Supplementary Information

Timelines for mitigating the methane impacts of using natural gas for carbon dioxide abatement

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1 Range of CH\textsubscript{4} emissions estimates

In this section we further describe the CH\textsubscript{4} emissions uncertainties presented in Methods 2.1 of the main text. We discuss CH\textsubscript{4} emissions from natural gas systems and from coal mining.

Natural gas. We model CH\textsubscript{4} emissions from natural gas electricity generation for a range of natural gas leakage rate estimates (Figure 1, main text). We draw on two main sources [1,2] that summarize estimates presented in a larger body of literature (e.g. [3–10]).

Studies published over the past decade have raised concerns about the EPA’s U.S. GHG Inventory because it: (1) uses outdated emission factors for certain technologies, (2) does not represent the full set of devices from which emissions originate, and (3) does not capture changes in device operating modes which may affect emission rates [2,4,11]. All three reasons have been used to explain reported differences between ‘bottom-up’ emissions estimates, such as the EPA’s, which aggregate emissions from individual devices to estimate site- or facility-level emissions, and ‘top-down’ studies, which measure total atmospheric methane

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concentration and thereby capture a larger number of devices and operating modes. Despite the discrepancies discussed in the literature, the EPA’s uncertainty estimates for CH$_4$ emissions from natural gas systems (+30% and −19%, with 95% confidence [1]) are relatively small as compared to recent work that report larger uncertainty ranges [12,13]. Confidence intervals in the EPA’s emissions inventory have remained unchanged between the inventories published in 2011 and 2017, which contain estimates for the years 2009 to 2015 [1,14–18]. We therefore use the EPA’s CH$_4$ emissions estimate to define a low estimate of the natural gas leakage rate and the resulting CH$_4$ emissions from natural gas electricity generation (figure 1c in the main article).

To compute a high estimate, we multiply the natural gas contribution to total power sector CH$_4$ emissions by an adjustment factor (figure 1d in the main article). This adjustment factor was developed based on a review of leakage rate estimates reported in the literature [2,19]. According to our review, 10 of 12 regional estimates in the literature fall within a range of one (1.05) to three (2.92) times the EPA’s mean estimate, when this estimate is scaled to regional production contexts to be compatible with each study’s measured or modeled emission factor [5–10,20–22]. One comparison was below this range, with a factor of 0.84 [23]. Another comparison resulted in an estimate 6.77 times as large as the EPA’s estimate (calculated in [19] based on [24]). We treat these two results as outliers, however, because all other measured or modeled rates fall within the 1–3 range. Expressed as natural gas leakage rates in the year 2014, our low and high leakage rate estimates of 1.5% to 4.9% are consistent with estimates published in the literature [1,3,25,26]. However, the range of natural gas leakage rates considered here should be treated as a rough estimate. Limited knowledge of natural gas CH$_4$ emissions currently precludes greater certainty [2,4,24,25,27].

The low end of our range of natural gas leakage rates assumes a 95% CH$_4$ content by volume of natural gas, and the high end assumes an 85% CH$_4$ content. Other hydrocarbons such as ethane, propane, and butane, as well as CO$_2$, hydrogen, nitrogen, and sulfur compounds make up the remaining content. Consistent with the goal of this analysis to compute system-wide, average changes in the natural gas leakage rate to meet climate policy goals, the 85–95% CH$_4$ content reflects a supply chain average for the U.S. Compositions in other locations and at different stages of natural gas processing may fall outside this range.

While the adjustment factor used for the high estimate was originally defined in comparison to 2008 CH$_4$ emissions (published in a 2013 EPA report [16]), we base our analysis on and apply the adjustment factor to the EPA’s 2016 estimate for 2014 emissions. Using 2017 EPA estimates (for the year 2015) instead of 2016 EPA estimates does not significantly alter the range of leakage rates (1.3–4.3%). However, since the adjustment factor was determined relative to an estimate for the year 2008 (from the U.S. GHG Inventory 2011/2013) that is roughly 14% higher than the 2014 mean (from the U.S. GHG Inventory 2016) [1,16], estimated CH$_4$ emissions presented in the main paper are conservative.

To test the sensitivity of the results shown in figure 2b in the main article to the choice of starting year CH$_4$ emissions estimate, we repeat the analysis using the EPA’s estimate for the year 2008 [16]. Estimated CO$_2$-equivalent emissions reductions by 2030, from 2005 levels, are in the range of 13.8 to 22.6% (compared to 18.7–26.0% in figure 2b in the main article), when using the ICI metric, and in the range of 24.9 to 27.9% based on the GWP(100) metric (compared to 28.7–30.9% in figure 2b the main article). Estimated CO$_2$-equivalent emissions cuts based on other metrics in our set and the EPA’s estimate for the year 2008
fall within this range. Larger reductions in power sector CH\textsubscript{4} emissions and in the natural gas leakage rate would therefore be needed to meet the 2030 CO\textsubscript{2}-equivalent target when using a different starting year CH\textsubscript{4} emissions estimate in the model.

**Effects of natural gas distribution pathways.** Power and heat producers share the same natural gas supply chain for production, processing, and transmission. Distribution pathways may differ, however, which could affect CH\textsubscript{4} emissions from natural gas distribution and related CH\textsubscript{4} mitigation requirements under a CO\textsubscript{2}-equivalent policy goal such as the one considered here. The effect of these differences is likely relatively small. CH\textsubscript{4} emissions from natural gas distribution are estimated to contribute less than 10% of CH\textsubscript{4} emissions from natural gas systems [1]. Natural gas leakage rate reductions required to meet CO\textsubscript{2}-equivalent targets can therefore be interpreted as changes in the system-wide natural gas leakage rate. Note that this assumption reflects the current state of knowledge, with significant uncertainties in emissions from all natural gas supply chain segments remaining (see discussion above). Better emissions data may allow for more targeted recommendations to reduce CH\textsubscript{4} emissions from individual supply chain segments.

**Power plant CH\textsubscript{4} emissions.** The EPA’s emissions inventory published in 2016 does not account for fugitive CH\textsubscript{4} emissions at natural gas–fired power plants [28]. We therefore use measurements presented in a recent study [29] to compute the change in our results when fugitive power plant CH\textsubscript{4} emissions are included. Due to the small sample size and the lack of other data sources on power plant CH\textsubscript{4} emissions, our calculation is rough. However, the calculation illustrates the possible magnitude of change in our results when accounting for CH\textsubscript{4} emissions at power plants.

We increase the low end of our baseline range of natural gas leakage rates by 0.16% (the lowest estimate for leakage at power plants reported by Lavoie et al. [29], and the high end by 0.32% (the highest estimate given in the same reference). In both cases we account for natural gas already lost in the supply chain leading up to the plant. For the adjusted low end of natural gas leakage rates (1.66%), the required reductions in leakage rates are 44.2% (GWP(100); low end of metric range considered) and 88.8% (ICI; high end of metric range considered) over the 2014–2030 period, to meet the 2030 CO\textsubscript{2}-equivalent emissions target, instead of 40.6% and 88.1%. Results using other emissions equivalency metrics fall into this range. Thus, the required percent reductions in the natural gas leakage rate are roughly 0.8–8.9% larger than the required percent reductions for baseline leakage rates. For the high end of natural gas leakage rates (5.2%), reductions of 42.0% and 88.4% would be needed over the 2014–2030 period, instead of 40.6% and 88.1%. The required leakage rate reductions in this case are roughly 0.3–3.4% larger than our baseline results. This change is small in comparison to other determinants of the scale of the CH\textsubscript{4} mitigation challenge to meet CO\textsubscript{2}-equivalent goals. For instance, for our baseline natural gas leakage rate (excluding power plant CH\textsubscript{4} emissions), required reductions in the natural gas leakage rate over the 2014–2030 period are 120% larger under the ICI metric than they are under the GWP(100).

