CLIMATE ANALYTICS

Briefing

The role of short-lived climate forcers in limiting overshoot and returning warming well below 1.5°C

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About Climate Analytics

Climate Analytics is a global climate science and policy institute. Our mission is to deliver cutting-edge science, analysis and support to accelerate climate action and keep warming below 1.5°C.

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Summary

The 1.5°C warming limit enshrined in the Paris Agreement remains the critical benchmark for avoiding the most severe impacts of climate change. However, after decades of insufficient climate action, the world could exceed this threshold as early as 2030.[1] Given the imminence of overshoot, policy focus must now shift to reducing its magnitude and duration. Recent analysis shows that overshoot can be limited, and that warming can be brought back well below 1.5°C this century.[2] However, delivering this requires robust evidence on how different mitigation actions shape temperature outcomes over time.

Previous studies have underscored that pairing deep reductions in carbon dioxide (CO_2) emissions, primarily through the transition away from fossil fuels (TAFF), with targeted mitigation of short-lived climate forcers (SLCFs) – including methane (CH_4), hydrofluorocarbons (HFCs), and black carbon (BC) – is essential to limiting near- and long-term warming while also delivering important air quality and health co-benefits.[2–8] Since SLCFs remain in the atmosphere for much shorter periods than CO_2, and have higher global warming potentials, cutting their emissions can deliver rapid temperature benefits.[9]

While there is consensus that SLCF mitigation is essential, estimates of how much it contributes to limiting warming vary widely between studies,[3,8,10] due to differences in scenario assumptions and experimental design. Moreover, since these studies were published, greenhouse gas emissions have continued to rise and new research and mitigation pathways have become available.[11,12] Decision-makers therefore require updated, quantitative evidence on how SLCF mitigation shapes temperature outcomes, both on its own and in conjunction with other levers, to inform policy design and investment decisions.

To address these needs, this new brief draws on the latest global emissions pathways from integrated assessment models (IAMs) to quantify the role that targeted SLCF reductions play in limiting overshoot and returning warming back well below 1.5°C, relative to and in combination with three other mitigation levers, namely TAFF, action to reduce land use, land use change and forestry emissions (LULUCF), and novel carbon dioxide removal (CDR). It quantifies how each of these levers, in isolation and in combination, can help reduce the rate of global warming, limit peak temperatures, and contribute to getting back below 1.5°C before 2100, while also assessing their limitations.

Our findings are as follows:

Cutting SLCFs is the fastest way to slow warming immediately, and combining these reductions with TAFF would halve the rate of warming in the 2030s

To maximise temperature benefits, TAFF and targeted SLCF mitigation must go hand in hand. Targeted SLCF mitigation is the quickest way to slow warming immediately, cutting warming rates by ~12% over the next 10 years relative to the reference case, slightly more than TAFF alone. The effect of both would increase over the next decade, in particular for TAFF, so that pairing SLCF and TAFF together can halve the rate of warming in the 2030s from 0.26°C/decade to 0.13°C/decade, the lowest rate of warming observed since about the 1960s.[13]

SLCF mitigation and TAFF together can peak global warming before 2050

Neither TAFF nor SLCF mitigation in isolation are enough to peak temperatures near mid-century. Under targeted SLCF cuts alone, warming is still continuing in 2100, and under TAFF alone, warming has just begun to plateau. But when combined, these levers can achieve a definitive peak in warming by 2049 at around 1.7°C. When looking at the temperature reductions achievable by mid-century, SLCF can avoid around 0.12°C of warming, and TAFF around 0.21°C. The combined effort of TAFF and SLCF mitigation covers around 80% of the total achievable avoided warming[1] in 2050.

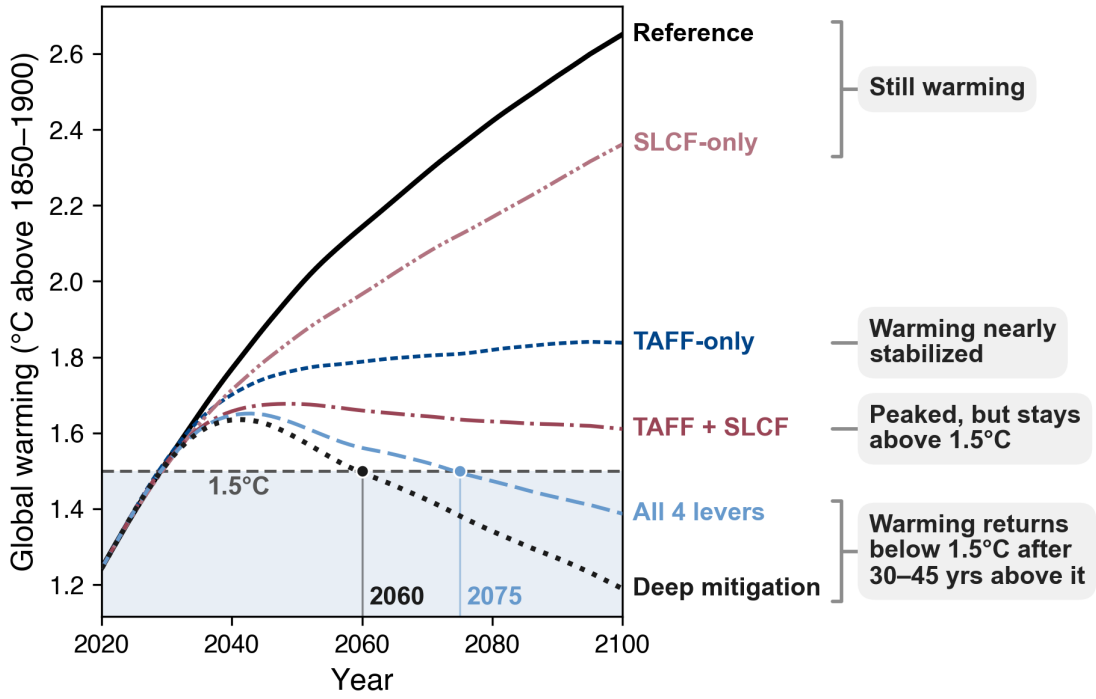
TAFF and targeted SLCF mitigation deliver most of the temperature benefit in 2100, but returning to below 1.5°C this century requires action across all four levers

Cutting SLCFs in line with the highest possible ambition can cut warming by around 0.29°C in 2100. TAFF can reduce temperatures by around 0.82°C. Pursuing them in tandem reduces warming in 2100 to 1.6°C – down by ~1°C compared to the reference case. However, to get back below 1.5°C in 2100, action is also required on LULUCF, novel CDR and other measures. Combining these together brings temperatures well below 1.5°C in 2100, to around 1.2°C, and also reduces peak warming further to 1.6°C (Fig. 1).

