Rapid literature review of the setting of national carbon budgets, framed within the Irish context, with recommendations for Ireland's first and second carbon budgets

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Executive Summary

What contribution should Ireland make to the global goals set out in the Paris Agreement, and what trajectory should it take to meet its own domestic decarbonisation targets?

Ireland's near-term target, now in a Bill before the Oireachtas at time of writing, is for 51% decline in annual greenhouse gas emissions from 2018 levels by 2030; in this report, this is assumed to be on a GWP100 basis, at least for the long-lived greenhouse gases. The legislation also contains a requirement for cumulative carbon budgets for consecutive five-year periods, starting with 2021-2025. The 2030 target constrains the range in which the first two carbon budgets might sit, given the incremental nature of most mitigation measures.

By accounting for the global carbon budget, an appropriate effort-sharing by Ireland as part of its contribution to the UNFCCC Paris Agreement, and an understanding of emissions trajectories that are practicable, this report calculates suitable budgets for the first two budget periods, 2021-2025 and 2026-2030.

Methane (CH_4), as a relatively short-lived greenhouse gas, has a more complicated relationship with global radiative forcing than the long-lived greenhouse gases do. In addition, the Amendment Bill requires explicit accounting for biogenic methane. To account for these factors, this report recommends following New Zealand's precedent of a split-gas approach.

This report proposes the following budgets and targets:

Target/Budget	MtCO2e (long-lived)	All methane $KtCH_4$
2021-2025 budget 1	229	3010
2026-2030 budget 2	156	2740
2030 target	25.3	527
2050 target	0	312

We also propose a significant degree of flexibility to be used between these two budgets, given the difficulty of the main task in hand, to meet the 51% 2030 target.

These targets and budgets would enable Ireland to make its fair contribution to the Paris Agreement. Given the presence of several different effort-sharing methods, and uncertainty over the actual global carbon budgets available, there is considerable flexibility in the interpretation of what compliance with the Paris Agreement might mean. Nevertheless, even under the most stringent effort-sharing method, these budgets represent a very high probability of compliance with the goal of keeping warming to below 2°C above pre-industrial levels, with a high probability of keeping it below 1.75°C.

These numbers will raise challenging questions about feasibility (which is dominated by the issues of affordability and acceptability, but also includes the issue of near-term availability of some mitigation options), and about the effort-sharing between different sectors, as indeed the 51% target itself does. The split-gas target offers more chance of finding a feasible route to deliver it, than a single-gas target based on GWP100 would.

The Global Carbon Budget

In recognition that IPCC publications, by their nature, lag the cutting edge of research, this report looks to the most recent literature to assess what the remaining global carbon budgets might be. Matthews et al (2021) provides a comprehensive overview. The following box summarises the available budgets for different probabilities of different global temperature increases:

+1.5°C: "***440 $GtCO_2$*** [median] from 2020 onwards, with a range of ***230–670 $GtCO_2$***, (for a 67–33% chance of not exceeding the target. Additional socioeconomic uncertainty related to human decisions regarding future non-CO_2 emissions scenarios can further shift the median 1.5°C remaining carbon budget by ***±170 $GtCO_2$***." (Matthews et al 2021, abstract)

+1.75°C: ***910 $GtCO_2$*** , range: ***670-1160 $GtCO_2$*** (67-33% chance) *(ibid, Supplementary Table S5):*

+2°C: ***1370 $GtCO_2$*** , range: ***1110-1660 $GtCO_2$*** (67-33% chance) *(ibid, Supplementary Table S5):*

Overall, this gives an immense range of budgets, which could be below 230 $GtCO_2$ or over 1660 $GtCO_2$, with a central estimate of 440 $GtCO_2$ from 2020 onwards for a 50% chance of staying below 1.5°C.

The paper separates out CO_2 from other gases. For the long-lived greenhouses gases (i.e. all except methane), the equivalent CO_2e budgets are, within the bounds of uncertainty, and for practical purposes, the same number of gigatonnes. The trajectory for methane will affect the total budget for other gases.

As the science progresses, it is highly likely that these global budgets will continue to be revised.

What top-down effort-sharing mechanisms have been considered?

Van den Berg et al (2020) provide a useful theoretical analysis of seven different effort-sharing mechanisms. Below is an adaption of their summary table with a brief description of each, its underlying principles, its justification, and its methodology.

