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Economics of enhanced methane oxidation relative to carbon dioxide removal

Conor Hickey^{1,3,*} and Myles Allen^{1,2} ¹ Environmental Change Institute, School of Geography and the Environment, University of Oxford, Oxford, United Kingdom² Atmospheric, Oceanic and Planetary Physics, Department of Physics, University of Oxford, Oxford, United Kingdom³ Harvard Business School, Harvard University, Boston, MA, United States of America

* Author to whom any correspondence should be addressed.

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Abstract

Mitigating short-term global warming is imperative, and a key strategy involves reducing atmospheric methane (CH₄) due to its high radiative forcing and short lifespan. This objective can be achieved through methods such as oxidising methane at its source or implementing enhanced oxidation techniques to reduce atmospheric CH₄ concentrations. In this study, we use a range of metrics to analyse both the impact and value of enhanced CH₄ oxidation relative to carbon dioxide (CO₂) removal on global temperature. We apply these metrics to a select group of model studies of thermal-catalytic, photocatalytic, biological and capture-based oxidation processes under different greenhouse gas (GHG) concentrations. Using a target cost of €220–1000/tCO₂ for CO₂ removal, our findings indicate that metrics valuing enhanced oxidation techniques based on their contribution to mitigating the long-term level of warming show these techniques are uncompetitive with CO₂ removal. However, when using metrics that value enhanced oxidation of CH₄ based on its impact on the immediate rate of warming, photocatalytic methods may be competitive with CO₂ removal, whereas biofiltration, thermal-catalytic oxidation and capture-based units remain uncompetitive. We conclude that if the policy goal is to target the immediate rate of warming, it may be more valuable to incentivise CO₂ removal and enhanced oxidation of methane under separate GHG targets.

1. Introduction

Average global temperatures continue on a sharply upward trend as a consequence of rising greenhouse gas (GHG) concentrations in the atmosphere [1, 2]. After a sustained pause since the start of the millennium, the concentration of atmospheric methane (CH₄) began to increase in 2007 and has continued for over a decade; however, the reasons for this change are still not well understood [3, 4]. Possible explanations for this growth may include increases in biogenic emissions (especially in the tropics and subtropics), decreases in CH₄ oxidation rates due to changes in atmospheric abundances of hydroxyl and/or chlorine radicals, and increased fossil fuel emissions coupled with declining biomass burning [3–10].

Emissions of biogenic CH₄ can be difficult to reduce as they present at lower concentrations in air (typically below 100 ppm) and are emitted over a larger land area relative to non-biogenic sources (e.g. >1000 ppm) [11]. There are proposed methods for reducing the atmospheric stock of non-CO₂ GHGs [11–14]; however, as the IPCC notes, there is a scarcity of literature assessing these methods [15]. In this paper, we compare the costs of scaled enhanced CH₄ oxidation to CO₂ removal, measured in ‘warming-equivalent emissions’. Our analysis focuses on a select group of model studies of enhanced CH₄ oxidation, for which heuristic cost estimates could be made, at concentrations ranging from atmospheric levels to 6000 ppm.

If a net-zero GHG target cannot facilitate the interchangeability between CH₄ and CO₂, there may

be a greater economic value in ameliorating the rapid growth in the atmospheric mixing ratio of CH₄, particularly when preventing the initial release of CH₄ is challenging. While recent years have witnessed incremental policies and regulatory frameworks addressing methane emissions in the fossil fuel sector [16], CH₄ from biogenic sources could remain significant. For example, even with ambitious climate policies, enteric fermentation in ruminants is projected to represent 40%–78% of remaining CH₄ emissions in 2100 [17]. This proportion exceeds the current total CH₄ emissions from the fossil fuel sector [18]. Additionally, enhanced oxidation may be necessary to address emissions arising from positive climate feedbacks [14, 19].

Reducing atmospheric concentrations of CH₄ has economic value tied to the lowest cost approach which achieves an equivalent climate impact through either removal or avoided emissions of CO₂ [20]. For CO₂ equivalence, emissions accounting typically uses the 100-year global warming potential (GWP) which equates 1 tCH₄ with 28 tCO₂ [21]. However, this does not reflect the impact of CH₄ emissions on either the rate (short-term) or absolute level of warming (long-term) to date relative to pre-industrial emissions. In this paper we consider CH₄'s impact on global temperature. For instance, the temperature response to a 1-tonne-per-year abatement of methane emissions (1 tCH₄ yr⁻¹), an initially rapid cooling followed by a centennial-timescale equilibration, can be considered equivalent and opposite to an emission of 128 tCO₂ yr⁻¹ for the first 20 years, followed by 8 tCO₂ yr⁻¹ thereafter [22]. The difference in values over time is due in part to the short atmospheric lifetime of CH₄ (9–12 years) relative to CO₂ (millennia).

