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A climate-goals-based, multicriteria method for system evaluation in Life Cycle Assessment

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Abstract

Purpose

Our ability to restrict global warming to the established objectives in the Paris Agreement depends on the metrics used to evaluate the climate change impact. Stemmed on the criticism of the current GWP metrics used with Life Cycle Assessment (LCA), this study proposes new indicators and an interpretation grid for climate change impact in LCA, which are adaptive to present, short-term, and long-term climate goals.

Methods

The global mean temperature change (GMTC) is used in the indicators' definition and time parameters are introduced for a multicriteria evaluation of climate change impact. We adopt calendar-related time targets instead of a fixed time horizon. The systems are analyzed on a real time scale and with respect to a climate-target point in time (for example 2050 as objective for climate neutrality), in contrast with conventional LCA. The objective is to provide flexibility in system evaluation, adaptable to current and future targets.

Results and discussion

Four indicators are introduced: (1) the amplitude of the temperature change ($GMTC_{max}$), representative for climate extreme events; (2) the time at which GMTC starts to definitely decrease and its distance with respect to the goal (t_{last_peak}); (3) the time climate neutrality is reached and its distance with respect to the goal ($t_{neutral}$); 4) the accumulated warming until a targeted time, representative for sea-level rise and ice melting (integrated GMTC at a given time target, for example at the end of century $iGMTC_{2100}$). An analysis grid is proposed based on these indicators, and illustrated on 26 emission profiles involving long and short lived greenhouse gases with various temporalities, as well as on two dynamic LCA case studies. In the group of neutral systems, temporality is responsible for variations in $GMTC_{max}$ and $iGMTC_{2100}$. Increasing the frequency of emission/capture events flattens both indicators and provides the best performance. Equal CO_2 emission systems are discriminated primarily by $t_{lastpeak}$, while in the case of methane, more relief is observed for all indicators. The method allows for the design of tailored mitigation solutions in LCA application examples.

Conclusions

The indicators are able to discriminate and rank systems that are considered to be non-impacting, equivalently impacting, or neutral in LCA-GWP metrics. Such metrics is necessary to correctly (avoid strong simplifications) and unambiguously (with unaltered physical parameters, closer to climate physics) evaluate the effect on climate, mitigation solutions, neutrality, and support decision-making.

1. Introduction

Climate change is currently a crucial issue determining major transformations in our society at all scales, from individuals to countries. The Paris Agreement (UNFCCC, 2015) states that the increase of the global mean surface temperature (GMST, e.g. recent observations of temperature levels in Valipour et al., 2021) must be maintained well below 2°C with respect to the pre-industrial level, and we must pursue efforts to limit the temperature increase at 1.5°C. This is referred to as the “long-term temperature goal” and requires the neutrality of greenhouse gas (GHG) emissions (emissions reduced to zero or compensating for all emissions) to be reached in the second half of this century. More recently, the IPCC emphasized the importance of containing global warming to less than 1.5°C (above the pre-industrial level) throughout the 21st century (and beyond) in order to limit irreversible or runaway natural phenomena (IPCC, 2018). This climate goal implies that net CO_2 emissions be offset by approximately 2050 and that non-CO_2 GHG emissions be drastically reduced. In addition, the latest version of the European Climate Law sets a framework to achieve climate neutrality by 2050, with the ambition of Europe becoming the first climate-neutral continent (European Commission, 2020). Moreover, an IPCC special report (IPCC, 2018) highlighted the need for adaptive mitigation approaches in which emissions are continuously adjusted to achieve the set temperature goal. For example, in France, the High Council on Climate (High Council on Climate, 2019) recommends on-going systematic ex-ante evaluations of GHG emissions for all economic and societal measures and regulations or mitigation options. However, evaluating and adjusting emissions (via policies, by decision makers, and economic actors) implicitly requires the use of relevant metrics by linking the GHG emissions to the climate goals (Rogelj et al., 2019).

One of the most used tools for environmental impact assessments of human activities (products, processes, and services) is the Life Cycle Assessment (LCA) method, formalized by the ISO 14040–14044 standards (ISO, 2006a, 2006b). The LCA method has evolved since the 1980s and currently evaluates a variety of impacts on three main areas of protection (natural resource depletion, ecosystem quality, and human health). It includes climate change impacts evaluated following IPCC recommendations (e.g., IPCC, 1990) using the global warming potential (GWP) and, more recently, the global temperature potential (GTP) as characterization factors for GHGs. Climatologists have explained and warned of the conceptual limitations of GWP for many years (e.g., IPCC, 1990; Fuglestvedt et al., 2003; Shine, 2009; Allen et al., 2016; Fuglestvedt et al., 2018); however, LCA practitioners have continued to employ GWP and the associated measurement unit kilogram CO_2-equivalent (kg CO_2-eq) as the unique metrics to measure the performance of a system with respect to climate change and to guide decision making. In the following, the main climate metrics proposed up to now and their use within LCA will only be briefly mentioned because state-of-the-art analyses of these issues were recently published (Levasseur et al., 2016; Cherubini et al., 2016). Instead, metrics and indicators explicitly linked to the climate goals and proposed in the recent literature will be emphasized.

1.1. Climate metrics for decision making

Criticism of GWP has as its starting point the basic concept itself (see the above cited literature). (1) It is calculated from the pulse emission of a gas, which does not reflect the real dynamics of the emissions over the lifetime of a system. (2) It introduced the concept of CO_2 equivalence using CO_2 as the reference gas for the metric normalization. However, the concept of CO_2 equivalence is hard to justify because CO_2 has a particular behavior as a result of its very long lifetime in atmosphere. (3) It requires the time horizon to be fixed, which is not scientifically justified. (4) The same is applied irrespective of the nature of the GHG, be it long lived (LLGHG) or short lived (SLGHG), which conceals the intrinsic behaviors and contributions of distinct types of GHGs. For example, GWP100 gives more importance to LLGHGs and underestimate the short-term (circa 20 years after emission) effects of SLGHGs (Aamaas et al. 2013; Allen et al, 2016). (5) GWP has application to tropospheric-generated GHGs, whereas other climate forcers (e.g., stratospheric emissions, short-lived non-mixed gases, and particles) are not or cannot be represented using the same concept. (6) Finally, GWP, being a conceptually very simplified metric, can mislead interpretations of the evaluation results and the decision to be adopted, especially when the climate target approaches in time (Aamaas et al.2013; Allen et al., 2016, 2018; Fuglestvedt et al., 2010, etc.). A simple example is the case of biogenic CO_2, which was considered neutral in LCA or other carbon footprint methods, when it is not.

The topical importance of climate change in the present and for the next decades, as well as the complex behavior of each GHG has promoted a diversification of the metrics used. To alleviate the above cited limitations, climatologists have proposed complementary emission metrics in parallel to GWP to provide more reliable evaluations for usage by practitioners and decision makers. Contrary to GWP, GTP is thought to be closer to the real climate impact and more relevant for all types of GHGs (Shine et al., 2005; Shine et al., 2007). However, the same principles used for GWP are at the core of the definition of GTP. In the last decade, synthesis analysis studies have been published on emission metrics that could be used with a large typology of GHGs (e.g., Aamaas et al., 2013, Tanaka et al., 2013; Fuglestvedt et al., 2018; Collins et al., 2020). Impulse and sustained emissions have been considered, as well as different time horizons and absolute and relative metrics (with respect to CO_2). One of the important outcomes of these studies is that each type of metric leads to different conclusions and, along with the nature of the GHG and the chosen time horizon, has strong implications for the calculated performance of a system and the ranking of compared systems (for example, the rankings of countries based on their GHG emissions is not the same for different metrics used).

