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# Evolution of Near-Term Atmospheric Methane and Associated Temperature Response Under the Global Methane Pledge: Insights From an Earth System Model

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**Key Points:**

- Current Global Methane Pledge cuts only 10% of anthropogenic emissions by 2030, far below the 30% target
- Maximum technically feasible reductions are needed to meet climate goals
- Arctic gains most, with up to 2°C less warming under stronger methane cuts

**Supporting Information:**

Supporting Information may be found in the online version of this article.

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## Abstract

Methane is a powerful greenhouse gas with a shorter lifetime than carbon dioxide ($CO_2$), making it an important target for near-term climate action. The Global Methane Pledge (GMP) aims to cut anthropogenic methane emissions by 30% from 2020 levels by 2030. Using an Earth system model with interactive $CH_4$ sources and sinks, we assess the Pledge's impact through 2050. Results show that current GMP commitments deliver only a 10% cut by 2030—well below the target. Only the maximum technically feasible reduction (MTFR) pathway can achieve the 30% goal. By 2050, current GMP commitments lowers methane concentrations by 3% relative to 2025, while MTFR achieves 8%. Both pathways slow warming slightly, avoiding about 0.1°C of global temperature rise, with the Arctic seeing the greatest benefits (up to 2°C less warming). Without wider participation, the GMP with current signatories will fall short of its targets and Paris Agreement goals.

## Plain Language Summary

Methane ($CH_4$) is a powerful greenhouse gas that warms the planet more strongly than carbon dioxide ($CO_2$) but lasts for a shorter time in the atmosphere. Because of this, cutting methane emissions can deliver fast climate benefits. The Global Methane Pledge (GMP) was launched to cut human-caused methane emissions by 30% from 2020 levels by 2030. This study used a climate model to test whether the GMP can reach its target. Results show that today's GMP commitments would only achieve a 10% cut by 2030-well short of the goal. By 2050, GMP leads to a 3% drop in methane concentrations, avoiding about 0.1°C of global temperature rise, with the Arctic gaining the most benefit. However, without more countries joining in-especially the largest emitters-the GMP may not meet its goals or align with Paris Agreement climate limits.

## 1. Introduction

Methane ($CH_4$) is a powerful greenhouse gas with a global warming potential about 28 times that of carbon dioxide ($CO_2$) over a 100-year timeframe (IPCC, 2023), and a relatively short atmospheric lifetime of roughly a decade (IPCC, 2023). $CH_4$ currently contributes a disproportionate share of anthropogenic warming (~25%–30%) (UNEP & CCAC, 2021). IPCC's Sixth Assessment Report finds that strong, rapid and sustained methane mitigation would significantly limit near-term global warming and improve air quality by reducing tropospheric ozone formation (IPCC, 2023), yielding climate benefits much more quickly than $CO_2$ reductions, and helping keep the Paris Agreement's 1.5°C target. UNEP's Global Methane Assessment found that a 45% reduction in human-caused $CH_4$ emissions by 2030 could avert nearly 0.3°C of global warming by the 2040s (UNEP & CCAC, 2021). Even the more modest goal of the Global Methane Pledge (GMP)—a 30% cut in $CH_4$ emissions by 2030—would avoid at least ~0.2°C of warming by 2050 (UNEP & CCAC, 2021).

The GMP is an international initiative to operationalize these science-based insights into policy action. Launched at the 26th Conference of the Parties in 2021, the GMP is non-binding and without country-specific quotas, and

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now has over 158 signatory countries collectively aiming to cut global $CH_4$ emissions by at least 30% below 2020 levels by 2030 (UNEP & CCAC, 2021). However, some large emitting countries, including China, India, Russia, and South Africa, responsible for much of the remaining 45% of global $CH_4$ emissions are currently not signatories. Participants agreed to develop national Methane Action Plans (MAPs) or roadmaps outlining mitigation policies across major $CH_4$-emitting sectors (energy, agriculture, and waste). As of April 2024, 12 countries (Brazil, Canada, China, Finland, Iceland, Netherlands, Norway, Republic of Korea, United Kingdom, USA, and Vietnam) plus the European Union had submitted detailed MAPs to the Climate and Clean Air Coalition (UNEP & CCAC, 2024). Analyses suggest that fully implementing the MAPs already identified in Nationally Determined Contributions to their maximum technical potential could achieve roughly a 30% global reduction, meeting the GMP goal. Available technologies could eliminate a large fraction of $CH_4$ emissions cost-effectively (e.g., up to 75% of methane from oil and gas operations can be abated with existing methods, roughly half at no net cost) (UNEP & CCAC, 2021). Recent research showed that $CH_4$ reductions could reduce climate-related damages in 2050 by more than a trillion dollars a year while costing only one sixth of the damages they would avoid (Stoerk et al., 2025).

Earth system models (ESM) are principal tools to assess the impacts of climate mitigation on the global and regional scale. In most cases, ESMs use prescribed atmospheric $CH_4$ concentration pathways; however, it is important to account for sources and sinks of $CH_4$ when assessing its impacts and future evolution (D. Shindell et al., 2024). Of all the ESMs that contributed to the Coupled Model Intercomparison Project Phase 6 (CMIP6: Eyring et al., 2016), only one—the NASA Goddard Institute for Space Studies (GISS) chemistry–climate model version E2.1 (GISS-E2-1-G: Kelley et al., 2020; Im, Tsigaridis, et al., 2025)—used interactive $CH_4$ emissions and chemistry. Since CMIP6, more ESMs have developed interactive $CH_4$ sources, including UK-ESM1 (Folberth et al., 2022), and EMAC (Stecher et al., 2025).

To date, very few studies assessed the impacts of the Pledge. Cael and Goodwin (2023) used an emulator to quantify the difference in global annual mean surface temperature of the GMP versus the equivalent amount of $CO_2$ emission reduction and found that the GMP initially results in greater relative cooling than the avoidance of the equivalent amount of $CO_2$ emissions over the same period. Predybaylo et al. (2025) used the EMAC model with interactive $CH_4$ emissions and found that reducing $CH_4$ emissions decelerates global warming through changes in radiative fluxes and shortening the lifetime of tropospheric $CH_4$ and other gases, as well as leading to air quality improvement from a reduction of surface ozone. These studies assumed a specific percentage of global reduction in $CH_4$ emissions. To our knowledge, our study is the first study that uses an ESM (GISS-E2.1-G) with interactive $CH_4$ sources to evaluate the impacts of the Pledge and the MAPs, using realistic emission projections based on the current status of the participation in the Pledge and/or MAPs.

