World Academy of Science, Engineering and Technology
International Journal of Environmental and Ecological Engineering
Vol:15, No:8, 2021

Methane versus Carbon Dioxide: Mitigation Prospects

Alexander J. Severinsky, Allen L. Sessoms

Abstract**—**Atmospheric carbon dioxide (CO_2) has dominated the discussion around the causes of climate change. This is a reflection of a 100-year time horizon for all greenhouse gases that became a norm. The 100-year time horizon is much too long – and yet, almost all mitigation efforts, including those set in the near-term frame of within 30 years, are still geared toward it. In this paper, we show that for a 30-year time horizon, methane (CH_4) is the greenhouse gas whose radiative forcing exceeds that of CO_2. In our analysis, we use the radiative forcing of greenhouse gases in the atmosphere, because they directly affect the rise in temperature on Earth. We found that in 2019, the radiative forcing (RF) of methane was ~2.5 W/m^2 and that of carbon dioxide was ~2.1 W/m^2. Under a business-as-usual (BAU) scenario until 2050, such forcing would be ~2.8 W/m^2 and ~3.1 W/m^2 respectively. There is a substantial spread in the data for anthropogenic and natural methane (CH_4) emissions, along with natural gas, (which is primarily CH_4), leakages from industrial production to consumption. For this reason, we estimate the minimum and maximum effects of a reduction of these leakages, and assume an effective immediate reduction by 80%. Such action may serve to reduce the annual radiative forcing of all CH_4 emissions by ~15% to ~30%. This translates into a reduction of RF by 2050 from ~2.8 W/m^2 to ~2.5 W/m^2 in the case of the minimum effect that can be expected, and to ~2.15 W/m^2 in the case of the maximum effort to reduce methane leakages. Under the BAU, we find that the RF of CO_2 will increase from ~2.1 W/m^2 now to ~3.1 W/m^2 by 2050. We assume a linear reduction of 50% in anthropogenic emission over the course of the next 30 years, which would reduce the radiative forcing of CO_2 from ~3.1 W/m^2 to ~2.9 W/m^2. In the case of "net zero," the other 50% of only anthropogenic CO_2 emissions reduction would be limited to being either from sources of emissions or directly from the atmosphere. In this instance, the total reduction would be from ~3.1 W/m^2 to ~2.7 W/m^2, or ~0.4 W/m^2. To achieve the same radiative forcing as in the scenario of maximum reduction of methane leakages of ~2.15 W/m^2, an additional reduction of radiative forcing of CO_2 would be approximately 2.7 -2.15 = 0.55 W/m^2. In total, one would need to remove ~660 GT of CO_2 from the atmosphere in order to match the maximum reduction of current methane leakages, and ~270 GT of CO_2 from emitting sources, to reach "negative emissions". This amounts to over 900 GT of CO_2.

Keywords**—**Methane Leakages, Methane Radiative Forcing, Methane Mitigation, Methane Net Zero.

I. Introduction

WITHIN the last 10 years, there have been a growing number of record weather events that many observers have attributed to climate change. The general understanding of this phenomenon is that it is driven by atmospheric greenhouse gasses, of which the primary component is carbon dioxide (CO_2). The global community has now agreed to reduce CO_2 emissions by 2050 to a much smaller value than is being emitted today. This has been codified in international agreements, primarily the Paris Climate Accord of 2015.

The other large contributor to global warming is methane CH_4 [1]. When projections for temperature increases were centered on 2100, the relative contribution of methane was calculated for the generally accepted 100-year time horizon. Now, however, with the change to a much shorter period of 30 years, the contribution of methane deserves to be re-evaluated.

In a whitepaper titled "Implications of Using Different GWP Time Horizons", the Center for Methane Research [2] noted that its stakeholders are pushing to use of a 20-year time horizon for the Global Warming Potential (GWP) climate metric, as opposed to "the currently-accepted 100-year time horizon".[1]

In another whitepaper by the International Gas Union, "Understanding Methane Impact on Climate Change" [3], there is a more detailed discussion of the issue:

> "Using the IPCC's latest 20-year GWP factors would reduce the share of CO_2 to just over 50% from 76% in the 2010 global GHG mix, while the share of methane would increase to over 40% from the 2010 estimate of 16%." [3]

Illustration of these changes is presented on Figs. 1 (a) and (b).

