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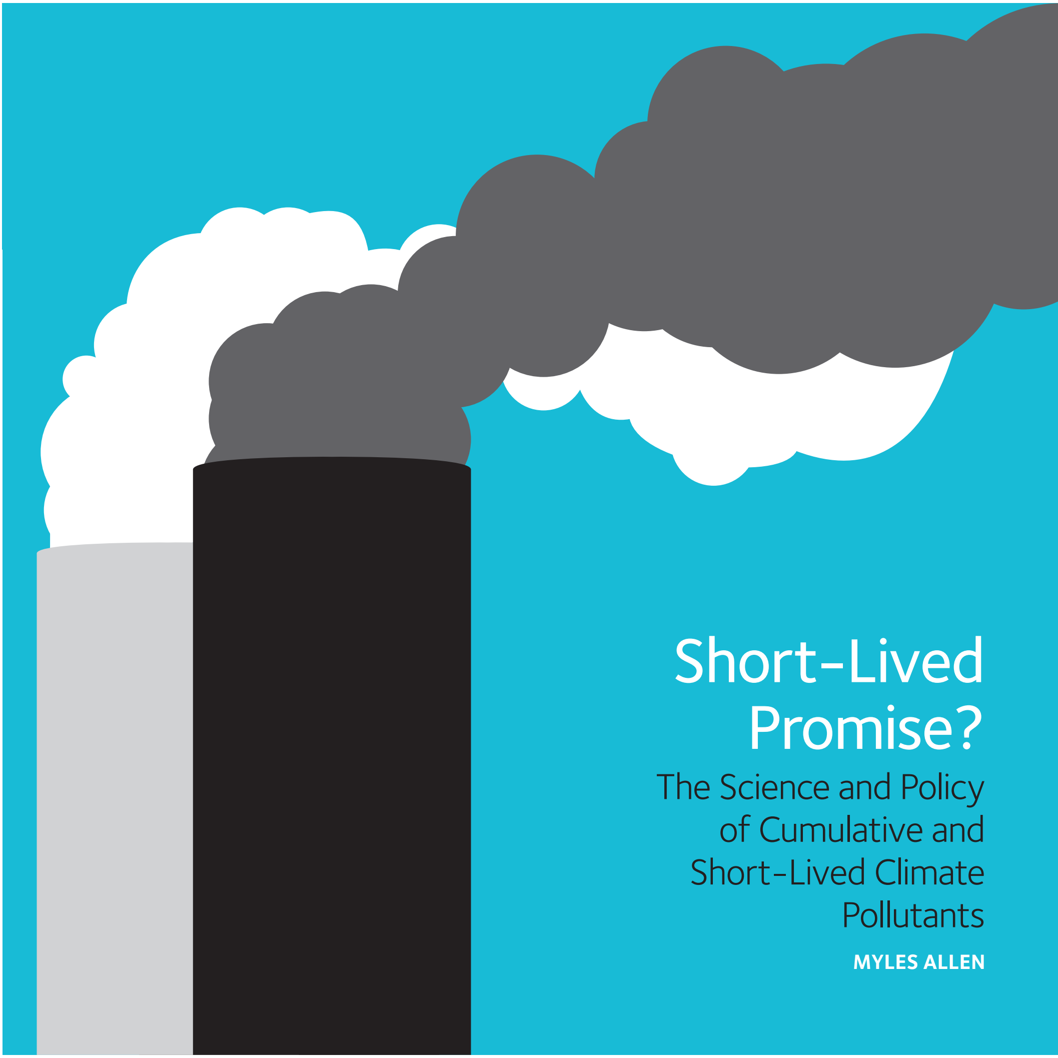

Short-Lived Promise?

The Science and Policy of Cumulative and Short-Lived Climate Pollutants

MYLES ALLEN

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Executive Summary

Immediate measures to reduce SLCP emissions could provide some climate benefit to the current generation through reduced warming over the next few decades, but would have little impact on peak warming unless CO_2 emissions are substantially reduced at the same time. Immediate reductions in CO_2 emissions would also deliver a more substantial climate benefit to future generations.

Discussions of climate policy often focus exclusively on carbon dioxide (CO_2), but these emissions are only one of the ways in which human activities affect global climate. Methane and other forms of atmospheric pollution also play an important role. International agreements, national policies and corporate strategies addressing climate change all involve setting priorities between reducing emissions of different climate pollutants.

For over 20 years, these priorities have been based on the notion of "CO_2-equivalent emissions" using a standard exchange rate or "emission metric" called the 100-year Global Warming Potential (GWP_{100}) to relate emissions of different greenhouse gases. Under the United Nations Framework Convention on Climate Change (UNFCCC), some countries have raised the possibility of adopting a different metric that would significantly reduce the value assigned to short-lived climate pollutants (SLCPs) like methane and thereby increase the relative emphasis on CO_2.

At the same time, initiatives such as the Climate and Clean Air Coalition are advocating an increased emphasis on SLCP reductions in climate policy. Other countries are proposing to include a broader range of SLCPs, including soot, in their UNFCCC contributions, effectively reducing the relative emphasis on CO_2. Early SLCP reductions, some proponents argue, would be cheaper and easier than reductions in CO_2. Many of the measures required to reduce SLCP emissions, such as reducing soot emissions from biomass burning and coal-fired power plants, would also have significant co-benefits for human health and welfare, making them much easier to achieve politically. Some commentators have even argued for a more radical reframing of climate policy, away from long-term temperature goals and towards shorter-term targets for the global energy imbalance, the key driver of rates of change: this could also re-focus attention on SLCP reductions.

This is a confusing situation for non-specialists. While the overall aim of reducing greenhouse gas emissions to stabilise global climate remains the same, arguments are being made for very different policy priorities that appear to depend on a relatively obscure and technical issue: the choice of emission metric for comparing different climate pollutants. Different countries are using different metrics in determining their contributions to reducing emissions under the UNFCCC, further complicating the challenge of assessing overall progress towards the goal of stabilising temperatures.

This policy paper provides a non-technical overview of these issues, and sets out policy recommendations as countries and companies prepare for the 21st Session of the Conference of the Parties to the UNFCCC, to be held in Paris in December 2015. In doing so, the paper explains how the 'short-lived' versus 'long-lived' discussion is not really a technical issue at all, but an expression of inter-generational priorities.

