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Climate impacts of energy technologies depend on emissions timing

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Energy technologies emit greenhouse gases with differing radiative efficiencies and atmospheric lifetimes[1–3]. Standard practice for evaluating technologies, which uses the global warming potential (GWP) to compare the integrated radiative forcing of emitted gases over a fixed time horizon[4], does not acknowledge the importance of a changing background climate relative to climate change mitigation targets[5,6]. Here we demonstrate that the GWP misvalues the impact of CH_4-emitting technologies as mid-century approaches, and we propose a new class of metrics to evaluate technologies based on their time of use. The instantaneous climate impact (ICI) compares gases in an expected radiative forcing stabilization year, and the cumulative climate impact (CCI) compares their time-integrated radiative forcing up to a stabilization year. Using these dynamic metrics, we quantify the climate impacts of technologies and show that high-CH_4-emitting energy sources become less advantageous over time. The impact of natural gas for transportation, with CH_4 leakage, exceeds that of gasoline within 1–2 decades for a commonly cited 3 W m^{-2} stabilization target. The impact of algae biodiesel overtakes that of corn ethanol within 2–3 decades, where algae co-products are used to produce biogas and corn co-products are used for animal feed. The proposed metrics capture the changing importance of CH_4 emissions as a climate threshold is approached, thereby addressing a major shortcoming of the GWP for technology evaluation[7,8].

Comparing the climate impacts of energy technologies is challenging because they emit differing types and quantities of greenhouse gases, most notably CH_4 and CO_2, and these gases have dissimilar properties (Fig. 1a,b). Present approaches to technology evaluation use an equivalency metric to convert emissions to their CO_2-equivalent value[1–3,9]. The most common metric is the global warming potential (GWP(τ)), which takes the ratio of the time-integrated radiative forcing of pulse non-CO_2 and CO_2 emissions over a fixed time horizon (τ), typically 100 years. The GWP(100) was initially intended as a placeholder[10], in large part because of its sensitivity to the arbitrarily selected time horizon[7] (Fig. 1c,d), but it remains the standard metric for technology evaluation.

Various alternative metrics have been proposed for the purposes of emissions trading[11–13] and demand-sector emissions evaluations[8,14]. These metrics are formulated to make either instantaneous[15,16] or time-integrated comparisons of gases[1,9], based on their relative contributions to radiative forcing[1,12], temperature change[15,16], or economic impacts[17,18]. Alternatively, some have argued that direct comparisons of gases are not feasible, and have called for a multi-basket emissions policy[5,6], where similar gases are grouped into baskets and trading between baskets is prohibited.

Technologies emit multiple gases during their life cycles, however, and therefore an equivalency metric is required to compare their climate impacts on a single scale. For technology evaluation, equivalency metrics must be forward-looking and robust to inherent uncertainties about the future climate scenario, to inform the advanced commitment needed to develop new technologies and infrastructure. Determining an appropriate metric for this application is becoming increasingly urgent as we consider major public and private investments in technologies with significant CH_4 emissions, including natural gas[1,19–22].

Although many equivalency metrics have been proposed, previous research has not emphasized testing their performance against intended climate goals to determine a principled treatment of time in metric formulations. Here we propose a new class of dynamic metrics that, unlike the static GWP(τ), are designed to avoid an overshoot of an intended radiative forcing stabilization level. We develop a method to test the performance of these and other metrics against this climate change mitigation goal. The new metrics differ from other dynamic metrics[16–18] in that they do not require detailed information about the emissions scenario for achieving the mitigation goal. Climate targets are commonly formulated around a stabilization level[23], which can be reached by a number of emissions scenarios. The proposed metrics are designed to evaluate technologies in this context.

