Assessing Ireland's fair contribution to the global effort to limit global warming to 1.5ºC or well below 2ºC

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Executive Summary

Global warming of ~1.1ºC above pre-industrial has already occurred due to total anthropogenic greenhouse gas (GHG) emissions up to 2020. Clarity in carbon budgeting for national policy planning and assessment is required because neither global nor Ireland's climate action are currently aligned with global carbon budgets to stay within the Paris Agreement (PA) temperature goals of limiting to "well below 2ºC" above pre-industrial and making efforts to limit to 1.5ºC', 'on the basis of equity' and 'best available science. In meeting the PA limits, the developed nations, including Ireland, agreed to lead mitigation efforts "by undertaking economy-wide absolute emission reduction targets". Carbon budgets constrain total future fossil fuel use, cement manufacture and land use, which result in carbon dioxide (CO_2) emissions, but such budgets also critically depend on achieving reductions in non-CO_2 climate pollution, particularly methane (CH_4) and nitrous oxide (N_2O) – gases that are highly relevant to Ireland's emissions profile.

Global temperature will be stabilised only when global CO_2 emissions reach net zero. If a national "fair share" of global climate action aligned with the PA temperature goals is exceeded then, for a period *beyond* reaching net zero emissions nationally, *net negative* societal emissions would be needed to return to the fair share level through urgent additional removal of CO_2 from atmosphere (CDR) and further permanent reductions in the CH_4 annual emissions rate.

Key points underpinning national carbon budgeting:

- Assessment by the IPCC finds that associated with each of the PA temperature limits is a finite *remaining global carbon budget* (rGCB), which is an estimated cumulative total of CO_2 emissions, from a base year, consistent with a stated probability of limiting warming to the temperature constraint, e.g., a 67% chance is often used for "well below 2ºC".
- Bounded estimates of rGCB are possible because global warming is directly and near-linearly related to cumulative CO_2 emissions. rGCB estimates are contingent on specified parallel mitigation of non-CO_2 pollutants that may increase the budget available for CO_2.
- By convention, PA targets and territorial emissions are assessed on the basis of UNFCCC emissions reporting using the GWP_{100} equivalence metric to aggregate the warming from different GHGs. However, this metric fails to account accurately for changes in the annual emissions of methane and F-gases, therefore to show Paris temperature target alignment national assessment of policy options may benefit from using more accurate metrics.
- Using the recently developed GWP* metric, aggregate warming from CO_2 and specific non-CO_2 can be assessed on the basis of cumulative *CO_2 warming equivalent* (CO_2we), denoted as rGCB*. This method internalises the specified non-CO_2 mitigation assumptions into an integrated carbon budget showing resultant temperature contribution across GHGs. Ireland has substantial CH_4 and N_2O emissions, therefore an rGCB* value incorporating these is a useful global basis for national cumulative emissions budgeting.
- Downscaling from an rGCB or rGCB* to a national emissions quota (NCQ or NCQ*) requires a values-based allocation among nations, which falls outside of physical science determination and for which there is no existing international agreement. Nonetheless, even though there is no current PA or other requirement to declare a national quota claim (fair or otherwise), tacit claims on the remaining global budget are already implicit in the

cumulative projected emissions totalled for projected national and EU policy pathways.

- The choice of a base year starting point for cumulative emissions is important as it affects equity: a later year is inherently inequitable in favour of higher emitting nations. As the year of the global agreement on temperature limits, 2015 can be seen as a reasonable year for deriving at least "minimally equitable" NCQ and NCQ* fair share values, which represent *maximum* values for countries with high per capita emissions in 2015.
- For Ireland, peer-reviewed studies to date have used 2015 and a straightforward "equal per capita" rGCB allocation based on the national share of global population in 2015.
- In meeting carbon budgets, "feasibility", like equity,

This review has found increasing literature support for using GHG equivalence metrics that can accurately indicate the aggregate temperature contribution of key GHGs including the substantial effect of CH_4 in the assessment of society-wide policy options to complement standard accounting. On this basis, from a [CO_2+N_2O+CH_4] rGCB* range (derived from IPCC SR15 scenarios as per McMullin and Price (2020a)) and equal per capita rGCB* allocation from 2015, this review finds the following ranges for Ireland's PA-limit fair-share maximum NCQ* from 2015:

1.5ºC low overshoot: 360–490 MtCO_2we [CO_2+N_2O+CH_4]
Well below 2ºC: 540–800 MtCO_2we [CO_2+N_2O+CH_4]

Overshoot of the 1.5ºC [CO_2+N_2O+CH_4] quota is immediately imminent as about 320 MtCO_2we was emitted from 2015 to 2020 and annual 2020 CO_2we emissions are in excess of 40 MtCO_2we per year. To limit overshoot and return to Ireland's he NCQ* level will require early, substantial and sustained reductions in gross emissions of all GHGs, with key potential mitigation contributions from agriculture, forestry and land use, in addition to urgent reductions in fossil fuel and cement gross CO_2 emissions. Early CH_4 reduction *would* serve to limit NCQ* overshoot, and *might* enable reversal of it in the very near term (10-20 years). Active CO_2 *removal* from atmosphere (CDR) will be essential to undo and prevent overshoot in the longer term and to balance minimised residual CO_2 and N_2O emissions.

In PA-aligned national carbon budgeting, adopting a separate CH_4 target, or failing to account for the long-term net negative emissions requirement *beyond* net zero, risks obscuring critical trade-offs between GHGs and sectors in policy assessment. By comparison, as put forward by this review, using a three GHG [CO_2+N_2O+CH_4] CO_2we PA-aligned basis for carbon budgeting is appropriate to Ireland's emission profile, providing an evidence-based method to complement and inform the ongoing parallel use of GWP_{100} CO_2eq in climate action decision-making.

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1. Paris Agreement temperature limits and the remaining Global Carbon Budget

In 1992, under the United Nations Framework Convention on Climate Change (UNFCCC, 1992), nation states agreed to take precautionary measures, commensurate with global climate change risk, to ‘prevent dangerous anthropogenic interference with the climate system’; and developed nations would lead in taking climate action. As agreed by all Parties to the Paris Agreement, PA (UNFCCC, 2015a), this means taking action to hold the human-caused increase in global average temperature to the science-informed risk levels of ‘well below 2°C’ above pre-industrial levels, and ‘pursuing efforts to limit the temperature increase to 1.5°C’. Moreover, the PA states that climate action should be achieved ‘in accordance with best available science’, and, in accord with the established UNFCCC (1992) principle of common but differentiated responsibilities and respective capabilities (CBDR+RC), ‘on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty’ (UNFCCC, 2015a, Article 2(2)).

