Assessing Negative Carbon Dioxide Emissions from the Perspective of a National 'Fair Share' of the Remaining Global Carbon Budget

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Abstract

We present an assessment of the plausible Paris-aligned *fair share* nett cumulative carbon dioxide (CO_2) quota for an example nation state, the Republic of Ireland. By *Paris-aligned* we mean consistent with the Paris Agreement adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, at Paris, France in December 2015 (UNFCCC 2015). We compare and contrast this quota with both the aspirations expressed in the current Irish *National Policy Position* and current national emissions projections. The fair share quota is assessed as a maximum of c. 391 million tonnes of carbon dioxide ($MtCO_2$), equal to 83 tonnes of carbon dioxide (tCO_2) per capita, from 2015, based on a precautionary estimate of the Global Carbon Budget (GCB) and specific interpretation of global equity. Given Ireland's high current CO_2 per capita emissions rate, this would correspond to sustained year-on-year reductions in nett annual CO_2 emissions of over -11% per year (beginning as of 2016). By contrast, the CO_2 mitigation target indicated in the National Policy Position corresponds to nett annual reduction rates in the range of only -4.7% per year (low ambition) up to a maximum of -8.3% per year (high ambition); and projections based on current and immediately planned mitigation measures indicate the possibility, instead, of sustained *increases* in emissions at a rate of the order of +0.7% per year. Accordingly, there is a large gap between Paris-aligned ambition and current political and policy reality on the ground; with a significant risk of early emergence of "CO_2 debt", and tacit reliance on rapid deployment of currently speculative (at relevant scale and feasible cost) negative CO_2 emissions technologies to actively remove CO_2 from atmosphere. While the detailed policy situation will clearly differ from country to country, we suggest that this methodology, and its *CO_2 debt* framing, may be usefully applied in other individual countries or regions. We recommend that such framing be incorporated explicitly into global mitigation strategy via the statements of Nationally Determined Contributions required to be submitted and updated by all parties under the Paris Agreement processes.

Keywords: climate change mitigation; global carbon budget; national carbon quota; climate policy; carbon debt; negative carbon dioxide emissions; carbon dioxide removal.

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1. Introduction

The primary international instrument governing global climate mitigation is the agreement adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change, at Paris, France in December 2015, generally known as the *Paris Agreement (UNFCCC 2015).* Parties to the Paris Agreement have committed to take action to limit global anthropogenic temperature increase to "well below 2°C" over pre-industrial levels and, moreover, to "pursue efforts" to hold the increase to a more stringent (lower impact/risk) level of 1.5°C. While this implies urgent mitigation of emissions of all human-caused climate pollutants, the single most important of these is carbon dioxide (CO_2), mainly from fossil fuel combustion. Given the currently dominant role of fossil fuels in the energy systems of virtually every Party, this will require rapid and deep decarbonisation of all national energy systems, as well as parallel action to mitigate non-energy CO_2 emissions, including from industrial processes such as cement manufacture, and arising from specific forms of land use or land use change. In devising and assessing policy measures proposed by any individual Party to bring about this energy decarbonisation transformation, it is critically important to identify the quantitative constraint(s) implied by the Paris Agreement temperature goals: that is to say, to determine a basis for understanding *whether proposed national or regional energy decarbonisation policies are quantitatively commensurate with the global Paris objectives*. The relevant policy question can no longer be whether Parties are doing *what they suggest is feasible*, but instead whether they are committed, collectively, to doing *what is physically necessary* to achieve these global Paris limits, with or without recourse to negative emissions by achieving carbon dioxide removal (CDR) – for example by 2100, that being the time horizon generally adopted in integrated assessment modelling undertaken to inform policy-relevant reporting by the Intergovernmental Panel on Climate Change (IPCC). This paper presents a case study of assessing such constraints for one exemplar developed country Party, namely the Republic of Ireland, a member state of the European Union.

Because CO_2 is relatively long-lived in the atmosphere (a significant fraction remaining for hundreds to thousands of years) it functions as a so-called *stock pollutant*. That is, the key quantitative factor in determining how much warming is ultimately caused by CO_2 is not the short-term emission *rate* (the amount released per year) but rather the total, net, *cumulative* amount released. This is largely independent of how quickly or slowly this release now takes place, within any meaningful human timescale. In effect, for any given global temperature rise limit (such as enshrined in the Paris Agreement), there is a corresponding, finite limit on how much more CO_2 can ever be released. This limit on remaining nett CO_2 emissions is termed the Global Carbon Budget (GCB).

The remaining GCB declines in time as it is effectively used up by ongoing nett positive global CO_2 emissions. Further, even at a fixed point in time, the GCB does not have a single, precise value: it depends on assumptions about the emissions of non-CO_2 climate pollutants, and on complex uncertainties in the GHG flux and energy-balance dynamics of the planetary system. Consequently, the GCB is best represented as a range of values, referenced to a specific temperature limit goal, and a given point in time. Of course, the implication of uncertainty, including the serious risk of practical irreversibility in the planetary warming dynamics (due to the triggering of so-called tipping points), is that *prudent* policy should focus particularly on meeting the lower extreme of this range, rather than a central estimate (or, worse again, the upper extreme). This would be in accordance with the precautionary principle as enshrined in the original United Nations Framework Convention on Climate Change: "Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures,..." (UNFCCC 1992 Article 3.3). The GCB, based on the Paris Agreement temperature goals and the UNFCCC precautionary principle, yields a *global* constraint on remaining nett CO_2 emissions. In itself, this does not identify how this finite budget should be divided among the Parties (nations), to yield what we will term here national CO_2 *quotas.*

Given that the legal framework of the Paris Agreement is based not on imposed top-down constraints, but on voluntary bottom-up commitments (the so-called *Nationally Determined Contributions*, or NDCs), we might say that, in practice, shares of the GCB are already being actively claimed or annexed. However, the Agreement is explicit that all aspects of its implementation must "... reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances." The appropriate interpretation and application of this principle to the sharing of the GCB is, not surprisingly, a matter of considerable contestation. Nonetheless, in this paper, we set out to identify a range of methods for the determination of good faith, fair share, national CO_2 quotas that have been proposed to date in the research literature, and we assess the resulting quota range for one case study Party to the Paris Agreement, namely the Republic of Ireland. We then compare this range of remaining national quota to the cumulative emissions that would be implied by current Irish policy and projections. Finally, we discuss the implications for mitigation policy in general, and consider especially the potential role of negative CO_2 emissions (also referred to as carbon dioxide removal or CDR) in respecting the identified national CO_2 quota.

2. The Paris-aligned Global Carbon Budget (GCB)

The Paris Agreement temperature goal of "well below 2°C" has been widely interpreted as requiring action to *at least* maintain a probability of 66% of limiting warming to no more than 2°C over pre-industrial levels — though even this is a complex assertion (Rogelj et al. 2017). Nonetheless, based on this interpretation, and referring to the most recent IPCC analysis contained in the Special Report on Global Warming of 1.5°C, SR15 (IPCC 2018) we can estimate a range for the remaining Global Carbon Budget as follows. Table 2.2 gives a central estimate for the GCB for a 66% probability of limiting warming to no more than +2°C as 1170 $GtCO_2$ (gigatonnes of carbon dioxide, one gigatonne being one thousand million tonnes) from 2018, excluding Earth system feedbacks, and using a median estimate of non-CO_2 effects. This central GCB estimate is subject to a variety of quantified uncertainties, also listed in Table 2.2. As noted in the main text (p. 107) these uncertainties cannot be formally combined. Nonetheless, it is advised that "current understanding of the assessed geophysical uncertainties suggests at least a ±50% possible variation for remaining carbon budgets"; while this is qualified as applying specifically to "1.5°C-consistent pathways", in the absence of an explicit alternative we take it as applicable also to the <2°C GCB estimates, giving a GCB *range* of 585-1755 $GtCO_2$ from 2018, excluding Earth system feedbacks. We then adjust by the central estimate for the effect of Earth system feedbacks of -100 $GtCO_2$, which better reflects the available GCB extended to 2100 (p. 107). We further add back global emissions for the period 2015-2017 to adjust to a GCB from 2015 (taken as an appropriate reference date based on adoption of the Paris Agreement text). This adjustment is estimated at +123 $GtCO_2$, including emissions from fossil fuel and industry (FFI) and from land use (LU), based on data from Le Quéré et al. (2018). This yields a GCB range of 610-1780 $GtCO_2$, from 2015 to 2100, including Earth system feedbacks, and allowing the median estimate for non-CO_2 effects.

