A consistent conceptual framework for applying climate metrics in technology life cycle assessment

Dharik Mallapragada and Bryan K Mignone
ExxonMobil Research and Engineering Company, Annandale, NJ, 08801, United States of America

1 Author to whom any correspondence should be addressed.
E-mail: dharik.s.mallapragada@exxonmobil.com

Keywords: climate change metrics, greenhouse gas abatement, methane, natural gas, technology assessment

Abstract

Comparing the potential climate impacts of different technologies is challenging for several reasons, including the fact that any given technology may be associated with emissions of multiple greenhouse gases when evaluated on a life cycle basis. In general, analysts must decide how to aggregate the climatic effects of different technologies, taking into account differences in the properties of the gases (differences in atmospheric lifetimes and instantaneous radiative efficiencies) as well as different technology characteristics (differences in emission factors and technology lifetimes). Available metrics proposed in the literature have incorporated these features in different ways and have arrived at different conclusions. In this paper, we develop a general framework for classifying metrics based on whether they measure: (a) cumulative or end point impacts, (b) impacts over a fixed time horizon or up to a fixed end year, and (c) impacts from a single emissions pulse or from a stream of pulses over multiple years. We then use the comparison between compressed natural gas and gasoline-fueled vehicles to illustrate how the choice of metric can affect conclusions about technologies. Finally, we consider tradeoffs involved in selecting a metric, show how the choice of metric depends on the framework that is assumed for climate change mitigation, and suggest which subset of metrics are likely to be most analytically self-consistent.

1. Introduction

In addition to being used for national and regional greenhouse gas (GHG) accounting, climate metrics are extensively used for life cycle assessment (LCA) of technologies that emit multiple GHGs. Thus, practitioners of LCA must often choose among available climate metrics based on the most relevant notion of impact for a particular application. Recently, several studies have summarized available information about climate metrics for LCA practitioners [1–3]. Some of these reviews reflect findings from a broader effort called the ‘Life Cycle Initiative’ under the United Nations Environment Program and the Society of Environmental Toxicology and Chemistry, which was designed to revise existing methodologies and provide global guidance for environmental impact assessment [4]. A consistent conclusion from these studies is that no single climate metric is likely to be appropriate in all situations. Rather, the applicability of any metric is inherently context-dependent.

Despite advances over the past two decades in developing a broader suite of metrics that capture a wider array of impacts, as well as more recent efforts to comprehensively evaluate available metrics, two broad challenges remain. First, while recent studies have advocated the use of multiple climate metrics [1, 2, 5], a conceptually consistent approach for choosing a manageable subset of metrics when evaluating the role of technologies in climate change mitigation has not been fully articulated. Second the application of climate metrics in LCA, and in technology assessment in particular, introduces other conceptual challenges, such as how to handle multiple timescales (e.g. climate time horizon and technology lifetimes) in the same problem. This has led to the development of customized metrics that effectively use modified forms of the climate metrics as inputs [6, 7]. However, a
general framework into which existing climate metrics could be inserted would enhance transparency and arguably provide greater value to the advancement of LCA practice.

This paper addresses both of the challenges identified above. First, it proposes a general framework for choosing among available physical climate metrics. Among the metrics considered, the global warming potential (GWP) is the most widely used cumulative metric [8, 9], whereas the global temperature change potential (GTP) is the most widely used end point metric [10]. Some have suggested that the GTP and end point metrics in general are more appropriate for comparing different GHGs in the context of global climate stabilization [11–13]. Consistent with these observations, our analysis starts from the premise that the underlying climate change mitigation framework determines which type of climate metric (cumulative or end point) is most appropriate.

A corollary to the findings of [11] is that when the metric is defined with climate stabilization in mind, it should presumably also vary with time as the stabilization objective nears. This realization has led to the development of other physical climate metrics—most recently, the cumulative climate index (CCI) and instantaneous climate index (ICI) [14]—that explicitly vary with time. These metrics are similar to dynamic versions of the GWP [15] and GTP [16], respectively. As discussed later in this paper, a static metric can be defined by fixing the time horizon (following the original GWP and GTP definitions), and a dynamic metric can be defined by fixing the end year (following the CCI and ICI, as well as the dynamic versions of the GWP and GTP).

In light of these considerations, available physical climate metrics can thus be placed into a matrix based on whether they measure cumulative or end point impacts and whether they consider a fixed time horizon or fixed end year (see inset in figure 1). Within a given quadrant of this matrix, it is possible to further distinguish physical metrics by the climate indicator being measured, which could be radiative forcing, temperature change, sea level rise, or something else (see, for example, figure 2 in [2]). Because these indicators tend to be causally linked by the climate system, the choice of quadrant tends to drive more significant differences between metrics than the choice of climate indicator within a quadrant, for a given choice of time horizon or end year. Thus, in this paper, we focus on one metric from each quadrant to illustrate the most relevant differences between the quadrants. A partial list of alternative metrics in each quadrant is provided in online supplementary table S1 available at stacks.iop.org/ERL/12/074022/mmedia.