We begin by examining the GWP(100) for later comparison with the new metrics proposed. Although it has been shown that the GWP(100) leads to an imperfect equivalency when used to replace CO_2 with CH_4 (ref. 5), and can lead to economically inefficient decisions in scenarios with exogenously constrained climate outcomes[24], its performance has not been tested against intended climate goals. We find that using the GWP(100) leads to a significant overshoot of radiative forcing stabilization targets. For example, on the basis of the GWP(100), compressed natural gas (CNG) seems to have an advantage over gasoline per kilometre travelled (Fig. 1c). However, in a hypothetical scenario in which CNG is used to meet US passenger vehicle energy demand, radiative forcing is significantly higher than GWP(100)-based projections suggest (Fig. 2a). In a scenario in which global transportation demand is supplied by an energy source with the CH_4 intensity of CNG, a stabilization target of 3 W m^{-2} is exceeded by almost 5% (Fig. 2b), and by 12% if CH_4 emissions are maintained at their present percentage of global CO_2-equivalent emissions. These errors become increasingly concerning over time as climate thresholds are approached.

The metrics developed here aim to address this concern by appropriately evaluating technologies with significant CH_4 emissions. The objective is to limit the risk of a significant and sustained overshoot of an intended radiative forcing stabilization level.

The first metric, the CCI, is based on the time-integrated radiative forcing from the emission time (t') to an intended

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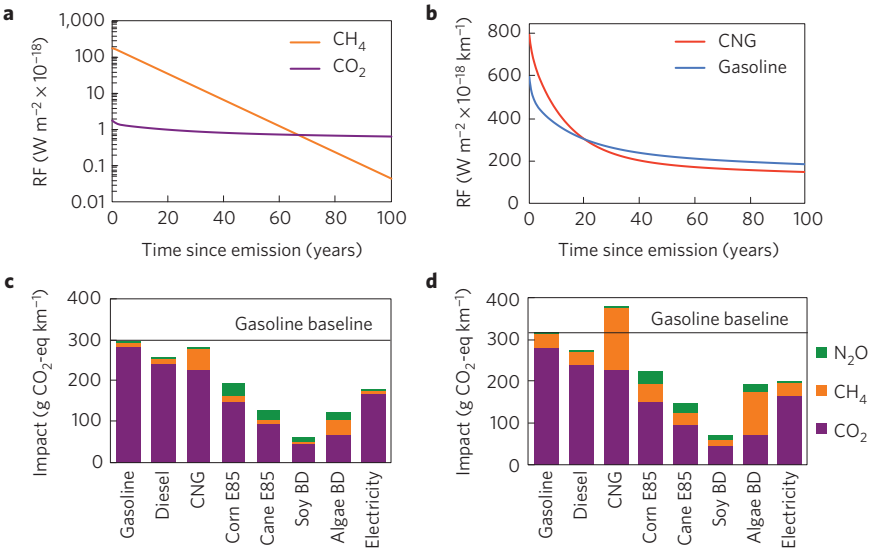

Figure 1 | Comparisons of greenhouse gases and technologies depend on the evaluation horizon. a, CH_4 has 102 times the radiative forcing per gram of CO_2 but decays more quickly, with the gases having equal radiative forcing (RF) 67 years after emission[4]. **b**, As a result, the impact of using technologies decays over time at different rates, as the comparison of gasoline and CNG illustrates. **c**,**d**, These dynamics explain why the impacts of technologies, notably algae biodiesel with a biogas co-product, change when evaluated over a 100-year (**c**) versus a 20-year (**d**) time horizon. (BD, biodiesel; CNG, compressed natural gas.)

stabilization time (t_S) and the second metric, the ICI, on the radiative forcing at time t_S:

$$\mathrm{CCI}(t',t_S) = \frac{A_M \int_{t'}^{t_S} f_M(t'',t')\mathrm{d}t''}{A_K \int_{t'}^{t_S} f_K(t'',t')\mathrm{d}t''} \quad \text{for all } t' \le t_S \tag{1}$$

$$\mathrm{ICI}(t',t_S) = \frac{A_M f_M(t_S,t')}{A_K f_K(t_S,t')} \quad \text{for all } t' \le t_S \tag{2}$$

where A is the radiative efficiency, $f(t,t')$ is the removal function (see equation (5) in Methods), and subscripts K and M refer to CO_2 and CH_4, respectively. For emission times $t' \le t_S$, the radiative forcing is evaluated over time t'' (from t' to t_S) for the CCI and at time t_S for the ICI. For emission times $t' > t_S$, both metrics are defined as the instantaneous radiative forcing ratio of the two gases. The CCI places a greater value on CH_4 emitted before t_S, after which time the two metrics are equivalent.

