ENVIRONMENTAL RESEARCH
LETTERS

PERSPECTIVE • OPEN ACCESS

Defining a ‘Paris Test’ of national contribution to global climate mitigation: the Irish exemplar

To cite this article: Barry McMullin *et al* 2024 *Environ. Res. Lett.* **19** 041006

ENVIRONMENTAL RESEARCH
LETTERS

PERSPECTIVE

Defining a 'Paris Test' of national contribution to global climate mitigation: the Irish exemplar

Barry McMullin[1,*], Paul R Price[1] and Aideen O'Dochartaigh[2]

[1] Faculty of Engineering and Computing, Dublin City University, Dublin, Ireland
[2] DCU Business School, Dublin City University, Dublin, Ireland
* Author to whom any correspondence should be addressed.

E-mail: barry.mcmullin@dcu.ie

Keywords: Paris Agreement, carbon budgets, climate mitigation, climate justice

Supplementary material for this article is available online

OPEN ACCESS

RECEIVED
10 November 2023

REVISED
18 March 2024

ACCEPTED FOR PUBLICATION
21 March 2024

PUBLISHED
9 April 2024

1. Introduction: framing 'consistency' with the Paris Agreement

The Paris Agreement [1] (hereafter 'PA') created a framework for global action commensurate with the original UNFCCC objective of *preventing dangerous anthropogenic* climate change [2, 3] (in so far as this is still possible). PA Article 2(1) specified, for the first time, a globally agreed quantitative mitigation objective in the form of a global temperature rise limit: 'holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C'. Crucially, PA Article 2(2) committed the Parties to implementation that reflects '… equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances' (CBDR-RC). PA Article 3 then prescribed a bottom-up architecture, placing the onus on the Parties *themselves*—nation states and regional blocs such as the European Union (EU)—to ensure that their mitigation plans, presented in statements of *voluntary* nationally determined contributions, adequately reflect these objectives and obligations.

As a corollary we suggest that any good faith Party to the Agreement, in developing its mitigation objectives, should itself explicitly and transparently *test* these for consistency with the Agreement; and continue to do so on an ongoing basis as circumstances (both global and local) evolve.

However: while it is commonplace to see political *assertions* that this or that national plan is 'aligned' with the Paris Agreement, it is much less common to see this supported by transparent quantitative analysis, grounded in explicit provision for CBDR-RC. One interesting exception is the case of *Ireland*. In this Perspective, we briefly describe, and also critique, this exemplar case of a transparent national 'Paris Test' of domestic mitigation ambition. In the conclusion, we relate this case to other PA Parties and consider the need for broader adoption of such an approach.

2. The Irish exemplar

In July 2021, the Irish parliament (Oireachtas) enacted climate legislation [4] (hereafter 'the Act') which mandated the adoption of successive 5 year 'carbon budgets' (legally binding constraints on total domestic GHG emissions), structured into a rolling 15 year programme. Recommendations for the quantitative budget amounts in each period are first formulated by an independent statutory body, the Irish climate change advisory council (CCAC), and submitted for legal adoption (potentially with revision) by the full parliament. Once adopted, successive Governments are legally required to bring forward and implement policies and measures to ensure 'in so far as practicable' that total emissions over each period are held within the required budget limit. By default, any excess of emissions in a given period should be carried forward and subtracted from the budget for the immediately following period.

Most critically, the Act requires that the actors involved (CCAC, Government, Ministers) must discharge their prescribed functions '… in a manner … *that is consistent with* … the steps specified in Articles 2 and 4(1)' of the Paris Agreement [4] (s. 3(3)(a)(ii) as amended; emphasis added). This PA consistency requirement therefore encompasses the (rolling) process of adopting the quantitative budgets.

Accordingly, in formulating its recommendations for the first 15 year budget programme (covering 2021–2035, in three 5 year periods) the CCAC considered explicitly how to assess these for PA consistency. This is not specified in detail in the Act;

so the CCAC itself formulated an explicit, quantitative *Paris Test*. The methodology of this Test, and the outcomes of applying it to their budget recommendations, were presented briefly in their published *Technical Report on Carbon Budgets* [5], and elaborated in a further advisory note [6]. A supporting spreadsheet was shared with the authors on request, and is publicly archived [7]. The outcome of the Test is shown in figure 1(a). The methodology is somewhat cumbersome, but will be summarised here as concisely as possible.