**Attribution of CH\textsubscript{4} emissions to natural gas and oil.** A number of devices used in natural gas production handle both oil and natural gas liquids in addition to natural
gas. Attributional errors may therefore be present in emissions estimates for these devices. Publicly available descriptions of the methods used in the EPA’s emissions inventory do not indicate an adjustment of emissions factors to account for the fact that not all CH$_4$ emitted from these devices is from natural gas production [28]. We therefore draw on the information provided in [30] to compute a rough estimate of the effect of these errors on the range of natural gas leakage rates used in our model. Based on the mass attribution done by Zavala-Araiza et al. [30], we assume that instead of 100%, only 85.1% of the CH$_4$ emissions from devices handling both natural gas and oil are due to natural gas–related processes, and 94.1% of emissions from devices handling natural gas and natural gas liquids. The resulting change to absolute masses of production emissions in 2014 is small; attribution-adjusted emissions are only 4% smaller than non-adjusted emissions. The resulting range of natural gas leakage rates in 2014 is 1.46–4.79% (instead of the baseline 1.50–4.91%). The small change in leakage rates leads to a similarly small change in our results. The required reductions in natural gas leakage rates are 39.93% (GWP(100)) and 87.97% (ICI) over the 2014–2030 period, to meet the 2030 CO$_2$-equivalent emissions target. These percentage reductions are 2% and 0.15% smaller than our central results (40.62% (GWP(100)) and 88.11% (ICI)). Results using other metrics fall into the range defined by the GWP(100) and the ICI.

**Regional variability in CH$_4$ emissions.** Leakage rates have been shown to vary across natural gas production regions in the U.S. The range of natural gas leakage rates we consider covers most of these estimates [2,31], but here we study the effect of incorporating outliers. Our baseline system leakage rate is 1.5%, and we adjust this baseline leakage rate to study the impact of regional variability. To the extent available, we combine region-specific leakage rates estimated in a recent study [31] (Uinta: 3.5%; Denver-Julesburg: 1.6%; Marcellus: 0.27%; Barnett: 0.15%; Fayetteville: 0.031%) and 2014 production data to compute a production-weighted average natural gas leakage rate for the year 2014. We do this by reducing the contribution of low-leakage regions in proportion to the ratio of the region-specific leakage rates reported in [31] to our baseline leakage rate, and by analogously increasing the contribution of high-leakage regions using the same scaling approach and reference. The contributions from processing, transmission, and distribution to total natural gas system emissions remain unchanged (as given in the EPA’s inventory). Because low-leakage regions contributed more to total dry natural gas production in 2014 than high-leakage regions, the resulting system leakage rate is lower than our baseline (1.4% instead of 1.5%). For this reduced leakage rate, a reduction in the natural gas leakage rate of 39.22–87.83% over the 2014–2030 period (ranging from the GWP(100) to the ICI) would be needed to achieve a 32% reduction in CO$_2$-equivalent emissions by 2030 from 2005 levels. These percentages are 3% (GWP(100)) and 0.3% (ICI) lower than the baseline percentages, with results using other emissions equivalency metrics falling into the range defined by the GWP(100) and the ICI.

**Coal.** We use the EPA’s mean estimate for 2014 CH$_4$ emissions from coal mining (published in the 2016 inventory) [1] to estimate CH$_4$ emissions from coal electricity generation. Given the amount of U.S. coal production in 2014, using EPA data on CH$_4$ emissions from coal production gives an emissions factor of approximately 3g/kg CH$_4$ [1]. This value falls into
the range commonly cited in the literature (e.g. [32]). (Note that the lower end of the range reported by Weisser for the U.S. is for open pit mines. It is lower than the EPA-based emissions factor, which includes the contributions from underground mining, which is more CH\textsubscript{4}-intensive than surface mining [1].)

In the main paper we do not apply an adjustment factor to CH\textsubscript{4} emissions from coal as we do for natural gas because the projected growth in natural gas production motivates a focus on natural gas related uncertainties. In addition, the EPA’s uncertainty estimates for CH\textsubscript{4} emissions from coal mining are smaller than those from natural gas systems (+15 and –12% deviation from the mean for high and low estimates compared to +30 and –19% for natural gas [1]). Incorporating the EPA’s high estimate for CH\textsubscript{4} emissions from coal [1] leads to minor changes in estimated 2030 CO\textsubscript{2}-equivalent emissions reductions relative to figure 2b in the main article (–18.3% from 2005 levels for high coal and natural gas CH\textsubscript{4} emissions when using the ICI, compared to –18.7% for the mean estimate, or –28.4% in 2030 using the GWP(100), compared to –28.7%). Changes under different emissions equivalency metrics in our sample set are similarly small.

2 Equivalency metrics and uncertainties

In this section we perform a sensitivity analysis to examine the effect of uncertainties in emissions equivalency metrics on estimated reductions of power sector CO\textsubscript{2}-equivalent emissions. As in figure 2 in the main article, we assume a 32% reduction in CO\textsubscript{2} emissions from electricity over the 2005–2030 period, and no reductions in the natural gas leakage rate relative to 2014 levels. We use uncertainty ranges as reported in the IPCC’s AR5 Chapter 8 for the GWP(100) [33,34], as well as upper and lower bound metric values based on a range of CO\textsubscript{2} removal rates used to calculate ICI and GTP metric values.

Our key results are robust to metric value uncertainties. The GWP(100) is the only metric under which estimated CO\textsubscript{2}-equivalent emissions based on lower bound metric values approach the 2030 CO\textsubscript{2}-equivalent target (figure S1). For other metrics, metric value uncertainties tend to result in higher metric values, placing more weight on CH\textsubscript{4} emissions rather than less. As a result, estimated CO\textsubscript{2}-equivalent reductions tend to be even further from the 32% target in 2030 when incorporating metric value uncertainties (figure S1).

Global warming potential. In the main text we use the GWP(100) metric value for fossil CH\textsubscript{4}. This fixed conversion factor of 30 grams of CO\textsubscript{2}-equivalent emissions per gram of CH\textsubscript{4} includes a radiative forcing contribution from the effect of CH\textsubscript{4} oxidation to CO\textsubscript{2} [34,35]. The sensitivity analysis is based on uncertainty ranges found by Reisinger et al. and cited in IPCC’s AR5 Chapter 8. For the referenced selection of uncertainties, GWP(100) metric values fall into a range of –30% and +40% of the central metric value. Using the maximum GWP(100) metric value, CO\textsubscript{2}-equivalent emissions reductions reach 25–29% below 2005 levels in 2030 and are thus closer to the results based on central GTP\textsubscript{t=2080} metric values (28–31%). Use of the minimum GWP(100) metric value results in smaller changes of CO\textsubscript{2}-equivalent emissions reductions (29.6–31.2% in 2030) compared to 28.7–30.9% under central metric values. We also estimated results when taking into account impacts of climate-carbon feedbacks, which increases the GWP(100) metric value by roughly 20% [34]. Applying
the same percent increase to the fossil GWP(100) metric value, estimated CO₂-equivalent emissions reductions in 2030 reach 26.6–29.9% from 2005 levels (instead of 28.7–30.9% under central GWP(100) metric values).