## 2. Materials and Methods

We used the GISS-E2.1-G ESM (Kelley et al., 2020), with a horizontal resolution of 2° latitude by 2.5° longitude and 40 vertical layers extending from the surface to 0.1 hPa in the lower mesosphere. GISS-E2.1-G includes inorganic tropospheric chemistry of Ox, NOx, HOx, CO, and organic chemistry of $CH_4$ (D. T. Shindell et al., 2013) and higher hydrocarbons using the CBM-IV scheme (Gery et al., 1989). $CH_4$ is only removed by oxidation via the hydroxyl radical (OH) and the soil sink. Other important chemical $CH_4$ sinks such as chlorine (Basu et al., 2022) are not included in the GISS-E2.1-G as tropospheric halogens are not part of the model (Im, Tsigaridis, et al., 2025).

$CH_4$ emissions from wetlands in GISS-E2.1-G are calculated online using upper layer soil temperature and precipitation anomalies (D. T. Shindell et al., 2003, 2004), with prescribed wetland locations and is lumped with $CH_4$ emissions from tundra (D. T. Shindell et al., 2013), which are then modified by the emissions model (D. T. Shindell et al., 2003). In addition, in the present study, the wetland emissions, which are very uncertain and comprise the largest contribution among the natural emissions (Saunois et al., 2025), have been tuned by a factor calculated to get a similar burden and lifetime as in the prescribed simulations (Im et al., 2021; Im, Tsigaridis, et al., 2025) during the historical period (1995–2023) in order to better follow the global observations (Saunois et al., 2020). This tuning approach does not consider the changes in OH or regional differences in $CH_4$ emissions and concentrations but improves the model performance by getting closer to the observed global $CH_4$ concentrations. The calculated wetland tuning factor for the 1995–2014 period is then applied also in the future period 2015–2050.

**Table 1**
*Emission Scenarios Used in the Present Study*

| Scenarios | Period | Perturbed emissions |
|---|---|---|
| Recent past (CLE) | 1990–2014 | No perturbation—Historical baseline |
| CLE | 2015–2050 | No perturbation—2015–2050 baseline |
| GMP | 2025–2050 | Anthropogenic + biomass burning $CH_4$ |
| MAP | 2025–2050 | Anthropogenic + biomass burning $CH_4$ |
| POL | 2025–2050 | Anthropogenic + biomass burning $CH_4$ |
| MTFR | 2030–2050 | Anthropogenic + biomass burning $CH_4$ + other SLCPs |

We used anthropogenic emissions from IIASA's GAINS model version 2.1 (Klimont et al., 2025). These are recent updates of emission scenarios for $CH_4$ described in more detail by Höglund-Isaksson (2012) and Höglund-Isaksson et al. (2020, 2023) and for air pollutants (International Institute for Applied Systems Analysis ECLIPSE scenarios) described in Stohl et al. (2015), and in our Supporting Information S1. Methods and assumptions for bottom-up estimation of sector-level $CH_4$ emissions in GAINS are documented in the Supplementary materials of Höglund-Isaksson (2012, 2017), Höglund-Isaksson et al. (2020, 2023), and Gómez-Sanabria et al. (2022). A comparison of global anthropogenic $CH_4$ emissions in year 2020 across recent studies (Figure S1 in Supporting Information S1) shows that the GAINS estimate of 350 Tg yr$^{-1}$ falls well within the range of 325–364 Tg yr$^{-1}$ of other independently produced bottom-up (BU) inventories, that is, EDGAR (Crippa et al., 2024), CEDS (Hoesly et al., 2024) and USEPA (2019, 2025). The Global Carbon Project (Saunois et al., 2025) presents global anthropogenic $CH_4$ emissions in year 2020 ranging between 345 and 409 Tg yr$^{-1}$ across referenced BU inventories and between 368 and 409 across top-down (TD) inverse model results. While EDGAR, CEDS, and USEPA (2025) estimate lower anthropogenic emissions of fossil origin than the TD range of 101–133 Tg yr$^{-1}$, GAINS and USEPA (2019) fall within the TD range.

The Current Legislation (CLE) scenario (2015–2050) assumes efficient implementation of current $CH_4$, and air pollution legislation enacted before 2018. The Maximum Technical Feasible Reduction (MTFR) scenario assumes full implementation of best available emission reduction technologies and practices. Further details on assumptions for the CLE and MTFR scenarios for $CH_4$ can be found in Höglund-Isaksson et al. (2020). In addition, three intermediate scenarios were developed for this study reflecting different levels of compliance with adopted $CH_4$ policy frameworks. The GMP scenario reflects future emissions when all GMP signatories jointly follow through on the Pledge, thus reducing their anthropogenic $CH_4$ emissions by 30%, and non-signatory countries continue along the CLE scenario trajectory. The MAP scenario is a model interpretation of the impact on future $CH_4$ emissions from full implementation of the measures mentioned in the MAPs, and assuming all countries having not submitted a MAP continue along the CLE scenario trajectory. The Full Policy scenario (POL) combines the GMP and MAP scenarios, that is, GMP signatory countries meet the pledged target and all measures mentioned in the MAPs are fully implemented.

We carried out five sets of fully-coupled simulations (Table 1), each consisting of three ensemble members, and initialized from fully coupled recent past simulations to ensure a smooth continuation from recent past to future. GMP, MAP, and POL scenarios only perturb anthropogenic $CH_4$, while the MTFR scenario also reduces other short-lived climate pollutants (SLCP) along with $CH_4$. Other greenhouse gases than $CH_4$, that is, $CO_2$ and $N_2O$, are prescribed using global annual mean concentrations used in CMIP6. All simulations have been performed at the LUMI supercomputer (https://lumi-supercomputer.eu/). One simulation year takes 6.33 hr, giving 6.6 days simulation time for one ensemble member for the recent past simulation, 9.5 days for one CLE simulation, 6.9 years for GMP, MAP, and POL simulations each, and 5.5 days for an MTFR simulation.

