Ireland's Warming Impact

Joe Wheatley[1,2*]

[1]School of Economics, University College Dublin, Belfield, Dublin 4
[2] Energy Institute, University College Dublin, Belfield, Dublin 4

---

[*]E-mail:joe.wheatley@ucd.ie

Date: 2 October, 2024

Executive Summary

Quantifying national contributions to global warming is valuable for two reasons. Firstly, knowledge of the details and drivers of the warming can shed light on the best ways to curb the country's future warming impact. Secondly, the magnitude of this impact is important when considering issues of responsibility and climate justice.

Ireland's greenhouse gas emissions profile is distinctive, with a higher share of shorter-lived gases such as methane and nitrous oxide from agriculture, compared to most developed nations. The prevalence of these gases introduces additional physical considerations that are less relevant in countries where emissions are predominantly driven by CO_2, as is the case for most EU member states. However, the standard approach of comparing greenhouse gases through Global Warming Potentials fails to accurately reflect the warming dynamics of these gases, particularly in scenarios involving deep emission cuts.

To tackle this issue, this report makes use of Simple Climate Models whose outputs include the global mean surface temperature. These models reflect the latest understanding of climate parameters, processes and uncertainties and are widely used in IPCC assessments. Here, the FaIR Simple Climate Model was used to efficiently analyse 1,196 emissions pathways for Ireland. These scenarios were developed by modelling teams from UCC, UCG, and Teagasc, commissioned by the Carbon Budgets Working Group. They cover a wide range of feasible mitigation options for Fossil Fuel & Industrial (FFI) and Agriculture, Forestry, & Other Land Use (AFOLU) emissions.

Based on these scenarios and other data, this report finds that:

1. On a per capita basis, Ireland's historical warming impact is significant and comparable to other developed countries. About half of this warming has arisen since the year 2000 (Section 2).
2. Without strong agricultural mitigation, Ireland's warming impact will continue to grow through 2050 even if net zero-CO_2 is reached in the 2040s (scenarios on the left-hand side of Figure ES1).
3. Robust agricultural gas mitigation is very effective in limiting Ireland's future warming impact (scenarios on the right-hand side of Figure ES1).

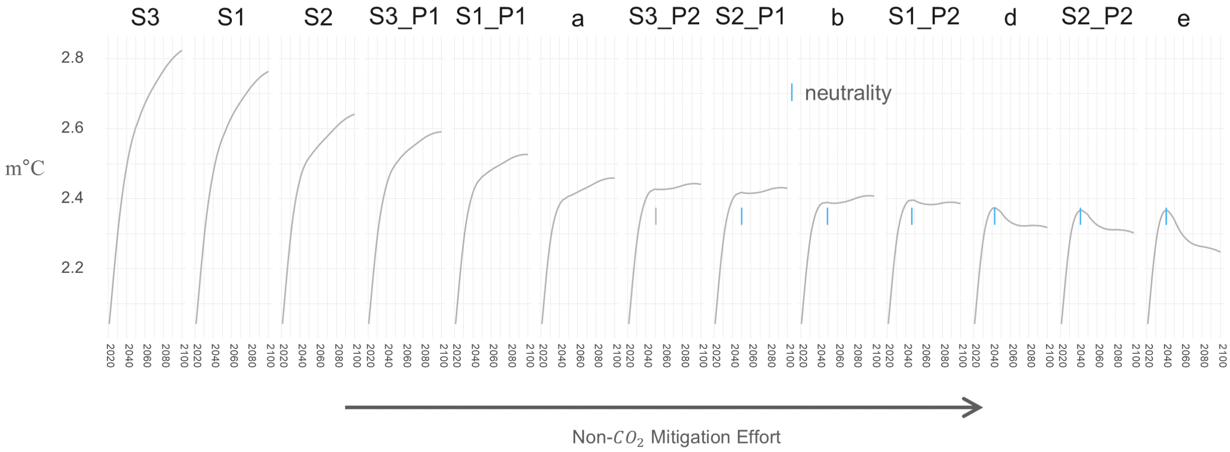

Figure ES1: *Median Irish warming impact in m°C for 2020-2100 for thirteen agricultural gas mitigation scenarios. Scenario labels are explained in Appendix A.1. In all cases, net zero-CO_2 occurs in 2043 with 2021-2050 emissions of 440 Mt. Cases where warming peaks before 2050 are indicated by blue bars. The background global pathway is* SSP1-26.

In the strongest agricultural mitigation scenarios (labelled d, S2_P2, and e in Figure ES1), agricultural greenhouse gases contribute little to no net additional warming, or even a slight cooling, between 2021 and 2050. This contrasts with 0.15-0.25°C of warming from FFI gases, depending on the CO_2 scenario (Section 3.2). This difference is due to the shorter atmospheric lifetimes of methane and nitrous oxide compared to CO_2. Methane and nitrous oxide emissions do not need to fall to zero to induce a cooling impact. While deep reductions are necessary in the case of nitrous oxide, calculations show this effect is relevant for Ireland (Section 3.2).

A scenario where Ireland's warming impact is still increasing in 2050 is incompatible with the national climate neutrality objective. The FaIR model was used to determine the probability which combinations of FFI and AFOLU mitigation pathways pass this neutrality test. This results in the "neutrality map" Figure ES2.