While there is ongoing critical discussion of the practical quantification of the GCB and its direct applicability in policy development (e.g., Peters 2018), nonetheless we adopt this SR15-based range as sufficiently robustly motivated and defined for the specific purposes of the current paper. We note that this GCB range estimate can also be compared to an earlier recommendation from Rogelj et al. (2016), based on the Synthesis Report from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC 2014), that Paris-aligned policy analysis should use a GCB range of 590-1240 $GtCO_2$ (mid-point 915 $GtCO_2$), dating from 2015 onward (for a 66% chance of limiting warming to no more than 2°C). While the high end of the SR15-based <2°C range is materially greater than the high end of this earlier AR5 based <2°C range, it is notable that the low end estimate is essentially unchanged. However, the most significant effect of the SR15 analysis is arguably not an alteration in the GCB for <2°C, but rather the finding of significant increase in impact risk between +1.5°C and +2°C, and the consequent importance of the Paris Agreement "efforts toward" respecting the lower temperature goal. We suggest that, in the context of a GCB range still based on the <2°C goal, this supports a focus primarily on the *lower* limit of the assessed range (i.e., 610 $GtCO_2$) as a minimally prudent basis for current assessment and planning of required action at both global and national levels. We shall return to this issue of varying interpretation of adequate *Paris alignment* in the concluding discussion.

The SR15-based GCB range estimate explicitly allows for specific (projected) mitigation of the warming contribution from non-CO_2 pollutants. If such non-CO_2 pollutants could be more strongly mitigated (compared to their baseline), then the GCB might be somewhat increased; or, conversely, if non-CO_2 pollutants are less strongly mitigated, then the available GCB will be even more tightly constrained. Beyond this qualitative observation, however, it is important to note that detailed analysis is required to quantitatively characterise this interaction between the GCB and non-CO_2 pollutants (Rogelj et al. 2015). Because of the essential time-differential nature of the distinction between stock (GCB) and flow (emission rate) pollutants, this cannot be done simply by applying algebraic CO_2 equivalence factors to respective cumulative emissions (as in the common convention using the 100 year Global Warming Potential, or GWP-100). Allen et al. (2018) provides a detailed discussion of this issue, and a concrete proposal for an alternative aggregation methodology (so called "cumulative CO_2-e*"), that might effectively address this. Nonetheless, it is clear that regardless of the precise mitigation of non-CO_2 pollutants, effectively limiting long duration (multi-century) warming commitment absolutely requires urgent, substantial and sustained CO_2 emissions reductions (Pierrehumbert 2014), to bring nett CO_2 emissions to zero (or below) more or less within the indicated cumulative GCB range. Accordingly, for the bulk of the current paper, we will focus our discussion primarily on CO_2, based on the assessed SR15 <2°C GCB range. However, our chosen case study country, Ireland, does present an emissions profile with a particularly strong non-CO_2 contribution, which we will therefore also return to in our concluding discussion.

3. Fair share GCB Division Principles

As noted, there is significant debate and contestation as to the appropriate principles to apply in dividing the GCB among nations. Raupach et al. (2014) suggest that, at any chosen or agreed reference year, the remaining GCB might be divided into national quotas in direct proportion to the then prevailing national shares of any of: annual global CO_2 emissions (which they term *inertia* division); annual global economic activity (measured by relative Gross Domestic Product or GDP); or global population – an equal per capita (EPC) division they term as *equity* and we term *population* or *pop*. We make use of this simple Raupach et al. blending method to straightforwardly examine the range from: an equal per capita GCB population allocation, with no inertia or 'grandfathering' component; through population-inertia blends; and up to GCB allocation based on full inertia, the latter greatly favouring nations with high current total or per capita emissions. As a strong critical commentary by Kartha et al. (2018) notes, EPC-derived allocations are often still inherently inequitable by failing to address historic, ethical and consumption biases explicitly. Also, even pathways described as EPC, 'equality' or similar terms, can be defined in ways that in fact include a tacit inertia component, for example by incorporating 'convergence' of projected future values (Robiou du Pont et al. 2016; van den Berg et al. 2019). Unlike such analyses, we will use the Raupach et al. method simply to make the inertia-inclusive GCB allocation range explicit and, for further clarity, we also choose a fixed base year for territorial emissions and population data to give a common starting point for projected (exponential) pathways across all methods – and, if extended, between all nations. One arguable choice for the reference year would be 2015 on the basis that this marked the adoption of the Paris Agreement text at the UNFCCC COP-21 meeting. However, this obviously overlooks differential national contributions to the excess atmospheric CO_2 already accumulated by that time. A variation would be to at least partially allow for this differential historical responsibility of separate nations by backdating the GCB division to some earlier point in time; such as, for example, 1990, the date of the first IPCC Assessment Report, which was formally noted by the United Nations General Assembly and triggered the process leading to the United Nations Framework Convention on Climate Change. Nonetheless, as the Paris Agreement set the politically agreed global objective of limiting to "well below 2ºC" temperature we use the adoption year, 2015, as the baseline reference year for global and national values for population and carbon emissions. A further proposed principle for GCB division is appropriate recognition of differences in relative *capability*, or capacity to act, arguably characterised by wealth, especially wealth per capita above some threshold level (Holz et al. 2017; Kartha et al. 2018); however, that introduces significant additional complexities and we do not pursue it further in the current paper.

Separately from *prima facie* division of the GCB among nations it can be argued that quotas could or should then be adjusted to take account of at least two kinds of transfers or trade between nations. Firstly, the economic or welfare benefits associated with CO_2 emissions in any given nation may be ultimately enjoyed by citizens in another (through trading of goods in which the emissions are effectively *embodied*). However, such transfers are difficult to measure or verify on a transparent basis. Secondly, it is also possible, in principle, that there could be direct trading of CO_2 quotas, so that a nation might legitimately gain access to a greater quota than would be indicated by any *prima facie* fair share division. However, given the severe constraint of the remaining GCB at global level (within which any quota trading would have to take place) and the need to support sustainable development (for nations with poor material welfare and that currently, or historically, have had relatively more modest CO_2 emission profiles) the practical scope for CO_2 quota trading appears likely to be extremely limited. Finally, while there are some precedents for international trading in aspects of mitigation action (such as under the Clean Development Mechanism of the Kyoto Protocol, the UNFCCC REDD+ programme addressing deforestation and forest degradation, and the European Union Emissions Trading Scheme), there are no currently existing, or even proposed, institutional mechanisms to support *GCB-based* quota allocation and trading *per se*.

It remains true, of course, that achieving a decarbonisation pathway consistent with a stated quota in any *single* nation will not be effective in meeting the global temperature goals unless other nations likewise achieve commensurate reductions (Robiou du Pont et al. 2016). However, the bottom-up structure of the Paris Agreement calls for individual Parties to each articulate and give effect to commensurate actions, based on emissions taking place within their own geographical jurisdictions. Accordingly, we will attempt to simply apply that bottom-up approach here, on a unilateral, fair share limit basis, without any complicating consideration of CO_2 quota transfers, either by direct quota trade, or indirectly by embodiment in traded goods.

4. CO_2 Quotas and Emission (Rate) Pathways

A cumulative CO_2 quota does not, in itself, determine a unique pathway of (declining) annual CO_2 emissions that a given nation must follow to be consistent with achieving the Paris Agreement goals. However, it does set a hard, overarching, *constraint* on the choice of such a pathway, namely that it must “add up”; that is, the integral, or area under the proposed future annual nett CO_2 emissions pathway, the sum of the annual emissions and removals into the indefinite future, must be no more than the specified or claimed quota.

Even though the choice or design of an emissions pathway is not uniquely determined by the specification of a quota, nonetheless it can be useful to translate quotas into example pathways (and vice versa), to give a sense of the speed and depth of decarbonisation that may be required, which can, in turn, be assessed against proposed measures to bring it about. For the purposes of this paper, we use a single systematic method for generating such example pathways by using a discrete exponential form. Such an exponentially declining pathway is uniquely determined by the current emissions rate and the remaining quota in the reference (starting) year. Further, it has the characteristic that the year-on-year fractional change in the emissions rate is constant over the pathway. We will denote this year-on-year fractional change as R. It is formally calculated as $R=(E_{k+1}/E_k)-1$ where E_k denotes the emissions rate in year k. This constancy of R would not be true of any other functional form for an emissions rate pathway (where R would, instead, vary in time). Usually expressed as a percentage, the (constant, negative) parameter R for an exponentially declining pathway corresponding to a given quota can be directly calculated as the ratio of the emissions rate in the reference (starting) year divided by the remaining quota. That is, denoting the emissions rate in the reference year by E_0 and the remaining quota from that year as Q, then $R=-E_0/Q$. The exponential pathway parameter R thus gives a useful, idealised, indicative measure of the annual rate of decarbonisation implied by any particular quota, that can also be directly compared between different nations, regions, or with the corresponding global constraint. Further, of all possible pathways consistent with the given quota, the exponential pathway presents the minimum-maximum value for R (excluding, for the moment, pathway forms that might allow nett negative emissions at some point). In a coarse way, this is one possible criterion for sharing or balancing year-on-year mitigation effort over the full course of the pathway. While commitment to properly *equitable* climate change mitigation is a key feature of the Paris Agreement (Pan et al. 2017; Winkler et al. 2018) it is not the central focus of the current paper; nonetheless, we note that the exponential pathway form might be argued to represent at least some *minimal* concession to *intergenerational equity* in climate mitigation effort *within* any single nation, at least as contrasted with, say, a comparable *linear* pathway form (corresponding to the same cumulative quota, without overshoot). Such a linear pathway would require that the year-on-fractional reduction in annual emissions (taken as a rough indicator of annual mitigation effort) actually *increases* in time, effectively back-loading overall mitigation effort such that it falls more heavily on future generations.

