



Reply to: Practical constraints on atmospheric methane removal

Robert B. Jackson^{1,2,3}✉, Edward I. Solomon^{4,5}, Josep G. Canadell⁶, Matteo Cargnello^{7,8}, Christopher B. Field^{1,2,3} and Sam Abernethy^{1,9}

REPLYING TO K.S. Lackner *Nature Sustainability* <https://doi.org/10.1038/s41893-020-0496-7> (2020)

As a pioneer of direct-air capture of CO₂ (ref. ¹), particularly in passive systems, Lackner is well positioned to comment² on our proposal to remove methane (CH₄) and other non-CO₂ gases industrially from the atmosphere³. Here, we respond briefly to his points.

Lackner is right to highlight² the cost and energy requirements of processing large volumes of air to remove dilute CH₄ (~1,865 ppb). We acknowledged this challenge in our original paper³. However, his estimate that it would require an “energy bill that is three orders of magnitude larger for a ton of methane” (compared with 220 MJ per ton of CO₂) seems premature, absent more specific engineering designs for CH₄ conversion or capture. The minimum thermodynamic work required to separate methane from air scales logarithmically with concentration, not linearly, and is less than double that of CO₂. His estimate of electricity costs of €3 kWh⁻¹ is fairly high today, let alone decades from now; processes such as CH₄ removal may also be a productive way to use solar and other renewable energy when supply exceeds demand, as already occurs at midday for some solar power generation. Furthermore, there may be ways to reduce the energy requirements of any given design. Air with CH₄ at concentrations higher than background would reduce energy needs, as we noted in our paper³. Using natural winds or existing blowers of exhaust gases could also drive down the energy needs. Nonetheless, passive systems, as championed by Lackner¹, do have some benefits over more energy-intensive systems with blowers.

Another advantage to be considered when comparing the costs of CH₄ and CO₂ removal is that methane can be used directly as a fuel or chemical building block if it is captured rather than converted and released back into the atmosphere. There are few viable large-scale processes that use CO₂ as a feedstock at present, thus reducing its post-capture value. Engineering demands may conspire to make CH₄ removal costs prohibitive. Time will tell—and research on catalyst performance, sorbents and engineering designs will all be important.

Our perspective differs from Lackner’s² on a few other issues. Using a framework of processing “the entire atmosphere in less than a decade”², as Lackner states, CH₄ removal appears (and perhaps is) more ambitious than proposed CO₂ removal, particularly when CH₄ is found at background concentrations two orders of magnitude lower than CO₂. On a mass basis, however, the total amount of CH₄ removed would be orders of magnitude smaller than for CO₂ removal. Concentrations of CH₄ could be restored to pre-industrial

levels of ~750 ppb by removing ~3.2 of the 5.3 Gt CH₄ currently in the atmosphere³. In contrast, ~40 GtCO₂ are released yearly from anthropogenic activities³, with 10 GtCO₂ removed yearly and hundreds of gigatons of CO₂ proposed to be removed cumulatively in many negative emissions scenarios.

Lackner also points out that “turning down the faucet” (that is, CH₄ mitigation) to a bathtub may be a better strategy than “bailing” (that is, methane removal from the atmosphere)². We agree. Mitigation of a greenhouse gas is almost always better than removing it after its release into the atmosphere: a drop of ink is easier blotted from a pen than extracted after it drips into a bathtub or a glass of water. However, not all CH₄ mitigation efforts are technologically or economically tractable. We envision ‘permanent’, ongoing CH₄ removal to offset the most intransigent and expensive emissions from the energy sector and, more likely, food production—including emissions from ruminants and rice farming. In fact, it may be impossible to eliminate global CH₄ emissions this century and hence stabilize the atmosphere without continued CH₄ removal, even when atmospheric restoration is achieved³.