**Instantaneous climate impact.** ICI metric values in the main article (see Methods, equation (5) for the functional form) have been computed using parameters from Joos et al. for CO₂ removal functions (Methods, equation (6) and [36]). Upper bound ICI metric values reflect a model for faster CO₂ removal (based on Hooss et al. [37]), which is among the higher removal rates found in the literature. We consider only higher removal rates in our sensitivity analysis because the removal rate used to compute metric values shown in figure 2a in the main article is already among the lower removal rates in the literature. Error bars in figure S1a therefore extend upwards, towards smaller CO₂-equivalent cuts resulting from higher metric values, but not downwards. Maximum ICI values exceed central values by 37–50% in the 2005–2030 period. Estimated CO₂-equivalent emissions cuts between 2005 in 2030 would thus be lower than the 32% target (14.2–24.0% for our range of natural gas leakage rates), compared to 18.7–26.0% reductions for the central ICI metric values used in the main article.

**Global temperature change potential.** To explore the range of GTP metric values, we vary CO₂ removal functions across the range cited in the literature [36,37]. For lower bound GTP(tₑ=2050) metric values, estimated CO₂-equivalent cuts from 2005 reach 15.8–24.7% by 2030, and are thus fairly similar to the results based on central metric values (15.5–24.6%) shown in figure 2b in the main text. For upper bound GTP metric values the changes relative to baseline emissions reductions are slightly larger (13.8–23.8% cuts from 2005 by 2030, compared to 15.5–24.6%). When using the GTP(tₑ=2080) metric, estimated CO₂-equivalent reductions over the 2005–2030 period are 28.5–30.5% for lower bound metric values and 26.3–29.7% for upper bound metric values (instead of 28.4–30.5% under central metric values).
Figure S1: Effect of metric value uncertainties on estimated power sector CO₂-equivalent emissions reductions by 2030, from 2005 levels, under a 32% CO₂ cut and without natural gas leakage rate mitigation. Dark (light) bars show results under high (low) natural gas leakage rates. CO₂-equivalent emissions reductions tend to be further away from the 2030 CO₂-equivalent target than under the metric values used to generate results in the main article (compare figure 2 in the main text).

3 Expanded emissions scenarios

In this section we discuss scenarios 1–5, presented in the main article, and consider additional scenarios (scenarios 6–9) that achieve a 32% reduction in power sector CO₂-equivalent emissions over the period 2005–2030. Consistent with the main article, we refer to this target as the ‘2030 CO₂-equivalent target’. We also examine the effects of low natural gas leakage rates on electricity mix changes in scenarios 2–9. (Figure 3 in the main article presents results under high leakage rates for scenarios 2–5.) Additional cases, for instance those in which the 2030 CO₂-equivalent target is not achieved, are discussed in SI section 6.

High-level scenario descriptions. Like scenario 1 presented in the main text, scenario 1.1 achieves the 2030 CO₂-equivalent target through a 32% reduction in CO₂ emissions combined with natural gas leakage rate reductions but uses an electricity mix with less natural gas and more coal and renewables compared to the mix in scenario 1. In contrast, scenarios 2–9 achieve the same target through deeper CO₂ emissions reductions, requiring no changes in the natural gas leakage rate.
Scenarios 2–9 assume high natural gas leakage rates in the base year (2005) and in the starting year for emissions reductions (2014). Scenarios 2.1–9.1 assume low natural gas leakage rates. (Scenarios 2–5 are also discussed in the main article.)

Scenarios 2–5 and 6–9 use the same strategy to reduce CO\(_2\)-equivalent emissions (CO\(_2\) reductions of more than 32%, no reductions in the natural gas leakage rate) but differ in the way CO\(_2\) reductions beyond 32% are achieved. Scenarios 2–5 reduce electricity generation from coal relative to scenario 1, scenarios 6–9 reduce electricity generation from natural gas relative to scenario 1. Figure S2 and table S1 show the electricity mix for all scenarios. Table S2 presents electricity sector emissions changes for all scenarios that meet the 2030 CO\(_2\)-equivalent target. Table S3 presents 2030 natural gas leakage rates that would allow for meeting the 2030 CO\(_2\)-equivalent target.

**Emissions intensities and emissions targets.** To solve for electricity supply mixes that meet 2030 emissions targets, we use life-cycle emissions intensity estimates from Argonne National Laboratory’s GREET database for fossil fuels [38] and results of a harmonization of life-cycle emission estimates for low-carbon technologies from the National Renewable Energy Laboratory [39]. We model expected heat rate improvements for a fraction of coal-fired power plants as projected by the EPA under the Clean Power Plan [40]. For scenario 1, the electricity supply mix is taken from the EPA’s projection under the Clean Power Plan [41]. In other scenarios, we vary the amount of non-hydroelectric renewables generation to supply carbon-free power. We keep hydroelectric and nuclear electricity generation constant at the levels projected for 2030 by the EPA [41]. However, any carbon-free source could be used to supply the required amount of carbon-free power, with small differences in the amount of carbon-free power required due to variations in the life-cycle emissions intensities of these technologies. We therefore use the general term ‘carbon-free’ when discussing the results in the main article and the SI.

Our 2030 CO\(_2\)-equivalent target achieves a 32% reduction in 2005 CO\(_2\)-equivalent emissions, including 2005 CO\(_2\) emissions from combustion and 2005 upstream CH\(_4\) emissions from coal and natural gas production. The CO\(_2\) portion of our 2030 emissions target is based on applying a 32% reduction to only combustion emissions in 2005 [41]. Setting the target in this way does not account for upstream CO\(_2\) emissions from constructing fossil, renewable, and nuclear power plants. If instead we were to assign full life-cycle CO\(_2\) emissions to power plants in 2005 and apply a 32% reduction in emissions, the allowable 2030 CO\(_2\) emissions would be a little higher. In other words, the target we use is a bit more stringent than it would be if it were based on an assumption of higher, life-cycle CO\(_2\) emissions in 2005. However, the difference is small. When measured against life-cycle CO\(_2\)-equivalent emissions in 2005 (which include CO\(_2\) emissions from plant construction), our 2030 CO\(_2\)-equivalent target achieves a reduction of 32.4%.

**Changes in CH\(_4\) emissions from coal.** In addition to reductions in the natural gas leakage rate, scenario 1 also requires a reduction in CH\(_4\) emissions from coal production for the power sector. The reductions needed in absolute terms over the 2014–2030 period are given in table S2 (the column ‘∆CH\(_4\)’ applies equally to CH\(_4\) from coal and natural gas). These reductions correspond to a 2–80% decline in the CH\(_4\) emissions intensity of coal
electricity over the 2014–2030 period for the set of emissions equivalency metrics we study (2%: GWP(100); 43%: GTP(t_e=2080); 68%: GTP(t_e=2050); 80%: ICI). CH_4 emissions from coal mining stem primarily from ventilation and degasification systems of underground coal mines, some of which already recover and use the CH_4 to reduce emissions [42]. Since our main focus is natural gas emissions, we do not discuss the required changes in CH_4 emissions from coal in the main article, but note that to meet the 2030 CO_2-equivalent target, increased deployment of CH_4 recovery systems would be needed in addition to reductions in the natural gas leakage rate (unless carbon-free power is expanded more rapidly, see scenarios 2–9).