The following is adapted from van den Berg et al (2020), pp1809-1810

Approach	Equity principle(s)	Justification	Methodology
1. Grandfathering (GF*)	Sovereignty	Falling under the category 'acquired rights', that is justified by established custom and usage.	*Emission pathway*: allocations of emission allowances remain in proportion to current (2010) emission shares *Carbon budget*: allocations of carbon budgets based on current emission shares
2. Immediate per capita convergence (IEPC*)	Equality	Based on the shared humanity and equal value of all humans, having equal claim to global collective goods (equal individual rights to atmospheric space); i.e. no (relevant) distinctive characteristic dictating some humans should get more/less access to an indivisible/collective good.	*Emission pathway*: allocations of emissions allowance are immediately in proportion to population shares *Carbon budget*: allocation of national carbon budgets based entirely on average (projected) population shares in the period 2010–2100
3. Per capita convergence (PCC*)	Sovereignty/ equality	Combination of GF* and IEPC*	*Emission pathway*: per capita emissions allowances across countries converge linearly over time from current levels towards equal per capita levels by a convergence date, then allowances are allocated based on an equal per capita basis *Carbon budget*: allocation of national carbon budgets based on both current emission shares and population shares (i.e. a combination of GF* and IEPC*)
4. Equal cumulative per capita emissions (ECPC*)	Equality/ responsibility	A large amount of cumulative emission allowances per capita in industrialised countries has disproportionately used global emission space.	*Carbon budget*: allocation of national carbon budgets based on cumulative emissions per capita in a certain period that is equal across countries. Incorporating historical cumulative emissions (responsibility) and based on the share of the population (equality) *Emission pathway*: not presented, as is usually calculated from a carbon budget
5. Ability to pay (AP*)	Capability/ need	Based on the ability to bear the burdens.	*Emission pathway and carbon budget*: Emission or carbon budget reduction targets from baseline are allocated based on annual GDP per capita (emission pathway) or average GDP per capita over the period 2010–2100 (budget approach), taking into account increasing marginal costs with steeper reductions
6. Greenhouse development rights (GDR*)	Responsibility/ capability/ need	Safeguarding people's right to reach a dignified level of sustainable human development.	*Carbon budget*: Considers both responsibility and capability. Emission reduction targets (or global carbon budget) from baseline are allocated based on a Responsibility-Capacity Index (RCI) that includes GDP per capita and measures of the income distribution. As data for RCI is only available until 2030, the RCI is kept constant from 2030 onwards to determine the average RCI over the period 2010–2100. *Emission pathway*: annual RCI numbers are used, and from 2030, a linear convergence to AP* outcomes are assumed.

Approach	Equity principle(s)	Justification	Methodology
7. Cost-optimal (CO)	Cost-effectiveness	Allowance according to the least-cost options from marginal abatement cost (MAC) curves.	Allocations of emission allowances based on mitigation potentials. The emissions could be reduced in each country to the extent that the marginal costs of further reductions are the same across all countries. The allocation highly depends on the assumed marginal abatement cost (MAC) curves.

Giraud et al (2017) tackles the question of consensual effort-sharing in national carbon-reduction commitments, with a 2.0°C target. It states: "Grandfathering is generally viewed as morally unacceptable, particularly in the developing world." (p2), and, at the other extreme, considers the purely egalitarian perspective to be politically unrealistic, and economically inefficient. It attempts to balance a capacity criterion, which measures a country's ability to mitigate emissions at relatively low cost, with a responsibility criterion which relates to a country's aggregate historic emissions. The result gives a relatively narrow range of target GHG emissions per capita for different groups of countries in 2030, 3.7-6.1 tCO_2e, with high-income OECD countries mostly in the range 4.4-4.8 tCO_2e per capita. Their method may prove useful for future budget-setting beyond 2030, and will need recalculating for revised global budgets.

Finally, we should consider the implicit effort-sharing that is the outcome, though not the design input, that arises from the target-setting and budget-setting that we have seen in some other developed countries. Where countries have set a Net Zero target around 2050, with a planned steady decline in emissions from now until then, then this in practice results in an emissions trajectory that looks very much like the trajectory that would be derived if one took a top-down grandfathering approach. For the purposes of classification, we will refer to this as implicit grandfathering.

Who's using carbon budgets now, and how are they using them?

New Zealand

New Zealand's carbon budgets are notable, given that, like Ireland, the country has a large share of CH_4 in its total GHG emissions, arising from agriculture, forestry, and land-use: these two countries are outliers among developed economies in this regard. Their planned trajectory for long-lived greenhouse gas emissions is broadly linear to 2050 Net Zero, and as such, it is in effect an implicit grandfathering approach; but at the same time, the end targets are set to ensure New Zealand makes an appropriate contribution to the Paris Agreement goals, and is thus arguably also an "ability to pay" approach. The proposed budgets have been set at levels that "would be the best way to put Aotearoa on track to meeting the 2050 target" (Climate Change Commission 2021, Evidence Ch.4 p3) – that is, the budgets are set as waypoints. New Zealand's Climate Change Response Act take a split-gas approach (Climate Change Commission 2021 Advice Report p23), with a target for long-lived gases, and one for short-lived gases (methane).