A crucial finding of climate science is that the global warming response of the climate system in terms of global mean surface temperature rise, is directly and near-linearly related to cumulative total CO_2 emissions (Allen *et al*., 2009; Meinshausen *et al*., 2009), meaning that peak warming due to CO_2 – reached approximately a decade after global net zero CO_2 – is largely insensitive to the exact CO_2 emission pathway over time. This result is confirmed by multiple studies using observations and climate modelling (see Matthews *et al*., 2018). The IPCC Fifth Assessment (AR5, 2013) and SR15 (IPCC, 2018a) reports made clear that this finding means that the globally agreed commitment to the Paris Agreement temperature target implies there is a hard physical limit – a *finite* ‘remaining global carbon budget’ (rGCB) – that can be defined for the remaining atmospheric capacity from a given date as expressed in CO_2-only or all-forcings (including all warming and cooling climate pollutants) terms for a specified probability of restricting global warming to stay within the specified temperature limit (Matthews *et al*., 2018).

Table 1. 1.5ºC, 1.75ºC and 2ºC CO_2-only remaining global carbon budgets for TCRE 67th percentile from IPCC SR15 (2018) and Matthews et al. (2021), adjusted to 2015 base year (shown in boldface).

Source reference	Temperature limit	Chance of budget not exceeding temperature limit	Climate forcing	Source base year	Remaining Global Carbon or GHG Budget	Correction applied to adjust to 2015	Remaining global carbon budget from 2015
	ºC				GtCO2	GtCO2	GtCO2
IPCC SR15 2018 Table 2.2	1.5	67%	CO2-only	2018	420	128	**540**
Matthews et al. 2021	1.5	67%	CO2-only	2020	230	210	**440**
IPCC SR15 2018 Table 2.2	1.75	67%	CO2-only	2018	800	128	**930**
Matthews et al. 2021	1.75	67%	CO2-only	2020	670	210	**880**
IPCC SR15 2018 Table 2.2	2.0	67%	CO2-only	2018	1170	128	**1290**
Matthews et al. 2021	2.0	67%	CO2-only	2020	1110	210	**1320**

The linear ratio between warming and total emissions is called TCRE, the *transient climate response to cumulative emissions of* CO_2, which has been reassessed as about 0.44ºC per 1000 $GtCO_2$ with a 5–95% range of 0.32–0.62ºC per 1000 $GtCO_2$ (Matthews et al., 2021), narrowing the TCRE range for the carbon budgets given in SR15 (Rogelj *et al*., 2018, Table 2.2). TCRE is more policy-relevant to guiding near-term emission reductions in line with PA temperature targets than the long-term equilibrium climate sensitivity (ECS) estimated by climate models (Knutti *et al*., 2017). Table 1 compares the results of IPCC AR5 and the more recent Matthews et al. 2021 (main case) for the TCRE of a 67% chance of the CO_2-only rGCB not exceeding 1.5ºC, 1.75 ºC or 2ºC, adjusted to 2015 as it is important to adjust for the total global CO_2 emissions between the date for which carbon budgets are given and a common reference year used for equitable GCB allocation. These CO_2-only rGCBs depend on assumptions regarding non-CO_2 climate forcing at peak net zero CO_2; in the Matthews et al. "main case" this equates to about 0.28ºC due to non-CO_2, so the Table values correspond to about 1.22ºC of warming from CO_2.

As summarised below, Matthews *et al*. (2020) and Rogelj *et al.* (2021) and others such as Geden and Löschel (2017) provide guidelines and checklists for clear, policy-relevant estimates of rGCBs from a specified base year and fair share national action:

- Estimate remaining carbon budgets for anthropogenic warming only (independent of natural variability) with clarity as to timing and the scope of emissions covered,
- Define rGCBs (for CO_2 related warming only) in relation to a stated ºC target,
- Clearly define the level of risk avoidance e.g., 66% chance of staying below 2ºC,
- Defining a common basis for "preindustrial", 1850–1900 is recommended,
- Ensure the chosen reference surface temperature metric is explicitly stated,
- State an rGCB as total CO_2 emissions up to net-zero *with no overshoot,* that is 'broadly consistent with a desired peak temperature target, rather than scenarios where temperature exceeds the target indefinitely or exceeds (overshoots) and returns to the target in question' (Matthews *et al*., 2020),
- Set out non-CO_2 emissions pathways for each climate pollutant to clarify their temperature contributions, individually and in aggregate up to and beyond peak CO_2 in policy options (Rogelj *et al*., 2019).
- Carbon budget accountability requires that any assumed global or national dependence on overshoot needs to provide clear constraints on the magnitude and duration of negative emissions required before and following net zero, and to assess the risks and include the full costs involved as a result (Geden and Löschel, 2017).

As these authors discuss, and as described in Section 4 below, in allocating national fair shares of an rGCB it is very important to set out the principles being applied in carbon budgeting, to use a common rGCB reference base year and a defined equitable allocation basis for all nations.

2. Ireland's current starting point for fair share climate action

Ireland has ratified the Paris Agreement (PA) as a Party to the UNFCCC and, separately, as a Member State of the EU. Under Ireland's existing climate act, national climate action in law and policy is supplemental and subsidiary to achieving early and equitable climate action in the overall context of PA and EU obligations (Oireachtas, 2015, Section 2). A national carbon quota (NCQ) of emissions can be estimated as a guiding fair-share of the global carbon budget of emissions associated with the respective PA temperature limits 1.5ºC and well below 2ºC. For Ireland, a low carbon transition equitably aligned with the PA temperature limits would require achieving net zero annual CO_2 emissions from energy, industry, and land use, likely before 2050, as well as substantial early and deep reductions in non-CO_2 emissions, particularly CH_4 and N_2O from agriculture (McMullin et al., 2020a; McMullin and Price, 2020a). Depending on the timing and effectiveness of these actions, more or less gross removals of CO_2 from atmosphere may be needed in addition, to achieve *net negative* CO_2 emissions over a sustained period and thus, reverse overshoot of the NCQ (McMullin and Price, 2019; Glynn *et al*., 2018).

Based on the currently used GWP_{100} values for comparing emission rates of different GHGs, provisional 2019 total national emissions, excluding land use, were 59.9 $MtCO_2eq$. The 2019 sectoral distribution of national emissions comprised: 35% agriculture, 20% transport, 16% "energy" [this is primarily electricity generation], 11% residential heat, 8% manufacturing, 3.8% industrial processes including cement manufacture, 3% commercial and public services 1.8% F-gases; and 1.5% waste (EPA, 2020a). At present, international aviation and shipping are not included in national targets though they may be included in the future, as has been recommended in the UK (UK-CCC, 2020a). In addition, LULUCF (Land Use, Land Use Change, and Forestry) CO_2-only emissions are about 3.4 $MtCO_2$/yr averaged over 2015–2019 (EPA, 2020b). Ireland's fair share of the global carbon budget is being annually depleted by each year's emissions total.