Short-lived and long-lived climate pollutants

Cumulative emissions of CO_2 largely determine global mean surface warming by the late 21st century and beyond. To limit the warming they cause to 2 °C, CO_2 emissions must be limited to a cumulative budget over the entire industrial epoch of about one trillion tonnes of carbon, almost 60% of which has already been released, and net global CO_2 emissions must reach zero before global temperatures reach 2 °C.

Current emissions of both CO_2 and SLCPs such as methane and soot affect the rate and magnitude of climate change over the next few decades.

Reductions in SLCP emissions could be achieved at relatively low cost and with substantial co-benefits for agriculture and human health. The climate benefits of reduced emissions on these short timescales could, however, be comparable to natural climate variability, particularly on regional scales, and implementing SLCP reductions immediately would have little impact on peak warming unless CO_2 emissions are substantially reduced at the same time.

Emission metrics and emission trading

Any emission trading system or climate policy that addresses emissions of several different greenhouse gases together in a single 'multi-gas basket' requires some form of metric to specify what a given amount of one greenhouse gas is 'worth' in terms of another. The choice of metric to compare the impact of emissions of methane and other SLCPs with the impact of CO_2 depends on the timescale of interest. If the policy goal is to limit peak warming, it also depends on the ambition and success of future mitigation measures.

The standard GWP_{100} metric provides (despite its name) an approximate indication of the relative importance of emissions of different gases to the increase in global temperatures over the next 20 to 40 years. GWP_{100} is therefore a measure of impact on peak warming if and *only* if temperatures are expected to be approaching stabilisation within 40 years, for which CO_2 emissions need to approach zero on a comparable timescale.

As long as CO_2 emissions continue to rise, the earliest possible time of peak warming remains many decades in the future and current SLCP emissions therefore have relatively little impact on peak temperatures. In this situation, policies that allow SLCP measures to be exchanged, traded or offset against CO_2 emission reductions using GWP_{100} over-value the impact of SLCPs on peak warming and hence might discourage the CO_2 emission reductions that are required to stabilise temperatures. Replacing GWP_{100} with a different metric would not solve this problem because any metric that is suitable for long-term impacts would be misleading for short-term impacts and vice versa. Using a metric that changes over time would help, but introduces greater complexity and uncertainty.

Recommendations: a "peak CO_2 first" strategy

Proponents of early action on SLCP emissions rightly emphasise the 'complementary' nature of SLCP and CO_2 mitigation, but it is important to be clear what this complementarity means: they are not two ways of achieving the same goal, but address fundamentally different goals, affecting different generations.

Early action on SLCP mitigation could affect the temperatures and climate impacts experienced by the generation of today's decision-makers, but will have little impact on the warming experienced by future generations. Unless it is accompanied by ambitious reductions in CO_2 emissions, early SLCP mitigation will also have very little impact on eventual peak warming.

In the context of the goals of the UNFCCC, this paper makes the following recommendations:-

- Any policy to prevent dangerous anthropogenic interference in the climate system must limit cumulative emissions of the main long-lived climate pollutant, CO_2. Hence policies must aim to reduce net global CO_2 emissions to zero before temperatures reach any given limit, such as 2 °C.
- Policies reducing both CO_2 and SLCP emissions could reduce the rate and magnitude of climate change over the next few decades, but near-term SLCP reductions only affect peak warming if CO_2 emissions are reduced at the same time.
- No single metric can represent both the short-term impact of SLCP emissions and the cumulative impact of CO_2 emissions. The standard GWP_{100} measures impact on peak warming if and only if net global CO_2 emissions are expected to be approaching zero within the next few decades.
- Rather than adjusting metrics in a single 'multi-gas basket' framework, specific policies are required to ensure that global CO_2 emissions are contained within a cumulative budget consistent with meeting the 2 °C goal. These policies must be independent of, and in addition to, any multi-gas emission goals.
- In effect, this implies a 'peak CO_2 first' strategy: the need to limit cumulative CO_2 emissions would over-ride most opportunities to offset CO_2 reductions against SLCP reduction measures until global CO_2 emissions are falling.
- As soon as CO_2 emissions are falling fast enough that there is a realistic prospect of meeting the cumulative budget, SLCP emission reductions will become a crucial priority to limit peak warming.

Introduction

The latest Scientific Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) has re-stated that substantial reductions in greenhouse gas emissions will be required to meet the internationally agreed goal of avoiding more than 2°C of global warming relative to pre-industrial temperatures.[1] Yet emissions of the principal greenhouse gas, carbon dioxide (CO_2), continue to rise.[2]

The challenges of securing international agreement, the perceived cost of CO_2 emission reductions, and the recognition that even relatively ambitious CO_2 measures may take decades to have a substantial impact on rising global temperatures, have together encouraged renewed interest[3] in reducing emissions of other agents that cause global warming, so-called short-lived climate pollutants (SLCPs), including methane, black carbon (soot) and tropospheric ozone.[4,5]

Some commentators have also begun to question an exclusive focus on an "effectively unachievable" global temperature target[6] and propose replacing the 2°C goal with targets for global energy imbalance in 2030 or 2050. One consequence of such a change of policy focus could be an increased emphasis on SLCP mitigation at the expense of CO_2.

A key attraction of action on SLCPs is that many of the measures required to reduce emissions of these agents are relatively low cost (such as reducing methane leakage from fossil fuel extraction and transport) and offer substantial co-benefits (such as improved health in developing countries from reduced soot emissions), making them potentially attractive even to governments unwilling to commit to stringent economy-wide climate targets.[7] All countries include methane in their contributions to the United Nations Framework Convention on Climate Change (UNFCCC), and some have begun to include black carbon.[8]

At the same time, the IPCC also emphasises[9] that, in the long-term, global temperatures are overwhelmingly determined by cumulative emissions of CO_2 over the entire 'Anthropocene' epoch, not the rate of emission of greenhouse gases in any given decade.[10,11] This recognition of the long-term importance of CO_2 has prompted renewed interest in the question of whether methane emissions, in particular, may be 'over-valued' in current climate policies, including the emission trading systems and other measures established by the UNFCCC.[12,13]

For the policy community, these appear to be two contradictory developments. On the one hand, the argument is being made that climate policies should place more emphasis on reducing emissions of SLCPs like methane. On the other hand, a counter-argument is made that methane emissions are already over-valued in the existing climate policy framework and that the main focus of efforts should be on CO_2.