[1] Shares of avoided warming are computed using the total achievable avoided warming when all possible mitigation measures are pursued at their highest possible ambition. This does not always precisely equal the sum of all shares as the shares are not strictly additive. This is because there is some overlap between different levers – for example targeted SLCF mitigation and TAFF can both cut methane emissions from the energy sector. There are also interactions between gases, such as VOC, NOx and methane, which means that the combination of levers can give a different outcome to the sum of their impacts in isolation.

TAFF and targeted SLCF mitigation stabilise warming by 2100; returning to 1.5°C and below requires action across all 4 levers

Global warming under each combination of mitigation levers, 2020–2100



	Peak warming (°C)	Peak year	2100 (°C)
Reference	–	after 2100	2.7
SLCF-only	–	after 2100	2.4
TAFF-only	1.8	2095	1.8
TAFF + SLCF	1.7	2049	1.6
All 4 levers	1.7	2043	1.4
Deep mitigation	1.6	2041	1.2

Figure 1. *Global mean surface temperature warming (relative to 1850–1900) under the optimistic reference scenario and successively more ambitious mitigation pathways, 2020–2100. The mitigation pathways are the isolated levers, SLCF (SLCF-only) and TAFF (TAFF-only); combined TAFF and SLCF (TAFF + SLCF), and all four levers (TAFF, SLCF, CDR, and LULUCF) combined; and a deep mitigation scenario, which includes additional mitigation in gases and sectors not prioritised in this study. Key warming metrics (peak warming, peak warming year, and end-of-century warming) for each mitigation scenario are indicated in the table above. For overshoot scenarios, the end of overshoot years are marked on their trajectories. Values are MAGICC v7.5.3 ensemble medians.*

CH_4 reductions deliver the largest temperature benefit within targeted SLCF mitigation

When TAFF is pursued at the highest possible ambition, targeted SLCF mitigation can add around an additional 0.086°C of avoided warming in 2050 and 0.23°C in 2100. CH_4 reductions deliver by far the largest share of this benefit, around 0.09°C in 2050 and up

to 0.24°C in 2100, more than the net total because some of the benefit is offset by warming from reductions in other SLCFs, which include warming and cooling species. Measures to reduce the CH_4 intensity of fossil fuel production remain important in the near-term while TAFF unfolds, though their additional benefit declines as TAFF drives down production and removes most energy-sector CH_4 by mid-century. Their role is larger in scenarios where TAFF proceeds more slowly. From mid-century onwards, the remaining opportunity lies mostly in reducing emissions from agriculture and waste. The residual avoided warming comes from HFC reductions, which yield a modest additional temperature benefit in both 2050 and 2100.

All levers are needed to minimise the magnitude and duration of overshoot

Critically, no single lever is sufficient to meet the Paris Agreement's 1.5°C limit. Comprehensive and ambitious action across all four is essential to limit overshoot and reverse warming. While LULUCF and novel CDR provide minimal temperature benefits in the next decade and the mid-century, they provide around 15% of the avoided warming in 2100 and are needed to bring warming below 1.5°C by 2100. Further action on emissions beyond the scope of these levers, such as nitrous oxide (N_2O), long-lived fluorinated gases, and industrial CO_2 could bring warming to approximately 1.2°C by 2100.

Approach

The overall objective of this analysis is to assess the role of targeted SLCF mitigation – relative to and in combination with TAFF, LULUCF, and novel CDR – in reducing the rate of warming, limiting the magnitude and duration of overshoot, and bringing warming back below 1.5°C by 2100. Full methodological details are provided in the accompanying technical annex. The analysis addresses three main research questions:

1. **What are the temperature benefits of targeted SLCF mitigation?** To understand the specific role that targeted SLCF mitigation plays in shaping temperature outcomes, we assess its effect on a set of warming metrics, including the rate of warming in the near, medium and long term, and its share of net avoided warming in 2050 and 2100.
2. **How do TAFF, LULUCF and novel CDR compare with targeted SLCF mitigation, and which combination of levers is needed to return warming to below 1.5°C by 2100?** To answer this, we quantify the temperature benefits delivered by each lever, individually and in combination.
3. **Beyond the reductions already achieved through TAFF, which targeted SLCF actions, such as cuts to CH_4, HFCs, and BC, deliver the greatest additional temperature benefit – and on which timescale?** To answer this question, we

assess the temperature benefit delivered by each gas individually, including CH_4 by sector.

The mitigation levers are defined as follows:

- **TAFF:** reduces fossil fuel production and use, cutting energy-related CO_2 emissions. It also leads to reductions in associated pollutants – CH_4 from the extraction, processing and distribution of fossil fuels, and air pollutants from their combustion, such as BC – which adds to the avoided warming by the CO_2 reductions. Our estimates of the climate benefits for TAFF include reductions in forcing agents (air pollutants) that have masked some of the warming effects of CO_2 emissions (sulphur dioxide, nitrogen oxides, organic carbon). The benefits of phasing out fossil fuels include substantial co-benefits, notably improved air quality from these emissions reductions.
- **Targeted SLCF mitigation:** reduces SLCF emissions via targeted measures beyond TAFF. This includes addressing fugitive CH_4 emissions in fossil fuel extraction, cutting CH_4 from agriculture and waste; phasing down HFCs; and reducing other air pollutants that are not linked with fossil fuel combustion, such as industrial process emissions.
- **LULUCF:** reduces emissions from deforestation and large-scale land burning. This cuts both CO_2 emissions but also co-emitted SLCFs such as BC and OC. It also covers the growth in CDR from conventional methods such as afforestation and reforestation. The warming avoided per tonne of CO_2 reduced or removed is not constant: for land-based removals, higher warming raises the risk that sequestered carbon is later re-released through wildfire, drought, or ecosystem breakdown, reducing the effective permanence of each tonne removed. For emission reductions more broadly, carbon-cycle feedbacks and the risk of crossing tipping points make the warming response less predictable as temperatures rise. The climate model used in this study captures the gradual weakening of the land and ocean carbon sinks, but not abrupt tipping-point dynamics, ecosystem collapse, or the reversal of land-based carbon removals.
- **Novel CDR:** removes CO_2 from the atmosphere for durable geological storage via engineered approaches such as bioenergy with carbon capture and storage (BECCS) and direct air capture with storage (DACCS).
- **Other measures.** While these four levers are the focus of our analysis, and capture most of the mitigation options available to policymakers, they do not cover a subset of remaining actions, including reducing emissions of N_2O, CO_2 from industrial processes, and fluorinated gases other than HFCs (PFCs and SF_6). To capture these, we also produce a deep mitigation scenario which also sets these emissions to their highest possible ambition, in addition to the four key levers.