Notwithstanding this additional consideration of intergenerational equity, we emphasise that we adopt the exponential pathway form here *primarily* because such pathways allow a mathematically simple heuristic translation between long term cumulative quota targets and the roughly commensurate short-term scale of action or relative effort required while still avoiding quota overshoot. By anchoring the per capita basis and reference level CO_2 to 2015 population and emissions rates, we use known data and respect the start date of the political commitment made in the Paris Agreement. The use of the exponential pathway form and this anchor date enables a straightforward and transparent basis for evaluation of current top-down and bottom-up mitigation urgency in and between nations, as compared to the array of allocations, pathway forms, and population projections shown in other assessments even for pathways similarly described as “equal per capita” (Robiou du Pont et al. 2016; van den Berg et al. 2019). We do not suggest that exponential pathways would necessarily represent an appropriate or feasible form for policy makers to achieve in practice, technically or socio-politically. As we shall see in our case study, for a nation state whose remaining quota is relatively small compared to its current annual emissions, the commensurate exponential rate is likely to be so high as to be classified as infeasible, and therefore feasible pathways (respecting the quota) will necessarily involve temporary quota overshoot and subsequent achievement of net negative emissions for a period of time until the overshoot can be reversed. Any such pathways are necessarily non-exponential because exponential decline pathways from any initially positive level always converge asymptotically to zero and cannot become negative. Conversely, a nation state whose remaining equitable quota is relatively large compared to its current annual emissions might reasonably consider that it is appropriate or indeed essential for emissions to continue to grow in the short or even medium term (e.g., to support material development) and only transition later to a more or less smooth decline to zero. Indeed, Raupach et al. (2014) present one generic formulation for so-called “capped-emissions” pathways having exactly this character: but again, they are necessarily non-exponential whereas exponential pathways are technically described as monotonic, meaning that they change consistently in one direction only; they cannot peak and then decline. Accordingly, the illustrative exponential pathways presented here are best thought of as idealised baseline or reference cases, against which practical or feasible pathways might be developed, or actually proposed pathways may be compared, all in the light of specific local circumstances.

As a baseline for later comparison, we can use the same mathematical relation outlined above to calculate an indicative exponential pathway at *global* level by dividing the GCB by reported global emissions in a given reference year. As of 2015, and using data from Le Quéré et al. (2018), global nett anthropogenic CO_2 emissions from land use (LU) and fossil fuel and industrial production (FFI) were estimated as 41.4 $GtCO_2$ per year. Dividing this into the SR15 <2°C GCB range of 610-1780 $GtCO_2$, from 2015 therefore gives an equivalent global R range of -6.8% per year to -2.3% per year.

Finally, in relation to emission rate pathways, it is important to distinguish decarbonisation targets expressed via a *cumulative quota*, and the more prevalent use of *point-in-time* emission rate targets. Thus, as will be discussed in more detail later, local Irish decarbonisation policy currently states only a point-in-time CO_2 emissions rate target for the fixed year of 2050 (namely, at least 80% below the 1990 level), without any specified functional form, exponential or otherwise, for the emissions pathway over the years in the interim, or beyond 2050, or any indication of alignment with some cumulative limit. The consequence is that this target, *in itself,* does not place any quantitative constraint on future Irish cumulative CO_2 emissions as there formally exist emissions pathways passing through that point in time target which have arbitrarily large cumulative emissions both up to and after that time. Therefore, it does not express any concrete limit on Ireland's claim on the GCB; or, what amounts to the same thing, Ireland's responsibility for further long-term CO_2-driven temperature rise. In other words, such point-in-time rate CO_2 targets do not, *in themselves*, allow assessment of good faith, fair share, contributions to meeting the temperature goals of the Paris Agreement, even on an aspirational basis.

5. Case study: Assessing a national CO_2 quota for Ireland

As a case study for fair share division of the GCB, we now estimate the range of Paris-aligned national CO_2 quotas for the Republic of Ireland, a member state of the European Union, with a relatively high level of economic development. The resulting quota estimates will be put in the context of current and projected Irish emissions pathways and used to discuss implications for Irish climate mitigation policy. While the choice of Ireland serves to illustrate the general approach and the stark challenge of achieving an adequate scale of mitigation in countries with an established *locked-in* reliance on high CO_2 emissions practices, we shall also see that Ireland presents some additional, relatively atypical, features in the extent of its non-CO_2 emissions.

Estimates of nett CO_2 quotas include all territorial CO_2 emissions to atmosphere, from fossil fuel use, industrial processes and land use; less all CO_2 removals from atmosphere, into forestry and soils, or potentially into more permanent and less reversible geologic reservoir storage (via carbon capture and storage and related technologies). For the purpose of converting quota estimates to exponential emissions pathways, we note that Ireland's nett CO_2 emissions in 2015 (as per UNFCCC reporting rules, not including international aviation and shipping) were ~42.7 million tonnes of carbon dioxide ($MtCO_2$) per year in total, comprised of ~38.4 $MtCO_2$ per year from fossil fuel use and some non-energy-related industrial processes (FFI), and ~4.3 $MtCO_2$ per year (nett) attributed to land use, land use change and forestry (LULUCF) (EPA 2017).

5.1. Methods

5.1.1. M1: Top-Down Division of Global Carbon Budget

Following the methodology adopted by Raupach et al. (2014), the GCB may be shared according to some combination of two general principles: *inertia*, based on preserving or locking in the current (inequitable) national shares of total annual emissions (also referred to generically as *grandfathering*); or population, based simply on share of global population at a fixed reference point in time. Raupach et al. refer to the latter as "equity"; however, as our subsequent discussion requires consideration of multiple facets of equity we will adopt the more neutral term population (or *pop*) for this sharing principle. Raupach et al. go on to define a linear interpolation or blending between inertia and population division, characterised by a "sharing index", denoted w. This ranges from *pure inertia*, with $w=0$, to *pure population*, with $w=1$.

We may note that the pure inertia case gives, by definition, quotas proportional to each nation's 2015 emissions rate, with the consequence that, expressed in terms of exponential emissions rate pathways, all nations would indicatively follow pathways with the same R. Conversely, a pure population division would mean different R values for different nations (those with higher current per capita emissions would have to decarbonise faster) but all nations would have the same per capita remaining cumulative quota in 2015. Raupach et al. suggest that an intermediate blend between inertia and population sharing (such as $w=0.5$) gives some balance between decarbonisation feasibility for already developed nations and development needs for developing nations. This work predates the Paris Agreement; but we should note that assessed feasibility is not, in fact, a principle explicitly recognised in that Agreement, whereas the need for "sustainable development" is.

There are a number of other methodologies for GCB division discussed in the literature. The *Regensburg model* (Sargl et al. 2016) generates CO_2 emissions pathways over time for different nations according to a principle of contraction and convergence. Global "contraction" (emissions rate reduction) ensures that total emissions are constrained within some selected cumulative limit, in our case the GCB. Separately, respective national per capita emissions rates are required to progressively converge until they become equal in some selected target year. While this differs in some important details from the Raupach et al. method, for any single country it still gives rise to a similar range of quotas as spanned by the Raupach et al. sharing index.

Rockström et al. (2017) begin from the (post-Paris) observation that "alarming inconsistencies remain between science-based targets and national commitments". To make Paris mitigation goals a reality, and based on a prudent GCB estimate of 700 $GtCO_2$ from 2017, they propose a "carbon law", a global exponential emissions reduction pathway, characterised by a repeated halving of nett anthropogenic CO_2 emissions from fossil fuel and industry, every decade starting from 2020 (equivalent to an annual R value, from 2020, of about -6.7% per year). In parallel, nett land use emissions are assumed to fall to zero by 2050. While not providing a detailed discussion of how this effort should be distributed, they state that this mitigation pathway should apply "to all sectors and countries at all scales". Such an application of a common exponential mitigation rate to all countries is essentially similar to the Raupach et al. inertia principle and, for any given GCB (and starting year), will yield a similar national quota.

