AVOID 2
Can we avoid dangerous climate change?

The contribution of non-CO_2 greenhouse gas mitigation to achieving long-term temperature goals

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Non-technical summary

This paper analyses the emissions and cost impacts of mitigation of non-CO_2 greenhouse gases (GHGs) at a global level, in scenarios which are focused on meeting a range of long-term temperature goals (LTTGs). The paper demonstrates how an integrated assessment model (TIAM-Grantham) representing CO_2 emissions (and their mitigation) from the fossil fuel combustion and industrial sectors is coupled with a model covering non-CO_2 emissions (GAINS) in order to provide a complete picture of GHG emissions in a reference scenario in which there is no mitigation of either CO_2 or non-CO_2 gases, as well as in scenarios in which both CO_2 and non-CO_2 gases are mitigated in order to achieve different LTTGs.

In the latest (fifth) assessment from the Intergovernmental Panel on Climate Change (IPCC) non-CO_2 emissions accounted for 28% of total GHG emissions in 2010, when measured on the basis of their global warming potential (relative to CO_2) over a 100-year timespan, a measure known as GWP100. The single largest source of these emissions is agriculture, with agricultural methane (CH_4) and nitrous oxide (N_2O) accounting for about half of all non-CO_2 GHGs. With population and incomes increasing, especially in emerging economies, these emissions could grow significantly in the future. Other major sources of non-CO_2 GHGs are fugitive CH_4 from the extraction and distribution of fossil fuels, N_2O from industrial production of nitric and adipic acid, as well as fluorinated gases (F-gases) from a range of industrial manufacturing and product uses.

In a reference case, non-CO_2 GHGs contribute about one third of total GHG emissions of 132 $GtCO_2e$ (on a GWP100 basis) by 2100, in a scenario which sees a median temperature change of 4.6^{O}C by 2100 compared to pre-industrial levels. If CO_2 from the fossil fuel and industrial sectors is mitigated in line with a 2^{O}C LTTG, then a significant portion (just over a third) of CH_4 is mitigated relative to the reference scenario by 2100, as result of the shift away from fossil fuel sources of energy, thereby hugely reducing fugitive CH_4 emissions. Furthermore, non-CO_2 GHGs can be mitigated directly, through a range of measures including: controlling remaining CH_4 leaks from fossil fuel extraction and distribution; reduction and better management of industrial waste; a range of agricultural practices including control of N_2O emissions through improved fertilizer use and reduction of CH_4 emissions from livestock through dietary changes or changed manure management practices; catalytic reduction of N_2O from industrial processes; and replacement of hydrofluorocarbons (HFCs) with alternatives for use in refrigerators, air conditioners, foam, solvents, fire-extinguishers and aerosol cans.

As reflected in previous studies, the majority of non-CO_2 mitigation measures are less costly than CO_2 mitigation measures in the latter half of the century,, with the vast majority of their abatement potential achievable at US2005\$100/tCO_2e or less throughout the 21st century (compared to a marginal CO_2 mitigation cost which rises to several thousand US2005\$ over the century in the most stringent mitigation scenario). This means that mitigation of non-CO_2 GHGs to even a fraction of the price of the CO_2 price in the fossil fuel and industrial sectors can limit global temperature change at a significantly lower cost than a mitigation strategy that targets CO_2 only. As an illustration, according to the analysis in this study, the total cumulative discounted cost over the period 2010-2100 (at a 5% discount rate) of limiting global average temperature change to 2.5^{O}C by 2100 is \$48 trillion (about 1.6% of cumulative discounted GDP over the period 2010-2100) if only CO_2 from the fossil fuel and industrial sectors is targeted, whereas the cost falls to \$17 trillion (0.6% of GDP) by including non-CO_2 GHG mitigation in the portfolio of options - a cost reduction of about 65%.

If non-CO_2 GHGs are mitigated to the same CO_2e price level as for CO_2 from the fossil fuel and industrial emissions sectors, then there is significant abatement of all non-CO_2 GHGs up to this CO_2e price, such that in the 2^{O}C scenario, by 2100 the fully mitigated level of non-CO_2 GHGs is just under 13 GtCO_2e, compared to more than 39 GtCO_2e in the unmitigated reference scenario. Of this approximate 27 GtCO_2e reduction, 69% occurs through the direct mitigation of the non-CO_2 GHGs and 31% through the indirect mitigation (mostly of CH_4) that follows from CO_2 mitigation. For each non-CO_2 GHG (CH_4, N_2O, and aggregated F-gases) the absolute emissions in the reference and mitigation scenarios are within the ranges of the database of scenarios presented in the IPCC's fifth assessment report, although the CH_4 reference emissions are at the higher end of the range, reflecting the relatively high socio-economic growth path and industrial output growth over the 21st century that underlies the scenario projections in this study. Furthermore, the percentage emissions reductions of each non-CO_2 GHG resulting from both direct and indirect mitigation are also comparable to those in the fifth assessment report database.

In summary, non-CO_2 GHG mitigation measures are likely to be very important in achieving long-term temperature goals in a cost-efficient way. However, these measures, their costs and barriers, as well as the options to reduce them through demand-side measures (such as changes to human dietary choices), remain relatively underexplored compared to CO_2 mitigation options, which recommends the need for further investigation into these gases.

Media interest

The economic benefits of mitigating non-CO_2 greenhouse gases as part of a cost-effective pathway to meeting stringent mitigation goals is already known. However, the later global coordinated mitigation action begins, the more economically beneficial a multi-gas strategy is likely to be, as indicated by this research which focuses on mitigation scenarios in which global coordinated mitigation action begins in 2020, compared to previous studies which have examined the benefits of non-CO2 GHG mitigation in “immediate” action scenarios starting in or before 2010. In addition, the indirect mitigation of fugitive methane emissions from reducing fossil fuel reliance is less widely quantified and forms an important and novel finding of this research. This has the potential to attract media interest at a time when there is a focus on the potential exploitation of new sources of fossil fuels (such as shale gas and shale oil).

1 Introduction

This paper analyses the emissions and cost impacts of mitigation of non-CO_2 greenhouse gases (GHGs) at a global level, in scenarios which are focused on meeting a range of long-term temperature goals (LTTGs). The objectives are threefold:

- First, to demonstrate how an integrated assessment model (TIAM-Grantham) representing CO_2 emissions (and their mitigation) from the energy and industrial sectors is coupled with a model covering non-CO_2 emissions (GAINS) in order to provide a complete picture of GHG emissions in a reference scenario in which there is no mitigation of either CO_2 or non-CO_2 gases, as well as in scenarios in which both CO_2 and non-CO_2 gases are mitigated in order to achieve different LTTGs;
- Secondly, to demonstrate the degree of indirect mitigation of non-CO_2 gases that results from mitigation of CO_2 sources. This principally applies to methane (CH_4) emissions reductions which result from reduced extraction and distribution of fossil fuels in CO_2 mitigation scenarios which see a shift from fossil fuel energy sources to renewables and nuclear.
- Thirdly, to analyse the costs associated with mitigating non-CO_2 GHGs to varying degrees, by considering different levels of CO_2e prices applied to the non-CO_2 GHG-emitting sectors, relative to the CO_2 prices that result from the CO_2 mitigation scenarios. This provides a picture of the marginal impact (in terms of temperature change in 2100) of varying the relative degree of effort in mitigating non-CO_2 gases when compared to CO_2 mitigation effort.

Non-CO_2 GHG emissions, at about 12 $GtCO_2e$ in 2010 (compared to 37 for CO_2 emissions) constituted about 28% of total GHG emissions in that year, measured on a CO_2-equivalent (CO_2e) basis using IPCC fifth assessment report 100-year global warming potentials (GWP100) for each gas [1],[2]. Agricultural CH_4 and N_2O emissions, at between 5.2 and 5.8 $GtCO_2e$ in 2010, are the largest contributor to non-CO_2 GHG emissions. Over the last three decades (comparing 1980-1989, 1990-1999 and 2000-2009) CH_4 and N_2O emissions from agriculture increased from about 4 to over 5 $GtCO_2e$ per year, with CH_4 emissions from livestock (enteric fermentation, mainly from cattle) accounting for just under half of this level throughout this period. Emissions growth from most agricultural sources (enteric fermentation, manure and fertiliser) in Africa, Asia and the Americas has been offset to some extent by emissions reductions in Europe [3], but future demand for food from these regions could be a major driver of emissions growth over the coming decades. Waste, fossil fuel extraction, transmission and distribution, and industrial production are other significant sources of non-CO_2 GHGs, principally CH_4 and N_2O.

As well as making a significant contribution to warming of the climate, some non-CO_2 species also lead to relatively large amounts of warming per tonne emitted. CH_4 for example, by mass, has a global warming potential over 100 years (GWP100) which is 34 times larger than that of CO_2 [1]. It is important to note that this value is higher than the value (25) used in the previous (fourth) IPCC assessment report [4]. This comparative measure of warming – that of an equivalent mass of CO_2 - is the basis for emissions accounting and allows one method of comparing the cost effectiveness of mitigation measures across different gas species for a given timeframe. The major sources and mitigation options for non-CO_2 GHGs are shown in Table 1.

Table 1: Source and mitigation options for non-CO_2 greenhouse gases

Non-CO_2 gas	**% of total emissions in 2010**	**Major sources**	**Mitigation options for each major source**
Methane (CH_4)	20%	• Livestock (enteric fermentation and manure management)	• Anaerobic digestion of manure with biogas capture and utilization • Animal diet changes
		• Rice cultivation	• Field water management
		• Crop residue burning	• Baling/mulching of crop residue
		• Wastewater • Municipal waste • Industry waste	• Source separation, recycling and treatment of biodegradable waste instead of landfill • Extending wastewater treatment from primary to secondary/tertiary
		• Fugitive emissions from coal, oil and gas extraction, transmission and distribution	• Reduced venting of associated waste gas from oil and gas production • Leakage control at oil and gas wells and from gas transmission and distribution networks • Pre-mining degasification of coal mines • Ventilation air methane oxidation on underground coal mine shafts
Nitrous oxide (N_2O)	6%	• Agricultural soils	• Improved N use efficiency • Precision nitrogen application
		• Combustion stationary sources	• Modified fluidized bed combustion
		• Nitric and adipic acid production	• Catalytic reduction • Twin reduction technology
F-gases	2%	• Perfluorocarbons (CF_4 and C_2F_6) from primary aluminium production • Perfluorocarbons (PFCs) from semiconductor industry	• Conversion to point-feeder prebake technology • Retrofit of aluminium plants with new anode materials • Replace PFCs with NF_3 in semiconductor industry
		• Sulphur hexafluoride (SF_6) from insulation for medium and high voltage switchgear	• Good practice leak control and SF_6 recycling
		• SF_6 from magnesium casting	• Replacement with SO_2
		• Hydrofluorocarbons (HFCs) from: ○ Insulation ○ Refrigeration ○ Air-conditioning ○ Geothermal heat pumps ○ Fire-extinguishers ○ Aerosols ○ Solvents ○ HCFC-22 production	• Replacing HFC with low-GWP alternatives • Leak control • Recycling • Ban on use of HFC's • Incineration of HFC-23 emissions from HCFC-22 production

Sources: Share of emissions for each gas from IPCC [2]*; Major emissions sources from Reay et al* [5]*; Montzka et al* [6]*; Rao and Riahi* [7]*; Mitigation options from Delhotal et al* [8]*; DeAngelo et al* [9]*; Schaefer et al* [10]*; Lucas et al* [11], *Höglund-Isaksson* [12]*; Höglund-Isaksson et al* [13].