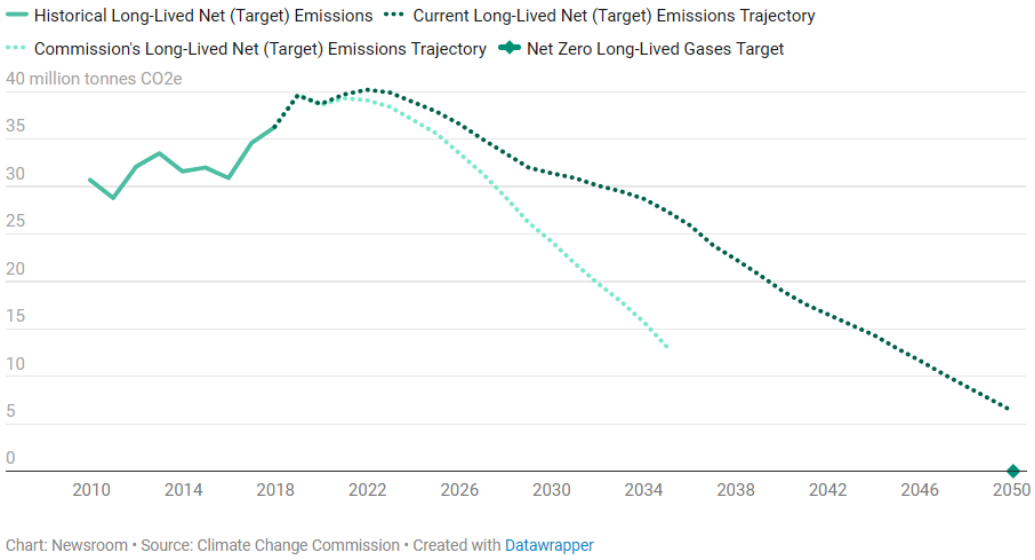


Chart source https://www.newsroom.co.nz/decarbonising-nz-the-numbers-that-count

As Frame (2016) notes, split-gas budgets led to the development of two separate approaches: net zero emissions of the long-lived gases; and stabilisation at levels significantly below current levels for short-lived gases. This ensures a stable net-zero forcing from New Zealand's annual emissions in 2050. It is designed with compliance with the 1.5°C target as an objective. As such, it is consistent with a target developed under the GWP* paradigm, which weights emissions rates based on the net change to radiative forcing. (Allen et al 2018). Although the GWP* paradigm remains under development, as a much younger metric than GWP100, it should be of future interest to Ireland, once the country is within a regime of year-on-year declines in methane emissions.

France

France's recent adoption of carbon budgets implements a linear trajectory to their 2050 Net Zero target (Mc Guire et al 2020) – as such, it is an implicit grandfathering approach.

Notably not only are there 5-year budgets (4 years for the 1st budget, 2015-2018) for total emissions excluding LULUCF, but each 5-year period also has individual budgets for six distinct sectors: transport, buildings, industry, energy, agriculture, and waste. Furthermore, there are four individual budgets by gas: CO_2, N_2O, CH_4, and F-Gases aggregated. The all-gases agriculture budget also has

gas-specific budgets for N_2O and CH_4, and the all-gases waste budget has a CH_4-specific budget too. In total each budget period has 14 budgets. (Ministère de l'Écologie 2020, p34)

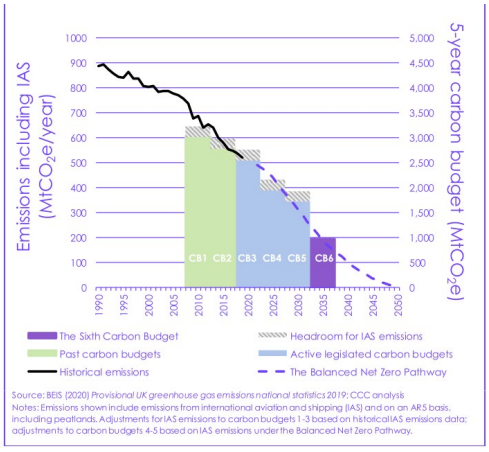
The decline in emissions from 2020 to 2050 is broadly linear. There is an increase in GHG sinks, and an overall 83% reduction in GHG sources by 2050 relative to 2015, excluding LULUCF. However, Agriculture and Forestry (excluding LULUC) are required to make a 46% reduction in emissions, with other sectors (transport, buildings, energy) required to make 95-97% reductions accordingly. (*ibid.*).

UK

The UK was the first country to set short-term and medium-term carbon budgets, when in 2008 it created three carbon budgets, for the periods 2008-2012, 2013-2017, and 2017-2022. It has subsequently set three more, for 2023-2027, 2028-2032, and 2033-2037.

A bottom-up approach to calculating the budgets based on feasibility, reconciled against the end target, led to a broadly linear decline in budget levels for the first five carbon budgets. Once more, this is an implicit grandfathering approach.

The UK's setting of carbon budgets has been somewhat complicated by the changing of the endpoint: when the first carbon budgets were set in 2008, the end target was for an 80% reduction from 1990 by 2050. This changed to a target of Net Zero by 2050 between the setting of the fifth and sixth carbon budgets. As a result, the sixth carbon budget requires a significant surge in mitigation for the period 2033-2037 (Committee on Climate Change, 2020, p14)



Denmark

While there are targets for 2030 (70% reductions from 1990 levels by 2030, and Net Zero no later than 2050), there is no legislated budget. Instead, the Danish Council to Climate Change has recommended a very challenging long-term national budget based on the immediate equal per-capita (IEPC) principle, scaling down a global carbon budget of 420-570 $GtCO_2$ (based on the 1.5°C target), and this was used to create the 2030 target. Furthermore, it sets indicative targets at 5-year intervals. (Mc Guire et al 2020, p8) Given the typically gradual change in year-on-year emissions within a 5-year period, this process could be seen to be creating carbon budgets indirectly.