Anderson and Broderick (2017), developing an earlier analysis of Anderson and Bows (2011), attempt to quantify the European Union's quota share of the GCB, referencing the Paris Agreement temperature limits and the need to act on the basis of equity. This method relies on differentiating effort between relatively wealthier nations that are members of the Organisation for Economic Cooperation and Development (OECD) and the relatively less wealthy nations that are not. Like Rogelj et al. (2016), the remaining GCB from 2011 onward is taken from the IPCC (2014, Synthesis Report Table 2.2 summary), but rather than using the range for "simple models" with IPCC Working Group 3 scenarios (as per Rogelj et al.), Anderson and Broderick use the values based on "complex models", with IPCC Representative Concentration Pathway (RCP) scenarios spanning a range of temperature goals from "33% chance of less than +1.5°C rise" to "66% chance of less than +2°C rise". They then adopt specific, intentionally optimistic, assumptions for stringent mitigation of CO_2 emissions from global deforestation and cement production as "global overhead" (a shared global responsibility), and for relatively early peaking and decline of CO_2 emissions by all non-OECD nations. The latter is interpreted as the minimal defensible concession to equity as between OECD and non-OECD nations. The remaining GCB balance then represents an upper limit on the OECD CO_2 energy-only quota, because, in this specific method, cement production and land-use/deforestation have already been allowed for at global level. This OECD quota is then sub-divided to yield a European Union (EU) quota, using, variously, the EU's share of OECD emissions, Gross Domestic Product (GDP), or population, over the period from 2010 to 2015. Due to the dominance of emissions by the United States of America (USA) within the OECD, the initial split between OECD and non-OECD groupings by Anderson and Broderick results in an EU equity quota bigger than its inertia quota, and therefore the outputs from their analysis are not comparable with the Raupach method used here to show illustrative inertia and equity pathways. We repeat that "equity" in the context of this particular method means division by population, not any wider judgement of what might be thought equitable. Given the overall divergence in assumptions and approaches, we do not pursue this method of Anderson and Broderick further here.

On the basis of these considerations, we calculate and present quotas for Ireland, based just on the Raupach et al. method, for the following three variant cases spanning the full range of both GCB and the Raupach et al. sharing principles (between population and inertia):

- **Low-GCB-Pop:** Low GCB (610 $GtCO_2$) with population sharing ($w=1.0$)
- **Mid-GCB-Blend:** Mid-point GCB (1190 $GtCO_2$) with blended sharing ($w=0.5$)
- **High-GCB-Inertia:** High GCB (1780 $GtCO_2$) with inertia sharing ($w=0.0$)

5.1.2. M2: Bottom-up National Policy Objectives (Aspirations)

The above top-down division method of Raupach et al. yields estimates of a finite national-level nett CO_2 quota, based on the Paris "well below +2°C" temperature goal (via IPCC SR15 analysis of the GCB range for that case): that is, they represent the CO_2 constraint implied by this specific interpretation of good faith participation in the multilateral Paris Agreement process.

By contrast, in this section, we present a complementary *bottom-up* methodology to estimate expected cumulative CO_2 emissions, at national level, based on *current* national policy. By comparing with the nominally Paris-aligned quota estimates from method M1, we can assess the extent to which current national CO_2 mitigation policy is or is *not* aligned with the voluntary commitment represented by the Paris Agreement.

Overall Irish decarbonisation policy is currently governed by the non-statutory *Climate Action and Low-Carbon Development National Policy Position*, adopted by the then government in 2014 (DECLG 2014). In relation to CO_2, this states a single point-in-time emissions rate target of "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 [EGBET] sectors". We will refer here to this sector- and CO_2-specific target as the sectoral *National Mitigation Objective*, denoted NMO (see CCAC 2016). In itself, this point-in-time NMO does not strictly constrain cumulative CO_2 emissions in these sectors either up to 2050, or thereafter, and therefore does not directly imply any specific finite quota. However, under some added assumption for the functional form of the emissions rate pathway over time, compatible with this point-in-time target and allowing extrapolation beyond 2050, a cumulative quota estimate can be arrived at by summation/integration. For direct comparison with the previous top-down method, allowance must also be made for (nett) CO_2 emissions from the sectors not explicitly mentioned (land use, in particular). Within this general approach, we consider the following specific cases:

- **NMO-80**: An exponential mitigation pathway for nett CO_2 emissions, across all CO_2 emitting sectors (not just EGBET), starting in 2015, and meeting the minimum target reduction of the National Policy Position, being a reduction of 80% relative to 1990 levels by 2050.
- **NMO-95:** Similarly, this envisages an exponential mitigation pathway for nett CO_2 emissions, across all CO_2 emitting sectors, starting in 2015, but achieving a higher reduction level of 95% relative to 1990 levels by 2050.

We note that potential CO_2 mitigation to 2050 point-in-time target levels of 80% and 95% reduction compared to 1990 (across fossil fuel and industry use) have been the subject of separate detailed national level modelling and notional-cost-effectiveness analysis (Ó Gallachóir et al. 2012).

For each case we estimate an implied cumulative CO_2 quota by the following method:

- Calculate the R parameter for the (unique) exponential pathway defined by the 2015 annual emissions rate and the target 2050 emissions rate.
- Calculate the cumulative CO_2 quota associated with extrapolating this exponential pathway for total nett CO_2 emissions to its asymptotic limit.

5.1.3. M3: Bottom-up National Policy Projections

Separately from the 2050 point-in-time emissions rate target in the Irish National Policy Position, there are also *projections* of future national emissions, prepared and updated regularly by the Irish Environmental Protection Agency (EPA 2018a). These are driven, not by the overall 2050 national *objectives,* which may be viewed as aspirational, but rather by the best available coupled economy-energy system models of what is currently transpiring in reality, given projected outcomes of concrete, known, policy measures and economic trends. In accordance with EU-wide methodologies, two distinct national projection scenarios are presented, as follows:

- **WEM** (With Existing Measures): assumes no additional CO_2 mitigation policies and measures, beyond those already in place by the end of 2016.
- **WAM** (With Additional Measures): assumes implementation of the WEM scenario in addition to further implementation of Government energy efficiency and renewable energy measures including those set out in the National Renewable Energy Action Plan (NREAP) and the National Energy Efficiency Action Plan (NEEAP).

As of early 2019 the projections were presented up to 2035. For both WEM and WAM, the projections show the annual CO_2 emissions rate still increasing between 2017 and 2035 by default (albeit the increase is significantly less for WAM compared to WEM). According to the EPA, this projected growth in emissions is "... largely underpinned by projected strong economic growth and relatively low fuel prices leading to increasing energy demand over the period" (EPA 2018a, Key Insights). That is, while the currently identified measures, both existing and additional, are expected to cause *some* decoupling of emissions from this growth, – somewhat reducing CO_2 *intensity per unit GDP* – this is projected to be insufficient to prevent continued *absolute* growth in CO_2 emissions. Indeed, while not explicitly cited as a factor in these projections, the general theory of efficiency rebound would suggest that, in the absence of strong measures to limit the rebound effect, reduced CO_2 intensity of GDP might actually act as a distributed economy-wide positive feedback to *enhance* GDP growth (Polimeni and Mayumi 2008; Alcott 2010). However, it should also be noted that the carbon price assumptions underlying these EPA projections appear low: for both ETS and non-ETS sectors, this was set at €15/tCO_2 for the period 2021-2025, €22.50/tCO_2 in 2026-2030, and €33.50/tCO_2 for the period 2031-2035 (EPA 2018a, Table 2.1). Whereas, as of Q4 2018, the ETS price was already consistently above €20/tCO_2; and the Irish Climate Change Advisory Council has recommended that the domestic carbon tax (effectively setting a carbon price for non-ETS CO_2 emissions) should be increased to €80/tCO_2 by 2030 (CCAC 2018) albeit this has not been adopted as official policy and therefore was excluded from the measures modelled by the EPA. As a general principle, increased carbon prices would be expected to have some emissions mitigation effect, even against a background of sustained economic growth (as measured by growth in annual GDP).

While not formally included in the EPA projections, for comparison purposes we will also consider a third steady-state projection scenario:

- **FLAT**: A pathway where nett CO_2 emissions remain constant (to 2035) at the 2015 level.

As with method M2, we fit approximate exponential pathways to the WAM and WEM scenarios, using the known 2015 emissions and the projected end-point (2035) emissions in each case. This yields corresponding values for the exponential parameter R; however, as the emissions are projected to increase over the period in both cases, the R value will be positive (growth) rather than negative (mitigation). For the FLAT projection scenario, $R=0$ by definition. In all three projection scenarios, therefore, if the pathways were extrapolated beyond 2035, they would have no cumulative limit, and do not give rise to a finite asymptotic quota that could be directly compared to the earlier pathways with sustained year-on-year mitigation. Accordingly, for such comparison purposes, we also calculate *fixed time partial quotas* over the finite period 2015-2035 for all other methods and scenarios.

5.2. Results

All detailed calculations underlying the results presented here have been published and archived[1] via the Zenodo open data repository[2] in both spreadsheet (Open Document[3]) and interactive notebook (Jupyter/iPython[4]) formats. (These resources are made available for reuse under the terms of the Creative Commons Attribution-ShareAlike 4.0 International License[5].)

The results are summarised numerically in **Table 1**. This shows the national nett cumulative CO_2 quota for all method M1 and M2 scenarios (finite asymptotic limit, from 2015 onward, denoted "Quota [2015+]"), together with the corresponding *per capita* quota and equivalent exponential pathway parameter R. For method M3 scenarios (projections-based), which do not have a finite asymptotic limit, the table shows the nett cumulative CO_2 quota for the period 2015-2035 only (denoted "Partial Quota [2015, 2035]") and the equivalent exponential pathway parameter R (being positive, denoting *growth*, in these cases); the corresponding 2015-2035 fixed-time partial quotas for the other scenarios are also shown for comparison purposes.