This policy paper sets out to explain this apparently paradoxical situation. In resolving the paradox, this paper will show how reducing SLCP emissions and reducing CO_2 emissions are not alternative ways of achieving the same goal, but should rather be seen as achieving different goals, both of which are desirable.

It is important that the significant opportunities for reducing SLCP emissions are grasped, particularly as the emerging economies from which many of these emissions originate play an increasingly prominent role in the international climate regime. But it is also important that these opportunities do not undermine progress in reducing and ultimately eliminating CO_2 emissions, which is essential in order to avoid dangerous climate change in the longer term.

To meet both of these objectives, mitigation policies must recognise the unique importance of *cumulative* carbon emissions.[14] This limits the degree to which CO_2 emission reductions can be exchanged or traded for SLCP emission reductions until CO_2 emissions are falling fast enough that there is a realistic prospect of the cumulative budget being met, and hence a realistic estimate of the remaining time to peak warming.

1. Defining long-lived climate pollutants, short-lived climate pollutants and emission metrics

1.1 The main long-lived climate pollutants

Carbon dioxide (CO_2) is the single most important greenhouse gas directly affected by human activity. About 38 billion tonnes of CO_2 were emitted in 2011, over 90% from the combustion of fossil fuels and cement production, the remainder from deforestation.[15] Cumulative CO_2 emissions since 1750 amount to 2,000 billion tonnes. About 45% remains in the atmosphere, raising concentrations from 278ppm in 1750 to over 390ppm in 2011. CO_2 has a very long atmospheric lifetime: 15-40% of the increase in CO_2 due to fossil fuel consumption is expected to remain in the atmosphere for over 1,000 years.[16] Hence there is no sustainable CO_2 emission level: global temperatures will continue to rise until net CO_2 emissions are reduced close to zero, with peak temperatures largely determined by cumulative CO_2 emissions up to that time. Reducing CO_2 emissions will require substantial and sustained changes to the global energy system.[17]

Nitrous oxide (N_2O) is the next most important of the long-lived climate pollutants, with a lifetime of about 120 years.[18] N_2O is mainly generated from artificial fertiliser use in agriculture. Tonne for tonne, N_2O is a more powerful greenhouse gas than CO_2, but emissions are much lower so the stock of N_2O in the atmosphere has much less impact on global climate than CO_2 at present. Substantially reducing N_2O emissions below today's levels is expected to be challenging because of their role in food production.[19]

1.2 The main short-lived climate pollutants

Methane (CH_4), the main constituent of natural gas, is the most important greenhouse gas directly affected by human activity after CO_2. Methane is released by a range of activities: over the past decade, 40% came from agricultural sources such as rice paddies and livestock, 30% from fossil fuel production and use (in particular the release of natural gas), 20% from landfill and waste management and 10% from biomass burning.[20] Methane has an atmospheric lifetime of about 12 years, so current methane emissions only affect climate for the next few decades. It is thought global methane emissions could be reduced by 25-50% at relatively low cost,[21] but eliminating the remainder would require behaviour changes whose cost is difficult to determine.[22]

Tropospheric ozone (O_3) concentrations are increased by various forms of air pollution, including vehicle emissions. It is also a side-effect of methane emissions, increasing their impact on climate by up to 80%.[23] Elevated ozone is hazardous to human and animal health and reduces agricultural crop productivity.

Black carbon aerosols, or soot emissions, are generated from incomplete combustion in sub-standard power stations, vehicle emissions, brick kilns and biomass sources such as wood-fuel cook-stoves. The net climatic impact of many of these processes is unclear: most processes generate mixtures of aerosols, some of which have a warming effect, while others cause cooling.[24] Soot and other particulate aerosols represent a significant health hazard: feasible improvements in air quality could prevent between one and five million premature deaths per year, mainly in developing countries.[25]

Hydrofluorocarbons (HFCs) are the industrial gases introduced to replace the chlorofluorocarbons (CFCs) banned for their impact on the ozone layer. Key HFCs have typical lifetimes of the order of one to 20 years: longer-lived HFCs are being phased out under the Montreal Protocol. Although their climatic impact to date is limited, HFC emissions are projected to rise substantially. Their role is illustrated below with HFC-134a and HFC-152a.

Table One: Key properties of long-lived and short-lived climate pollutants

Name	Chemical formula	Atmospheric lifetime [26]	2011 emissions [27] (Mt = million tonnes)	Impact of past emissions on the planetary energy budget in 2011[28] (W/m^2)
Carbon dioxide	CO_2	Centuries to millennia	38,000 Mt CO_2	1.7
Nitrous oxide	N_2O	120 years	7 Mt N_2O	0.17
Methane	CH_4	12 years	330 Mt CH_4	0.64 (direct)
HFC-134a	CH_2FCF_3	13.4 years	0.04 Mt HFC-134a	<0.01
HFC-152a	CH_3CHF_2	1.5 years	0.03 Mt HFC-152a	Negligible
Tropospheric ozone	O_3	Weeks	n.a.	0.4 (approx.)
Black carbon	n.a.	Days	2-29 Mt C [29]	0.7 (approx.)

1.3 Emission metrics

The climate policy framework established by the UNFCCC allows flexibility in how countries meet their commitments to reduce greenhouse gas emissions. A country whose activities generate large volumes of methane can, for example, opt to reduce those emissions first before reducing CO_2 emissions. Similarly, Emission Trading Systems allow companies to exchange reductions in CO_2 emissions for reductions in other greenhouse gases. In principle, this 'multi-gas basket' approach can identify the most cost-effective measures for reducing greenhouse gas emissions. It requires, however, an exchange rate, known as an emission metric, defining what emissions of different greenhouse gases are worth in terms of each other.[30]

At present, emissions accounting and trading systems use the 100-year Global Warming Potential, or GWP_{100}, to assign relative values to different greenhouse gases. GWP is defined as the cumulative impact, over a specified time horizon, that the emission of a tonne of a greenhouse gas would have on the planetary energy budget ("how much heat will this tonne trap over a set number of years?"), relative to a tonne of the reference gas CO_2. A tonne of methane emitted today, for example, will have 28 times as much direct impact on the planetary energy budget over the next 100 years as a tonne of CO_2, so methane is assigned[31] a GWP_{100} of 28. This direct value does not account for the impact of methane on ozone, or the additional CO_2 released by carbon cycle feedbacks, which may be substantial.[32]

An alternative metric is the Global Temperature Change Potential, or GTP,[33] which is defined as the impact the emission of a tonne of a greenhouse gas would have on global temperatures at some specified time in the future ("how much warming will this tonne cause in a given future year?"), again relative to a tonne of CO_2. Since methane has a short lifetime, the impact of a tonne of methane emitted today on temperatures in 100 years' time is small, so the GTP_{100} for methane is seven times lower than its GWP_{100}. Both GWP and GTP ignore impacts that occur after the specified time-horizon.

