Proposed policymaker-friendly metric of radiative effects of greenhouse gases

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Abstract.

This paper proposes a simple metric for the dynamic evaluation of the cumulative, combined impact on global warming of greenhouse gasses. As an illustration, the metric is applied to methane (natural gas) when used for energy production. The proposed metric accounts for the effect on a decadal timescale of energy policies based on natural gas as a purported bridge fuel. Results of a thought experiment evaluated by the proposed metric explicitly show problematic policy aspects of the commonly employed global warming potential of methane with a 100-year time horizon which:

1: lacks a solid scientific basis and is incompatible with crucial timescales;

2: does not allow for continuous-time dynamic tracking of greenhouse gas emissions; and

3: is incompatible with the Precautionary Principle.

1 Introduction

Hansen et al. (2008) argue that atmospheric CO_2 concentration exceeding 350 ppm poses a serious threat to human existence and life on earth in general. As the authors put it in their abstract:

> If humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that. The largest uncertainty in the target arises from possible changes of non-CO_2 climate forcings.

The paper warned that continued growth of greenhouse gas emissions for just another decade—after 2008—would make it practically impossible to avoid catastrophic effects on the climate system. A decade later, atmospheric CO_2 is fluctuating around 410 ppm (Pro Oxygen, 2018) and it still appears to be increasing at a rate roughly in the range of 2–2.5 percent per year.

In the aforementioned quote, the authors qualify the critical number, 350 ppm, mentioning that it is likely too high, as it fails to account fully for the dangers of non-CO_2 forcings. Of these, atmospheric methane is dominant. What is more, methane forcing today is far more impactful than it was in 2008. For instance, Turner et al. (2016) concluded on the basis of satellite and surface data that there had been a large increase in the methane emissions of the United States over the decade prior to their study. Worden et al. (2017) subsequently traced this increase back to fossil fuel sources.

At the same time, as numerous publications over the last decade have made clear, the climate system is changing at a rate outpacing projections, those of the Intergovernmental Panel on Climate Change (IPCC) in particular. For instance, Rahmstorf et al. (2007) mention that projections may have underestimated changes in sea level rise. Hansen et al. (2013) mention that end of summer Arctic sea ice has been declining a factor of four faster than in IPCC models. Also the *Third National Climate Assessment* (Melillo et al., 2014) states that the "only real surprises have been that some changes, such as sea level rise and Arctic sea ice decline, have outpaced earlier projections." Brown and Caldeira (2017) discuss rapid nonlinear melting of the Greenland and Antarctic ice sheets not represented in IPCC model assessments.

There are numerous other such under-predicted developments such as, for example, the Arctic amplification documented in recent *Arctic Report Cards* issued by the National Oceanic Atmospheric Administration (a, b). Underestimates should not come as a surprise. Indeed, Brysse et al. (2013) *et al.* discuss a series of examples of scientists "erring on the side of least drama."

Developments of the cryosphere clearly have a large decadal component and indeed, as Steffen et al. (2018) and also Rintoul et al. (2018) have argued, decisions made during the next one or two decades may lead to irreversible changes of the climate system. Nonetheless, and in spite of critical observations of IPCC going back to its *Second Assessment Report* (Houghton et al., 1995), the global warming potential (GWP) with a 100-year time horizon has become the metric employed— pursuant to the United Nations Framework Convention on Climate Change (UNFCCC)— to assess public policy with respect to multi-gas (usually called CO_2 equivalent) emissions.

With the considerations in mind it should be noted that IPCC's *Fifth Assessment Report* (AR5) explicitly states that there is no scientific argument for using the 100-year GWP horizon—see, *e.g.,* page 711 of Stocker et al. (2013).[1] In fact, as AR5 puts it: "All choices of metric contain implicit value-related judgements such as type of effect considered and weighting of effects over time." Note against this background that Ocko et al. (2017) have pressed for more transparency in climate policy issues with respect to the often hidden implied temporal trade-offs.

The climate system of the earth is a complex system far from thermodynamic equilibrium with many inseparable time- and lengthscales. In such a system, uncontrolled, scientifically hard to justify approximations will always characterize any attempt to isolate simple metrics for use by policy makers to gauge—as was IPCC's design purpose—the relative radiative effects of divers greenhouse gasses.