Five bottom-up annual national GHG emissions scenarios (disaggregated by gas) were first developed, covering the period from 2021 to 2050. These were constrained to meet specific guidance in the Act, namely 'to provide for' total 2030 emissions, aggregated in CO_2eq terms (via GWP_{100}), being 51% below the 2018 level, and that emissions beyond 2050 should be 'climate neutral'. The Act defines 'climate neutral' as a situation where '… greenhouse gas emissions are balanced or exceeded by the removal of greenhouse gases'. This was interpreted as requiring that annual total emissions and removals should net to zero in 2050 *when aggregated in CO_2we terms*, via (a version of) the GWP* aggregation method [9][3]. The scenarios *differed* in the distribution of emissions between CO_2, CH_4 and N_2O, while representing similar aggregate emissions in CO_2eq. The motivation for developing multiple bottom-up scenarios that differ primarily in CO_2 vs non-CO_2 mitigation is that Irish non-CO_2 emissions are dominated by N_2O and CH_4 from agricultural activities. Thus, the scenarios map closely onto potential subsequent policy trade-offs, within fixed CO_2eq budgets, between levels of mitigation in agriculture as compared to other activities (primarily energy related but also including significant net emissions from LULUCF).

It is important to emphasise the two distinct GHG aggregation methods that are being used in different contexts of the methodology: CO_2eq (via GWP_{100}) and CO_2we (via GWP*). CO_2eq/GWP_{100} is the standard method in UNFCCC inventory reporting, and has been stipulated as the basis for expressing the Irish *statutory budgets*. However, cumulative CO_2eq provides a poor proxy for temperature impact, especially if, as is the case for Ireland, the emissions inventory contains a significant component of CH_4 [10, 11].

[3] We note that the definition of 'climate neutrality' in the Irish Act is distinct from, but clearly modelled on, PA Article 4(1); and similar to PA Article 4(1), it is open to potentially different interpretations. Further, PA Article 4(1) is expressed as being 'in order to achieve' the PA Article 2 *temperature* goal. In our view, this is one reason why the Irish CCAC Paris Test example is internationally notable: it proposes, on behalf of one Party, relatively precise interpretations of PA Articles 2 and 4(1), and a specific way of relating them. Of course any such Party-specific interpretations are properly subject to critique and challenge by other Parties: but that is beyond the immediate scope of this Perspective.

The CCAC took the view that the 'climate neutral' requirement of the Act should be interpreted in the sense of Irish emissions contributing no *additional* forcing (warming commitment) beyond 2050. Zero aggregate annual CO_2we (via GWP*) beyond 2050 is then a defensible proxy for this. It must be acknowledged here that the interpretation of 'climate neutrality' and its relationship with temperature goals, is a complex and contested topic, with its own extensive literature (e.g. [12–15]); but this Perspective restricts itself to following through the implications of this particular interpretation adopted by the Irish CCAC.

It follows that, even though the scenarios are characterised by similar CO_2eq budgets over 2021–2035, and similar total cumulative CO_2eq over the full 2021–2050 period, they differ significantly in CO_2we terms, which is to say warming commitment. Accordingly, they require separate assessment for consistency with the PA 2(1) temperature rise objective.

The CCAC 'Paris Test' for any given national GHG scenario then consists in making an estimate of the steady-state (post-2050) contribution to warming commitment, 'upscaling' this to the global level (on a specified interpretation of 'equity'), and comparing that to an estimate of 'available' warming, based on the PA 2(1) global temperature objective. If the upscaled warming is less than the 'available' warming threshold then the Test is passed. If all scenarios pass, then their (approximately) common underlying 15 year aggregate (CO_2eq) GHG budget programme is deemed 'consistent' with the Paris temperature objective.

The warming commitment contribution for each scenario is (crudely) estimated via the cumulative CO_2we from the scenario start date (start 2021) until it reaches steady-state (end 2050, by design), scaled by a (central estimate of) the Transient Climate Response to Cumulative CO_2 Emissions (TCRE) per IPCC AR6 WGI [16].