To account for the behavioral differences between LLGHGs and SLGHGs, a sustained or step emission profile has been proposed, in addition to or in combination with pulse emission, to calculate complementary indicators (e.g., Allen et al., 2016; Allen et al., 2018; Fuglestvedt et al., 2010; Collins et al., 2020). Based on observations that integrated indicators such as GWP or integrated-GTP equally weight the climate impact over a given time scale, Collins et al. (2020) proposed the use of two metrics, based on the absolute GWP or on the absolute GTP, calculated at the time of interest (the climate target time) and being the ratio of the step response (the accumulated radiative forcing or the global mean temperature change) of a GHG to the impulse response of CO_2. These combined metrics, called CGWP and CGTP, have units of $kg_{GHG}\ yr^{-1}\ kg^{-1}{}_{CO2}$. The time at which the indicators are calculated needs to be fixed in agreement with the climate goals. The use of different emission standards (pulse and step) to calculate emission metrics has the advantage of providing a more realistic account of SLGHGs while maintaining the concept of CO_2 equivalence, which has a strong and long-established use in climate policy for decision makers and society in general. However, the authors recognized the limitations of these new methods when applied to systems with different lifetimes and emission timings (e.g., the short lifetime of an emitting system is not compatible with the concept of step emissions).

In a different vein, Kirschbaum (2014) proposed the replacement of classical indicators with what the author called the “climate change impact potential” based on the explicit quantification of the global mean temperature change over time. Three metrics were proposed that were compatible with three main damages based on their functional relationships with increasing temperature: (1) the temperature variation in time responsible for extreme weather events, heat waves, and coral bleaching; (2) the rate of warming (rate of temperature change over time) responsible for the maladaptation of ecosystems and socio-economic systems; and (3) the cumulative warming (integrated temperature variation over time) responsible for the melting of glaciers and sea level rise. In the same line, Sterner et al. (2014) and Shine et al. (2005) proposed metrics based on temperature and RF to estimate impacts on sea level rise (the “global sea level rise potential” and its integral) and on precipitation change (the “global precipitation change potential”), respectively. However, such estimations of endpoint climate impacts is more uncertain as a result of our current limited knowledge (Fuglestvedt et al. 2003).

1.2. Metrics and indicators in LCA and the climate goals

At present, LCA databases related to Life Cycle Inventory (LCI) and Life Cycle Impact Assessment (LCIA), e.g., ecoinvent 3.6, include the IPCC Fifth Assessment Report results (IPCC, 2013) for GWP and GTP (time horizons of 20 and 100 years) for well-mixed GHGs (LLGHGs and SLGHGs) without climate–carbon-cycle feedback. GHGs with lifetimes shorter than the hemispheric mixing time, e.g., volatile organic compounds and carbon monoxide, called near-term climate forcers, are included only via their global (non-regionalized) values.

The way in which climate impact assessment is performed in LCA has strong implications at the decision-making level when responding to major decision goals (Royne et al., 2016) such as (i) reducing the climate impact of a product, (ii) choosing the product with the lowest impact, and (iii) designing systems for reducing either the long-term or short-term climate impact. In this context, an analysis of the existent emission metrics (GWP and very recently GTP) and practices for climate change impact assessment in LCA was presented by Cherubini et al. (2016) and Levasseur et al. (2016) as a contribution to the UNEP/SETAC Life Cycle Initiative. The authors highlighted the limitations of the existent emission metrics and the need to tightly couple the evolution of the LCA method with progress in climate science. Conclusions were presented in Jolliet et al. (2018), with recommendations for LCA practitioners to (1) asses the short-term climate change with GWP100, which is numerically close to GTP40, and, as such, is thought to sufficiently evaluate the temperature impacts within the next four decades, and (2) evaluate long-term climate change with GTP100, which is numerically equivalent to GWP for several centuries. Such guidance may be confusing for LCA practitioners and decision makers, who could end up feeling lost between the time horizons and the real significance of the results obtained. One of the strongest limitations of such metrics is that a fixed time horizon is not compatible with the present and further climate temporal goals (e.g. the GWP time horizon of 100 years is well beyond the near neutrality target of 2050 or 2100 for not exceeding 2°).

Several studies have adopted instantaneous RF and integrated RF (iRF), calculated as a function of time from the emission time zero to a sufficiently long time horizon, as a means to describe the climate impact in LCA (Cherubini et al., 2011; Levasseur et al., 2012). In addition, time-dependent characterization factors based on RF have been proposed by Levasseur et al. (2010), with a calculation time step of 1 year, for different GHGs. This method has been applied in several different LCA case studies, with the results expressed as RF and iRF as a function of time (e.g. works of Levasseur et al., 2010, 2012; Fouquet et al., 2015; Cherubini et al., 2011). GMTC has also been used as a parameter calculated as a function of time (Ericsson et al., 2013; Shimako et al., 2018; Negishi et al., 2019). Meanwhile, Kirschbaum (2017) applied climate change impact potentials, defined in Kirschbaum (2014), to LCA for bioenergy, making the climate change evaluation a multicriteria evaluation. The calculated climate perturbation was normalized using its maximum forecast from the Representative Concentration Pathway (RCP) scenarios, making the impact result dependent on the background CO_2 concentration in the atmosphere. However, there was no discussion of the real implication of using absolute or normalized values on judgements of the impact gravity and mitigation priorities. Jorgensen et al. (2014) proposed the use of the atmospheric capacity for receiving a particular GHG at a target time (e.g., 2100) without overshooting the atmospheric threshold of kg CO_2-eq (e.g., 450 ppm CO_2-eq, chosen from RCP6). This new characterization factor for application in LCA is called the "climate tipping potential" and can be calculated with respect to a climate target time. However, the GWP methodology of considering impulse emission and the reference to CO_2 were still retained. Another limitation is that the atmospheric threshold is already expressed as a CO_2 equivalent (tainted by the shortcomings exposed above), which entails inherently misleading interpretations when applied to different GHGs.

Applications of the cited approaches with LCA are still sparse but are becoming increasingly frequent. However, these approaches have only been used with portions of LCI treating a targeted part of a studied life cycle system. Recent developments of dynamic LCA (DLCA) approaches at both the LCI and LCIA levels (Beloin-Saint-Pierre et al., 2020; Sohn et al., 2020) have significantly broaden the possibilities for relevant impact evaluations. Applications of DLCA/climate change have recently been demonstrated (Shimako et al., 2018; Negishi et al., 2019; Pigné et al., 2019), with the global mean temperature change (GMTC) calculated as a function of the emission timing over the whole life cycle of the studied systems and for all GHGs emitted. Despite these new developments, consideration of climate goals is still not integrated into the design of the impact indicators and, therefore, there is no clear key to interpreting the dynamic indicator results.

1.3. Objective of this work

Albeit scientists have been pointing out *discrepancies between the climate objectives and the metrics proposed for policy and decision makers* (Fluglestvedt, 2018; Cherubini et al., 2016; Collins et al., 2020), LCA method still uses overly simplified concepts and indicators designed 30 years ago. Indeed, for simplicity reasons, an indicator used for a large number of GHGs need to aggregate their effects (e.g., via CO_2 equivalence); however, at present and in the future, these indicators cannot be disconnected from the decision goals, which could address the impact reduction in time or the climate neutrality of a system.