## 3. Results

Anthropogenic $CH_4$ emissions continue to increase in the baseline (CLE) scenario, while the MAP scenario initially leads to a small emission reduction, but then continues to increase (Figure 1a). The (current status) GMP scenario leads to a reduction of 10% by 2030 in global anthropogenic $CH_4$ emissions, to 314 Tg $CH_4$ yr$^{-1}$, however, does not reach the GMP target level of 30% below the 2020 level (245 Tg $CH_4$ yr$^{-1}$). The POL scenario, which is the combination of GMP and MAP leads to a slightly larger reduction (to 307 Tg $CH_4$ yr$^{-1}$) than GMP

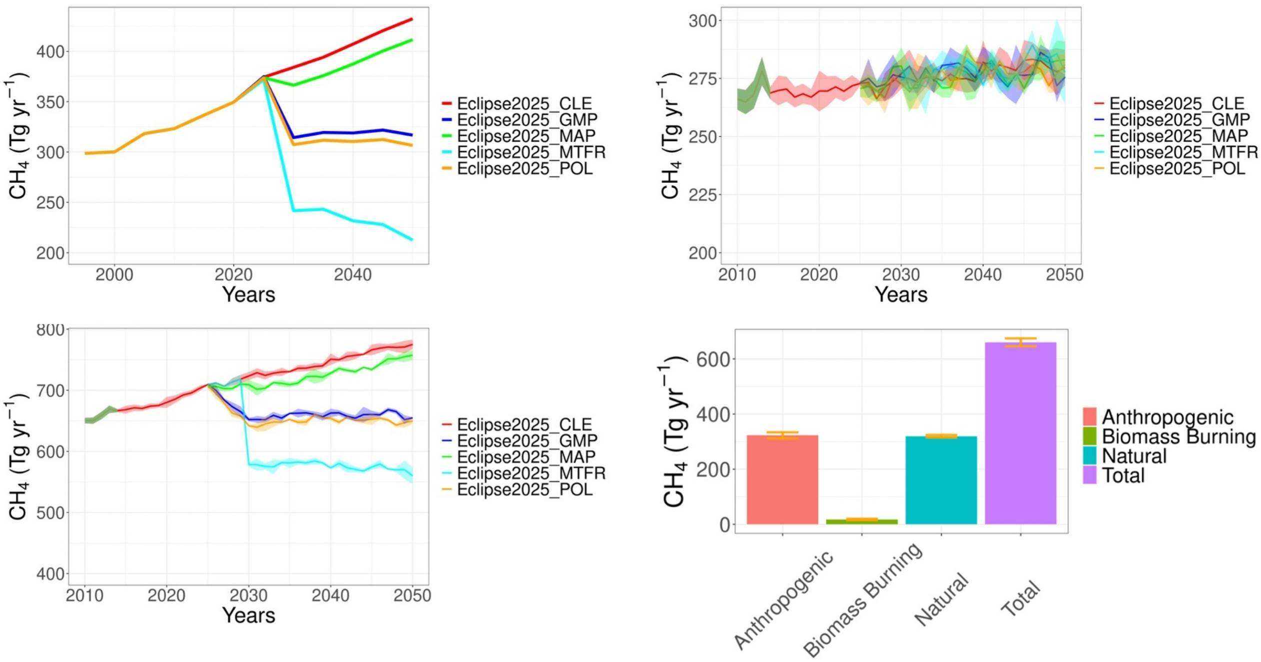


**Figure 1.** Global anthropogenic (a), wetland (b) and total (c) $CH_4$ emissions in the 2010–2050 period, and the 2000–2015 mean break down of global $CH_4$ emissions in anthropogenic, biomass burning, natural (wetlands and tundra, termites, ocean), with yellow bars indicating standard deviation (d).

alone but still cannot achieve the GMP target value. Only the MTFR scenario can fulfill the Pledge's emission reduction objective, leading to a reduction to 242 Tg $CH_4$ $yr^{-1}$. Therefore, the MTFR scenario corresponds, approximately, to full fulfillment of the Pledge, also in agreement with the 30% reduction scenarios implemented in Predybaylo et al. (2025).

As wetland $CH_4$ emissions continue to increase slightly in all simulations (Figure 1b), the total emissions (Figure 1c) follow a very similar trend to that of the anthropogenic emissions. The natural annual $CH_4$ emissions (320 ± 5 Tg $CH_4$ $yr^{-1}$) averaged over the 2000–2015 period, dominated by the wetland $CH_4$ emissions (272 ± 5 Tg $CH_4$ $yr^{-1}$) are comparable to the anthropogenic $CH_4$ emissions (323 ± 11 Tg $CH_4$ $yr^{-1}$) (Figure 1d). Depending on the level of reduction of the anthropogenic emissions under different scenarios, this balance between the anthropogenic and natural emissions either shifts toward more anthropogenic emissions under CLE and MAP, or toward natural sources under GMP, POL, and MTFR, where larger anthropogenic emission reductions take place (Figure S2 in Supporting Information S1). Our 272 Tg $CH_4$ $yr^{-1}$ wetland $CH_4$ emissions are higher than the estimate of 155–217 Tg $CH_4$ $yr^{-11}$ (Saunois et al., 2020). On the other hand, the global anthropogenic $CH_4$ emission in the present study (323 Tg $CH_4$ $yr^{-1}$) is slightly lower than a recent estimate of 369 Tg $CH_4$ $yr^{-1}$ (Saunois et al., 2025). Other natural methane sources in our study are fixed at values of 20 Tg $yr^{-1}$ for termites, close to the 25 Tg $CH_4$ $yr^{-1}$ by Saunois et al. (2025). The combined geological + ocean + lake sources are fixed to and 27 Tg $CH_4$ $yr^{-1}$ taken from Fung et al. (1991). These are likely on the low side compared to recent literature, where global oceanic $CH_4$ emissions are estimated to be 6–12 Tg $CH_4$ $yr^{-1}$ (Weber et al., 2019) and lake emissions are estimated to be 24.0 ± 8.4 Tg $CH_4$ $yr^{-1}$ (Zhuang et al., 2023).