Decreasing the atmospheric concentration of CH₄ can be accomplished by either ceasing the emitting activity or through post-emission enhanced oxidation techniques such as thermal or photocatalysis and biofiltration [11, 12, 14, 23–27]. Zeolites and other technologies have also been proposed to reduce atmospheric CH₄ concentrations to preindustrial levels [12]. The economic cost of oxidising CH₄ using these methods is heavily influenced by its 200 times lower abundance in the atmosphere compared to CO₂, resulting in higher air processing requirements. In contrast to CO₂, all the costs of enhanced CH₄ oxidation occur at the capture stage, with monitoring costs and the risk of re-release being minimal. For many approaches, cost and reaction rates outside of a laboratory environment are not available which limits the scope and certainty of the analysis (e.g. enhancing the natural hydroxyl radical sink).

The paper is structured as follows: the next section outlines the methods and data used to generate cost estimates for each technique at different GHG concentrations. Section 3 defines a range of metrics

which encompasses CH₄'s maximum and minimum value relative to CO₂. Each technique's cost per tonne of CH₄ oxidised is used to illustrate these values. Finally, the paper concludes that offsetting ambient methane with CO₂ removal is typically more cost-effective than enhanced oxidation of CH₄.

2. Methods and cost analysis

In this section, we outline models and cost estimates using a levelised cost of oxidation (LCO) per tonne of CH₄ approach for four forms of enhanced CH₄ oxidation: thermal-catalytic, photocatalytic, biofiltration, and capture-based oxidation. While a broader range of techniques exist, our focus is on methods for which cost estimates can be derived.

2.1. Thermal-catalytic oxidation

The catalytic thermal degradation of CH₄ is achievable by heating air over a catalyst, such as Hopcalite, with the main cost stemming from the energy required to heat the air [11]. Our analysis focuses on a proposed process for oxidising CH₄ by heating air to 400 °C using an electric furnace [11, 28], and a heat exchanger recovers waste heat from the process.

The LCO is determined using equation (1), with additional details found in Note 1 of the supplementary material. In this equation, the energy requirement (q) for oxidising one tonne of CH₄ is multiplied by the energy cost (ec):

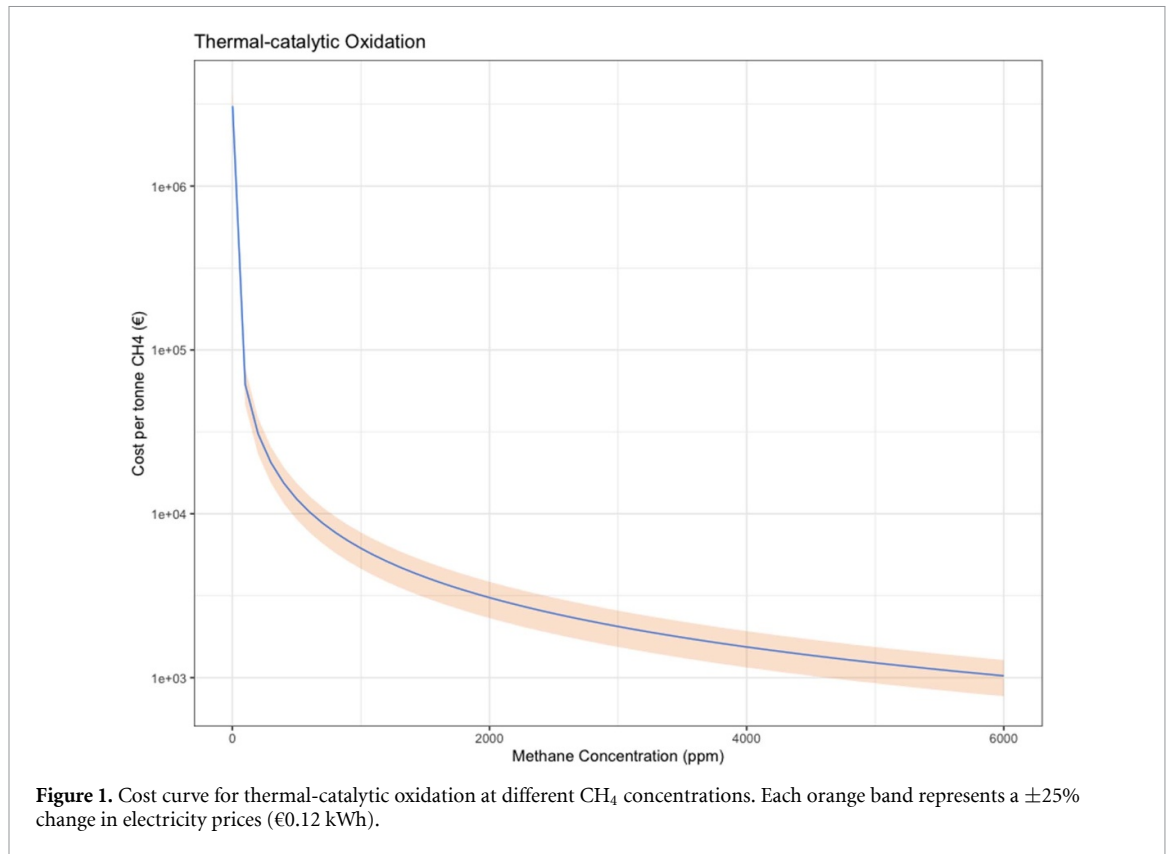
$$\text{LCO} = ec_{\text{€/kWh}} \cdot q_{\text{heat(kWh)}} \quad (1)$$