In order to alleviate such weaknesses, *this study builds on DLCA principles and proposes new indicators and an interpretation grid for climate change impact in LCA, which are adaptive to present, short-term, and long-term climate goals. The indicators discriminate systems at different points in time, evaluate mitigation scenarios and climate neutrality.* The novelty of the proposed method lies in the consideration of climatic objectives in terms of temperature and time, as reference points for the analysis of a system's performance.

In the followings, the concept behind the proposed indicators is presented (section 2) and then applied to theoretical emission profiles (section 3). The method is also demonstrated on two DLCA case studies (section 3).

2. Materials and methods

2.1. The climate goals

Currently, the climate goals are defined by the global mean temperature level and a time dimension. In the Paris Agreement, the condition limiting GMST to 2°C prior to 2100 requires achieving climate neutrality in the second half of this century. A more ambitious condition, following IPCC 2018, of keeping the warming below 1.5°C in this century relies on a strong reduction in GHGs by 2030 and neutrality by 2050. Recently, the European Commission (2020) fixed an objective in which Europe would become the first climate-neutral continent, with a time target of 2050. Here, "neutrality" can be interpreted either in terms of the net CO_2 balance or globally based on the GHG balance. The latter is so-called climate neutrality. The significance and metrics of "neutrality" have been discussed in recent publications (Fuglestvedt et al., 2018; Rogelj et al., 2019), and one possibility is to refer to the stabilization of the RF. Using kg CO_2-eq metrics (e.g., as done in the National Low-Carbon Strategy (SNBC, 2020) regulation in France) to measure the neutrality condition is ambiguous due to the shortcomings cited in the Introduction section. The targeted values of GMST and time may vary when the near-term time of the goal is approached because of climate uncertainties and our knowledge improvement, as happened recently with the new targeted GMST of 1.5°C versus 2°C (IPCC, 2018).

Accordingly, three reference time points were chosen in this study: (1) the time of peak GMST followed by GMST decline or stabilization in the short term (prior to 2050), denoted t_{goalST}, with, for example, $t_{goalST} = 2050$; (2) the time climate neutrality should be accomplished, around mid-century, denoted t_{goalN}, with, for example, $t_{goalN} = 2050$; and (3) a time for an additional long-term target, denoted t_{LT}, with $t_{LT} = 2100$.

2.2. Climate change indicators for LCA

To be consistent with the Paris Agreement, three elements must be monitored (Rogelj et al., 2019): (1) the time at which GMST reaches its peak; (2) the level of warming at this time point; and (3) GMST evolution after its peak, either stable or decreasing. Likewise, Collins et al. (2020) argued that instantaneous metrics related to temperature and RF as a function of time are more relevant than the integrated metrics.

Given the actual need to dynamically correlate the GHG emissions with climate responses and adaptive mitigation, the impact indicators must be functions of time and adaptive with respect to the climate targets (t_{goalST} and t_{goalN}).

Including the time dimension in impact calculations in LCA is a relatively new topic in the sense that methods and tools have only very recently been proposed and their use in practice is still emergent. The interbreeding of temporal issues in LCA with real dynamics in the technosphere has been addressed in recent works (Pigné et al., 2019; Tiruta-Barna et al., 2016; Beloin-Saint-Pierre et al., 2020). The objective of DLCA is to calculate temporally differentiated inventories (e.g., GHG emissions) distributed over the entire life cycle time (as in real life) and then to evaluate the time-dependent impacts. Therefore, the proposed indicators considering the climate goals, need to be compatible with the DLCA approach because their calculation relies on the time-distributed GHG inventory and on the time-dependent impacts.

Indeed, the proposed climate impact indicators, relaying on the DLCA concept, are based on the estimation of GMST as a function of time and should be able to explicitly link each GHG emission to the climate goal. The GMST value estimated by available modeling approaches is noted here as GMTC (global mean temperature change) to distinguish between the "real" (estimated from climate data) and simulated parameters, respectively. The integrated temperature iGMTC is also considered. The temperature was chosen instead of RF for the following reasons: (i) GMTC is preferred to RF because the Paris Agreement focuses on temperature goals and GMTC is closer to the climate target GMST and its desired temporality and (ii) iGMTC is preferred to iRF for its coherence with GMTC, even though iRF and iGMTC give similar profiles (Collins et al., 2020). However, care must be taken when using integrated metrics, especially when close to the climate target time, because they give equal importance to climate impacts that occur at different points in time (i.e., the information about the peak occurrence is lost).

Appropriate climate indicators need to allow comparisons of systems based on the amplitudes of the temperature parameters (GMTC and iGMTC) and the timing of the temperature events. Moreover, the impact indicators need to discriminate between systems having the same global net emissions (commonly expressed in kg CO_2-eq) but with different temporalities and consequently different climate effects (to avoid, for example, postponing GHG emissions beyond 2050, or accelerating the current warming). Finally, the indicators need to correctly evaluate climate neutrality. Concerning the temporality, the selected points in time need to be able to describe the temperature evolution in a manner consistent with the Paris Agreement goals and be easily updatable following adjustments of these goals (e.g., achieving neutrality by t_{goalN} = 2050 or by t_{goalN} = 2070, etc.).

Table 1. Proposed indicators for a multicriteria evaluation of climate change impact in LCA.

Category of impact & Parameter	**Indicator**	**Notation**
Temperature-related		
Global mean temperature change (GMTC)	Temperature maximum peak registered	$\mathbf{GMTC_{max}}$
	Paris Agreement - Climate neutrality Time of climate neutrality achievement when GMTC=0	$t_{GMTC=0}$
	-Deviation from the goal	$\mathbf{t_{neutrality}} = t_{GMTC=0} - t_{goalN}$
	If climate neutrality not achieved Time of the last temperature peak or the beginning of temperature decrease or stabilization	$t_{T\ starts\ decrease}$
	-Deviation from the goal	$\mathbf{t_{last\_peak}} = t_{T\ starts\ decrease} - t_{goalST}$
Heat-related		
Accumulated heat (iGMTC)	Integrated temperature change at long term, taken here as 2100	$\mathbf{iGMTC_{LT}}$ for t_{LT} = 2100

The calculation principles rely on RF and GMTC modeling using the impulse response function approach (IPCC, 2013) and are given in the Supplementary Information (SI). The derived indicators are presented in Table 1. For all indicators, "smaller is better" is the ranking rule between the compared systems, as justified below.

- The temperature peak is directly responsible for climate perturbation phenomena (IPCC, 2013), with larger climate impacts for higher peak amplitudes.

- Climate neutrality, in its physical interpretation (Fuglestvedt et al., 2018), signifies that RF stabilizes in time; thus there is no additional global temperature increase, i.e., GMTC is zero (or preferably negative) from this point in time ($t_{neutrality}$) forward. Obviously, early neutrality is preferred.

- Concerning t_{last_peak}, an early peak temperature followed by a decrease is preferred to a later peak because, as the peak approaches the time target, the probability of exceeding the temperature goal increases and it becomes increasingly difficult to deploy efficient carbon capture and storage (CCS) techniques to keep GMST below 1.5°C (or 2°C).

- In case of systems with multiple events like temperature peaks and/or neutrality points (GMTC=0), the last event is considered as time indicator (the time of the last peak, the time of the last neutral point) in order to not conceal temperature rebounds on the time course. $GMTC_{max}$ corresponds to the highest peak.

- Finally, iGMTC is a measure of the accumulated heat that causes impacts such as ice melting and sea level rise; a smaller iGMTC results in a smaller impact.