The global $CH_4$ concentrations simulated under the different emission scenarios are presented in Figure 2a, along with the global and annual mean observations during the 2010–2024 period from NOAA (Lan et al., 2025). The simulated global $CH_4$ concentrations agree well with the observations, with a Pearson correlation ($r$) of 0.99 and a normalized mean bias ($NMB$) of −3%. The global $CH_4$ concentrations continue to increase in the CLE and MAP scenarios from 1.88 ± 0.01 ppm in 2025 to 2.13 ± 0.001 ppm (13%) under CLE and 2.07 ± 0.001 ppm (10%) under MAP in 2050. The (current) GMP scenario leads to a decrease in global $CH_4$ concentrations from 1.88 ± 0.01 ppm in 2025 to 1.82 ± 0.003 ppm (−3%) in 2050, while the POL scenario leads to a slightly larger decrease, to 1.79 ± 0.01 ppm (−5%). The largest reduction is simulated for the MTFR scenario, which leads to a decrease from 1.92 ± 0.01 ppm in 2030 to 1.77 ± 0.01 ppm (8%) in 2050 (a reduction of 6% compared to 2025). These responses to emission changes are lower than in Predybaylo et al. (2025) and Allen et al. (2021). However

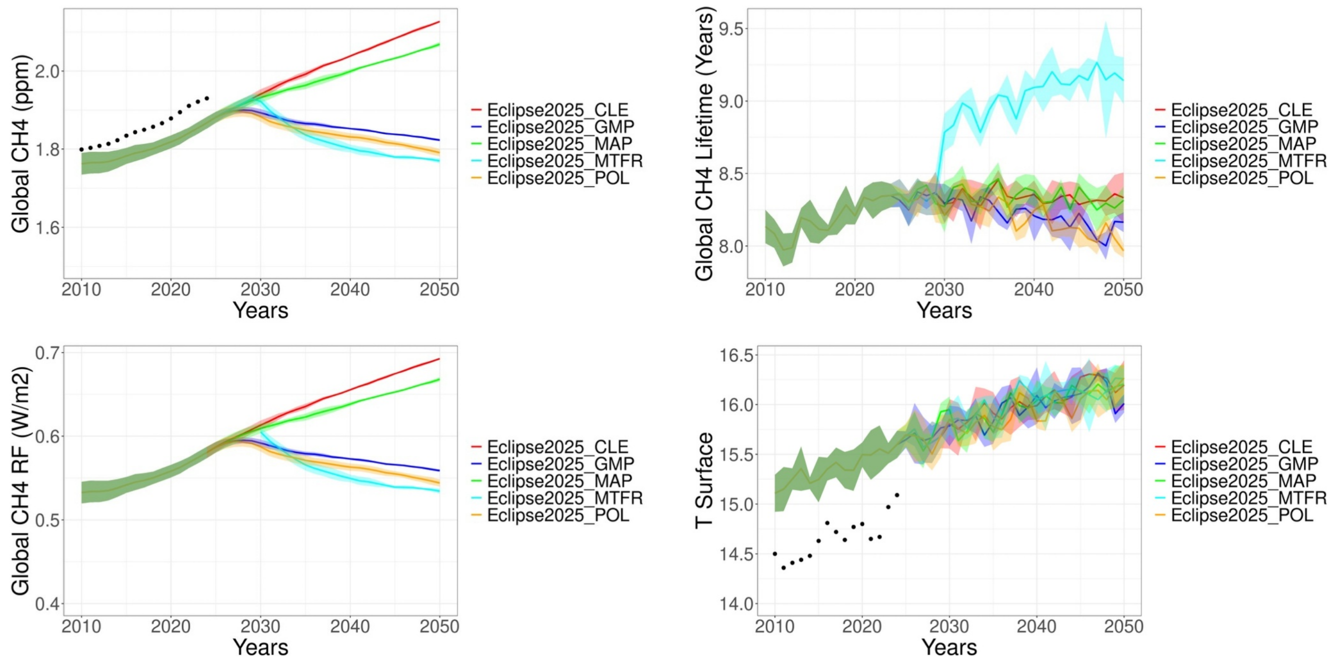


**Figure 2.** Annual mean global mean $CH_4$ concentrations (a), lifetime (b), top-of-the-atmosphere radiative forcing (c) and surface temperature (d) in the different simulations. Black dots in (a) and (d) show global and annual mean observations from NOAA and ERA5, respectively.

these studies assumed a full compliance to a global 30% and 40% $CH_4$ emission reduction while our study only considers the current signatories to the Pledge, which is much smaller than a full compliance (Figure 1a).

The global $CH_4$ lifetime (Figure 2b) is estimated to be around 8–8.5 years in all scenarios, except for the MTFR, which increases the lifetime to more than 9 years. Although the lifetime substantially increases in the MTFR scenario, the decrease in global average concentration is greatest under this scenario, which means that the model is driven by the large reduction in the emissions (Figures 1a and 1b). The GMP and the POL scenarios lead to a slight decrease in the lifetime of $CH_{4,}$ from 8.4 years in 2025 to 8.1 years by 2050, while the MAP scenario follows the CLE scenario.

The top-of-the-atmosphere (TOA) $CH_4$ radiative forcing ($RF_{CH_4}$) has been calculated based on Etminan et al. (2016) and is shown in Figure 2c. It should be noted that all scenarios except for MTFR quantify the direct radiative forcing from $CH_4$-only changes, while for MTFR, the estimated forcing is due to a combination of changes in $CH_4$ and other SLCF emissions. Under CLE, $RF_{CH_4}$ continues to increase from $0.53 \pm 0.01$ W $m^{-2}$ in 2010 to $0.59 \pm 0.01$ W $m^{-2}$ in 2025, then to $0.69 \pm 0.01$ W $m^{-2}$ under CLE and to $0.68 \pm 0.02$ W $m^{-2}$ under the MAP scenario in 2050. Under the GMP and POL scenarios $RF_{CH_4}$ decreases from $0.59 \pm 0.01$ W $m^{-2}$ in 2025 to $0.56 \pm 0.02$ W $m^{-2}$ and $0.54 \pm 0.04$ W $m^{-2}$ in 2050, respectively. The largest reduction is calculated under the MTFR scenario, which reduces the $RF_{CH_4}$ to $0.61 \pm 0.01$ W $m^{-2}$ in 2030 and to $0.53 \pm 0.03$ W $m^{-2}$ in 2050, bringing the forcing back to 2010 levels.

