. Protecting existing carbon stocks (in peat and managed forest) should be the strongest priority for near-term mitigation of land-use carbon dioxide emissions.