3. Results and discussion

3.1. Application to various emission profiles: GMTC and iGMTC results

In this section, the relevance of the proposed indicators is analyzed for several emission typologies for which the indicators were calculated. Two representative gases, CO_2 as an LLGHG and CH_4 as a SLGHG, were considered. These scenarios were inspired by real systems and most were chosen to shed light on the importance of the emission temporality. All the graphical representations consider the time origin, t = 0, to be the year 2020; therefore, negative values indicate times prior to 2020. On this scale, 2050 and 2100 correspond to years 30 and 80, respectively. The *x*-axes on the graphs were not scaled in calendar years to show the flexibility if regulations and policies evolve, enabling other climate time goals to be set (t_{goalN}, t_{goalST}, or t_{LT}). For all the emission profiles, the obtained results for GMTC and iGMTC are shown and analyzed. Complementary results for RF and iRF are also presented in the SI. Application of the proposed indicators is discussed in section 3.2.

Group 1 and 2 – common emission profiles

The first two groups consist of scenarios with CO_2 or CH_4 emissions of 1 kg with different shapes, i.e., impulse, step, or decreasing, spread over different emission durations from 1 year to 50 years (denoted E1–E6 (group 1) and E1_CH4–E5_CH4 (group 2), respectively). The objective here is to test the capability of the indicators to discriminate between systems with equal GWP-based impacts but with different temporalities, and to apply for LLGHG and SLGHG gases (Figures 1 and 2).

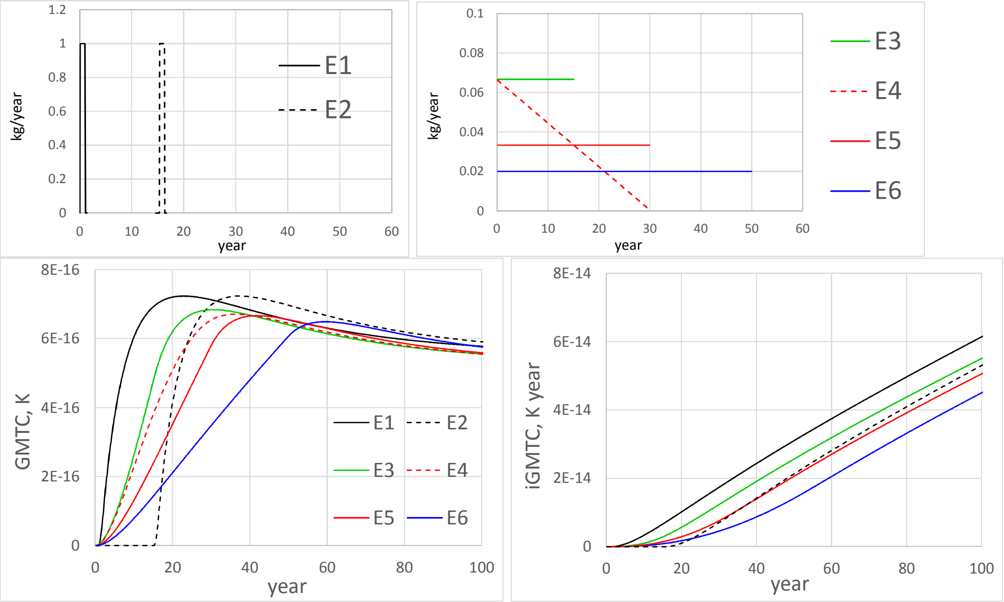


Figure 1. Group 1. Emission of a LLGHG: 1 kg of CO_2 emission, different temporalities. Emission profiles and GMTC and iGMTC results.

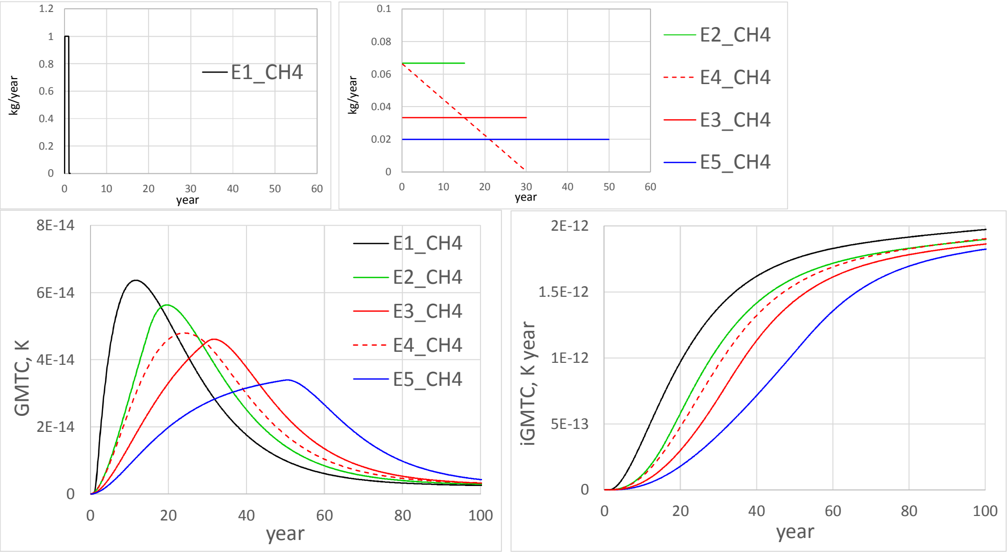


Figure 2. Group 2. Emission of a SLGHG: 1 kg of CH_4 emission, different temporalities. Emission profiles and GMTC and iGMTC results.

Groups 1 and 2 clearly show the influence of the temporality of the emissions on the GMTC and iGMTC curves. GMTC and iGMTC values are higher at short term (e.g. year 20) when the emission takes place earlier and over a shorter time interval (case E1 compared to E2; E1 and E1_CH4 compared to E6 and E5_CH4 respectively). An impulse emission shifted in time generates the same GMTC and iGMTC profiles (E1 and E2; not represented for CH_4).

The end-of-life time determines the point from which GMTC decreases (this point is delayed with respect to the end of emissions by the climate processes).

Group 3 and 4 - neutrality

Climate neutrality is a global goal. This goal can be achieved by drastically reducing emissions and/or by adopting permanent CCS technologies. Carbon capture and temporal storage is also possible in soils and in manufactured products with very long lifetimes. However, systems achieving neutrality, either by GHG reduction to zero, or by associating CCS activities (as done for waste treatment), should replace those currently in place in industry and all other human activities. For these systems, CCS could be integrated in their life cycle as waste (GHG) management solution. Evaluating the benefits of these systems is challenging because the GWP metric fails, as will be shown later. In order to highlight the effect of emission/capture timing, group 3 includes seven examples with carbon neutral systems (following the GWP approach), i.e., 1 kg CO_2 emitted and 1 kg CO_2 captured, but with different temporalities, resulting in various climate-neutral situations (figure 3). For example, (i) N1 and N2 include capture after two emission decades and for different durations, as could occur when adopting, over the course of time, a CCS technology in a factory; (ii) N3 and N4 present early capture for a long duration, as done by trees planted for compensating a system's emissions, followed by later emissions due to tree end of life and soil re-emission (here, the later emissions were included in the global net zero kg CO_2-eq); and (iii) periodic emission–capture is presented in N5, N6, and N7 with periods of 1, 5, and 10 years, respectively, as a very simplified representation of plant cultivation (carbon capture) and use (carbon emission) with different rotation periods, or any other alternating emission–capture processes. These behaviors were chosen to understand the influence of the periodicity of such processes on the chosen climate indicators.