In addition to the technical supply side measures shown in Table 1, mitigation could also come through changes in consumer preferences for meat and dairy products and reduced losses and waste of food [3], [5], [14] although there is in general less evidence on these demand-side emissions mitigation options [3].

There have been relatively fewer studies on the mitigation potential of non-CO_2 GHGs compared to CO_2 from the energy and industrial sectors. A number of sector specific studies were carried out in the late 1990s and early 2000s [15], [16], [17], many of which formed the basis of more comprehensive assessments included in a 2006 special issue of the Energy Journal (deAngelo et al. [9] for CH_4 and N_2O from agriculture; Delhotal et al. [8], for CH_4 and N_2O from waste, energy and industry; Schaefer et al. [10] for F-gas emissions sources) . These studies were undertaken in order to construct marginal abatement cost curves for 2010, which were then extrapolated for use in integrated assessment studies analysing multi-gas mitigation scenarios as part of the 21st Stanford Energy Modelling Forum (EMF) exercise [7], [18]. Further work by Lucas et al. [11] extended the MACs more systematically to 2100. This analysis, as well as some more recent analysis [19], has formed the basis of relatively recent estimates of long term mitigation in for example the agricultural sector [20].

A consistent message from the multi-gas modelling studies is that the cost of mitigation to achieve a given temperature goal is less when mitigation of non-CO_2 GHGs is included amongst the mitigation options available, but only while the relatively cheap options are used up. For example, Rao and Riahi [7] find that carbon prices associated with achieving a radiative forcing level of 4.5 W/m^2 by 2100 when using a multi-gas mitigation approach are about half those when using a CO_2-only set of mitigation measures. Kurosawa [21] finds that a multi-gas approach (again, to achieve a 4.5W/m^2 forcing level by 2100) leads to a global mitigation cost of 3.8% of GDP by 2100, compared to 8.6% of GDP with a CO_2-only approach. Lucas et al. [11] find that a multi-gas approach lowers mitigation costs between 3-21% (by 2050) and 4-26% (by 2100) compared to a CO_2-only approach, to achieve a 550 ppm CO_2e stabilisation concentration of GHGs.

More recent analysis of a multi-gas model inter-comparison in the European LIMITS project [22] highlights the increasing importance of non-CO_2 gases over time in a stringent mitigation (450 ppm CO_2e) scenario, in which in several models CO_2 emissions are mitigated to very low or in some cases negative values in the latter half of the 21st century. The models show a range of emissions reductions (by 2100) for CH_4 to 35-71% below a baseline (i.e. unmitigated) range of about 10-16 GtCO_2e per year; for N_2O to 10-42% below a baseline of about 2-6 GtCO_2e per year; for F-gases to 52-90% below a baseline of about 1-10 GtCO_2e per year. This shows first the large range of estimates of unmitigated emissions from these sources, and secondly the large available abatement potential across models (though again, with greatly varying estimates of mitigation potential as part of an overall multi-gas least-cost optimisation scenario to meet the 450 ppm CO_2e target).

The model used in this assessment, the Greenhouse Gas Air Pollution Interactions and Synergies (GAINS) model, has a comprehensive, multi-country and region representation of non-CO_2 GHG emissions sources, as well as the measures and costs for their mitigation [23], [24]. The cost data used here is from the 2013 update of the GAINS model. It has been used in recent studies of the mitigation potential of CH_4 [12], as well as other climate forcing species such as black carbon, with a view to assessing not just climate but also air quality, health and agricultural crop yield benefits of mitigating these short-lived species [25]. As such, it has been chosen because of its relatively recent development, its state-of-the-art level of detail of mitigation options for the non-CO_2 GHGs, as well as its geographical detail which allows aggregation of countries into regions which closely match the 15 regions represented in Imperial College London's global TIMES Integrated Assessment Model (TIAM-Grantham) [26], [27]. This model represents the global energy and industrial system in these regions, including low-carbon technologies and their costs, and associated CO_2 emissions. It is an inter-temporal optimisation model which finds the welfare maximising solution to the objective of meeting future energy service and industrial product demands across all economic sectors within a given climate or CO_2 emissions constraint. It has been used in a model inter-comparison study as part of the AVOID 2 research programme to analyse the technologies and costs of a range of long-term temperature targets [28]. It should be noted that this analysis covers the well-mixed GHGs and does not explicitly model emissions of aerosols and precursors, for example black carbon – for each scenario these have been estimated using the methods described in the next section.

2 Methods

There are in many cases interactions between measures that mitigate different GHGs. For example mitigation of CO_2 frequently consists of substituting non-fossil energy sources for fossil fuels, which results in reduced fugitive CH_4 emissions from the extraction and distribution of these fuels [29]. In addition to accounting for such interactions, it is important to ensure a high level of consistency between the drivers of energy and industrial CO_2 emissions and those for non-CO_2 emissions sources, principally agricultural activity responsible for CH_4 and N_2O emissions.

In order to maximise consistency between the energy and industrial CO_2 mitigation modelling in the TIAM-Grantham model, and the non-CO_2 mitigation modelling in the GAINS model, a number of steps have been undertaken, as described in detail in the Annex. In summary:

- For each LTTG (in this study 2100 temperature change levels of 2^{O}C, 2.5^{O}C and 4^{O}C are assessed) a cumulative 2000-2100 global CO_2 budget for the fossil fuel and industrial (FFI) sectors has been estimated from a simple interpolation of the budget from the Representative Concentration Pathways (RCPs) and projections of their corresponding global temperature change when simulated with a probabilistic version of MAGICC (as detailed in [30]) using a distribution of equilibrium climate sensitivity from the Fifth Coupled Model inter-comparison Project (CMIP5), as detailed in [31];
- The TIAM-Grantham model has been used to produce an unmitigated reference scenario, as well as mitigation scenarios based on these estimated CO_2 budgets, using a standard set of socio-economic drivers, specifically the OECD variant of the Shared Socio-Economic Pathways 2 (SSP2), which has been used in order to represent a future world in which recent socio-economic trends continue [32];
- The GAINS model, also using SSP2 socio-economic inputs, as well as energy price and fossil fuel supply and demand outputs from the TIAM-Grantham model scenarios, has been used to produce a "baseline" level of non-CO_2 emissions for each TIAM-Grantham scenario, as well as marginal abatement cost (MAC) curves for each ten-year time point (2020, 2030, 2040 etc.) for each non-CO_2 GHG species (CH_4, N_2O, F-gases);
- For each scenario, the 2100 temperature when mitigating non-CO_2 GHGs to different prices (on a GWP100 basis, with prices relative to the CO_2 price for each TIAM-Grantham scenario) has been calculated, using the same version of the MAGICC used to estimate the initial CO_2 budgets;

- Where the non-CO_2 and CO_2 prices are equal, if there is a major (in this case, greater than 0.1^{O}C) difference in the calculated 2100 temperature change relative to the initially-intended LTTG, a revision to the initial CO_2 budget has been made and the process repeated.

As indicated above, the MAC curves derived from GAINS allow analysis of non-CO_2 mitigation up to a CO_2e price equal to the CO_2 price which was output from the TIAM-Grantham model (thereby equating marginal mitigation “effort” for CO_2 and the non-CO_2 GHGs) as well as at CO_2e prices at different fractions of the TIAM-Grantham CO_2 price (thereby considering different marginal effort levels for non-CO_2 GHGs when compared to CO_2 mitigation effort). This approach allows analysis of the 2100 median temperature change and overall mitigation cost (i.e. considering both CO_2 and non-CO_2 mitigation options) when considering lower and higher levels of “effort” of non-CO_2 GHG mitigation measures compared to CO_2 mitigation measures. For each mitigation scenario, as well as the 2100 temperature change, the cumulative discounted cost (using a discount rate of 5% per year) of both CO_2 and non-CO_2 GHG mitigation is calculated, relative to the reference (unmitigated) scenario.

3 Results

3.1 Mitigation of non-CO_2 emissions

Figure 1 shows the emissions level for each GHG in the unmitigated reference scenario where there is no price or constraint on any of the GHGs, using the GWP100 equivalence measure (as taken from the IPCC’s fifth assessment report [1]). This unmitigated scenario follows from running the TIAM-Grantham model to produce a scenario for a least-cost energy system that meets future energy needs under the SSP2 shared socio-economic pathways assumptions [32], but with no climate constraints. Emissions rise from 50 $GtCO_2e/yr$ in 2010 to 132 $GtCO_2e/yr$ in 2100. The resulting median warming in 2100 is 4.6^{O}C. For both 2100 emissions and temperature change, these figures are closer to the upper end of the range for the high emissions scenarios presented in the IPCC’s 5th Assessment Report, WGIII [2], reflecting the relatively strong socio-economic growth throughout the century represented by the SSP2 input scenarios. It can be seen that CO_2 is the largest contributor to GHG emissions throughout the period (reaching 93 $GtCO_2e/yr$ by 2100), with CH_4 and N_2O continuing to remain significant. By comparison, the RCP8.5 pathway, which has the highest emissions of the RCPs, sees global GHG emissions reaching 120 $GtCO_2e/yr$ in 2100, albeit with much lower global GDP by 2100 (a seven-fold increase over the 21st century [33], compared to an 11-fold increase in this study). Of this 120 $GtCO_2e/yr$, approximately 80 $GtCO_2e/yr$ is from CO_2 and the remainder from non-CO_2 gases (compared to 93 and 39 $GtCO_2e/yr$ respectively in this study) [34].

Hence, both RCP 8.5 and this study see non-CO_2 emissions accounting for about a third of the total GHG emissions by 2100, slightly higher than the upper end of the range (16-27%) in recent multi-gas mitigation scenarios [35]. In fact in these recent scenarios the maximum 2100 non-CO_2 emissions level (across the six models compared) is 30 $GtCO_2e/yr$, with CH_4 emissions at 15 $GtCO_2e/yr$. This is about 10 $GtCO_2e/yr$ below the emissions in this study, mainly because in this study CH_4 makes up 25 $GtCO_2e/yr$ in 2100. This results from the relatively high-growth socio-economic assumptions driving future emissions growth in this study, as well as the considerably higher GWP100 value for CH_4 (34) taken from the IPCC’s latest (i.e. fifth) assessment report compared to the lower value (25) used in the recent multi-gas mitigation scenarios [22] and also the IPCC's earlier fourth assessment report [1].