More specifically, as argued above, the disruption of the climate system of the earth and the human role in it clearly have important decadal timescale features. Given this, use of the 100-year horizon as the basis of major energy policy decisions has no basis in science. Whatever value judgments may have led to general acceptance of this 100-year metric, it appears to be irreconcilable with the Precautionary Principle, number 15 of the Rio Declaration of the United Nations General Assembly; United Nations Change Change. For further discussion of this see Section 2.

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[1] The following is a representative list of comments about the global warming potential to be found in various IPCC assessments: Houghton et al. (1995) pages 21 and 73; and Stocker et al. (2013) pages 58, 663, 710, and 711.

In addition to these general considerations and because of the shift in the United States over the last decade to natural gas,[2] which is used increasingly for the generation of electricity, it is imperative to provide policymakers with tools that do not downplay the effects of non-CO_2 emissions with very strong near-term effects on the climate.

The simple dynamical metric proposed here produces order of magnitude estimates based the instantaneous global warming potential rather than the one based on the 100-year horizon. The results show that simple, user-friendly alternatives exist for the 100-year time horizon global warming potential. Edwards and Trancik (2014) presented a similar approach, one that also focuses on a dynamical approach rather than the static one implicit in the use of any non-instantaneous global warming potential.

The layout of the paper is as follows: Section 2 reviews some of the well-known basic properties of methane and introduces the proposed simple dynamical metric. Section 3 presents results of some simple energy policy thought experiments. Finally, Section 4 summarizes the conclusions.

2 Methane basics

The global warming potential, as mentioned in Section 1, is a simple tool designed to estimate the relative effect of greenhouse gasses on global warming. It was designed and accepted to assist in policy making. This quantity is a dimensionless multiplier that converts the effect of the emission of a unit mass pulse of a greenhouse gas under consideration to a mass of CO_2 that would have the same global warming effect, the CO_2 equivalent (CO_2e) mass. A pulse of CO_2 injected into the atmosphere is taken up by the ocean, biosphere and soil and decays by half in about 25 years but 20% is still in the atmosphere after 500 years; see Fig. 4A in Hansen et al. (2013). Atmospheric CH_4, on the other hand, has a half-life of less than a decade.

More explicitly, the global warming potential, as defined in Section 8.7.1.2 of Stocker et al. (2013), is a fraction: the time-integral of the radiative forcing due to a pulse emission of a given greenhouse gas divided by same quantity for a pulse of an equal mass of CO_2. Due to the atmospheric dynamics of both CO_2 and CH_4 the resulting global warming potential depends on the time interval used in the integrals, aka the time horizon. The global warming potential is denoted by G_t with t the time horizon in units of years.

The choice of the time horizon t is a major source of arbitrariness. In addition to the value judgment mentioned in Section 1 and acknowledged by the Intergovernmental Panel on Climate Change (IPCC), there is the issue of the timescales relevant to the physical process and policy decisions under consideration.

For a project small on a global scale, averaging emissions over the expected life time of that project might make physical sense, but for matters of global scale, such as the energy policy major global greenhouse gas emitting nations, the horizon should be set by the timescale of the global climate change phenomena and the danger they pose to life on earth. Therefore, as mentioned in Section 1, there notably are the following considerations, among others:

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[2] Exploration and production subsidies from the federal government have increased dramatically, during the Obama administration; see, *e.g,* Oilchange International. This trend is expected to accelerate during the Trump administration.

1. The arguments made by Hansen (2005) and the well-known difficulty of predicting instabilities (aka state shifts or tipping points) such as the sudden and, on a human multi-generational timescale irreversible, disintegration of ice sheets; *i.e.,* as Drijfhout et al. (2015) put it, the fact that tipping points "notoriously difficult to foresee;"
2. Recent developments on a decadal timescale in the Arctic (National Oceanic Atmospheric Administration, a, b);
3. The fact that decisions made in the next one or two decades may determine the fate of the future of Antarctica and the Southern Ocean, as argued by Rintoul et al. (2018) argue, or set the climate system on a for all practical purposes irreversible trajectory to what Steffen et al. (2018) refer to as "Hothouse Earth;"
4. The international treaty obligation of the Precautionary Principle 15 of Rio Declaration mentioned in the Section 1 (United Nations General Assembly; United Nations Change Change).

Based on these matters, and the simple, mathematical fact that non-instantaneous global warming potentials cannot be used straightforwardly in a dynamical approach, the metric proposed in this paper uses the instantaneous global warming potential G_0, the instantaneous radiative forcing relative to that of CO_2.