The geographical distribution of the concentration response to the different emission scenarios, averaged over the 2046–2050 period, relative to the CLE scenario are shown in Figure S3 in Supporting Information S1. Smallest concentration reductions take place in remote areas, over the southern hemisphere and over the Southern Ocean. Largest reductions take place over land, especially where the emission regions are located such as in North America and Europe. Particularly large reductions are simulated over the Persian Gulf region in the GMP and thus POL scenarios. Southeast Asia, which is one of the largest emitting regions, lacks signatories to the GMP; some countries in the region have, however, submitted MAPs. Therefore, the model predicts a large response over Southeast Asia under the MAP and POL scenarios, as well as under the MTFR scenario.

The surface temperature response to the changes in $CH_4$ emissions are shown in Figure 2d. The model results are in good agreement with the ERA5 observations (Hersbach et al., 2020) for the 2010–2024 period, with a *r* of 0.77

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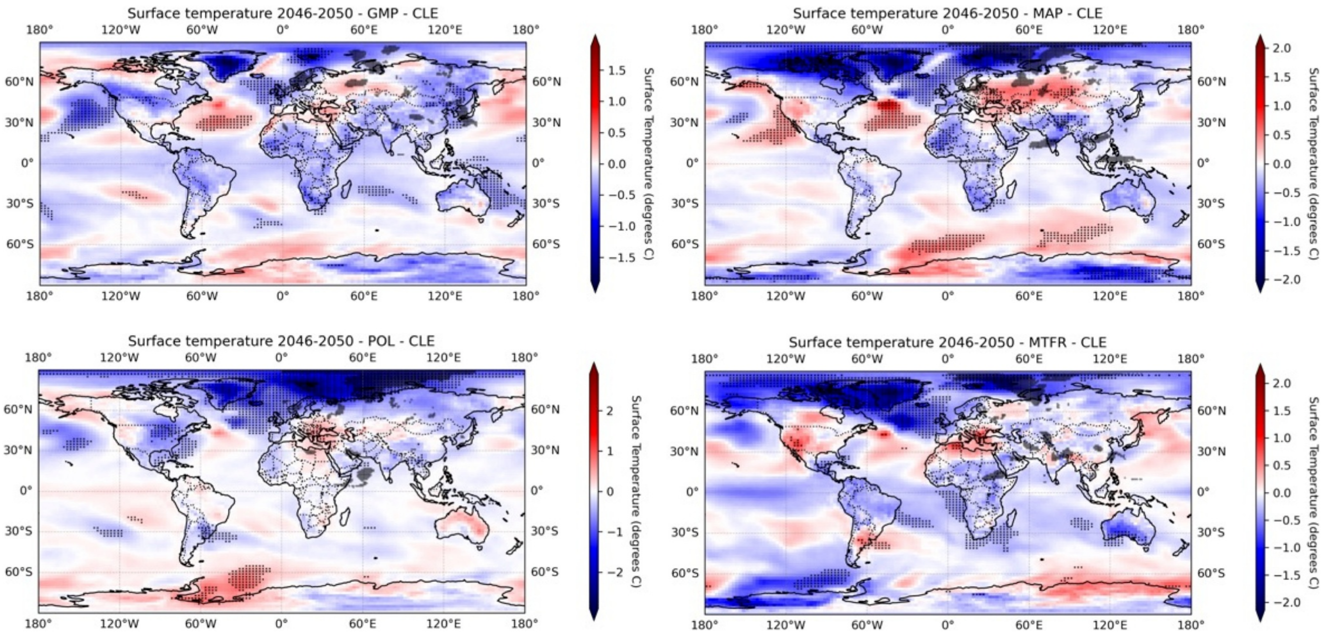


**Figure 3.** Simulated surface temperature differences between Global Methane Pledge (a), Methane Action Plan (b), POL (c), and maximum technically feasible reduction (d) versus Current Legislation averaged over 2046–2050. The dotted areas show responses within 95% confidence interval.

and a *NMB* of +4%. Under all scenarios, surface temperatures continue to increase, in agreement with earlier studies (e.g., Predybaylo et al., 2025), from 15.1 ± 0.19°C in 2010 to 16.2 ± 0.10°C in 2050. In order to evaluate the extent to which global surface temperatures respond to the different emission scenarios, we compared the 2046–2050 mean global surface temperature from the CLE scenario with that of the GMP, MAP, POL and MTFR scenarios. The GMP scenario avoids 0.11 ± 0.11°C warming compared to the CLE scenario, while the MAP and POL scenarios avoid 0.07 ± 0.16°C and 0.09 ± 0.15°C, respectively. The MTRF scenario avoids 0.13 ± 0.12°C warming compared to the CLE scenario. These estimates are lower and have greater associated uncertainties than those in a previous study by Cael and Goodwin (2023), which estimated 0.21 ± 0.06°C lower global warming under a $CH_4$ emissions reduction scenario by 2055, and lower than the objective of 0.2°C avoidance aimed for in the Pledge.

Above changes in 2046–2050 mean surface temperatures are, however, not homogeneous over the globe (Figure 3). GMP (Figure 3a) avoids warming over a large part of the globe, with exceptions over the North Atlantic, the Northwest Pacific, and the Southern Ocean, as well as over Eastern Europe and the Mediterranean, which experience more warming compared to the baseline scenario (CLE). Largest relative cooling is simulated to be over the Arctic and the Northeast Pacific. The avoided warming over the Arctic and the North Atlantic under the MTFR scenario (Figure 3d) is even greater, but this scenario also leads to more pronounced warming over the Mediterranean, Western US, South America (Argentina), over southern and Eastern Asia, and over the Antarctic. The figure also shows the areas where the responses are within the 95% confidence interval based on student *t* test. Overall, the simulated responses in surface temperatures are not significant in many regions, with the exception of the Arctic region, where the response is consistently significant under all scenarios. This is the case especially in MAP, where some large emitters like China are signatories, although they have not signed in GMP, and in POL, which is the combination of GMP and MAP, and MTFR, where all technically feasible reductions are considered. This response agrees with literature, which shows that Arctic temperatures respond largest to emission changes in Asia (Sand et al., 2016). This amplified response over the Arctic can be mainly attributed to feedback mechanisms rather than to concentration differences. As $CH_4$ is well-mixed, the concentration changes are rather spatially uniform (Figure S3 in Supporting Information S1), and $CH_4$ amplifies Arctic processes that are already sensitive to perturbations outside the Arctic (Christensen et al., 2019; Quinn et al., 2008; Taylor et al., 2022).