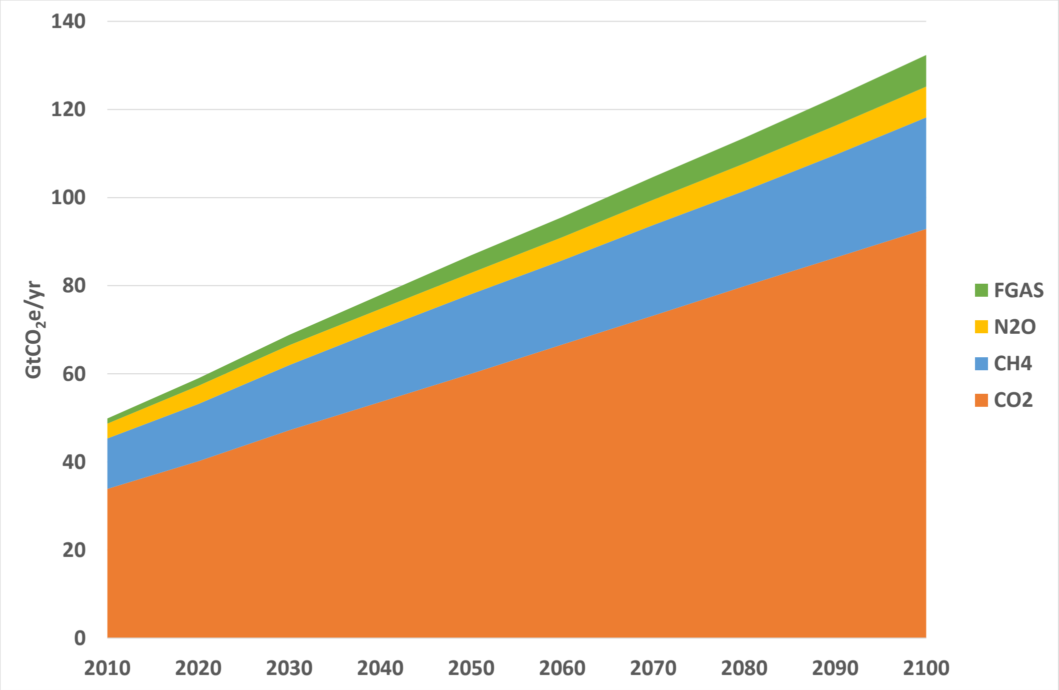

Figure 1: Global greenhouse gas emissions in the (unmitigated) reference scenario

Notes: The approximately linear nature of these GHG emissions curves is coincidental only. Emissions values follow from detailed modelling of the energy and non-CO_2 GHG emitting sectors in 10 year time-steps from the TIAM-Grantham and GAINS models used in this analysis.

Table 2 shows the estimated CO_2 budgets as well as the median temperature change that results from mitigation of non-CO_2 GHGs to a CO_2e price (using GWP100) equal to the CO_2 price from the TIAM-Grantham model for each budget (taking the scenarios with delayed action to 2020). Also shown is the median 2100 temperature change resulting from the unmitigated TIAM-Grantham and GAINS scenarios (i.e. resulting from the emissions levels shown in figure 1).

Table 2: Original estimates of 2000-2100 cumulative CO_2 from fossil fuel combustion and industry sectors, with associated calculated 2100 median temperature change

Scenario	**CO_2 cumulative budget estimate (2000-2100), $GtCO_2$**	**Later calculation of 2100 median temperature change in MAGICC, ^OC**
Baseline	No budget constraint – results in cumulative CO_2 of 6,000 $GtCO_2$	4.62
2^OC with delayed action to 2020	1,340	2.00
2.5^OC with delayed action to 2020	2,260	2.45
4^OC with delayed action to 2020	5,280	3.88

Figure 2 shows the non-CO_2 GHG emissions for a 2^OC mitigation scenario with global mitigation action starting in 2020 (and weak country/regional policy actions to 2020), after

CO_2 mitigation has occurred to meet the cumulative CO_2 budget, but before any specific mitigation has occurred in the non-CO_2 sectors. Also shown is the completely unmitigated level of non-CO_2 GHG emissions that derive from the reference scenario with no mitigation action for any GHGs (which in the case of non-CO_2 means action beyond that prescribed in existing legislation). In other words, figure 2 shows the indirect mitigation of the non-CO_2 GHGs that occurs as a result of changes in the energy system when transitioning to low-carbon (and in particular lower fossil fuel reliance) over the century. There is significant mitigation of CH_4 (about 9 $GtCO_2e$/yr by 2100) resulting from reduced fossil fuel extraction and distribution, and therefore lower fugitive CH_4 emissions. The importance of accounting for this indirect mitigation effect has been highlighted in recent studies [21], [36].

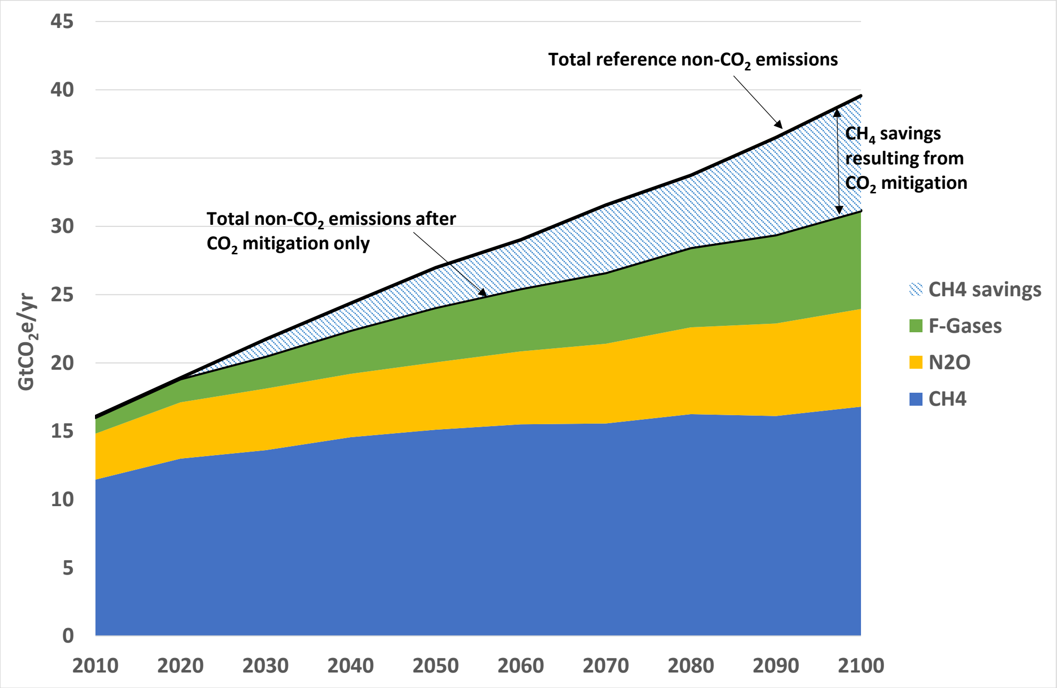

Figure 2: Non-CO_2 GHG emissions in unmitigated reference scenario, with indirect savings resulting from fossil fuel and industry CO_2 mitigation measures in 2^{O}C scenario with global mitigation action delayed to after 2020

Figure 3 shows the effect of indirect mitigation for a range of long-term temperature goals. As expected, the degree of mitigation increases as the temperature goal decreases, resulting from an increasingly marked shift from a fossil fuel-based energy system to a low-carbon system in which non-fossil sources such as nuclear and renewables dominate.

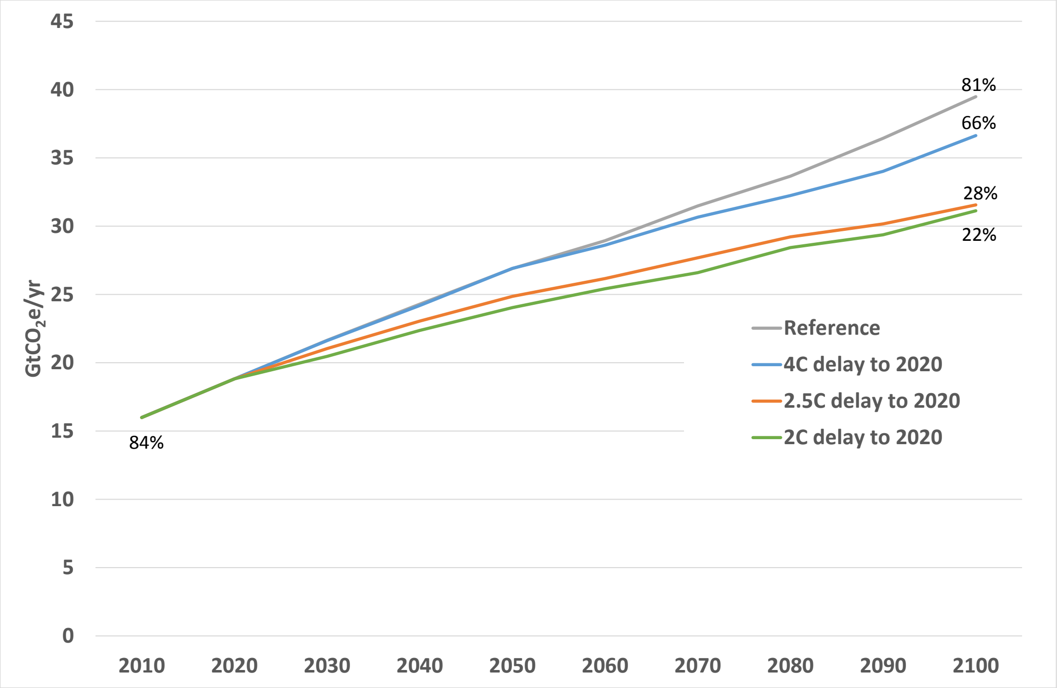

Figure 3: Non-CO_2 GHG emissions savings (relative to unmitigated reference scenario) from CO_2 mitigation measures, in a range of scenarios targeting different long-term temperatures with global mitigation action delayed to 2020

Notes: % figures show the share of fossil fuels in total primary energy supply in 2010 and 2100 for each scenario.

Figure 4 shows the further mitigation of non-CO_2 GHGs resulting from mitigation measures targeted specifically towards these gases, for the 2^{O}C scenario with delayed action to 2020. Also shown are the levels of each non-CO_2 GHG for the indirectly mitigated case. The figure shows for each time step the mitigation of non-CO_2 GHGs up to the CO_2e price that is equal to the CO_2 price in the TIAM-Grantham model (i.e. the shadow price of CO_2 associated with achieving the least cost mitigation pathway to meet the specified 21st century cumulative CO_2 budget). As such, this equates a level of mitigation effort for CO_2 and non-CO_2 GHGs according to the marginal cost of abatement at any given time. In the case of figure 4, this marginal abatement cost is calculated on a GWP100 basis.