The effect of the choice of the time horizon manifests itself explicitly in the critical fraction f_c of fugitive CH_4 above which the global warming impact of the unburned, fugitive methane cancels out its higher energy density per unit emitted CO_2. To find f_c, suppose one generates energy from one mole of CH_4 a fraction f of which escapes unburned. The part that is burned adds $(1-f)$ moles of CO_2 to the atmosphere. Given G_t, the global warming potential of CH_4, the fraction f of fugitive CH_4 adds $(4/11)fG_t \equiv G'_t$ to the atmospheric CO_2 equivalent. The total increase is $1-f+fG'_t$. Note that the molecular mass ratio $4/11$ of CH_4 and CO_2 appears because of the conventional definition of the global warming potential G_t, which compares the effects of a *unit mass* of CH_4 of to the effect of the same mass of CO_2, rather than the same number of *moles*; see (Stocker et al., 2013, p. 710).

Different fuels emit different amounts of CO_2 per unit energy produced upon combustion. Suppose that per unit CO_2 produced, CH_4 generates a factor ε more energy than some other fuel, say coal or oil. For coal the calculations in this paper use typical values: $\varepsilon = 2$ and for oil $\varepsilon = 4/3$ (U.S. Energy Information Administration (EIA), 2018). Taking into account the fugitive gas loss of CH_4, to produce the same amount of electric energy as from CH_4, one has to burn a relative amount of $(1-f)\varepsilon$ coal or oil.

The critical fraction f_c for which both processes have the same impact on the climate follows from the equation

$$1 - f_\mathrm{c} + f_\mathrm{c} G'_t = (1 - f_\mathrm{c})\varepsilon, \tag{1}$$

so that

$$f_\mathrm{c} = \frac{\varepsilon - 1}{\varepsilon - 1 + G'_t}. \tag{2}$$

Tab. 1 shows the critical fractions for fugitive CH_4 for various time horizons and fuels.[3]

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[3] For the global warming potential G_t see (Stocker et al., 2013, Table 8.7), which contains the numbers for the 20- and 100-year horizons, *viz.* 86 and 34. For further details and the instantaneous global warming potential see Fig. 8.29, Tables 8.7 and 8.A.1 on pages 712, 714, and 731, *ibid.*

Table 1. Critical fractions f_c for coal and oil for global warming potentials G_t with various time horizons t in units of years.

	$G_0 = 120$	$G_{20} = 34$	$G_{100} = 86$
$\varepsilon = 2$ (coal)	2.2%	3.1%	7.5%
$\varepsilon = \frac{4}{3}$ (oil)	0.76%	1.1%	2.6%

Before discussing the relevant kinetic equations, we recall that the solution of the decay equation with decay time τ for any $g(t)$ with source $s(t)$ subject to initial condition $g(0) = 0$,

$$\dot{g}(t) = -g(t)/\tau + s(t), \tag{3}$$

where $\dot{g} = dg/dt$, is given by

$$g(t) = \int_0^t e^{-(t-t')/\tau} s(t')\, dt', \tag{4}$$

for $t \geq 0$.

For the kinetic equations it is convenient to use molar number densities: $c(t)$ for CO_2, $m(t)$ for CH_4, and $c_e(t)$ for the CO_2 equivalent of the mix. Generalization is straightforward, but to simplify the thought experiment presented in this paper and obtain the order-of-magnitude estimates of interest—the results of which are in Section 3—it suffices to account only for the greenhouse gases CO_2 and CH_4. The CO_2 equivalent is given by:

$$c_e(t) = c(t) + G_0' m(t). \tag{5}$$

Because of the mass convention used in the definition of the global warming potential, this equation once again contains G_0' rather than G_0. A further assumption in this thought experiment is that all of the *increase* in atmospheric CO_2 comes from the hypothetical future use of methane only. As a consequence, there are the following sources for increased emissions: *(i)* the combustion of CH_4; and *(ii)* the oxidation of fugitive CH_4 as it decays in the atmosphere. This will correspond to two source terms in the kinetic equations.