Scenarios

For each lever, we produce a set of scenarios which show how emissions would develop under current policies, and how they would develop under a deep mitigation scenario. We develop these scenarios using a statistical approach, relying on an ensemble of the latest integrated assessment model pathways, including from ELEVATE, ScenarioMIP-CMIP7, and the Scenario Compass Initiative.[11,12,14]

To reflect uncertainty in how current policies will be implemented, our results are compared against two reference case scenarios: a reference case reflecting ongoing delivery of current policies and a policy-failure case reflecting weaker, incomplete future delivery of existing policies. The deep mitigation pathway[2] for each lever is drawn from an ensemble of 1.5°C-aligned scenarios, selecting the scenario that represents the highest possible ambition for that lever. Results are presented using the current policy reference scenario, in which temperatures continue to rise to 2.7°C above pre-industrial levels by 2100. Results for the policy-failure scenario are shown in the technical annex.

Recognising that our TAFF scenario represents one of the most ambitious decarbonisation pathways across the IAMs, we also explored an Intermediate Ambition Scenario in which TAFF is pursued slower, to assess how a delayed transition impacts the benefits delivered by different levers. For more details see the technical annex.

Temperature assessment

Emissions pathways are converted into changes in global mean surface temperature (GMST) relative to 1850–1900 using the climate emulator MAGICC v7.5.3 with its IPCC Sixth Assessment Report calibration.[15,16] We report the median temperature outcome from MAGICC.

Results

This section describes the impact of targeted SLCF mitigation, both on its own and in combination with other levers, on key temperature outcomes: the rate of warming, peak temperatures, and end-of-century warming. It compares SLCF mitigation with other levers and identifies which targeted SLCF actions deliver the greatest temperature benefits.

[2] We note that this "deep mitigation" scenario is a synthetic construction which brings together estimates of the mitigation consistent with highest possible ambition across all sectors, drawing from a wide range of integrated assessment models. In our deep mitigation scenario, warming peaks at 1.6°C in 2041 and falls to 1.2°C by the end of the century. The most ambitious scenarios in the literature peak warming between 1.6°C and 1.7°C, with this synthetic scenario at the bottom of the range.

Key message 1: Cutting SLCFs is the fastest way to slow warming immediately, and combining these reductions with TAFF could halve the rate of warming in the 2030s

The rate of warming matters for several climate risks, as faster warming increases the frequency of record-breaking climate extremes and allows less time for societies and ecosystems to adapt.[17,18] We therefore first examine the impact of targeted SLCF mitigation, relative to and in combination with other levers, on the rate of warming over two key periods – 2026-2035, and 2031-2040. This shows how different levers can help reduce the rate of warming over the next 10–15 years.

Over the next decade (2026-2035), targeted SLCF mitigation is the most effective lever for slowing the rate of warming. At its highest possible ambition, it cuts the warming rate by around 12%, from 0.25°C/decade in the reference case to 0.22°C/decade (Fig. 2), in line with previous studies.[8] Targeted SLCF mitigation is effective at slowing warming in the next decade or two because SLCFs have much shorter atmospheric lifetimes than CO_2 and thus can deliver more rapid temperature benefits. TAFF also slows the rate of warming over this period, but by slightly less, to around 0.23°C/decade, an 8% reduction. This is because, in addition to the temperature benefits of CO_2 cuts being slower to emerge, phasing out fossil fuels also cuts co-emitted aerosols, such as sulphur dioxide, that currently cool the climate. The loss of this cooling, known as aerosol unmasking, partly offsets any early benefits of TAFF (see technical annex for further discussion on aerosol unmasking).

Targeted SLCF reductions slow near-term warming; TAFF accelerates cuts over the next decade

Rate of near-term warming over 10-year windows

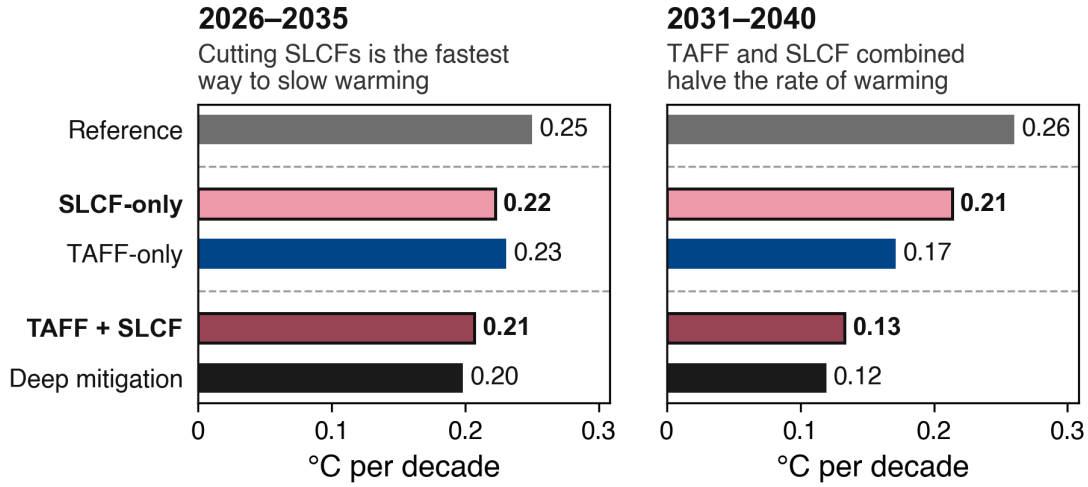


Figure 2. *Rate of warming over 2026–2035 (left panel) and 2031-2040 (right panel), under the reference scenario and individual and combined mitigation levers. The mitigation pathways are the isolated levers (TAFF-only and SLCF-only); combined TAFF and SLCF (TAFF + SLCF); and a deep mitigation scenario, which includes additional mitigation in gases and sectors not prioritised in this study. All values are MAGICC v7.5.3 ensemble medians.*