It can be seen that there is significant abatement of all non-CO_2 GHGs up to this CO_2e price, such that by 2100 the fully mitigated level of non-CO_2 GHGs is just under 13 $GtCO_2$e/yr, compared to 39 $GtCO_2$e/yr in the unmitigated reference scenario. Of the 27 $GtCO_2$e/yr reduction, 69% occurs through the direct mitigation of the non-CO_2 GHGs and 31% through the indirect mitigation (mostly of CH_4) that follows from CO_2 mitigation. Of the unmitigated reference 2100 level of each non-CO_2 GHG, 67% of CH_4, 37% of N_2O and 99% of F-gases are mitigated, leaving 7.8, 4.5 and 0.1 $GtCO_2$e/yr of CH_4, N_2O and F-gases respectively. These reductions compare to recent modelled scenarios (focusing specifically on the issue of non-CO_2 GHG mitigation) in which by 2100 up to 71% of CH_4, 42% of N_2O and 90% of F-gases are mitigated [22], as well as the broader IPCC fifth assessment report database (https://secure.iiasa.ac.at/web-apps/ene/AR5DB/) in which, across all of the most stringent mitigation scenarios, 44-74% of CH_4, 9-42% of N_2O and 45-90% of F-gases are mitigated by 2100, compared to the relevant unmitigated baseline scenario for each model used In this database, the range of 2100 CH_4 emissions is 12-25 $GtCO_2$e/yr (using the most current CH_4

GWP100 value of 34) in the reference scenario and 4-11 $GtCO_2e/yr$ in the mitigation scenarios, compared to 25 $GtCO_2e/yr$ and 7.8 $GtCO_2e/yr$ in the $2^{O}C$ scenario of this study. The database's range of 2100 N_2O emissions is 3.0-8.8 $GtCO_2e/yr$ in the reference and 2.1-8.1 $GtCO_2e/yr$ in the mitigation scenarios, compared to 7.0 and 4.5 $GtCO_2e/yr$ in this study. The database's range of 2100 F-gases emissions is 1.2-10 $GtCO_2e/yr$ in the reference and 0.06-1.7 $GtCO_2e/yr$ in the mitigation scenarios, compared to 7.2 and 0.08 $GtCO_2e/yr$ in this study.

Hence, the reference and mitigation emissions levels in this study are within the AR5 database range, although the CH_4 reference emissions are at the higher end of the range, reflecting the relatively high socio-economic growth path and industrial output growth over the 21st century, as previously mentioned.

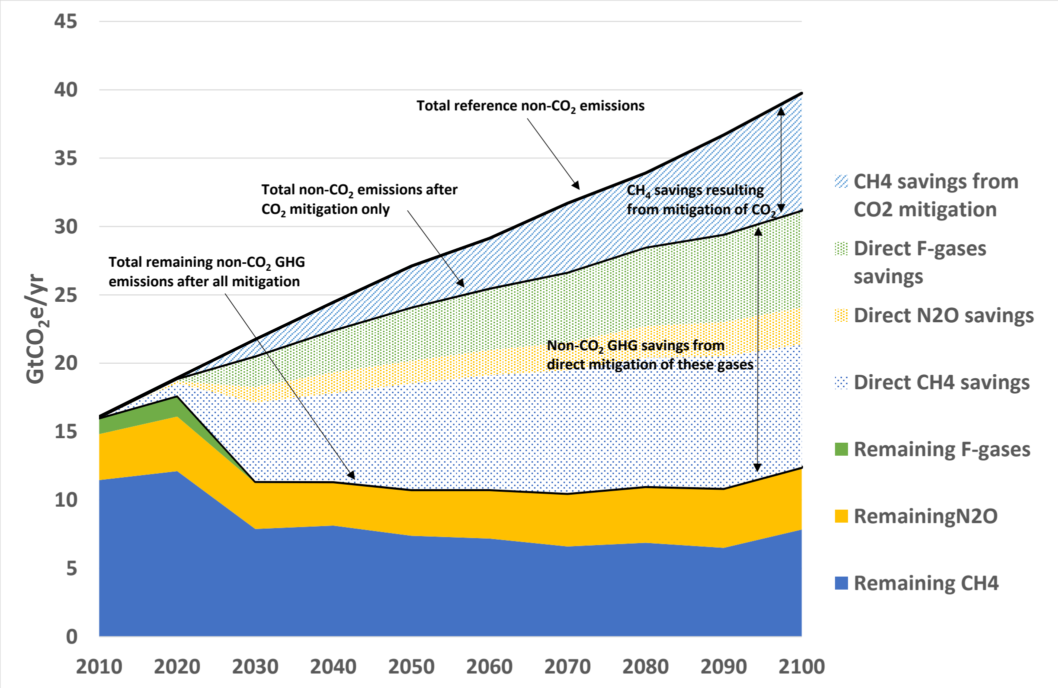

Figure 4: Non-CO_2 GHG direct emissions savings (relative to baseline) as a result of applying a CO_2e price equal to the fossil fuel and industry CO_2 price, $2^{O}C$ scenario with action delayed to 2020

3.2 Costs of mitigation considering non-CO_2 gases

Figure 5 shows the time-dependent global marginal abatement cost curves for the total non-CO_2 GHGs starting from the point at which any indirect mitigation occurring as a result of CO_2 mitigation has already occurred, for the $2^{O}C$ scenario in which global mitigation action starts in 2020. Of note is that, even in 2100, there is expected to be significant abatement potential at marginal costs of \$50/tCO_2e or less, with the majority of abatement in all years available at below \$100/tCO_2e. The increase in mitigation potential between 2050 and 2100 is entirely driven by changes in activity levels, e.g. population, economic growth and changes in the energy-system. No effects of learning or technological development are taken into account in the assessments of future mitigation potentials. A reason is that there is a lack of empirical basis for adopting general assumptions about the rate at which non-CO_2 regulations would drive long-term technological development. Most likely, this drive is not as strong for non-CO_2 as for CO_2, where regulations reinforce already existing incentives to improve energy efficiency in order to save on energy costs. Hence, in the absence of a firm basis for assumptions on technological development of non-CO2 mitigation measures, the estimated future potentials for non-CO2 mitigation should be considered conservative rather than optimistic.

Also of note is the presence of some significantly negative cost mitigation measures in all years. These measures are not profitable with today's energy prices, but expected to become profitable in the future conditional on a rise in future energy prices. This effect is not accounted for in the reference scenario as it is defined as a scenario without further mitigation actions. Whether measures that become profitable in the future as a result of rising energy prices will be taken up automatically or not depends on more factors than pure short-run cost-effectiveness [37]. Without additional regulations in place, the presence of x-inefficiency, institutional inertia and uncertainty regarding future regulations and energy prices, are likely to discourage investments in mitigation in the reference scenario. To avoid speculation, such investment opportunities appear here as negative cost mitigation measures in the cost curves and are likely to be among the first measures to be taken up once regulations have been introduced.

Figure 6 shows the marginal abatement cost curves for 2050, for three different LTTGs (2^{O}C, 2.5^{O}C and 4^{O}C median global warming by 2100), in scenarios with global mitigation action starting in 2020. At higher LTTGs, there is less indirect mitigation, which means that the total direct mitigation potential at a given CO_2 price is greater.

Table 3 sets out some significant mitigation options for each non-CO_2 GHG within different cost ranges.

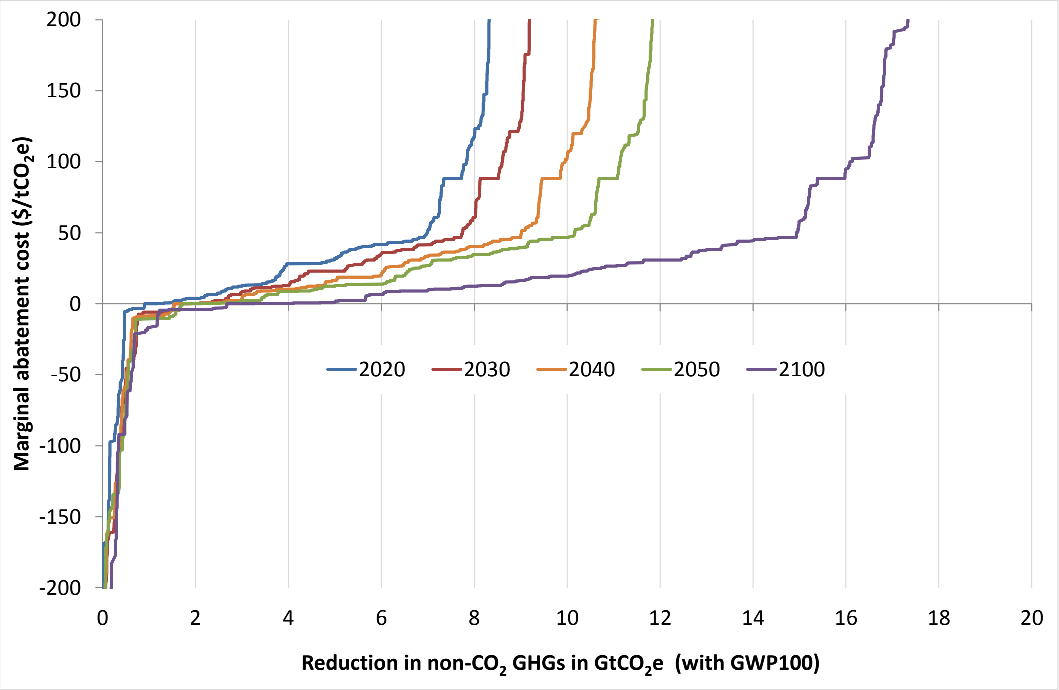

Figure 5: Time-dependent global marginal abatement cost curves for the total non-CO_2 GHGs (GWP100 basis) for 2^{O}C scenario with global mitigation action starting in 2020, relative to the case where indirect non-CO_2 GHG mitigation resulting from CO_2 mitigation has already occurred

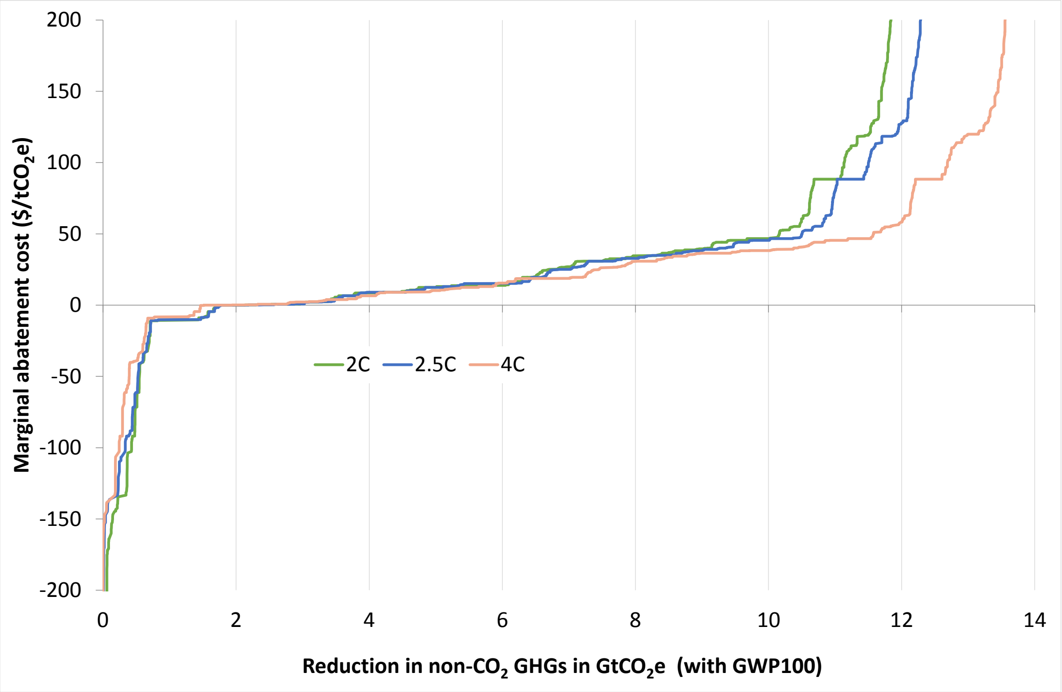

Figure 6: Global marginal abatement cost curves in 2050 for the total non-CO_2 GHGs (GWP100 basis) for different LTTGs, relative to the case where indirect non-CO_2 GHG mitigation resulting from CO_2 mitigation has already occurred