These dynamic metrics, in contrast to the static GWP(τ), explicitly account for climate stabilization goals in their formulation (Supplementary Section 2.1). As the emission time (t') nears the intended stabilization time (t_S), the evaluation time horizon decreases and the CO_2-equivalent value of CH_4 increases, to limit the overshoot of the intended stabilization level. (Any overshoot arises from CH_4 rather than CO_2 emissions, because CO_2 emissions are evaluated directly, not through an equivalency metric (Supplementary Section 3).) Unlike previously proposed dynamic metrics (Supplementary Section 2.2), including those comparing the cost effectiveness of emissions reductions along a mitigation scenario[17] and those based on temperature[15,16,18], the CCI and ICI are formulated so that the only input they require on the climate scenario is the intended radiative forcing stabilization level. A set of possible stabilization years is determined based on this level, giving a range of metric values for each emission year.

The approach developed to compute the metrics and test their performance is illustrated with an example below. The approach involves developing reference scenarios for emissions and radiative forcing stabilization (equations (3)–(6) in Methods and Supplementary Section 1.1), calculating metric values for the reference scenario range (equations (1) and (2) and Supplementary Section 2.1), and testing metrics against the reference scenarios (equations (7) and (8) in Methods and Supplementary Section 1.2 and 3).

To calculate the emission-time-dependent CCI and ICI values, a range of possible scenarios is determined for a commonly cited 3 W m^{-2} radiative forcing threshold (Fig. 3a), which in equilibrium is associated with a 2 °C temperature change. These scenarios define a range of years when radiative forcing must stabilize to avoid exceeding 3 W m^{-2}. This roughly 15-year range defines the possible values of t_S for calculating the CCI and ICI. Figure 3b shows the CCI and ICI for this range of t_S values.

We simulate emissions decisions using the ICI, CCI and GWP(100) to test the metrics' performance. Figure 3c,d shows the results under two scenarios that span the set of feasible scenarios for a 3 W m^{-2} stabilization level. Radiative forcing remains below

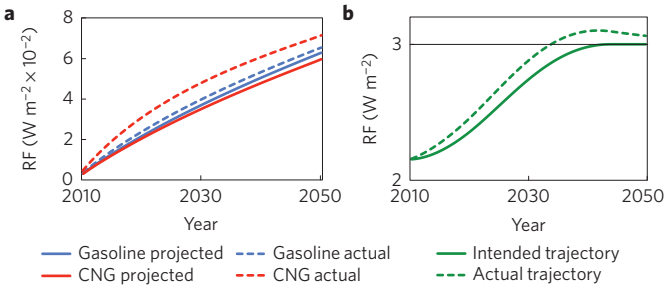

Figure 2 | GWP(100) underestimates the radiative forcing contribution of CH_4-emitting technologies. a, The actual radiative forcing (RF) impacts of satisfying constant US passenger vehicle energy demand with gasoline versus compressed natural gas (CNG) differ from GWP(100)-based projections, with a greater discrepancy for CNG due to its higher CH_4 intensity. **b**, A hypothetical situation is shown (based on scenario C in Fig. 3a), in which global transportation emissions are replaced by emissions from a technology with the CH_4 intensity of CNG, using the GWP(100) to determine CO_2 equivalence (Supplementary Section 1.2). This results in a significant deviation from the intended radiative forcing scenario.