Method	Variant	Partial Quota [2015, 2035] ($MtCO_2$)	Quota [2015+] ($MtCO_2$)	Quota per capita [2015+] (tCO_2)	R % per year
M1: Raupach	Low-GCB-Pop	356	391	83	-10.95%
	Mid-GCB-Blend	600	996	211	-4.30%
	High-GCB-Inertia	717	1839	389	-2.33%
M2: Policy	NMO-95	433	517	109	-8.27%
	NMO-80	581	917	194	-4.67%
M3: Projections	FLAT	898			0.00%
	WAM	937			+0.42%
	WEM	964			+0.70%

Table 1: Estimates of Ireland's nett CO_2 quota (FFI and LU) and related comparative parameters under different mitigation scenarios. See text for detailed definitions.

[1] All resources available at: https://doi.org/10.5281/zenodo.3257409

[2] https://zenodo.org

[3] http://opendocumentformat.org/

[4] http://jupyter.org/

[5] https://creativecommons.org/licenses/by-sa/4.0/

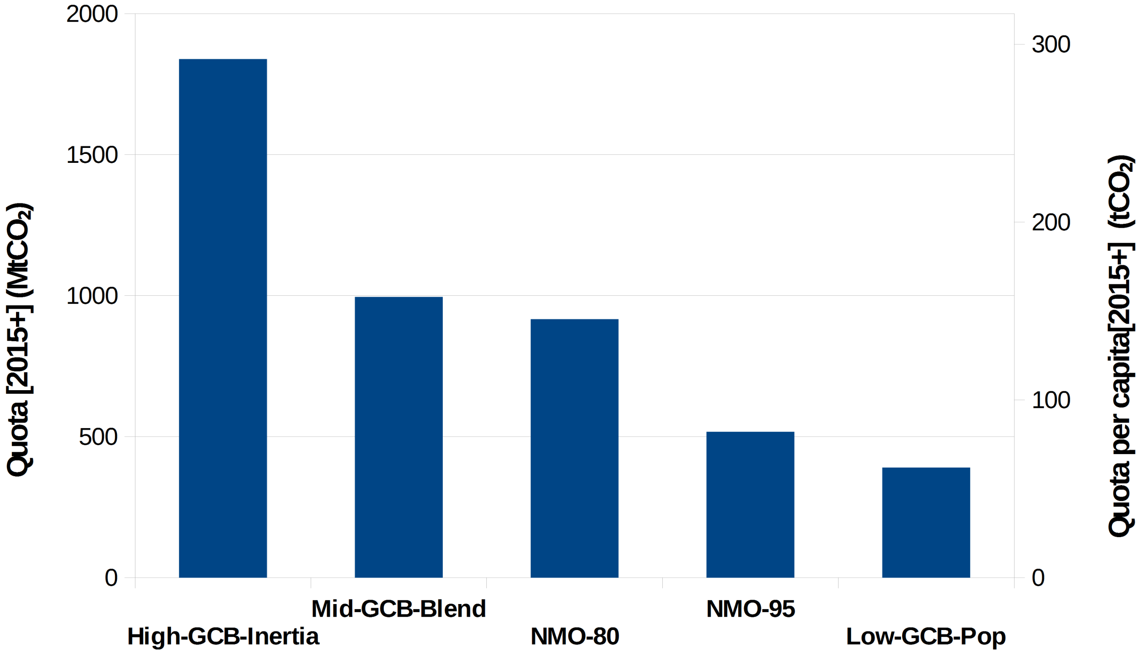

Fig. 1: *Nett remaining "fair share" CO_2 Quotas for Ireland from 2015 under method M1 and M2 mitigation scenarios. See text for detailed definition of each scenario.*

Fig. 1 charts the national nett cumulative CO_2 quota for all method M1 and M2 scenarios (finite asymptotic limit, from 2015 onward). **Fig. 2** graphs the corresponding exponential annual emissions pathways for all scenarios.

The estimate for Ireland's national CO_2 quota ranges from a maximum of 1839 $MtCO_2$ (scenario: **High-GCB-Inertia**) down to a minimum of 391 $MtCO_2$ (scenario: **Low-GCB-Pop**). This corresponds to an R rate parameter ranging from c. -2.3% per year up to -11% per year. It is important to emphasise again that, in these exponential-form pathways, this fractional mitigation rate must be sustained, compounding year on year, with no easing or regression; or if it is not achieved at any point then a correspondingly increased fractional mitigation rate would then become necessary in following years; alternatively, negative carbon dioxide emissions (nett removals) may become necessary.

The CO_2 quotas estimated by M2, based on low and high ambition interpretations of the existing NMO target are 917 $MtCO_2$ and 517 $MtCO_2$ respectively, with corresponding R rate parameter values of about -4.7% per year and -8.3% per year. Therefore, these bottom-up quotas and pathways, corresponding to possible interpretations of the National Policy Position, at least, fall within the Raupach et al. range identified by the top-down method M1. This is also graphically seen in **Fig. 2**, where the M1 central and low pathways, **Mid-GCB-Blend** and **Low-GCB-Pop,** bracket the NMO-95 (higher ambition) and NMO-80 (lower ambition) pathways.

By contrast, the three bottom-up projections-based scenarios, reflecting the expectations from policies currently in place, have no finite asymptotic CO_2 quota, and correspond to non-negative R rate parameters (growth rather than mitigation) ranging from 0.0% per year (by definition, for the steady-state or **FLAT** scenario) up to about +0.7% per year for the WEM scenario assuming only

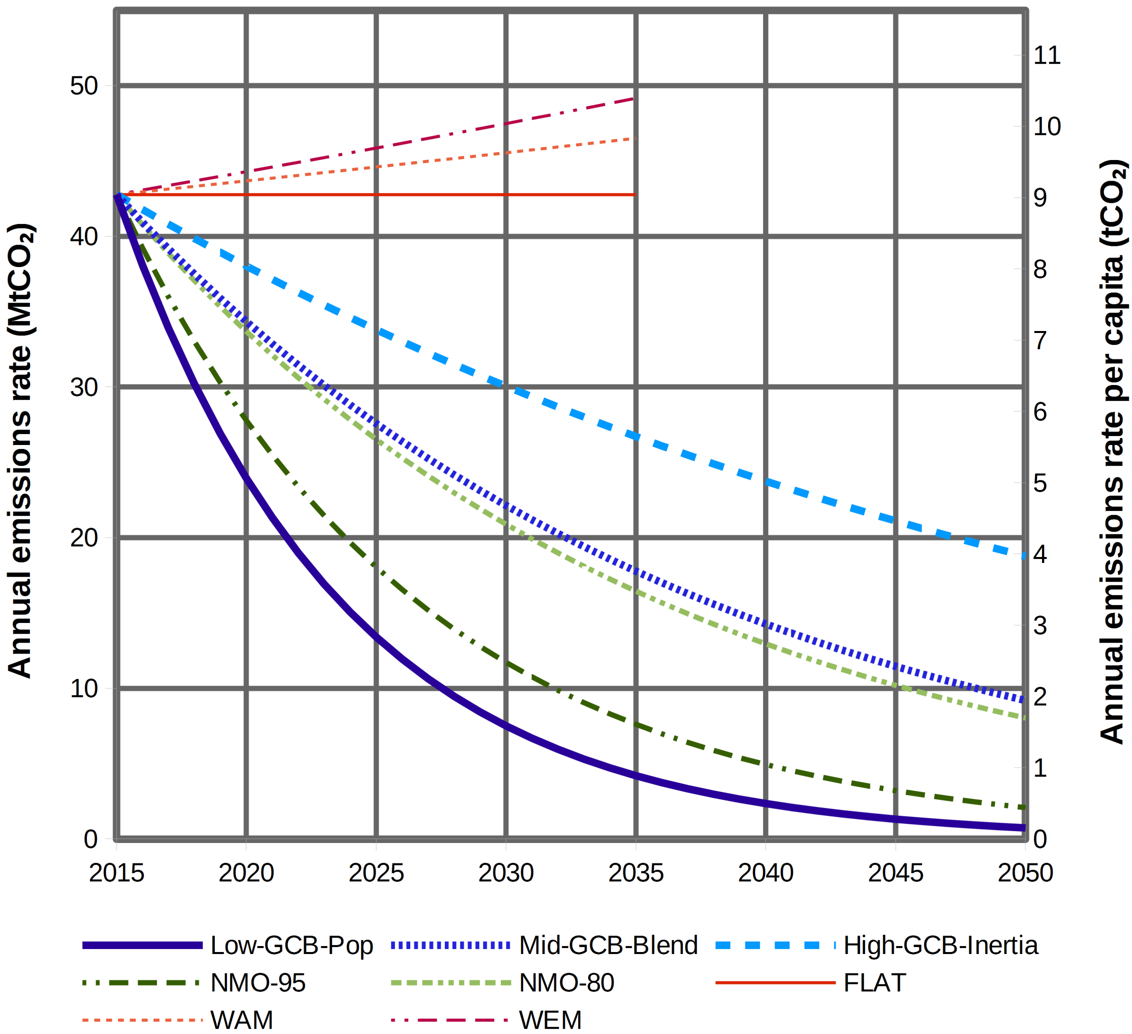

Fig. 2: *Illustrative exponential emission rate pathways for Ireland under all considered mitigation scenarios. See text for detailed definition of each scenario.*