Given that limiting future warming is often cited as the primary goal of climate policy, this discrepancy between GWP and GTP has led some[34] to argue that present-day methane emissions may be overvalued by the use of GWP_{100}. Over shorter timescales, however, the impact of methane is higher still: a tonne of methane has almost 70 times more impact than a tonne of CO_2 on warming over the ensuing 20 years. If the aim of climate policy were to reduce the global energy imbalance in the short term, then 20-year GWP, GWP_{20}, would be a more appropriate metric. Hence metric choice depends on climate policy priorities.[35] It is primarily an issue for short-lived gases: a tonne of nitrous oxide (N_2O), a long-lived gas, is equivalent to about 270 tonnes of CO_2, and this value is relatively independent of metric choice.

Many different metrics have been proposed, reflecting different policy considerations.[36] Most of these are found to behave either like GWP or GTP with an appropriate choice of time horizon. In fact, inspection of the table below shows that, for practical purposes, the issue of metric choice is quite simple: for all gases shown except for the very short-lived HFC-152a, values of GWP_{100} are similar to their 40-year GTPs. Hence GWP_{100} may be understood, informally, as a measure of the relative impact of different greenhouse gases on temperature rise over the next 40 years or less, while GTP_{100} is a measure of relative impact on temperatures in the early 22nd century. The choice between GWP_{100} and GTP_{100} is therefore, to a good approximation, simply a decision as to whether we wish to prioritise reducing climate change over the next few decades or reducing climate change in the more distant future.

Table Two: 'Greenhouse gas exchange rates', or what a tonne of each gas is worth in terms of tonnes of CO_2 under various climate metrics, for the three most important greenhouse gases and two illustrative HFCs.[37]

Gas	Global Warming Potential		Global Temperature Change Potential		
	GWP_{20}	GWP_{100}	GTP_{20}	GTP_{40}	GTP_{100}
Carbon dioxide	1	1	1	1	1
Nitrous oxide	264	265	277	285	234
Methane	84	28	67	26	4
HFC-134a	3710	1300	3050	1173	201
HFC-152a	506	138	174	36	19
Black carbon[38]	3200	910	925	n.a.	130

2. The different impacts of SLCP and CO_2 mitigation on global temperatures

This section explains the potential impact of immediate reductions in SLCP and CO_2 emissions on future climate change. Figure One shows three scenarios for CO_2 emissions (based on the Representative Concentration Pathways[39] – RCPs – used by the IPCC). Under the high emissions scenario, in red, global CO_2 emissions continue to increase at about 1.8-2% per year. The solid blue line represents an ambitious mitigation scenario under which climate policies are introduced to meet the goal of avoiding more than 2°C of warming relative to pre-industrial temperatures. The dashed line shows a "delayed mitigation scenario" which assumes the same percent-per-year reductions in emissions as the solid blue line, but starting 20 years later,[40] in 2035.

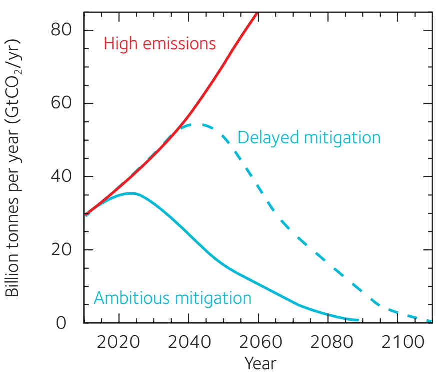


Figure One: Idealised CO_2 emission scenarios used in this policy paper. Red scenario based on IPCC RCP8.5 scenario. Solid blue scenario assumes same percent-per-year rates of change of emissions as projected in RCP3PD from 2010, but starting in 2015. Dashed scenario computed likewise, but starting in 2035.

The solid lines in Figure Two show the potential impact on global temperatures[41] of the solid red and solid blue scenarios in Figure One assuming the same scenario for non-CO_2 climate drivers in both cases. This paper uses the average of a 'high' (RCP8.5) and an 'ambitious mitigation' (RCP3PD) scenario for these non-CO_2 drivers, which gives approximately stable methane and nitrous oxide emissions from 2020 onwards. It is, of course, artificial to assume strenuous efforts to reduce CO_2 have no impact on efforts to reduce other emissions, but this is an idealised example to illustrate the respective impact of CO_2 and non-CO_2 mitigation.[42]

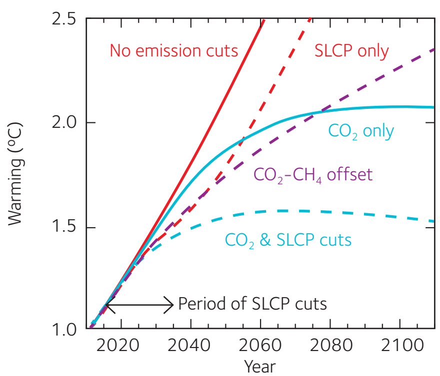


Figure Two: Temperature response to idealised CO_2 emission profiles with and without immediate reductions in short-lived climate pollutants. Red implies high CO_2 emissions scenario (solid red line in Figure One), blue implies ambitious CO_2 mitigation scenario (solid blue line in Figure Two). Solid lines assume approximately stable SLCP emissions from 2020 onwards. Dashed lines assume ambitious measures to reduce methane and black carbon emissions over the period 2015-2035. Dashed blue line assumes both ambitious CO_2 and SLCP measures occur. Dashed purple line is the same as the dashed blue scenario except that methane reductions are offset by an "equivalent" increase in CO_2 emissions using the GWP_{100} metric.

The solid red scenario shows temperatures continuing to rise rapidly throughout the 21st century and beyond. Under the solid blue scenario, global temperatures stabilise by the end of the century as CO_2 emissions approach zero, but the goal of keeping global temperatures below 2°C is missed (under this particular model of the response).