That is, if $p(t)$ is the rate of increase in CO_2 produced by coal or oil, using methane to generate the same power, yields the following rate of increase of CO_2:

$$\dot{c}(t) = p(t)/\varepsilon + m(t)/\tau, \tag{6}$$

where the last term arises from the CO_2 production rate due to the oxidation of atmospheric CH_4; here $\tau = 12.4$year, the atmospheric decay time of CH_4 ((Stocker et al., 2013, Table 8.7)). The rate of increase of CH_4 is:

$$\dot{m}(t) = -m(t)/\tau + \frac{f}{(1-f)\varepsilon} p(t), \tag{7}$$

the last term accounts for the emission of fugitive CH_4. The desired solution of the differential equations corresponds to the hypothetical case in which for $t < 0$ power generated by combustion of coal and oil only. At $t = 0$ the a complete switch takes place to $\mathrm{CH_4}$. The corresponding solution, subject to initial condition $m(0) = 0$—a simplification made for the purpose of this thought experiment—is

$$m(t) = \int\limits_0^t e^{-(t-t')/\tau}\,\frac{f}{(1-f)\varepsilon}p(t_1)\,dt_1. \tag{8}$$

Substitute Eq. (8) into Eq. (6) and integrate, assuming $c(-\infty) = 0$

$$c(t) = \int\limits_{-\infty}^{0} p(t_1)\,dt_1 + \int\limits_0^t [p(t_1)/\varepsilon + m(t_1)/\tau]\,dt_1. \tag{9}$$

An additional assumption made in the choice of this metric is that $\mathrm{CO_2}$ is treated as an atmospheric gas with an an *infinite decay time.* In other words, for $\mathrm{CO_2}$ the first term on the right-hand side of Eq. (3) vanishes, so that $\mathrm{CO_2}$ evolves by simply adding up for ever. The justification for this approximation is that, as shown by Matthews et al. (2009), the total allowable emissions, *i.e.,* the budget for climate stabilization, is approximately independent of the time and place of those emissions. At the same time, the metric developed here is set up so that policy makers can track the expenditures to be charged to that budget as a result of their policies.

The final result for the atmospheric $\mathrm{CO_2}$ equivalent concentration at time $t > 0$ is obtained by substituting Eqs. (8) and (9) into Eq. (5). Subject to the specified initial conditions, the solution of the differential equations is:

$$c_{\mathrm{e}}(t) = \int\limits_{-\infty}^{0} p(t)\,dt + \frac{1}{\varepsilon}\int\limits_0^t p(t_1)\,dt_1 + \frac{f}{(1-f)\varepsilon}\left[G_0'\int\limits_0^t e^{\frac{t_1-t}{\tau}}p(t_1)\,dt_1 + \frac{1}{\tau}\int\limits_0^t\int\limits_0^{t_1} e^{\frac{t_2-t_1}{\tau}}p(t_2)\,dt_2\,dt_1\right]. \tag{10}$$

Note that the first two terms represent the cumulative emissions since the Industrial Revolution, approximated here as having occurred at $t = -\infty$ and the additionally accumulated amount as of $t = 0$, when the in this thought experiment hypothetical switch to $\mathrm{CH_4}$ occurs. The third term represents the $\mathrm{CO_2}$-equivalent of the accumulated fugitive $\mathrm{CH_4}$. The fourth term accounts for the accumulated $\mathrm{CO_2}$ by oxidation of fugitive $\mathrm{CH_4}$, oxidized at various times starting at $t = 0$.

In the case discussed in this paper, the function p is represented accurately by a simple exponential, as shown in the next Section 3, so that the integrals can be done exactly; in more complicated cases, numerical integration is straightforward. In practical applications of a dynamical scheme of this sort, it would suffice to use a finite-difference approximation based on yearly data and appropriately chosen initial conditions.

3 Results

Estimates of total carbon dioxide emissions from the beginning of the Industrial Revolution are available from the Carbon Dioxide Information Analysis Center (CDIAC) (2014). As shown in Fig. 1, the data can be represented surprisingly accurately by a simple exponential growth curve; the curve shown in Fig. 1 satisfies the equation

$$C_{\text{global}}(t) = 9.00\,e^{0.025(\frac{t}{\text{year}}-2010)}\ \text{GtC/year}. \tag{11}$$