To calculate the levelised cost of oxidation, we first determine the volume of air (v) needed to oxidise one tonne of CH₄ at each CH₄ concentration. Subsequently, we estimate the energy required to heat v to 400 °C using an electric furnace and with a heat pipe heat exchanger. The levelised cost of oxidation is calculated by multiplying the per unit energy cost (€0.12 kWh) by the energy required (kWh) to oxidise 1 tonne of CH₄.

Figure 1 illustrates a cost curve for the thermal-catalytic oxidation of methane at different concentrations of CH₄ in ppm. Cost estimates for oxidation ranged from €3000 000/tCH₄ at atmospheric concentrations, €61 000/tCH₄ at 100 ppm and €1000/tCH₄ at concentrations of 6000 ppm.

2.2. Photocatalytic oxidation

Photocatalysts react to light energy, which then facilitates the oxidation of CH₄ into CO₂ and H₂O. We model a simple photoreactor in which a photocatalytic surface is exposed to sunlight and natural airflow. For example, photocatalytic paint could cover the rooftop of a large building. This is consistent with prior studies proposed or studied for GHG mitigation, including existing surfaces covered in photocatalytic paint [11].



$$\text{LCO} = \frac{\text{CRF}_{(\%)}}{\text{Annual CH}_4 \text{ Oxidised}} \cdot (\text{CAPEX}_{\text{catalyst}(\text{m}^2)} + \text{CAPEX}_{\text{coating}(\text{m}^2)}) + \text{OPEX}_{\text{m}^2 \text{ yr}}. \quad (2)$$

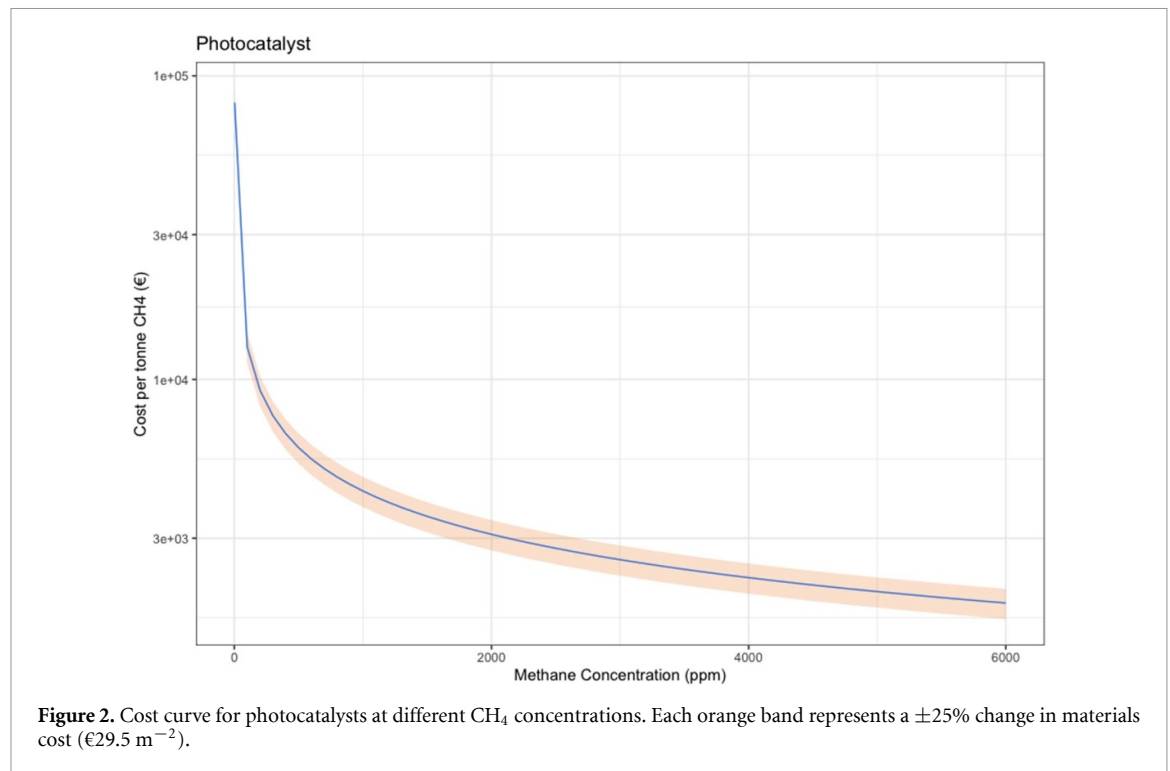
The primary cost for passive photocatalytic oxidation is the capital investment enabling the oxidation process [11]. Our calculation (equation (2)) of the levelised costs of photocatalytic oxidation assumes an existing rooftop is fabricated with photocatalytic paint to oxidise 1 tCH₄ yr⁻¹. The capital recovery factor (CRF) determines the annual repayment percentage for recovering total capital costs. The derivation of equation (2) and assumptions used can be found in note 2 of the supplementary material. The first step involved deriving reaction rates for CH₄ oxidation using a silver-decorated zinc oxide nanocatalyst based on a Langmuir–Hinshelwood model. Subsequent steps involve estimating the hourly change in the molar mass of CH₄ in the reactor during oxidation by using the derived reaction rates. We then scaled the reactor to estimate the required square meters of catalyst to oxidise 1 tonne of CH₄. We assume a 10-year lifetime for the catalyst and that the photocatalytic coating is cleaned annually.