Across the 2030s, the picture shifts. Under targeted SLCF mitigation, the warming rate stays roughly the same as in the previous decade, at around 0.21°C/decade, a 19% reduction compared to the reference case. Over the same period, TAFF overtakes targeted SLCF mitigation as the most effective lever, slowing the rate of warming by around 35%, from 0.26°C/decade to 0.17°C/decade. Three factors drive this. First, as TAFF builds pace, the cumulative benefits of reduced CO_2 have an increasing impact on warming rates. Second, the benefits of TAFF are no longer offset by aerosol unmasking from fossil fuel phase-out, as most of that unmasking has already occurred by the 2030s: coal, the dominant source of sulphur emissions, is phased out first, because it is by far the most carbon-intensive fuel per unit of useful energy, while oil and gas carry little sulphur after decades of fuel standards. Finally, TAFF also reduces SLCFs linked to fossil fuels, such as CH_4 from fossil fuel extraction and BC from combustion. Under TAFF, CH_4 and BC emissions from the energy sector fall dramatically by roughly 70% and 64% over the 2030s, respectively. An early and ambitious TAFF can therefore deliver benefits even in the near term, in line with past studies which demonstrate that rapid emissions cuts from TAFF can begin to slow the rate of warming within one to two decades.[18,19]

These results are dependent on TAFF being pursued in line with highest possible ambition. If TAFF is pursued with less ambition, then the warming benefits of a fossil phase-out would be delayed by over a decade. In our scenario with weaker TAFF ambition, TAFF does not deliver cuts to the rate of warming over the 2030s but rather continues to increase the rate of warming even by 2040 (see technical annex).

Implementing TAFF and SLCF together makes an even larger difference on the rate of near-term warming. When combined, these measures can cut the warming rate by around 16% over 2026–2035. Over the 2030s they can halve the warming rate from 0.26°C/decade to 0.13°C/decade. Cutting the rate of warming substantially in the 2030s would bring near-immediate benefits for reducing climate impacts which are dependent on the rate of warming and allow time for adaptation to catch up. Action to reduce LULUCF emissions and scale-up novel CDR are less important in the near term, as warming rates remain unchanged when these measures are combined with TAFF and SLCF reductions. Meanwhile, in the deep mitigation scenario, which also includes reductions in industrial CO_2, N_2O and non-HFC fluorinated gases, the warming rate falls further to 0.12°C/decade in the 2030s.

Key message 2: Only the combination of TAFF and targeted SLCF mitigation can peak warming by mid-century

To limit the magnitude and duration of overshoot above 1.5°C and minimise the adverse impacts linked to overshoot, it is critical to peak warming as early as possible, ideally before or around mid-century.[20,21]

Neither SLCF nor TAFF in isolation are sufficient to peak warming by mid-century.

When targeted SLCF mitigation is raised to its highest possible ambition on top of the optimistic reference case, warming continues in 2041-2050, although the pace is roughly 31% slower than in the reference case (0.16°C/decade compared with 0.23°C/decade; Fig. 3). However, without action on the other levers, warming does not peak this century and would continue even into the 2100s (Fig. 1).