those existing measures that are already actually in place. Just looking at the period up to the published projection horizon of 2035, the cumulative budget range to that point of 898-964 $MtCO_2$ is already close to, or above, the full asymptotic limit of even the lower ambition **NMO-80** aspiration (917 $MtCO_2$), and is more than *twice* the full asymptotic limit of the minimum top-down M1 quota (**Low-GCB-Pop**, 391 $MtCO_2$). Further, cumulative emissions under these scenarios would implicitly continue growing beyond 2035, without any identifiable limit. It should be emphasised that method M3 is projecting outcomes based on no further new mitigation measures or policies being brought forward: that is, it may be argued that, on the contrary, new measures and policies *should be expected to be brought forward* to at least partially address the gap between the results from M2 and M3. However, due to the cumulative nature of this gap, continuing delay means that the available quota, as implied by the NMO in method M2, is already being depleted much faster than would be compatible with the M2 exponential pathways beginning from 2015 given the minimum-maximum R value from that time. Therefore the required *future* R rate required to correct this is growing non-linearly, and will continue to do so as long as the then required rate is not achieved and/or the full quota is already exhausted.

6. Discussion

6.1. Comparison to Other Sub-global Quota Assessments

Relatively few sub-global or nation-specific analyses appear to be available to date which explicitly address equitable carbon quotas, or quota-constrained emission pathways. They will be briefly summarised here and compared where possible with the results obtained above.

At the sub-national level, Anderson, Stoddard, and Schrage (2017) have recently estimated a Paris-aligned CO_2 quota for the Swedish Municipality of Järfälla to inform local mitigation planning. Similar analyses have been presented for the Greater Manchester region and the City of Manchester (UK) by Kuriakose et al. (2018a, b). In each of these cases, the methodology adopted is related to that of Anderson and Bows (2011), and, as discussed previously, is not directly comparable to the analysis presented in the current paper, although the conclusions in terms of the overall scale of local mitigation effort now required in these relatively highly developed regions are similar.

Donner and Zickfield (2016) generate national level CO_2 quotas for Canada (and corresponding emission pathways, using a logistic function form) based on different probabilities of limiting warming to less than 1.5°C, 2°C and 3°C over pre-industrial. They find that, at its current CO_2 emissions rate, Canada would have exhausted its (population based) quota for a 50% chance of limiting to +1.5°C rise by the end of 2018, and by 2026 for a 66% chance of a +2°C limit. We will review this *year of quota exhaustion* metric further below for Ireland; but, based on the +2°C limit, this is estimated as c. 2024 on current trends, very similar to the result for Canada.

Pye et al. (2017) re-examine UK emission pathways to align UK climate mitigation policy within inertia and population-based sharing of the AR5-based GCB range proposed by Rogelj et al. (2016). Decarbonisation rates of -11% per year, -4% per year and -2% per year are found for the range from the smallest population-based quota to the largest inertia quota – broadly comparable to the results reported above for Ireland (albeit using the somewhat different, SR15-based GCB range). It is proposed by Pye et al. that achieving these nett pathways could be facilitated by deploying gross CO_2 *removals* equivalent to approximately 250%, 100% and 30% of the respective nett quotas. We will consider this approach further below for Ireland, when we present the concept of *national cumulative CO_2 debt*.

Glynn et al. (2018) have independently examined Paris-aligned, energy-economy system pathways to zero carbon emissions specifically for Ireland. They use Irish-TIMES, a multi-decade energy system model, applying partial equilibrium notional cost optimisation, coupled with a macroeconomic model (MACRO-stand-alone or MSA). They investigate Irish national CO_2 quotas derived using population-based sharing of a GCB ranging from 1200 $GtCO_2$ down to 200 $GtCO_2$ (from 2015). The low end of this range falls significantly below, and so is more ambitious than, the minimum of the SR15-based GCB Range adopted in the current paper (610 $GtCO_2$) primarily due to considering stronger interpretations of the Paris Agreement temperature goals (up to requiring a 66% probability of stabilizing below +1.5°C). As with the analysis presented in the current paper, they indicate a need for far greater mitigation effort than existing EU policy goals, requiring significantly greater and earlier reduction in nett CO_2 emissions. Consistent with these findings, additional Irish-TIMES based modelling by Winning et al. (2018) finds that delaying Irish mitigation action increases fossil fuel lock-in and would increase an implied commitment to investment toward future carbon dioxide removal (CDR). Also using the Irish-TIMES model, Yue et al. (2018) likewise note the increased costs of delayed mitigation, suggesting that the lowest "technically achievable" CO_2 quota (GCB share) for Ireland alone, from 2015 to 2070, is c. 360 $MtCO_2$ with over 80% emission reduction needed by 2030 relative to 1990 and notional marginal carbon emission abatement costs potentially escalating to c. €5000/tCO_2 by 2050. It should also be noted that nett land use CO_2 emissions are not included in any of these three analyses, i.e., they tacitly allocate all available CO_2 emissions quota to the energy and industrial process sectors alone; whereas, in fact, unabated continuation of these land use emissions would significantly reduce the CO_2 quota available to the energy and industrial process sectors.

6.2. The Paris Agreement and Good Faith Alignment

All of the methods used here can provide only indicative values for Ireland's CO_2 quota under the described methods and assumptions. They all embody tacit ethical values and choices which can, and should, be the subject of wide societal discussion and critique.

While, as noted, the bottom-up aspirations of method M2 fall within the range of top-down values from method M1, it would be difficult to argue that this is properly consistent with good faith alignment with the Paris Agreement.

Firstly, the adopted M1 GCB is based on a temperature target of only a 66% probability of limiting global temperature rise to no more than +2°C over pre-industrial. This is at best a questionable interpretation of the Paris Agreement language of limiting the temperature rise to "well below" +2°C; and surely falls significantly short of making "efforts" in support of the more stringent Paris goal of limiting temperature rise to +1.5°C. As discussed by, for example, Glynn et al. (2018), a stronger interpretation of the temperature goal could lead to a GCB which would fall significantly below the minimum of range used here.

Secondly, within method M1, although we have so far considered the full SR15-based GCB range, existential risks of increasing damage are anticipated for large parts of global human society as well as pervasive disruption of the biosphere as a whole as temperatures progressively breach and are sustained above the +2°C level (e.g., Burke et al. 2015). Given the extreme difficulty, and uncertain climate response, to reversing temperature overshoot, then application of the precautionary principle, as explicitly articulated in the United Nations Framework Convention on Climate Change (UNFCCC 1992), would suggest that prudent *policy* should be based on the *lowest* end of the assessed GCB range.

Thirdly, although aligning collective global policy with a GCB must include all CO_2 emissions from all sectors, in the current UNFCCC framework (and specifically including the Paris Agreement), emissions from international aviation and shipping are treated as falling outside the scope of nation state territorial emissions, which introduces significant additional uncertainty into effective governance of mitigation in these sectors (Bows-Larkin 2015). As a minimum, this implies that the GCB available for sharing among nation state quotas should first be reduced by the amount of current and projected emissions from such international aviation and shipping. But such a global level top-slice allocation would implicitly distribute responsibility for such emissions on an equal global per capita basis – despite the highly unequal per capita participation in aviation and shipping between nation states. Accordingly, it may be argued that responsibility should instead be distributed in proportion to relative nation state participation in, or benefits from, international aviation and shipping and thus be counted in a differentiated way against nation state CO_2 quotas. This would mean that highly developed countries, such as Ireland, would see a proportionally much greater reduction in their remaining quotas for strictly domestic CO_2 emissions. It is of note that the UK's long term (2050) mitigation target already covers all sectors, including international aviation and shipping; though the latter have not yet been formally reflected in the UK system of statutory 5-year carbon budgets (Priestley 2019). In relation to aviation specifically, Larsson et al. (2019) provide a timely overview of interactions between top-down global governance and emerging bottom-up interventions at both national and regional scales.

Finally, both the UNFCCC and the Paris agreement imply good-faith commitment to equitable action: under method M1 it may be argued that the pure population division basis, which still omits considerations of historical responsibility and differentiated capacity and vulnerability (Kartha et al. 2018), represents a *minimum* interpretation of such equity.

Based on all these considerations, we recommend that the *minimum* quota from M1 (**Low-GCB-Pop**, 391 $MtCO_2$ from 2015) should be regarded as an *absolute maximum* that could still represent properly good faith alignment with the Paris agreement goals. By that perspective, the total CO_2 quota estimated here by method M2 (on the basis of the Irish National Mitigation Objective for the EGBET sector), clearly indicates a current quota *claim* well in excess of Paris alignment: already by 32% even for the higher ambition **NMO-95** case, and by over 135% for the lower ambition **NMO-80** scenario.