In mass-related terms[1], average Irish GHG emissions for 2015–2019 were:

- CO_2, from energy, cement, agriculture and waste, 38.9 $ktCO_2$/yr excluding LULUCF,
- CO_2, from LULUCF 3.38 $MtCO_2$/yr, mostly peaty soil emissions only partially compensated by removals into forest growth and wood products,
- CH_4, 585 $ktCH_4$/yr (93% from agriculture), plus ~17 $ktCH_4$/yr from LULUCF,
- N_2O, 21.6 ktN_2O/yr (93% from agriculture) plus ~1.4 ktN_2O/yr from LULUCF,
- F-gases from industrial use, 1.23 $MtCO_2eq$/yr (EPA, 2020).

This means that Ireland, like other developed nations, is rapidly depleting its remaining per capita 2015 emission budget compared to most developing nations that have much lower per capita emissions. Unlike most other developed nations, which generally show net LULUCF removals, Ireland also has (rising) net LULUCF *emissions*, predominantly due to substantial land use CO_2 emissions – mostly from *Grassland* peaty soils and *Wetland* bogs, that are not balanced by (decreasing) CO_2 removals from Forestland and related transfers to *Harvested Wood Products*. Ireland's substantial LULUCF net emissions cumulatively reduce the carbon budget available for future fossil energy use, cement manufacture and agriculture.

3. Non-CO_2 warming contributions and GHG equivalence metrics in carbon budgeting

For global and national carbon budgeting it is important to include the warming contributions from non-CO_2 climate pollutants as well as CO_2 – this is especially true for Ireland given its substantial profile of CH_4 and N_2O emissions. N_2O is relatively long-lived in the atmosphere, so, even though it is not as long-lived as CO_2, for policy-relevant purposes it can also be considered as a cumulative long-lived climate pollutant or LLCP (Smith *et al.*, 2012). Agriculture is the main global source of N_2O, the IPCC Land Report highlighted the 800% increase in global nitrogen fertiliser usage since 1960 (IPCC-SRCCL, 2019, Fig. 2) and in Ireland nearly all N_2O emissions are from agriculture (EPA, 2020a). Arable tillage farming emits N_2O due to reactive nitrogen (Nr) fertiliser inputs but is much more nitrogen efficient compared to intensive animal agriculture, which similarly emits N_2O through fertiliser-fed growth of grass, silage and animal feed but also again through substantial N_2O from animal excreta (Davidson, 2014, 2009). As cumulative emissions of CO_2 and N_2O both result in a near-linearly related increase in warming the standard GWP_{100} metric used in UNFCCC GHG reporting provides a sufficiently accurate aggregation method to

[1] As submitted by the Environmental Protection Agency on behalf of Ireland, in UNFCCC reporting for years prior to 2021 the non-CO_2 gases are reported as CO_2 equivalent emissions (CO_2eq) by multiplying the mass values by IPCC AR4 GWP_{100} metric factors including: for CH_4 a GWP_{100} of 25, and for N_2O a GWP_{100} of 298. For years from 2021 these values will change to 28 and 265 respectively.

show the warming effect of CO_2 and N_2O in cumulative CO_2eq emissions.

Short-lived climate pollutants (SLCPs) such as CH_4 and hydrofluorocarbons have atmospheric lifetimes of the order of a decade or less, significantly less than CO_2 and N_2O, and some like black carbon and (cooling) sulphates only last a few days (Allen *et al*., 2016). SLCPs do have some long-term *stock* effect due to climate-carbon and ocean feedbacks (Fu *et al*., 2020; Solomon *et al*., 2010) but their impact on temperature change is primarily dependent on changes in their *rate of emission* over time (Allen *et al*., 2018). CH_4 is second to CO_2 as the most important GHG in terms of global forcing (Myhre *et al*., 2013) and is the most important SLCP for climate mitigation in meeting stringent climate targets (Collins *et al*., 2018; Jones *et al*., 2018) due to substantial anthropogenic emissions, primarily from (ruminant and rice) agricultural, fossil and waste sources (Saunois *et al*., 2020).

The relatively simple linear TCRE relationship well describes the very long-lasting warming due to CO_2 (and N_2O) emissions (Archer and Brovkin, 2008). By comparison, the temperature change due to short-lived climate pollutants is more complex and time-related, so non-CO_2 impact on future warming is generally scenario dependent in relation to timing relative to peak CO_2 emissions (Gernaat *et al*., 2015). UNFCCC and PA use of the GWP_{100} metric for administrative reporting of annual emissions is likely to continue, as in the forthcoming PA Global Stocktake in 2023 (UNFCCC, 2020), however, this metric does not accurately represent the temperature change due to SLCPs as it underestimates the impact of recent annual emission rate changes and over-estimates the temperature impact of a constant rate of annual emissions. GWP_{100} is especially inaccurate if permanent reductions in annual emissions are being achieved because GWP_{100} always shows positive CO_2eq values when SLCP emissions are reducing even though such mitigation would actually achieve warming reduction (Allen *et al*., 2016). To account for this SLCP rate of change impact on warming, a new GHG equivalence metric called GWP* has been defined in terms of CO_2 *forcing equivalent emissions*, denoted CO_2fe (Allen *et al*., 2018).

Notably, the use of this GWP* methodology in assessing a forcing equivalent global carbon budget including all CO_2 and non-CO_2 forcings has been confirmed by Mengis and Matthews (2020), showing a linear transient climate response to cumulative CO_2 forcing equivalent emissions (TCRFE) of 0.5ºC/1000 GtCO_2-fe. Particularly focussing on CH_4, GWP* has been further refined as CO_2 *warming equivalent* (CO_2we) to allow for inclusion of CH_4's stock effect, further improving accuracy and enabling the use of CO_2we in integrated "carbon" budgeting that encompasses arbitrary long-lived forcers (especially CO_2 and N_2O) together with CH_4 (Cain et al., 2019; Lynch et al., 2020; Smith et al., 2021). Though the metric has been critiqued as inappropriate for international carbon accounting unless fairness issues are fully considered (Rogelj and Schleussner, 2019; Schleussner *et al*., 2019), this would not necessarily be the case if fair share action were based on an rGCB* analysis (IPCC SR15 Ch. 1, Allen and Dube, 2018) and allocated equitably. Furthermore, the use of GWP* has been shown to be immediately useful in national carbon budgeting analysis to examine trade-offs between gases (McMullin and Price, 2020a) in meeting an NCQ* derived from a PA-relevant rGCB*.