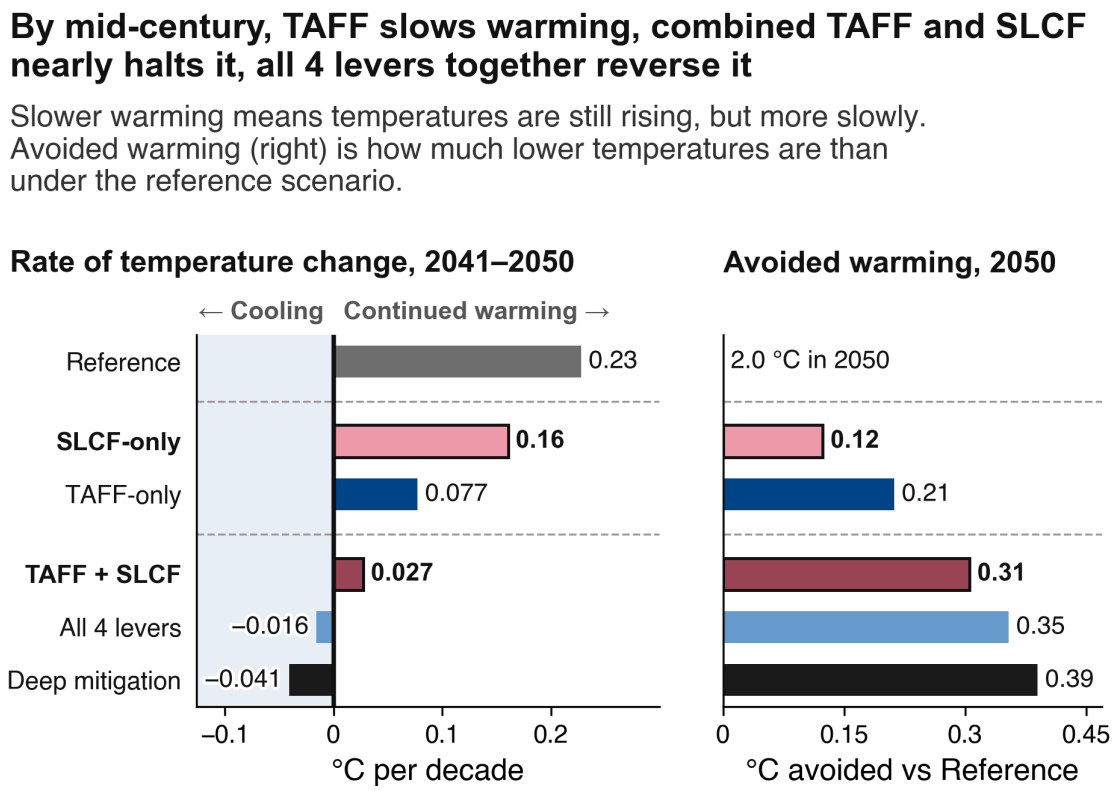


Figure 3. *Rate of temperature change over 2041–2050 (left) and avoided warming relative to the optimistic reference scenario in 2050 (right) under individual and combined mitigation levers. The mitigation pathways are the isolated levers (SLCF-only and TAFF-only); combined TAFF and SLCF (TAFF + SLCF); all four levers (TAFF, SLCF, CDR and LULUCF) combined; and a deep mitigation scenario, which includes additional mitigation in gases and sectors not prioritised in this study. Negative rates indicate cooling. All values are MAGICC v7.5.3 ensemble medians.*

Similarly, when TAFF is pursued at its highest possible ambition, warming is still ongoing at mid-century, although at a rate around 67% lower than in the reference case

(0.077°C/decade). TAFF alone can stabilise temperatures at 1.8°C by the end of the century, but cannot set global warming on a declining path (Fig. 1).[3]

Both TAFF and SLCF mitigation are much more effective when combined than when pursued in isolation.

If SLCF is paired with TAFF, this can turn a temperature plateau into a peak, and bring forward the date of peak temperatures by around 50 years to mid-century. In this scenario, the rate of warming falls to 0.027°C/decade in the 2040s, and temperatures peak in 2049 at around 1.7°C (Fig. 1). Afterwards, the warming trajectory reverses and warming begins to decline slowly. Further action on LULUCF and novel CDR allow peak warming to occur even earlier, in 2043, while in the deep mitigation scenario where all additional levers are pulled at highest possible ambition, the peak is in 2041, at around 1.6°C. Only by pursuing action across multiple different mitigation options can we peak temperatures before 2050 and start to return to below 1.5°C.

When looking at the avoided warming from each lever in 2050, we find that targeted SLCF mitigation avoids roughly 0.12°C of warming by 2050 compared to the reference case (Fig. 3). This represents around 30% of all the avoided warming that could be achieved in 2050.

Ambitious TAFF avoids around 0.21°C of warming by 2050 compared to the reference case (Fig. 3), which represents just over half of the total avoided warming. The combined effort of TAFF and SLCF mitigation delivers roughly 80% of the total avoided warming (0.31°C). With further action to curb LULUCF and scale up novel CDR, this increases to around 90% of the total avoided warming (0.35°C).[4]

[3] This occurs under the optimistic reference case, which assumes actions are already taking place to curb SLCF emissions growth. Under the pessimistic reference case, in which methane emissions continue to grow, TAFF is not enough to stabilise temperatures by 2100 and temperatures continue to rise (see technical annex).

[4] These shares are not strictly additive. This is because there is some overlap between different levers – for example targeted SLCF mitigation and TAFF can both cut methane emissions from the energy sector. There are also interactions between gases, such as VOC, NOx and methane, which means that the combination of levers can give a different outcome to the sum of their impacts in isolation.

Key message 3: TAFF and targeted SLCF mitigation lead to 2100 warming of about 1.6°C, but returning to 1.5°C and below requires action across all four levers

Returning warming well below 1.5°C after overshoot is essential to limit long-term impacts and to meet the Paris Agreement's temperature limit.

When raised to its highest possible ambition on its own, targeted SLCF mitigation avoids around 0.29°C of warming in 2100 compared to the reference case. This is roughly 19% of the total warming that can be avoided in 2100. Yet, end-of-century warming still reaches 2.4°C and warming is still ongoing in 2100 (Figs. 1 and 4). The relative magnitude of the avoided warming delivered by targeted SLCF mitigation compared to other levers falls from 2050 to 2100 because SLCFs are short-lived, so the benefits of cutting them arrive quickly but plateau in the long run, whereas the benefits of CO_2 reductions continue to grow over time. LULUCF and novel CDR deliver much less on their own, around 0.061°C and 0.17°C of avoided warming in 2100, respectively, and warming also continues in both scenarios (Fig. 4).

By 2100, TAFF and SLCF cut warming by at least 1°C, but LULUCF and novel CDR are needed to bring warming below 1.5°C

Slower warming means temperatures are still rising, but more slowly. Avoided warming (right) is how much lower temperatures are than under the reference scenario.