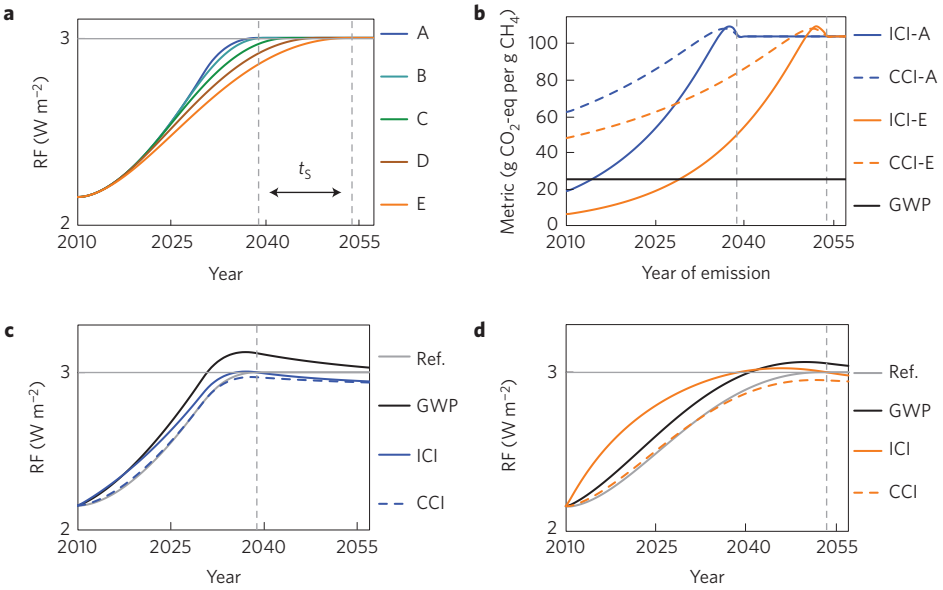

Figure 3 | Metric development. a, A range of scenarios, consistent with a 3 W m^{-2} stabilization level, is used to calculate equivalency metrics. They range from a delay scenario followed by rapid emissions reductions (scenario A, $t_S = 2039$), to a gradual emissions reduction scenario (scenario E, $t_S = 2054$). **b**, We compare the valuation of CH_4 under the ICI, CCI and GWP(100), using A and E to represent the range of scenarios consistent with the 3 W m^{-2} threshold. **c**,**d**, The radiative forcing (RF) resulting from using these metrics to allocate 5% of CO_2-equivalent emissions to CH_4 is shown, using scenario A (**c**) and scenario E (**d**).

3 W m^{-2} for all scenarios using the CCI but exceeds this value using the GWP(100). Using the ICI under scenario E, a gradual emissions reduction scenario with a later t_S, radiative forcing temporarily exceeds 3 W m^{-2} before t_S because of a lower impact value placed on CH_4 emissions early on (Supplementary Section 3). Radiative forcing remains below this level when applying the ICI under scenario A, a delay scenario followed by rapid emissions reductions. Both the ICI and CCI avoid the sustained threshold overshoot that results from applying the GWP(100), with the ICI resulting in a temporary overshoot for some scenarios and the CCI preventing any overshoot.

Using the GWP(100) and the CCI/ICI with t_S defined by scenario C (Fig. 3a), we then compare the climate impacts of several prominent energy technologies (where technology refers to a fuel and conversion technology) that emit both CH_4 and CO_2. Pairwise comparisons are performed for gasoline and CNG, corn ethanol and algae biodiesel (with corn co-products used for animal feed and algae co-products used to produce biogas), and coal and natural gas electricity (Fig. 4 and Supplementary Fig. 9 for other comparisons). We also generate low-CH_4 emissions scenarios for the three high-CH_4 emitters (CNG, algae biodiesel and natural gas electricity) and compare the results with our baseline scenario (Supplementary Sections 4 and 5). Results for the low-CH_4 scenarios are indicated by curly brackets. Notably, for the two pairs of transportation technologies, the rank ordering of climate impact depends on the emissions time.