Lackner also raises the possibility of curtailing other natural emission sources of CH₄, rather than removing CH₄ from the atmosphere¹. As noted in our paper³, any source of methane that results in higher-than-background concentrations in air would lower the energy requirement and cost of methane removal. Top-down estimates suggest that natural CH₄ emissions total ~230 Tg of CH₄ compared with ~330 Tg CH₄ from anthropogenic sources⁵. However, most natural sources come from wetlands (~170 Tg CH₄), with smaller contributions from freshwater ecosystems, natural geological seeps and fires⁵. Modest CH₄ mitigation from geologic seeps and fires seems more practical than mitigating larger and more diffuse wetland and freshwater sources.

Finally, Lackner suggests reasons to consider nitrous oxide (N₂O) removal as an alternative to CH₄ removal, a point we highlighted several times in our paper³, including the possibility of coupling N₂O and CH₄ removal. With an atmospheric lifetime of ~116 years (ref. ⁶), N₂O is longer lived than CH₄ and far more potent than both CH₄ and CO₂ on a mass basis. For many reasons, research on N₂O removal seems warranted. However, N₂O has the disadvantage of being even more dilute in the atmosphere (~330 ppb) than CH₄. Current conversion processes often produce pollutants NO and NO₂ from N₂O, not just N₂ and O₂ (for example, ref. ⁷).

¹Department of Earth System Science, Stanford University, Stanford, CA, USA. ²Woods Institute for the Environment, Stanford University, Stanford, CA, USA.

³Precourt Institute for Energy, Stanford University, Stanford, CA, USA. ⁴Department of Chemistry, Stanford University, Stanford, CA, USA. ⁵SLAC National Accelerator Laboratory, Stanford University, Stanford, CA, USA. ⁶Global Carbon Project, CSIRO Oceans and Atmosphere, Canberra, Australian Capital Territory, Australia. ⁷Department of Chemical Engineering, Stanford University, Stanford, CA, USA. ⁸SUNCAT Center for Interface Science and Catalysis, Stanford University, Stanford, CA, USA. ⁹Department of Applied Physics, Stanford University, Stanford, CA, USA. ✉e-mail: rob.jackson@stanford.edu

Finally, N₂O conversion does not have the extensive industrial research programme already in place today for oxidizing methane to methanol (CH₃OH).

We believe that CH₄ removal will eventually be practical and is likely to be deployed for decades to come. Our goal³ was, and remains, to stimulate research in the neglected field of negative emissions for methane, nitrous oxide and other gases beyond CO₂ alone.

Received: 5 November 2019; Accepted: 21 February 2020;
Published online: 23 March 2020

References

1. Lackner, K. S. et al. Capture of carbon dioxide from ambient air. *Eur. Phys. J. Spec. Top.* **176**, 93–106 (2009).
2. Lackner, K. S. Practical constraints on atmospheric methane removal. *Nat. Sustain.* <https://doi.org/10.1038/s41893-020-0496-7> (2020).
3. Jackson, R. B., Solomon, E. I., Canadell, J. G., Cargnello, M. & Field, C. B. Methane removal and atmospheric restoration. *Nat. Sustain.* **2**, 436–438 (2019).
4. Friedlingstein, P. et al. Global Carbon Budget 2019. *Earth Syst. Sci. Data* **11**, 1783–1838 (2019).
5. Saunio, M. et al. The global methane budget 2000–2012. *Earth Syst. Sci. Data* **8**, 697–751 (2016).
6. Prather, M. J. et al. Measuring and modeling the lifetime of nitrous oxide including its variability. *J. Geophys. Res. Atmos.* **120**, 5693–5705 (2015).
7. Fan, X., Kang, S., Li, J. & Zhu, T. Conversion of dilute nitrous oxide (N₂O) in N₂ and N₂-O₂ mixtures by plasma and plasma-catalytic processes. *RSC Adv.* **8**, 26998–27007 (2018).

Author contributions

All authors contributed to the ideas expressed in the paper. R.B.J. drafted the initial response.

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to R.B.J.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

© The Author(s), under exclusive licence to Springer Nature Limited 2020