Table 3: Major non-CO_2 GHG mitigation measures in different cost ranges

Non-CO_2 GHG	**<= \$0/tCO_2e**	**< \$50/tCO_2e**	**< \$100/tCO_2e**	**> \$100/tCO_2e**
CH_4	• Increased recycling and energy recovery of biodegradable solid waste instead of landfill • Farm-scale anaerobic digestion on large pig farms • Recovery and use of associated waste gas from gas production • Reduced leakage from gas transmission pipelines in Russia and Eastern Europe	• Oxidation of ventilation air methane from underground coal mines • Pre-mine degasification of coal mines • Recovery and use of currently vented associated waste gas from oil production • Reduced leakage from oil and gas production • Dietary feed changes for indoor-fed livestock • Intermittent aeration of rice fields	• Waste optimisation • Replacing cast iron gas distribution networks	• More expensive gas leakage reduction measures • More expensive waste reduction options
N_2O	• Best Available Technology in nitric acid production • Reduced and regulated use of N_2O in anaesthetics and propellants • Optimise domestic wastewater treatment	• Catalytic reduction of N_2O in nitric acid production • Reduction and improved timing of fertiliser application	• Nitrification inhibitors in agriculture	• Precision farming • Replace N_2O in anaesthetics
PFCs		• Replace PFCs with NF_3 in semiconductor industry		• Inert anodes in primary aluminium production
SF_6	• Leakage control of SF_6 in mid-high voltage switches			
HFCs	• End-of-life recollection of HFCs in domestic refrigeration	• Replace HFCs with lower GWP HFCs and HFO in air conditioning, refrigeration • Leakage control in air conditioning and refrigeration • Replace HFCs with Fluoro Ketone in fire extinguishers	• Replace HFCs with CO_2 in refrigeration in industry and transport	• Replace HFCs with CO_2 in ground source heat pumps, air conditioning and commercial refrigeration

Notes: All CO_2e prices calculated using GWP100 basis; many mitigation options span a range of costs, depending on region, practices and local costs – hence figures are illustrative and do not reflect all details of estimated cost curves.

Figure 7 shows, for the different scenarios explored, the total cumulative discounted cost over the period 2010-2100 (at a discount rate of 5%) associated with mitigation of CO_2 to

2100, as well as mitigation of non-CO_2 GHGs to 2100 at a range of CO_2e prices, the latter as a percentage of the CO_2 price from the TIAM-Grantham model for each time point. This cost is calculated by combining two costs: the first is the present value (using a discount rate of 5%) of the additional cost of the energy system in the TIAM-Grantham model when comparing the 2^{O}C scenario with the unmitigated reference scenario; the second is the present value (again at a discount rate of 5%) of the sum of annual non-CO_2 mitigation costs as calculated from the area under the marginal abatement cost curve for each year in the GAINS model. Mitigation at a zero price on non-CO_2 (thereby allowing only negative cost measures) results in a 2100 median temperature change of just under 2.5^{O}C. This is because the cumulative CO_2 budget for the fossil fuel and industrial sectors in order to produce a 2100 median warming level of 2^{O}C is appropriate only if there is also significant abatement of non-CO_2 GHGs [38](broadly in line with the level of mitigation achieved in the RCP 2.6 scenario [39]).

Mitigation of non-CO_2 GHGs even to a small fraction (20%) of the price of CO_2 from fossil fuels and industry leads to significant abatement of non-CO_2 GHGs, and a 2100 median temperature change of much closer to 2^{O}C (about 2.04^{O}C), at an additional cumulative discounted cost of around 0.08% of 2010-2100 GDP. Even at this 20% fraction of the fossil fuel and industry CO_2 price, the non-CO_2 GHG price rises to \$1,170/tCO_2e by 2100. For this reason figure 7 also shows the median warming (as well as total mitigation cost) at sustained prices of (2005) \$50/tCO_2e and \$100/tCO_2e throughout the century, reflecting the significant degree of mitigation potential available up to these prices, as shown in figure 5. As expected, the scenarios with these CO_2e prices lead to median warming levels which are lower than the 2.5^{O}C median warming that results when a zero CO_2e price is applied to non-CO_2 GHGs.

However, the scenarios with a uniformly-applied CO_2e price are not as cost-efficient as the scenarios in which the CO_2e price is applied as a fixed fraction of the (rising) CO_2 price, which is to say that that they do not achieve as low a level of 2100 median warming at the same cumulative cost as the fractional price scenarios. For example, figure 7 shows that applying a CO_2e price of 20% of the CO_2 price throughout the mitigation period (during which the CO_2e price rises from \$0/tCO_2e in 2020 to \$38/tCO_2e in 2030, \$62/tCO_2e in 2040 and then to \$1,170/tCO_2e in 2100) is actually less costly, and achieves a lower 2100 temperature change, than applying a \$50/tCO_2e price uniformly from 2020 to 2100. This is because, with the uniform non-CO_2e prices, some of the mitigation effort in the early part of the century which targets short-lived CH_4 and F-gases (particularly over the decades 2020-2040, in which the uniformly applied CO_2e price is on average higher than the steadily-rising fractional CO_2e price) has no impact on the 2100 median warming level, and is in some ways therefore “wasted” effort (and cost) with regard to the 2100 median temperature change. This additional mitigation cost of the uniform non-CO_2e price, which doesn’t achieve a benefit in terms of 2100 warming, outweighs the (discounted) cost saving of the uniform price being lower than the fractional price in later decades.

This result is, however, highly dependent on the discount rate used (with lower discount rates de-emphasising the cost of applying a uniform price in the short term, compared to the higher fractional cost in the long term). Perhaps more importantly, it is feasible that early action on mitigation of non-CO_2 gases would reap benefits in terms of learning and associated cost reductions in future mitigation measures. Hence, further analysis is required before any policy conclusions can be drawn on the timing and degree of effort in mitigating short-lived gases such as CH_4.

Also of note from figure 7 is that where the non-CO_2e price is higher than the CO_2 price (the “120%” point) there is relatively little impact on 2100 median temperature change, since the vast majority of non-CO_2 abatement is already taken up at lower non-CO_2e prices.

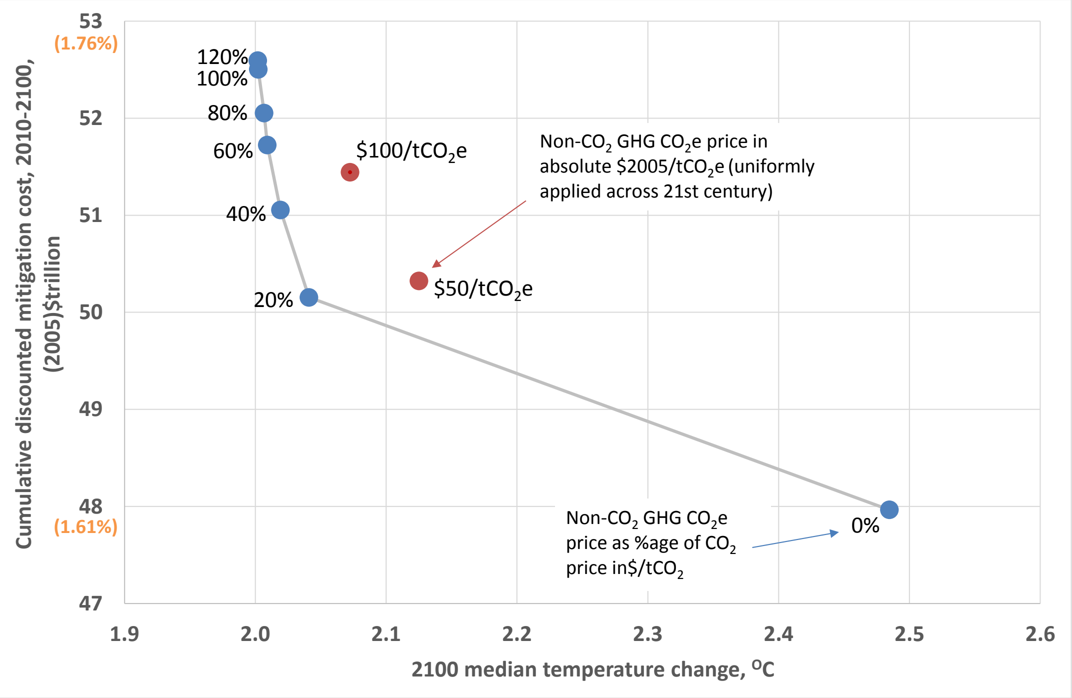

Figure 7: Cost of meeting 2100 temperature change levels with non-CO_2 GHG mitigation at a range of CO_2e prices relative to CO_2 mitigation, for 2°C scenario with delayed action to 2020

Notes: Figures in parenthesis on Y-axis show costs as a share of cumulative 2000-2100 discounted GDP (at 5% per year discount rate); blue points on chart are for non-CO_2 GHG prices which vary over time (as a fixed fraction of CO_2 prices) whereas red points show time-invariant non-CO_2 GHG prices.

A similar analysis is shown for the 2.5°C and 4°C scenarios, in figures 8 and 9 respectively. Of note is that the overall mitigation cost is significantly lower than the 2°C pathway, which gives a sense of the relative degree of challenge involved in meeting the 2°C long-term goal. In fact, in the case of the 4°C scenario, the very low mitigation costs for CO_2 are slightly outweighed by negative cost measures for non-CO_2 gases, leading to an overall marginal negative cost of meeting the 4°C goal. Whether this is realisable in practice depends on the realism of achieving these measures. These stem principally from recycling in developing countries, with the assumption that recycled products would be sold at international market prices – in practice the recycled products may have less economic value than this if they cannot reach these markets.

In both the 2.5 and 4 °C scenarios, there is actually over-achievement of the long-term goal (i.e. temperature change is less than 2.5 and 4°C respectively) when the CO_2 and non-CO_2 prices are equal, indicating that the target may be achieved in a less costly way with a little less CO_2 mitigation effort. Nevertheless, the final estimated median temperature changes are sufficiently close to the desired goals to prove useful as an indicative scenario of the costs and measures associated with meeting these goals.