---

2 The terms ‘cumulative metric’ and ‘end point metric’ are defined formally in the next section.

3 Alongside physical metrics, several economic metrics that draw from the widely-used approaches of cost-benefit and cost-effectiveness analysis have been discussed for over two decades. One such metric is the global damage potential (GDP), which extends the GWP by considering explicit economic (i.e. human welfare) impact, rather than just physical impact (e.g. effect on radiative forcing) [25, 34]. A related metric, the global cost potential (GCP), focuses on marginal abatement costs (associated with a climate stabilization objective) rather than climate damages [36]. Several studies have compared and considered the relationship between the economic and physical metrics [11, 15, 25, 34, 35, 46], with [11] providing the most conceptually complete framework relating the four metrics discussed above (GWP, GTP, GDP and GCP) [11]. Most importantly for our study, [11] show that the GWP can be considered an approximation to the GDP, which follows from a cost-benefit framework, and that the GTP can be considered an approximation to the GCP, which follows from a cost-effectiveness framework.

4 It is worth noting, however, that the uncertainties are magnified as one moves down the causal chain from radiative forcing to temperature and sea level rise [3].
For any given climate indicator in any given quadrant, climate metrics can be further distinguished by differences in time horizons or end years, whether the background state of the climate system is assumed to vary, whether impacts from a pulse emission or sustained emissions are considered, and other mechanical aspects of the calculation, among other differences (see, e.g. figure 1 in [3]). While the choice of timeframe is not the focus of this paper, we discuss this issue briefly in the discussion and in the supplemental material. In addition, because other studies have explicitly considered the time-dependence of metrics that results from changes in the underlying state of the physical system [17–19], we do not discuss this issue here.

Finally, the choice between pulse and sustained emissions relates directly to the second broad challenge identified above. Specifically, we show that the existing suite of climate metrics can be applied directly to dynamic LCA, without further adjustment, thereby simplifying calculations and enhancing transparency relative to approaches that require development of customized climate metrics. Thus, for each climate metric, there is a corresponding technology metric. These technology metrics can be considered climate metrics that account for sustained emissions in a particular context.

In developing a consistent conceptual framework for the selection of climate metrics and their application to LCA, this paper thus operationalizes recent recommendations to conduct greater sensitivity analysis in order to capture both short and longer-term aspects of climate change in LCA. It does so by proposing that these impacts be evaluated simultaneously and consistently in the context of a particular climate mitigation framework, from which the choice of metric type follows. A key practical insight for LCA is that the number of consistent climate and technology assessment metrics can be reduced once the interactions among the choices are understood. An additional insight relevant to climate change mitigation is that the attractiveness of technologies with non-trivial emissions of GHGs whose lifetimes are shorter than CO2 depends significantly on the framework that is used for climate change mitigation more broadly.

The remainder of this paper consists of four sections. Section 2 introduces the metrics that will be compared. Section 3 uses a simple example to illustrate how results can vary with the choice of metric. Section 4 discusses the tradeoffs involved in selecting a metric and introduces the simplifying framework. Section 5 concludes with some broader insights.

2. Methods

The GWP of a greenhouse gas is defined as the cumulative radiative forcing from a given quantity of gas (say 1 kg) over a certain time horizon (TH) after its release into the atmosphere (at \( t = 0 \)), relative to the cumulative radiative forcing over the same time horizon from the release of the same quantity of CO2 [20]. The GTP, is defined as the change in mean surface temperature \( \text{TH} \) years after a pulse emission of a GHG (at \( t = 0 \)), relative to the change in mean surface temperature \( \text{TH} \) years after a pulse emission of CO2 [20] (see online supplementary section S.2 for mathematical definitions of these metrics).

Whereas the GWP is a cumulative measure of climate impact that integrates the radiative forcing over the entire chosen time horizon, GTP is an end point metric that measures the climate impact at the end of the chosen time horizon (see section S.2 for...
discussion). Even though the definitions for GWP and GTP assume an emission pulse at \( t = 0 \), it is straightforward to define these metrics more generally for emissions occurring in future time periods. The value of the metric is unchanged as long as the effective time horizon (the number of years between the time bounds) does not change.