Figure 2 depicts a cost curve detailing the photocatalytic oxidation of methane across varying

concentrations of CH₄ in ppm. The cost estimates for oxidation exhibit a range, starting from €82 000 t/CH₄ at 2 ppm, €12 800/tCH₄ at 100 ppm and decreasing to €1835 t/CH₄ at concentrations of 6000 ppm.

2.3. Biofiltration

Biotrickling filtration systems are composed of bacteria, i.e. methanotrophs, which can oxidise methane. In our review of biotrickling filtration systems for CH₄ oxidation only one techno-economic study could be found [29]. In their analysis, they find that enhanced oxidation at atmospheric concentrations is ineffective when using these methanotrophic biofilters, as the amount of methane is too low to support cell survival. If the concentration is increased to 500–6000 ppm, similar to that found above landfills and in concentrated animal feeding operations, 4.98–35.7 tonnes of CH₄ can be oxidised per biofilter per year. This is assuming biotrickling filters of typical size (3.66 m in diameter and 11.5 m in height) [29].



$$\text{LCO} = \frac{\text{CRF}(\%) \cdot (\text{CAPEX}_{\text{biolfilter}}) + \text{OPEX}_{\text{kWh}_{\text{yr}}}}{\text{Annual CH}_4 \text{ Oxidised}} \quad (3)$$

The calculation of biofiltration costs for CH₄ oxidation involves three key steps (see Note 3 of the supplementary material). First, reaction rates at each CH₄ concentration are derived using data from Yoon *et al* [29]. Second, resource requirements are estimated through techno-economic analysis based on cost information from an existing bio-trickling filtration system. The third step involves calculating the cost to oxidise one tonne of CH₄ using equation (3), which considers annualised capital expenditure, annual energy costs, and annual CH₄ oxidised.

Figure 3 illustrates that at 500 ppm, the cost of oxidation through biofiltration is approximately $\text{€}24\,000/\text{tCH}_4$ with heating and $\text{€}13\,000/\text{tCH}_4$ without heating. Meanwhile, for concentrations of 6000 ppm, the cost estimates range from $\text{€}3600/\text{tCH}_4$ (heat) to $\text{€}2000/\text{tCH}_4$ (no heat).

2.4. Capture-based oxidation

Capturing and concentrating CH₄ could reduce oxidation costs for each of the previously analysed methods. Zeolites and polymeric materials have also been proposed to capture and oxidise non-CO₂ GHGs [12, 30, 31]. However, designs for air capture systems for non-CO₂ GHGs are still mainly conceptual or lab-based, which limits techno-economic analysis [12].