Of course, the method M3 bottom-up *projections* of CO_2 emissions (as opposed to the NMO *aspiration)* indicate a current trajectory that is wholly incompatible with *any* plausible interpretation of good faith action under the Paris Agreement: even on the M3 steady-state scenario (**FLAT**), the Paris-aligned M1 quota (**Low-GCB-Pop**) would be exhausted in just 9 years from 2015 (i.e., as early as 2024).

6.3. CO_2 Debt (and tacit commitment to Negative CO_2 Emissions)

The discussion so far has been strictly in terms of *nett* territorial CO_2 (annual emissions pathways, and cumulative quotas). Following the publication of IPCC Assessment Report 5 (IPCC 2014), it has been recognised that the great majority of its studied scenarios to limit temperature rise to below +2°C involve a presumption of global CO_2 *nett removal* from atmosphere (negative emissions), at large scale, in the second half of this century; and indeed, significant *additional gross removal,* over and above currently projected removals via existing "nature based" interventions such as afforestation and reforestation (Smith et al. 2015; Smith 2016; Griscom et al. 2017), starting from as early as 2030. This largely tacit expectation of greatly enhanced CO_2 sink activity (via a combination of nature based and technological measures) has been highlighted by Anderson and Peters (2016) as raising considerable *moral hazard*, meaning that, in the short to medium term, mitigation of gross CO_2 emissions (at global, regional and national levels) may fall significantly short of what would prudently be required by the Paris temperature goals, but this may be tolerated –

particularly by policy makers confronted by immediate, difficult and conflicting socio-political pressures – on the explicit or implicit premise that this mitigation shortfall *may* still be compensated at some more or less distant future time by rapidly expanding the level of gross CO_2 removals, up to and including the achievement of nett removal on a global basis, which becomes a necessity if atmospheric CO_2 concentration overshoots beyond a level consistent with the Paris Agreement goals. This would be controversial, at the least, as the modelling community has recognised (Fuss et al. 2014; Lenzi et al. 2018), because it summarily transfers very substantial risks (that the required level of additional removals will not be achieved, and temperature targets will therefore be exceeded) to different current and future global communities; communities who have no effective say in these decisions, and, in many cases, may be exposed to disproportionately early and severe climate impacts (Mander et al. 2017; Larkin et al. 2017).

While Anderson and Peters make this analysis primarily at a global level, the logic can be applied at a regional or national level. In the context of the current paper, this is represented in **Fig. 3**. This takes the previously identified good faith Paris-aligned M1 nett quota (**Low-GCB-Pop**) of ~391 $MtCO_2$ and plots its depletion in time under each of the identified national emissions scenarios. By construction, the remaining nett quota approaches zero asymptotically under the M1 **Low-GCB-Pop** exponential mitigation scenario; but for all other scenarios, the remaining nett quota becomes negative at a relatively early point in time (between 2024 and 2032). This effectively represents a situation where a national nett CO_2 *debt* begins to accumulate. By the interpretation suggested here of good faith participation in the Paris Agreement, this “debt” makes explicit an otherwise tacit national commitment to subsequently achieving nett CO_2 *removals* to “repay” it, and progressively return nett cumulative emissions to below the allowed quota. While there is some time flexibility in discharging this debt, this is strictly limited by the global temperature response to radiative forcing: this is likely of the order of 2-3 decades at most (Hansen et al. 2005).

In principle, it does not necessarily follow that such CO_2 debt may be discharged *only* by large scale nett removals at national level. As discussed earlier, it *might* be addressed by international trading of CO_2 quotas; but given the legitimate sustainable development objectives of current relatively low emitting nations, it seems doubtful that such quota trading can emerge at significant scale, with adequately robust monitoring and verification. A somewhat more plausible alternative might be that there could, in the future, be a formalised international trade, not in quotas *per se*, but in CO_2 *removal services*: but even this would face significant difficulties in demonstrating, monitoring and verifying clear additionality to removals that might already be counted towards any given nation’s own Paris commitments (Peters and Geden 2017).

A concept of cumulative CO_2 debt has been previously presented by Gignac and Matthews (2015). This was in the context of a somewhat different approach to equity in global climate change mitigation, based on the contraction and convergence framework. While essentially equivalent to the notion of CO_2 debt introduced above, Gignac and Matthews calculate debt based on a reference year of 1990 rather than 2015 (arguably better representing historical responsibility), and do not explicitly interpret the debt in terms of tacit commitments to negative emissions or CO_2 removal. However, as the global CO_2 budget rapidly approaches exhaustion, the latter interpretation appears to become progressively more physically required.

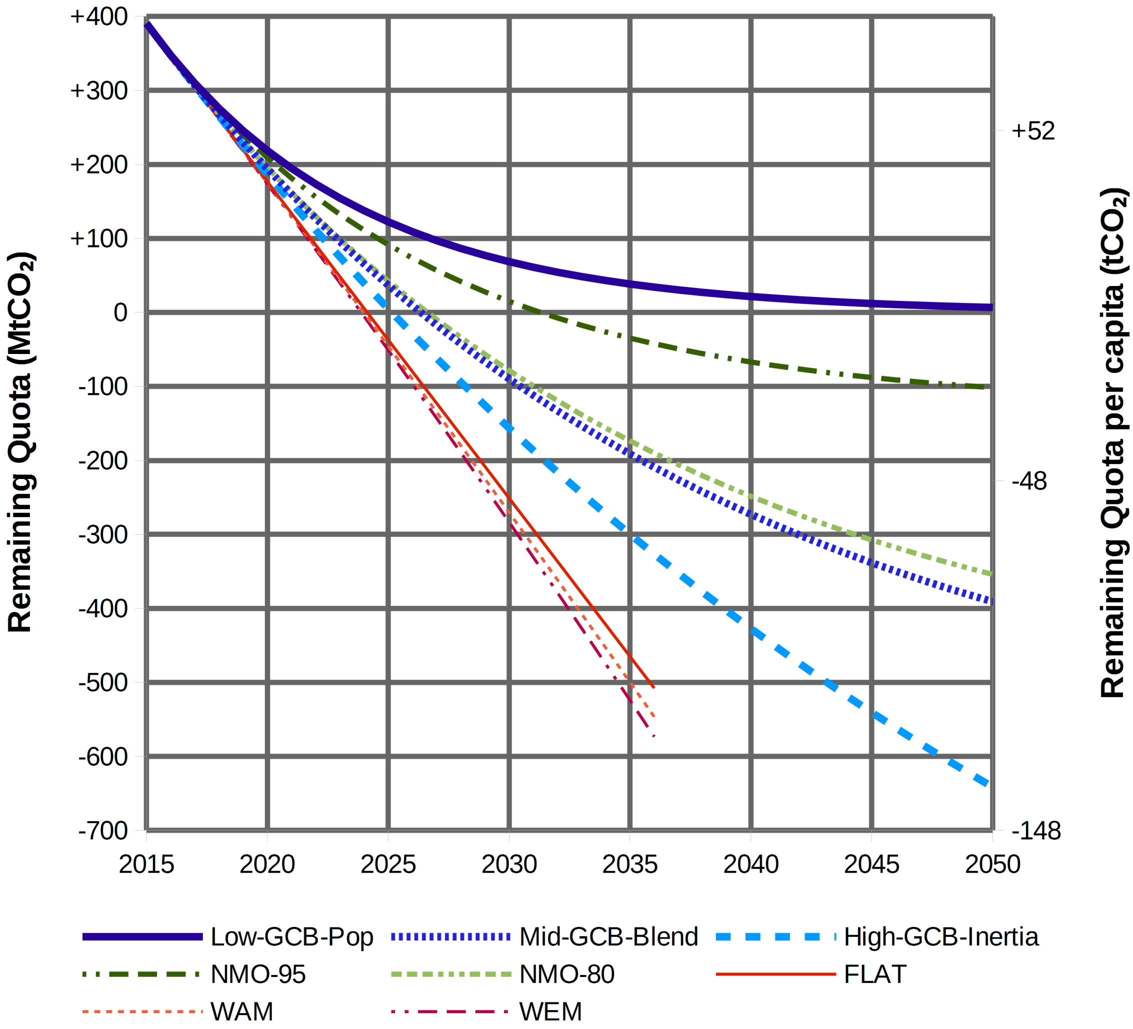

***Fig. 3:** Potentially early emergence of "national CO_2 debt" ("negative remaining CO_2 quota") due to depletion of a Paris-aligned (**Low-GCB-Pop**) nett CO_2 quota for Ireland under all considered mitigation scenarios. By definition/construction, **Low-GCB-Pop** is the only scenario which does not go negative (does not enter CO_2 debt relative to that chosen quota). See text for detailed elaboration of the "CO_2 debt" concept, and definitions of each scenario.*

In summary then, the emergence and accumulation of nett CO_2 debt for any given nation appears to represent a progressively increasing risk of national mitigation policy failure, or what we may call simply "CO_2 bankruptcy". Unfortunately, unlike financial bankruptcy, the physical constraints of the climate system do not admit any analog of "debt restructuring"; rather the consequence would be continuously intensifying risks and impacts, having no fixed upper limits, and being potentially irreversible, which are unilaterally imposed on other communities, more distant in time and/or space.