Whereas the time horizon used in the GWP and GTP is independent of when the emissions pulse occurs, other proposed metrics explicitly link the time horizon to the year in which radiative forcing is assumed to stabilize. For example, Edwards and Trancik [14] propose two metrics, the CCI and the ICI. The CCI resembles the GWP as a cumulative metric except that the radiative forcing is integrated from some actual year \( t \) to some year of stabilization \( (t_s) \). Similarly, the ICI resembles the GTP as an end point metric, except that the impact is evaluated at some fixed stabilization year \( (t_s) \) rather than TH years after the pulse emission (see supplementary section S.3 for mathematical definitions).

Figure 1 shows the four metrics (comparing CO\(_2\) to methane (CH\(_4\)) as a function of the year of the pulse emission \( (t) \) for TH equal to 100 years or \( t_s \), assumed to be 100 years from today (see supplementary section S.7 for an alternative in which TH and \( t_s \) are equal to 50 years and related discussion). GWP and GTP do not vary with the time of emission, but they increase as TH decreases (compare figure 1 to figure S2), because the climate impact of CH\(_4\) relative to CO\(_2\) is greater close to the time of emission. CCI and ICI increase as a function of time, as the fixed stabilization year is approached, because the effective time horizon \((t_e-t)\) decreases as a function of the time of emission. These metrics also increase as \( t_s \) decreases (compare figure 1 to figure S2) because the effective time horizon at any given year \( (t) \) decreases.

It is straightforward to use any one of the above metrics to compare the climate impacts of technologically alternative, which may each have life cycle emissions of several GHGs (assumed here to be CO\(_2\) and CH\(_4\)). Such a metric, \( T_X \), where \( X \) is one of the four climate metrics above, can be constructed by summing, for the new technology, the emissions per functional unit (e.g. MJ of energy, km travelled) of CO\(_2\) and CH\(_4\) (multiplying the emissions of CH\(_4\) by the chosen climate metric) and dividing by the same quantity for the incumbent technology. Mathematically, this can be expressed as:

\[
T_X(t, t_s, TH) = \frac{E_{2,CH_4} \cdot X_{CH_4}(t, t_s, TH) + E_{2,CO_2} \cdot X_{CO_2}(t, t_s, TH) + E_{1,CO_2} \cdot X_{CO_2}(t, t_s, TH) + E_{1,CH_4} \cdot X_{CH_4}(t, t_s, TH)}{GWP_{CH_4}(TH) + GTP_{CH_4}(TH) + CCI_{CH_4}(t, t_s) + ICI_{CH_4}(t, t_s)}
\]

where \( X_{CH_4}(t, t_s, TH) = \)

In equation (1), \( E_{1,CH_4} \) and \( E_{1,CO_2} \) are the emission factors for an incumbent technology, and \( E_{2,CH_4} \) and \( E_{2,CO_2} \) are the emission factors for a new technology. When \( T_X \) is less than unity, the climate impact of the new technology in a given year \( t \) is lower than the climate impact of the incumbent technology (subject to the definition of climate impact embedded in the chosen climate metric). An important observation is that \( T_{GWPG} \) and \( T_{GTP} \) are independent of time \( (t) \), because the underlying climate metrics (GWP and GTP) are time-independent, whereas \( T_{CCI} \) and \( T_{ICI} \) are time-varying, since both of the underlying climate metrics (CCI and ICI) depend on the actual year of emission \( (t) \).

Any \( T_X \) metric provides a measure of the relative climate impact of two technologies for a given year of emission, and for this reason may be considered an instantaneous technology metric. Since the lifetime of most energy technologies is generally on the order of decades rather than years, there is often need to make a further judgment about how to combine information about emissions from different years. Such judgments can be important when the instantaneous technology metric changes as a function of time and crosses unity during the period of interest, implying that one technology would have less climate impact over some part of the period and that the other technology would have less climate impact over the remainder of the period.

To provide a means to compare technologies that persist for many years, integrated technology metrics can incorporate information about the emissions over the lifetime of each technology. As shown in equation (2), a generalized integrated technology metric \( (I_X) \) can be constructed by integrating any \( T_X \) metric between some start year, \( t_{start} \), and \( t_{end} \), corresponding to when the commitment to that technology expires. Note that the definition of equation (2) assumes that the emission factors of the technologies remain constant over time. Under these conditions, \( I_{GWPG} \) and \( I_{GTP} \) are time-independent (they depend on neither \( t_{start} \) nor \( t_{end} \)), because \( T_{GWPG} \) and \( T_{GTP} \) are time-independent, whereas \( I_{CCI} \) and \( I_{ICI} \) are time-varying because \( T_{CCI} \) and \( T_{ICI} \) are time-varying. Note that, given the expression below, \( I_X \) is similar to the technology metric defined in equation (1) where the time-dependent climate metric \( X \) has effectively been replaced with a time-invariant climate
metric (Y) that represents the average value of X over the specified commitment period.