Using national time series of annual emissions reported for SLCPs in GWP_{100} terms, GWP* enables the calculation of *cumulative* CO_2we values for SLCPs that can then be aggregated into carbon budget analysis with CO_2 and N_2O (using the GWP_{100} value for N_2O). Use of the GWP* metric shows that permanently increasing the CH_4 flow of annual emissions by 1 tCH_4/yr equates to a substantial temperature contribution increase, equivalent to a one-off addition of 2900–3300 tCO_2 to the atmosphere; and the reverse is true for a decrease in CH_4 flow, a permanent cut by 1 tCH_4/yr equates to the temperature effect of a one-off *removal* of this amount of CO_2 from the atmosphere. Collins *et al.* (2020) suggest the GWP* metric may underestimate this 'CH_4 flow change to CO_2 step equivalence' by 20% as appears to be confirmed by a recent revision to GWP* (Smith et al., 2021). The SR15 SPM illustrative pathways P1–P4 (IPCC, 2018b, Figs. 3a and 3b) classified as meeting the 1.5ºC goal, assuming similar CO_2 pathways to 2050, show the trade-off in global negative forcing options between CH_4 reduction and carbon dioxide removal (CDR). Toward meeting PA temperature limits, Collins *et al*. (2018) find that early and deep global CH_4 mitigation significantly increases the remaining carbon budget for the total of other climate pollutants, even while maintaining a parallel primary focus on achieving net zero global CO_2, if at all possible without overshoot, is critical (Lynch et al., 2021).

4. Equitable allocation of the Remaining Global Carbon Budget

Under the Paris Agreement (UNFCCC, 2015b) nations have agreed to act equitably in constraining emissions to meet the temperature limits. Given the scientific definition of associated rGCB and rGCB* values it is logical to consider how to allocate these carbon budgets among the UNFCCC Parties in some way equitably, informed by the concept of 'common but differentiated responsibilities and respective capabilities' (CBDR+RC). However, this necessarily involves value judgements that are open to bias and contestation, and that cannot be determined by physical science (Clarke L *et al*. and Jiang, 2014; Meinshausen *et al*., 2015). Initial assessment of nations' own proposed Nationally Determined Contributions (NDCs) under the PA show nations are collectively committing to carbon budgets claims that would substantially breach the temperature goals (Holz *et al*., 2017; Pan *et al*., 2017; Rogelj *et al*., 2016) and this remains the case prior to the 2023 stocktake (UNFCCC, 2021). Many nations' NDCs fail to acknowledge equity or 'consider the consequences of their approach when applied to all countries' (Winkler *et al*., 2018) – though the EU's (Council of the European Union, 2020) has been updated to do so, its "net zero by 2050" ambition does not necessarily equate to equitable achievement of the temperature target unless this is more explicitly defined (McLaren et al., 2019; Rogelj et al., 2021). Nations and other actors also fail to indicate an understanding of the consequences of delay: Lewandowsky *et al*. (2014) show that 'uncertainty compels a stronger, rather than weaker, concern about unabated warming than in the absence of uncertainty', which favours precautionary climate action to 'significantly reduce the risks and impacts of climate change' (PA, Article 2). This concern, due to *deep uncertainty*, requiring consideration of worst-case scenarios of severe and potentially irreversible impacts (Hallegatte *et al*., 2016), can justifiably focus ambition on lower-bound global carbon budgets, based on higher TCRFE range values. Climate policy certainty is impossible given such radical uncertainty, so a precautionary approach is likewise advocated to address climate-related financial risks (Chenet *et al*., 2021).

Multiple effort-sharing alternatives have been proposed and assessed in terms of equity, responsibility (based on past and present emissions) and capacity for action (based on ability to pay) but none has yet been agreed at the global level (Höhne *et al*., 2014). Sharing can be defined in terms of a range between *inertia*, inequitably 'grandfathering' emission allocation according to current global shares (favouring current high per capita emitters) through to (somewhat) more equitable *population*-allocation by equal per capita budgets (Raupach *et al*., 2014; Robiou du Pont *et al*., 2016). However, even equal per capita sharing may still be judged as highly inequitable on the basis of: historic responsibility for past emissions; radically differing national capacity for mitigation action; and time-variant factors such as population or human development rights, including poverty eradication, or "survival" versus "luxury" emissions (Baer, 2013; Kartha *et al*., 2018). In assessing a wide-range of effort-sharing approaches, Van den Berg *et al*. (2019) find that all of the methods examined allocate smaller or much smaller carbon quotas to developed nations compared to quotas estimated by a globally-oriented notionally "cost optimal" model (whereby emission reductions are achieved wherever is notionally cheapest), indicating that global cost-optimal approaches intrinsically *embed* inequity.

The base year for global comparison on national budget allocation matters because moving to a later year gives nations with higher emissions a correspondingly greater share, inequitably "moving the goalposts" by ignoring prior emissions. For example, within a well below 2ºC global carbon budget from 2015, the combined NDCs of only the EU, USA and China leave very limited emissions space for other all countries (Peters *et al*., 2015). This space would be reduced still further if the base year moved to a later year. McMullin et al (2019) define 2015 as the latest base year for "minimally equitable" national carbon budget allocations, as it is the year of PA global consensus when temperature limits to global risk were accepted, and choosing a later year inequitably "grandfathers" emissions in favour of nations with high per capita emissions.

Integrated assessment models (generally assuming indefinitely continued economic growth), as evaluated by IPCC AR5 (Clarke L *et al*. and Jiang, 2014) suggest potentially substantial mitigation requirements for large-scale negative emissions enabled by associated technologies (NETs) to extend gross carbon emission budgets by CDR through land carbon storage or bioenergy with carbon capture and storage (Fuss *et al*., 2018; Luckow *et al*., 2010; Rogelj *et al*., 2018). However, over-reliance on NETs in carbon budgeting may represent an unjust moral hazard (Anderson and Peters, 2016) by risking failure if not delivered at the scale required in models or anticipated by policy (Larkin *et al*., 2017). Assessments indicate that NETs have 'only limited realistic potential to remove carbon from the atmosphere and not at the scale envisaged in some climate scenarios' (EASAC, 2017). Large-scale deployment of land carbon NETs may risk unacceptable ecological and social impacts (Dooley and Kartha, 2017) with highly contested politics and carbon accounting rules (Dooley and Gupta, 2017). Separate national carbon budget accounting and pathway targets are necessary to define NETs timelines, bottlenecks for NETs delivery, duration, and quantities, to avoid distraction from the core climate action requirement for substantial and sustained reductions in gross GHG emissions (Fajardy *et al*., 2019; McLaren *et al*., 2019). Fair burden sharing of modelled global CDR budgets indicate that major emitters have 2–3 times larger responsibility for deployment of CDR compared to notionally cost optimal pathways (Fyson *et al*., 2020). Importantly for accurate carbon budgeting, recent literature is inconsistent in defining "negative emissions" from a process or technology, therefore Tanzer and Ramirez (2019) define key criteria: GHGs must be *physically removed* from the atmosphere (as opposed to gross emissions from some pre-existing process being counterfactually reduced) 'in a manner intended to be permanent'; and, all upstream and downstream GHG emissions associated with the process must be aggregated in the overall balance such that the gross total removed is greater than that emitted. This assessment is obviously especially complex when more than one GHG species is in scope but the balance can be estimated using GWP* CO_2we.