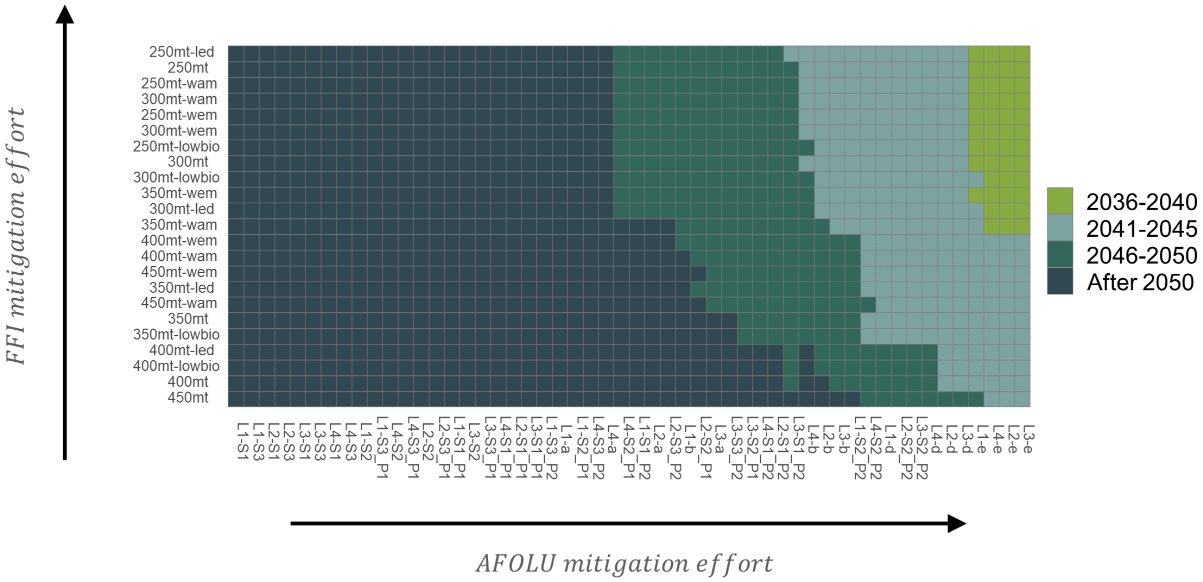

Figure ES2: *Neutral year ranges for all combinations of FFI and AFOLU scenarios analysed in this report. AFOLU scenarios are arranged along the x-axis in order of increasing mitigation strength. FFI scenarios are arranged in order of increasing mitigation strength along the y-axis so that the strongest mitigation scenarios occur in the top right-hand corner of the map. The probability threshold for neutrality has been set at* $\frac{2}{3}$*. Dark squares are the FFI/AFOLU combinations that are not temperature neutral before 2050 with probability greater than* $\frac{2}{3}$*. The global pathway is* SSP1-26*. The Irish scenario codes are explained in Appendix A.1*

.

Additional findings from Figure ES2 include:

4. A surprisingly wide range of FFI and AFOLU mitigation scenario combinations pass the neutrality test.
5. The range of viable AFOLU options declines when 2021-2050 FFI CO_2 emissions are above 300 Mt, and conversely, broader AFOLU options are available when FFI emissions are 300 Mt or lower.
6. Strong agriculture mitigation scenarios, such as S2_P2 (2021-250 reductions: methane -252 kt, nitrous oxide -13.4 kt) or d, are likely to be neutral by 2045 when 2021-2050 FFI CO_2 emissions are kept at 400 Mt or below (Figure ES2).

Contents

1 Introduction

The United Nations Framework Convention on Climate Change agrees to limit global warming in the range 1.5-well below $2.0^{\circ}C$. The task of setting climate targets consistent with this goal, taking account of "common but differentiated responsibilities", is delegated to national governments and supranational organisations [1]. Direct calculation of a warming impact at national level can help inform this process and details of such calculations for Ireland are described in this report.

The International Panel on Climate Change (IPCC) interprets the global temperature as a multi-decadal average of the global mean surface temperature relative to an early industrial 1851-1900 reference period [2]. Stabilisation of the global warming requires "*approximately net zero CO_2 emissions and declining net energy imbalance due to other climate drivers*" [3]. For example, a global scenario in which net zero-CO_2 is reached in the 2070's, accompanied by cuts in methane (CH_4) of $\approx$50% and in nitrous oxide (N_2O) of $\approx$30% by 2050 is deemed compatible with a $2.0^{\circ}C$ temperature ceiling. This high ambition scenario (Shared Socio-Economic Pathway *SSP1-26*) establishes a cooling trend well before the end of this century [4, 5]. In a similar way, this report attempts to identify national emissions scenarios that are compatible with Ireland's National Climate Objective (NCO) [6].

Ireland's current greenhouse gas (GHG) emissions profile differs from the global profile with a higher share of agricultural gases (CH_4 and N_2O). Table 1 shows that Ireland was responsible for 0.10% of global fossil-fuel and industrial (FFI) CO_2 in 2022, but 0.17% of CH_4 and 0.33% of N_2O emissions. The profile is even more unusual compared to the European average. Ireland accounted for 4% of of the EU's CH_4 and 5.5% of N_2O emissions in 2022 compared to 1.7% of FFI CO_2 emissions.