**Main conclusions.** The additional scenarios we consider support the same conclusions drawn in the main article. We estimate that a significant natural gas leakage mitigation effort will be needed to achieve a 32% reduction in power sector CO_2-equivalent emissions over the 2005–2030 period, unless power sector CO_2 reductions over the same period are deeper than 32%. The only scenario that achieves a 32% CO_2 emissions reduction between 2005 and 2030 with only modest natural gas leakage rate cuts (below 10%, see scenario 1.1, tables S1–S3) uses the GWP(100) metric and reduces the amount of natural gas electricity produced relative to today’s levels. Reducing natural gas electricity generation represents a departure from most U.S. electricity supply projections (e.g. [43]). Achieving greater CO_2 emissions reductions through reduced natural gas use (scenarios 6–9) instead of reduced coal use leads to similar required levels of carbon-free power in 2030. The emissions equivalency metric remains the most important determinant of the level of carbon-free power required in 2030. The second most important determinant is the natural gas leakage rate.

**Detailed description of scenarios 1 and 1.1: 32% CO_2 cut combined with natural gas leakage rate reductions.** The U.S. EPA lays out two illustrative compliance scenarios in the regulatory impact analysis published along with the final Clean Power Plan (CPP) rule [41]. Under rate-based compliance, referred to as scenario 1 in the main article, target CO_2 emission rates are reached by averaging power plant emission rates across affected generating units within the borders of individual U.S. states. In the mass-based compliance scenario, cumulative masses of power plant CO_2 emissions in the target year must be less than or equal to the total CO_2 emissions granted to a state [1]. Both types of performance goals, target rates and target masses, are derived from emission rates defined by the EPA for fossil fuel–fired electric utility steam generating units and stationary combustion turbines.

Differences between primary energy production levels projected by the EPA for the rate-based and mass-based option are small. Estimated CO_2-equivalent emissions reductions over the 2005–2030 period are therefore roughly equal for both compliance scenarios. Slightly higher expected coal consumption in the mass-based scenario is compensated by lower natural gas consumption. For the mass-based compliance option, and employing the ICI metric, expected CO_2-equivalent emission reductions by 2030 (below 2005 levels) fall within a range of 19.1–26.1% by 2030 (instead of 18.7% to 26.0%, see red bars in figure 2 in the main article). Results for the mass-based compliance option are equally close to the rate-based option (scenario 1, figure S2) when using the GWP(100) metric, where 2030 emission reductions range between 28.9–30.9% (compared to 28.7–30.9% under the rate-based compliance option, see magenta bars in figure 2 in the main article).
Estimated percentage reductions for the GTP\( (t_e=2050) \) and the GTP\( (t_e=2080) \) metrics are close to results for scenario 1, reaching 16.0–24.7\% (compared to 15.5–24.6\%), while reductions under the GTP-metric with an evaluation year \( t_e=2080 \) reach 28.6–30.5\% (compared to 28.4–30.5\%).

We also examine a scenario that meets the CO\(_2\)-equivalent target through a 32\% reduction in CO\(_2\) emissions (from 2005 levels, by 2030), combined with natural gas leakage rate reductions, but uses less natural gas and more carbon-free electricity than scenario 1. We refer to this scenario as scenario 1.1. Using less natural gas leads to smaller required natural gas leakage rate changes and power sector CH\(_4\) emissions than under scenario 1. However, the amount of CH\(_4\) emissions mitigation needed under dynamic metrics to meet the 2030 CO\(_2\)-equivalent target can nevertheless be substantial. The electricity mix and the required emissions changes under scenario 1.1 are presented in figure S2 and in tables S1–S3.

**Detailed description of scenarios 2–9: Deeper CO\(_2\) cuts, no natural gas leakage rate reductions.** Scenarios 2–9 achieve the 2030 CO\(_2\)-equivalent target through CO\(_2\) reductions of more than 32\%. They require no natural gas leakage rate reductions. In scenarios 2–5 presented in the main article, these additional CO\(_2\) emissions reductions are achieved by reducing coal electricity generation relative to the amount in scenario 1. The depth of 2005–2030 CO\(_2\) emissions reductions is adjusted to offset CH\(_4\) emissions from natural gas electricity generation (which is held constant) in CO\(_2\)-equivalent terms. In contrast, scenarios 6–9 presented in tables S1–S3 achieve additional CO\(_2\) cuts by reducing natural gas electricity generation relative to scenario 1, instead of reducing coal electricity generation. Here the depth of the CO\(_2\) cuts is adjusted to offset CH\(_4\) emissions from coal electricity in CO\(_2\)-equivalent terms. In both scenario groups (2–5 and 6–9), individual scenarios differ by the metric used to convert CH\(_4\) emissions to CO\(_2\)-equivalent emissions.

Since each emissions equivalency metric assigns a different weight to power sector CH\(_4\) emissions in 2030, the electricity mix and the required percentage of CO\(_2\) reductions depend on the metric and on the natural gas leakage rate. Table S1 presents the electricity mix that allows achieving the 32\% CO\(_2\)-equivalent cut for low and high natural gas leakage rates to complement the results presented in figure 3 in the main article, which is based on high natural gas leakage rates. Table S2 presents CO\(_2\) and CH\(_4\) emissions cuts under all scenarios considered, and table S3 presents the corresponding target natural gas leakage rates. As shown in table S1, use of dynamic metrics results in more carbon-free power being required when natural gas leakage rates are high, and less when natural gas leakage rates are low. Using the GWP(100) metric, high natural gas leakage rates in the base year require less carbon-free power in the target year because the metric value is constant, and because a higher natural gas leakage rate results in a larger CO\(_2\)-equivalent budget in 2030.
Figure S2: 2030 electricity supply scenarios to meet the 2030 CO₂-equivalent target. Scenarios 1 and 1.1 combine a 32% CO₂ reduction over the 2005-2030 period with natural gas leakage rate (NG LR) mitigation. The amount of NG LR mitigation depends on the metric (see table S3 for target leakage rates in 2030), and on the electricity mix. In scenario 1, the electricity mix is based on a projection by the U.S. EPA [41]. In scenario 1.1, the 32% CO₂ reduction is achieved using less natural gas and more coal electricity generation as compared to scenario 1. Scenarios 2–9 meet the 2030 CO₂-equivalent target through CO₂ reductions that are deeper than 32%, requiring no NG LR changes relative to today. Scenarios 2–9 (2.1–9.1) assume a high (low) NG LR in the base year (2005) to define the emissions budget. Deeper CO₂ reductions are achieved through a shift away from coal electricity (scenarios 2–5 and 2.1–5.1) or natural gas electricity (scenarios 6–9 and 6.1–9.1) relative to scenario 1. Scenarios 6–9 require larger amounts of carbon-free power to meet the 2030 CO₂-equivalent target because a larger mass of 2030 CO₂-equivalent emissions (from coal) is held constant as compared to scenarios 2–5. The amount of carbon-free power depends on the metric and the NG LR, but a minimum 40% share is needed across all scenarios except scenario 1.1. Total estimated 2030 electricity supply is 4122 TWh in all scenarios, including a fixed contribution from hydroelectric electricity generation, nuclear fission, and other sources such as municipal waste [41]. Scenarios 1–5 are discussed in the main article.
Table S1: 2030 electricity scenarios to meet the 2030 CO\textsubscript{2}-equivalent target (a 32% reduction from 2005 levels). Scenarios 1 and 1.1 combine a 32% CO\textsubscript{2} cut with natural gas leakage rate (NG LR) mitigation. Scenario 1 achieves this CO\textsubscript{2} cut through a coal-to-gas transition (see main article), scenario 1.1 achieves the same CO\textsubscript{2} cut using less natural gas and more carbon-free power. Scenarios 2–9 meet the 2030 CO\textsubscript{2}-equivalent target through deeper CO\textsubscript{2} cuts than in scenario 1, and without reductions in the natural gas leakage rate. In scenarios 2–5, additional CO\textsubscript{2} cuts are achieved by reducing coal electricity relative to scenario 1. In scenarios 6–9, natural gas electricity is reduced instead and CO\textsubscript{2} and CH\textsubscript{4} emissions from coal held constant relative to scenario 1. Scenarios 6–9 require larger amounts of carbon-free power to meet the 2030 CO\textsubscript{2}-equivalent target because a larger mass of 2030 CO\textsubscript{2}-equivalent emissions (from coal) is held constant as compared to scenarios 2–5. Results for scenarios 2–9 (2.1–9.1) assume high (low) natural gas leakage rates. Lower leakage rates generally require smaller amounts of carbon-free power to meet the 2030 CO\textsubscript{2}-eq. target. Total estimated 2030 electricity demand is 4122 TWh in all scenarios, including a fixed contribution from hydroelectric and nuclear electricity generation, as well as other sources such as municipal waste [41]. Scenarios 1–5 are discussed in the main article.