The 'upscaling' basis from national to global level is chosen as the ratio of the Irish population to the global population as of the scenario start year. This is motivated via Kant's 'categorical imperative' [17]. It is evidently intended to reflect the PA CBDR-RC provisions, via a form of equal-per-capita (EPC) sharing of the globally 'available' warming estimated to be still remaining as of the scenario start date.

This 'available' global warming threshold is estimated in a somewhat obscure way, by taking the difference between 1.5 °C and the estimated global temperature rise already experienced at a stated reference date, and then further subtracting an estimate of peak *non*-CO_2 warming, based on a 50% probability of not exceeding 1.5 °C total rise. It is thus an estimate of warming specifically attributable to CO_2 available from the stated date onward. The CCAC used the start of 2020 as the reference date, and calculated

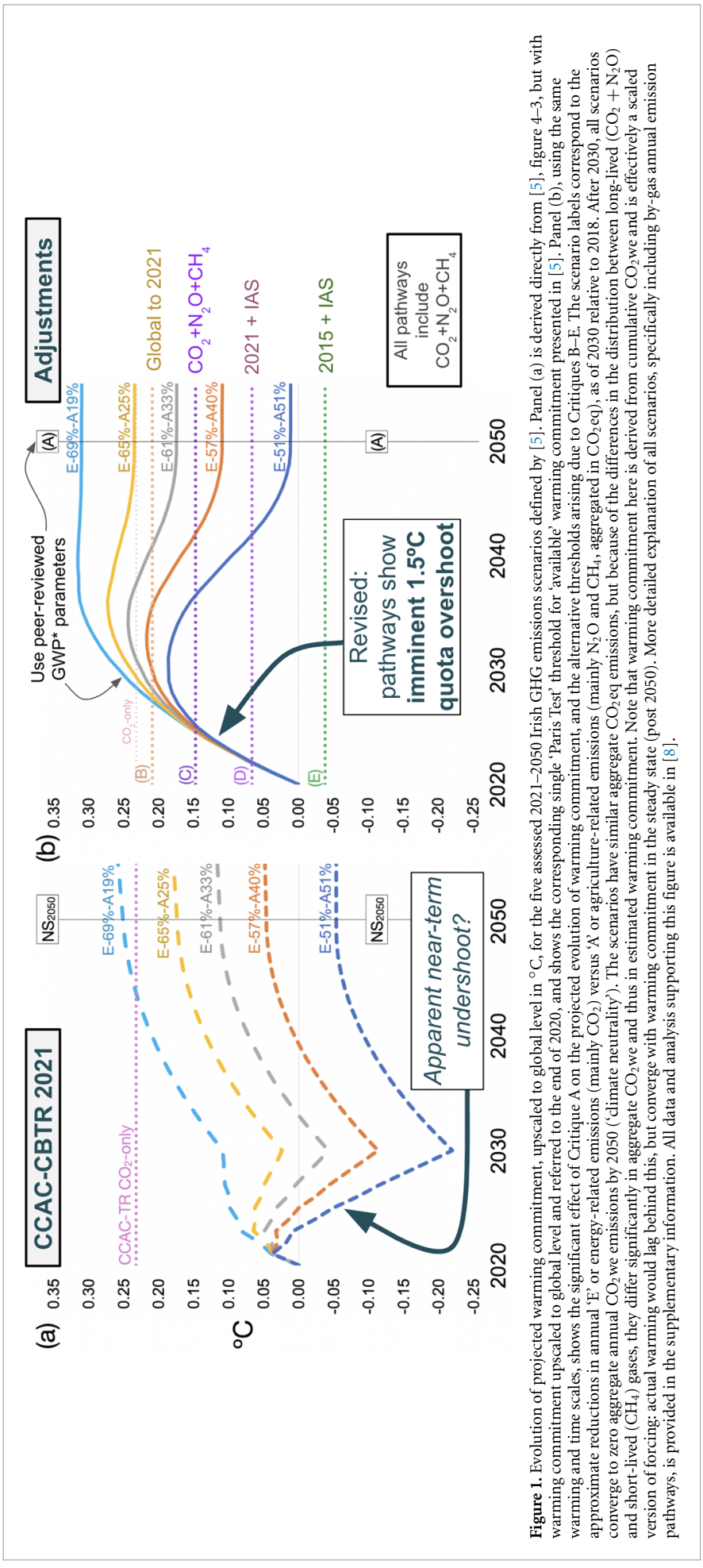

Figure 1. Evolution of projected warming commitment, upscaled to global level in °C, for the five assessed 2021–2050 Irish GHG emissions scenarios defined by [5]. Panel (a) is derived directly from [5], figure 4–3, but with warming commitment upscaled to global level and referred to the end of 2020, and shows the corresponding single 'Paris Test' threshold for 'available' warming commitment presented in [5]. Panel (b), using the same warming and time scales, shows the significant effect of Critique A on the projected evolution of warming commitment, and the alternative thresholds arising due to Critiques B–E. The scenario labels correspond to the approximate reductions in annual 'E' or energy-related emissions (mainly CO_2) versus 'A' or agriculture-related emissions (mainly N_2O and CH_4, aggregated in CO_2eq), as of 2030 relative to 2018. After 2030, all scenarios converge to zero aggregate annual CO_2we emissions by 2050 ('climate neutrality'). The scenarios have similar aggregate CO_2eq emissions, but because of the differences in the distribution between long-lived ($CO_2 + N_2O$) and short-lived (CH_4) gases, they differ significantly in aggregate CO_2we and thus in estimated warming commitment. Note that warming commitment here is derived from cumulative CO_2we and is effectively a scaled version of forcing; actual warming would lag behind this, but converge with warming commitment in the steady state (post 2050). More detailed explanation of all scenarios, specifically including by-gas annual emission pathways, is provided in the supplementary information. All data and analysis supporting this figure is available in [8].

the corresponding available warming threshold as 0.23 °C. (We note that this procedure is problematic in multiple respects: we will revisit it in the Critique section below.)