Our analysis focuses on a conceptually simple method that assesses the basic energy requirements

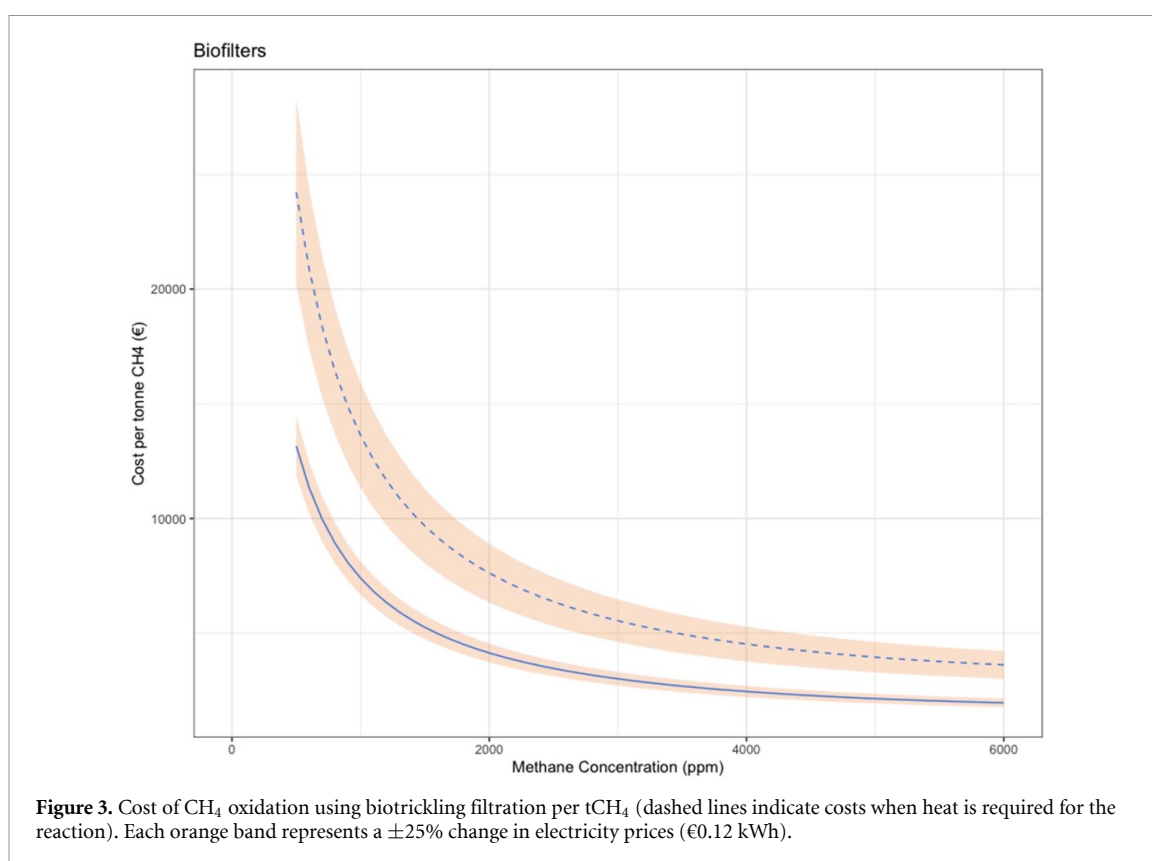
to operate a fan-driven system for CH₄ oxidation, using estimates from existing CO₂ capture systems. Theoretical estimates of the energy requirement alone to operate CH₄ capture systems have been suggested as prohibitive [32, 33]. Therefore, our approach will focus on quantifying these energy requirements in monetary terms.

To calculate the levelised cost of capture (LCC), we first calculate the volume of air (v) that would need to be processed to capture 1 tCH₄. Second, we adjust this requirement (v) to account for the fraction of CH₄ captured per unit of processed air. Third, we estimate the energy requirements to process v . For a detailed description please see note 4 of the supplementary material.

A detailed study by Keith *et al* describes a process for capturing CO₂ from the atmosphere [34]. The study demonstrates that 61 kWh of fan energy is required to process enough air for the removal of 1 tonne of CO₂ at a concentration of 400 ppm. The process achieves a capture rate of 74.5% and fan efficiency of 70%. Using these assumptions, we calculate the amount of energy required (q) to process a cubic meter of air, assuming $0.75 \text{ gCO}_2 \text{ m}^{-3}$ at 400 ppm. We then multiply q by v to get q per tonne of methane. The price per unit of electricity (ec) is then multiplied by q per tonne of CH₄ to estimate the cost per tonne of CH₄ captured (equation (4)):

$$\text{LCC} = ec_{\text{€/kWh}} \cdot q_{\text{fan energy(kWh)}} \quad (4)$$

We find that the energy cost estimates to capture CH₄ could range from $\text{€}3900/\text{tCH}_4$ at 2 ppm and



decrease to €78 tCH₄ at a concentration of 100 ppm. In Jackson *et al*, they propose a much lower capture rate of 20% compared to the capture rate of 74.5% achieved for CO₂ removal [12]. We find that a 20% capture rate cost could range from €14 600 tCH₄ at 2 ppm to €292 tCH₄ at 100 ppm.