| Scenario | Natural gas (TWh) | Coal (TWh) | Non-hydro renewables (TWh) |
|----------|------------------|------------|---------------------------|
| **Scenarios with a 32% CO\textsubscript{2} cut** | | | |
| Scenario 1: All metrics | 1368 | 1131 | 488 |
| Scenario 1.1: All metrics, lower NG use | 884 | 1292 | 811 |
| **Scenarios with deeper CO\textsubscript{2} cuts** | | | |
| Scenario 2: GWP(100), high NG LR | 1368 | 981 | 638 |
| Scenario 2.1: GWP(100), low NG LR | 1368 | 1045 | 574 |
| Scenario 3: GTP(t_e=2080), high NG LR | 1368 | 978 | 641 |
| Scenario 3.1: GTP(t_e=2080), low NG LR | 1368 | 1035 | 584 |
| Scenario 4: ICI(t_s=2050), high NG LR | 1368 | 734 | 885 |
| Scenario 4.1: ICI(t_s=2050), low NG LR | 1368 | 925 | 694 |
| Scenario 5: GTP(t_e=2050), high NG LR | 1368 | 648 | 971 |
| Scenario 5.1: GTP(t_e=2050), low NG LR | 1368 | 891 | 728 |
| Scenario 6: GWP(100), high NG LR | 1117 | 1131 | 739 |
| Scenario 6.1: GWP(100), low NG LR | 1091 | 1131 | 765 |
| Scenario 7: GTP(t_e=2080), high NG LR | 1084 | 1131 | 772 |
| Scenario 7.1: GTP(t_e=2080), low NG LR | 1109 | 1131 | 687 |
| Scenario 8: ICI(t_s=2050), high NG LR | 770 | 1131 | 1086 |
| Scenario 8.1: ICI(t_s=2050), low NG LR | 965 | 1131 | 891 |
| Scenario 9: GTP(t_e=2050), high NG LR | 719 | 1131 | 1137 |
| Scenario 9.1: GTP(t_e=2050), low NG LR | 915 | 1131 | 941 |
Table S2: Electricity sector emissions changes ($\Delta$CO$_2$, $\Delta$CH$_4$) and natural gas leakage rate changes ($\Delta$NG LR) to meet the 2030 CO$_2$-equivalent target. The reductions in power sector CH$_4$ emissions in column 3 ($\Delta$CH$_4$) apply equally to CH$_4$ from natural gas and CH$_4$ from coal. Scenarios with a greater than 32% CO$_2$ cut from 2005 levels, by 2030, require no changes in the natural gas leakage rate. If CH$_4$ emissions decline exponentially, these electricity sector emissions cuts meet the U.S. nationally determined contribution (NDC) to the Paris Agreement in 2025 (26–28% cut in CO$_2$-equivalent emissions from 2005 levels). Scenarios 1–5 are discussed in the main article.

| Scenarios | $\Delta$CO$_2$ | $\Delta$CH$_4$ | $\Delta$NG LR |
|-----------|----------------|----------------|--------------|
|           | 2005–2030      | 2014–2030      | 2005–2030    |
| Scenarios with a 32% CO$_2$ cut |               |                |              |
| Scenario 1: GWP(100) | -32%           | -19%           | -32%         |
| Scenario 1: GTP($t_c=2080$) | -32%           | -19%           | -61%         |
| Scenario 1: ICI($t_i=2050$) | -32%           | -19%           | -78%         |
| Scenario 1.1: GWP(100), lower NG use | -32%           | -19%           | -32%         |
| Scenario 1.1: GTP($t_c=2080$), lower NG use | -32%           | -19%           | -61%         |
| Scenario 1.1: ICI($t_i=2050$), lower NG use | -32%           | -19%           | -78%         |
| Scenarios with deeper CO$_2$ cuts |               |                |              |
| Scenario 2: GWP(100), high leakage | -35%           | -23%           | -1%          |
| Scenario 2.1: GWP(100), low leakage | -33%           | -20%           | -13%         |
| Scenario 3: GTP($t_c=2080$), high leakage | -36%           | -23%           | -1%          |
| Scenario 3.1: GTP($t_c=2080$), low leakage | -33%           | -21%           | -14%         |
| Scenario 4: ICI ($t_i=2050$), high leakage | -45%           | -34%           | -5%          |
| Scenario 4.1: ICI ($t_i=2050$), low leakage | -38%           | -26%           | -17%         |
| Scenario 5: GTP($t_c=2050$), high leakage | -48%           | -38%           | -6%          |
| Scenario 5.1: GTP($t_c=2050$), low leakage | -39%           | -27%           | -18%         |
| Scenario 6: GWP(100), high leakage | -34%           | -21%           | -12%         |
| Scenario 6.1: GWP(100), low leakage | -35%           | -22%           | +14%         |
| Scenario 7: GTP($t_c=2080$), high leakage | -35%           | -22%           | -14%         |
| Scenario 7.1: GTP($t_c=2080$), low leakage | -33%           | -20%           | -18%         |
| Scenario 8: ICI ($t_i=2050$), high leakage | -40%           | -29%           | -34%         |
| Scenario 8.1: ICI ($t_i=2050$), low leakage | -37%           | -25%           | -26%         |
| Scenario 9: GTP($t_c=2050$), high leakage | -41%           | -30%           | -38%         |
| Scenario 9.1: GTP($t_c=2050$), low leakage | -38%           | -26%           | -28%         |