\[ I_X(t_{\text{start}}, t_{\text{end}}, \text{TH}, t) = \frac{E_{2, \text{CH}_4} Y_{\text{CH}_4}(t_{\text{start}}, t_{\text{end}}, \text{TH}) + E_{2, \text{CO}_2}}{E_{1, \text{CH}_4} Y_{\text{CH}_4}(t_{\text{start}}, t_{\text{end}}, \text{TH}) + E_{1, \text{CO}_2}} \]

where \( Y_{\text{CH}_4}(t_{\text{start}}, t_{\text{end}}, \text{TH}) \) is defined as:

\[ Y_{\text{CH}_4}(t_{\text{start}}, t_{\text{end}}, \text{TH}) = \frac{\int_{t_{\text{start}}}^{t_{\text{end}}} \text{X} \cdot \text{CH}_4(t') Y(t', \text{TH}) \, dt'}{t_{\text{end}} - t_{\text{start}}} \]

Finally, an additional integrated technology metric, the Technology Warming Potential (TWP) proposed by Alvarez et al. [6] combines features of the different \( I_X \) metrics above. The TWP is an integrated metric, in that sense resembling \( I_{\text{GWP}} \) or \( I_{\text{CCI}} \). Furthermore, the TWP is independent of the year in which the technology transition begins, similar to the \( I_{\text{GWP}} \). However, the time period for evaluating the climate impacts associated with different pulses are allowed to vary, resembling the \( I_{\text{CCI}} \) (see section S.4 for the TWP definition).

3. Results

In order to provide a concrete example of how these metrics can be applied, this section considers the choice between compressed natural gas (CNG) fueled vehicles and gasoline-fueled vehicles for light duty transportation, which has been studied by several papers using different estimates of life cycle GHG emission factors and different climate metrics [6, 14, 21, 22]. An alternative example of technology choice in the power sector is provided in supplementary section S.8. Using information in table S3 about the life cycle GHG transportation, which has been studied by several vehicles and gasoline-fueled vehicles for light duty

If one assumes a time horizon shorter than 100 years, such as 50 years (or a stabilization year that is 50 years from today), then metrics that accumulate impacts of an emission pulse over time, namely \( T_{\text{GWP}} \) and \( T_{\text{CCI}} \), are greater than unity for all years (see figure S3). For the same time horizon of 50 years (or stabilization year that is 50 years from today), however, end point metrics such as \( T_{\text{GTP}} \) and \( T_{\text{CCI}} \) that measure the impact of an emission pulse in a future year are less than unity for at least some future years (see figure S3).

Figure 3 considers the same technology comparison using integrated technology metrics, rather than instantaneous technology metrics, assuming that the lifetimes of the technologies are either 10 years (panel A) or 20 years (panel B). \( I_{\text{GWP}} \) and \( I_{\text{CCI}} \) are identical to the corresponding instantaneous metrics, \( T_{\text{GWP}} \) and \( T_{\text{CCI}} \). Since the instantaneous metrics are not time-varying, including information about future years (through integration) when evaluating the choice in a given start year does not change the value of the metric. The values of \( I_{\text{GWP}} \) and \( I_{\text{CCI}} \) just like \( T_{\text{GWP}} \) and \( T_{\text{CCI}} \) only depend on the assumed time horizon (e.g. \( \text{TH} = 100 \) in figure 3 or \( \text{TH} = 50 \) in figure S4). Additionally, since the GWP is always larger than the GTP for short-lived GHGs, the \( I_{\text{GWP}} \) is always greater than the \( I_{\text{GTP}} \).

The TWP is similar to the \( I_{\text{GWP}} \) in that its value is independent of the start year of the technology transition, as represent by the horizontal line in figure 3. However, as discussed above, it values emission pulses at different times differently. Consequently, the effective ‘average’ time horizon parameter, averaged over all the emission pulses considered, is less than the chosen TH parameter, and this explains why the TWP is larger than the \( I_{\text{GWP}} \) in figure 3 (and figure S4). For a given start year \( (t_{\text{start}}) \), the values of \( I_{\text{CCI}} \) and \( I_{\text{CCI}} \) in figure 3 are larger than the corresponding values of \( T_{\text{CCI}} \) and \( T_{\text{CCI}} \) in figure 2 because the integration incorporates information about future years. In effect, these integrated metrics anticipate the increasing importance of \( \text{CH}_4 \) that is assigned by the underlying instantaneous metrics, as the assumed stabilization year is approached.