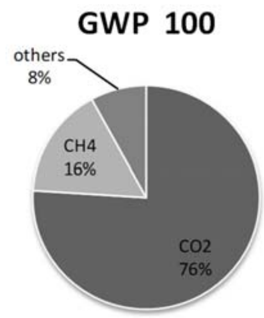

Fig. 1 (a) Averaging time horizon is 100 years

A.J. Severinsky is the Principal of American Development Laboratories, Washington, DC 20007, USA (corresponding author, e-mail: ajseverinsky@aol.com).

A.L. Sessoms is the managing partner of the Higher Education Innovation Group.

This work is voluntary, without any sponsors or financial support.

[1] "For methane, this change inflates the reported impact that each pound of methane released to the atmosphere has on climate by a factor of 3 (86 vs. 28) compared to a pound of carbon dioxide."

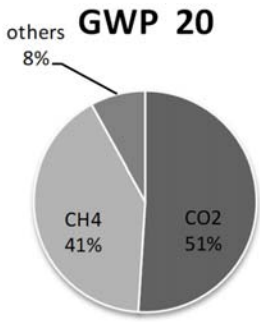

Fig. 1 (b) Effect of changing time horizon to 20 years

> "The selection of timescale substantially redefines the climate problem. Using 20-year GWP values, instead of 100-year figures, puts a much greater emphasis on short-lived gases like methane, while sharply reducing the weight of long-lived gases, particularly CO_2" [3].

Approximately 60% of total global methane emissions come from human activity, with the other 40% occurring naturally. In order of magnitude, the largest sources of anthropogenic methane emissions are agriculture, fossil fuels, and industry. These re-evaluations prompted us to analyze the existing technical data on the relative greenhouse effects of methane and carbon dioxide in order to calculate effects of possible and/or required reduction actions, and then compare relative impacts of both on global warming trends.

II. Radiative Forcing and GWP

The GWP is the time-integrated Radiative Forcing (RF) due to the pulse emission of a given component of atmospheric gas, such as CH_4, relative to a pulse emission of an equal amount of a reference gas, CO_2.

RF directly affects the Earth's rise in temperature. There is a simple relation explained in IPCC TAR-06 [4]:

> "The climate sensitivity parameter (global mean surface temperature response ΔTs to the radiative forcing ΔF) is defined as:
>
> $$\Delta Ts \;/\; \Delta F = \lambda,$$
>
> where λ is a nearly invariant parameter, typically about 0.5 $^{o}C/(Wm^{-2})$ for a variety of radiative forcing, thus introducing the notion of a possible universality of the relationship between forcing and response. It is this feature which has enabled the radiative forcing to be perceived as a useful tool for obtaining first-order estimates of the relative climate impacts of different imposed radiative perturbations".

We will use the RF of methane and carbon dioxide to compare prospective mitigation actions.

The RF of Methane Assuming No Emissions beyond 2019

In order to set this benchmark, we calculate the RF for methane, assuming no emissions after 2019. This will allow us to demonstrate the impact of ongoing continuing emissions beyond that point. The main source is [6], the National Oceanic and Atmospheric Administration (NOAA) Annual Greenhouse Index, which was updated in Spring 2020. In the referenced report, RF is calculated in reference to 1750, the same reference year as in the IPCC reports, as an average for a 100-year time horizon. These values must be corrected based on recent research in [7]. The resulting corrected ΔF_{100} is 0.516 + 0.13 = 0.646 W/m^2. This is the "anchor" value that we use to calculate the methane average RF at other time horizons.

In [5], RF and GWP are presented for an expanded set of gases. In the same report [5], on page 712, Fig. 8.29 shows the GWP of methane as a function of time horizon. These data are included here as Fig. 2.