The dashed red and blue lines show warming under the same scenarios for CO_2 emissions but, instead of increasing, methane emissions are reduced to 75% of their 2015 values over the 20 years 2015-2035 and held constant thereafter, and measures to reduce black carbon emissions result in a further 0.25 W/m^2 reduction in non-CO_2 climate warming over the same period.[43] This corresponds to a relatively optimistic scenario for reducing SLCP emissions, although comparable to published estimates of what might be possible, just as the solid blue scenario in Figure One is at the optimistic end of scenarios for reducing CO_2 emissions. Detailed assessment of the cost of these illustrative scenarios is beyond the scope of this paper, but it should be noted that estimates of the cost of SLCP reductions of this magnitude are substantially lower than estimates of the cost of these CO_2 reductions.

Figures such as this one have been used to justify the claim that, as the United Nations Environment Programme/World Meteorological Organization report[44] put it, "near-term emission control measures [on methane and soot], together with measures to reduce CO_2 emissions, would greatly improve the chances of keeping Earth's temperature increase to less than 2°C." Even with very ambitious mitigation, reductions in CO_2 emissions take some decades to impact global temperatures because CO_2 emissions accumulate in the climate system. Reductions in SLCP emissions have a more immediate impact, so the red dashed line (with SLCP measures, but no CO_2 mitigation) remains below the blue solid line (only CO_2 measures) beyond 2050.

Hence if the sole focus of climate policy were to limit warming to 2050, then these SLCP measures would undoubtedly be far more cost-effective than these CO_2 reductions. If we consider other proposed climate targets such as global energy imbalance[45] in 2050, a similar picture emerges: these SLCP measures would reduce the global energy imbalance by a similar amount (0.8 W/m^2) to these CO_2 emission reductions, at a much lower cost. It is clear from the figure, however, that a world in which the global energy imbalance has been reduced by 0.8 W/m^2 through SLCP measures would be in a very different position in 2050 to a world in which the same reduction had been achieved with CO_2 emission reductions: the former would be still warming rapidly, while the latter would be approaching climate stabilisation. Hence setting goals for temperatures or energy imbalance in 2050 will never be sufficient if policies are also concerned with what happens thereafter.

A danger with idealised modelling studies such as that shown in Figures Two (above) and Three (below) is that they conceal the importance of natural, and unpredictable, climate variability. Recent studies[46] have shown that the impact of such variability can be high, particularly on climate changes on regional scales, potentially overwhelming any externally driven trend on 20- to 40-year timescales even under a relatively high forcing scenario. Hence the climatic benefits of SLCP mitigation on these timescales should be kept in perspective: SLCP mitigation could delay the time at which a threshold is crossed by up to 20 years, but internal climate variability could also delay, or bring forward, that time by a similar margin.

The combination of aggressive CO_2 and SLCP mitigation (dashed blue line) remains comfortably below the 2°C 'guardrail', but it must be stressed that this assumes both sets of mitigation measures are taken, and that no resources are diverted from the CO_2 mitigation effort by SLCP mitigation. The dashed purple line shows what happens if SLCP mitigation measures are taken as in the dashed blue line, but those achieving these rapid methane reductions are allowed to 'sell' or offset them against CO_2 reductions, using the conventional GWP_{100} metric of exchange.[47] There would be a clear incentive for this to occur unless it were explicitly prohibited, since methane emissions are already routinely traded against CO_2 emissions using the GWP_{100} metric, and under an aggressive mitigation scenario such as this one, the incentives to find alternatives to CO_2 mitigation would be considerable. Such large-scale offsetting, if it were to occur, would wipe out the impact of methane reductions in the short term, while in the longer term it would result in substantially more warming because the additional CO_2 released continues to warm the climate long after the impact of avoided methane emissions has dissipated.

In the absence of CO_2 mitigation, shown by the dashed red line, SLCP measures only delay, but do not prevent, temperatures crossing any particular threshold. The red dashed line tracks the red solid line (no mitigation effort at all) 15-20 years later. This has prompted some, in the popular press, to suggest that action on SLCPs could "give politicians two extra decades to tackle the less tractable question about what to do about CO_2",[48] but this is a serious misinterpretation, as this paper will show in the next section.

3. The impacts of delaying emission reductions

Figure Three compares the impact of the CO_2 and SLCP emission measures shown in Figure Two with the impact of the same measures initiated 20 years later.[49] The negative impact of a 20-year delay in CO_2 mitigation is much greater than the positive impact of any possible SLCP measures that might be taken in the meantime. Since CO_2 accumulates in the climate system, as long as emissions continue to increase at 1.8-2%/year as they are doing at present, the eventual peak warming to which we are committed is increasing at the same rate, which is much faster than observed temperatures are increasing.[50]

The CO_2 emission reduction rates that would have met the goal of limiting warming to 2°C if initiated in 2010 would only meet a 2.2°C goal if initiated in 2015, when emissions will be 10% higher. If CO_2 emissions continue to rise as they are doing, a 20-year delay would add almost 50% to eventual peak warming, shown by the difference between the red scenarios (delayed CO_2 measures) and blue scenarios (early CO_2 measures) in Figure Three. The only exception to this rule would be if a period of delay were used explicitly to invest in technologies that allowed CO2 emissions to be reduced much more rapidly after the emissions peak (accepting the additional risk that such rapid reductions might not prove possible).

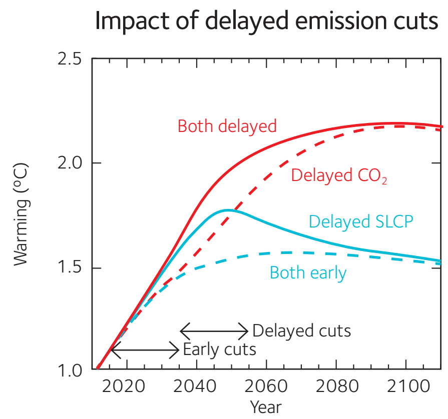


Figure Three: Impact of delayed emission cuts on global temperatures. Dashed blue line: CO_2 and SLCP measures initiated immediately, in 2015, as in Figure Two. Solid blue line: SLCP cuts delayed to 2035, CO_2 cuts initiated in 2015. Dashed red line: CO_2 cuts delayed to 2035, SLCP cuts initiated in 2015. Solid red line: both delayed to 2035.