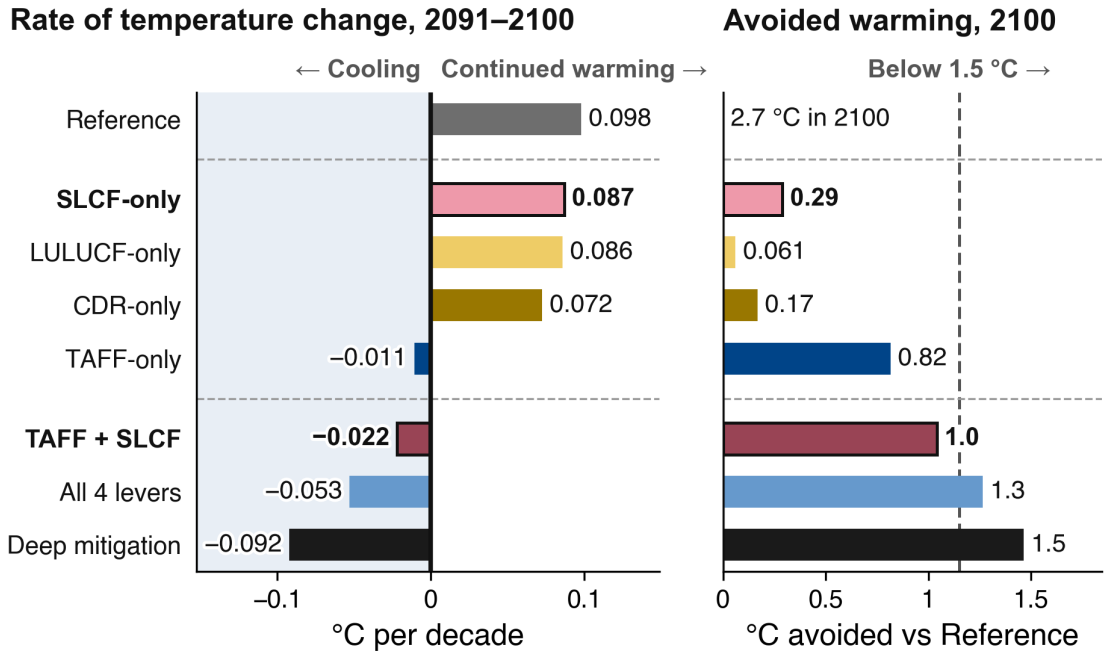


Figure 4. *Rate of temperature change over 2091–2100 (left) and avoided warming relative to the optimistic reference scenario in 2100 (right) under individual and combined mitigation levers. The mitigation pathways are the isolated levers (LULUCF-only, CDR-only, SLCF-only and TAFF-only); combined TAFF and SLCF (TAFF + SLCF); all four levers (TAFF, SLCF, CDR and LULUCF) combined; and a deep mitigation scenario, which includes additional mitigation in gases and sectors not prioritised in this study. Negative rates indicate cooling. Dashed line in the right panel denotes the avoided warming needed to bring 2100 warming below 1.5°C. All values are MAGICC v7.5.3 ensemble medians.*

TAFF delivers by far the largest avoided warming of any single lever, around 0.82°C in 2100 – more than half of total avoided warming from the deep mitigation scenario – and is the only single-lever scenario where warming has effectively stabilised by the last decade of this century (−0.011°C/decade; Fig. 4).

When the two levers that deliver the most benefits, TAFF and targeted SLCF mitigation, are combined, warming is declining by 2091-2100 (-0.022°C/decade) and avoided warming in 2100 increases to around 1.0°C, roughly two thirds of total avoided warming (Figs. 1 and 4). However, end-of-century warming remains at 1.6°C, still above the 1.5°C threshold (Fig. 1).

Only by combining all four mitigation levers – TAFF, targeted SLCF mitigation, LULUCF, and CDR – can warming be brought back below 1.5°C in 2100 – with end-of-century warming decreasing to around 1.4°C (Figs. 1 and 4). In the deep mitigation scenario, which also includes action to cut N_2O, industrial process emissions from CO_2 and non-HFC F-gases, warming is reduced further to around 1.2°C in 2100 (Fig. 1).

Returning warming below 1.5°C by 2100 requires all levers to be pulled in line with the highest possible ambition. In our sensitivity analysis where TAFF proceeds at a slower pace, warming does not return to below 1.5°C by 2100, even when all other levers are pursued at their highest possible ambition [5]. This shows that targeted SLCF mitigation, while critical to curbing near-term warming rates and bringing down peak and long-term temperatures, cannot substitute for a transition away from fossil fuels in line with highest possible ambition, nor can novel CDR or action to cut LULUCF emissions. An ambitious and rapid TAFF must be the bedrock of climate action, and be paired with, not substituted for, action on all other levers. Therefore, pursuing TAFF at its highest possible ambition is essential for any strategy that aims to bring warming back below 1.5°C.

[5] Similar sensitivities could be conducted for SLCF, LULUCF and CDR, but we focus here on TAFF as the lever with the greatest impact in our scenarios.

Key message 4: Within targeted SLCF mitigation, CH_4 reductions deliver the largest temperature benefit.

Finally, we assess which targeted SLCF measures deliver the largest temperature benefit. As TAFF provides the largest avoided warming of any single lever, we treat it as the foundation of any mitigation pathway and assess which targeted SLCF measures provide the most additional avoided warming on top of TAFF.

Additional action on SLCFs avoids an additional ~0.086°C of warming by 2050, and ~0.23°C by 2100 (Fig. 5).

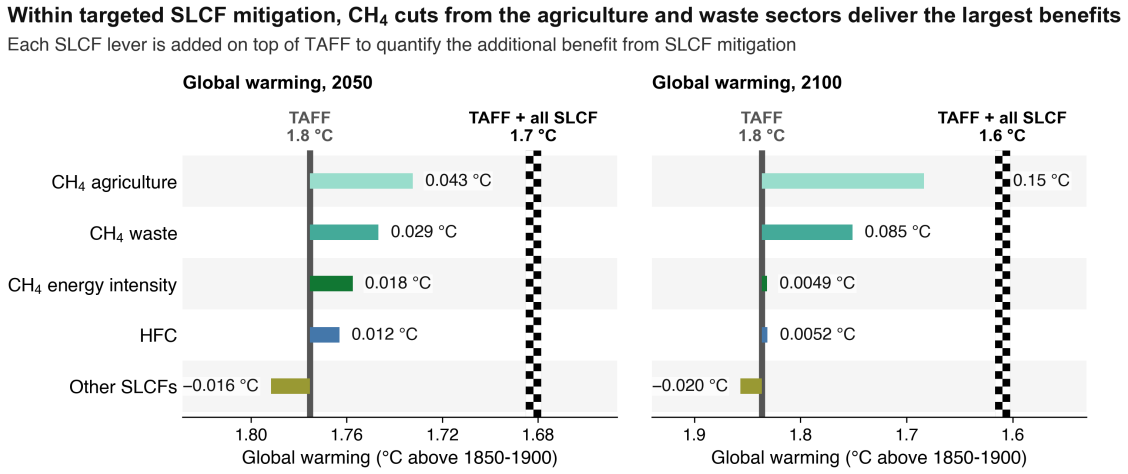


Figure 5. *Global warming in 2050 and 2100 (relative to 1850–1900) from individual targeted SLCF measures added to TAFF. The individual SLCF measures are CH_4 reductions from energy intensity, waste and agriculture, HFC reductions, and mitigation of other SLCFs. Bars run from the TAFF scenario (grey line) towards TAFF combined with all SLCF measures (checkered finish line); labels give the avoided warming. Note the reversed x-axis and the different scales in each panel. All values are MAGICC v7.5.3 ensemble medians.*

CH_4 reductions deliver more than this net total, around 0.09°C of avoided warming in 2050 and 0.24°C in 2100, because part of their benefit is offset by other SLCF measures (see below; Fig. 5). Agriculture and waste reductions provide most of the CH_4 benefit: agricultural CH_4 accounts for around 48% in 2050 and 63% in 2100, and waste-sector CH_4 for around 32% and 35%, respectively. By contrast, targeted cuts to fugitive CH_4 emissions add relatively little when TAFF is pursued at the highest possible ambition, because the phase-out of fossil fuels already removes most of these emissions (Fig. 6). Their contribution is largest at mid-century, at around 15% of the CH_4 benefit, while fossil fuel production is still being phased down, and shrinks to roughly 1% by 2100.