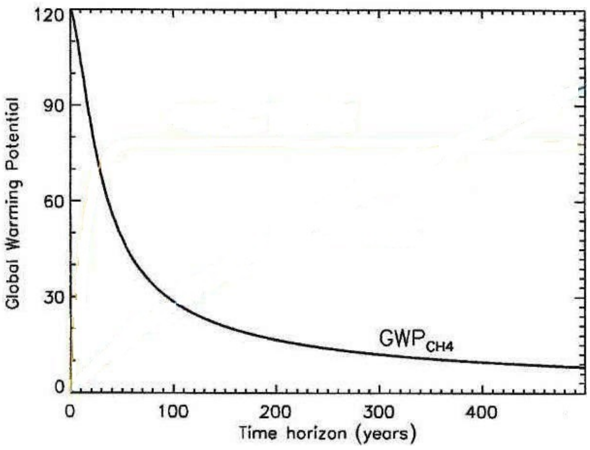

Fig. 2 GWP of methane

The graph marked "GWP_{CH4}" is for a relative change in the RF of methane, in comparison with carbon dioxide, from 120 at a time of emission to an ~84 average of the first 20 years, and further to a ~28 average in the 100 years since original emission.

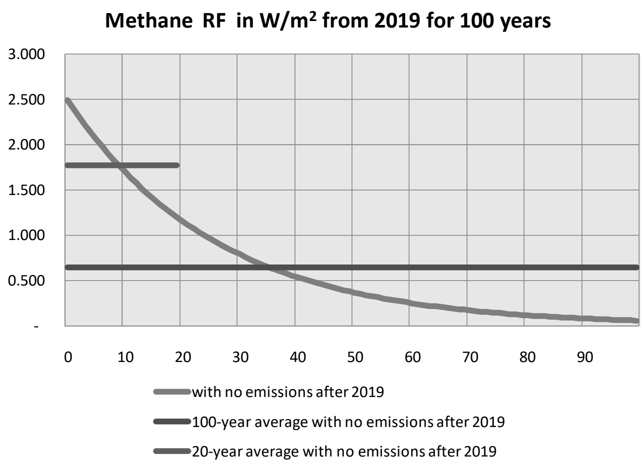

Fig. 3 Methane RF as a function of time after initial emission

We calculated the annual reduction coefficient of methane RF using the following three values: 120 for year 0 in [5], 84-86 for a 20-year average, and 28-34 for a 100-year average [3]. At the annual decay coefficient value of 0.962224 and the function value of 120 at year 0, the 20-year average is 85 and the 100-year average is 31, which agrees with values of [3]. The summary of this calculation anchored in a 100-year average value of 0.645 is presented in Fig. 3.

The calculations show that ΔF at the time of emission is ~2.49 W/m^2, the 20-year average is ~1.77 W/m^2, and the 100-year average is 0.645 W/m^2. These results are predicated on the reliability of methane abundance measurements presented in Butler [5]. We include Fig. 1 from this NOAA report as Fig. 4. Of note is the legend in the lower left corner that defines "open symbols" as representing inactive sites. The main sources of methane emissions are in the Arctic Ocean, over the tundra, in China, and in the Middle East, where measurement capabilities are limited. In the future, after 2022, the advent of comprehensive satellite data will provide more complete coverage of these areas.