Based on a literature review, a report by Höhne *et al*. (2019) finds that '(t)he EU has essentially already spent its fair share of greenhouse gas emissions and would need to reduce greenhouse gas emissions to zero almost immediately (by 2030 - 2040)' to ensure remaining emissions space for developed nations. Examining the cumulative emissions for the declared policy emission pathways of the UK and Sweden compared to apportioning an rGCB on the basis of CBDR+RC without reliance on global NETs, Anderson *et al*. (2020) find that the fair share carbon budget quotas of the "climate progressive" UK and Sweden are less than half that implied by their proposed climate action policy pathways, indicating a failure to align action equitably with Paris temperature commitments.

5. Defining Ireland's fair contribution "National Carbon Quota" (NCQ or NCQ*) share of the Global Carbon Budget of GHGs

Published analyses for Ireland's fair contribution carbon budget by Glynn *et al*. (2018) and McMullin *et al*. (2019, 2020a) have estimated remaining CO_2-only NCQs for Ireland, primarily using equal per capita rGCB *population* apportionment, based on Ireland's 0.064% share of the 2015 global population, to give NCQs for depletion from 2015. Glynn *et al*. derives a higher-risk, well below 2ºC NCQ value of 766 $MtCO_2$ from 2015 (with adjusted budgets from 2020), and a 1.5ºC NCQ low–high range of 128–223 $MtCO_2$ from 2015. Glynn *et al*. allocate the entirety of these NCQs to energy and cement, suggesting that Ireland's large proportion of agricultural GHG emissions and '(t)he reduced scale of mitigation options in agriculture…places a disproportionately high burden on the energy system to decarbonize relative to other [EU] member states'. It must be noted that, since 2010, dairy output per head and increases in cow numbers have been resulted in *increasing* emissions from the agricultural sector (EPA, 2018, p. 4). Using the *Irish TIMES* notional-cost optimisation model in combination with a decomposition general equilibrium method[2], Glynn *et al*. provides a (notional) least cost assessment of *energy* transition pathways for Ireland within the stated national carbon quotas although finding that 'applying carbon budgets to the energy system results in non-linear CO_2 emissions reductions over time, which contrast with current EU policy targets', and 'none of the 128 $MtCO_2$ [1.5 ºC] scenarios proved technically feasible' (Glynn *et al*., 2018), meaning that no solutions existed within the specified model constraints (including inelastic energy demand premised on exogenously assumed economic growth).

Examining a range of fair share carbon budget contribution for Ireland, McMullin *et al*. (2019) presented three variant cases based on combining, a Low–Mid–High risk range of rGCB values, based on the IPCC SR15 report's values for a 66%–50%–33% chance of staying well below 2ºC (adjusted to 2015), with the Raupach *et al*. (2014) sharing principles, ranging from *population* to *inertia* (see Section 4). This results in an extended CO_2-only NCQ range of 390–1780 $MtCO_2$ from 2015. However, *only* the low end NCQ of 390 $MtCO_2$ from 2015 (66% chance of 2ºC, equal per capita share from 2015) is recommended for policy use by McMullin *et al*., on the basis that this already an absolute maximum for alignment with the Paris Agreement goals. This is due to: this target falling short of 1.5ºC effort; the need for prudence and precaution in the face of existential risk to human society; the omission of aviation and shipping from current national carbon accounting; the assumption of non-CO_2 mitigation that may not materialise; and that an earlier base year or distribution on the basis of responsibility or capacity would be more equitable than simple per capita sharing of a latest possible base year GCB. McMullin *et al*. also note that Ireland has substantial net land use carbon emissions which, if continued, cumulatively reduces the remaining CO_2 emissions budget for energy and industry. Net annual emissions from land use averaged 3.4 $MtCO_2$/yr for 2015–2019 and are projected to reach 7.0 $MtCO_2$/yr by 2035 with cumulative emissions for 2015–2040 of 130 $MtCO_2$ (EPA, 2020c). McMullin and Price (2019, p.26–27 and Fig. 3-6) argue that only very considerable changes in and enforcement of strict land use policies to reduce land carbon losses and increase removals (including limiting peat and timber extraction, rewetting peat soils under *Grasslands* and *Wetlands* and policies enabling permanently forested areas with limited harvest) would enable a scenario where 100% of the

[2] This modelling does depend on exogenous energy demand inputs predicated on neoclassical economics theory expectations of long-term growth and equilibrium correction (Bergin *et al*., 2017; de Bruin and Yakut, 2019) – assumptions that have been strongly critiqued as lacking in forecasting validity (Hendry, 2018; Keen, 2020).

NCQ CO_2 could be allocated to energy and industry. Acting in the near-term to limit forest harvest (currently exceeding past planting rates) could reduce the projected reductions in CO_2 removals due to *Forest land* and *Harvested Wood Products*. Without such radical changes in land use policy a significant fraction of Ireland's NCQ would be used up in land carbon losses, rather than easing energy transition by achieving net LULUCF removals.

In EPA Report 354 for *Society-wide Scenarios for Effective Climate Change Mitigation in Ireland*, McMullin and Price (2020a, see also Technical Report, 2020b) show that Ireland's substantial non-CO_2 emissions, of CH_4 and N_2O strongly influence the aggregate CO_2we temperature contribution pathway in societal mitigation scenarios. Illustrative scenarios examine the trade-offs between GHGs, available to Ireland in meeting a fair-share PA-aligned carbon budget as soon as possible and with minimal national level overshoot. Analysing the IPCC SR15 pathway database (Huppmann *et al*., 2018) for the *1.5C lowOS* [reaching 1.5ºC after minimal overshoot] and *Lower 2C* scenario sets, the GWP* methodology (see Section 3) was used to estimate the 10th–50th–90th percentiles of cumulative *global* CO_2we (for CO_2+N_2O+CH_4) to peak warming. The 10^{th}–90^{th} percentile range can then be described as a GCB* range estimate for each PA temperature limit. From a GCB* range an NCQ* range can be derived using the minimally equitable (from 2015) equal per capita allocation per McMullin *et al*. (2019). By this method of McMullin and Price (2020a) estimates Ireland's fair-share carbon budget contribution from 2015 to meet the PA limits (rounded to the nearest 10 MtCO_2we) as[3]:

- 1.5ºC low overshoot: NCQ* = 360–490 MtCO_2we [CO_2+N_2O+CH_4],
  - based on a GCB* [CO_2+N_2O+CH_4] peak range of 560–770 GtCO_2.
- Well below 2ºC: NCQ*= 540–800 MtCO_2we [CO_2+N_2O+CH_4] MtCO_2we
  - based on a GCB* [CO_2+N_2O+CH_4] peak range of 840–1250 GtCO_2