The role of targeted fugitive CH_4 cuts therefore depends on the pace of the transition. Under intermediate TAFF ambition, where the transition is delayed, cutting the CH_4 intensity of fossil fuel production delivers a much larger share of the energy-sector CH_4

benefit (Fig. 6). However, the total energy-sector CH_4 benefit is smaller than under high TAFF ambition (0.061°C versus 0.082°C in 2050, and 0.13°C versus 0.15°C in 2100), and a delayed transition does not return warming to below 1.5°C this century (see Key message 3). Targeted CH_4 measures cannot substitute for TAFF, but they are an important complement while fossil fuels are phased out, as cutting the CH_4 intensity of fossil fuel production alongside scaling down fossil fuel use delivers the greatest benefit.

When TAFF ambition is lower, targeted CH_4 intensity cuts deliver more of the energy-sector CH_4 benefit

Energy-sector CH_4 benefit split into lower fossil activity under TAFF and lower CH_4 intensity from targeted mitigation, under high vs intermediate TAFF ambition

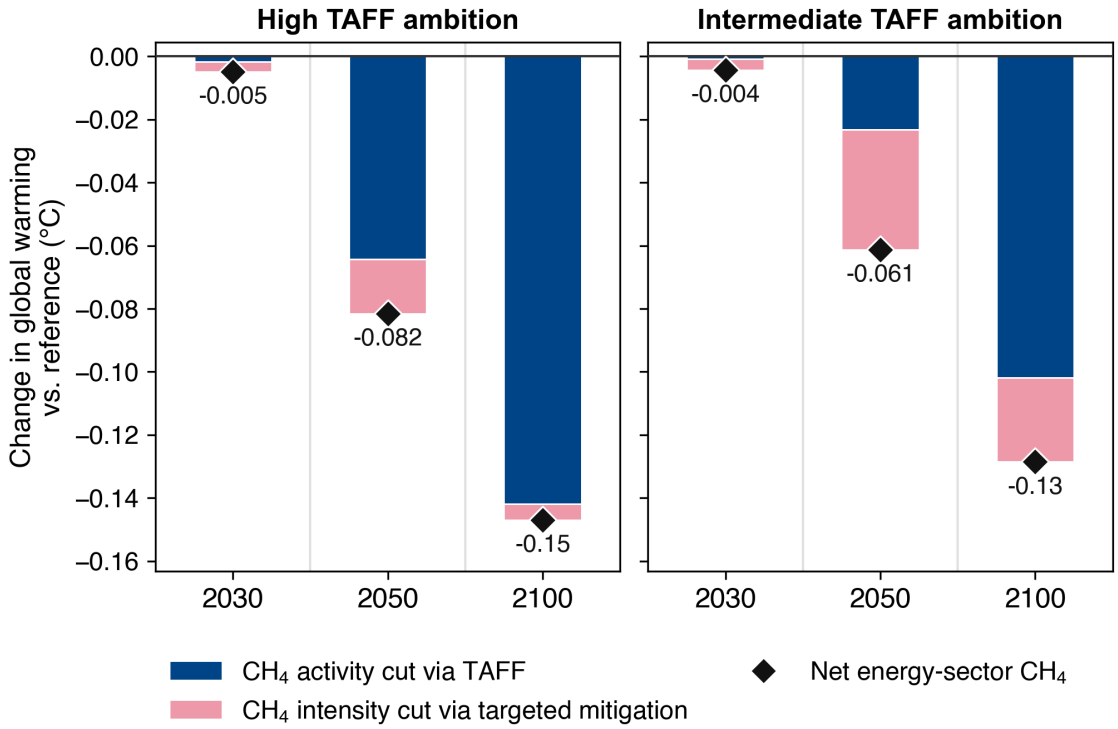


Figure 6. *Avoided warming from energy-sector CH_4 reductions under high and intermediate TAFF ambition. Change in global warming relative to the reference scenario in 2030, 2050 and 2100. Bars split the total energy-sector CH_4 reduction into those from lower fossil fuel activity under TAFF (blue) and the additional reduction from targeted mitigation of CH_4 intensity on top of TAFF (pink). Diamonds indicate the net change. All values are MAGICC v7.5.3 ensemble medians.*

HFC reductions also contribute to the additional avoided warming, although much less than CH_4 cuts: around 0.012°C of additional avoided warming in 2050 and 0.0052°C in 2100 (Fig. 5). These modest values partly reflect the fact that our reference case already assumes compliance with the Kigali Amendment to the Montreal Protocol[22,23], which removes most HFC emissions before any additional mitigation. Under our policy-failure case, which does not include implementation of the Kigali Amendment, HFC mitigation avoids roughly 0.026°C of warming in 2050 and 0.09°C in 2100, roughly three and 18

times more, respectively (see technical annex). Fully implementing the Kigali Amendment is therefore essential, and measures that go beyond it can deliver further benefits.

Targeted mitigation of the remaining non-energy SLCFs, mainly industrial process emissions, slightly increases warming, by around 0.016°C in 2050 and 0.020°C in 2100 (Fig. 5). This is because these emissions include both warming and cooling species, and cutting the cooling ones (e.g. sulphur dioxide) removes part of their masking effect. Nonetheless, reducing these SLCFs remains important, as many are also air pollutants with adverse effects on human health, ecosystems and agriculture.[9,24,25]

Conclusion

With global temperatures on track to overshoot 1.5°C as early as 2030, limiting the magnitude and duration of overshoot, and bringing temperatures back well below this critical threshold, is an increasingly urgent research and policy priority. Our analysis draws on the latest global emissions pathways from IAMs to assess how targeted SLCF mitigation, relative to and in combination with TAFF, novel CDR, and LULUCF, shapes temperature outcomes. In doing so, it provides decision-makers with quantitative evidence on how each lever impacts the rate of warming, peak temperatures, and mid- and end-of-century outcomes, thereby facilitating more informed action.