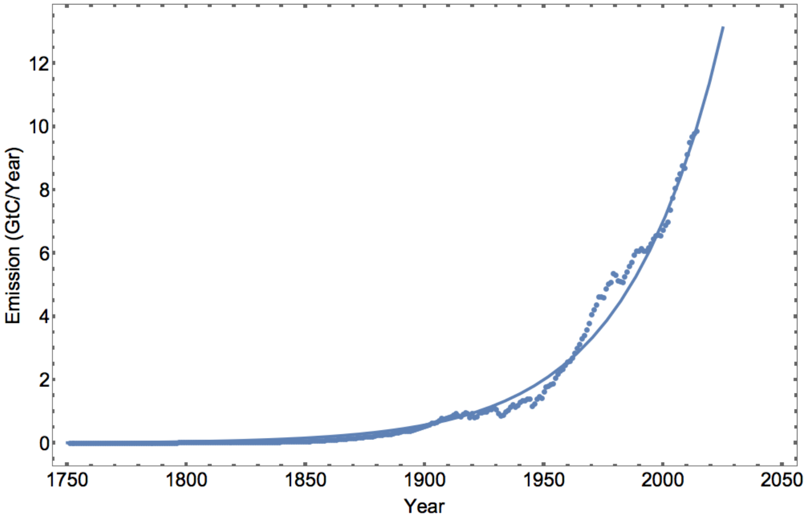

Figure 1. Global CO_2 emissions in gigatons of carbon per year with exponential fit, Eq. (11).

This equation is used to define *business-as-usual.* The expression was obtained by a least squares fit, followed by a slight adjustment of the normalization constant so that the integral from $-\infty$ to year 2011 reproduces

$$\int_{-\infty}^{2011\,\text{year}} C_{\text{global}}(t)\,dt = 365\,\text{GtC}, \tag{12}$$

the CDIAC estimate of 2011 cumulative emissions.

Given that CO_2 emissions are the predominant driver of global warming, it is not surprising that temperature anomaly T, shown in Fig. 2, is consistent with the climate forcing resulting from these emissions. The temperature anomaly data of NASA/GISS (NASA, 2017) can be used for a linear regression, two-parameter least-squares fit using the same exponential function featured in Eq. (11). This yields the following expression

$$T(t) = -0.3\,^\circ\text{C} + 1.0\,^\circ\text{C}\,e^{0.025(\frac{t}{\text{year}}-2010)}, \tag{13}$$

shown as the solid curve in Fig. 2.

Here are the results of one thought experiment: assume, first of all, that business-as-usual continues and that global energy consumption keeps growing exponentially, and, secondly, that power is generated by combustion of coal or oil before 2018 and of CH_4 after that, corresponding to time $t = 0$ in Section 2 and the vanishing upper limit in the first integral and lower limits of the integrals in Eq. (10).

This produces Fig. 3 in which the solid black curve on the left represents the actual, historical development, a trajectory continued on the right. The blue curve starting in 2018 corresponds to a hypothetical, complete switch to CH_4 in that year with 6% of the CH_4 escaping unburned, *i.e.,* half of the estimate in Howarth (2015). The red curve corresponds to 12% fugitive CO_2. Also included is a black-dashed curve for the critical fraction of fugitive methane as specified in Tab. 1. Fig. 4 is the

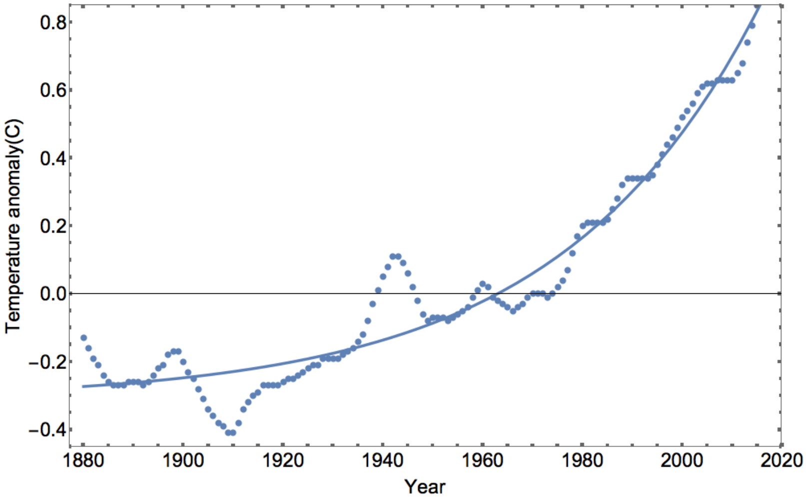

Figure 2. Temperature anomaly, the change in the global surface temperature relative to 1951–1980 average temperature (NASA, 2017). Dots represent five-year moving averages; the solid curve is given by Eq. (13).