To demonstrate the scope of mitigation policy alternatives, the report describes illustrative GHG scenarios by gas for 2015–2100 with mitigation beginning from 2020 aiming to meet a well below 2ºC 540 MtCO_2 NCQ* no later than 2100, aligned with the low peak GCB*. Charts (McMullin and Price, 2020b, Figs. 7.1–7.6) show annual and cumulative CO_2we emissions of net CO_2, N_2O and CH_4. (For net CO_2 no particular mix of gross CO_2 emissions or removals is assumed or given.) Both GWP_{100} CO_2eq and GWP* CO_2we values are charted for CH_4 and aggregate GHGs. A *FLAT* no-mitigation scenario, maintaining current annual emissions of each gas to 2100, results in rapidly escalating NCQ* overshoot. All scenarios, including aggressive mitigation of all gases, overshoot the NCQ* by 2028. Only scenarios with net CO_2 becoming net negative by 2050 with *at least* a 50% mass flow reduction in CH_4 and N_2O plausibly satisfy the NCQ* requirement while limiting net CDR requirement close to, or under the prudential upper policy limit on Ireland's achievable cumulative CDR up to 2100 of 200 MtCO_2 proposed by McMullin *et al*. (2020a).

This preliminary research showed it is possible to estimate a GCB* that can then be downscaled to a minimally equitable NCQ* relevant to Ireland's emissions profile of significant N_2O and CH_4 as well as CO_2. Compared to typical carbon budgeting based on CO_2-only or CO_2eq this study showed the superiority of GWP* policy analysis for national mitigation scenario comparison in meeting a PA constraint. Given Ireland's large fraction of N_2O+CH_4 emissions and the wide

[3] Particularly for 1.5 ºC SR15 database scenarios, the low end of these peak ranges is likely to be higher than the temperature target GCB* as many scenarios have substantial negative emissions after the peak and through to 2100 to cancel out cumulative budget overshoot by 2100. Based on 2100 cumulative GCB* values the lower Ireland NCQ* ranges found were: for 1.5 ºC, 20–260 MtCO2we; for well below 2 ºC, 440–750 MtCO2we.

variation in their combined cumulative CO_2we contribution among the range of possible aggregate GHG pathways, adopting a CO_2-only carbon budget framework would make policy and societal trade-offs between major sectoral action opaque at the very least. The study also clearly shows that a GWP_{100} CO_2eq cumulative budgeting framework would be highly misleading for policy analysis for any country with significant CH_4 emissions. Therefore, as it is anchored in the underlying climate physics relating to the temperature target (Collins *et al*., 2018), the use of cumulative GWP* CO_2we, where the scope is CO_2+N_2O+CH_4, can be recommended for use in a national cumulative budget framework as a notable improvement on the current UK's Sixth Carbon budget process (UK-CCC, 2020b), the current EU ESR/ESD process, or Kyoto reporting.

Mengis and Matthews (2020) confirm that:

> *'the framework introduced by Allen* et al*. (2018) holds, and that we need to account explicitly for the non-CO_2 climate forcing to obtain an accurate estimate for the carbon budget for peak warming or climate stabilisation.'*

As Mengis and Matthews show, the reduction in fossil fuel cooling aerosols related to global fossil fuel phase-out in stringent mitigation scenarios results in a decrease in the fraction of the remaining carbon budget for non-fossil fuel and industry emissions. A focus on the main GHGs in a [CO_2+N_2O+CH_4] cumulative CO_2we budget framework is therefore warranted because the *scale* of what would be falling outside that would now be comparatively small, though there may be a need for *some* later parallel treatment of other forcers (setting separate, potentially case-by-case, targets, not using the device of a cumulative budget). Therefore, there is no scientific reason to delay the immediate deployment in Ireland of a *national* carbon budgeting framework on a [CO_2+N_2O+CH_4] basis within a context of a PA-aligned NCQ*.

A working paper (Price and McMullin, 2020) looks at Irish agricultural CH_4, comparing a mitigation scenario with the actual path of increasing CH_4 to 2020, again illustrating the usefulness of GWP* in policy analysis of alternative scenarios. The paper also identifies unresolved issues in GWP* conventions and usage relating to the 20-year lag in temperature contribution effect of CH_4 emission changes and shows that use of the GWP* CH_4 equivalence to a one-off subtraction of CO_2 indicates the substantial full technical CH_4 mitigation opportunity that can be compared to CDR negative forcing options in policy cost-effectiveness. Unlike Glynn *et al*. (2018) the article and research reports by McMullin *et al*. do not attempt a notional cost-effectiveness analysis, rather focusing on clarifying the by-gas GHG trade-offs meeting the targets – the PA-aligned NCQ and NCQ* estimates that near-term policies need to address in order to show cost-effective alignment (Price *et al*., 2018) [4].

Relevant to CH_4 and its carbon budget impact, as one of a list of matters the Minister and the Government shall have regard to, the published draft revision to the Climate Act included:

> *3(3)(y) 'the distinct characteristics of biogenic CH_4 referred to in the Special Report on Global Warming published by the Intergovernmental Panel on Climate Change on 8 October 2018.' (Government of Ireland, 2020)*

This framing is problematic for three reasons: first, it risks misrepresentation by failing to clarify that *all* anthropogenic CH_4 adds to warming and is subject to climate reporting, whether the carbon in it is derived from fossil fuel or cement manufacture, or from biogenic sources in agriculture; second, the SR15 report does not mention "biogenic" CH_4 at all or note any distinction

[4] Only policy pathways aligned with meeting an acknowledged policy goal, such as the PA temperature targets, can be included in cost-effective analysis. By economic definition, a diverging policy not aligned with the policy target is not cost-effective (DPER, 2012; Ackerman *et al*., 2009, p. 312; Price *et al*., 2018, Section 4.2.3).

from fossil CH_4; and, third, the GWP_{100} values of biogenic CH_4 are only marginally less than for fossil CH_4 (moreover, for both, their updated scientific values are higher than the out-of-date values used in the politically agreed UNFCCC reporting)[5]. No matter what, the final Act's wording states, in PA-aligned climate action the non-CO_2 gases must still *somehow* articulate with the national carbon budget for any agreed PA temperature target. Whether directly or indirectly, GWP* is recommended for derivation of an appropriate NCQ* and to enable aggregation of [CO_2+N_2O+CH_4] into cumulative CO_2we to examine alternative national policy pathway options.