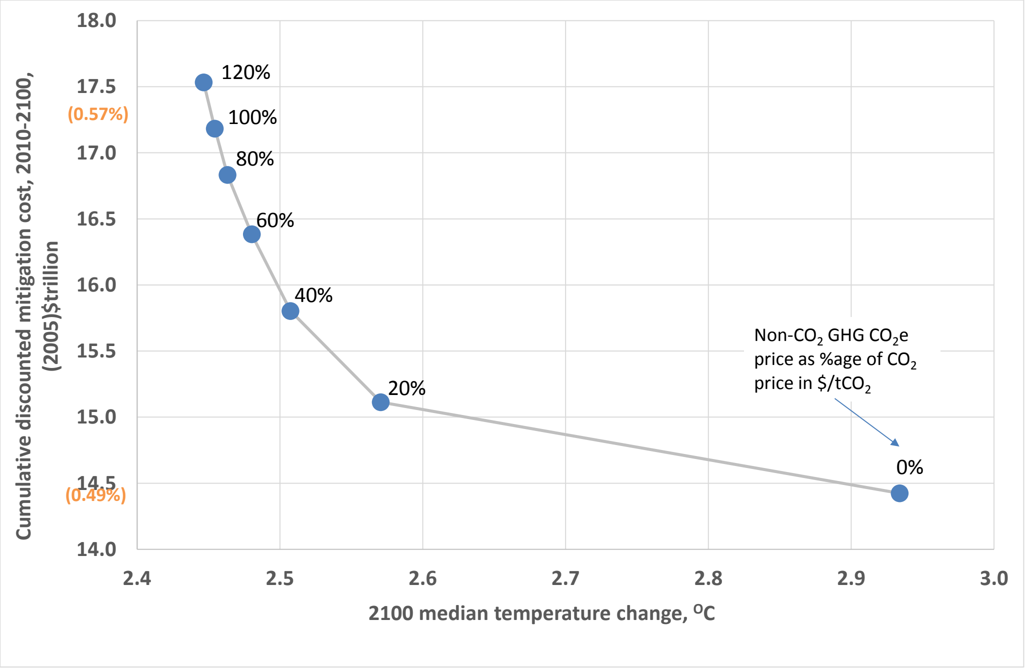

Figure 8: Cost of meeting 2100 temperature change levels with non-CO_2 GHG mitigation at a range of CO_2e prices relative to CO_2 mitigation, 2.5^{O}C scenario with delayed action to 2020

Notes: Figures in parenthesis on Y-axis show costs as a share of cumulative 2000-2100 discounted GDP (at 5% per year discount rate).

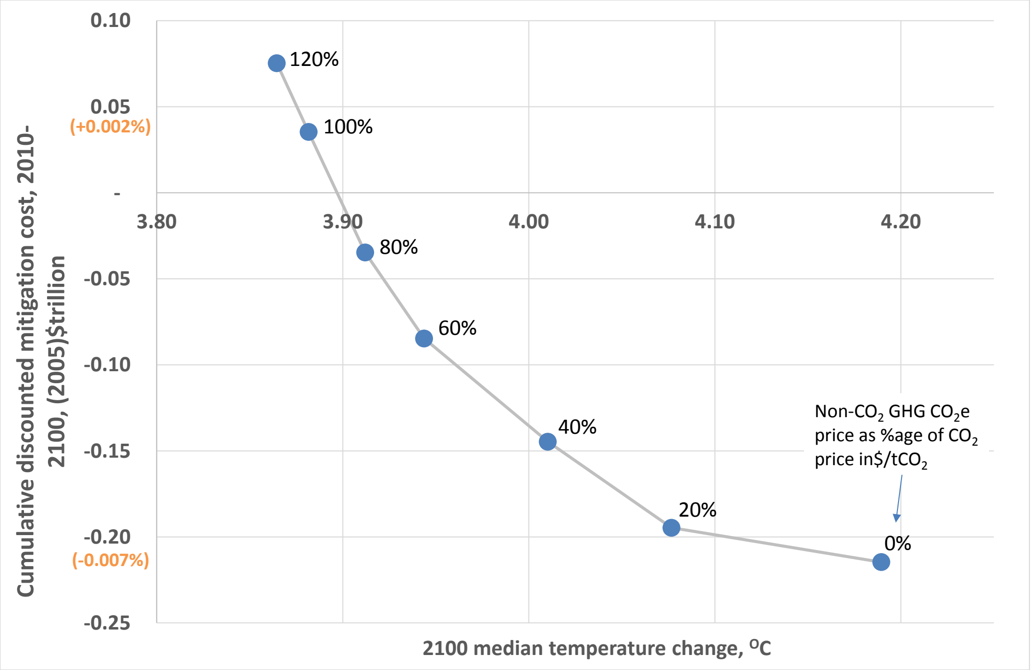

Figure 9: Cost of meeting 2100 temperature change levels with non-CO_2 GHG mitigation at a range of CO_2e prices relative to CO_2 mitigation, 4^{O}C scenario with delayed action to 2020

Notes: Figures in parenthesis on Y-axis show costs as a share of total cumulative 2000-2100 discounted GDP (at 5% per year discount rate).

Figure 10 shows a subsection of the data from figures 7 to 9, so as to demonstrate the change in total mitigation cost and median 2100 temperature change as the non-CO_2 GHG price (in \$/tCO_2e using GWP100) changes as a fraction of the CO_2 price (in \$/tCO_2). This demonstrates first the significant additional cost of meeting the 2^{O}C target compared to the 2.5^{O}C and 4^{O}C targets, as well as the significant reduction in 2100 temperature change achievable by including non-CO_2 GHG options in the overall mitigation portfolio. This is most clearly illustrated with reference to the vertical dashed line around the 2.5^{O}C mark in figure 10: this LTTG is achievable either at a cost of \$48 trillion by focusing only on CO_2 mitigation, or alternatively at \$17 trillion by including non-CO_2 GHG mitigation in the portfolio of options, a cost reduction of about 65%. This compares to the figures discussed in Section 2, in which Rao and Riahi [7] find an approximate halving of carbon price, Kurosawa [21] finds an approximate 55% cost saving by 2100, and Lucas et al [20] find a 4-26% mitigation cost reduction by 2100, when achieving a 550 ppm CO_2e stabilisation concentration using a multi-gas approach compared to a CO_2-only approach. The greater percentage cost savings in this study are most likely to stem from the fact that the scenarios shown in figure 10 are for global mitigation action starting from 2020, whereas the above-quoted cases are immediate action scenarios. As such, this makes it more challenging and costly to meet any given long-term target with CO_2 alone as a result of lock-in to CO_2 – intensive infrastructure and technologies with delayed action, thereby increasing the benefit of including non-CO_2 GHG mitigation.

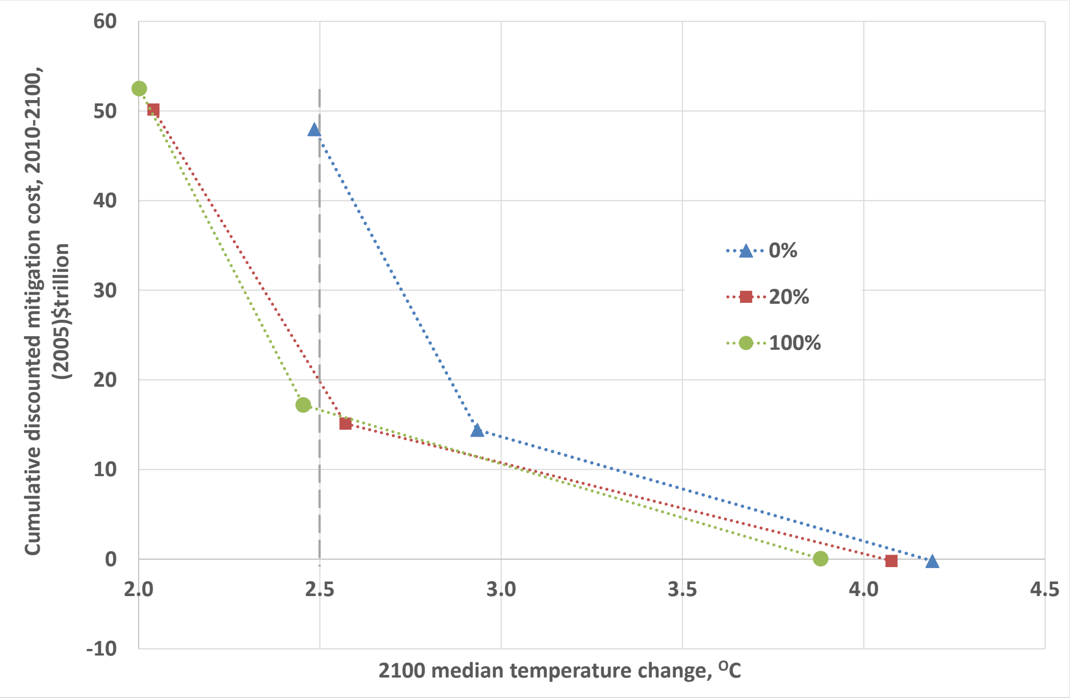

Figure 10: Costs of achieving different long-term temperature goals with varying degrees of non-CO_2 mitigation (in terms of CO_2e prices as a fraction of CO_2 prices)

4 Discussion

The 21st century cumulative CO_2 budgets estimated for the $2^{O}C$, $2.5^{O}C$ and $4^{O}C$ long-term temperature goals achieve 2100 median temperature changes of $2.00^{O}C$, $2.45^{O}C$, and $3.88^{O}C$, once mitigation of non-CO_2 GHGs is taken into account up to a CO_2e price equal to the CO_2 price in the fossil fuel combustion and industrial process sectors.

Significant mitigation of non-CO_2 GHGs, particularly CH_4, results from the transition from a fossil fuel intensive to low-carbon energy and industrial system. This is primarily because fugitive CH_4 emissions from oil, coal and gas extraction, transmission and distribution activities decline with total primary fossil fuel demandFurther significant mitigation of the majority of non-CO_2 GHGs is available at relatively low CO_2e prices, with the majority of options below \$100/t CO_2e (when calculated on a GWP100 basis). This means that the mitigation of non-CO_2 GHGs even to CO_2e prices at a fraction of the fossil fuel and industrial CO_2 price yields significant reductions in 2100 median temperature change. The most cost-effective non-CO_2 mitigation options include:

- Increased recycling and energy recovery of biodegradable solid waste instead of landfill, reduced leakage from gas pipelines in Russia and Eastern Europe, extended recovery of associated waste gas from gas and oil production, and farm-scale anaerobic digestion of manure on large pig farms;
- For N_2O, reduced emissions from nitric acid production through improved technologies and catalytic reduction, as well as optimised wastewater treatment practices and improved fertiliser application regimes in agriculture;
- For F-gases, reduction of leakage of HFCs from refrigeration, as well as replacement of HFCs with alternatives in refrigeration and air conditioning.

Although the mitigation potentials and costs in the GAINS model take account of purely technical barriers to adoption on a regional basis, there are other barriers which are more difficult to account for e.g., behavioural or institutional. Such barriers may add to costs at the local level. On the other hand, the purely technical nature of the cost estimates also means not accounting for potential co-benefits of mitigation in terms of improved health and reduced agricultural damages from methane as an ozone precursor [25]. In addition, a number of mitigation options associated with demand-side measures, notably human dietary changes, are not included. These could yield significant additional non-CO_2 emissions reductions [20], [40]. Finally, the analysis does not assume technological development and associated cost reductions in the non-CO_2 mitigation measures over time. Implementation of climate policies, which incentivise the wide-spread adoption of non-CO_2 abatement technology, are likely to drive the development of cheaper and more effective abatement technology as time and learning progress.

This analysis, combined with the fact that non-CO_2 GHG mitigation options, particularly on the demand side, remain relatively less well explored compared to CO_2 options, highlights the importance in undertaking further research into the drivers, barriers and costs of mitigating these gases, so that policy makers can understand the trade-offs between early, gradual and delayed adoption of non-CO_2 mitigation measures.

References

[1] G. Myhre, D. Shindell, F.-M. Breon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura, and H. Zhang, ‘Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]’. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

[2] IPCC, ‘Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change’. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[3] P. Smith, M. Bustamante, H. Ahammad, H. Clark, H. Dong, E. A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C. W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello, ‘Agriculture, Forestry and Other Land Use (AFOLU). In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]’. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014.