3. Valuing the enhanced oxidation of atmospheric CH₄ relative to CO₂

This section contextualises the cost analysis of each enhanced oxidation technique with CH₄'s minimum and maximum value relative to CO₂.

3.1. Overview of methane metrics and the value of enhanced oxidation

Short-lived climate forcers (SLCFs) can provide fast mitigation, potentially avoiding warming of up to 0.3 °C by the 2040s [35]. Their longer-term impact is estimated at up to 1.2 °C by 2100 [36, 37]. It is important to note that much of this estimate accounts for preventing additional warming in baseline 'business as usual' scenarios in which SLCF emissions increase. Actual reductions in global temperature are attributed to SLCF emission reductions [38].

CH₄ emissions to date have contributed approximately 0.5 °C to human-induced warming since the 19th century [39]. Eliminating anthropogenic CH₄ emissions entirely would lead to a decline in CH₄ concentrations, approaching pre-industrial

levels. However, as long as CO₂-induced warming persists, CH₄ concentrations are likely to remain elevated due to Earth system feedbacks. This outcome would take centuries to materialise due to the gradual thermal adjustment of the oceans to past radiative forcing. Approximately half of this potential cooling would become evident in the first few decades.

This behaviour stands in stark contrast to CO₂, where eliminating emissions would only lead to a stabilisation of CO₂-induced warming, even over multi-century timescales. To reduce CH₄-induced warming by more than this amount would require active enhanced oxidation of CH₄ in ambient air to reduce atmospheric concentrations below pre-industrial levels. Hence, methane-induced warming to date represents a very generous upper bound on the amount by which global temperatures could be reduced through methane emission reductions alone.

Comparing mitigation outcomes, whether through avoided emissions or GHG removals, requires relating emissions to CO₂, the usual reference. GHG emission metrics provide simplified information about the effects that emissions of different GHGs have on global temperature or other aspects of climate, expressed relative to the effect of emitting CO₂.

GWP and global temperature change potential (GTP) are the main metrics used by the IPCC and UNFCCC. Nearly all scenarios in the literature use GWP-100 in cost-optimisation, reflecting the existing

policy approach [40]. This metric considers the relative ability of a GHG, compared to CO₂, to trap extra heat in the atmosphere over a 100-year period.

While GWP and GTP describe the marginal impact of each unit of emission relative to the absence of that emission [41], an alternative approach of ‘warming-equivalent emissions’ [42–44] can be used to calculate the additional warming resulting from new or ongoing emissions and removals [41]. Warming-equivalent emissions refer to the quantity of CO₂ emissions that would result in an equivalent temperature change as a multi-gas emissions trajectory assessed over a multi-decade period. This calculation considers prior emissions and, consequently, the atmospheric conditions at the beginning of that period.

The choice of metric, including time horizon, should reflect the policy objectives for which the metric is applied [45]. The Paris agreement relates to the level of warming (over the long-term). There is no mention of any agreement on the rates of warming (short-term), which are strongly affected by internal climate variability. Warming-equivalent emissions provide information on the impact of SLCF emissions on both the expected rate (averaging over possible realisations of variability) and long-term level of warming. This approach utilises a ‘flow’ term to represent the short-term impact of changes in SLCF emission rates, and a ‘stock’ term to represent the longer-term adjustment to past increases.

In the formulation presented by Smith *et al*, warming-equivalent emissions equate a one-tonne-per-year increase in CH₄ emission rate (1 tCH₄ yr^{−1}) with an emission of 128 tCO₂ yr^{−1} over the 20 years after the increase occurs, followed by 8 tCO₂ yr^{−1} thereafter [46]. The rapid initial cooling, succeeded by a centennial-timescale equilibration resulting from CH₄ oxidation, can be considered equivalent and opposite to an emission of 128 tCO₂ yr^{−1} for the first 20 years, followed by 8 tCO₂ yr^{−1} thereafter. The factor of 128 reflects the substantial impact of any change in the CH₄ emission rate on expected temperatures over the next 20 years, while the smaller factor of 8 reflects the ongoing adjustment of the climate system to increases or decreases in CH₄ emissions that have occurred more than 20 years ago, but still within the industrial epoch.