Table 1: *Global, EU27 and Irish emissions of major GHGs in 2022. The totals exclude emissions from land-use land-use change and forestry (LULUCF).*

gas	Global[a]	EU[a]	Ireland[b]
CO_2	36.2 Gt	2.2 Gt	37.5 Mt
CH_4	366.4 Mt	15.9 Mt	628 kt
N_2O	6.7 Mt	0.4 Mt	22 kt

[a] CEDS [7]
[b] National Inventory Report, 2024

The high shares of non-CO_2 gases in Table 1 is significant for Ireland's warming impact because the agricultural gases are shorter-lived than CO_2. If all GHG emissions ceased the atmospheric concentration of CO_2 would decline initially but it would not return to it's pre-industrial value for many hundreds or thousands of years [8]. In contrast, the concentrations of CH_4 and N_2O would fall back towards their pre-industrial values, with relaxation times of approximately 12 and 109 years (perturbation lifetimes [2]).

Global Warming Potentials (GWPs) are the standard GHG reporting metric since Kyoto and are often used to compare climate impacts across sectors or countries. This metric does not fully capture the distinction between shorter-lived gases and CO_2 outlined in the previous paragraph. Indeed, it is well understood that application of "CO_2 equivalents" in a warming analysis can lead to qualitatively incorrect conclusions. To remedy this, the Climate Change Advisory Council has previously employed GWP* [9, 10], an alternative metric that takes better account of the short lifetime of CH_4. Similarly, the Danish Climate Council has used a Simple Climate Model (MAGICC) to estimate the warming impact of future Danish emissions [11].

1.1 Simple Climate Models

There is a near linear relationship between cumulative CO_2 emissions and warming [12]. This "transient climate response to cumulative emissions" (*TCRE*) is assessed to be $0.45 m^{\circ}C$ per $TtCO_2$ [2]. *TCRE* is the simplest model of warming impact. However, a more sophisticated approach using Simple Climate Models[1] (SCMs) is needed to describe additional climate driving by non-CO_2 GHGs, aerosols (sulfur), ozone, as well as further feedbacks in the climate system due to these gases.[2] SCMs give the aggregate responses of the climate system to radiative forcing using energy balance. They are parameterised using value ranges of physical parameters and climate sensitivities calibrated from sources such as historical temperature data, Earth System Models, etc. Three SCMs were used in preparing this report FaIRv2.1 [13], MAGICC7 [14] and Hectorv3.2 [15]. The findings presented here were obtained from FaIRv2.1 with a constrained ensemble of parameter configurations to capture uncertainty in the climate response [13].[3] The median peak warming in the *SSP1-26* global scenario described in Section 1 is $1.9°C$ in agreement with MAGICC7. SCMs are the primary tool for policy analysis in IPCC reports [16] and have previously been applied to Ireland [17].

Questions that can be answered using an SCM include:

1. How much warming is Ireland responsible for (based on territorial emissions)?
2. How much additional warming will Ireland cause in future and when will this increasing warming impact stop?
3. What is the role of different greenhouse gases in limiting future warming?
4. What inferences can be garnered for emissions targets?

2 Assessing Ireland's historical global warming impact

The main purpose of this report is to assess future warming impacts in feasible emissions mitigation scenarios for Ireland. However, knowledge of historical emissions is also needed for two reasons. Firstly, the pattern of historical emissions affects future warming. Secondly, the magnitude of the historical warming impact is important in its own right as it might influence policy judgments.

Global warming in 2022 is assessed at $1.2°C$ relative to the early industrial period 1851-1900 [18]. To evaluate Ireland's territorial contribution to the observed global warming, a dataset of Ireland's historical emissions is required. Historical atmospheric concentrations of GHGs are also needed because the climate forcing effect of one unit of a GHG varies with atmospheric concentration of the gas.[4] Equivalently, as done here, a global emissions dataset can be used to generate the required historical concentrations using an SCM. Pre-1990 Irish emissions data is based on the Community Emissions Data System [7] (CEDS) as well as other sources [17] (Appendix A.1).

Given these datasets, the two possible methodologies for calculating a country's warming impact are "leave-one-in" (LOI) and "leave-one-out" (LOO). LOI calculates the historical warming impact of the country in isolation, neglecting emissions by all other countries. LOO takes the difference in global warming with and without the country's emissions. When CO_2 predominates, these quantities are almost identical because of approximate linearity *TCRE* Section 1.1. However, they differ somewhat for a country with significant non-CO_2 emissions provided that the atmospheric concentrations of these gases varies appreciably over the calculation period. In this case, LOO advantages countries with high non-CO_2 emissions, while the opposite is the case for LOI. Therefore, the choice of methodology would need agreement between parties. It can be shown that the likely consensus allocation of warming is $\frac{1}{2}(LOI + LOO)$. For Ireland, calculations show that LOI is $\approx$ 20% higher than LOO when warming in calculated relative to 1851-1900, so that the warming allocation to Ireland is $\approx$10% higher than calculated using LOO. The LOO or marginal approach is more common in the scientific literature and, bearing in mind that Ireland's true warming impact will be slightly higher, this approach is followed here [19, 17].

Much of Ireland's warming impact is of recent origin. Using the constrained ensemble in FaiRv1.2, median LOO warming in 2022 is estimated at $2.1m°C$, or $\approx$ 0.2% of the observed global warming. The warming impact in 1950 is estimated at just $0.3m°C$, rising to $0.5m°C$ by 1975. This was almost entirely due to agriculture with near cancellation of the warming and cooling contributions from FFI gases (CO_2 and sulfur) in FaIR.[5] Warming reached $1.1m°C$ in 2000 with $\approx$$0.7m°C$ from AG gases and net $\approx$$0.4m°C$ from FFI gases. De-sulfurisation in the 2000's lead to a rapid decline in aerosol cooling and an "unmasking" of FFI warming, resulting in a doubling of Ireland's total warming impact between 2000 and 2022. At present, FFI accounts for $\frac{2}{3}$ of Ireland's historical warming impact relative to 1851-1900.