This procedure yields projected global (upscaled) warming commitment for each of the scenarios, as shown in figure 1(a). As already anticipated, despite all scenarios corresponding to similar cumulative CO_2eq emissions, they show significantly different warming commitments, according to each scenario-specific distribution of gases. All but one of the scenarios is shown as projecting (somewhat surprisingly) a sharp short-term *reduction* in warming commitment (up to 2030), and as unequivocally passing the Test when warming commitment stabilises (in 2050). The one remaining scenario[4] lacks any short-term reduction in warming commitment, and marginally exceeds the PA available warming limit by 2050. On the basis of this assessment of the scenario ensemble, and acknowledging that the methodology tests only 'a minimum level of consistency with the Paris temperature goals', the CCAC nonetheless concluded that 'the proposed carbon budgets are broadly consistent with the legislated criteria regarding the UNFCCC and the Paris Agreement' [5] (p 75).

The final quantitative budgets proposed were 295 $MtCO_2$eq, for 2021–2025, and 200 $MtCO_2$eq for 2026–2030, representing reductions relative to constant emissions at a nominal pre-pandemic level (2018) of c. 12% and 40% respectively. These quantitative budgets were adopted, without change, by Ireland's parliament in April 2022, thus becoming legally binding under the Act.

It is important to recognise and commend the achievement here. Firstly, that the Irish parliament voluntarily adopted a statutory domestic emissions budget framework that was explicitly bound to expert assessment of consistency with the (collective) PA temperature objective. Secondly, that the CCAC, in discharging this assessment obligation, provided clear and transparent access to their methodology, including articulation of some relevant (necessarily value-laden) equity judgements (specifically the EPC principle for upscaling from national to global level). Thirdly, that even with the complexity of a multi-gas budget system, legally stipulated to use CO_2eq aggregation, the CCAC nonetheless identified a pragmatic, scientifically well-founded, mechanism to assess temperature impact via a scenario exploration of the distribution of emissions across gases, coupled with the (relatively novel) GWP*/CO_2we aggregation approach. Finally, this work was conceived and executed within an extremely tight timeframe: the legislation was formally enacted in July 2021, and the CCAC recommended the first budget programme in October 2021.

[4] Labelled 'E69%–A19%', and representing the minimum assessed level of reductions in agriculture relative to energy-related GHGs.