Therefore, when viewed as a means to maintain temperatures below a certain level over multi-decade timescales, a sustained CH₄ removal of 1 tCH₄ yr^{−1} has a value of approximately 8 tCO₂ yr^{−1}. Note that this equivalence only applies to the impact of emission on global temperature. Methane emissions may have local impacts elsewhere. However, for shorter term action to reduce global temperatures (rate of warming), the value of CH₄ could increase to 128 tCO₂ of warming equivalent. Consequently, the value of CH₄ oxidation depends on whether the

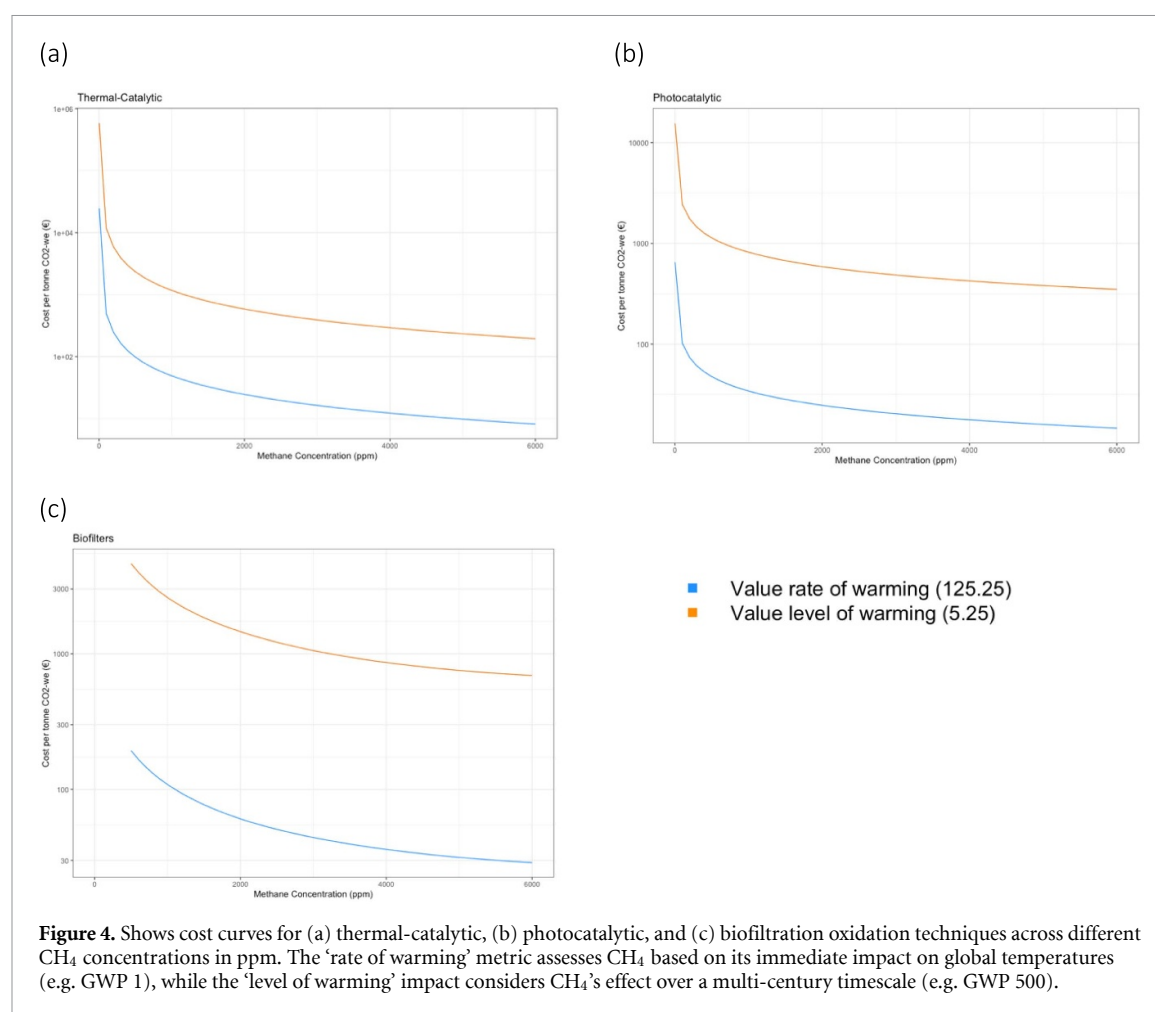
policy focus is on changing the level of warming (which is low because of the gradual climate adjustment to past SLCF increases) or the rate of warming (which is high because of the substantial impact of SLCF emissions on warming rates). These values can also represent the range of values which compare methane metrics at different timescales from GWP 1 equating to 128 tCO₂ and GWP 5007.9 tCO₂ [42]. For reference, IPCC AR6 cites GTP 50 and GTP 100 metrics which equate to 11 tCO₂ and 5.4 tCO₂ respectively [42].