A CCAC (2019) *Carbon Budgeting Background Paper* sets out the options for a legislated long-term goal as: (1) Legislate the existing National Policy Position (noting that carbon neutrality is not yet defined); (2) Net Zero GHG emissions by 2050 (noting that non-CO_2 mass emissions do not go to zero in IPCC illustrative pathways); or (3) reduce all GHGs except biogenic CH_4 to net zero by 2050 and reduce biogenic CH_4 emissions by a quantified amount as has been legislated for and stated in policy in New Zealand. However, based on the GWP* method using by-gas and aggregate cumulative CO_2we (Lynch *et al.*, 2020), the use of GWP* illustrated by McMullin and Price (2020a) shows that a fourth option is possible and is the only one that can be robustly aligned with a fair share contribution to meeting the overarching Paris temperature goals through temperature contribution, through the mechanism of adopting a target NCQ* together with a date by which net cumulative GWP* emissions must balance out relative to that goal.

6. Relating a Rolling Carbon Budget programme to Ireland's NCQ or NCQ*

Echoing established practice in the UK and elsewhere, Ireland's Programme for Government, PfG (Fianna Fail *et al.*, 2020) and draft amended Climate Act (Government of Ireland, 2020) set out the principle of a rolling carbon budget programme of three sequential 5-year carbon budgets with the fourth period carbon budget being issued at least 12 months prior to the expiry of the first. MaREI (2020) have analysed the feasibility of the PfG pathways. The PfG commits to 'an average 7% per annum reduction in overall greenhouse gas emissions from 2021 to 2030 (a 51% reduction over the decade) and to achieving net zero emissions by 2050.' However, aligning *cumulative* (rather than point-in-time) emissions with PA or other targets is the crucial test of climate action effectiveness (Matthews *et al.*, 2018; Millar *et al.*, 2016). Following the current de facto EU policy basis of linear CO_2eq (GWP_{100}) pathways within cumulative time period limits, a policy advisory (McMullin *et al.*, 2020b) therefore, notes that 'average 7% per annum reduction' and '51% reduction over the decade' are *not* equivalent or interchangeable targets when considered in cumulative terms. Rather, the only scientifically well-founded meaning of the PfG phrasing is that 'the maximum allowed cumulative emissions ("carbon budget") over the full period must correspond to that of a constant 7% per annum pathway', meaning that any carbon budget shortfall in the first 5 years would result in substantial change in the required 2030 point-in-time target – for example, to meet the same 10-year carbon budget as implied by a target 7%/yr reduction pathway to 2030, but actually achieving say only a 3%/yr annual emissions reduction up to 2025 would then require a very steep pathway in the second 5-year period to

[5] It is important to note that focussing on the short-lived atmospheric effect of a single pulse or year's emissions of CH_4 (with a half-life of about a decade) can be highly misleading because it is the ongoing *flow* of CH_4 from sources, such as total livestock output, that sustains the related CH_4 temperature contribution at about 25 times that of a single year's pulse and, moreover, changes in CH_4 annual emissions flow take 40 years to have their full effect (Allen *et al.*, 2016, Fig. 2e.).

reach an 83% point-in-time aggregate reduction by 2030 relative to 2020.

In any case, as per Section 5, the use of GWP* CO_2we for [CO_2+N_2O+CH_4], rather than CO_2-only or GWP_{100} CO_2eq, is recommended as the better-founded basis for a national carbon budget framework. Near term (15-year) budgets should be formulated within the context of an explicit long term *finite cumulative budget limit* (here termed **NCQ***), where overshoot ("cumulative budget deficit"), if any, must be fully reversed by a specified date. This adoption of a concrete NCQ* limit should be informed by the PA obligation to make an equitable and prudential contribution to meeting the global temperature goals. "Equity" should be considered with multiple related scopes: within the state, at EU level, globally and, perhaps most critically, *inter-generationally* (Howarth and Norgaard, 1992; Shue, 2018). The adoption and ongoing review of this long-term limit could ideally be the subject of wide societal participation and consensus-building (Markkanen and Anger-Kraavi, 2019). Whatever framework is used, carbon budgeting effort will need to be partitioned between the initial 15-year period and beyond, noting the importance of early and deep reductions in gross GHG emissions, given the imminence of overshoot of plausible long term NCQ* limits. Delaying deep mitigation is narrowing options for effective action to enable climate resilience (see IPCC WGII SPM, Fig. SPM.9 in Field et al., 2014), thereby increasing expected societal costs (den Elzen et al., 2010; Luderer et al., 2013; Winning et al., 2019).

To give an illustrative example, Figure 1 shows 5-year carbon budgets for 2016 to 2100 for an emissions scenario shown in Figure 2. This scenario is aligned with an NCQ* of 540 $MtCO_2$we from 2015 with active mitigation from 2021 onward. In this scenario, *net zero* CO_2we, stabilising Ireland's warming contribution, occurs in 2037, with a peak NCQ* overshoot of 550 $MtCO_2$we. Reversing this overshoot takes until net zero in 2065 at the NCQ* level through a succession of net negative aggregate CO_2we 5-year budgets. The five-year CH_4 CO_2we budgets become negative from 2031 to 2070, meaning net negative agricultural sector CO_2we emissions delivering more than -100 $MtCO_2$we warming reduction for each of the four 5-year budgets from 2036–2055 – nonetheless, by mass and as measured by CO_2eq the sector's emissions are still net positive though reduced by 50% by 2050 relative to 2020. As shown in Figure 2 by the lines for cumulative totals, a CO_2we carbon budget framework (solid red line), confined to [CO_2+N_2O+CH_4], gives meaningful carbon budget information in a PA-aligned context for Ireland, whereas CO_2-only (black) or CO_2eq (dashed red) carbon budget frameworks would not.

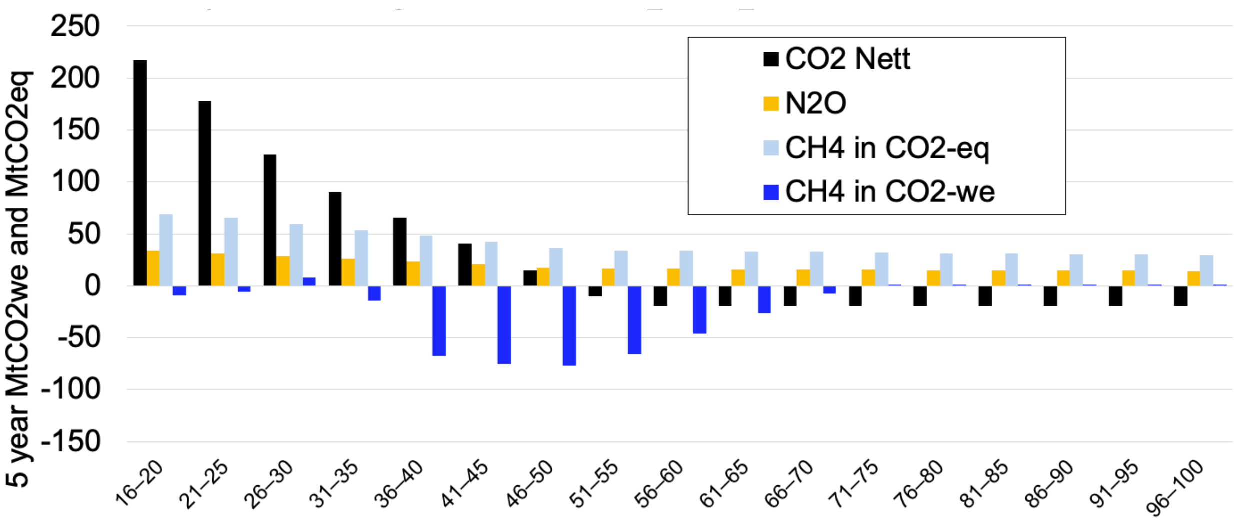

Figure 1. Example 5-year carbon budgets for 2016 to 2100 for one illustrative scenario shown in