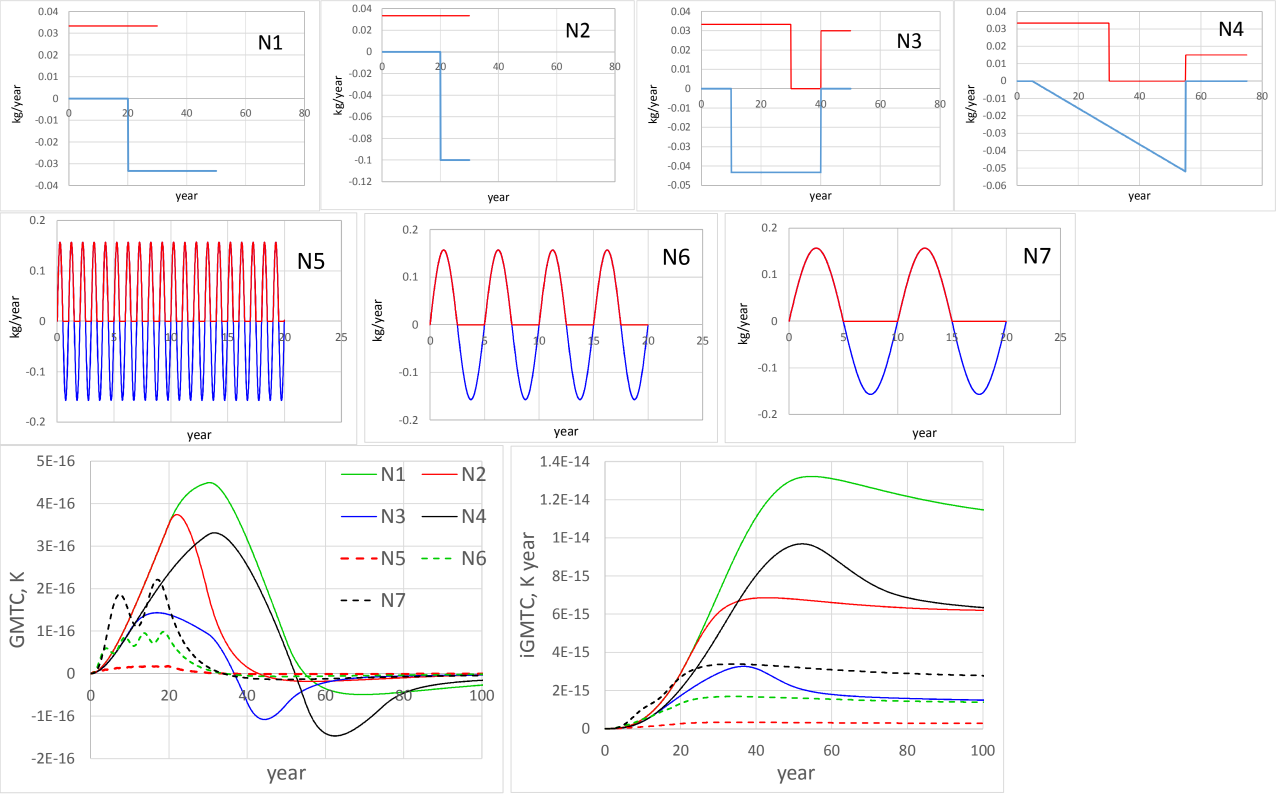


Figure 3. Group 3. Neutrality: CO_2 emission 1kg (red line) and CO_2 capture 1kg (blue line), with different temporalities. Emission profiles and GMTC and iGMTC results.

Group 4 proposes examples of systems emitting a SLGHG (CH_4) with CO_2 capture to achieve neutrality from the conventional LCA point of view, i.e., zero kg CO_2-eq net emission. Here, the effect of different GHGs is expected to be observed.

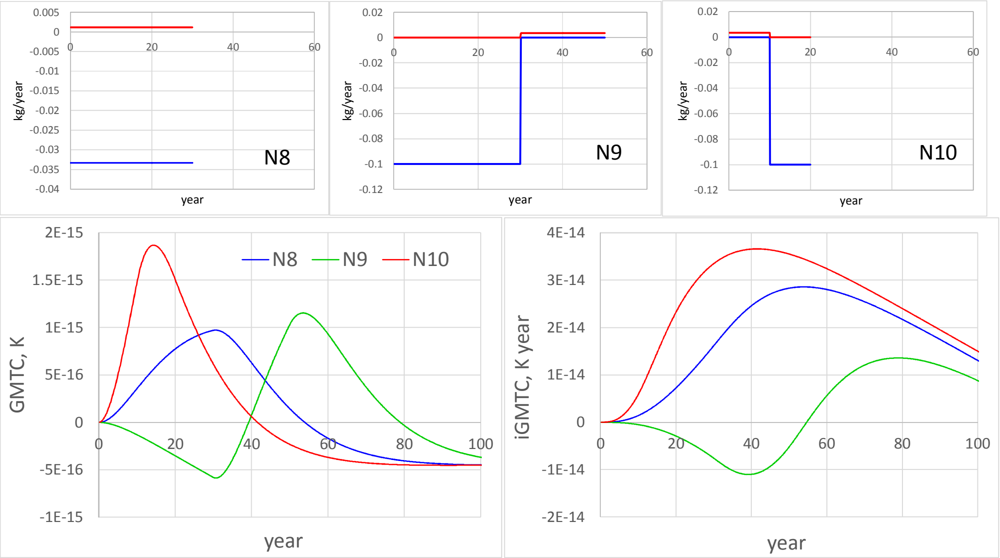
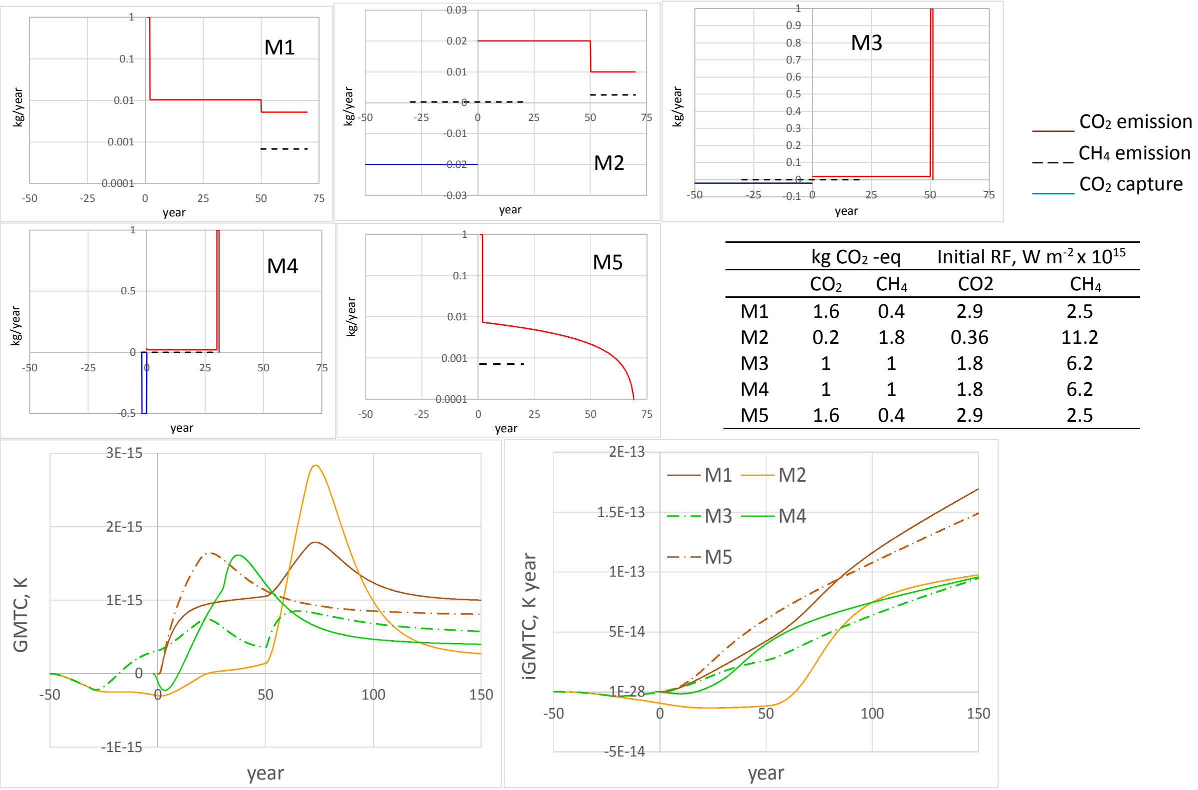