Electricity demand uncertainties. Future electricity demand is a source of additional uncertainty when projecting emissions. All scenarios discussed in the main article and the SI assume a slow increase in electricity demand based on a projection by the EPA [41], with total annual demand reaching 4122 TWh in 2030, as compared to 4093 TWh in 2014. For scenarios that meet the 2030 CO$_2$-equivalent target through a 32% reduction in CO$_2$ emissions combined with natural gas leakage rate reductions, changing electricity demand in 2030 does not alter our main conclusions. This insensitivity results from natural gas
Table S3: Target leakage rates in 2030 for all scenarios. Scenario 1 and 1.1 combine a 32% reduction in power sector CO\textsubscript{2} emissions (from 2005 levels, by 2030) with reductions in the natural gas leakage rate in order to meet the 2030 CO\textsubscript{2}-equivalent target. Target leakage rates are shown for low to high natural gas leakage rates assumed in the emissions model. For each case we show a range covering a 85–95% CH\textsubscript{4} content in natural gas (a lower CH\textsubscript{4} content leads to higher leakage rates due to a smaller number in the denominator of the leakage rate). In scenarios 2–9, CO\textsubscript{2} emissions are reduced by more than 32% from 2005 levels, by 2030, to meet the 2030 CO\textsubscript{2}-equivalent target without reductions in the natural gas leakage rate. The range of target (2030) leakage rates therefore equals the 2014 range of leakage rates, and applies to all metrics. Scenarios 1–5 are discussed in the main article.

| Scenarios          | Target leakage rate, low 2030 | Target leakage rate, high 2030 |
|--------------------|--------------------------------|--------------------------------|
| Scenario 1, GWP(100) | 0.89–1.0%                      | 2.61–2.92%                     |
| Scenario 1, GTP(\text{te}=2080) | 0.52–0.58%               | 1.51–1.69%                     |
| Scenario 1, GTP(\text{te}=2050) | 0.29–0.32%               | 0.84–0.94%                     |
| Scenario 1.1, GWP(100) | 0.17–0.19%                      | 0.52–0.58%                     |
| Scenario 1.1, GWP(\text{te}=2080) | 1.40–1.57%               | 4.11–4.59%                     |
| Scenario 1.1, GTP(\text{te}=2050) | 0.81–0.91%               | 2.40–2.66%                     |
| Scenario 1.1, GTP(\text{te}=2050) | 0.45–0.51%               | 1.33–1.48%                     |
| Scenario 1.1, GTP(\text{te}=2050) | 0.28–0.31%               | 0.82–0.92%                     |
| Scenarios 2–9 and 2.1–9.1 | 1.50–1.68%                      | 4.39–4.91%                     |

leakage rate reductions being primarily determined by the 32% CO\textsubscript{2} emissions reduction and by the CO\textsubscript{2}-equivalent target. If CO\textsubscript{2}-emitting generation were reduced commensurate with lower demand, CO\textsubscript{2} reductions would be greater than 32% over the 2005–2030 period. Conversely, if CO\textsubscript{2}-emitting generation were increased commensurate with higher demand, CO\textsubscript{2} reductions would be less than 32% over the 2005–2030 period. Thus, since the scenario is designed to achieve a 32% reduction in CO\textsubscript{2} emissions, lower (higher) demand would need to take the form of smaller (larger) amounts of carbon-free generation, and required natural gas leakage rate changes would be very similar to those in scenario 1 or 1.1.

For scenarios that meet the 2030 CO\textsubscript{2}-equivalent target through deeper CO\textsubscript{2} reductions, the depth of additional CO\textsubscript{2} emissions reductions depends on the amount of additional 2030 electricity demand (that in excess of 4122 TWh) met by fossil fuels. In these scenarios, a limit is reached when the overshoot of the 2030 CO\textsubscript{2}-equivalent budget cannot be compensated by deeper CO\textsubscript{2} emissions reductions. This limit is reached when, for instance, excess masses of CO\textsubscript{2}-equivalent emissions from natural gas CH\textsubscript{4} emissions in 2030 in scenarios 2–5, are larger than CO\textsubscript{2} emissions from coal generation in 2030. Compensating for all excess natural gas CH\textsubscript{4} emissions in CO\textsubscript{2}-equivalent terms would then require carbon dioxide capture and storage to achieve a reduction in CO\textsubscript{2} emissions below zero. However, since the smallest amount of coal generation (scenario 5) is roughly 650 TWh in 2030, the strategy applied in scenarios 2–9 should be applicable even if 2030 electricity demand exceeds our estimate by 10%.  

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4 Effect of other regulated greenhouse gases

The U.S. nationally determined contribution (NDC) to the Paris Agreement includes carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O) emissions, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF$_6$), and nitrogen trifluoride (NF$_3$). The energy sector is a main contributor to CO$_2$ and CH$_4$ emissions, which we discuss in the main article, and to N$_2$O emissions, which we examine here. We perform a sensitivity analysis in which we include N$_2$O emitted during the combustion of coal and natural gas for electricity generation [44] and estimate changes to these emissions due to changes in the electricity supply mix in our modeled scenarios. The goal of this sensitivity analysis is to examine whether N$_2$O emissions preclude natural gas leakage rate reductions’ ability to achieve a 32% reduction in power sector CO$_2$-equivalent emissions over the period 2005–2030.

We estimate that CO$_2$-equivalent emissions cuts are 32.04–32.06% over the 2005–2030 period under all scenarios considered when including N$_2$O in the analysis. The emission cut is larger than 32% because estimated N$_2$O emissions are larger in 2005 than they are projected in 2030, and therefore add more to the allowable CO$_2$-equivalent emissions budget in 2030 (which is equal to 2005 emissions minus 32%) than they remove.

The electricity sector is also a major contributor to SF$_6$ emissions from power transmission and distribution systems. These emissions have significantly decreased over the past three decades [1] due to increased awareness and the use of alternative gases in switching technologies. Including SF$_6$ emissions in our analysis would allow for higher power sector CO$_2$-equivalent emissions. We omit this calculation here because it would require a projection of 2030 SF$_6$ emissions, which cannot be based directly on projected fuel consumption levels as is possible in the case of N$_2$O.

5 Temperature impacts

The temperature model is described in the methods section of the main article. Here we present radiative forcing (RF) impacts of different CO$_2$ and CH$_4$ emissions mitigation scenarios that meet the 2030 CO$_2$-equivalent goal (a 32% reduction from 2005 levels). We also examine temperature impacts for a range of equilibrium climate sensitivities (ECS) and discuss the effects of choosing different atmospheric lifetimes for CH$_4$.