If the rest of the world's population had emitted in the same way as Ireland, current global warming would be $\approx$3.6°C (likely range 3.2 °C to 3.9 °C).

---

[1] SCMs are "simple" relative to large-scale spatially resolved Earth System Models.

[2] SCMs are "simple" relative to large-scale spatially resolved Earth System Models.

[3] Greens functions derived from CMIP6 Earth System Models link temperature and forcing in the FaIR ensemble.

[4] For instance, the climate forcing effect of a unit mass of CH_4 is 40% weaker today compared to pre-industrial era.

[5] "Cooling" refers to a reduction in a global mean *surface* temperature. Radiative forcing is still positive and results in continued heat flux to the oceans.

Equivalent estimates for other developed countries are: United States, $5.7^{\circ}C$, Germany $4.0^{\circ}C$, UK $4.2^{\circ}C$ [20]. The unexpectedly high per capita warming estimate for Ireland may be explained by net positive land-use emissions and a large contribution from ruminant agriculture.

The Climate Change Advisory Council (CCAC) has previously used a "Paris Test" to constrain carbon budgets in line with a $1.5^{\circ}C$ global temperature ceiling [10]. Passing the test necessitates use of a more recent reference year than the 1851-1900 reference period used in the previous paragraph. The alternative approach is to constrain emissions targets based on a climate neutrality or net zero principle. This approach is taken in Section 5.

3 Assessing Ireland's future warming impact

Warming impact projections can be made by joining future and historical emissions datasets and repeating the calculation of Section 2 [17]. In this report *SSP1-26* is used as a representative high ambition global scenario that determines the future atmospheric concentrations of GHGs [4]. The CCAC Carbon Budgets Working Group (CBWG) commissioned detailed emissions scenarios for Ireland from three distinct models: UCC *TIM* (FFI CO_2), UCG *GOBLIN* (LULUCF and AG gases) and Teagasc *FAPRI* (AG gases). The reports from the individual modelling groups should be consulted for full details of these datasets, however some general characteristics relevant to the warming impact analysis are summarised below and in Appendix A.1.

Most of the CBWG scenarios reach net zero-CO_2 in the 2040s as a consequence of rapid reductions in FFI CO_2 (least-cost modelled to 2050) and a rapidly growing forest sink (modelled to 2100). Cumulative 2021-2050 total CO_2 emissions lie in the interval 225-475 Mt. The forest sink ranges from -1.4 Mt to -6.8 Mt in 2050, and from -5.1 Mt to -14 .4 Mt by the end of the century (see Appendix A.1 Table 5). The combined FFI and LULUCF CO_2 scenarios are shown in Figure 3. Note that the *TIM* FFI CO_2 scenario data have been extended to 2100 using the 2050 values. From *TCRE*, the expected additional warming impact from CO_2 is in the range 0.1-0.2$m^{\circ}C$.

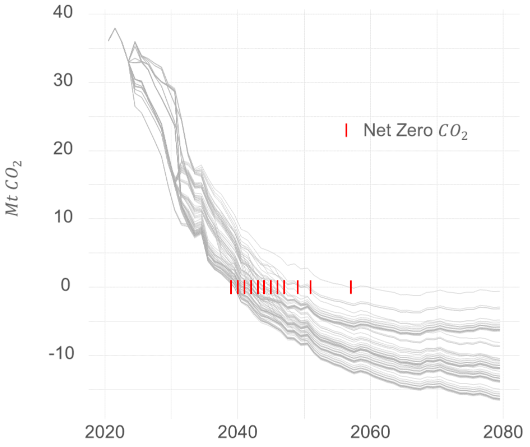

Figure 3: *92 CO_2 emissions scenarios resulting from combinations of FFI and LULUCF scenarios. Red bars indicate the timings of Net Zero.*

There are thirteen agricultural mitigation scenarios modelled in *GOBLIN* and *FAPRI* to 2050. These are shown in Figure 4 for CH_4 and Figure 5 for N_2O. For example, the strongest *FAPRI* S2_P2 scenario has cuts in N_2O of 75% (-15 kt) and of 43% in CH_4 (-252 kt) (see Appendix A.1 Table 6). The AG scenarios were extended assuming constant emissions from 2050 to 2100 i.e. no further abatement measures and constant activity. This allows the continuing effect of earlier AG cuts to be seen.

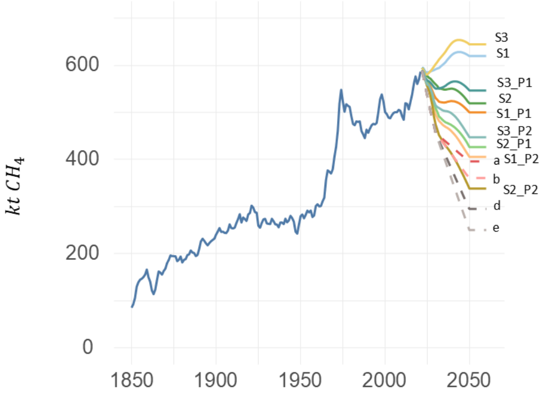

Figure 4: *1850-2070 CH_4 data for Ireland used in this report in 13 AG scenarios.* GOBLIN *scenarios are indicated by dashed lines.*