Generally, CH₄ metrics do not account for the carbon dioxide emitted during CH₄ oxidation [11, 47]. To address the 2.75 tCO₂ emitted per 1 tCH₄ oxidised, we further adjust these values to 125.25 tCO₂ and 5.25 tCO₂, respectively [12]. Although these figures represent a broad range of potential ‘exchange rates’, they are useful in assessing the cost-effectiveness of enhanced CH₄ oxidation relative to CO₂ removal. Costs of permanent CO₂ removal can range from €220 tCO₂ to €1000 tCO₂ [34, 48, 49]. If a CH₄ oxidation approach costs less per tCH₄ than CO₂ removal of 5.25 tCO₂, then that option would be attractive whatever the timescale considered. Likewise, if a CH₄ oxidation option costs more per tCH₄ than CO₂ removal of 125.25 tCO₂, then that option would be unattractive for all climate policy priorities (although it might still be attractive if non-climate co-benefits could be identified).

3.2. Comparison of relative costs of removing CH₄ and CO₂ from the atmosphere

In this section, we use the methane metrics from section 3.1 to compare the cost-effectiveness of enhanced methane oxidation techniques (section 2) with carbon dioxide removal.

Figure 4 presents cost curves for each oxidation type using a range of methane conversion metrics. Cost estimates for thermal-catalytic oxidation at atmospheric concentrations ranged from €586 000/tCO₂we when using the level of warming metric to €25 000/tCO₂we when using the rate of warming metric. Costs for photocatalytic oxidation ranged from €15 500/tCO₂we for the level of warming to €650/tCO₂we for the rate of warming metric. Above 100 ppm, the costs of oxidation can reach €2400/tCO₂we and €100/tCO₂we respectively. For enhanced oxidation through biofiltration estimates are approximately €4600/tCO₂we (level of warming) and €200/tCO₂we (rate of warming) where heating is required at CH₄ concentrations of 500 ppm. Cost estimates range from €2500/tCO₂we (level of warming) and €100/tCO₂we (rate of warming) for no heating. We estimate energy costs for capturing CH₄ at atmospheric concentrations to range from €474/tCO₂we (level for warming) and €31/tCO₂we (rate of warming).



The three oxidation approaches analysed exceed the earlier established target cost (€220–1000/tCO₂) of removal at atmospheric concentrations. Applying the rate of warming metric to the photocatalytic approach to methane could make it competitive. A comparable target energy cost for CO₂ capture (€7 tCO₂) is generated by multiplying the energy required (61 kWh/tCO₂) by the electricity cost (€0.12 kWh). Capture costs for CH₄ far exceed this amount and are therefore unlikely to form part of a process to rival CO₂ removal. The conclusion of this analysis holds when using GTP 50 and GTP 100 metrics also.

4. Discussion

In the absence of high CH₄ concentrations or low-cost adsorption, all methods could be prohibitively more expensive than permanent CDR. Passive photocatalytic methods could present the lowest cost option of CH₄ oxidation. However, measuring the amount of CH₄ oxidised by photocatalysts could be challenging. Both thermal-catalytic, biofiltration and capture-based units seem unlikely to compete well on a least cost basis with permanent CDR techniques as part of a multi-gas approach to negative emissions. It has been argued that separate targets for CH₄

and CO₂ could be beneficial [50]. In this context, enhanced CH₄ oxidation could hold greater value, particularly when abatement activities are limited. Setting a specific target for a gas may necessitate considering its oxidation.

It remains an open question which enhanced CH₄ oxidation techniques will prove commercially viable at scale; all the options presented here require further research and development. For many of the conceptual techniques, further work is needed on the design and expected performance. Once the resource requirements for each oxidation technique has been established, cost estimates can follow. The analysis in this paper is limited in its representation of these costs and the technical characteristics of each approach. However, the application of the warming-equivalent emissions to heuristic cost estimates presented here is useful to understand the relative competitiveness of these approaches to CO₂ removal. Further work may also consider the co-oxidation of CH₄ and N₂O or co-removal with CO₂ [12].

5. Conclusion

This study investigates the cost-effectiveness of enhanced methane oxidation compared to carbon dioxide removal. Evaluating thermal-catalytic,

photocatalytic, biofiltration and capture-based methods, the analysis uses a broad range of methane metrics to understand their value for mitigating warming on immediate and long-term timescales. Photocatalytic oxidation emerges as a potentially cost-effective option, though challenges persist in quantifying its real-world impact. The study illustrates the economic challenges of enhanced methane oxidation, with costs potentially outweighing benefits, especially for thermal-catalytic and biofiltration. Despite challenges, offsetting ambient methane with CO₂ removal appears more economically viable, emphasising the need for ongoing research and development. Distinct targets for methane and carbon dioxide reduction may prove prudent, if the policy priorities are focused on addressing the rate of warming. This study informs policy on negative emissions, emphasising the potential need to have separate targets for each GHG.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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ORCID iDs

Conor Hickey  <https://orcid.org/0000-0001-7611-562X>

Myles Allen  <https://orcid.org/0000-0002-1721-7172>

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