Figure S3 shows the RF increase resulting from CO$_2$ and CH$_4$ emissions in scenarios 2–5 relative to the IPCC’s representative concentration pathway 2.6 (RCP2.6) [34]. Figure S4 shows the temperature increase for the same scenarios and a range of ECS values (figure 5 in the main paper is based on the results for an ECS value of 2.5 °C.) We assume that CO$_2$ and CH$_4$ emissions cease in 2030. Deeper CO$_2$ emissions cuts (figures S3b, S3d) provide more persistent RF reductions as compared to a 32% reduction in CO$_2$ emissions combined with natural gas leakage rate reductions (figures S3a, S3c). Compared to using the GWP(100) to implement the 2030 target, dynamic metrics (ICI, GTP) result in up to twice the RF reduction from a no-policy scenario. CO$_2$ and CH$_4$ emissions under scenarios 6–9 are similar to those in scenarios 2–5 and thus these scenarios produce similar temperature profiles (not shown here).
Figure S3: Radiative forcing increase over RCP 2.6 due to power sector CO$_2$ and CH$_4$ emissions that comply with the 2030 CO$_2$-equivalent target. (a, c) A 32% CO$_2$ reduction from 2005 by 2030 combined with natural gas leakage rate reductions causes less persistent radiative forcing reductions from a no-policy scenario [41] (black) compared to (b, d) deeper CO$_2$ cuts and no reductions in the natural gas leakage rate between 2014 and 2030 (ICI(t$_s$=2050), red, GTP(t$_e$=2080), light blue, GTP(t$_e$=2080), green, GWP(100), magenta). Results are shown for (a, b) high and (c, d) low natural gas leakage rates. Choosing the ICI or the GTP(t$_e$=2050) can double radiative forcing reductions from the no-policy scenario compared to the GWP(100). All emissions cease after 2030 (grey shaded area).

Equilibrium climate sensitivity. We use an ECS of 2.5 $^\circ$C to compute the results presented in the main paper. This value was chosen based on a series of recent studies that compare ECS values generated by Atmosphere-Ocean General Circulation Models (AOGCMs) (like those presented in the CMIP5 study) to models based on observational records and energy budgets and tend to find lower ECS values, e.g. 2 $^\circ$C in [45]. A recent study cites 2.5 $^\circ$C as the current best estimate after incorporating the full observational temperature record between 1765 and 2011 [46]. The results in [46] accurately reproduce observed surface temperatures including the recent slow-down of warming (‘hiatus’). Nevertheless, substantial uncertainties remain and the short time-frame over which a slower warming rate has been observed require the consideration of a broad range of ECS values. In figure S4 we therefore reproduce temperature results for the lower and upper bounds of the ECS range presented as ‘likely with high confidence’ in IPCC’s AR5 (1.5-4.5 $^\circ$C). The results we highlight are based on relative not absolute differences between temperature impacts. Differences between temperature reductions that result from a given policy scenario and the no-policy scenario are insensitive to the ECS value employed. Using a linearized impulse response function to model
the temperature change due to radiative forcing changes (see equation (16) in methods, main article) implies that any change in ECS corresponds to a linear scaling factor proportional to the ratio of a modified (4.5 or 1.5 °C) to a central case ECS value (2.5 °C). For a high ECS value of 4.5 °C, for instance, more stringent metrics like the GTP(t_e=2050) and the ICI metric can allow for 1.5 to 1.9 times as much temperature increase to be avoided than the GWP(100) (the range covers both low and high CH_4 emissions), as compared to 1.7 to 1.9 times as much for an ECS value of 2.5 °C. The equivalency metric–dependent ranking of temperature reductions is consistent across the range of ECS values recommended by the IPCC. The ICI achieves the largest reduction, the GTP(t_e=2050) the second largest, the GTP(t_e=2080) the third largest and the GWP(100) the smallest reduction from the no-policy scenario.

**Choice of representative concentration pathway.** In the main paper, avoided temperature increase is calculated using the IPCC’s RCP2.6 as baseline. CO_2 and CH_4 emissions pathways (interpolated based on figure 4 in the main text) are added to total GHG emissions in RCP 2.6. The temperature increase resulting from CO_2 and CH_4 emissions under various scenarios is then compared to the temperature increase in a no-policy scenario with higher power sector CO_2 and CH_4 emissions added to the RCP 2.6 pathway. Given the similarity of all four representative IPCC concentration pathways until 2030, and the time lag between concentration change and temperature response, the CO_2 and CH_4 emissions pathways added have a greater influence on 2030 temperature change than the RCP used as a baseline. For the small resulting changes in CO_2 and CH_4 concentration, radiative efficiency remains roughly constant, so any RCP could be chosen.

**CH_4 lifetime.** The temperature results shown in figure S4 are based on the steady state lifetime of CH_4 (9.1 years [47]), while the emissions equivalency metrics use the perturbation lifetime of CH_4 (12.4 years). Estimated lifetimes based on more complex climate models fall in between the assumed steady state lifetime of 9.1 and the perturbation lifetime of 12.4 years [48]. By taking this approach, we follow the convention defined by the IPCC’s AR5 for metric calculations, but choose a ‘conservative’ CH_4 lifetime to avoid overvaluing the influence of CH_4 reductions on warming. However, the effect of employing the longer CH_4 lifetime on the temperature increase is shown in figure S4. Using the perturbation lifetime of CH_4 (12.4 years) in our model leads to a temperature increase (relative to RCP 2.6) that is 1–5% higher than that for a steady state CH_4 lifetime of 9.1 years shown in figure S4. (The smallest difference (1%) is observed for the CH_4 mitigation scenario (scenario 1) under the ICI and a low natural gas leakage rate, and the largest difference (5%) is observed for the no-policy scenario.) The choice of ECS has a much larger effect than that of the CH_4 lifetime.
Figure S4: Temperature increase from RCP2.6 due to CO₂ and CH₄ emissions under a 32% reduction in CO₂-equivalent emissions, shown for equilibrium climate sensitivities (ECS) of 1.5, 2.5 and 4.5 °C. (a, c) A 32% reduction of power sector CO₂ emissions by 2030 combined with natural gas leakage rate reductions leads to less persistent temperature reductions from a no-policy scenario [41] (black) as compared to (b, d) deeper CO₂ reductions. Using the ICI(tₑ=2050), red, or the GTP(tₑ=2050), light blue, to compute CH₄ and CO₂ emissions pathways can double temperature reductions from the no-policy scenario compared to the GWP(100), magenta, and the GTP(tₑ=2050), green. This holds across different ECS choices. The highest ECS considered (4.5 °C) raises the maximum temperature increase by about 80% compared to the value used in the main article (2.5 °C). Results are shown for for high (a/b, dashed lines) and low (c/d, solid lines) natural gas leakage rates. The ECS range of 1.5 to 4.5 °C was considered as likely with high confidence in IPCC’s AR5 [34]. We assume that all CO₂ and CH₄ emissions cease in 2030 (grey shaded area).

6 Alternative policy examples

The main article examines scenarios where CO₂ reductions of 32% or more are pursued in the power sector to achieve a 32% reduction in CO₂-equivalent emissions in the year 2030 (from 2005 levels). However, the CO₂-equivalent emissions target, the target year, and the emissions reduction strategies (whether to focus on reductions of CO₂ emissions or other greenhouse gases) are uncertain. While this is true for any future target in any country, uncertainties may be particularly important in a U.S. context following the Supreme Court’s decision to stay the implementation of the Clean Power Plan, and the Trump administration’s announcement in 2017 to exit the Paris Agreement [49,50]. We therefore discuss alternative
policy examples for the U.S. case in more detail after examining a general case of a country or sector trying to meet a CO₂-equivalent target. We conclude with examples of other countries.