Carbon budgets designed but not adopted

Many carbon budgets and (closely related) detailed decarbonisation trajectories have been designed but not adopted, for various countries and regions. Below, we present a small selection, as examples of some of the processes, trajectories and rationales used.

Australia – Climate Change Authority

In 2014, the Climate Change Authority of Australia recommended targets for 2030 and 2050, with budgets for 2013-2020 and 2013-2050 (Climate Change Authority, 2014). Short-term targets were based on setting them at a similar level of ambition to similar high-emitting highly developed countries (p54). As such, this was closest to the implicit grandfathering approach. Their recommendations have not yet been adopted.

Germany – Helmholtz Climate Initiative

This trajectory follows the contraction and convergence model, reducing per capita emissions by 2035 to an equal per capita share of global emissions, and then steadily falling to Net Zero by 2050. The figure below is Figure 2 on p4. The total emissions by Germany for the period 2018-2050 would be 10 $GtCO_2e$, which represents 13.3 years of emissions at the estimated 2019 rate. This trajectory has no legal recognition at time of writing. (Helmholtz Climate Initiative 2020).

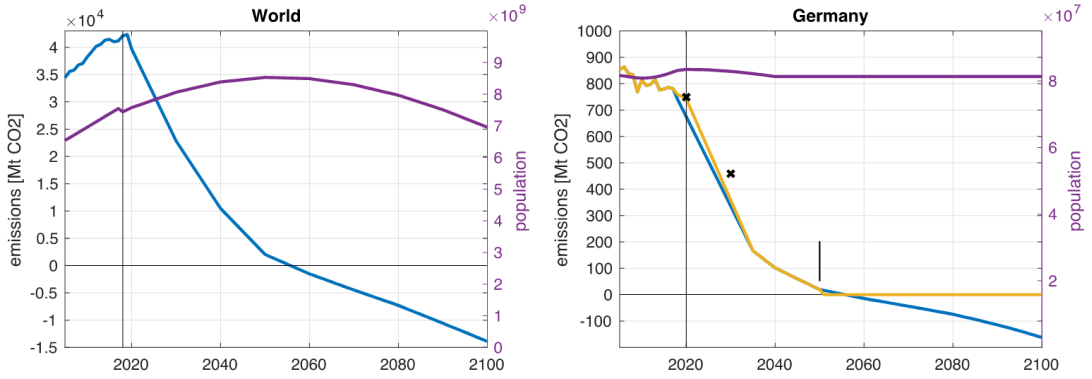


Figure 2: **(left) SSP1** global population development (purple line) and emissions trajectories corresponding to an end of the century temperature change of 1.5 °C (SSP1-1.9, blue line). **(right)** Germany's population projection (BMWi 2019, purple line), and emissions estimates following SSP1-1.9 (blue), applying the contraction and convergence approach with a convergence year of 2035. The Net-Zero-2050 trajectory as described in Section 3 (yellow). For comparison the CO_2 emissions reduction targets from the German Government as given by BMWi 2019 (black crosses and black bar).

Mexico

Sierra Brozon et al (2020) presents a national carbon budget for Mexico. It takes account of aggregate national and global historic emissions, and as such, is closest to the "equal cumulative per capita emissions" effort-sharing method. As a significant producer of oil and gas, and an emerging market, we do not consider Mexico to be a good example for Ireland: however, their work is distinctive because of the effort-sharing method used.