## 4. Discussion and Conclusions

Our results show that the GMP objective of achieving a reduction by 30% in 2030 global $CH_4$ emissions below the 2020 levels is not accomplished in the current GMP scenario or the POL (GMP + MAP) scenarios. This is, however, expected as 158 countries, accounting for roughly 55% of the global anthropogenic emissions, have yet signed the Pledge.

Results show that the goal of avoiding 0.2°C of warming by 2050 cannot be achieved even under the most ambitious scenario. MTFR avoids a warming of 0.13 ± 0.12°C; the current commitments reflected in the GMP scenario only avoid 0.11 ± 0.11°C by 2050. Results suggests that a full participation in the Pledge can have the potential to achieve the Pledge's objectives as taking the large standard deviation into account. Results also show that the temperature response in the GMP and MTFR scenarios are not proportional to the methane reductions. Thus, even given the large uncertainties in the temperature response, it is challenging to conclude whether or not there is really non-linearity in the response (Im, Tsigaridis, et al., 2025). The GMP aims mitigation applied by ~2020, whereas our study considers emissions cuts starting a few years later (2025), though this should only have a small impact. In addition, the GMP derived the 0.2°C goal based on the baseline emissions projections available in the GMA, whereas our CLE scenario includes policies put into place since that time that led to lower "baseline" emissions.

Results show that surface ozone ($O_3$) concentrations decrease slightly, from 24.5 ± 0.10 ppb in 2025 to 24.3 ± 0.06 ppb (by 1%) under GMP, while under the MTFR scenario global surface $O_3$ concentrations can reduce by 23% to 18.9 ± 0.02 ppb in 2050. It should be noted in all scenarios except for MTFR, the change in $O_3$ concentrations is due to changes in $CH_4$ emissions only, while for MTFR, the estimated surface $O_3$ response is due to a combination of changes in $CH_4$ and other SLCP emissions.

Our results are based on a single ESM with a small ensemble size. Ideally it should be followed-up in a multi-model ensemble experiment, such as in the Methane Model Intercomparison Project (MethaneMIP: England et al., 2025, https://www.methanemip.org). We have used the GISS-E2.1-G interactive $CH_4$ simulations with five ensemble members in CMIP6 (Allen et al., 2021) to estimate the impact of the ensemble size on surface temperature responses. We have compared the standard deviation in the 3 and 5 member ensembles, respectively. In both subsets, the standard deviation in the 2046–2050 period under SSP1-2.6 and SSP2-4.5 compared to SSP3-7.0 (~0.21 and ~0.32°C, respectively) remains much larger than the ensemble mean (~−0.07 and ~−0.15°C), which suggests that the ensemble size may not be the governing factor of the large uncertainty in the temperature responses.

Previous studies have highlighted that the response of $CH_4$ concentrations to changes in emissions is not necessarily linear as the chemistry is non-linear, and dependent on the oxidative capacity of the atmosphere, also due to other species that impact OH (Im, Tsigaridis, et al., 2025). For example, without halogens, models often overestimate methane lifetime, since halogens contribute to an additional $CH_4$ sink (Saiz-Lopez & von Glasow, 2012; Sherwen et al., 2016; Schmidt et al., 2016) and underestimate its near-term removal efficiency following emission reductions (Hossaini et al., 2016) and can overestimate its concentrations and radiative forcing. These imply that models need to be improved in their representation of chemical composition and processes that influence chemical sinks of $CH_4$, and $CH_4$ emissions from natural sources such as oceans, lakes, and permafrost should be better quantified.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Data Availability Statement

The model output used to perform the analyses and create plots are provided in Zenodo: https://doi.org/10.5281/zenodo.16755923 (Im, Shindell, et al., 2025). The GISS-E2.1 model code used in the present study, modelE2.1.2, is available under the GISS Model E Source Code Snapshots webpage: https://simplex.giss.nasa.gov/snapshots/modelE2.1.2.tgz (NASA, 2025).

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## References

Allen, R. J., Horowitz, L. W., Naik, V., Oshima, N., O'Connor, F. M., Turnock, S., et al. (2021). Significant climate benefits from near-term climate forcer mitigation in spite of aerosol reductions. *Environmental Research Letters*, *16*(3), 034010. https://doi.org/10.1088/1748-9326/ABE06B

Basu, S., Lan, X., Dlugokencky, E., Michel, S., Schwietzke, S., Miller, J. B., et al. (2022). Estimating emissions of methane consistent with atmospheric measurements of methane and $\delta^{13}C$ of methane. *Atmospheric Chemistry and Physics*, *22*(23), 15351–15377. https://doi.org/10.5194/acp-22-15351-2022

Cael, B. B., & Goodwin, P. A. (2023). Global methane pledge versus carbon dioxide emission reduction. *Environmental Research Letters*, *18*(10), 104015. https://doi.org/10.1088/1748-9326/acf8dd

Christensen, T. R., Arora, V. K., Gauss, M., Höglund-Isaksson, L., & Parmentier, F. J. W. (2019). Tracing the climate signal: Mitigation of anthropogenic methane emissions can outweigh a large Arctic natural emission increase. *Scientific Reports*, *9*(1), 1146. https://doi.org/10.1038/s41598-018-37719-9

Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf, E., et al. (2024). *GHG emissions of all world countries*. Publications Office of the European Union. https://doi.org/10.2760/4002897