The impact of delaying SLCP mitigation measures is very different. As would be expected, delaying SLCP measures by 20 years results in more warming over the 2015-2035 period: the difference between the solid lines and the dashed lines. In the longer term, however, the impact of the timing of SLCP measures on peak warming depends on what happens to CO_2 emissions in the meantime. If CO_2 emissions are reduced immediately (blue lines), then failing to reduce SLCP emissions at the same time could add a few tenths of a degree to peak warming (blue solid versus blue dashed lines). But if CO_2 emission reductions are also delayed for 20 years, it makes no difference to peak warming whether SLCP measures are implemented immediately or deferred until after 2035 (red solid versus red dashed lines).

Again, this is a simple illustration of a more general point: SLCP emissions only have an impact on peak warming under circumstances in which CO_2 emissions are either already falling or about to fall rapidly.[51] Hence, if the main objective of climate policy is to limit peak warming, then SLCP mitigation could be delayed until after global CO_2 emissions have started to decline and are expected to continue to decline towards zero. It is quite wrong to suggest that bringing forward SLCP emission reductions can "buy time" to procrastinate over CO_2: quite the reverse. Early SLCP measures only have an impact on peak warming if ambitious CO_2 mitigation measures are already under way.

4. The implications for climate metrics

The simple scenarios shown in Figures One, Two and Three suggest that ambitious measures to reduce SLCP emissions like methane over the next 20 years would have more of an impact on global temperatures out to 2050 than equally ambitious (and potentially much more expensive) cuts in CO_2 emissions. On the other hand, the scenarios also show that unless CO_2 emissions are being reduced at the same time, it makes almost no difference to peak warming whether SLCP emissions are reduced now, or reduced in some later decade closer to the time that temperatures peak. So what is a tonne of methane emitted today 'worth' relative to a tonne of CO_2?

The example shows that there can be no exact equivalence between any given amount of methane emissions and a given amount of CO_2. Any decision on a metric or 'exchange rate' stating what a tonne of methane emissions is worth in terms of equivalent CO_2 depends not only on the properties of the two gases (their atmospheric lifetimes and relative potency as greenhouse gases), but also on assumptions about how the climate system will respond to emissions, and decisions about the relative importance of impacts on different time-scales.

This much is well known. What is less widely appreciated is that the appropriate metric to use today also depends on future emissions. If policies like the goal of avoiding more than 2°C of warming refer to maximum climate change independent of timescale, then assumptions about future emissions, which determine the timing of peak warming, affect priorities today. Under these conditions, the choice of metric represents, at some level, a bet on the success or failure of future climate mitigation policy. Hence there is no purely technical method of determining the correct metric of exchange between a tonne of methane and a tonne of CO_2. Whatever metric is adopted may have distortionary and potentially surprising implications for mitigation outcomes.[52]

One option that has been proposed[53] that would better reflect the actual climatic impact of CO_2 and SLCPs would be to allow a tonne of CO_2 to be released in exchange for a *permanent* reduction in the *rate* of emission of a SLCP. It is difficult to see how this could be implemented in an emission-trading scheme because, while emissions in any given year can be verified, it is unclear how an indefinite commitment to reduce an emission rate could be enforceable. Nevertheless, in comparing policies, it may be useful to recall that every tonne of CO_2 released has an effectively permanent impact on climate, while only permanent changes in SLCP emission rates have a comparable long-term impact.[54]

5. The impact of metrics on mitigation priorities: are SLCPs like methane over-valued or under-valued?

The implications of metric choice on mitigation priorities are illustrated in Figure Four, which shows 2011 emissions of these three main greenhouse gases expressed as CO_2-equivalent emissions using GWP_{20}, GWP_{100} and GTP_{100} respectively. Under the GWP_{20} metric, 2011 methane emissions are equivalent to almost 30 billion tonnes of CO_2 per year, over two thirds of 2011 CO_2 emissions. The current standard metric, GWP_{100}, assigns three times lower weight to methane emissions than GWP_{20}, while the GTP_{100} metric assigns a weight to current methane emissions that is seven times lower still.

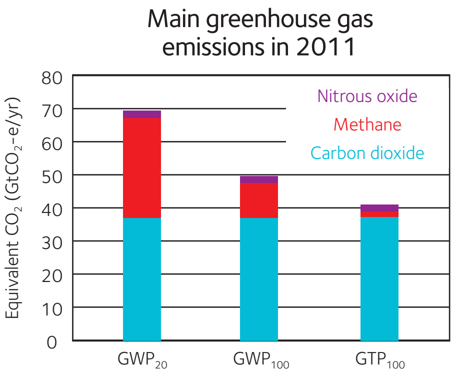


Figure Four: Emissions of three main greenhouse gases in 2011 expressed in terms of CO_2-equivalent using the GWP_{20}, GWP_{100} and GTP_{100} metrics.

Variation of the nominal impact of current methane emissions by a factor of 20 makes the issue of metric choice seem impossibly arbitrary, but in fact these numbers can be easily understood by reference to the example in Figure Two. GWP_{20} is a measure of the impact of greenhouse gas emissions on energy imbalance and warming rates over the coming 20 years, so the high value of methane emissions under GWP_{20} reflects the observation in Figure Two that a halving of methane emissions would be as effective in reducing warming over the following couple of decades as an immediate 40% reduction in CO_2 emissions. Hence if the sole priority of climate policy is to reduce warming or global energy imbalance over the next 20 years, it could be argued that GWP_{100} under-values current methane emissions, and we should instead use a metric like GWP_{20}.

In contrast, if the aim of climate policy is to limit warming in 100 years' time, then the relevant metric is GTP_{100}, which suggests that a 50% reduction in 2011 methane emissions would be equivalent to only a 2.5% reduction in CO_2 emissions. Again, this can be understood by the example in Figure Three: it makes almost no difference to temperatures at the end of the century whether SLCP measures are taken now or taken in 20 years' time: a tonne of methane emitted today has almost no impact on temperatures in 2100. Hence if 100-year warming is the main focus of climate policy, then GWP_{100} vastly overstates the importance of current methane emissions.

Hence a case can be made that the GWP_{100} overstates the importance of present-day methane emissions, and also that it understates it, depending on whether the aim of climate policy is to limit warming in 2100 or to limit climate change over the next 20 years. This is essentially restating, in terms of climate metrics, the results shown in Figures Two and Three: the relative importance of present-day SLCP emissions depends on the time-frame of interest, and if the goal is to limit peak warming, then it also depends on the success of future mitigation policies that determine when peak temperatures are reached.