**General case.** As shown in equation (1) (which is the same as equation (14) in Methods, main article), the fractional cut \( p_M \) over the period \( t - t' \), where \( t \) is the base year of a policy (e.g. 2005) and \( t' \) is the target year (e.g. 2030), can be written as a function of the ratio of CO₂ emissions and CH₄ emissions \( \frac{e_K(t)}{e_M(t)} \) in the base year, of the change in the metric values used for CH₄ in base and target years \( \frac{\mu(t)}{\mu(t')} \), and of the fractional emissions targets for CO₂ and CO₂-equivalent emissions \( p_K, p \).

\[
p_M(t, t') = 1 - \left[ \frac{1}{\mu(t')} \cdot \frac{e_K(t)}{e_M(t)} \cdot (p_K(t, t') - p(t, t')) + \frac{\mu(t)}{\mu(t')} \cdot (1 - p(t, t')) \right] \tag{1}
\]

The first case we consider in the main article (scenario 1) is one with equal fractional reduction targets for total CO₂ and CO₂-equivalent emissions \( p_K = p \). CO₂ emissions can be cut by a maximum of 100% \( p_K = 1 \). Thus, for any CH₄ metric that increases over time, the fractional cut in CH₄ emissions from the base year or a policy will be greater than the fractional cut in CO₂ emissions \( p_M > p_K \). Reductions relative to the start year, \( p_{M, start} \) will be lower than \( p_M \) only if CH₄ emissions have declined between the base and start year (compare CH₄ cuts over the 2005-2030 period to those over the 2014–2030 period in table S2).

In the second case, the reduction in CO₂ emissions is larger than the reduction in CO₂-equivalent emissions (see scenarios 2–9, tables S1–S3). The first term in the bracket will be positive and its contribution to the fractional cut in CH₄ negative. Thus, \( p_M \) increases if 1) \( e_M \) decreases, 2) the change in metric values increases, and 3) the fractional CO₂-equivalent cut increases.

The third case is where the CO₂-equivalent target is more stringent than the CO₂ cut. The first term in the bracket will be negative, thereby increasing the fractional cut in CH₄ emissions in proportion to the difference between fractional CO₂ and CO₂-equivalent cuts.

**Alternative U.S. policy examples.** Here we discuss the effects of different policy uncertainties on our conclusions regarding CH₄ mitigation requirements in the U.S. and provide selected quantitative examples.

- **Depth of CO₂-equivalent target.** For fixed CO₂ emissions reductions, any less (more) ambitious CO₂-equivalent target would also lower (increase) the need for CH₄ mitigation. However, a less ambitious CO₂-equivalent target could also slow CO₂ reductions. For instance, the U.S. EIA projects that in 2025 natural gas electricity use will be similar in a ‘no Clean Power Plan’ case (1282 TWh) and a Clean Power Plan (CPP) case (1310 TWh). However, the no CPP case includes 10% higher coal use for electricity production (1406 TWh as compared to 1256 TWh) \[43\]. CO₂ emissions are therefore higher than in the CPP case. 2025 electricity sector CO₂-equivalent emissions would reach an estimated 16–19% reduction from 2005 levels (the CO₂ cut is 20%), where the lower end of this range is based on using the ICI metric, while the upper end is based on the GWP(100). Results based on other emissions equivalency metrics fall
within this range. Thus, reaching equal CO$_2$ and CO$_2$-equivalent cuts (of e.g. 20%) would again require reductions in the natural gas leakage rate.

- **Emissions reductions used to achieve a CO$_2$-equivalent target.** Since CO$_2$-equivalent emission cuts in the above case would fall short of the 26–28% target set in the U.S. NDC to the Paris Agreement [51] for 2025 (the base year is 2005), either deeper CO$_2$ cuts or additional CH$_4$ cuts would be needed. Assuming zero CH$_4$ leakage in 2025 (a 100% reduction in the natural gas leakage rate) results in a reduction in electricity sector CO$_2$-equivalent emissions of 19% (ICI) to 24% (GWP(100)) by 2025, from 2005 levels. Although the CO$_2$-equivalent target might be almost met using the GWP(100), differences in the long-term and peak temperature effects between a CO$_2$- and a CH$_4$-focused strategy will be important to consider. Early reductions in short-lived climate pollutants like CH$_4$ can reduce near-term temperature increase but cannot substitute for CO$_2$ cuts needed to mitigate peak and long-term warming [52,53].

- **Timing of CO$_2$-equivalent target.** Here we compute natural gas leakage rate reductions for a CO$_2$-equivalent emissions target set for the year 2025 instead of the year 2030, as is consistent with the target year of the U.S. NDC [51]. In 2025, for a 28% cut in CO$_2$-equivalent emissions, the required changes in the natural gas leakage rate range between roughly 30 and 80% from 2014 levels (compared to 40–90% in 2030 in scenario 1). The low end is based on using the GWP(100) metric, the high end on using the ICI metric. Corresponding reductions in total electricity CH$_4$ emissions range between 28% (GWP(100), same as CO$_2$ cut) and 80% (ICI) from 2005 levels, by 2025. The NDC target is also met in our scenarios in the main paper, if an exponential decline towards target natural gas leakage rates in 2030 is assumed.

Based on these results, the qualitative conclusions drawn in the main paper apply across a range of policy cases, which differ from the scenarios in the main article in terms of ambition and timing. We further illustrate this robustness by computing rough estimates of CH$_4$ emissions changes needed to meet CO$_2$ equivalent emissions targets in non-U.S. countries.

**Examples from other countries.** Table S4 shows fractional reductions in electricity sector CH$_4$ emissions to meet CO$_2$-equivalent targets in two countries with substantial production and use of natural gas: the United Kingdom and Australia. To compute the fractional CH$_4$ cut over the 2014–2030 period we set fractional CO$_2$ emissions reductions equal to fractional CO$_2$-equivalent cuts, as done for the U.S. case. For the UK case, we assume a 57% emissions cut from 1990 levels, by 2030, which reflects the government’s fifth carbon budget for the 2028-2032 period [54]. For Australia, we take the mid-range value from the country’s NDC target, a 26–28% reduction in economy-wide CO$_2$-equivalent emissions by 2030, from 2005 levels (a 19% cut from 2014 levels) [55]. Emissions data are taken from national greenhouse gas inventories and government emission statistics [56–58]. We use the ICI metric to bound the maximum CH$_4$ cuts needed from 2014 levels. Results under all other metrics whose values are presented in figure 2a in the main paper fall into the range between ICI-based fractional reductions and static metric–based CH$_4$ reductions. We find that the results obtained for the UK and Australia are comparable to those obtained for the U.S.
Table S4: Fractional CO$_2$ and CH$_4$ emission cuts over the 2014–2030 period $(p_{K,t_0,t'}, p_{M,t_0,t'})$ to meet 2030 CO$_2$-equivalent targets in selected countries.

| Country            | $p_{K,t_0,t'}$ | $p_{M,t_0,t'}$ |
|--------------------|----------------|----------------|
| U.S.               | 0.19           | 0.86           |
| United Kingdom     | 0.30           | 0.82           |
| Australia          | 0.23           | 0.86           |

As discussed in the main article and in section 1 of the Supplementary Information for the U.S. case, CH$_4$ emissions from coal mining and natural gas systems carry substantial uncertainty. A detailed analysis of the effects of various uncertainties in other countries is beyond the scope of this work. We therefore view the numbers given in table S4 as rough estimates used to illustrate that reductions of CH$_4$ emissions may be important also for other natural gas–using countries in order to meet CO$_2$-equivalent emissions targets.
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