Initially the impact of CNG is lower than that of gasoline, based on the ICI, but then exceeds it in 6–21 {18–28} years, or 11 {24} years for scenario C. The more conservative CCI, in contrast, indicates a lower CNG impact in all years {after 9–21 years}. Algae biodiesel shows a significantly lower impact than corn ethanol initially, but then surpasses it in 23–38 years when applying the ICI and 21–35 years when applying the CCI, owing to CH_4 emissions in the production of biogas from algae co-products. The impact of algae biodiesel remains lower than corn ethanol for all years, however, under the low-CH_4 emissions scenario, highlighting the importance of co-product processing techniques in determining the climate impacts of biofuels. Natural gas electricity starts at 53% {52%} the climate impact of electricity from coal (using the ICI), but then rises to 82% {72%} the impact of coal over time.

We then simulate the radiative forcing resulting from several hypothetical scenarios where all US passenger vehicle energy demand is met with a single technology. These simulations approximate how technologies are assessed through the lens of each metric. Figure 5a compares the results to the sector radiative forcing budget, again determined using scenario C (from Fig. 3a). Figure 5b shows the corresponding vehicle kilometres travelled. Assessing technologies with the GWP(100) results in a large radiative forcing budget overshoot, due to relatively high energy consumption, which endures past t_S (Supplementary Section 3). Applying the ICI results in a significantly lower and more temporary overshoot that is reduced before t_S, concurrent with a decrease in energy consumption. Application of the more conservative CCI avoids a threshold overshoot and results in the lowest energy consumption.

These results shed light on technology evaluation debates. One debate focuses on natural gas[19,20]. Using the GWP(100), the US natural gas mix has a slight climate advantage over gasoline, although this conclusion depends on assumptions about the source of the gas and associated emissions, with unconventional natural gas having higher emissions during well construction but conventional gas generally having higher emissions during production[21]. Based on the ICI and CCI, CNG used today ranges from slightly advantageous to slightly disadvantageous, whereas CNG used in 2040 has a significantly higher climate impact and lower climate-goal-compliant consumption than gasoline. These general conclusions also hold under the low-CH_4 emissions scenario (Supplementary Section 5.1).

Another debate focuses on the climate benefits of various biofuels and co-product processing techniques. For the processes studied (Fig. 4b), algae biodiesel seems more favourable than corn ethanol in 2010. However, using the ICI and CCI we observe that by 2040 the climate impact of algae biodiesel surpasses that of corn ethanol, owing to CH_4 leakage in biogas production from algae co-products, which partially offsets the energy requirements