6. The special case of methane, GWP_{100} and the 2 °C goal

GWP_{100}, despite its name, is an indicator of the relative impact of present-day methane and CO_2 emissions on temperature rise between now and the 2050s: the reason is that methane's GWP_{100} is close to the value of its GTP_{40}, which is a measure of the relative impact of current emissions on temperatures roughly 40 years from now.[55]

The increase in temperatures between now and the 2050s matters for the goal set by the UNFCCC in Cancun in 2010 of limiting human-induced warming to 2 °C above pre-industrial, because temperatures are already about 0.8 °C above pre-industrial and are projected to rise by about another half a degree by 2030.[56] If the 2 °C goal is to be met, then temperatures will have to start to stabilise by mid-century. The impact of emissions today on temperatures in the 2050s is thus a very approximate indicator of their impact on peak warming, *if and only if* emissions of both CO_2 and other climate pollutants are reduced substantially over the coming decades to stabilise temperatures shortly thereafter.

The argument can be made, therefore, that GWP_{100} represents a reasonable metric to use to compare the impact of different gases on peak warming, but *only* under stringent mitigation scenarios that achieve the aspirational 2 °C goal now adopted by the Parties to the UNFCCC. Use of the GWP_{100} metric (which implies a relatively high priority to SLCP mitigation over the coming decade) therefore *assumes* that the 2 °C goal will in fact be met. If CO_2 emissions are not reduced in the near term and temperatures continue to rise through 2070 and beyond, the impact of present-day methane emissions on peak warming is vastly overstated by GWP_{100}.

As long as aggregate national commitments to reduce greenhouse gas emissions are insufficient to meet the 2 °C goal, as is the case at present,[57] continued use of GWP_{100} as a metric to compare and exchange emission reductions of different gases implies that the true goal of climate policy is to minimise the increase in temperatures over the next 40 years or so, and not to limit peak warming at all. This would be a coherent policy objective, but if it has become the primary objective of governments engaged in the UNFCCC process, they should arguably say so. It is very misleading to base climate policy on the assumption that the 2 °C goal will be met in the absence of any concrete plan for meeting it.

7. The implications of metric choice for carbon markets

Much of the interest in SLCP emissions arises from the fact that these emissions could be reduced at relatively low cost compared to the equivalent quantity of CO_2 emissions. These 'Marginal Abatement Costs'[58] are very uncertain, but the cost differentials are thought to be so great that many SLCP emission reductions would still appear desirable whatever metric is used to compare them to CO_2 emissions.[59] If, however, SLCP emissions are traded or offset against CO_2 while climate policy goals are still set in terms of total CO_2-equivalent emissions, as in the purple dashed line in Figure Two, then metric choice could matter a great deal through its impact on CO_2 emissions, as this section explains.

Suppose, for the sake of an idealised example, that 50% of current methane emissions can be eliminated at very low cost while the remaining 50% would be much more difficult and expensive to eliminate. Suppose also that nitrous oxide emissions are prohibitively expensive to reduce.

Figure Five shows the implications for CO_2 emissions of a 10% and 50% reduction in total CO_2-equivalent emissions of these three gases, using three different metrics to calculate CO_2-equivalence. Under GTP_{100}, CO_2-equivalent emissions are almost entirely dominated by CO_2 itself, so any reduction in CO_2-equivalent emissions requires reductions in CO_2. Under GWP_{100}, a 10% reduction in total CO_2-equivalent emissions could be achieved with methane alone, leaving actual CO_2 emissions almost unchanged. Under GWP_{20}, a 10% reduction in total CO_2-equivalent emissions could be accompanied by a 20% increase in CO_2 emissions.

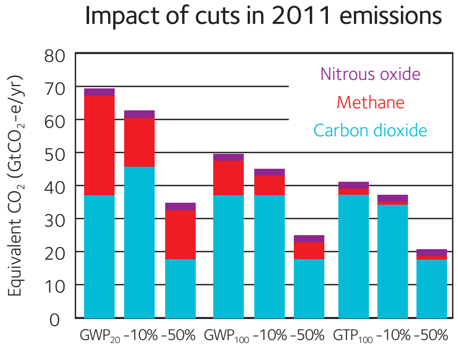
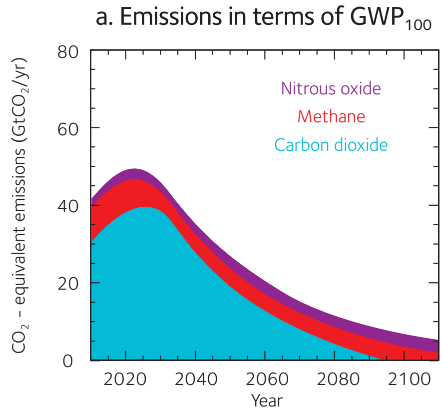


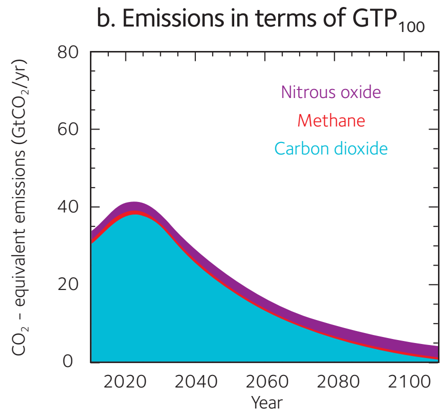
Figure Five: Impacts of 10% and 50% cuts in 2011 total 'CO_2-equivalent' emissions under different emission metrics. It is assumed that 50% of methane emissions can be abated at very low cost, and that the remainder, plus nitrous oxide emissions, are very expensive to abate. CO_2 emissions are calculated to give correct total emission cuts, expressed in terms of CO_2-equivalence using the GWP_{20}, GWP_{100} and GTP_{100} metrics.

For a 50% reduction in CO_2-equivalent emissions, CO_2 emissions themselves have to be reduced no matter what metric is used to define CO_2-equivalence. Hence, in the long term, meeting climate policy goals will require very substantial reductions in all greenhouse gas emissions regardless of the metric used to compare them.[60] In the short term, however, the greater the 'value' assigned to methane emissions, the less CO_2 mitigation will be required for any given reduction in total CO_2-equivalent emissions: the impact of metric choice on methane emissions is not whether or not methane emission reductions occur, but the volume of CO_2 emissions that countries and companies are allowed to offset against them.