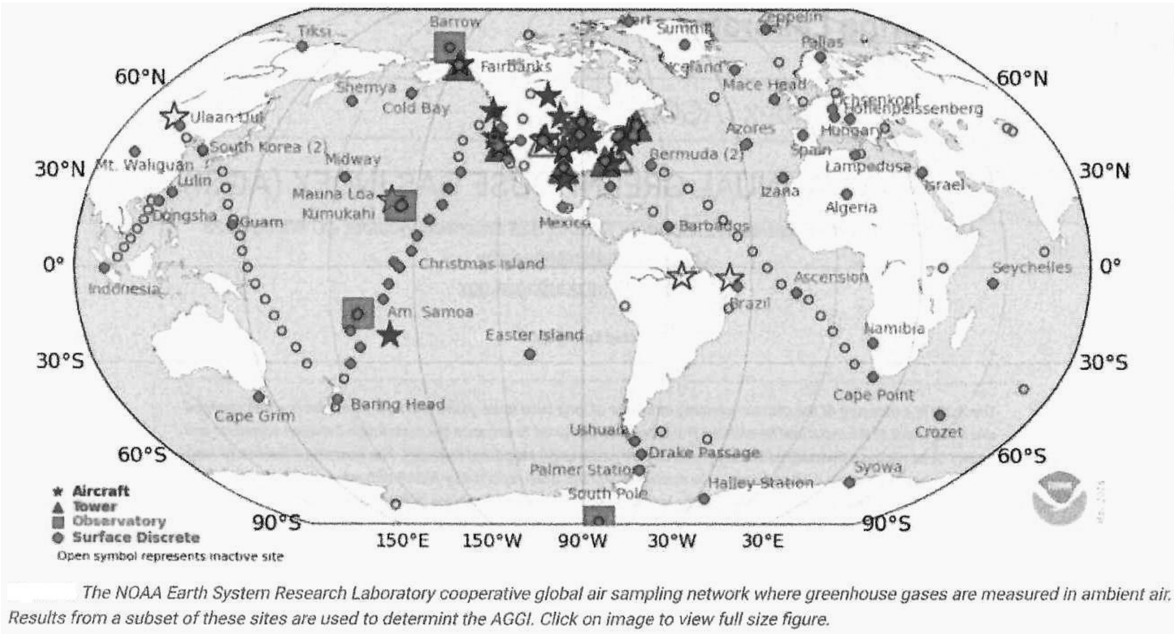

Fig. 4 Map of measurement sites for greenhouse gases [5]

The RF of Methane Assuming Constant Future Emissions at 2019 Levels

Any new annual emissions of methane will provide the same increase in RF. Since RF is reduced naturally, as depicted in Fig. 3, new emissions will increase these values. As follows from Fig. 3, at the time of emission, the RF is 2.49 W/m^2 and will be reduced in a year using reduction coefficient 0.962224 to 2.395, which is a difference of 0.094 W/m^2.

We find in [6] that, in the last five years, the NOAA 100-year average RF increased from 0.499 W/m^2 in 2014 to 0.516 W/m^2 in 2019. This is (0.516-0.499)/5 = 0.0034 W/m^2/year. At the time of emission, the RF is 2.49 W/m^2, in comparison with that of 0.516 W/m^2 as NOAA's 100-year average. Changing the annual emissions in the same proportion, we calculate that the contemporaneous increase in RF annually at the time of emission is 0.0034 x (2.49/0.516) = 0.0164 W/m^2. The RF at the time of emission is the sum of the reduction by natural effects and the recorded increase, and thus it is 0.094 + 0.0164 = 0.1104 W/m^2.

Now, we can calculate how the RF of methane will change over time, given a 0.1104 W/m^2 annual increase. We do this on an annual basis by reducing prior year RF using coefficient 0.962224 and adding a fixed amount of the new emissions of 0.1104 W/m^2. The results are shown in Fig. 5.

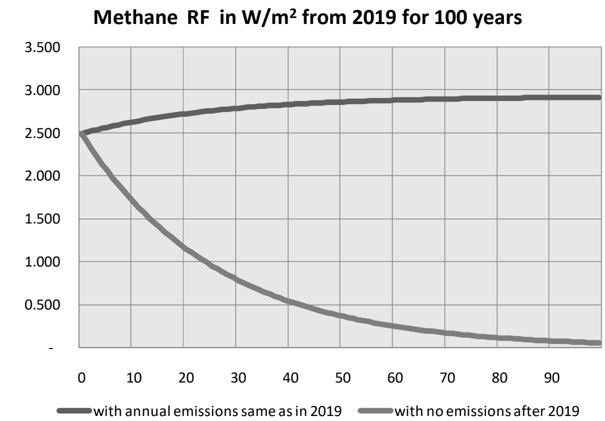

Fig. 5 Methane RF based on additional annual emissions of 2019 (dark line) and no additional emissions (grey line)

The difference is large. For reference, 30 years from time 0, the RF will increase from 2.49 W/m^2 to ~2.78 W/m^2, and in 100 years, it will increase to ~2.91 W/m^2. This is in comparison with ~0.82 in 30 years and 0.055 in 100 years without new emissions after time 0.