3. Critique

Of course, it is important to consider whether there are aspects of this exemplar that should be improved: both within the specific Irish context (reassessment is required on a 5 year cycle as the budget program is rolled forward), and in considering any generalisation to other PA Parties. Below, we identify six specific points (A–F) for potential improvement, while still staying within the overall design of the CCAC Test. Point A affects the projected overall temporal dynamics and stabilisation levels of all scenarios. Points B–E all affect the assessed *warming threshold* for PA consistency, with each one suggesting a progressively lower threshold. Points A-E are quantitative and estimates of their potential effects are illustrated in figure 1(b). Point F, though not quantified here, is of considerable conceptual significance.

A. As noted, the CCAC adopted the GWP* methodology to translate the by-gas emissions scenarios into estimated warming commitment. However: based on review of the supporting spreadsheet, it is clear that the calculations adopted a time averaging period for CH_4 flows (Δt) of 1 year rather than the standard 20 years recommended for short lived GHGs under GWP*; further, they did not use the most recently recommended values for other parameters of this methodology [11]. Figure 1(b) shows the result of applying updated/corrected GWP* parameters. The temporal dynamic is dramatically different. Contrary to [5], instead of a sharp near-term reduction in warming commitment, the corrected projections are for very significant near-term *overshoot*, with subsequent decline to the 2050 steady-state levels. This (correct) representation of the national overshoot dynamic is primarily due to the correction in Δt, and now strongly emphasises the essential prudential role of immediate and deep mitigation action [18], whereby 'uncertainty is not our friend' [19]. The correction of Δt, together with updating of other parameters also leads to significantly higher *steady-state* warming commitments, which are critical for the ultimate Test outcomes. We also note that though cumulative GWP* is preferable to cumulative GWP_{100} in estimating warming commitment, it is still a very simplistic indicator [20], which neglects the much more complex climate system dynamics assessed, for example, by IPCC AR6 WGI [16]. Thus, there is a strong argument to entirely replace the use of GWP* in the CCAC Test with a reduced complexity climate model [21]. However, we do not explore that further here, as it goes beyond our

chosen scope (of working within the original CCAC methodology).