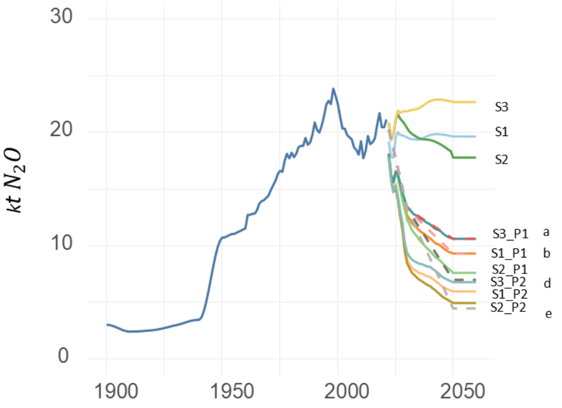

Figure 5: *1900-2070 N_2O data in 13 AG scenarios.* GOBLIN *scenarios are indicated by dashed lines.*

A total of $23 \times 4 \times 13 = 1,196$ scenarios (i.e. approximately independent combinations of FFI, LULUCF and AG scenarios) were assessed using FaiRv2.1 [13]. Further descriptions of the scenarios and projections for other climate drivers are given in Appendix A.1.

3.1 Efficacy of non-CO_2 emissions reduction

The median warming impact for the years 2020-2100 in thirteen AG scenarios is shown in Figure ES1. The AG scenarios are ordered by increasing mitigation strength from left to right. The same CO_2 scenario is used in each case. The CO_2 scenario (450mt-WAM L4) has cumulative 2021-2050 CO_2 emissions of 440 Mt with net zero-CO_2 reached in 2043.

Figure ES1 shows the striking effect of cuts in agricultural gases in curbing Ireland's future warming impact. The *FAPRI* S1, S2 and S3 scenarios on the left hand side are business-as-usual AG scenarios with decreasing levels of activity but no adoption of mitigation measures. These scenarios are far from climate neutral in 2050 even though net zero-CO_2 is achieved. The warming impact curves bend more strongly as AG mitigation increases. Temperature neutrality (blue bars) is achieved in the middle of the graph, including the *FAPRI* S2_P1 and *GOBLIN* b scenarios. On the right hand side, temperatures decline strongly after 2050 even though no further abatement measures have been assumed after 2050. Sharp reductions in the emissions of shorter-lived AG gases are expected to be even more effective in limiting warming for Ireland than in the global case because of the larger role they play in Ireland's emissions profile, Table 1. Figure ES1 suggests that this is indeed the case.

The maximum warming impact is lower when the peak occurs sooner in Figure ES1. The absolute differences in peak warming impact between the different AG scenarios is of interest. Table 2 shows the year of peak warming (or neutral year) and corresponding warming impact in the neutral scenarios of Figure ES1. For example, the peak warming difference between FAPRI S1_P2 and S2_P2 (which have different levels of activity, see Appendix A.1 Table 6) is 0.02 $m°C$. This is the equivalent to 44 Mt of cumulative CO_2 emissions on a *TCRE* basis.

Table 2: *Neutral year and median warming for the six agricultural scenarios that are neutral by 2050 in Figure ES1.*

AG-scenario	neutral year	$m°C$
S2_P1	2050	2.42
S1_P2	2047	2.39
b	2045	2.37
S2_P2	2042	2.37
d	2042	2.36
e	2041	2.36

3.2 Warming impact by gas

A breakdown of the warming contributions of individual gases can help to shed further light on the role played by shorter-lived AG gases and other climate drivers. This is illustrated in Figure 6 for the period 1990-2100 for the strong AG mitigation scenario S2_P2. The CO_2 scenario used in Figure 6 (400mt-WAM L4) has 2021-2050 emissions of 391 $MtCO_2$ and reaches net zero in 2042.

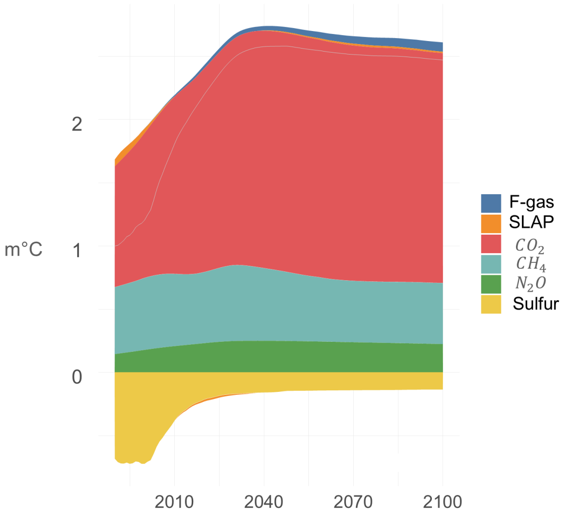

Figure 6: *Warming contribution by gas for the period 1990-2100 in a strong agriculture mitigation scenario. The contribution of sulfur (SO_2) is separated from other short-lived air pollutants (SLAPs). The white line indicates the total warming impact.*

Figure 6 shows that all three major greenhouse gases contribute to temperature neutrality before

2050. This is particularly true for CH_4 whose warming impact peaks in the early 2030's. However, the contribution of N_2O also has a broad peak in 2038. Although N_2O emissions are non-zero, when sufficiently strong cuts are made the rate at which N_2O is being added to the atmosphere is less that the amount being removed by natural processes. Therefore the warming impact of this gas declines, even though it is not normally considered a short-lived GHG. Thus N_2O makes an important contribution to temperature neutrality in strong AG mitigation scenarios that is easily overlooked. This point is discussed further in Appendix A.2.