Sources of Methane Emissions

Data on methane emissions are presented by IEA (International Energy Agency) [8] over the past four years, 2017-2020. The emissions summary is in Table I. Extensive discussions of these sources are also given in [17] and [18]. The main addition is in natural emissions in the range 245 to 488, with an average value of 371 million tons. Studies indicate that estimates are based on some inventories and some *modeling* and give the total range of ~600 to 880 million tons.

TABLE I
METHANE EMISSIONS SUMMARY

Category	Major Sources	Annually, Million tons
	Gas distribution	45
Fossil fuels	Oil wells	39
	Coal mines	39
Biofuels	Anaerobic digestion	11
	Enteric fermentation	
Industrial agriculture	Rice paddies	145
	Manure management	
Biomass	Biomass burning	16
	Solid waste	
Consumer waste	Landfill gas	68
	Wastewater	
	Anthropogenic Emission	363
Wetlands	Wetland methane	194
	Geologic seepages	
	Volcanic gas	
	Arctic melting	
Other natural	Permafrost	39
	Ocean sediments	
	Wildfires	
	Termites	
	Natural Emissions	233

Analysis of Methane Leaks

In this study, we analyze methane emissions or leakages from natural gas production, distribution, and use. Methane is the main compound of natural gas. The reason is practical - out of all anthropogenic sources, the reduction of leakages from natural gas seems to be the easiest to implement. Out of the total amount, 70-100 million tons [17], [18] are attributable to oil and gas leakages, and approximately half from each source, 35-50 million tons, is attributable to natural gas emissions. This value is small in comparison with the near 900 million tons in total. There exists a large number of business, public, technical, and scientific publications that describe planned actions to reduce natural gas leakages based on these estimates. We wanted to “ground truth” the accuracy of such small relative estimates of leakages, especially since they are based in part on modeling.

First, we looked into the worldwide production values of natural gas. In 2018, there were approximately 4,000 billion m^3 (cubic meters) of natural gas produced. At an average density of 0.8 kg/m^3, this equals approximately 3,200 million metric tons.

Comparing the estimated leakages of 35-50 million tons to the 3,200 million tons produced implies a leakage rate of ~1-1.5%, which appeared to us as being much too low. Eliminating such small amounts of leakage will not change methane RF to any meaningful degree and would not justify the current efforts to eliminate them.

Given the limited global monitoring of methane leaks, we have opted to rely on publicly available information [2], [3], [4], [5], [6]. By triangulating all of this evidence, we can estimate the global natural gas leakages from production to consumption as summary of worldwide methane leakages:

- Drilling and fracking (production): 6%
- Transportation to customer terminals: 3%
- Customer distribution: 3%
- Total: 12%.

This estimate is based on a comparative analysis of numerous mutually independent statements and studies and must be bracketed into a range. On the high side, it is hard to imagine that 20% is lost without also drawing the owner's attention to the economic losses. On the low side, there are aerial measurements of methane emissions in the Permian basin in Texas which give 3-4% methane leakage from production. This allows us to assume that, on a low side, leakages might be a half, or 6% in total. Of course, the reduction of large leakages will lead to a conclusion of a prospective large reduction of RF which might be too optimistic. Hence, conservatively, we analyze RF reductions at two values for leakages: 12% and 6%. At 3,200 million tons of annual production, this corresponds to ~380 and ~190 million tons.

RF of Methane with Reductions of Leakages

We summarize our findings of methane emissions in million tons per year by using minimum and maximum scenarios.

TABLE II
SHARE OF NATURAL GAS LEAKAGES FOR PROSPECTIVE REDUCTION IN CLIMATE MITIGATION ACTION.