The results in figure 3 show that the interpretation about technology again depends on which metric is chosen for the analysis. For instance, in the case of climate stabilization occurring 100 years from the present and a typical vehicle lifetime of 10 years (figure 3(a)), the \( I_{\text{CCI}} \) suggests that CNG vehicles can provide some climate benefits as long as they are introduced within the next \( \sim \)70 years and retired after their lifetime, whereas the \( I_{\text{GWP}} \) suggests that the two technologies are nearly identical in terms of their climate impact regardless of when they are introduced. Increasing the commitment to CNG vehicles beyond 10 years (to 20 years as in figure 3(b)) decreases the window during which their introduction would provide climate benefits relative to gasoline vehicles.
(using the \(I_{\text{CCI}}\)), but the same qualitative differences between the metrics apply.

Overall, analysis using \(I_{\text{CCI}}\) supports previous findings [22] that switching to CNG vehicles in the near term and subsequently transitioning to lower \(\text{CH}_4\)-emitting technology options could provide climate benefits when used in place of gasoline vehicles. However, if one uses other metrics, such as the \(I_{\text{GWP}}\) then the climate benefits of CNG are more ambiguous. When climate stabilization is assumed to occur sooner, say in 50 years (or equivalently the time horizon for evaluating impacts is 50 years), then analysis with the \(I_{\text{CCI}}\) suggests that CNG vehicles provide modest climate benefits relative to gasoline vehicles (figure S4). These examples highlight how the choice of metric can affect conclusions about the climate impacts of different technologies.

4. Discussion

The description of the metrics and the example above suggest that there is not likely to be a single metric that is appropriate for comparing technologies in all situations, a finding that is consistent with prior studies [1–5]. Rather, the choice of metric depends on the context in which it is used. To assist LCA practitioners with this choice, this section reviews several distinct issues that underlie the choice of metric and, for each of these issues, discusses when particular choices are most appropriate. Specifically, this section examines the following issues: (1) when to utilize a cumulative or end point metric; (2) when to evaluate climate impacts over a fixed time horizon (varying end year) or up to a fixed end year (varying time horizon); and (3) when choices about aggregation of emissions over multiple years are most likely to affect the outcome.

From the definitions of the four physical climate metrics discussed above (GWP, GTP, CCI and ICI), it is clear that some metrics (GWP and CCI) are cumulative metrics that consider the total climate impact over some period, whereas others (GTP and ICI) are end point metrics that consider the climate impact in some future year, ignoring impacts prior to that time\(^8\). Fundamentally, as discussed by [11], the choice between a cumulative metric and an end point metric depends on the broader framework in which climate change mitigation is considered. When comparing alternatives in the context of cost-benefit analysis (CBA), then a cumulative metric is most appropriate, because CBA involves the comparison of impact streams, which are integrated (and discounted, if monetized). An explicit assumption in CBA is that the time path (not only the end point) matters. While not an economic metric, the GWP is broadly consistent with this framework, since the impact stream of one action (e.g. the release of a unit emission

\(\text{CH}_4\) to the instantaneous efficiency of \(\text{CO}_2\)\(^{[14]}\).

\(\text{Figure 3. Integrated technology metrics plotted as a function of the start year of the transition (t}_{\text{start}}\) for a hypothetical switch from gasoline-fueled vehicles to CNG-fueled vehicles. A value less then unity implies that integrated emissions from a CNG vehicle over its lifetime have a lower climate impact than the integrated emissions from a gasoline vehicle. \(I_{\text{GWP}}\) and \(I_{\text{GTP}}\) are plotted for an effective time horizon (TH) of 100 years, whereas \(I_{\text{CCI}}\) and \(I_{\text{ICI}}\) are plotted for an effective stabilization year (\(t_s\)) that is 100 years from today \((t_{\text{start}}=0)\). Technology lifetimes \((t_{\text{end}}-t_{\text{start}})\) are assumed to be 10 years (panel A) or 20 years (panel B). Note that for \(I_{\text{CCI}}\) and \(I_{\text{ICI}}\), when \(t > t_s\) the underlying climate metrics are defined to be the ratio of the instantaneous radiative efficiency of \(\text{CH}_4\) to the instantaneous efficiency of \(\text{CO}_2\)\(^{[14]}\).
of CH₄) and a relevant alternative (the release of a unit emission of CO₂) are represented in the numerator and denominator of this metric, respectively.

On the other hand, when comparing alternatives as part of a broader cost-effectiveness analysis in which future stabilization of radiative forcing or temperature is the assumed objective to be achieved at the least cost, then an end point metric is more appropriate, because the future impact of an action today is most relevant to the objective. The GWP is broadly consistent with this framework, since the impact in a given future year of one action (e.g. the release of a unit emission of CH₄) and a relevant alternative (the release of a unit emission of CO₂) are represented in the numerator and denominator of this metric, respectively.