We recommend therefore that this concept of *cumulative CO_2 debt*, specifically interpreted as commitment to future CO_2 removal, should be adopted as an additional communicative framing between researchers, policy makers and wider society, to make tangible the scale and urgency of national action required, and the large and expanding gaps firstly between the Paris requirements and currently stated national mitigation ambition (NDCs etc.), and secondly between national mitigation ambition and current and immediately projected national action. This may help facilitate early nation-level societal discussion of whether, or how much, CO_2 debt can or should be taken on, and the interaction of this with alternative pathways for earlier, deeper, mitigation of *gross emissions* which would allow that ultimate debt to be reduced or avoided altogether. We specifically recommend that global mitigation strategy should adopt a policy framework, at both national and global levels, which incorporates explicit measures to effect an *automatic negative feedback* between actual cumulative nett CO_2 and both global and nationally targeted quota depletion trajectories. National trajectories should include explicit limits on the allowed level and duration of any temporary excursion into CO_2 debt (Geden and Löschel 2017). That is, if depletion (or, indeed, overshoot into CO_2 debt) were found to be running ahead of the planned pathway, then this should prompt not just achievement of the originally committed year-on-year emissions mitigation rate, but mitigation at a *higher* rate, potentially including achievement of progressively higher gross removals, in order to counteract the ongoing excess quota usage. Such an approach could also allow for progressive improvement in knowledge of the feasibility and costs of removals: if large scale removal services prove difficult or infeasible to scale up, then this should prompt earlier and more severe limitation on the accumulation of CO_2 debt. Such a nation state CO_2 debt perspective, if widely adopted, could support and reinforce the bottom-up, polycentric structure of action underlying the Paris Agreement (Dorsch and Flachsland 2017), specifically enhancing scope for mutual accountability and pressure for adequate collective ambition as a strategy for global mitigation.

6.4. Irish Policy Approach to *non*-CO_2 GHGs

The above analysis has been based on the current Irish *Climate Action and Low-Carbon Development National Policy Position* (DECLG 2014), and specifically its stated point-in-time CO_2 reduction of “at least 80%” by 2050 compared to 1990 levels. However, as noted, that stated target strictly applies only to the “electricity generation, built environment and transport” sectors (EGBET). The Policy Position also specifies a separate parallel target of “an approach to carbon neutrality in the agriculture and land-use sector, including forestry [AFOLU], which does not compromise capacity for sustainable food production.” While emissions in the EGBET sectors are dominated simply by CO_2, emissions from the AFOLU sectors are dominated by methane (CH_4) and nitrous oxide (N_2O), and also involve significant emissions and removals of CO_2 in land-use and forestry. The concept of carbon neutrality in AFOLU is therefore not a straightforward one and will apparently involve aggregation of the effects of different gases to achieve a neutral or nett-zero emissions level.

In current Kyoto-protocol based inventory accounting, this aggregation is done using the so-called GWP-100 equivalence factors to yield CO_2-equivalent or CO_2e values (EPA 2017). On this basis, as of 2017, non-CO_2 gases accounted for approximately 35% of total annual CO_2e emissions (derived from EPA 2018b). This is an unusually high proportion compared to most other nation states, driven primarily by the relatively large, grass-fed, ruminant agriculture sector in Ireland, driving high emissions of both CH_4 and N_2O. However, while GWP-100 is an established approach to aggregating annual emission *rates*, it is well understood that it is not suitable to comparing the effects of different GHGs to *cumulative* CO_2 in a budget (GCB) or quota framework (Allen et al.

2018). On the contrary, the different physical climate effects of CO_2 relative to non-CO_2 emissions mean that the shorter-lived GHGs (such as CH_4 and F-gases) are best treated in a separate policy basket to the longer-lived N_2O and CO_2 (Smith et al. 2012; Solomon et al. 2013). The former might be usefully subjected to an aggregate annual emission rate target, based on GWP-100 or otherwise, which does not necessarily go to nett zero (or negative); while the latter should be *separately* aggregated in a cumulative budget framework, which does imply a nett zero (or potentially negative) requirement. Alternatively, a single, aggregated, cumulative metric may be used, but this should be based not on conventional GWP-100 equivalence, but, for example, on the so called "cumulative CO_2-e*" methodology proposed by (Allen et al. 2018). Of course, corresponding fair share, Paris aligned, national quota targets, now incorporating non-CO_2 pollutants, would have to be re-calculated to reflect any such methodology.

For the purposes of the current paper, we have focussed on CO_2, as the single largest anthropogenic contribution to climate change, and the primary gas that can be directly treated using the cumulative budget framework. In applying this framework to Ireland, we have therefore cut across the EGBET and AFOLU division of the existing National Policy Position, in order to aggregate *all* CO_2, including both emissions and removals from all of: industrial processes, fossil fuel combustion, forestry and land use (collectively, FFI+LULUCF). This is consistent with the use of the global budget range derived from SR15 (IPCC 2018) but as emphasised there, in order to assess the total temperature rise impact and limit this to any Paris-aligned level, this GCB range incorporates assumptions of commensurate mitigation of non-CO_2 pollutants. While it is beyond the scope of the current paper to attempt to assess any detailed division of this separate and additional non-CO_2 mitigation effort among individual nations, it is clear that the national Irish CO_2 quota estimates presented here do pre-suppose *some* fair share level of effective mitigation of non-CO_2 pollutants also, which would necessarily impact primarily on the ruminant agriculture sector.

Unfortunately, as with CO_2, current trends and projections, and indeed national policy in relation to expansion of agricultural production in Ireland, are, in fact, leading to *increasing* rates of emission also of key non-CO_2 gases, particularly CH_4 and N_2O (EPA 2018a, b). At the very least this is a further reason to treat the Irish CO_2 nett quota suggested above (~391 $MtCO_2$, from method M1, **Low-GCB-Pop**) as an *absolute upper limit* to Paris-alignment for CO_2 emissions specifically, across FFI+LULUCF combined.

7. Conclusion

We have presented an assessment of the plausible Paris-aligned, *fair share* nett cumulative CO_2 quota remaining for Ireland from 2015 (method M1) and have compared and contrasted this with both the *aspirations* expressed in the current *National Policy Position* (method M2) and the current national *projections* (method M3). The fair share quota is assessed as a maximum of c. 391 $MtCO_2$ (83 tCO_2 per capita) from 2015, based on the Global Carbon Budget derived from (IPCC 2018) and specific interpretations of prudence and equity. This quota would correspond to a sustained (exponential) reduction in nett annual emissions of over -11% per year (beginning as of 2016). By contrast, the CO_2 mitigation target indicated in the National Policy Position is assessed as corresponding to nett reduction rates in the range -8.3% per year (higher ambition) down to -4.7% per year (lower ambition); while projections based on current and immediately planned mitigation measures indicate the possibility, instead, of sustained *increases* in emissions at a rate of the order of +0.7% per year.

For this case study example, it is clear then that there is a very large gap between Paris-aligned ambition and current political and policy reality on the ground; with a significant risk of early emergence of CO_2 debt, and tacit reliance on rapid deployment of negative CO_2 emissions through CO_2 removal interventions and technologies. This involves a significant risk that these technologies may fail to deliver, as their development is currently highly speculative at relevant required scale and feasible cost (Larkin et al. 2017). While the detailed policy situation will clearly differ with respect to different CDR technologies (Minx et al. 2018) and from country to country (e.g., Smith et al. 2016; McGeever et al. 2019) we recommend that this methodology, and in particular the use of CO_2 quota depletion as a policy metric (**Fig. 3**), should be applied in other individual countries or regions (sub-national or supra-national), as a specific basis for strategy to achieve effective *global* climate change mitigation.

In relation to energy systems decarbonisation, the key message from this analysis is that, for developed countries with heavy fossil fuel reliance, current approaches to decarbonisation are grossly inadequate. The corresponding risk of catastrophic policy failure is starkly illustrated by the Low-GCB-Pop CO_2-debt trajectories for developed nations (as we show in the case of Ireland), graphically stating the urgency of near-term action now required particularly to reduce unabated fossil fuel combustion radically. By contrast, NDC and mitigation gap analyses tend to stress the long-term and sectoral measures or percentage renewable energy penetration targets that can divert attention from the urgent mitigation priority of reducing fossil carbon combustion quickly. From a climate perspective, the core recommendation for both national and global mitigation strategy must be the prioritisation of achieving nett zero CO_2 emissions energy systems *within* a stated overarching nett CO_2 cumulative quota constraint, limiting commitment to CO_2 debt, and rigorously respecting a nett CO_2 emissions rate pathway which is *commensurate* with satisfying this cumulative constraint.

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