Methane emission sources	MIN.	MAX.
Natural	488	245
Anthropogenic	393	349
NG leakages included	-50	-35
Our triangulated leakages value	190	380
Total Emission Estimate	1,021	939
80% of triangulated NG leakages	152	304
Share of NG leakages	0.15	0.32

The designations "MIN" and "MAX" indicate the share of methane (natural gas) leakages in the total methane emissions estimate. We follow the same 80/20 rule for prospective reduction of total leakages, as in other plans for the reduction

[2] "…about 10% of gas transformed into liquefied natural gas is released into the atmosphere between production and consumption, according to Shell." [9]

[3] "More than half of the *natural* gas leaked is emitted during drilling and fracking operations, but the remaining 40% is emitted in other stages, including distribution to customers…" [10]

[4] "In the PHMSA database, which lists more than 1,400 *natural* gas companies, 72 companies reported lost and unaccounted *gas* for rates of 10% or higher. 275 companies had a rate between 3 and 9.9%." PHMSA stands for "The federal (USA) Pipeline and Hazardous Materials Safety Administration." [11]

[5] "The owner Gazprom reports ~0.3% leakages from pipelines … while majority of other estimates are 8-15 times larger," 2.5 to 4.5%." [12]

[6] "The new study used a rate of 2.7%, basing it off a number in a 2015 study for Boston, which, like Providence, has a large percentage of old pipes made of outdated materials." "Washington Gas Light Co., which serves the greater District of Columbia, had a 3.65% loss rate in 2012." [13]

of carbon dioxide or methane leakages. We will not speculate on how these leakages might be reduced over time, or from which systems in production, processing, and/or distribution. We simply want to compare this with the RF without a reduction of leakages.

To calculate the graphs of RF over time for both scenarios, we use the same method leading to Fig. 5. We reduced annual RF addition of 0.1104 W/m^2 by 15% for MIN scenario, and 32% for MAX scenario. The results are depicted in Fig. 6. These are interesting results. First, let us compare the RF of methane in 2020 to that of in 2100. In the MIN share scenario, there is no reduction of this forcing at all, while in the MAX scenario, there is a reduction from ~2.5 to ~2.0, or 0.5 W/m^2. Secondly, there are much larger reductions in comparison with future RF under the existing annual emissions scenario. For the MIN scenario, in 30 years the reduction in RF will reach ~0.3 W/m^2, and in 100 years, it will be 0.43 W/m^2. For the MAX scenario, these values are ~0.64 and ~0.92 W/m^2, respectively. Now, let us compare these reductions in RF with the mitigation actions that are necessary in order to achieve the same results for reductions in carbon dioxide emissions alone.

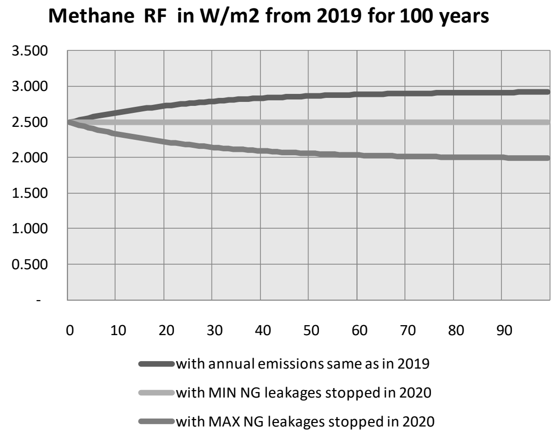

Fig. 6 Methane RF with and without the reduction of natural gas leakages by 80%

III. Reduction of RF by the Reduction of Carbon Dioxide in Atmosphere

First, we will look at the existing RF of carbon dioxide and then project the values going forward using the trend in the last five years, the same as we did for methane. From the same source, [6], we find the data in Table III. From these data, we derive annual average RF increase of 0.0336 W/m^2/year.

TABLE III
Historical RF of Carbon Dioxide

Year	W/m^2
2014	1.908
2015	1.938
2016	1.985
2017	2.013
2018	2.044
2019	2.076

In CO_2 sources, [14]-[16], we find the data for CO_2 emissions that are presented in Table IV.

TABLE IV
Global Carbon (Carbon Dioxide) Emissions.