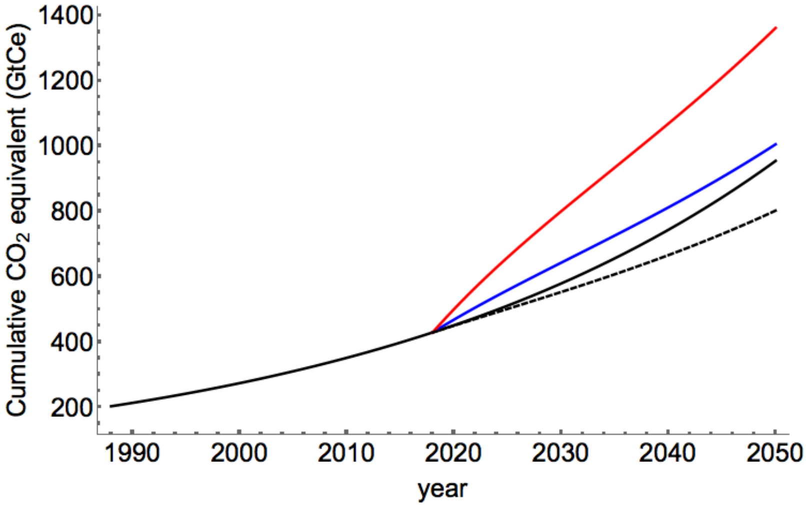

Figure 3. Four emission scenarios: (1) Business-as-usual using coal (black curve); after 2018: (2) CH_4 with 6% fugitive (blue); (3) CH_4 with 12% fugitive (red curve)); (4) CH_4 with critical fugitive fraction, (dashed) 2.2%, as shown in Tab. 1.

same assuming that combustion of oil generates power before 2018. Because the efficiency increase is considerably less in this case, the deleterious effect of the fugitive CH_4 is more pronounced.

Of course real life is not quite as simple as this thought experiment. However that may be, the results strongly suggest that, although the red and blue CH_4 curves will ultimately cross the black coal or oil curves, this does not happens sufficiently rapidly, *i.e.* within one or two decades, to justify the purported role of CH_4 as a bridge fuel.

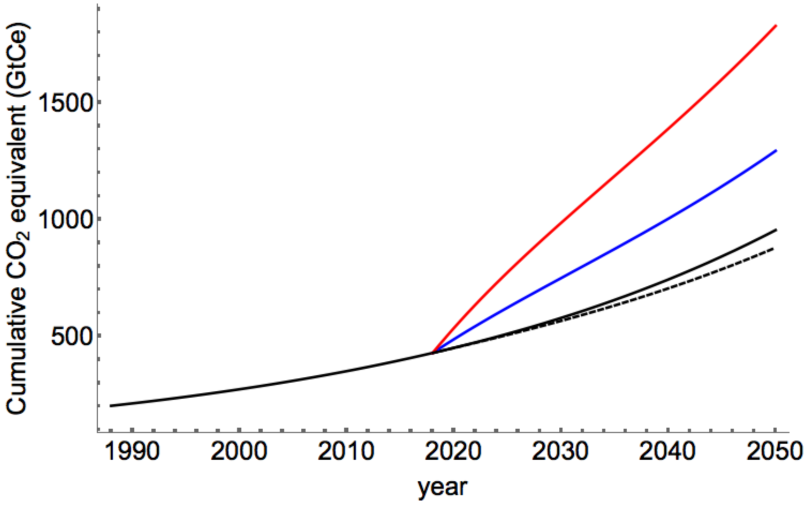

Figure 4. Four emission scenarios: (1) Black: business-as-usual using oil (black curve); after 2018: (2) CH_4 with 6% fugitive (blue); (3) CH_4 with 12% fugitive (red); (4) CH_4 with critical fugitive fraction, (dashed) 0.76%, as shown in Tab. 1.

Business-as-usual is one pathway, another one is to stay within a finite carbon budget. Fig. 5 shows two pathways to phase out fossil fuels starting in 2018. These pathways are consistent with the carbon budget proposed by Hansen et al. (2013). The area under both curves starting at $t = -\infty$, that is the total CO_2 put into the atmosphere, is 525 GtC, a number chosen because it reproduce the rates of emission reduction contained in the Hansen et al. (2013) paper, *i.e.* 3.5% in 2003, 6% in 2013, and 15% in 2020.