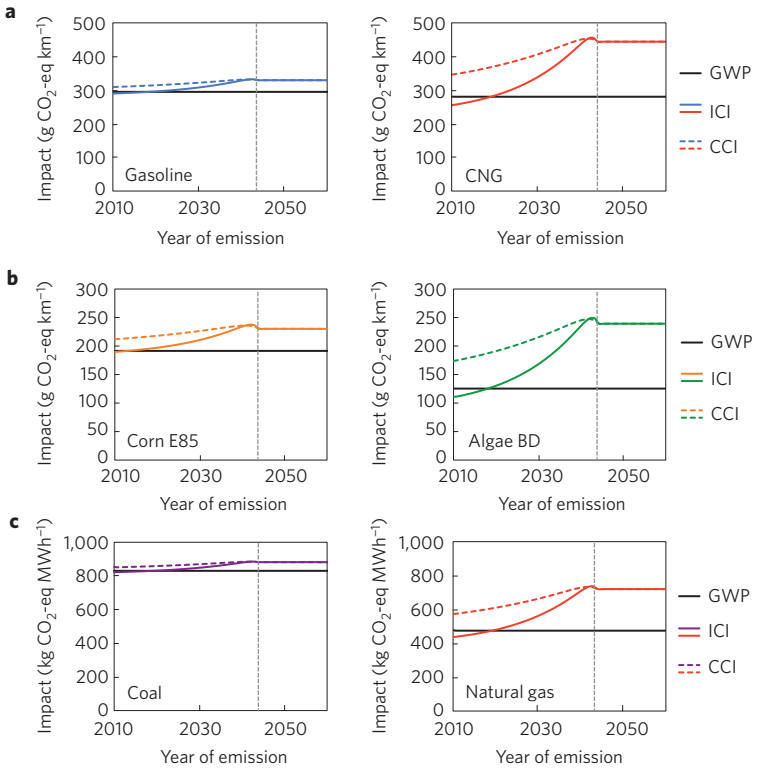

Figure 4 | Technology comparisons. a–c, Gasoline and compressed natural gas (CNG) with CH_4 leakage (**a**), corn ethanol without and algae biodiesel (BD) with biogas production (**b**), and coal- and natural gas-fired electricity (**c**) are compared using the GWP(100), ICI and CCI. The relative impacts change over time. Under baseline CH_4 emissions assumptions, the impact of CNG overtakes that of gasoline after 11 years when applying the ICI using scenario C in Fig. 3a, and 6–21 years based on the full range of stabilization scenarios investigated. Algae biodiesel overtakes corn ethanol after 28 years for scenario C and the ICI, and 23–38 years based on all scenarios.

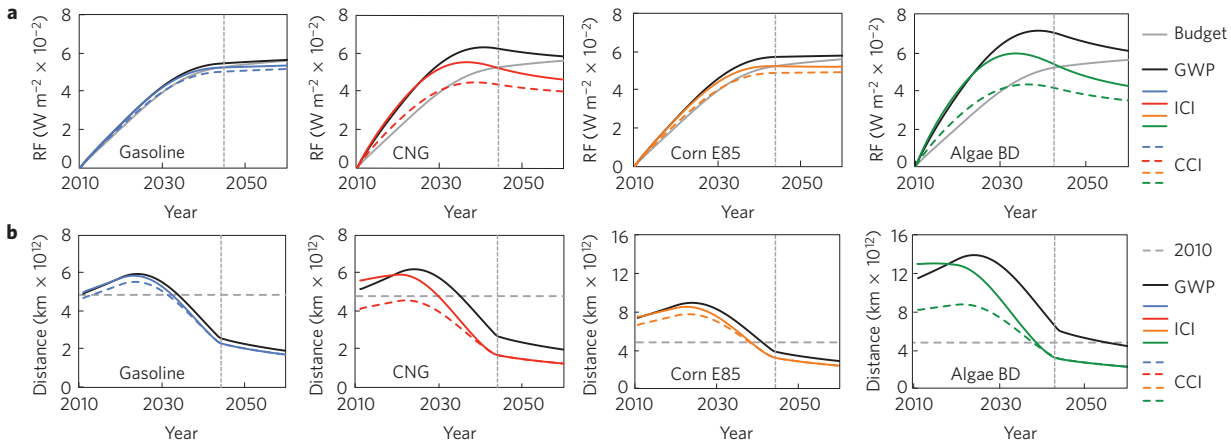

Figure 5 | Simulations of radiative forcing and vehicle kilometres travelled. a,b, Using metrics to examine hypothetical technology pathways results in differing radiative forcing trajectories, as compared with the sector budget (**a**), and differences in vehicle kilometres travelled (**b**). The sector budget is calculated by allocating a percentage of global emissions, based on scenario C (Fig. 3a), to the US passenger vehicle sector, based on the present value (∽3%), and simulating the associated radiative forcing (RF) (Supplementary Section 1.2.2). The metric-based radiative forcing is determined by using a metric to calculate emissions and associated energy consumption levels. Average present vehicle efficiencies and driving patterns are assumed (Supplementary Section 4).

of algae production and processing[2]. Although these offsets make biodigestors attractive, with applications in corn ethanol production[25] and other biofuels, resulting CH_4 emissions may make this process less advantageous over time. An alternative catalytic hydrothermal gasification process may achieve much lower CH_4 emissions (Supplementary Fig. 8). These results suggest the importance of developing alternative low-CH_4 co-product processing techniques[26].