Year	Anthropogenic C in GT	Natural C on GT
2014	9.61	1.66
2015	9.62	1.70
2016	9.66	1.54
2017	9.77	1.47
2018	9.98	1.51
Annual Average CO_2	35.65	5.77

The standard deviation for the combined emissions is ~1%, suggesting a nearly constant level of annual emissions. This means that the annual RF increases nearly linearly, and thus leads us to conclude that we can estimate increases in RF going forward in proportion to changes in emissions.

We selected a time interval from 2020 to 2050 because it reflects the current thinking for achieving "net zero" carbon dioxide emissions. This includes "negative emissions" efforts, which assume removing carbon dioxide from the atmosphere. British Petroleum has suggested that going forward, this means that there must be a 50/50 split between eliminating anthropogenic emissions and removing leftover emissions from the atmosphere [19]. By applying this ratio to the data listed in Table III, we find that by 2050, the reduction in annual emissions should be ~18 GT out of ~42 GT, or ~43%. Further applying to the RF reduction by 2050, it will be today's average increase of 0.0336 W/m^2/year reduced by 43%, resulting in 0.0195 W/m^2/year. While we assumed in the estimate of methane emissions that 80% of leakages could essentially be eliminated immediately, we will also make the assumption that the speed of carbon dioxide emissions reduction is much slower due to the large socio-economic-political difficulties that coincide with doing so. We assume that the RF annual increases would be reduced linearly from 0.0336 to 0.0195 W/m^2 between now and the year 2050.

The calculations for both scenarios are presented in Fig. 7.

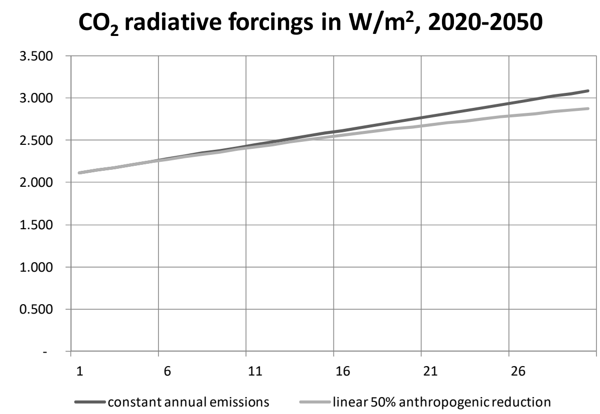

Fig. 7 CO_2 RF under BaU (dark line) and "net zero" (grey line) Scenarios

If we were to add "negative emissions" for another 50% of anthropogenic emissions in the same linear fashion, then this will add another ~0.2 W/m^2 reduction by 2050.

IV. Comparison of Mitigation Projections for Methane and Carbon Dioxide by 2050

We combined all of the data for RF in different prospective mitigation projections in Table V.

TABLE V
SUMMARY OF THE RF OF METHANE VS. CARBON DIOXIDE

RF, in W/m²	2020	2050	Δ	Δ over BaU
Methane				
BaU	2.49	2.78	0.29	
Natural gas leakages stopped in 2020				
MIN.	2.49	2.49	0.00	-0.29
MAX.	2.49	2.15	-0.34	-0.63
Carbon dioxide				
BaU	2.11	3.08	0.97	
"net zero"				
linear reduction of 50% of anthropogenic	2.11	2.88	0.77	-0.20
plus "negative emissions" for the other 50%	2.11	2.68	0.57	-0.40
Deficit over methane				
"net zero" vs. MIN.		0.19		
"net zero" vs. MAX.		0.53		

We observe that methane RF is substantially larger than that of carbon dioxide in 2020, but that carbon dioxide RF increases more rapidly. The reason for this is that methane emissions are "burned" in the atmosphere to some degree, but carbon dioxide only accumulates. By 2050, the opposite becomes true, with carbon dioxide RF becoming larger than that of methane.