Figure 4. Group 4. Neutrality: CH_4 emission (red line) 1 kg CO_2-eq, CO_2 capture (blue line) 1 kg CO_2 –eq, with different temporalities. Emission profiles and GMTC and iGMTC results.

The "neutral" group 3 systems demonstrate that the relative dynamics of the emissions and captures play an important role with respect to the GMTC and iGMTC values and shapes. The higher the frequency of captures, the smaller the GMTC peak and iGMTC (N5 – N7). Even if the temperature is stabilized at the desired level (GMTC <0), iGMTC remains important for centuries (e.g. Figure 3, at year 100). Climate neutrality is achieved when GMTC becomes zero. When different GHGs are combined (group 4) to result in a total zero impact in terms of kg CO_2-eq, the results are far from foreseeable. For example, in N9, CO_2 capture precedes CH_4 emission; however, a temperature peak is registered before achieving neutrality near year 80. Systems achieving neutrality allow "cooling" as observed on iGMTC shapes, after a peak period located around the time of neutrality. Decreasing iGMTC in time is not observed for the other systems.

Group 5 – various profiles with identical kg CO_2-eq net emission

The last group considers mixed emissions of both CO_2 and CH_4 with different quantities and temporalities, as encountered in real life. The common point of these scenarios is that they all have the same conventional GWP impact, i.e., 2 kg CO_2-eq. Figure 5 presents the emission/capture profiles, the share of GWP between CO_2 and CH_4 and the initial RF potential of both gases (the mass multiplied by the specific RF), and the temperature results. The objective here is to apply the new method to complex systems (different GHG and emission profiles) with similar performance in terms of GWP. For example, M1 includes emission of CO_2 over the entire lifetime and CH_4 at the end of life (e.g., building utilization followed by building waste landfilling); M2 and M3 are similar systems with respect to carbon capture but have different end-of-life processes (e.g., trees grow and are used as materials, followed by landfilling or incineration); M4 is similar to M3 but with shorter lifetimes; and M5 has continuously diminishing emissions.



	kg CO_2 -eq		Initial RF, W m^{-2} x 10^{15}	
	CO_2	CH_4	CO2	CH_4
M1	1.6	0.4	2.9	2.5
M2	0.2	1.8	0.36	11.2
M3	1	1	1.8	6.2
M4	1	1	1.8	6.2
M5	1.6	0.4	2.9	2.5

Figure 5. Group 5. Various CO_2 and CH_4 emission/capture profiles, for a total of 2 kg CO_2 –eq. Emission profiles and GMTC and iGMTC results.

In group 5, the combination of CH_4 and CO_2 emission–capture for a global 2 kg CO_2-eq in GWP metrics shows the effect of: (i) late SLGHG emission in M2 on GMTC (a high peak) and iGMTC (a low value), (ii) early CO_2 emissions in M1 and M5 resulting in higher iGMTC values, for the considered timespan. These examples show that the more complex the emissions are in terms of substances and temporality, the more difficult it is to imagine the effects on GMTC and iGMTC without a calculation tool.

3.2. Application examples: comparison and ranking

Despite the useful information provided by graphical representations in DLCA, comparing and ranking systems is not straightforward and requires pinpointing the most significant information. Accordingly, the scenarios were ranked following the indicators defined in Table 1 and these ranking results are presented in Table 2.

Table 2. Ranking of the emission examples following the four proposed indicators, and according to GWP metrics

	$GMTC_{max}$	K	$t_{neutrality}$	years	$t_{last\ peak}$	years	$iGMTC_{2100}$	K.year	GWP kg CO_2-eq
Lowest value	N5	1.76E-17	N7	3.80	E1_CH4	-18	N5	2.88E-16	N1 to N10
	N6	9.84E-17	N6	4.09	N10	-15.2	N6	1.44E-15	= 0
	N3	1.43E-16	N5	4.20	N3	-13	N3	1.58E-15	
	N7	2.21E-16	N3	6.70	N7	-11.6	N7	2.89E-15	E1 to E6
	N4	3.31E-16	N10	11.60	N6	-11.3	N2	6.32E-15	and
	N2	3.74E-16	N2	12.70	E2_CH4	-10.4	N4	6.86E-15	E1_CH4 to
	N1	4.49E-16	N4	22.30	N5	-10.2	N1	1.22E-14	E5_CH4
	E6	6.49E-16	N8	24.00	N2	-8	N9	1.36E-14	= 1
	E5	6.67E-16	N1	24.60	E1	-7.9	N8	2.17E-14	
	E4	6.71E-16	N9	49.10	M5	-6	N10	2.40E-14	M1 to M5
	E3	6.84E-16			E4_CH4	-5.6	E6	3.32E-14	= 2
	E2	7.23E-16			N8	0.7	E5	3.92E-14	
Impact increases ↓	E1	7.23E-16			N1	1	E2	4.10E-14	
	M3	8.50E-16	NN		N4	1.3	M2	4.18E-14	
	N8	9.73E-16			E3_CH4	1.4	E4	4.22E-14	
	N9	1.15E-15			E3	1.6	E3	4.38E-14	
	M4	1.61E-15			E4	6	M3	4.94E-14	
	M5	1.64E-15			E2	6.8	E1	4.97E-14	
	M1	1.78E-15			M4	8	M4	6.44E-14	
	N10	1.87E-15			E5	12.7	M1	8.74E-14	
	M2	2.82E-15			E5_CH4	20.5	M5	9.04E-14	
	E5_CH4	3.40E-14			N9	23.4	E5_CH4	1.70E-12	
	E3_CH4	4.61E-14			E6	29.5	E3_CH4	1.78E-12	
	E4_CH4	4.80E-14			M3	36.6	E4_CH4	1.83E-12	
Highest value	E2_CH4	5.63E-14			M1	43.15	E2_CH4	1.83E-12	
	E1_CH4	6.37E-14			M2	44.5	E1_CH4	1.92E-12	

Grey field: the value exceeds the target time of 2050

NN : The other scenarios don't achieve neutrality until the considered time horizon of 2170 (GMTC calculation over 150 years)

The ranking highlights the five groups especially according to the temperature indicator. The "neutral" cases (N1–N10) form the cluster of the best-performing systems, a result that was expected. As an exception, the CH_4–CO_2 neutral N8–N10 scenarios present high temperature peaks ($GMTC_{max}$) as a result of the high specific RF of CH_4. Next is the cluster of CO_2 emission scenarios, E1–E6 (group 1), and then the cases, M1–M5 (group 5). This ranking can be explained by the higher GHG quantities, as well as the specific RF, emitted in group 5. Finally, group 2, with the CH_4 emission scenarios E1_CH4–E5_CH4, has the worst performance, which is explained by the high specific RF of the emitted CH_4 compared to the other scenarios. In contrast, the time indicator t_{last_peak} classifies the groups differently, especially group 2. Indeed, the time at which a temperature peak occurs is independent of the peak amplitude, justifying the choice of time as a complementary climate indicator.