In contrast to scenario gases CO_2, CH_4 and N_2O, the warming impact of F-gases, sulfur and ozone precursors (SLAPs) all *increase* in Figure 6. In the case of sulfur, this is a residual climate response following the rapid reductions of this pollutant in the 2000's and cannot be avoided. The F-gas WAM projection to 2050 used in preparing this report, which include both long and short-lived gases, has increasing emissions (Appendix A.1) and more favourable scenarios may be possible in this case.

Table 3 shows warming by gas for the periods 2021-2050 and 2050-2100 in the same scenario. CO_2 is the dominant source of future warming, contributing an addition $0.22m^{\circ}C$ between 2021 and 2050. In contrast CH_4 shows net cooling over 2021-2050. This increases after 2050 even though no additional measures are assumed. N_2O also contributes to cooling after 2050. The ongoing climate response to near elimination of SO_2 emissions makes a surprisingly large warming contribution of $0.05m^{\circ}C$ during 2021-2050.

Table 3: *Warming impact by gas in $m^{\circ}C$ for the periods 2021-2050 and 2050-2100 in the same scenario as Figure 6.*

gas	$m^{\circ}C$	
	2021-2050	2050-2100
CO_2	0.22	-0.03
CH_4	-0.02	-0.05
N_2O	0.01	-0.02
Sulfur	0.05	0.02
F-gases	0.01	0.03
SLAP	0.03	0.00

4 Climate Neutrality

Climate neutrality is a key component of the national climate objective [6]. There are different interpretations of what it means for a country to be climate neutral.

(A) Net zero-GHG using an agreed policy metric, almost always GWP100.
(B) Net zero-CO_2 with prescribed deep cuts in CH_4 and N_2O.
(C) Stabilisation (and subsequent reversal) of the country's warming impact.
(D) Reversal of the country's historic contribution to increased atmospheric concentration of GHGs above pre-industrial levels so that the flux of excess heat into the oceans ceases.

Net zero-GHG (A) is easy to apply but has the disadvantage that it is ambiguous in terms of warming outcomes when applied to countries with high shares of agricultural GHGs. It also omits the impact of SLAPs. (C) ensures that the warming impact is not increasing but fails to provide an explicit ceiling aligned with a global temperature goal. (D) is the most general and ambitious definition of neutrality. This would be necessary to prevent further contributions to sea level rise.

(D) would require enormous amounts of carbon dioxide removal and will not be achieved by 2050. Therefore (D) is not a viable interpretation of the NCO or of the Paris Agreement. Climate neutrality is often assumed to mean (A). However, none of the 1,196 CBWG scenarios discussed here satisfy (A) by 2050. The temperature neutral condition (C) can be used to rule out emissions scenarios that have increasing warming impact in 2050 on the basis that this is contrary to climate neutrality. This criterion is discussed in Sections 4.1 and 4.2.

4.1 Uncertainty in the climate system

The climate system's sensitivity to GHGs and other forcing agents is uncertain, implying that an emissions scenario can only be deemed temperature neutral with a certain degree of confidence. This uncertainty is represented in a Simple Climate Model (SCM) by using a range of alternative parameter configurations, such as the constrained FaIR ensemble [13]. To illustrate this, Figure 7 shows the warming impact of Ireland in a ≈400 Mt CO_2 *FAPRI* S1_P1 scenario. The warming impact is shown for 53 distinct model parameterisations that make up the constrained ensemble. The neutral year is indicated for each configuration, if it exists. Note that neutrality is more likely to occur in the lower climate sensitivity configurations. In this instance, less than 20% of the configurations are temperature neutral by 2050, therefore this scenario is unlikely to be temperature neutral by 2050 and can be ruled out.

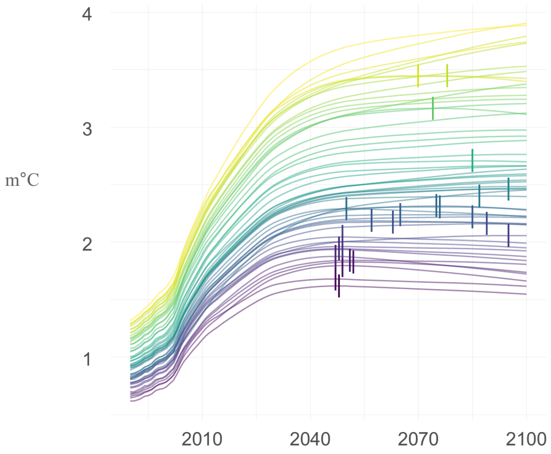

Figure 7: *Irish warming impact for the 53 FaiR model configurations of the constrained ensemble used in this report. The emissions scenario in this case is 400 Mt CO_2 S1_P1. Higher climate sensitivity configurations are shown in yellow and green. Vertical bars indicate temperature neutral points.*

4.2 Temperature neutrality

The calculation illustrated in Figure 7 can be repeated for all CBWG scenarios, counting the proportion of configurations that are neutral in each case. Here, the probability threshold for neutrality is set at $\frac{2}{3}$, meaning that the outcome is "likely" according to IPCC uncertainty guidance [2]. A 50% probability threshold for neutrality could be considered too low, as this would reduce adherence to NCO to the toss of a coin. Of course, a stricter 90% "very likely" threshold could also be used. For the remainder of this section, a neutral scenario means a combined FFI/AFOLU scenario that is likely to be temperature neutral by 2050 in a background global *SSP1-26* pathway.