[4] Intergovernmental Panel on Climate Change, *Climate Change 2007: Working Group III: Mitigation of Climate Change*. 2007.

[5] D. S. Reay, E. A. Davidson, K. A. Smith, P. Smith, J. M. Melillo, F. Dentener, and P. J. Crutzen, ‘Global agriculture and nitrous oxide emissions’, *Nat. Clim. Change*, vol. 2, no. 6, pp. 410–416, Jun. 2012.

[6] S. A. Montzka, E. J. Dlugokencky, and J. H. Butler, ‘Non-CO2 greenhouse gases and climate change’, *Nature*, vol. 476, no. 7358, pp. 43–50, Aug. 2011.

[7] S. Rao and K. Riahi, ‘The Role of Non-CO2 Greenhouse Gases in Climate Change Mitigation: Long-term Scenarios for the 21st Century’, *Energy J.*, vol. 27, pp. 177–200, Oct. 2006.

[8] K. C. Delhotal, F. C. De la Chesnaye, A. Gardiner, J. Bates, and A. Sankovski, ‘Mitigation of Methane and Nitrous Oxide Emissions from Waste, Energy and Industry’, *Energy J.*, vol. 27, pp. 45–62, Oct. 2006.

[9] B. J. DeAngelo, F. C. de la Chesnaye, R. H. Beach, A. Sommer, and B. C. Murray, ‘Methane and Nitrous Oxide Mitigation in Agriculture’, *Energy J.*, vol. 27, pp. 89–108, Jan. 2006.

[10] D. O. Schaefer, D. Godwin, and J. Harnisch, ‘Estimating Future Emissions and Potential Reductions of HFCs, PFCs, and SF_6’, *Energy J.*, vol. 27, pp. 63–88, Jan. 2006.

[11] P. L. Lucas, D. P. van Vuuren, J. G. J. Olivier, and M. G. J. den Elzen, ‘Long-term reduction potential of non-CO2 greenhouse gases’, *Environ. Sci. Policy*, vol. 10, no. 2, pp. 85–103, Apr. 2007.

[12] L. Höglund-Isaksson, ‘Global anthropogenic methane emissions 2005–2030: technical mitigation potentials and costs’, *Atmos Chem Phys*, vol. 12, no. 19, pp. 9079–9096, Oct. 2012.

[13] L. Höglund-Isaksson, W. Winiwarter, and P. Purohit, ‘Non-CO2 greenhouse gas emissions, mitigation potentials and costs in the EU-28 from 2005 to 2050: GAINS model methodology’. International Institute for Applied Systems Analysis (IIASA), 04-Dec-2013.

[14] E. Stehfest, L. Bouwman, D. P. van Vuuren, M. G. J. den Elzen, B. Eickhout, and P. Kabat, ‘Climate benefits of changing diet’, *Clim. Change*, vol. 95, no. 1–2, pp. 83–102, Feb. 2009.

[15] J. Bates, ‘Economic Evaluation of Emission Reductions of Nitrous Oxides and Methane in Agriculture in the EU: Bottom-up Analysis,” Contribution to a Study for DG Environment, European Commission by Ecofys Energy and Environment, AEA Technology Environment and National Technical University of Athens’. 2001.

[16] R. Wassmann, R. S. Lantin, H. U. Neue, L. V. Buendia, T. M. Corton, and Y. Lu, ‘Characterization of Methane Emissions from Rice Fields in Asia. III. Mitigation Options and Future Research Needs’, *Nutr. Cycl. Agroecosystems*, vol. 58, no. 1–3, pp. 23–36, Nov. 2000.

[17] H. A. D. van der Gon, P. M. van Bodegom, R. Wassmann, R. S. Lantin, and T. M. Metra-Corton, ‘Sulfate-containing amendments to reduce methane emissions from rice fields: mechanisms, effectiveness and costs’, *Mitig. Adapt. Strateg. Glob. Change*, vol. 6, no. 1, pp. 71–89, Mar. 2001.

[18] D. P. Van Vuuren, B. Eickhout, P. L. Lucas, and M. G. J. Den Elzen, ‘Long-Term Multi-Gas Scenarios to Stabilise Radiative Forcing -- Exploring Costs and Benefits Within an Integrated Assessment Framework’, *Energy J.*, vol. 27, pp. 201–233, Oct. 2006.

[19] R. H. Beach, B. J. DeAngelo, S. Rose, C. Li, W. Salas, and S. J. DelGrosso, ‘Mitigation potential and costs for global agricultural greenhouse gas emissions1’, *Agric. Econ.*, vol. 38, no. 2, pp. 109–115, Mar. 2008.

[20] A. Popp, H. Lotze-Campen, and B. Bodirsky, ‘Food consumption, diet shifts and associated non-CO2 greenhouse gases from agricultural production’, *Glob. Environ. Change*, vol. 20, no. 3, pp. 451–462, Aug. 2010.

[21] A. Kurosawa, ‘Multigas Mitigation: An Economic Analysis Using GRAPE Model’, *Energy J.*, vol. 27, pp. 275–288, Oct. 2006.

[22] D. E. H. J. Gernaat, K. Calvin, P. L. Lucas, G. Luderer, S. A. C. Otto, S. Rao, J. Strefler, and D. P. van Vuuren, ‘Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios’, *Glob. Environ. Change*, vol. 33, pp. 142–153, Jul. 2015.

[23] W. Winiwarter, L. Höglund-Isaksson, W. Schöpp, A. Tohka, F. Wagner, and M. Amann, ‘Emission mitigation potentials and costs for non-CO2 greenhouse gases in Annex-I countries according to the GAINS model’, *J. Integr. Environ. Sci.*, vol. 7, no. sup1, pp. 235–243, Aug. 2010.

[24] L. Höglund-Isaksson, W. Winiwarter, P. Purohit, P. Rafaj, W. Schöpp, and Z. Klimont, ‘EU low carbon roadmap 2050: Potentials and costs for mitigation of non-CO2 greenhouse gas emissions’, *Energy Strategy Rev.*, vol. 1, no. 2, pp. 97–108, Sep. 2012.

[25] D. Shindell, J. C. I. Kuylenstierna, E. Vignati, R. van Dingenen, M. Amann, Z. Klimont, S. C. Anenberg, N. Muller, G. Janssens-Maenhout, F. Raes, J. Schwartz, G. Faluvegi, L. Pozzoli, K. Kupiainen, L. Höglund-Isaksson, L. Emberson, D. Streets, V. Ramanathan, K. Hicks, N. T. K. Oanh, G. Milly, M. Williams, V. Demkine, and D. Fowler, ‘Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security’, *Science*, vol. 335, no. 6065, pp. 183–189, Jan. 2012.

[26] R. Loulou and M. Labriet, ‘ETSAP-TIAM: the TIMES integrated assessment model Part I: Model structure’, *Comput. Manag. Sci.*, vol. 5, no. 1–2, pp. 7–40, Feb. 2007.

[27] R. Loulou, M. Labriet, and A. Kanudia, ‘Deterministic and stochastic analysis of alternative climate targets under differentiated cooperation regimes’, *Energy Econ.*, vol. 31, Supplement 2, pp. S131–S143, Dec. 2009.

[28] A. Gambhir, T. A. Napp, A. Hawkes, D. L. McCollum, O. Fricko, P. Havlik, K. Riahi, L. Drouet, V. Bosetti, D. Bernie, and J. A. Lowe, ‘Aessessing the challenges of global long-term mitigation scenarios - AVOID 2 WPC2a’. AVOID 2, Nov-2015.

[29] J. Rogelj, M. Schaeffer, M. Meinshausen, D. T. Shindell, W. Hare, Z. Klimont, G. J. M. Velders, M. Amann, and H. J. Schellnhuber, ‘Disentangling the effects of CO2 and

short-lived climate forcer mitigation', *Proc. Natl. Acad. Sci.*, vol. 111, no. 46, pp. 16325–16330, Nov. 2014.

[30] J. A. Lowe, C. Huntingford, S. C. B. Raper, C. D. Jones, S. K. Liddicoat, and L. K. Gohar, 'How difficult is it to recover from dangerous levels of global warming?', *Environ. Res. Lett.*, vol. 4, no. 1, p. 014012, Jan. 2009.

[31] P. M. Forster, T. Andrews, P. Good, J. M. Gregory, L. S. Jackson, and M. Zelinka, 'Evaluating adjusted forcing and model spread for historical and future scenarios in the CMIP5 generation of climate models', *J. Geophys. Res. Atmospheres*, vol. 118, no. 3, pp. 1139–1150, Feb. 2013.

[32] B. C. O'Neill, E. Kriegler, K. Riahi, K. L. Ebi, S. Hallegatte, T. R. Carter, R. Mathur, and D. P. van Vuuren, 'A new scenario framework for climate change research: the concept of shared socioeconomic pathways', *Clim. Change*, vol. 122, no. 3, pp. 387–400, Feb. 2014.

[33] K. Riahi, A. Grübler, and N. Nakicenovic, 'Scenarios of long-term socio-economic and environmental development under climate stabilization', *Technol. Forecast. Soc. Change*, vol. 74, no. 7, pp. 887–935, Sep. 2007.

[34] K. Riahi, S. Rao, V. Krey, C. Cho, V. Chirkov, G. Fischer, G. Kindermann, N. Nakicenovic, and P. Rafaj, 'RCP 8.5—A scenario of comparatively high greenhouse gas emissions', *Clim. Change*, vol. 109, no. 1–2, pp. 33–57, Aug. 2011.

[35] D. E. H. J. Gernaat, D. P. Van Vuuren, M. van den Berg, K. Calvin, P. Lucas, G. Luderer, S. A. C. Otto, S. Rao, and J. Strefler, 'Understanding the contribution of non carbon dioxide gases in deep mitigation scenarios. LIMITS Deliverable No. 32'. LIMITS, Oct-2014.

[36] J. Rogelj, M. Schaeffer, M. Meinshausen, D. T. Shindell, W. Hare, Z. Klimont, G. J. M. Velders, M. Amann, and H. J. Schellnhuber, 'Disentangling the effects of CO2 and short-lived climate forcer mitigation', *Proc. Natl. Acad. Sci.*, vol. 111, no. 46, pp. 16325–16330, Nov. 2014.

[37] W. A. Pizer and R. Kopp, 'Chapter 25 Calculating the Costs of Environmental Regulation', in *Handbook of Environmental Economics*, vol. 3, K.-G. M. and J. R. Vincent, Ed. Elsevier, 2005, pp. 1307–1351.

[38] J. Rogelj, M. Meinshausen, M. Schaeffer, R. Knutti, and K. Riahi, 'Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming', *Environ. Res. Lett.*, vol. 10, no. 7, p. 075001, Jul. 2015.

[39] D. P. van Vuuren, E. Stehfest, M. G. J. den Elzen, T. Kram, J. van Vliet, S. Deetman, M. Isaac, K. K. Goldewijk, A. Hof, A. M. Beltran, R. Oostenrijk, and B. van Ruijven, 'RCP2.6: exploring the possibility to keep global mean temperature increase below 2°C', *Clim. Change*, vol. 109, no. 1–2, pp. 95–116, Nov. 2011.