The findings show that these levers play distinct but complementary roles. Targeted SLCF mitigation is the fastest way to slow warming immediately, with methane cuts providing the largest benefits. TAFF, meanwhile, delivers the largest benefit of any single lever, with benefits that continue to grow over time. Together, they form the backbone of an effective mitigation strategy – drastically slowing the rate of warming, peaking temperatures near mid-century, and delivering the bulk of avoided warming in both 2050 and 2100. However, TAFF and targeted SLCF action alone are not enough to bring warming below 1.5°C by 2100. Novel CDR and efforts to reduce deforestation each deliver relatively smaller temperature benefits on their own but remain essential parts of the mitigation strategy to bring warming back below 1.5°C by 2100. Further action on emissions beyond the scope of these levers, such as N_2O, long-lived fluorinated gases, and industrial CO_2, could bring warming to approximately 1.2°C by 2100.

Ultimately, the results of this analysis reaffirm that limiting overshoot and bringing temperatures back below 1.5°C remains possible, but requires coordinated, early, and ambitious action across all mitigation levers – with TAFF and accelerated action to reduce SLCFs playing especially critical roles.

Lessons for policymakers

- *Accelerate the transition away from fossil fuels*
  TAFF delivers the largest avoided warming by any single lever in both mid- and end-of-century. Relative to the optimistic reference case, TAFF avoids around 0.21°C of warming in 2050 and 0.82°C in 2100, roughly half of the avoided warming delivered by the deep mitigation pathway. While a rapid TAFF is necessary to deliver the deep and sustained reductions in CO_2 required for a 1.5°C-aligned pathway, it also reduces several SLCFs co-emitted with CO_2 from fossil fuel production and use, including CH_4, BC, NO_x and VOCs. Governments should develop and implement credible, ambitious roadmaps to accelerate the transition.

  At the same time, TAFF alone is not enough to cause warming to peak and decline this century.

- *Pursue ambitious SLCF mitigation in parallel with TAFF*
  While TAFF reduces some SLCFs as fossil fuel production and use declines, it does not tackle all sources. Ambitious SLCF mitigation is therefore a necessary complement to decarbonisation – to significantly reduce the rate of warming while delivering important air quality and health co-benefits. On its own, targeted SLCF mitigation is the fastest lever for slowing warming immediately – reducing the warming rate by around 12% in 2026-2035 relative to the reference case. After TAFF, it delivers the second largest temperature benefit – accounting for 33% of avoided warming in 2050 (0.12°C) and 19% in 2100 (0.29°C).

  Combining TAFF with targeted SLCF action halves the rate of warming in 2031-2040 and avoids approximately 0.31°C of warming in 2050 and 1.0°C in 2100 – around 80% and 67% of the total avoided. SLCF mitigation and TAFF together can also peak global warming before 2050.

  Governments should pursue ambitious SLCF mitigation agendas in parallel with TAFF, integrating targeted measures into their Nationally Determined Contributions and other climate action plans, with clear targets, policies, and funding. These measures must complement CO_2 reductions, not replace them. As our analysis underscores, TAFF and SLCF mitigation must go hand-in-hand – relying on SLCF mitigation alone, or delaying ambition on TAFF, would undermine the Paris Agreement's 1.5°C limit.

- *Prioritise early and ambitious methane mitigation*
  CH_4 reductions deliver by far the largest temperature benefit among the SLCF measures assessed – around 0.09°C in 2050 and up to 0.24°C in 2100 – underscoring the need for rapid, sustained cuts across all sectors. Most of this

comes from agriculture, which provides roughly 48% of the CH_4 benefit in 2050 and 63% in 2100, followed by waste, at around 32% and 35%, respectively. Both sectors therefore offer significant opportunities for deep cuts, over both the medium- and longer-term.[26]

Relative to our optimistic reference case, the energy sector contributes around 15% of the additional SLCF benefit in 2050 and only 1% in 2100, since a rapid TAFF has already removed most fossil CH_4. These TAFF-driven reductions account for about 85% and 98% of the total avoided warming from energy-sector CH_4 in 2050 and 2100, respectively. Nevertheless, as TAFF unfolds, targeted measures to reduce methane intensity at remaining fossil-fuel infrastructure – including expanded leak detection and repair programmes and bans on routine venting and flaring – can deliver important benefits in the medium-term.

While 159 countries and the European Union have signed the Global Methane Pledge to reduce global CH_4 emissions by 30% below 2020 levels, and signatories and non-signatories alike have introduced a growing number of methane targets and policies, emissions continue to rise.[27] Governments must close the gap by strengthening and enforcing policies that deliver rapid, sustained reductions.

- *Fully implement existing HFC controls and accelerate the phase-down*

  HFC reductions deliver the second largest share of the additional warming avoided through targeted SLCF mitigation.

  The Kigali Amendment to the Montreal Protocol requires countries to phase down production and consumption of HFCs on agreed schedules and has been ratified by over 170 countries.[28] Our analysis underscores that cuts beyond the current commitments in the Kigali Amendment are possible and can deliver further temperature benefits. Governments should fully implement these commitments and accelerate the phase-down, especially as more extreme heat drives up demand for cooling.

- *Accelerate all mitigation levers in parallel*

  Limiting overshoot and returning temperatures to well below 1.5°C remains possible, but requires governments to pursue the highest possible ambition across all mitigation levers. In our scenario, combining the highest possible mitigation for the four levers assessed – TAFF, SLCF mitigation, LULUCF and novel CDR – means warming peaks at 1.7°C in 2043 and falls to 1.4°C by 2100. Further action beyond these levers, including reducing N_2O, long-lived fluorinated gases and CO_2 emissions from industrial processes, could lower peak warming to 1.6°C and end-of-century warming to 1.2°C.

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