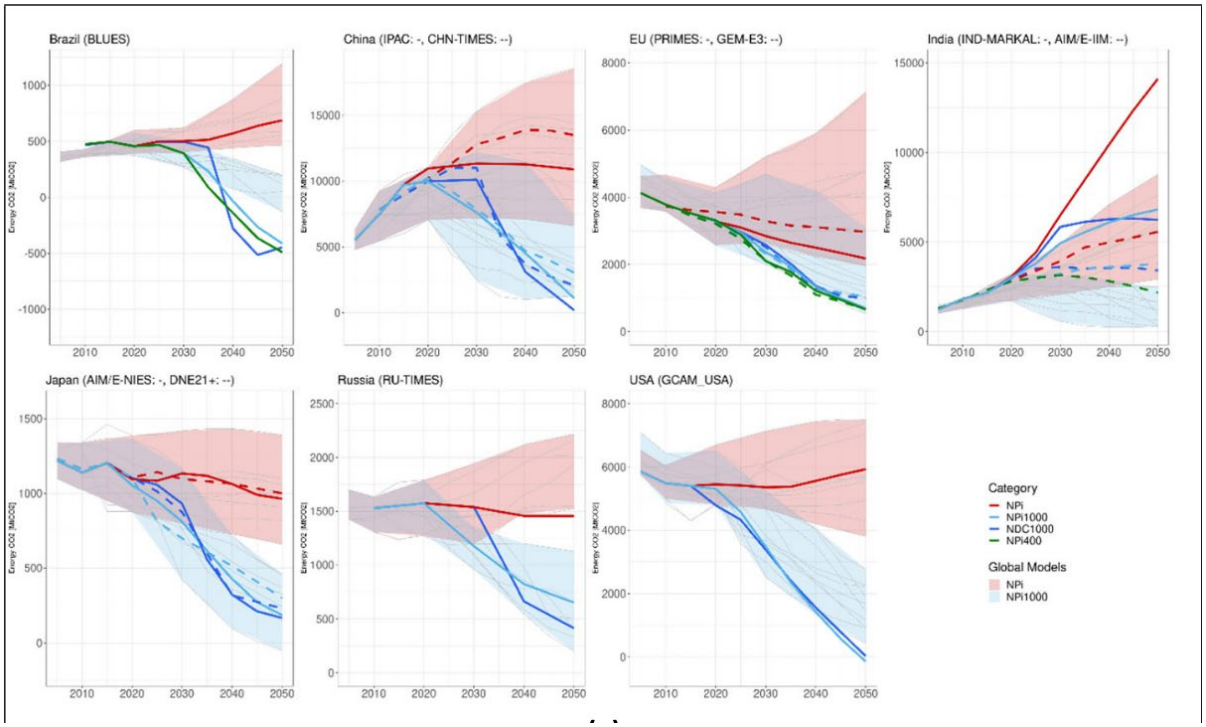
Sweden, and Järfälla Municipality

Anderson et al (2017) calculated carbon budgets not only for Sweden, but for an individual municipality within Sweden, Järfälla. Two national budgets are calculated, one on the principle of grandfathering, the other on equal per-capita shares. This provides a range, which is then disaggregated to municipalities, using grandfathering. The report provides a useful example of how national budgets can be disaggregated spatially. The national equal per-capita method would

require a national mitigation rate of 7% per annum, in line with the new 2030 target for Ireland. The grandfathering method would require a much more challenging 15% per annum mitigation rate.

Other trajectories

Arising from systems modelling work, there is a wide range of decarbonisation trajectories seen in the literature, and Schaeffer et al 2020 provides a useful overview. These trajectories tend to follow one of two patterns. For developed countries, we see a broadly linear decline to Net Zero. For developing countries, the pattern is one of a short-term increase in annual emission, a plateau, and then a decline. (Japan is the exception here, and its peculiar pattern can in part be explained by the extraordinary impact of the Fukishima disaster on its nuclear output, and the resulting challenges posed to decarbonising its electricity supply.)



source: Schaeffer et al 2020

What lessons can be learnt from them?

Despite the UK's ambition, its institutional capacity, and its strong track record in reducing greenhouse gas emissions, almost no action since 2008 has taken place in some crucial sectors, particularly housing and agriculture. The soft, easy low-hanging fruit of electricity decarbonisation has produced large, rapid reductions, enabling the near-term budgets to be met. And yet the UK has remained off-course to meet its later targets, due to very weak enforcement of building regulations for new build, and the postponement of more stringent regulation. Economy-wide carbon budgets alone are not enough to guarantee that the slow-acting measures to reach the harder, high-hanging fruit (the "coconuts" of mitigation, as it were) will be put in place early enough. Carbon budgets in and of themselves may not solve the problem of politicians wanting to defer action beyond their current term of office.

New Zealand's current situation looks most comparable to Ireland's, as a developed economy with a large agricultural sector, from which high methane emissions arise. Its split-gas approach to targets gives sufficient flexibility to allow agriculture to make an important contribution to emissions without collapsing the sector, and we consider this a crucial precedent for Ireland.

France's detailed disaggregation of targets creates a large bureaucratic workload for monitoring, and may not be a suitable model for Ireland.

Denmark's very ambitious 2030 target, based on a tough effort-sharing method, offers a precedent for Ireland's own very tough proposed target for 2030; however, there are major structural differences that favour Denmark's ability to deliver: for example, in the domestic sector, where high grades of thermal efficiency, and uptake of district heating networks make decarbonisation much simpler than it will be in many other countries including Ireland.

Although various effort-sharing algorithms have been deployed, most developed countries with planned trajectories have ended up with a largely linear decline in projected emissions. If we take a very crude heuristic of a steeper mitigation slope requiring a higher unit cost of abatement, then this linear approach is consistent with minimising excess abatement costs over the trajectory.

Setting Carbon Budgets for Ireland

Let us first consider the mechanism that is usually the most stringent for developed economies, the immediate equal per-capita shares. The population of Ireland in 2020 was 5.0m, and by 2050 is forecast to be around 6.1m (taking the average of the most recent CSO projections). Similarly, the forecasts for global population are 7.8b in 2020 and 9.7b in 2050. Averaging the 2020 and 2050 population figures for each (thus assuming linear change in each, a crude but sufficient assumption for these purposes) gives Ireland an average 0.06% of the global population over those 30 years. We can apply this percentage to the remaining carbon budgets as estimated by Matthews et al 2021:

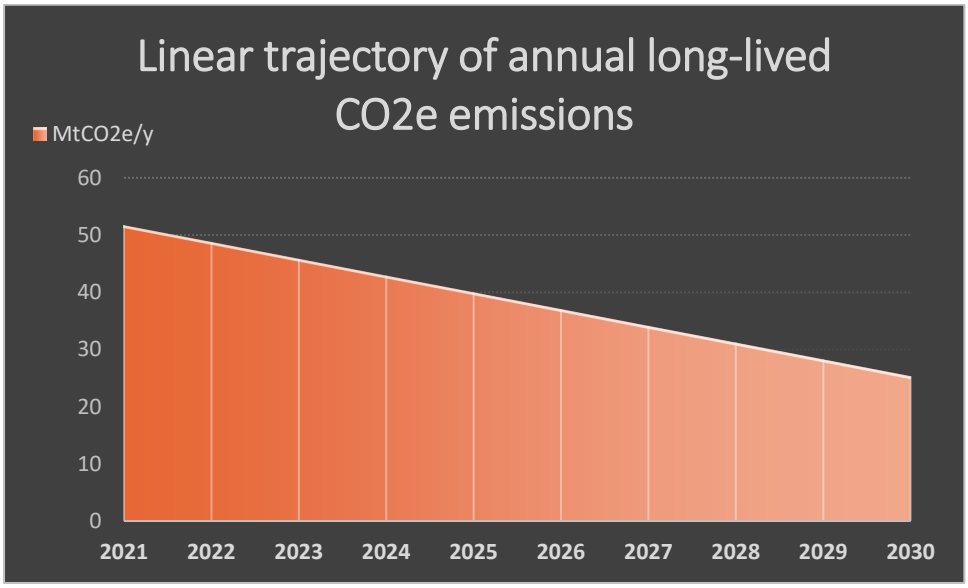
Temperature rise	$GtCO_2$ global budget (67%-50%-33%)	$MtCO_2$ Ireland budget, pro rata per capita
1.5	230-440-670	150-280-420
1.75	670-910-1160	420-580-740
2.0	1110-1370-1660	700-870-1050

Even with using only a single effort-sharing mechanism, the IEPC, which is designed to ignore existing country-specific emissions and development status, we see a huge range of potential total CO_2 budgets for Ireland in the range 150-1050 $MtCO_2$. When we consider what a reasonable total might look like in this context, which we might say is in the range 420-700 $MtCO_2$, we find ourselves in the range of at best a 67% chance of limiting the rise to 1.75°C; and at worst a 67% chance of limiting it to 2.0°C. It is not surprising that this most stringent requirement looks very taxing, within the context of the Paris Agreement (UNFCCC 2015), assuming immediate equal per-capita shares of the remaining budget. Other mechanisms will provide more generous budgets for Ireland.

There are very tight constraints on what can be achieved in the first two years of the first carbon budget, as most policies take time to pass and to implement, and then affect markets and behaviours incrementally. It should not be surprising that the required ambition for the first carbon budget is lower than the second: many of the measures required to deliver the second carbon budget and the 2030 target will have to be implemented during the lifetime of the first budget.

From the 2021 National Emissions Inventory (Chapter 10), the emissions for 2018 are 67.3 MtCO2e, including LULUCF and indirect emissions (GWP100, AR4 basis). Of this, 15.6 MtCO2e is methane, and 51.7 MtCO2e is from long-lived gases. For the purposes of calculating budgets, these are assumed to be the emissions in 2021 too. Following the New Zealand example, separate budgets will be calculated for each of these.

Using the lessons from other countries, and taking a linear trajectory of emissions to 2030, enables the calculation of budgets for the first two budget periods.



The numbers arising from this trajectory are 229 $MtCO_2e$ and 156 $MtCO_2e$ for the first two budget periods, for the long-lived gases.

Note that these numbers are built on an assumption that the target of 51% reductions in greenhouse gases within the legislation applies specifically to the *long-lived* greenhouse gases (GWP100), rather than the GWP100 calculation of all greenhouse gases. This creates space for the possibility of finding carbon budgets which are both compliant with the proposed amendment, *and* could possibly be achieved by a package of measures that is socially, economically, and politically acceptable.

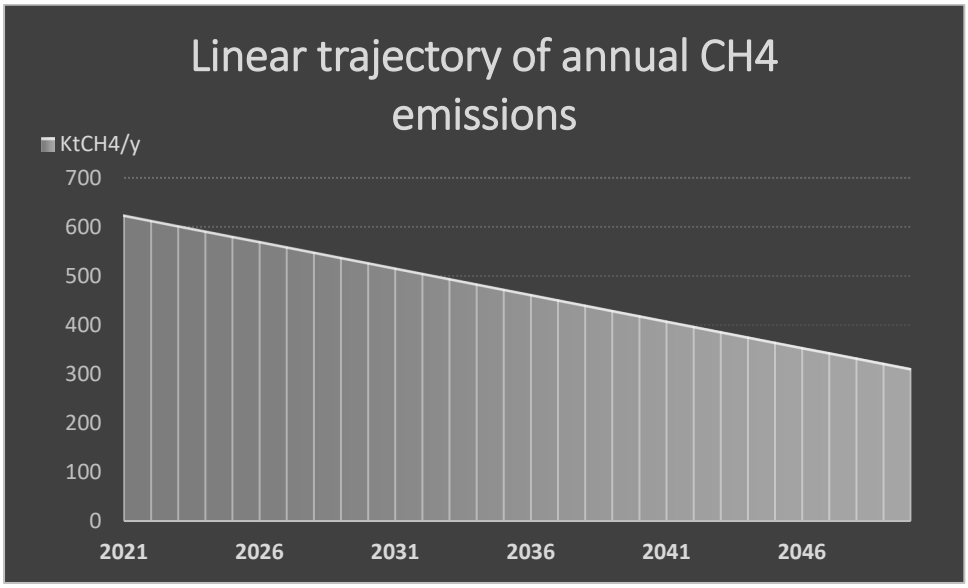
If Ireland were to continue on this very demanding trajectory, then we would reach Net Zero by 2039; and the cumulative emissions of long-lived GHGs in the period 2021-2040 would be 482 $MtCO_2e$, which is within the range of what could be considered a fair effort, as outlined above. With stable emissions of methane, this is compliant with a higher than 50% chance of keeping warming below 1.75°C, and a very high chance of keeping warming below 2°C.