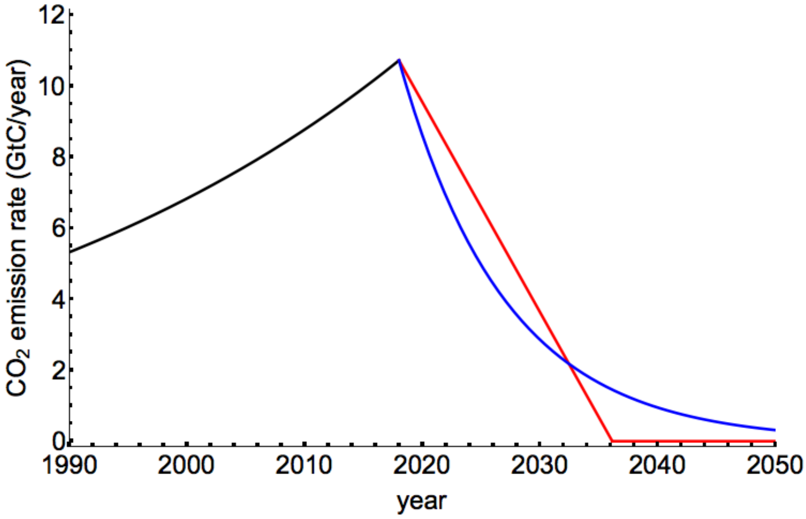

Figure 5. Global phase-out of fossil fuels: business-as-usual until 2018 followed by exponential (blue) and linear decay (red).

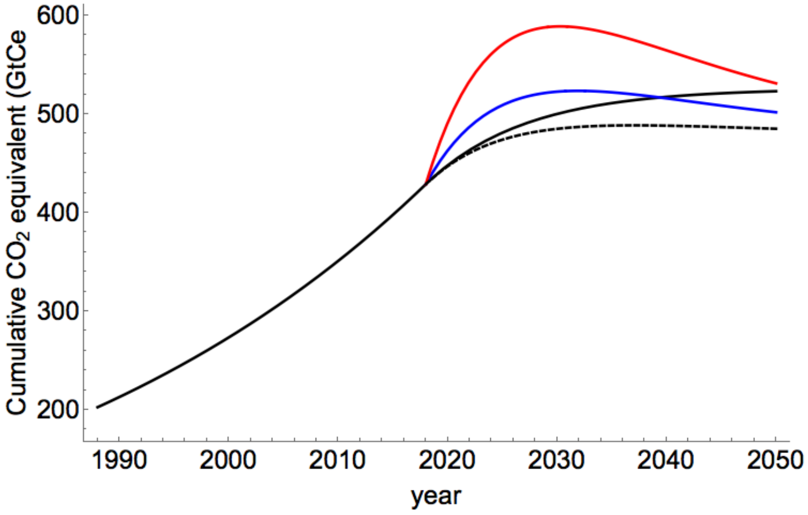

Figure 6. Four emission scenarios: exponential phase out of fossil fuel assuming (1) coal (black curve); (2) after 2018: CH_4 with 6% fugitive (blue); (3) CH_4 with 12% fugitive (red); (4) CH_4 with critical fugitive fraction, 2.2% (dashed), as shown in Tab. 1.

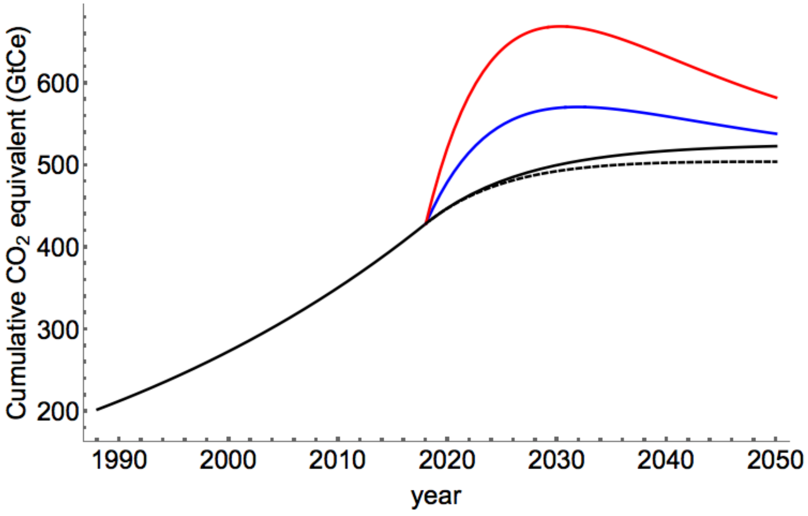

Figure 7. Four emission scenarios: Exponential phase out of fossil fuel assuming (1) oil (black curve); after 2018: (2) CH_4 with 6% fugitive (blue); (3) CH_4 with 12% fugitive (red); (4) CH_4 with critical fugitive fraction, 0.76% (dashed), as shown in Tab. 1.