Lower 2C	Low-GCB*-Pop	540 MtCO2we
Overshoot of NCQ* MtCO2we	Cumulative CDR to 2100 MtCO2	Annual net CDR stable MtCO2/yr
235	-187	-3.9

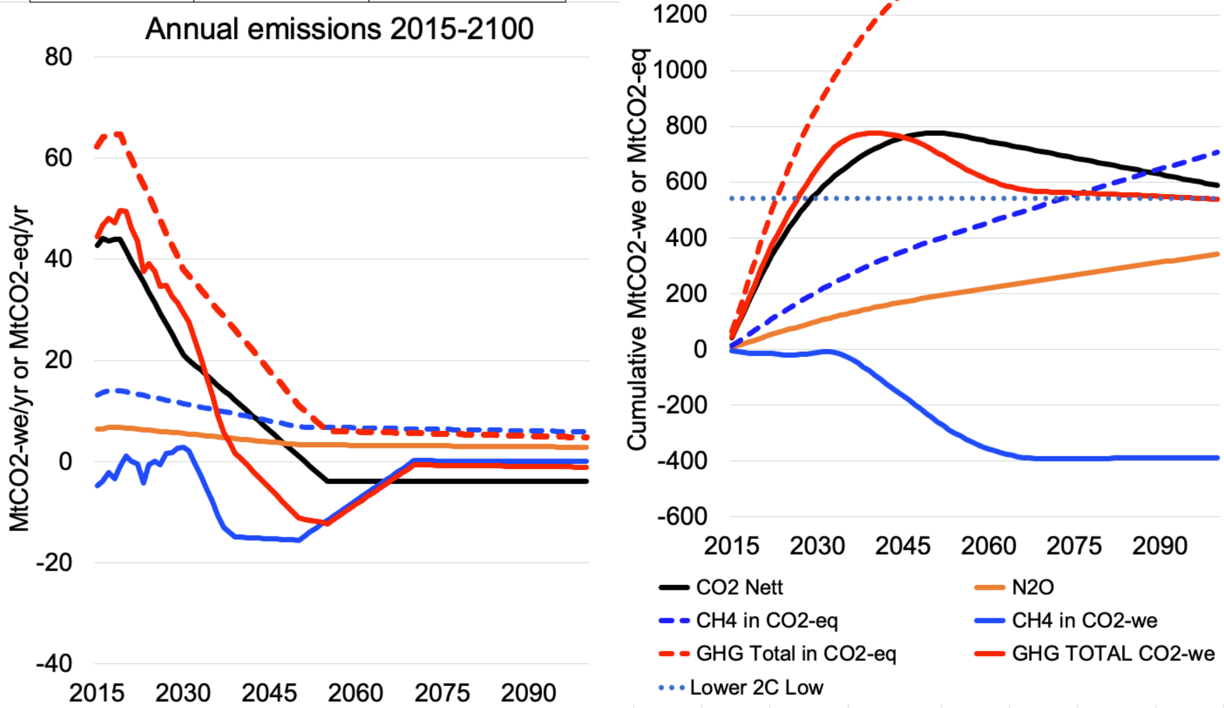

Figure 2. Example illustrative scenario, with the aggregate and by-gas pathways as for 5-year budgets in Figure 1, meeting NCQ carbon budget from 2015 of 540 $MtCO_2we$ with mitigation from 2021 onward. CH_4 and N_2O mass emissions are cut by 50% by 2050 relative to 2020. Net CO_2 emissions including LULUCF cut by 51% to 2030, then to net zero by 2050 with net negative CO_2 thereafter. Aggregate CO_2we (solid red) overshoots NCQ* to net zero annual CO_2we in 2037 before returning to NCQ* net zero by about 2065.*

Conclusion

National carbon budgeting can provide a quantitative guide for climate action that can be related to the global carbon budgets scientifically associated with the Paris Agreement temperature targets. Physical climate science now enables estimation of a remaining global carbon budget rGCB* of all or some of the key climate pollutants in terms of CO_2 warming equivalent emissions, aggregating multiple anthropogenic forcings relative to a base year. From this, a multi-GHG national carbon quota (NCQ*) can be derived. The global risk assessment has now been politically agreed at global level in setting out the PA temperature limits to warming without overshoot. Within this context, there are still very significant value judgements for society in assessing “feasibility”, as well as in assessing a “fair share” of the available global cumulative-GHG budget, and in balancing the rights and needs of current and future generations, globally and nationally. Nonetheless, however it is defined, Ireland’s fair share is currently being used up rapidly and will imminently overshoot the lower bounds of the carbon budget ranges assessed y this review. From the literature, these is robust evidence that a national carbon budget framework utilising the GWP* metric or similar, based on the three key GHGs [CO_2+N_2O+CH_4] and explicitly constrained by the need to achieve cumulative balance with a stated, finite, NCQ*, by a specified date, is a significant improvement on CO_2eq or CO_2-only methods.

Based on assessment of the IPCC climate model database and a minimally equitable, equal per capita sharing from 2015, it is likely that overshoot of Ireland's fair contribution NCQ* has already occurred or is imminent. As shown by the literature, good faith commitment to the PA limits requires radical cuts in fossil, cement and land CO_2 emissions, bringing them as close to zero as possible. In addition, significant reductions in methane and nitrous oxide emissions are required as a key climate mitigation lever to limit NCQ* overshoot. Substantial and permanent reductions in methane from now onward would limit overshoot and limit commitment to large scale net CO_2 removal.

Summarising the widening gulf between what is needed to meet the Paris temperature target and national climate action to date (in terms of commitments and emissions trajectories), senior climate researchers have commented:

> *'The gap is so huge that governments, the private sector and communities need to switch into crisis mode, make their climate pledges more ambitious and focus on early and aggressive action. Otherwise, the Paris agreement's long-term goals are out of reach. We do not have another ten years.' (Höhne et al., 2020)*

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