B. The CCAC estimate of available warming at the global level is derived from IPCC AR6; but that is referenced to the *start* of 2020. Whereas the estimated warming contributions from the (upscaled) Irish emissions scenarios are referenced to the *end* of 2020 (start of 2021). This is a clear discrepancy. Accordingly, the available warming threshold should be reduced by an amount corresponding to global GHG emissions in 2020.
C. The CCAC estimate of available warming at the global level is based on the contribution of CO_2 *only*; whereas, the Irish emissions scenarios include *all* GHGs. Accordingly, the warming threshold should reflect global emissions of all GHGs (but should indeed exclude non-GHG effects, especially aerosols).
D. The Irish legislation stipulates that the *budgets* should be expressed exclusive of emissions from international aviation and shipping (IAS). However, legal analysis indicates that IAS emissions *do* fall within the mitigation responsibilities of the PA Parties [22]. Accordingly, the assessment of PA consistency should still allow for them: that is, either an Irish contribution to IAS emissions should be included in the national scenarios, or (equivalently) the warming threshold should be reduced by the estimated, upscaled, total cumulative effect of those Irish IAS emissions. In figure 1(b) line (D) we use the latter method, upscaling the temperature effect of cumulative emissions from Irish IAS emissions bunker fuels, as projected up to 2040 [23], followed by linear reduction to zero by 2050.
E. The CCAC effectively adopt the start year of their emission reduction *scenarios* (2021) as an overall historical reference year for their *Paris Test*, but without any explicit motivation for why these should coincide. The choice of Test reference year is, in fact, highly value laden, reflecting tacit CBDR-RC positions, with potentially very significant effect on the outcomes. It essentially separates global anthropogenic contributions to climate change between a *strictly common* phase with no differentiation of mitigation responsibility among the PA Parties (mitigation responsibility is effectively 'globalised' up to that point), and a *differentiated* phase with different Parties carrying 'common but differentiated' mitigation responsibilities only from then onward. It should be noted that the CCAC use of GWP* raises a distinct and contested question around whether this metric *in itself* may introduce a distinct risk of 'unintentional unfairness' by tacitly 'grandfathering' an additional 'avoidable' emissions share into the future based on differentiated historical levels of CH_4 emissions in particular (see [24–26]). Nonetheless, for our immediate purposes here we limit ourselves to examining the effect of changing the historical reference year while continuing to use the CCAC GWP* methodology. In general, under an EPC sharing approach, Parties with ongoing per capita emissions that are higher than the global average, benefit from delayed differentiation (a later reference year) and *vice versa* for Parties with ongoing per capita emissions below the global average. Given the UNFCCC and PA commitments to CBDR-RC, the choice of reference year in a PA Test therefore merits clear and explicit motivation. In this light, The CCAC choice of 2021 seems very problematic, tacitly finessing differentiation of historical responsibility prior to that year. A case can be made for much earlier years, such as the adoption of the Paris Agreement itself (2015), or of the adoption of the UNFCCC (1992), or the year of the IPCC First Assessment Report (1990) [27]. For illustrative purposes, line (E) in figure 1(b) shows the potential for a significant effect on the Test outcomes via an adjustment of the warming threshold that would reflect a *minimal* shift of the sharing reference year back to just 2015. As the per capita warming commitment of Ireland's emissions for 2015–2021, including IAS, significantly exceeded the global per capita contribution over that period, the warming threshold still available to Ireland is further reduced: in fact, now falling *below* the starting level for all the CCAC scenarios. Equivalently, this can be restated as saying that if global per capita emissions had risen to the Irish level over that period, then the global budget for a 50% chance of meeting the 1.5 °C limit, (expressed in CO_2we terms for $CO_2 + N_2O + CH_4$) would already have been exceeded by end 2020 (i.e. a state of global budget overshoot would already have been reached).
F. Finally, we note that, quite aside from the issues of differentiating historical responsibility via the choice of reference year, the choice of EPC upscaling for effort sharing in ongoing mitigation is itself also highly value laden [28]. While the CCAC does offer *some* motivation in this case (the Kantian 'categorical imperative'), it is at least questionable whether this represents an adequate reflection of CBDR-RC. In particular, EPC does not reflect any differentiation among the Parties in relation to relative severity of (per capita) climate *impacts* or (per capita) *capacity to act* (either in mitigation or adaptation). There is, of course, an extensive literature dealing with alternative approaches to mitigation effort sharing (see e.g. [29]) and it would certainly be appropriate for the CCAC to subject its approach to further critical assessment.

In summary, figure 1(b) shows that, as each of the quantitative adjustments A–E are applied, fewer

of the CCAC scenarios meet the Test threshold. If all were applied, then the conclusion would be that Ireland was *already* in overshoot relative to its cumulative warming share even before the first budget programme formally started in 2021. As none of the scenarios reverse this by 2050, all would then decisively fail the Test. Taken together, these points clearly suggest a need for much more robust Test design, which is likely to prescribe significantly smaller budgets, becoming net negative (in CO_2eq terms) well within the upcoming second cycle of the Irish budget programme (extending to 2040). This already mandates a radically stronger ('emergency' scale) national mitigation response in the immediate term.

4. Conclusion

Declarations of a climate 'emergency' have become relatively commonplace at diverse governance levels in recent years: but in general, they neither present quantitative analysis of the scale of response that is actually required at global level, nor offer an equitable basis for sharing that effort. That is, they are infused with *implicatory denial*, where:

> …What is denied or minimized are the psychological, political, and moral implications of the facts for us. People fail to accept responsibility for responding; they fail to act when the information says they should … [30]

Notwithstanding the relatively weak force of the Paris Agreement, *pro tem* it is the only existing framework for collective global climate action. It is therefore incumbent on good faith Parties to the Agreement to move beyond implicatory denial, and to use the PA framework to bring forward, on a collective global basis, *near term* action that is both commensurate with the PA temperature objective and genuine in its commitment to CBDR-RC. There are emerging examples of Parties starting to contextualise domestic mitigation efforts in terms of their 'share' of meeting the global temperature objective (e.g. the EU [31, 32] and Aotearoa (New Zealand) [33]). However, Ireland has arguably provided the most explicit example to date of a PA Party *quantitatively testing* its voluntary domestic commitments for consistency with the PA objectives under an explicitly stated CBDR-RC sharing approach. Its Paris Test (with the refinements proposed above) provides a strong starting point for such assessment: other PA Parties could usefully adopt and tailor this Test according to individual circumstances.