Thus, even with the very stringent IEMC effort-sharing mechanism, this would be compliant with the Paris Agreement's goal of limiting global warming to well below 2°C, if – in parallel to these emissions reductions – a significant reduction in Ireland's methane emissions is realised too, thus reducing the total radiative forcing from Ireland's aggregate emissions.

We therefore recommend the above figures (229 $MtCO_2e$ & 156 $MtCO_2e$) be used as the first two budgets for Ireland's long-lived greenhouse-gases, and that supplementary budgets and targets be set for methane, and that these should cover methane emissions from the fossil-fuel sector and agriculture, land-use, land-use changes and forestry.

As the starting point for the discussion about effort-sharing within sectors, and feasibility, we propose a 50% reduction in annual emissions of methane (from a 2018 baseline) by 2050, and a 15.5% reduction by 2030, with a linear trajectory from 2021-2050. This gives targets for 2030 of 12.9 MtCO2e, and for 2050 7.6 MtCO2e annual emissions of methane on an AR4 basis. These translate to

actual emissions of 624 $KtCH_4$ in 2018 (and assumed in 2021), and targets of 518 $KtCH_4$ in 2030, and 306 kTCH4 in 2050. The equivalent first and second budgets for CH4 are 3010 $KtCH_4$ & 2740 $KtCH_4$.



Conclusions and Recommendations

There is little experience in the world of setting and delivering against explicit carbon budgets: only one country – the UK - has been through a full cycle of setting carbon budgets, delivering against at two budgets, and then setting further budgets. As such, this remain an art more than a science, and one that has been driving primarily by local circumstances rather than global needs.

Most developed countries with budgets and targets studied here have used an implicit or explicit grandfathering approach, with broadly linear declines in greenhouse gas emissions to a Net Zero target. New Zealand has notably taken a split-gas approach, allowing an allocation for methane emissions in 2050 that are stable, and below current levels, leading to a net zero of carbon forcing, rather than a net zero of greenhouse-gas quantities emitted. France took a stronger approach to disaggregation, with 14 separate budgets for each period disaggregated by gas and by sector. Denmark chose a different method to calculate its effort sharing, based on taking a global per-capita approach to the remaining carbon budget, and as a result has an extremely challenging target for 2030. Several other effort-sharing algorithms have been described in the literature, though have not been legally adopted into national carbon budgets at time of writing.

For Ireland, a carbon budget to net zero in 2050 that is based on a linear decline in long-lived greenhouse gas emissions calculated on a GWP100 basis from 2021 to 2030 would split out the equivalent of 4.4 years of 2018-rate emissions allocated to the period 2021-2025, and 3.0 years for 2026-2030, 1.6 years for 2031-2035, and 0.3 years in total thereafter.

The latest estimate of total emissions for 2018 (EPA 2021) is 67.3 MtCO2e, including LULUCF and indirect emissions (GWP100, AR4 basis). Of this, 15.6 MtCO2e is methane, and 51.7 MtCO2e is from long-lived gases. The targets and budgets presented in the table below rest on the following assumption: the 51% reduction target for 2030 is for the long-lived gases only; a linear decline between 2021 and 2030; 2021 emissions are at 2018 levels; and a supplementary target for methane emissions of 50% from 2018 levels by 2050, with stable emissions 2018-2021, and a linear decline 2021-2050.

Target/Budget	MtCO2e (long-lived)	$KtCH_4$
2021-2025 budget	229	3010
2026-2030 budget	156	2740
2030 target	25.3	527
2050 target	0	312

These targets would give Ireland cumulative greenhouse-gas emissions that are consistent with the Paris Agreement.

Afterthoughts

Changing the baseline

As more is learnt about Ireland's emissions, it is likely that significant revisions will be made to the 2018 baseline. It is recommended that as this happens, the budgets be revised pro-rata to the new values. Significant changes may be made in various places, including: in accounting for international aviation and navigation; in improved measures of sinks and sources for agriculture, forestry and land use; and from real measurements of leakage rates from the fossil-gas transmission and distribution networks. We recommend that all three of those areas be developed over the coming 2-3 years.