One of the most important improvements that the new indicators bring to climate change impact evaluations is the ability to *discriminate between systems considered to be equivalent in conventional LCA*. Within each group, the systems are LCA-wise equivalent (the same net kg CO_2-eq) but perform differently according to the new indicators. More, clear difference is observed between CO_2-only and CH_4-containing scenarios, in contrast to the GWP metric which does not discriminate between them. For each group, the results by indicator, normalized by the maximum value in the group, are compared in Figure 6. For groups 1, 2 and 5, neutrality is not reached, so $t_{neutrality}$ is not represented.

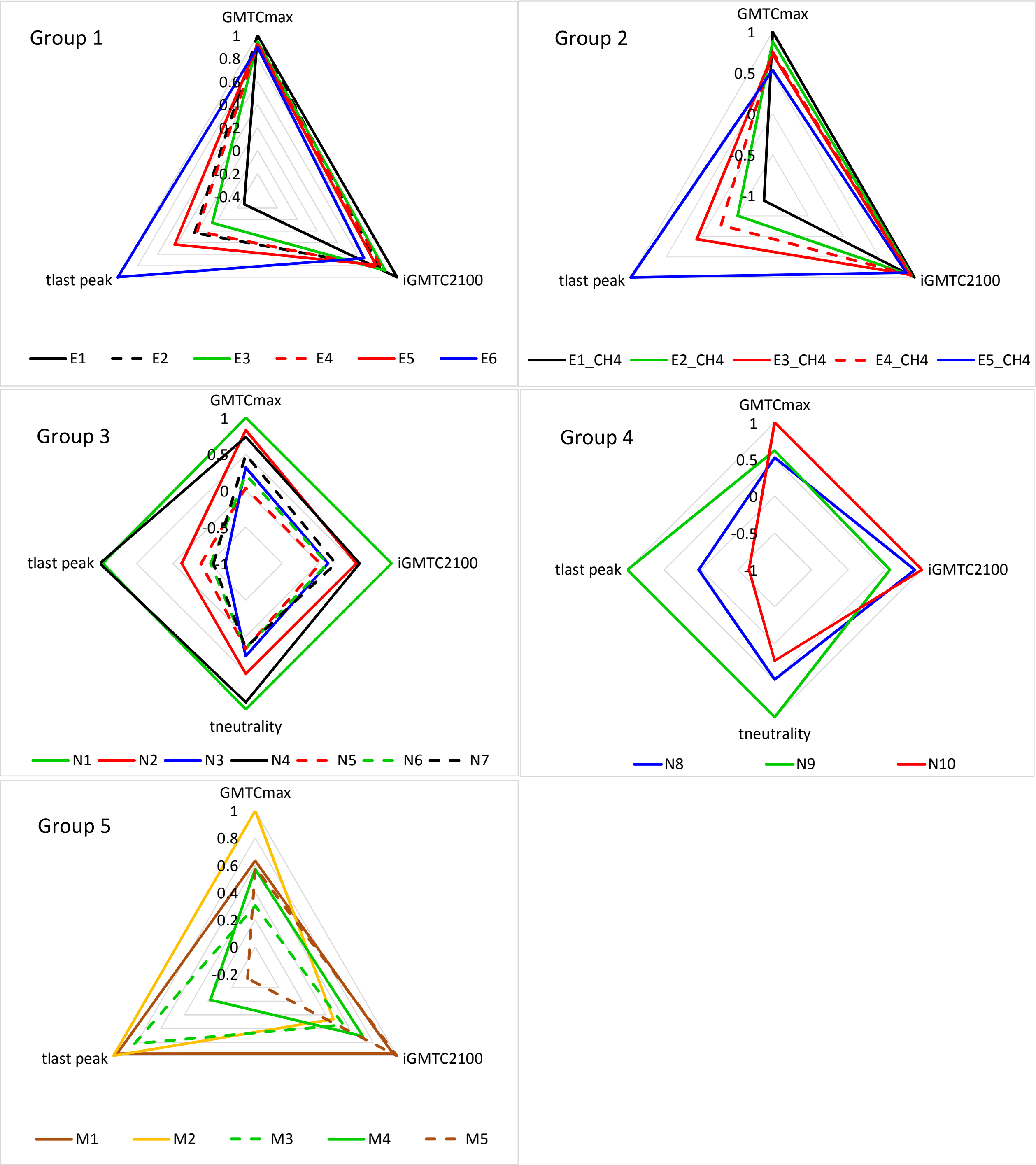


Figure 6. Ranking of scenarios inside each group: group 1: CO_2 emissions; group 2: CH_4 emissions; group 3: neutral CO_2 systems; group 4: neutral CH_4 and CO_2 systems; and group 5: mixed CO_2 and CH_4 systems with emission–capture.

For *group 1 and 2,* the difference between the scenarios lays only in the duration of the emissions for the same CO_2 or CH_4 quantity (1 kg). The graphical representation for group 1 shows that the most sensitive indicator is t_{last_peak} (which, in these examples, coincides with the timing of $GMTC_{max}$). The next sensitive indicator is $iGMTC_{2100}$ because iGMTC embeds the memory of RF and therefore earlier emissions result in a higher indicator at a given point in time (Figure 1). Conversely, $GMTC_{max}$ slightly discriminates between the scenarios and ranks them in a different order (see also Table 2). The temperature indicators are more sensitive to the nature of the GHG, as observed in the group 2 representation. In addition to t_{last_peak}, imposed by the emission timing, $GMTC_{max}$ discriminates between the scenarios and ranks them in a different order. The results confirm that the short lifetime of CH_4 makes $iGMTC_{2100}$ less sensitive to emissions occurring in the first part of the century. When comparing the behaviors of groups 1 and 2, the differences observed are due to the different lifetimes of CO_2 and CH_4. Groups 1 and 2 clearly highlight that, for simple emission profiles of the same gas amount, a longer duration results in lower accumulated heat at a given point in time ($iGMTC_{2100}$) (Figures 1 and 2) and lower $GMTC_{max}$. However, a scenario with late emission, such as E6 or E5_CH4, is inconceivable from the perspective of the Paris Agreement. Of the considered cases, only E1, E1_CH4, E2_CH4, and E4_CH4 comply with the climate target time of 2050 (Table 2). These examples show that a single ranking based on GWP metrics is not relevant in the current context.