But while a robust Paris Test is important in providing a bottom-up articulation of an equitable and commensurate Party-level contribution to meeting the PA goals, the critical next step is for governments to communicate and act upon the *implications* of such analysis. Unfortunately, the uncomfortable reality is that even in Ireland, over half-way through its first formal 5 year carbon budget period (at the time of writing), there is already a rapidly widening gap between actual emissions and even the *minimally* Paris-consistent budgets that have been adopted [34]. As we have seen in the recent examples of the global financial crisis and the Covid-19 pandemic, the hallmark of a *real* emergency is the triggering of responses of a scale and nature that would be politically unthinkable in 'normal' times. We therefore urge all good faith parties to the Paris Agreement to acknowledge and mobilise the genuinely *emergency scale* responses that are now so manifestly required.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://zenodo.org/doi/10.5281/zenodo.10090749.

Acknowledgments

The authors acknowledge the support of Dublin City University for all aspects of this work. The article was significantly improved by the comments and suggestions of the anonymous peer reviewers. Errors remain the responsibility of the authors.

Funding

This work was supported by a Climate Change Advisory Council (Ireland) Fellowship awarded to PRP, and supervised by BMcM and AOD. The award was funded by the Environmental Protection Agency (Ireland) on behalf of the Government of Ireland.

ORCID iDs

Barry McMullin https://orcid.org/0000-0002-5789-2068
Paul R Price https://orcid.org/0000-0002-7995-6712
Aideen O'Dochartaigh https://orcid.org/0000-0003-1209-2371

References

[1] UNFCCC 2015 Decision 1/CP.21: adoption of the Paris Agreement (United Nations) FCCC/CP/2015/10/Add.1 (available at: https://tinyurl.com/ParisClimate2015)
[2] UNFCCC 1992 United nations framework convention on climate change (United Nations) (available at: http://tinyurl.com/od8tdn6)
[3] Mace M J 2016 Mitigation commitments under the Paris Agreement and the way forward *Clim. Law* **6** 21–39
[4] Oireachtas 2021 Climate action and low carbon development (Amendment) act 2021 (Houses of the Oireachtas (Parliament of Ireland)) No. 32 of 2021 (available at: https://tinyurl.com/IE-ClimateAct2021)
[5] CCAC 2021 *Technical report on carbon budgets* (Climate Change Advisory Council (Ireland)) (available at: https://tinyurl.com/CCAC-CB-TR)