Interestingly, stopping leakages of methane without affecting its use has a much larger mitigation effect than the draconian reduction in fossil fuels usage that is required in "net zero" scenarios. In full 100% anthropogenic "net zero," CO_2 radi RF is decreased by 0.4 vs. 3.08 BaU, but 80% of methane leakages reduction in 2020 in the MAX scenario decreases RF by 0.63 vs. 2.78 BaU. Such advantages led us to inquire as to what volume of these gases are involved in reaching these reductions in RF. The calculated volumes are summarized in Table VI.

In our calculations, we used our findings of 0.0336 W/m^2/year increase in carbon dioxide RF for 42 GT annual emissions.

The results are sobering. In order to reduce RF by 0.63 W/m^2, we need to stop 0.3 GT of methane leakages in 2020. To reduce RF of carbon dioxide by the same 0.63 W/m^2, we first need to reduce linearly the use of 50% of all anthropogenic sources within the next 30 years. We need to stop 270 GT of such emissions. In addition, much more sobering is the act of removing carbon dioxide from the atmosphere. It includes 270 GT of the remaining 50% of anthropogenic emissions, plus ~660 GT to match this 0.63 W/m^2 reduction; 930 GT in total. Moreover, if we want to maintain the RF of carbon dioxide at 2020 levels, just as in the methane MIN scenario, then we need to add another 50 GT. This is a quite a revealing result: removing just 0.3 GT of methane vs. 930 to 980 GT of carbon dioxide gives the same reduction in the RF.

TABLE VI
COMPARATIVE VOLUMES OF METHANE AND CARBON DIOXIDE

Required Reduction Volume, in GT	2020	2050
Methane leakages stopped in 2020		
MIN.	0.15	
MAX.	0.30	
Carbon dioxide		
linear reduction of 50% of anthropogenic	0	270
to be removed from atmosphere		
"negative emissions" for other 50%	0	270
to compensate for deficit vs. MIN methane	0	237
to compensate for deficit vs. MAX methane	0	662
to maintain RF at 2020 level, like in methane MIN scenario	0	50

An overwhelming cost of the implementation of carbon dioxide mitigation scenarios is in energy. Stopping methane leakages is not energy intensive. For carbon dioxide, this is the major issue. To obtain some idea of what this means, we calculate the energy released in the production of this amount of carbon dioxide. The most plausible option for storing such a large amount of carbon dioxide is to convert it back to the very same compounds from which it originated. For example, a study from the University of Heidelberg[7] demonstrated that pumping carbon dioxide into underground reservoirs mineralizes only 10%, with the other 90% being taken back into air through dissolution in water. The combustion energy of carbon is ~9 kJ/g. For 930 GT or $930x10^{(9+6)}$ g, it is ~$8.4x10^{18}$ kJ. A year is approximately $31x10^6$ seconds, and so, if we were to remove this amount in 30 years using only anthropogenic means, we would need new electricity generating capacity of $8.4x10^{18}/30/31x10^6 = 9$ TW. For comparison, the global electric energy consumption was ~2.6 TW in 2019. To this energy, we must also add the energy for the extraction of carbon dioxide from atmosphere and the entropy of processes recovering carbon from carbon dioxide. For reference, in combustion processes, the entropy is nearly twice as large as the amount of work energy that is received.

Acknowledgment

The authors are grateful to Dr. James Baker, for alerting us to the paper by M. Etminan et al.

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[2] Center for Methane Research (CMR), 1700 S. Mount Prospect Rd. Des Plaines, Illinois 60018 www.gastechnology.org; Implications of Using Different GWP Time Horizons. https://www.gti.energy/wp-content/uploads/2019/02/CMR-Implications-Using-Different-GWP-Time-Horizons-White-Paper-2019.pdf

[7] "Gilfillan et al.' (page 614 of this issue) illuminate this crucial matter by showing that dissolution in groundwater is by far the most important trapping mechanism for CO_2, in the subsurface environment. In other words, sequestering CO_2 in geological formations would probably produce vast quantities of highly CO_2-enriched sparkling water. …overall conclusion is that in the nine gas fields investigated, covering different geological settings, solubility trapping played a major part, removing up to 90% or more of the initially emplaced CO_2. Mineral trapping played a minor part at best." [20]

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