The CCI and ICI identify high-CH_4, low-CO_2 technologies as candidates for near-term but not long-term climate change mitigation. Based on an intended radiative forcing stabilization level, these metrics identify an approximate bridging timeline to transition away from CH_4-emitting, short-term mitigation technologies. The approximate bridging time is not particularly scenario dependent, owing to the constrained range of emissions scenarios and stabilization years that correspond to commonly

cited stabilization targets. The results of applying the metrics to CH_4-emitting algae biodiesel and natural gas for electricity and transportation are particularly notable, highlighting the dependence of their mitigation potential on their time of use. The proposed technology and metric evaluation approach can also be adapted to new information on the timing, location and form of climate thresholds[23,27,28], and the desired trade-off between the risks of exceeding thresholds and the benefits of economic activity[29] (Supplementary Section 2.2). Although no equivalency metric is perfect, we find that dynamic metrics that are based on an approximate climate stabilization target and corresponding time horizon can improve technology evaluation for policymaking, private investment and engineering design.

Methods

In this section we describe the approach to generating the reference scenarios used to calculate the range of CCI and ICI values and to test metric performance. We also describe the technology emissions data used in the research.

Reference scenarios. The reference scenarios are CO_2 emissions, multi-gas concentration scenarios: all emissions in the simulation are composed entirely of CO_2, but previous emissions of non-CO_2 greenhouse gases are also modelled (Supplementary Section 1.1). These reference scenarios are used to calculate the CCI and ICI and to test all metrics, by allocating a portion of CO_2-equivalent emissions to non-CO_2 gases using the metrics.

Emissions scenarios are constructed[30], where initial emissions e_0 change over time according to

$$e(t') = e_0 \exp\left[\int_0^{t'} g(t'')\mathrm{d}t''\right] \tag{3}$$

where $g(t'')$ is an evolving, exponential growth rate (t'' is a dummy, integration variable). Emissions grow at a constant rate g_0, based on present growth rates, until the mitigation onset time (t_1), after which $g(t'')$ is reduced by a fixed annual amount until it reaches the final growth rate g_f.

Concentrations $c_i(t)$ of each gas i are a function of pre-industrial concentrations $c_i(t_0)$, historical emissions ($t_0 < t' \leq 0$) and new emissions ($0 < t' \leq t$),

$$c_i(t) = c_i(t_0) + \int_{t_0}^{0} f_i(t,t')\, e_i(t')\,\mathrm{d}t' + \int_0^t f_i(t,t')\, e_i(t')\,\mathrm{d}t' \tag{4}$$

where $f_i(t,t')$ gives the fraction of a gas emitted at t' remaining at time t (ref. 4),

$$f_i(t,t') = a_0 + \sum_{j=1}^{n} a_j \cdot \exp\left(-\frac{t-t'}{\tau_j}\right) \tag{5}$$

and a_i and τ_i are constants (see Supplementary Table 2 for CO_2, CH_4 and N_2O values). (Equation (5) is also used in the CCI and ICI formulations (equations (1) and (2)), where t is replaced by t'' for the CCI, which ranges from t' to t_S, and is replaced by t_S for the ICI.) As $n=1$ and $a_0=0$ for non-CO_2 greenhouse gases, no information about the emissions timing is needed to calculate concentrations from historical emissions. For CO_2, where $n=3$ and $a_0 \neq 0$, the rate of removal must be approximated using historical emissions data (Supplementary Section 1.1.2).

Radiative efficiency (radiative forcing per unit concentration) values are used to determine radiative forcing from concentrations[4].

$$\mathrm{RF}(t) = \mathrm{RF_A}(t) + \sum_i \left[A_i\left[c_i(t) - c_i(0)\right] + \mathrm{RF}_i(c_i(0))\right] \tag{6}$$

where $\mathrm{RF_A}(t)$ refers to all radiative forcing not due to the presence of modelled gases i, and A_i is the radiative efficiency of gas i (Supplementary Section 1.1.3).