In Fig. 6, the black curve shows cumulative emissions corresponding to a phase-out of fossil fuels following the exponentially decaying pathway, the blue curve in in Fig. 5. The blue curve corresponds to a complete switch-over from coal to CH_4 in 2018 with 6% fugitive CH_4; the red curve is the analog with 12% fugitive CH_4. Fig. 7 differs only in that the switch-over is from oil to CH_4. Once again, because the increase in efficiency (4/3) is less in this case, the relative importance of fugitive CH_4 is more pronounced. In both cases the dashed curves correspond to the respective fugitive fractions of coal and oil.

4 Conclusions

Overspending the carbon budget (mentioned in Section 2) while maintaining a for humans habitable climate is unlikely to be compatible with the time table imposed by the laws of nature. The required replacement of fossil fuels by renewables and energy conservation requires global collaboration and redistribution of wealth on an unprecedented scale. In this context it is worth noting that Hansen et al. (2017) have concluded, in view the industrialized world's lack of action since Hansen et al. (2013), that the climate can only be stabilized by "negative emissions," *i.e.,* by extracting CO_2 from the atmosphere.

As illustrated in Figs. 3, 4, 6, and 7, application of the policymaker-friendly tool proposed in this paper—a tool based on the instantaneous global warming potential—clearly supports what has been clear for some time, namely that *"By The Time Natural Gas Has A Net Climate Benefit You'll Likely Be Dead And The Climate Ruined,"* as Joe Romm summarized it in the title of one of his post (Romm, 2014).

In other words, the order-of-magnitude time estimates implied by the graphs presented in Section 3 underscore that there is no scientific justification for using the 100-year horizon in energy policy choices involving natural gas as a bridge fuel. Indeed, reporting based on CO_2 equivalents using the 100-year horizon, which is standard practice (World Resoures Institute & World Business Council For Sustainable Development, 2013), obscures short-term effects and is irreconcilable with both the observed timescale of developments of the climate system (National Oceanic Atmospheric Administration, a, b; Hansen et al., 2017) and with that of policy making, a point made by Steffen et al. (2018); Rintoul et al. (2018).

Employing the proposed policy tool, the numerical thought experiments presented in Section 3 demonstrate that using more a realistic, continuous-time dynamic approximation—one that is consistent with the timescale of climate change—is technically straightforward. At the same time, such a tool that respects the relevant timescales may be pivotal in public policy making that stands a chance of preserving a habitable climate for present and future generations.

There is general agreement that humanity has a finite carbon budget overspending of which is likely to cause irreparable harm to life on earth. The Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5) quoted as its estimate for this budget $2900\,\mathrm{GtCO_2}$ (Intergovernmental Panel on Climate Change, 2014). Accounting for the molar mass ratio ($\frac{12}{44}$) of carbon to carbon-dioxide this corresponds to $800\,\mathrm{GtC}$. This number rests on the ill-founded, by now mostly abandoned, assumption that a $2\,°\mathrm{C}$ global mean temperature increase is a "guardrail" that protects the biosphere from the essentially irreversible harm of run-away climate change (Geden, 2015; Friedman, 2015; Knutti et al., 2016). Indeed, the climate science research over last decades implies that relying on this upper limit is irreconcilable with the precautionary approach of Principle 15 of the 1992 Rio Declaration, a treaty signed and ratified by many countries, including the United States (National Oceanic and Atmospheric Administration—Office of General Counsel).

Fig. 5 is consistent with $1\,°\mathrm{C}$ as the "guardrail," a choice based on paleoclimate and other arguments presented in detail by Hansen *et al.* in (Hansen et al., 2008, 2013; Hansen and Kharecha, 2013; Hansen et al., 2017). This simple policy tool presented here can keep track of how much of the global greenhouse gas budget is spent in carbon-equivalent units, defined in a way that that *is consistent* with the Precautionary Principle.

As Figs. 6 and 7 make clear, there no scientific argument can be made for phasing out fossil fuels while at the same time engaging in replacing coal and oil power plants by natural gas-fired ones. The same, but to an even higher degree—as is clear from the critical fugitive fractions in Tab. 1— applies to the introduction of natural gas vehicles, a conclusion supported by a “pump-to-wheels” study by Clark et al. (2017) that does not take into consideration the full life-cycle, “wells-to-wheels” emissions associated with propulsion.

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Competing interests. No competing interests are present.

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