[6] CCAC Secretariat 2021 Consistency of the bottom up national scenarios with the Paris Agreement temperature goals (Climate Change Advisory Council (Ireland)) (available at: https://tinyurl.com/CCAC-ParisTest-2021)
[7] CCAC 2022 Ireland scenarios with LULUCF 2021 [Excel workbook] (Secretariat of the Climate Change Advisory Council of Ireland) (https://doi.org/10.5281/zenodo.7075669)
[8] McMullin B, Price P R and O'Dochartaigh A 2024 *Ireland Carbon Budget Paris Test: Reanalysis dataset* (Dublin City University) (https://doi.org/10.5281/zenodo.10090749)
[9] Lynch J, Cain M, Pierrehumbert R and Allen M 2020 Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants *Environ. Res. Lett.* **15** 044023
[10] Allen M R, Shine K P, Fuglestvedt J S, Millar R J, Cain M, Frame D J and Macey A H 2018 A solution to the misrepresentations of CO_2-equivalent emissions of short-lived climate pollutants under ambitious mitigation *npj Clim. Atmos. Sci.* **1** 16
[11] Smith M A, Cain M and Allen M R 2021 Further improvement of warming-equivalent emissions calculation *npj Clim. Atmos. Sci.* **4** 1–3
[12] Allen M R, Friedlingstein P, Girardin C A J, Jenkins S, Malhi Y, Mitchell-Larson E, Peters G P and Rajamani L 2022 Net zero: science, origins, and implications *Annu. Rev. Environ. Resour.* **47** 849–87
[13] Fuglestvedt J, Rogelj J, Millar R J, Allen M, Boucher O, Cain M, Forster P M, Kriegler E and Shindell D 2018 Implications of possible interpretations of "greenhouse gas balance" in the Paris Agreement *Phil. Trans. R. Soc.* A **376** 20160445
[14] Tanaka K and O'Neill B C 2018 The Paris Agreement zero-emissions goal is not always consistent with the 1.5 °C and 2 °C temperature targets *Nat. Clim. Change* **8** 319–324
[15] van Soest H L, den Elzen M G J and van Vuuren D P 2021 Net-zero emission targets for major emitting countries consistent with the Paris Agreement *Nat. Commun.* **12** 2140
[16] IPCC 2021 AR6 WGI summary for policymakers (available at: https://tinyurl.com/IPCC-AR6-WG1-SPM)
[17] Johnson R and Cureton A 2022 Kant's moral philosophy *The Stanford Encyclopedia of Philosophy* ed E N Zalta and U Nodelman (Metaphysics Research Lab, Stanford University)
[18] Geden O and Löschel A 2017 Define limits for temperature overshoot targets *Nat. Geosci.* **10** 881–2
[19] Knutti R and Rogelj J 2015 The legacy of our CO_2 emissions: a clash of scientific facts, politics and ethics *Clim. Change* **133** 361–73
[20] Mastropierro M, Tanaka K, Melnikova I and Ciais P 2023 'Testing GWP* to quantify non-CO_2 contributions in the carbon budget framework: the case under overshoot scenarios *In Review Preprint* (https://doi.org/10.21203/rs.3.rs-3206717/v1) (posted online 26 July 2023, accessed 18 September 2023)
[21] Nicholls Z R J 2021 On the state of reduced complexity climate modelling *PhD Thesis* The University of Melbourne (available at: http://hdl.handle.net/11343/281894)
[22] Dehon E 2021 Legal Advice regarding Inclusion of emissions from international aviation and shipping in nationally determined contributions (Cornerstone Barristers Legal opinion commissioned by Transport and Environment) (available at: https://tinyurl.com/Dehon-PA-IAS)
[23] EPA 2022 Ireland's greenhouse gas emissions projections 2021–2040 (Environmental Protection Agency (Ireland)) (available at: https://tinyurl.com/EPA-IE-GHG-2021-2040)
[24] Rogelj J and Schleussner C-F 2019 Unintentional unfairness when applying new greenhouse gas emissions metrics at country level *Environ. Res. Lett.* **14** 114039
[25] Cain M, Shine K, Frame D, Lynch J, Macey A, Pierrehumbert R and Allen M 2021 Comment on 'Unintentional unfairness when applying new greenhouse gas emissions metrics at country level' *Environ. Res. Lett.* **16** 068001
[26] Rogelj J and Schleussner C-F 2021 Reply to comment on 'Unintentional unfairness when applying new greenhouse gas emissions metrics at country level' *Environ. Res. Lett.* **16** 068002
[27] IPCC 1990 *IPCC First Assessment Report* (World Meterological Organisation (WMO)) (available at: https://tinyurl.com/IPCC-FAR-1990)
[28] Dooley K *et al* 2021 Ethical choices behind quantifications of fair contributions under the Paris Agreement *Nat. Clim. Change* **11** 300–5
[29] van den Berg N J *et al* 2019 Implications of various effort-sharing approaches for national carbon budgets and emission pathways *Clim. Change* **162** 1805–22
[30] Campbell I 2023 Climate denial: literal, interpretive and implicatory (CarbonIndependent.org) (available at: www.carbonindependent.org/147.html)
[31] European Commission 2018 In-depth analysis in support of the commission communication Com(2018) 773 (European Commission Brussels) (available at: https://tinyurl.com/EC-2018-773-supp)
[32] ESABCC 2023 Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050 (European Scientific Advisory Board on Climate Change) (available at: https://tinyurl.com/ESABCC-2040-EU-Climate)
[33] CCC-NZ 2021 Ināia tonu nei: a low emissions future for Aotearoa (He Pou a Rangi/Climate Change Commission of Aotearoa/New Zealand) (available at: https://tinyurl.com/CCC-NZ-2021-LE-Future)
[34] An Taisce 2023 Ireland's carbon budgeting situation is far more pressing than the EPA projections report has indicated (An Taisce, The National Trust for Ireland Media release) (available at: https://tinyurl.com/AT-GHG-2023)