Beyond Net Zero

It is likely that the world will overshoot its cumulative emissions goal, and take the climate into a regime which is less amenable to civilisation as we know it. Indeed, there is a case to be argued that we have already passed this point. With that realisation, will come global discussions about the effort-sharing arrangements for going beyond Net Zero, and reducing GHG concentrations to more acceptable levels. We raise this now, because it should inform considerations of the balance to be made in Ireland between reducing sources, and increasing sinks, on the road to Net Zero. Discussions have already started in the literature of effort-sharing for carbon dioxide removal from the atmosphere: see, for example, Pozo et al (2020), "Equity in allocating carbon dioxide removal quotas".

Bibliography

Allen, M. R., Shine, K. P., Fuglestvedt, J. S., Millar, R. J., Cain, M., Frame, D. J., & Macey, A. H. (2018). A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. *Npj Climate and Atmospheric Science*, *1*(1), 16. https://doi.org/10.1038/s41612-018-0026-8

Anderson, K., Stoddard, I., & Schrage, J. (2017). *Carbon budget and pathways to a fossil-free future in Järfälla Municipality*. Retrieved from https://www.diva-portal.org/smash/get/diva2:1382717/FULLTEXT01.pdf

Climate Change Authority. (2014). *Reducing Australia's Greenhouse Gas Emissions: Targets and Progress Review—Final Report*. Climate Change Authority, Melbourne.

Climate Change Commission. (2021). 2021 Draft Advice for Consultation. Retrieved from https://www.climatecommission.govt.nz/get-involved/our-advice-and-evidence/

Committee on Climate Change. (2020). The Sixth Carbon Budget. https://www.theccc.org.uk/publication/sixth-carbon-budget/ . London.

EPA (2020). *Ireland's Final Greenhouse Gas Emissions 1990-2018*. Retrieved from https://www.epa.ie/pubs/reports/air/airemissions/ghg2018/Ireland%20GHG%201990-2018%20Final%20Inventory_April%202020.pdf

EPA (2021) *National Inventory Report 2021* http://www.epa.ie/pubs/reports/air/airemissions/ghg/nir2021/

Frame, D. (2016). Report on New Zealand's Recent Climate Policy Developments.

Giraud, G., Lantremange, H., Nicolas, E., & Rech, O. (2017). National Carbon Reduction Commitments: Identifying the Most Consensual Burden Sharing. *Documents de Travail Du Centre d'Economie de La Sorbonne*. Retrieved from https://ideas.repec.org/p/hal/cesptp/halshs-01673358.html

Helmholtz Climate Initiative. (2020). *Defining the German carbon budget*. https://elib.dlr.de/139478/1/2_carbonbudget_web.pdf

IPCC (2018): Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty[V. Masson-Delmotte, P. Zhai, H. O. Pörtner, D. Roberts, J. Skea, P.R.Shukla, A. Pirani, W. Moufouma-Okia, C.Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, T. Waterfield(eds.)]

Mc Guire, J., Rogan, F., Daly, H., Glynn, J., & Gallachóir, B. Ó. (2020). *The role of carbon budgets in translating the Paris Agreement into national climate policy*. Retrieved from https://www.marei.ie/wp-content/uploads/2020/09/Discussion-Paper_The-role-of-carbon-budgets-in-translating-the-Paris-Agreement-into-national-climate-policy.pdf

Matthews, Damon, H. et al. (2021). An integrated approach to quantifying uncertainties in the remaining carbon budget. *Communications Earth & Environment*, *2*(1), 1–11. https://doi.org/10.1038/s43247-020-00064-9

Ministère de l'Écologie (2020). *National low carbon strategy: The Ecological and Inclusive Transition Towards Carbon Neutrality*. Paris. Retrieved from https://www.ecologie.gouv.fr/sites/default/files/en_SNBC-2_complete.pdf

Pozo, C., Galán-Martín, Á., Reiner, D. M., Mac Dowell, N., & Guillén-Gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nature Climate Change*, *10*(7), 640–646. https://doi.org/10.1038/s41558-020-0802-4

Reisinger, A., & Leahy, S. (2019). Scientific aspects of New Zealand's 2050 emission targets. https://www.nzagrc.org.nz/policy,listing,593,scientific-aspects-of-new-zealands-2050-emission-targets.html

Ricke, K. L., & Caldeira, K. (2014). Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters*, *9*(12). https://doi.org/10.1088/1748-9326/9/12/124002

Schaeffer, R., Köberle, A., van Soest, H. L., Bertram, C., Luderer, G., Riahi, K., … Potashnikov, V. (2020). Comparing transformation pathways across major economies. *Climatic Change*, *162*(4), 1787–1803. https://doi.org/10.1007/s10584-020-02837-9

Sierra Brozon, L., Jano Ito, M. A., Ruiz Vilar, A., & Islas Cortés, I. (2020). *National Carbon Budget for Mexico and 2030 Decarbonisation Pathways*. Mexico City. www.iniciativaclimatica.org/wp-content/uploads/2020/11/NationalCarbonBudgetMX_2020.pdf

UNFCC 2015, United Nations / Framework Convention on Climate Change (2015) Adoption of the Paris Agreement, 21st Conference of the Parties, Paris: United Nations. https://unfccc.int/process/conferences/pastconferences/paris-climate-change-conference-november-2015/paris-agreement

van den Berg, N. J. et al (2020). Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change*, *162*(4), 1805–1822. https://doi.org/10.1007/s10584-019-02368-y