[40] A. Bows-Larkin, C. McLachlan, S. Mander, R. Wood, M. Röder, P. Thornley, E. Dawkins, C. Gough, L. O'Keefe, and M. Sharmina, 'Importance of non-CO2 emissions in carbon management', *Carbon Manag.*, vol. 5, no. 2, pp. 193–210, Mar. 2014.

[41] M. Meinshausen, S. J. Smith, K. Calvin, J. S. Daniel, M. L. T. Kainuma, J.-F. Lamarque, K. Matsumoto, S. A. Montzka, S. C. B. Raper, K. Riahi, A. Thomson, G. J. M. Velders, and D. P. P. van Vuuren, 'The RCP greenhouse gas concentrations and their extensions from 1765 to 2300', *Clim. Change*, vol. 109, no. 1–2, pp. 213–241, Aug. 2011.

[42] D. Bernie and J. A. Lowe, 'Analysis of climate projections from the IPCC working group 3 scenario database. AVOID 2 deliverable WPA.1'. AVOID 2, 2014.

[43] K. E. Taylor, R. J. Stouffer, and G. A. Meehl, 'An Overview of CMIP5 and the Experiment Design', *Bull. Am. Meteorol. Soc.*, vol. 93, no. 4, pp. 485–498, Apr. 2012.

[44] M. Meinshausen, N. Meinshausen, W. Hare, S. C. B. Raper, K. Frieler, R. Knutti, D. J. Frame, and M. R. Allen, 'Greenhouse-gas emission targets for limiting global warming to 2 °C', *Nature*, vol. 458, no. 7242, pp. 1158–1162, Apr. 2009.

[45] M. R. Allen, D. J. Frame, C. Huntingford, C. D. Jones, J. A. Lowe, M. Meinshausen, and N. Meinshausen, 'Warming caused by cumulative carbon emissions towards the trillionth tonne', *Nature*, vol. 458, no. 7242, pp. 1163–1166, Apr. 2009.

[46] H. D. Matthews, N. P. Gillett, P. A. Stott, and K. Zickfeld, ‘The proportionality of global warming to cumulative carbon emissions’, *Nature*, vol. 459, no. 7248, pp. 829–832, Jun. 2009.
[47] IPCC, *Climate Change 2014: Working Group III: Mitigation of Climate Change*. IPCC, United Nations, 2014.

Annex: Deriving temperature goal-consistent 21st century CO_2 budgets and emissions profiles

The TIAM-Grantham and GAINS models are used to derive time profiles of emissions of CO_2, CH_4, N_2O and total F-Gas emissions from a given cumulative CO_2 budget for fossil fuels and industry (FFI) in order to meet a given long-term temperature goal (LTTG) – the temperature change in 2100. In order to make climate projections (verifying the CO_2 budgets) the total F-Gas emissions must be broken down into constituent species and emissions of other gases must also be estimated. The process of constructing the full set of emissions required and the iterative process used to determine the 21st century (i.e. 2000-2100) CO_2 FFI budget is detailed here. A schematic of the information flow through the RCPs, TIAM-Grantham, GAINS and Met Office Hadley Centre (MOHC) calculations is illustrated in figure A1.

1. Projections of global temperature change for the four RCPs is made using emissions relating to the RCPs [41]. Emissions are used rather than concentrations as this takes fuller account of uncertainty carbon cycle feedbacks. Following Bernie and Lowe [42], probabilistic projections are made using values of equilibrium climate sensitivity from models in the fifth Couple Model Inter-comparison Project (CMIP5) [43] along with uncertainty distributions of ocean mixing and carbon cycle feedbacks.
2. In each year land use emissions of CO_2 are linearly interpolated from the RCPs on the basis of each RCP's median 2100 projected temperature and the LTTG of the scenario.
3. Initial estimates of 21st century cumulative CO_2 emissions from the FFI sectors are also linearly interpolated from the RCPs on the basis of future temperature projections and the scenario LTTG.
4. The cumulative CO_2 FFI budget is then used to calculate emissions of CO_2 from FFI, CH_4, N_2O and F-gases:
    a. A time profile of CO_2 emissions from FFI is then calculated from the cumulative CO_2 FFI along with a carbon price profile;
    b. The CO_2 FFI emissions profile and aspects of the underlying energy system structure (in particular the fossil fuel energy mix) are then passed to GAINS to calculate non-CO_2 GHG no-mitigation baselines and corresponding MAC curves;
    c. The CO_2 FFI profile from TIAM-Grantham and the non-CO_2 GHG baselines and MAC curves from GAINS are then used to calculate the emissions of CH_4, N_2O and total F-Gas emissions, at different levels of CO_2e price applied to the non-CO_2 GHGs (using GWP100 values).
5. Individual F-gas emissions are then needed, but the constituent F-gases in the categories used by GAINS do not exactly match those used by MAGICC. Whilst this has a very small influence on the overall CO_2e emissions, the individual gas species are needed by MAGICC. To estimate emissions of individual F-gases it is assumed that the relative emissions rate of each F-gas to the total F-gas emissions will change with time in line with the "unmitigated" RCP 8.5 scenario. Based on this assumption the emissions of each F-gas in RCP8.5 are scaled by a ratio of the total F-gas emissions from GAINS to the total F-gas emissions in the unmitigated baseline. So for example if the F-gas emissions from GAINS are 20% of the unmitigated F-gas emissions for that scenario, then this factor is applied to emissions of each individual F-gas from RCP8.5. This approach circumvents the issue of different gases being included in the calculation by GAINS and those needed by MAGICC. While other assumptions are possible, given the relatively small effect of differences in F-gas

emissions between the RCPs, this is an appropriate level of detail for the scope of the current study.

6. The emissions of non-Kyoto GHG and other gases needed by MAGICC (principally NOx, CO, NMVOC and SO_2) are all based on the ratio of the emissions of each gas to the emissions of CO_2 from the FFI sector in the RCPs being applied to the CO_2 FFI emissions from TIAM-Grantham. For example, if the CO_2 FFI emissions from GAINS in a given year where 80% of the way between RCP4.5 and RCP6.0, the SO_2 emissions would be the product of the CO_2 FFI from TIAM-Grantham multiplied by a weighted mean of the ratio of SO_2 to CO_2 FFI in those two RCPs, with 4 times more weight given to the ratio from RCP6.0.
7. Projected median 2100 temperature change is then calculated and if within 0.1 °C of the original LTTG, the CO_2 FFI budget is accepted, or else the CO_2 budget for the scenario is re-estimated, before repeating the above procedure to re-calculate 2100 median temperature change.

It should be noted again that the temperatures resulting from the emissions derived from a given budget are verified as meeting the target. With the cumulative CO_2 FFI being the only variable here the process used in iterating its value for each target warming level is unimportant. However, the use of a simple interpolation of cumulative CO_2 emissions to determine eventual warming is a notion that has become widely accepted in recent years [44], [45], [46]. Its use here to initially estimate the CO_2 budget for specific target warming levels implicitly assumes that the contribution of non-CO_2 gases to warming is linearly related to the emissions of CO_2. While this may appear to be broadly the case across the wide range of scenarios from the IPCC’s AR5 WGIII report [47], the wide spread in IAM construction and the experimental design across the scenarios available is likely to obscure more subtle relations from IAM scenarios constructed under specific sets of assumptions on constraints. For example, two scenarios with similar CO_2 emissions profiles but which focus on either energy demand reduction or the heavy use of bio-energy with carbon capture and storage (BECCS) would likely have different non-CO_2 contributions to warming. Similarly, emissions scenarios with different climate targets derived from a common approach, such as here, would not necessarily produce a robustly linear relation of warming to CO_2 when the nuances of the underlying technological, economic and social assumptions and constraints are considered.

The breakdown of linearity in the relation between of cumulative emissions and temperatures is itself demonstrated by the need for iteration when determining cumulative CO_2 budgets for each of the scenarios in this study. While the required iterations to budgets to meet specific climate targets is small, it illustrates the inherent uncertainty in the cumulative CO_2 and temperature relation and warrants careful verification of projections developed on this basis.

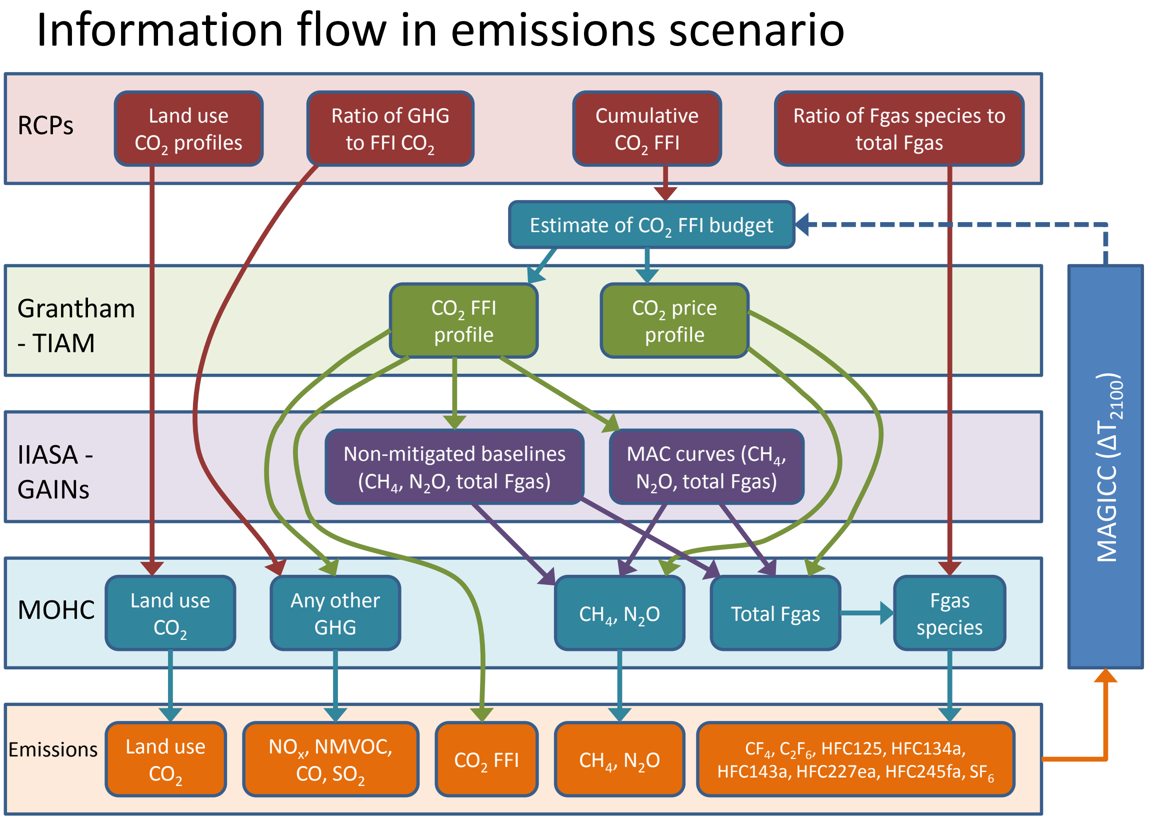

Figure A1: Schematic illustrating the process used to derive emissions scenarios from CO_2 budgets and iterate for target temperature levels where appropriate.