A scenario family is a set of pathways $\mathrm{RF}(t)$ that stabilize at the same radiative forcing threshold but approach it at different rates. To generate stabilization scenarios, emissions are adjusted after the threshold is reached such that radiative forcing equals the threshold value in all subsequent years. Emissions scenarios within a scenario family are defined based on their values of t_1, which is varied to the greatest extent possible. Earlier values of t_1 result in gradual emissions reductions, whereas later values of t_1 result in delayed emissions reductions followed by rapid reductions. The scenario family for 3 W m^{-2} stabilization defines the range of stabilization times (t_S) for the analysis presented in the paper.

Metric testing. The performance of emissions metrics is tested by budgeting a trajectory $e(t')$ for total CO_2-equivalent emissions, and allocating a fraction q of these emissions to a non-CO_2 greenhouse gas. Consider the case of two gases, CO_2 and CH_4. Given a metric $\mu(t')$, the sum of CO_2 emissions $e_K(t')$ and CO_2-equivalent CH_4 emissions $\mu(t')e_M(t')$ must equal $e(t')$. The radiative forcing scenario can be derived from equation (6),

$$\begin{aligned}\mathrm{RF}(t) = {} & A_K\left[\left(c_K(t_0) + c_{KL}(t) + (1-q)\int_0^t e(t')f_K(t,t')\mathrm{d}t'\right) - c_K(0)\right] + \mathrm{RF}_K(c_K(0)) \\ & + A_M\left[\left(c_M(t_0) + c_{ML}(t) + q\int_0^t e(t')f_M(t,t')\cdot\frac{1}{\mu(t')}\mathrm{d}t'\right) - c_M(0)\right] \\ & + \mathrm{RF}_M(c_M(0)) + \mathrm{RF_A}(t)\end{aligned} \tag{7}$$

where K and M subscripts refer to CO_2 and CH_4 respectively, all other contributions to radiative forcing are encompassed in the term $\mathrm{RF_A}(t)$, and concentrations are disaggregated into the three contributions given in equation (4): pre-industrial concentrations, concentrations from historical emissions (abbreviated $c_{iL}(t)$), and concentrations from new emissions. The difference between the actual radiative forcing in the mixed gas case (where $q \neq 0$) and the budgeted, CO_2 emissions case (where $q=0$) is

$$\Delta\mathrm{RF}(t) = q\int_0^t e(t')\left[A_M f_M(t,t')\cdot\frac{1}{\mu(t')} - A_K f_K(t,t')\right]\mathrm{d}t' \tag{8}$$

A similar approach is used to test metric performance for technology evaluation, given a budgeted emissions trajectory $e(t')$ and using historical data to allocate a fraction p of these emissions to the sector of interest (Supplementary Section 1.2.2).

Data. Global emissions, concentration and radiative forcing data are published by the International Institute for Applied Systems Analysis. Technology life-cycle emissions are taken from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Version 2012, published by Argonne National Laboratory. In GREET, natural gas CH_4 emissions that arise from liquid unloading in conventional production offset increased leakage during unconventional well completion, with conventional gas having 27% higher emissions than unconventional gas. Present US breakdowns of conventional and unconventional gas are used[22]. In GREET, corn co-products are used as animal feed and algae co-products are used to create biogas in a state-of-the-art facility with CH_4 leakage rates of 2% (ref. 2). Emissions for electricity generation technologies are taken from a recent study[1]. Low-CH_4 emissions scenarios for natural gas are based on updated EPA estimates of natural gas system leakage and an alternative catalytic hydrothermal gasification scenario for algae biodiesel[2] (Supplementary Section 4).

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Author contributions

J.E.T. developed the concept and designed the methods for the study, M.R.E. and J.E.T. performed the analysis, J.E.T. and M.R.E. wrote the paper.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.E.T.

Competing financial interests

The authors declare no competing financial interests.