Neutral scenarios are shown in Figure ES2. AFOLU (*GOBLIN/FAPRI*) scenarios are arranged loosely by increasing mitigation effort along the x-axis. FFI (*TIM*) scenarios are arranged loosely by increasing mitigation effort along the y-axis. Therefore the top right-hand region of the plot corresponds to the strongest overall GHG abatement effort. The dark region corresponds to FFI-AFOLU scenarios which fail the neutrality test. However, more than 40% of the scenario combinations are neutral. 23% of the scenarios are neutral by 2045.

Remarkably, the strongest *GOBLIN* L2, L3, L4 e AFOLU scenarios (CH_4 -322 kt) are likely to be neutral by 2040, although this requires FFI budgets of 350 Mt or lower. Similarly, the *FAPRI* S2_P2 scenario is always neutral before 2045 in FFI scenarios of 350 Mt or lower. In fact, all AFOLU scenarios stronger than L1 S2_P2 are neutral by 2050 irrespective of the FFI scenario. While strong AG emissions cuts are required, it is encouraging that the range of CBWG scenarios that pass the neutrality test as defined here is quite wide.

5 Context and limitations

In this report, a warming impact was allocated to Ireland based on a physical science approach. A strength of this approach is that no implicit judgements were required to calculate the warming impact e.g. the choice of a method to scale emissions or warming impact. Another strength is that, while there are differences in detail, comparisons between FaIR and MAGICC7 SCMs showed good agreement. The conclusions of this report are not sensitive to the choice of SCM.

Several data limitations should be pointed out. First, pre-1990 historical datasets for Ireland are of lower quality compared to the reliable post-1990 inventory emissions data. Additionally, no consideration has been given to pre-1990 emissions of CFCs, which were eventually banned under the Montreal Protocol. Furthermore, the air pollutant projections used in this analysis are not directly linked to the modelled scenarios, as they ideally should be. For instance, NH_3 emissions should be tied specifically to agricultural emissions. No doubt these deficiencies will be addressed in future analyses but they are unlikely to alter the conclusions reached in this report.

Another limitation to consider is that a specific "green road" *SSP1-26* global pathway was chosen for this analysis [4]. The actual global trajectory may diverge from this high ambition scenario in future. Paradoxically, failure to reduce CH_4 globally in line with *SSP1-26* makes it easier to achieve temperature neutrality at national level. Of course, this would not be a desirable outcome as broader climate goals are undermined.

Perhaps the main limitation of this report is it's narrow scope. A mathematical procedure has been used to discriminate between alternative split-gas emissions pathways, but no consideration has been given to their differing societal, economic, biodiversity or ethical implications. However, the numerical information on warming impacts would form part of these judgements.

A Technical Appendix

A.1 Drivers and scenarios

The 24 Irish climate drivers used here are listed in Table 4.

Table 4: *Irish climate drivers used in this report with historical and projection data sources.*

gas	historical	projection
FFI-CO_2	NIR 2024	UCC
LULUCF-CO_2	NIR 2024	UCG
AG-CH_4	NIR 2024	UCG/Teagasc
LULUCF-CH_4	NIR 2024	UCG
N_2O	NIR 2024	UCG/Teagasc
WASTE-CH_4	NIR 2024	WAM[a]
HFC-23	NIR 2024	WAM[b]
HFC-32	NIR_2024	WAM[b]
HFC-125	NIR_2024	WAM[b]
HFC-134a	NIR_2024	WAM[b]
HFC-143a	NIR_2024	WAM[b]
HFC-152a	NIR_2024	WAM[b]
HFC-227ea	NIR_2024	WAM[b]
CF_4	NIR_2024	WAM[b]
C_2F_6	NIR_2024	WAM[b]
c-C_4F_8	NIR_2024	WAM[b]
SF_6	NIR_2024	WAM[b]
NF_3	NIR_2024	WAM[b]
SO_2	EPA	EPA
NOx	EPA	EPA
NMVOC	EPA	EPA
NH_3	EPA	EPA
BC	EPA	EPA
OC	EPA	EPA
CO	CEDS_2024	other

[a] 2050 WAM projection [21]

[b] Inferred from 2050 WAM using f-gas mix from NIR.

Table **??** summarises the *GOBLIN* LULUCF-CO_2 scenario labels used in Figure ES2, for example.

Table 5: *Land sink in* GOBLIN *scenarios.*

scenario	Mt CO_2	
	2050	2100
L_1	-1.4	-5.0
L_4	-4.3	-9.9
L_2	-5.5	-11.0
L_3	-6.8	-14.3

Table 6 summarises the agricultural gas emissions reductions in the *FAPRI* scenarios. S1, S3 and S2 refer to constant, higher and lower activities, and P1 and P2 refer to the level of abatement measure adoption.

Table 6: *2021-2050 agricultural gas reductions in* FAPRI *scenarios.*

scenario	%	
	CH_4	N_2O
S3	9.0	4.5
S1	4.6	-3.3
S3_P1	-7.4	-47.0
S2	-12.1	-18.1
S1_P1	-15.2	-53.4
S3_P2	-24.3	-65.8
S2_P1	-27.7	-62.2
S1_P2	-31.3	-70.1
S2_P2	-42.7	-75.2

A.2 Emissions and lifetimes

Climate forcing by a greenhouse is related to the excess atmospheric concentration of the gas over the pre-industrial level. Lowering the climate forcing impact of a greenhouse gas means lowering the atmospheric concentration.