8. The implications of metric choice for the timing of emission reductions

Figure Six shows how metric choice might affect the timing of mitigation decisions under an ambitious mitigation scenario. In this example, total CO_2-equivalent emissions are required to peak within eight years of 2015 and then decline steadily to less than half 2015 emissions by 2050. Methane emissions are reduced by 50% over 2015-2035, nitrous oxide emissions are unchanged and CO_2 emissions adjusted to make up the remainder.





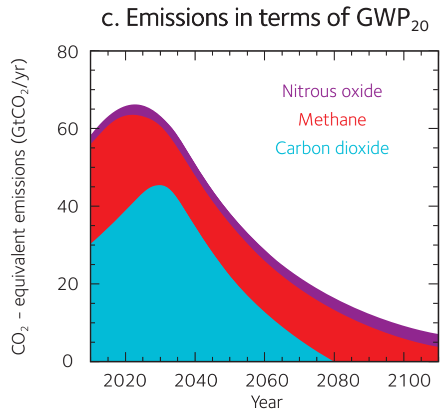


Figure Six: Emissions of the three main greenhouse gases under an idealised ambitious mitigation scenario defined in terms of total CO_2-equivalent emissions but using three different metrics to define CO_2-equivalence.

When CO_2-equivalence is defined in terms of either GWP_{100} or GTP_{100} (panels a and b), this yields similar reductions in all three gases, at least out to 2050. So, under an ambitious mitigation scenario, the same decisions would be made at a global level to meet a given total CO_2-equivalent emission target whether GWP_{100} or GTP_{100} is used, although the choice might still have substantial implications for how the burden of reductions is distributed across countries and sectors.

When CO_2-equivalence is defined in terms of GWP_{20} (panel c), corresponding to a policy focused on short-term goals for global energy imbalance rather than temperature,[61] this yields a rather different scenario. Methane emissions are still reduced by 50% by 2035, but because they play a much larger nominal role in present-day emissions, the target for total CO_2-equivalent emissions can be met while allowing CO_2 emissions themselves to continue to rise. At that point, because of the assumed high cost of further methane reductions, CO_2 emissions have to fall sharply.

In the short term, using a metric that assigns a relatively high weight to methane and other SLCPs gives the impression that climate mitigation can be achieved relatively cheaply. This might be politically advantageous in terms of building momentum for climate mitigation,[62] and might not matter in the long term *provided* CO_2 emissions are successfully and rapidly reduced when they need to be.

Any delay in initiating CO_2 emission reductions represents, however, a substantial risk, because we still do not know how difficult and costly these reductions will be, either technically or politically. Long-term climate change is overwhelmingly determined by cumulative CO_2 emissions, so the longer actual reductions in CO_2 emissions are postponed, the more difficult it becomes to limit long-term warming. The same rate of CO_2 emission reductions that would limit CO_2-induced warming to 3 °C if initiated now would only limit it to 4 °C if initiated after 15 more years of emissions growth at 2% per year.

9. Conclusion and recommendations

The authors of the UNFCCC recognised that the goals of climate policy could not be summed up in a single sentence. Article 2 of the Convention states:

> *"The ultimate objective of this Convention [is] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."*

The first sentence was, and remains, a commitment to future generations. The greatest risks of dangerous anthropogenic interference in the climate system are unlikely to manifest themselves within the lifetime of anyone who was alive when the Convention was opened for signature in 1992, and very possibly not in the lifetime of anyone alive today in 2015. But the second sentence recognises more immediate concerns: allowing ecosystems to adapt and ensuring food production and economic development can continue.

Reduced to its simplest form, the debate over emission metrics and SLCP versus CO_2 mitigation can be conceived as addressing the two sentences of this Article. It is necessary to limit cumulative emissions of CO_2 to stabilise climate and hence limit the risk of dangerous anthropogenic interference in the climate system in the long term. But reducing SLCP emissions may well be a more cost-effective way to limit the rate of climate change over the coming decades to ensure that ecosystems, food production and the economy can adapt, which also has a role in avoiding dangerous climate change.

Proponents of early action on SLCP emissions frequently emphasise the 'complementary' nature of SLCP and CO_2 mitigation, but it is important to be clear what this complementarity means: they are not two ways of achieving the same goal, but address fundamentally different goals, affecting different generations. Early action on SLCP mitigation could affect the temperatures and climate impacts experienced by the generation of today's decision-makers, but will have little impact on the warming experienced by future generations. Unless it is accompanied by ambitious reductions in CO_2 emissions, early SLCP mitigation will also have very little impact on eventual peak warming.

Just as the objective of the UNFCCC could not be summed up in a single sentence, so there is no single emission metric that makes reducing emissions of SLCPs like methane equivalent to reducing emissions of CO_2. They have different objectives, emphasising the interests of different generations, and there is no alternative to designing and monitoring climate policies to ensure that *both* of these vital objectives are met.

To meet the goals of the UNFCCC, policies are required to ensure that global CO_2 emissions are contained within a cumulative budget consistent with limiting warming to a safe level. These policies must be independent of, and in addition to, any multi-gas emission goals. In effect, this implies a 'peak CO_2 first' strategy: the need to limit cumulative CO_2 emissions would over-ride most opportunities to offset CO_2 reductions against SLCP measures until global CO_2 emissions are falling fast enough that there is a realistic prospect of meeting the cumulative budget. As soon as those conditions are met (for example, when CO_2 emissions are projected to reach zero before global temperatures reach 2 °C), SLCP emission reductions will become a crucial priority to limit peak warming.

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Agreements and strategies addressing climate change involve setting priorities between reducing emissions of different climate pollutants. While avoiding dangerous climate change ultimately requires reducing emissions of long-lived greenhouse gases like carbon dioxide to zero, action on short-lived climate pollutants such as methane and soot may be a cheaper way of mitigating warming over the next few decades, with substantial co-benefits to agriculture and human health. This paper explains how the 'short-lived' versus 'long-lived' discussion is not really a technical issue at all, but an expression of inter-generational priorities; the standard policy framework or metric used to compare different climate pollutants, the '100-year Global Warming Potential', prioritises the interests of the current generation over future generations. The paper provides a non-technical overview and sets out policy recommendations, notably a 'peak CO_2 first' strategy, as countries and companies prepare for the UN Climate Change Conference in Paris in December 2015.

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