England, M., Shindell, D., O'Connor, F., Smith, C., Xu, Y., Chuan, F., et al. (2025). An introduction to MethaneMIP: Investigating the climate and health benefits of methane mitigation using Earth System Models. In *EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-4867*. https://doi.org/10.5194/egusphere-egu25-4867

Etminan, M., Myhre, G., Highwood, E. J., & Shine, K. P. (2016). Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, *43*(24), 12614–12623. https://doi.org/10.1002/2016GL071930

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. https://doi.org/10.5194/gmd-9-1937-2016

Folberth, G. A., Staniaszek, Z., Archibald, A. T., Gedney, N., Griffiths, P. T., Jones, C. D., et al. (2022). Description and evaluation of an emission-driven and fully coupled methane cycle in UKESM1. *Journal of Advances in Modeling Earth Systems*, *14*(7), e2021MS002982. https://doi.org/10.1029/2021MS002982

Fung, I., John, J., Lerner, J., Matthews, E., Prather, M., Steele, L. P., & Fraser, P. J. (1991). Three-dimensional model synthesis of the global methane cycle. *Journal of Geophysical Research*, *96*(D7), 13033–13065. https://doi.org/10.1029/91JD01247

Gery, M., Whitten, G. Z., Killus, J. P., & Dodge, M. C. (1989). A photochemical kinetics mechanism for urban and regional scale computer modelling. *Journal of Geophysical Research*, *94*, 18925–18956. https://doi.org/10.1029/JD094iD10p12925

Gómez-Sanabria, A., Kiesewetter, G., Klimont, Z., Schoepp, W., & Haberl, H. (2022). Potential for future reductions of global GHG and air pollutants from circular waste management systems. *Nature Communications*, *13*, 6. https://doi.org/10.1038/s41467-021-27624-7

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Hoesly, R., Smith, S. J., Prime, N., Ahsan, H., Suchyta, H., O'Rourke, P., et al. (2024). CEDS v_2024_07_08 Release Emission Data (v_2024_07_08) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.12803197

Höglund-Isaksson, L. (2012). Global anthropogenic methane emissions 2005–2030: Technical mitigation potentials and costs. *Atmospheric Chemistry and Physics*, *12*, 9079–9096. https://doi.org/10.5194/acp-12-9079-2012

Höglund-Isaksson, L. (2017). Bottom-up simulations of methane and ethane emissions from global oil and gas systems 1980 to 2012. *Environmental Research Letters*, *12*(2), 024007. https://doi.org/10.1088/1748-9326/aa583e

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., & Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe—Results from the GAINS model. *Environmental Research Communications*, *2*, 025004. https://doi.org/10.1088/2515-7620/ab7457

Höglund-Isaksson, L., Purohit, P., Gomez-Sanabria, A., Kaltenegger, K., Pauls, A., Rafaj, P., et al. (2023). Non-$CO_2$ greenhouse gas emissions in the EU27 from 2005 to 2070 with technical mitigation potentials and costs-results from the GAINS model. In *Methodology report produced by IIASA for the European Commission DG-CLIMA*. International Institute for Applied Systems Analysis (IIASA). Retrieved from https://pure.iiasa.ac.at/id/eprint/19546/1/GAINS_Methodology_nonCO2_EU27_10oct2023_Final.pdf

Hossaini, R., Chipperfield, M. P., Saiz-Lopez, A., Fernandez, R., Monks, S., Feng, W., et al. (2016). A global model of tropospheric chlorine chemistry: Organic versus inorganic sources and impact on methane oxidation. *Journal of Geophysical Research Atmosphere*, *121*(23), 14271–14297. https://doi.org/10.1002/2016JD025756

Im, U., Shindell, D., Tsigaridis, K., Bauer, S., Olivié, D., Wilson, S., et al. (2025). Data for Im et al. Methane Pledge manuscript [Dataset]. https://doi.org/10.5281/zenodo.16755923

Im, U., Tsigaridis, K., Bauer, S., Shindell, D., Olivié, D., Wilson, S., et al. (2025). Future CH4 as modelled by a fully coupled Earth system model: Prescribed GHG concentrations vs. interactive CH4 sources and sinks. *Environmental Research: Climate*, *4*(1), 015008. https://doi.org/10.1088/2752-5295/adb3c0

Im, U., Tsigaridis, K., Faluvegi, G., Langen, P. L., French, J. P., Mahmood, R., et al. (2021). Present and future aerosol impacts on Arctic climate change in the GISS-E2.1 Earth system model. *Atmospheric Chemistry and Physics*, *21*(13), 10413–10438. https://doi.org/10.5194/acp-21-10413-2021

IPCC. (2023). AR6 synthesis report: Climate Change 2023—Summary for policymakers. In *IPCC – Statement on benefits of methane mitigation*.

Kelley, M., Schmidt, G. A., Nazarenko, L. S., Bauer, S. E., Ruedy, R., Russell, G. L., et al. (2020). GISS-E2.1: Configurations and climatology. *Journal of Advanced of Modeling Earth Systems*, *12*(8), e2019MS002025. https://doi.org/10.1029/2019MS002025

Klimont, Z., Heyes, C., Hoglund-Isaksson, L., Lindl, F., Kim, Y., Rafaj, P., et al. (2025). Global gridded anthropogenic emissions of air pollutants and methane for the period 1990–2050 (V2.1) [Dataset]. *Zenodo*. https://doi.org/10.5281/zenodo.14748815

Lan, X., Thoning, K. W., & Dlugokencky, E. J. (2025). Trends in globally-averaged $CH_4$, $N_2O$, and SF6 determined from NOAA Global Monitoring Laboratory measurements. Version 2025-05. https://doi.org/10.15138/P8XG-AA10

NASA. (2025). GISS model E source code snapshots [Software]. Retrieved from https://simplex.giss.nasa.gov/snapshots/modelE2.1.2.tgz

Predybaylo, E., Lelieveld, J., Pozzer, A., Gromov, S., Zimmermann, P., Osipov, S., et al. (2025). Surface temperature and ozone responses to the 2030 Global Methane Pledge. *Climatic Change*, *178*(4), 78. https://doi.org/10.1007/s10584-025-03908-5

Quinn, P. K., Bates, T. S., Baum, E., Bond, T., Burkhart, J. F., Fiore, A. M., et al. (2008). The impact of short-lived pollutants on Arctic climate. In *AMAP Technical Report No. 1 (2008)*. Arctic Monitoring and Assessment Programme (AMAP).