The discussion above may help a practitioner choose between a cumulative metric and an end point metric, but it does not help choose among cumulative metrics (e.g. between the GWP and CCI) or among end point metrics (e.g. between the GTP and ICI). Once again, the assumed analytical framework is important. Cost-effectiveness analysis compares alternative pathways to a given stabilization outcome. For example, the IPCC defines four ‘representative concentration pathways’ (RCPs) that reach 2.6, 4.5, 6.0 and 8.5 W m⁻² [23]. The implied radiative forcing in the lowest of these (RCP 2.6) stabilizes prior to 2050, whereas RCP 4.5 stabilizes prior to 2100 and RCP 6.0 and RCP8.5 do not stabilize before the end of the 21st century. The choice of end point in an end point metric therefore further depends on the specification of the climate change mitigation objective and the year in which that objective is assumed to be achieved [14].

In CBA, the appropriate time horizon or end year is not directly related to an assumption about the climate change mitigation objective. In effect, in the GWP, the time horizon parameter substitutes for explicit discounting, among other factors, and the discount rate does not vary with the assumed objective [24]. In practice, a horizon of 100 years is common for the GWP and generally more consistent with central values of explicit economic estimates of impact (i.e. GDP) to which the GWP can be viewed as an approximation [25, 26].

The discussion above suggests that the first two issues—the choice between a cumulative and end point metric, and the choice between a fixed time horizon and a fixed end year—are conceptually related. Specifically, if a CBA framework is adopted, then the GWP, or a metric that evaluates cumulative impacts over a fixed time horizon, is most consistent with this framework. On the other hand, if a cost-effectiveness framework is adopted in which the assumed objective is stabilization of radiative forcing or temperature in some future year, then the ICI, or a metric that evaluates the impact in the predetermined future year, is most consistent with this framework. Therefore, the set of self-consistent physical climate metrics is reduced to two broad types—specifically, those found in the two diagonal quadrants of the framework matrix (inset in figure 1). The choice among these two broad types then depends on the framework assumed for climate change mitigation.

Finally, in any analytic framework, it is natural to aggregate the effects of an action that is assumed to persist for many years. However, the timescale associated with the lifetime of the technologies being evaluated is distinct from the timescale used for evaluating climate impacts, and this separation highlights an additional parameter choice faced by the practitioner. Using the GWP in a dynamic LCA leads to the I_Climate cumulated GWP (ICCl GWP) which does not depend on assumptions about the lifetimes of the technologies being evaluated because the GWP does not depend on time. While some have argued that this lack of time-dependence highlights an inconsistency within LCA [7, 27], the time horizon parameter in the GWP reflects an economic choice about how to value the impacts of a pulse emission in a given year (i.e. the effective discount rate), which does not depend on the time of emission. In this framework, a pulse emission should have identical ‘value’ regardless of whether it starts at the beginning or end of the time horizon used to describe the technology transition. In contrast, using the ICl in a dynamic LCA leads to the I_Climate cumulated ICI (ICCI) which does depend on assumptions about technology lifetimes because the underlying climate metric is rising over time, so longer technology lifetimes generally increase the value of the technology metric for a given start year.

Figure 4 summarizes the choices involved in selecting a technology metric. First, an analyst must choose between two overarching climate mitigation frameworks: CBA and cost-effectiveness analysis, both of which are common in climate change assessment [28]. If the former framework is adopted, then a cumulative fixed time horizon metric is the technology metric type most consistent with this choice, whereas if the latter framework is adopted, then an end point fixed end year metric is the most consistent. Under each framework, a relevant time parameter must be specified. While this choice is also context-dependent, it is worth noting that the choice of TH = 100 is most consistent with the underlying economic metric (GDP) to which GWP may be considered an approximation, and that the choice of t_i = 50 would be consistent with a stabilization scenario in between RCP 2.6 and RCP 4.5. Finally, in the case of the I_Climate, the choice of technology lifetime can be important in some applications, since the underlying technology metric is time-dependent. While the comparison between any two technologies will depend on many of the choices above, one important generalization is that use of end point, fixed end year metrics such as the I_Climate tend to favor technologies that emit GHGs with lifetimes significantly shorter than CO₂—often called short-lived climate forcers or ‘SLCFs’—in the
near-term and penalize those technologies in the long-term, compared to cumulative, fixed time horizon metrics such as the IGWP.

Although the technology examples considered in this paper focus on emissions of CH₄ and CO₂, the framework presented here is equally applicable to other GHGs, including SLCFs such as black carbon. In fact, based on the response functions suggested by the IPCC, the temperature response following a pulse emission of common SLCFs is similar to that following a pulse emission of CH₄, albeit with faster decay and higher values at the time of emission (see figure 1 of [29]). Recent recommendations to consider the sensitivity of LCA to the inclusion of SLCFs are thus consistent with the approach discussed here, because all of the metrics discussed in this paper can be applied to any GHG.