Apart from CO_2, greenhouse gases decay approximately exponentially with a mean residence or lifetime τ. It follows that if the rate of anthropogenic emissions exceeds the amount removed by natural decay then the concentration of the gas increases and vice versa. For gases that decay exponentially, the annual rate of natural removal is ${}^{\Delta M_t}/_{\tau}$ where ΔM_t is the excess mass of the gas in the atmosphere.

For example, the anthropogenic atmospheric mass of CH_4 corresponding to the increased atmospheric mixing ratio (concentration) over pre-industrial level (≈1200 ppb [18]) is 3.3 Gt. With a perturbation lifetime of 11.8 years, this corresponds to an anthropogenic emissions threshold of 280 Mt per year to stabilize forcing. Anthropogenic emissions are currently ≈320 Mt which suggests that a cut of more than 13% in global anthropogenic methane emissions is sufficient to reduce forcing from this source. For N_2O the numbers are different due to the longer lifetime of this gas. Global emissions of N_2O are ≈10.6 Mt [18]. The anthropogenic increase in mixing ratio (≈ 66 ppb [18]) is equivalent to atmospheric mass increase of 553 Mt, implying that the threshold for falling concentration is 4.9 Mt or about half of the current emissions. This is well below the currently assessed global mitigation potential for this gas [16]. However, Table 6 suggests a higher mitigation potential for Ireland, raising the possibility of negative warming impact from this gas (Section 3.2).

References

[1] United Nations Framework Convention on Climate Change (UNFCCC). *Paris Agreement*. Adopted on 12 December 2015, entered into force on 4 November 2016. 2015. URL: `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`.

[2] *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Intergovernmental Panel on Climate Change (IPCC), 2021. DOI: `10.1017/9781009157896`. URL: `https://www.ipcc.ch/report/ar6/wg1/`.

[3] Myles R Allen et al. "Net zero: science, origins, and implications". In: *Annual Review of Environment and Resources* 47.1 (2022), pp. 849–887.

[4] International Institute for Applied Systems Analysis (IIASA). *The Shared Socioeconomic Pathways (SSPs) Database*. 2020. URL: `https://tntcat.iiasa.ac.at/SspDb`.

[5] Claudia Tebaldi et al. "Climate model projections from the scenario model intercomparison project (ScenarioMIP) of CMIP6". In: *Earth System Dynamics* 12.1 (2021), pp. 253–293.

[6] Government of Ireland. *Climate Action and Low Carbon Development (Amendment) Act 2021*. 2021. URL: `https://www.irishstatutebook.ie/eli/2021/act/32/enacted/en/html`.

[7] Steven J. Smith, Rachel M. Hoesly, et al. *Community Emissions Data System (CEDS): Historical Emissions for 1850–2024*. `https://github.com/JGCRI/CEDS`. Version 2024-01-01, Accessed: 2024-09-10. 2024.

[8] Fortunat Joos et al. "Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios". In: *Global Biogeochemical Cycles* 15.4 (2001), pp. 891–907.

[9] John Lynch et al. "Demonstrating GWP*: A means of reporting warming-equivalent emissions that captures the contrasting impacts of short-and long-lived climate pollutants". In: *Environmental Research Letters* 15.4 (2020), p. 044023.

[10] Barry McMullin, Paul R Price, and Aideen O'Dochartaigh. "Defining a 'Paris Test'of national contribution to global climate mitigation: the Irish exemplar". In: *Environmental Research Letters* 19.4 (2024), p. 041006.

[11] Danish Climate Council. *Denmarks Climate Targets*. Accessed: 2024-10-03. 2023. URL: `https://klimaraadet.dk/en/analysis/denmarks-climate-targets`.

[12] Andrew H MacDougall. "The transient response to cumulative CO2 emissions: a review". In: *Current Climate Change Reports* 2.1 (2016), pp. 39–47.

[13] Nicholas J Leach et al. "FaIRv2. 0.0: a generalized impulse response model for climate uncertainty and future scenario exploration". In: *Geoscientific Model Development* 14.5 (2021), pp. 3007–3036.

[14] Malte Meinshausen et al. "The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500". In: *Geoscientific Model Development* 13.8 (2020), pp. 3571–3605.

[15] Kalyn Dorheim et al. "Hector V3. 2.0: functionality and performance of a reduced-complexity climate model". In: *Geoscientific Model Development* 17.12 (2024), pp. 4855–4869.

[16] Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by R. Pichs-Madruga, D. Ürge-Vorsatz, P. R. Shukla, et al. Cambridge University Press, 2022. URL: `https://www.ipcc.ch/report/ar6/wg3/`.

[17] Joseph Wheatley. "Temperature neutrality and Irish methane policy". In: *Climate Policy* 23.10 (2023), pp. 1229–1242.

[18] Piers M Forster et al. "Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence". In: *Earth System Science Data* 16.6 (2024), pp. 2625–2658.

[19] Christopher W Callahan and Justin S Mankin. "National attribution of historical climate damages". In: *Climatic Change* 172.3 (2022), p. 40.

[20] Carbon Brief. *Analysis: Which countries are historically responsible for climate change?* 2021. URL: `https://www.carbonbrief.org/analysis-which-countries-are-historically-responsible-for-climate-change`.

[21] *GovReg: National projections of anthropogenic greenhouse gas emissions*. 2024. URL: `https://reportnet.europa.eu/`.