Saiz-Lopez, A., & von Glasow, R. (2012). Reactive halogen chemistry in the troposphere. *Chemical Society Reviews*, *41*(19), 6448–6472. https://doi.org/10.1039/C2CS35208G

Sand, M., Berntsen, T., von Salzen, K., Flanner, M. G., Langner, J., & Victor, D. G. (2016). Response of Arctic temperature to changes in emissions of short-lived climate forcers. *Nature Climate Change*, *6*(3), 286–289. https://doi.org/10.1038/nclimate2880

Saunois, M., Martinez, A., Poulter, B., Zhang, Z., Raymond, P. A., Regnier, P., et al. (2025). Global Methane Budget 2000–2020. *Earth System Science Data*, *17*(5), 1873–1958. https://doi.org/10.5194/essd-17-1873-2025

Saunois, M., Stavert, A. R., Poulter, B., Bousquet, P., Canadell, J. G., Jackson, R. B., et al. (2020). The Global Methane Budget 2000–2017. *Earth System Science Data*, *12*(3), 1561–1623. https://doi.org/10.5194/essd-12-1561-2020

Schmidt, J. A., Jacob, D. J., Horowitz, H. M., Hu, L., Sherwen, T., Evans, M. J., et al. (2016). Modeling the observed tropospheric BrO background: Importance of multiphase chemistry and implications for ozone, OH, and mercury. *Journal of Geophysical Research: Atmospheres*, *121*(19), 11819–11835. https://doi.org/10.1002/2015JD024229

Sherwen, T., Schmidt, J. A., Evans, M. J., Carpenter, L. J., Großmann, K., Eastham, S. D., et al. (2016). Global impacts of tropospheric halogens (Cl, Br, I) on oxidants and composition in GEOS-Chem. *Atmospheric Chemistry and Physics*, *16*(18), 12239–12271. https://doi.org/10.5194/acp-16-12239-2016

Shindell, D., Sadavarte, P., Aben, I., Bredariol, T., Dreyfus, G., Höglund-Isaksson, L., et al. (2024). The methane imperative. *Frontiers in Science*, *2*, 1349770. https://doi.org/10.3389/fsci.2024.1349770

Shindell, D. T., Faluvegi, G., & Bell, N. (2003). Preindustrial-to-present-day radiative forcing by tropospheric ozone from improved simulations with the GISS chemistry-climate GCM. *Atmospheric Chemistry and Physics*, *3*(5), 1675–1702. https://doi.org/10.5194/acp-3-1675-2003

Shindell, D. T., Pechony, O., Voulgarakis, A., Faluvegi, G., Nazarenko, L., Lamarque, J.-F., et al. (2013). Interactive ozone and methane chemistry in GISS-E2 historical and future climate simulations. *Atmospheric Chemistry and Physics*, *13*(5), 2653–2689. https://doi.org/10.5194/acp-13-2653-2013

Shindell, D. T., Walter, B. P., & Faluvegi, G. (2004). Impacts of climate change on methane emissions from wetlands. *Geophysical Research Letters*, *31*(21), L21202. https://doi.org/10.1029/2004GL021009

Stecher, L., Winterstein, F., Jöckel, P., Ponater, M., Mertens, M., & Dameris, M. (2025). Chemistry–climate feedback of atmospheric methane in a methane-emission-flux-driven chemistry–climate model. *Atmospheric Chemistry and Physics*, *25*(10), 5133–5158. https://doi.org/10.5194/acp-25-5133-2025

Stoerk, T., Rising, J., Shindell, D., & Dietz, S. (2025). Global methane action pays for itself at least six times over. *Science*, *390*(6772), eadu7392. https://doi.org/10.1126/science.adu7392

Stohl, A., Aamaas, B., Amann, M., Baker, L. H., Bellouin, N., Berntsen, T. K., et al. (2015). Evaluating the climate and air quality impacts of short-lived pollutants. *Atmospheric Chemistry and Physics*, *15*(18), 10529–10566. https://doi.org/10.5194/acp-15-10529-2015

Taylor, P. C., Boeke, R. C., Boisvert, L. N., Feldl, N., Henry, M., Huang, Y., et al. (2022). Process drivers, inter-model spread, and the path forward: A review of amplified arctic warming. *Frontiers in Earth Science*, *9*, 2021. https://doi.org/10.3389/feart.2021.758361

UNEP & CCAC. (2021). Global Methane Assessment: Benefits and costs of Mitigating Methane Emissions, United Nations Environment Programme—Key findings on methane's warming impact and mitigation potential.

UNEP & CCAC. (2024). *National Methane Action Plans. Climate and Clean Air Coalition to reduce short-lived climate pollutants—A UNEP convened initiative*. United Nations Environment Program. Retrieved from https://www.ccacoalition.org/resources/national-methane-action-plans

USEPA. (2019). *Global Non-$CO_2$ greenhouse gas emission projections & marginal abatement cost analysis: Methodology documentation. EPA-430-R-19-012*. U.S. Environmental Protection Agency, RTI International, Abt Associates, Inc. and ICF. Retrieved from https://www.epa.gov/sites/default/files/2019-9/documents/nonco2_methodology_report.pdf

USEPA. (2025). *Non-$CO_2$ greenhouse gas emission projections & mitigation*. U.S. Environmental Protection Agency.

Weber, T., Wiseman, N. A., & Kock, A. (2019). Global ocean methane emissions dominated by shallow coastal waters. *Nature Communications*, *10*(1), 4584. https://doi.org/10.1038/s41467-019-12541-7

Zhuang, Q., Guo, M., Melack, J. M., Lan, X., Tan, Z., Oh, Y., & Leung, L. R. (2023). Current and future global lake methane emissions: A process-based modeling analysis. *Journal of Geophysical Research: Biogeosciences*, *128*(3), e2022JG007137. https://doi.org/10.1029/2022JG007137

## References From the Supporting Information

IEA (2023). *World Energy Outlook 2023*. International Energy Agency (IEA).