5. Conclusion

The discussion above highlights the main practical insights of this paper, namely that (a) the choice of climate metric type (cumulative with fixed time horizon or end point with fixed end year) depends on the framework in which climate change mitigation is considered; (b) that either type of climate metric can be used in dynamic LCA; (c) that this choice determines whether the particular $I_X$ metric will be time-dependent; and (d) that other climate metrics such as the static GTP and the CCI (and their associated $I_X$ metrics) are less internally self-consistent. These insights provide a set of principles that can be adopted by LCA practitioners to enhance the consistency of dynamic assessment and technology comparisons, in particular.

Additionally, this analysis provides broader insights about the roles of certain types of technologies in climate change mitigation. The time path of the ICI in figure 1 (or figure S2) suggests that if climate change mitigation is considered from the perspective of climate stabilization (assuming the objective is not attained for several decades in the future), the ‘value’ of mitigating CH₄ (relative to CO₂) in the near-term is relatively small. However, CH₄ emissions closer to stabilization strongly impact the radiative forcing in the assumed stabilization year and thus the ‘value’ of mitigating is substantially greater. This suggests that the impact associated with CH₄-emitting technologies and their role in climate change mitigation depends to a large extent on what is assumed about the underlying mitigation framework.

Finally, the metrics used here can also be used to assess how current technology would have to evolve in order to remain attractive (in an emission sense) compared to alternatives. For example, when the $I_X$
metric begins below unity but rises above it over time, there is a potential opportunity to improve the technology in such a way that it never rises above unity. However, this improvement provides more value when the metric is strongly rising over time (importance of CH$_4$ is increasing), so the choice of framework not only informs technology deployment choices today but also potentially affects the value of innovation in certain areas [22].

References

[1] Cherubini F et al 2016 Bridging the gap between impact assessment methods and climate science Environ. Sci. Policy 64 129–40
[2] Levassor A et al 2016 Enhancing life cycle impact assessment from climate science: review of recent findings and recommendations for application to LCA Environ. Indic. 71 663–74
[3] Tanaka K, Peters G P and Fuglestvedt J S 2010 Policy update: multicomponent climate policy: why do emission metrics matter? Carbon Manage 1 191–7
[4] Frischknecht R et al 2016 Global guidance on environmental life cycle impact assessment indicators: progress and case study Int. J. Life Cycle Assess. 21 429–42
[5] Cherubini F and Tanaka K 2016 Amending the inadequacy of a single indicator for climate impact analyses Environ. Sci. Technol. 50 12350–1
[6] Alvarez R A, Pacala S W, Winebrake J I, Chameides W L and Hamburg S P 2012 Greater focus needed on methane leakage from natural gas infrastructure Proc. Natl. Acad. Sci. USA 109 6435–40
[7] Lavasseur A, Lesage P, Margni M and Deschenes L S R 2010 Considering time in LCA: dynamic LCA and its application to global warming impact assessments Environ. Sci. Technol. 44 3169–74
[8] Lashof D A and Ahuja D R 1990 Relative contributions of greenhouse gas emissions to global warming Nature 344 529–31
[9] Rodhe H 1990 A comparison of the contribution of various gases to the greenhouse effect Science 248 1217–9
[10] Shine K P, Fuglestvedt J S, Hailemariam K and Stuber N 2007 Comparing the climate effect of emissions of greenhouse gases to the greenhouse effect Clim. Change 88 281–302
[11] Tol R S, Berntsen T K, O’Neill B C, Fuglestvedt J S and Shine K P 2012 A unifying framework for metrics for comparing climate effects of different emissions Environ. Res. Lett. 7 044006
[12] Schrag D P 2012 Is shale gas good for climate change? Daedalus 141 72–80
[13] Fuglestvedt J S, Shine K P, Bernsten T, Cook J, Lee D S, Stenke A, Skeie R B, Velders G J M and Waizt I A 2010 Transport impacts on atmosphere and climate: metrics Atmos. Environ. 44 4648–77
[14] Edwards M R and Tranck J E 2014 Climate impacts of energy technologies depend on emissions timing Nat. Clim. Change 4 547–52
[15] Tanaka K, Johansson D I, O’Neill B C and Fuglestvedt J S 2013 Emission metrics under the 2 °C climate stabilization target Clim. Change 117 933–41
[16] Shine K P, Berntsen T K, Fuglestvedt J S, Skeie R B and Stuabor N 2007 Comparing the climate effect of emissions of short- and long-lived climate agents Philos. Trans. R. Soc. A 365 1903–14
[17] Reisinger A, Meinshausen M and Manning M 2011 Future changes in global warming potentials under representative concentration pathways Environ. Res. Lett. 6 020200
[18] Wigley T M L 1998 The kyoto protocol: CO$_2$, CH$_4$ and climate implications Geophys. Res. Lett. 25 2285–8
[19] Tanaka K, O’Neill B C, Rokityanskii D, Obersteiner M and Tol R S J 2009 Evaluating global warming potentials with historical temperature Clim. Change 96 443–66
[20] Myhre G et al 2013 Anthropogenic and natural radiative forcing Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press)
[21] Tong F, Iaramillo P and Azevedo I M L 2015 Comparison of life cycle greenhouse gases from natural gas pathways for light-duty vehicles Environ. Sci. Technol. 29 6008–18
[22] Roy M, Edwards M R and Tranck J E 2015 Methane mitigation timelines to inform energy technology evaluation Environ. Res. Lett. 10 114024
[23] Cubbasch U, Wuebbles D, Chen D, Facchini M C, Frame D, Mahowald N and Winther J-G 2013 Introduction Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press)
[24] Fearnside P M 2002 Why a 100-year time horizon should be used for global warming mitigation calculations Mitigation Adapt. Strateg. Glob. Change 7 19–30
[25] Marten A L, Kopitz E A, Griffiths C W, Newbold S C and Wrolverson A 2013 Incremental CH$_4$ and N$_2$O mitigation benefits consistent with the US Government’s SC-CO$_2$ estimates Clim. Policy 15 272–98
[26] Kendall A 2012 Time-adjusted global warming potentials for LCA and carbon footprints Int. J. Life Cycle Assess. 17 1042–9
[27] Kolstad C et al 2014 Social, economic and ethical concepts and methods Climate Change 2014: Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press)
[28] Allen M R, Fuglestvedt J S, Shine K P, Reisinger A, Piercehumert R T and Forster P M 2016 New use of global warming potentials to compare cumulative and short-lived climate pollutants Nat. Clim. Change 6 773–6
[29] Peters G P, Amaas B, Bernstein T and Fuglestvedt J S 2011 The integrated global temperature change potential (iGTP) and relationships between emission metrics Environ. Res. Lett. 6 044021
[30] Azar C and Johansson D J A 2012 On the relationship between metrics to compare greenhouse gases - the case of IGTP, GWP and SC-GTP Earth Syst. Dynam. 3 139–47
[31] Gillett N P and Matthews H D 2010 Accounting for carbon cycle feedbacks in a comparison of the global warming effects of greenhouse gases Environ. Res. Lett. 5 034011
[32] Stern F, Johansson D J A and Azar C 2014 Emission metrics and sea level rise Clim. Change 127 335–51
[33] Kandlikar M 1995 The relative role of trace gas emissions in greenhouse gas abatement policies Energy Policy 23 879–83
[34] Johansson D J A 2012 Economics- and physical-based metrics for comparing greenhouse gases Clim. Change 110 125–41
[35] Mann F and Richards R G 2001 An alternative approach to establishing trade-offs among greenhouse gases Nature 410 673–7
[36] Laurenz I and Jersey G R 2013 Life cycle greenhouse gas emissions and freshwater consumption of Marcellus shale gas Environ. Sci. Technol. 47 4996–903
[37] Heath G A, O’Donoughue P, Arent J D and Bazilian M 2014 Harmonization of initial estimates of shale gas life cycle greenhouse gas emissions for electric power generation Proc. Natl. Acad. Sci. USA 111 E3467–76
[38] National Energy Technology Laboratory 2012 Power Systems Life Cycle Analysis Tool (Power LCAT) (Pittsburgh, PA: National Energy Technology Laboratory)
[40] Farquharson D, Jaramillo P, Schivley G, Klima K, Carlson D and Samaras C 2016 Beyond global warming potential: a comparative application of climate impact metrics for the life cycle assessment of coal and natural gas based electricity J. Ind. Ecol. at press

[41] National Energy Technology Laboratory 2016 Life Cycle Analysis of Natural Gas Extraction and Power Generation (Pittsburgh, PA: National Energy Technology Laboratory)

[42] Brandt A R, Heath G A and Cooley D 2016 Methane leaks from natural gas systems follow extreme distributions Environ. Sci. Technol. 50 12512–20

[43] Wigley T M L 2011 Coal to gas: the influence of methane leakage Clim. Change 108 601–8

[44] Zhang X, Myhrovd N P, Hausfather Z and Caldeira K 2016 Climate benefits of natural gas as a bridge fuel and potential delay of near-zero energy systems Appl. Energy 167 317–22

[45] Stocker T, Qin D, Plattner G-K, Alexander L V and Allen S K 2013 Technical summary Climate Change 2013: The Physical Science Basis. Contributions of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) pp 33–115

[46] Fuglestvedt J S, Bernsten T K, Godal O, Sausen R, Shine K P and Skodvin T 2003 Metrics of climate change: assessing radiative forcing and emissions indices Clim. Change 58 267–331