Groups 3 and 4 achieve neutrality during this century. However, for all cases, the target value t_{goalN} of 2050 is exceeded for neutrality point ($t_{neutrality}$>0), even if the last peak occurs before this target. The results show that all indicators are sensitive. In group 3, later capture leads to higher $GMTC_{max}$ and $iGMTC_{2100}$ (Figure 3). The best performance is achieved when the capture is simultaneous with the emission and in the same amount. This also applies to the periodic emissions in the N5–N7 cases: system with the longest period has the highest temperature peak, with N5 having the best overall performance in the group. In group 4, with a mix of GHGs, three different rankings are obtained according to the main three indicators ($t_{neutrality}$ and $t_{last\ peak}$ perform similarly). All of the presented cases exceed the 2050 target to different extents for the $t_{neutrality}$ indicator. For example, N9 exceeds this target the most with a relatively high peak in the near term of t_{LT}= 2100 (late CH_4 emission), which should be avoided. N10 is the closest to the target but with the highest $GMTC_{max}$ and $iGMTC_{2100}$ values. The best compromise is represented by N8 because it best satisfies the simultaneity of emission and capture.

Group 5 brings together different emission–capture scenarios with various amounts of emitted CO_2 and CH_4 and various initial RF potentials (figure 5) but with the same total kg CO_2-eq, and without neutrality. The three indicators are sensitive and rank the five scenarios differently. M2 is the worst with respect to $GMTC_{max}$ and t_{last_peak}, despite the CO_2 capture, because of its highest initial RF potential (high CH_4 emitted) and its late, near-term 2100 CH_4 emission. M1 emits much more CO_2 and less CH_4, with a low initial RF potential but near-term 2100 emission; therefore, its temperature peak is smaller while its accumulated heat is higher compared to M2. M5 emits the same GHG amounts as M1 with the same lifetime but with different dynamics: early CH_4 emission and continuously decreasing CO_2 emission make this scenario better than M1. Finally, M3 and M4, with similar initial potential RF, show differences as a result of their temporalities, with a shorter emission duration with higher $GMTC_{max}$ and $iGMTC_{2100}$ (due to higher emission flows) and a lower t_{last_peak} for M4. M4 performs better than M3 with respect to the temporality; however, because of its early emission, the cumulative effect for M4 is higher and the emission intensity generates higher RF. For both cases, the effect of the initial CO_2 capture is not beneficial around the time targets of t_{goalN} or t_{LT}.

Another feature is that, *applied to systems with distinct kg CO_2-eq net emissions, the new indicators can rank them in a different order than the conventional GWP metric*. Table 2 shows, for example, that group 2 (1 kg CO_2-eq) is worse than group 5 (2 kg CO_2-eq) for $GMTC_{max}$ and $iGMTC_{2100}$; $t_{last\ peak}$ ranks the systems independently of their GWP-wise performance, e.g. neutral N9 is worse than M4, M5 (2 kg CO_2-eq); etc.

It is remarkable that systems with early and high flow emissions, such as M4, N1, N10, E1, and E1_CH4, have the highest accumulated heat by 2100 ($iGMTC_{2100}$) and therefore the highest impact on sea level and ice melting. In general, these systems also generate the highest, or among the highest, $GMTC_{max}$ values in their groups because of the higher emitted flow (kg/year). Conversely, systems with early emission (low t_{last_peak}) and only limited temperature increases are preferred to other systems from the climate perturbation point of view.

3.3. Ranking criteria and mitigation

The proposed methodology introduces a multicriteria evaluation for climate change following two endpoints, (1) temperature-related effects like the climate perturbation and (2) heat-related effects like the sea level/melting ice, with time-dependent GMTC and iGMTC, respectively, as metrics. Given the approaching goals in terms of temperature and timing, mid- and end-century calendar-fixed time horizons are proposed instead of system-related time horizons (e.g., 20 and 100 years, as in current GWP metrics). Moreover, the time parameter becomes an indicator with two significant points on the temperature curve: the time of neutrality (where GMTC = 0) and the time when the temperature peaks before decreasing. For negative values, the systems comply with the Paris Agreement in the time dimension. Conversely, the temperature values cannot be compared with the GMST goal of 1.5°C (or 2°C) but rather serve as comparison criteria between systems. However, a reference can be defined for absolute value judgments, as proposed by new approaches combining LCA and Planetary boundaries methods (e.g. Bjørn et al. 2016; Ryberg et al. 2018; Sala et al., 2020)

The rankings obtained following the proposed criteria are not reducible to a single rank, which is normal, because, in reality, the amount of an emission, its dynamics, and its calendar are three independent parameters. Consequently, the improvements and mitigation actions of a system need to be directed toward these three distinct aspects. Finally, actions that achieve one or more of the following effects are beneficial.

(i) Reducing the emission total amounts (kg) will reduce the effect on the temperature parameters. However, the obtained effect depends on the nature of the GHG, that is, reducing LLGHGs affects all end point impacts (here, GMTC and iGMTC), while reducing SLGHGs improves GMTC. The effect depends strongly on the specific RF.

(ii) Reducing the time span of the emissions. This means that the amount of emissions is also reduced, which is equivalent to attaining zero emission at some point in time. However, this does not mean achieving climate neutrality in every case (as argued later). The temperature will decrease continuously only after the end of the emission period (e.g., the system lifetime) when the system no longer produces emissions (the exception is systems with continuously decreasing emissions, e.g., M5).

(iii) Avoiding emissions late in calendar will comply with the climate time targets. Systems with long lifetimes should avoid peak temperatures at the end of life or at any other near-term moment. This condition can be achieved by modifying the emission dynamics, e.g., by continuously decreasing and stopping emissions (via technological improvements) or by CCS simultaneous with the emissions.

(iv) Achieving climate neutrality. This is obviously a strong recommendation.

3.4. Case of neutrality

In the case of systems that achieve neutrality, ranking needs to be performed and mitigation is also necessary. Emissions with high potential RF (e.g., CH_4) can induce high GMTC if the CO_2 capture is not correctly scheduled and even high iGMTC, as demonstrated by the global ranking of group 4 (N8 and N9) and group 3 (N1–N7) (Table 2) even though all these scenarios emit and capture 1 kg CO_2-eq.

More, a comparison between neutral and non-neutral systems following t_{last_peak}, $GMTC_{max}$ and $iGMTC_{2100}$ remains fully relevant and, therefore, a neutral system can be worse than a non-neutral one at short-term, with higher temperature indicators.

A system can achieve climate neutrality at a given moment in time via the following actions: (i) capture of the necessary amount of CO_2 inside the boundaries of the system (e.g., a CCS process unit is combined with an emitting production process) with dynamics and temporality that are thoroughly adapted to the emission characteristics; (ii) association with an independent CCS system, resulting in a system with enlarged boundaries from the LCA point of view (e.g., an emitting factory purchases CCS for the necessary CO_2 quantity in order to achieve neutrality); and (iii) reduction of the emissions to zero.

Reduction of the GHG emissions of a system to zero can also lead to climate neutrality at some point in time. In this case, from the conventional LCA point of view, the global net emission is not zero kg CO_2-eq over the entire lifetime of the system. Conversely, the new indicators can assess such a system. However, neutrality via emission reduction can only be achieved when the RF generated becomes zero, and thus GMTC becomes zero. In the case of CO_2 emission reduction to zero over the course of the lifetime of a system, this condition is not achievable as a result of the long life of CO_2 in the atmosphere (zero residual RF is impossible). SLGHGs could allow this type of neutrality under the condition of not generating LLGHGs; for example, CH_4 cannot satisfy this type of neutrality because it is transformed into CO_2 over time.

3.5. Illustration of the proposed method on two LCA case studies

Herein, two actual DLCA case studies are presented to illustrate the application of the presented method. The objective here is not to perform DLCA but to show, using realistic data, the added value of the proposed indicators for the interpretation of the DLCA results for climate change.

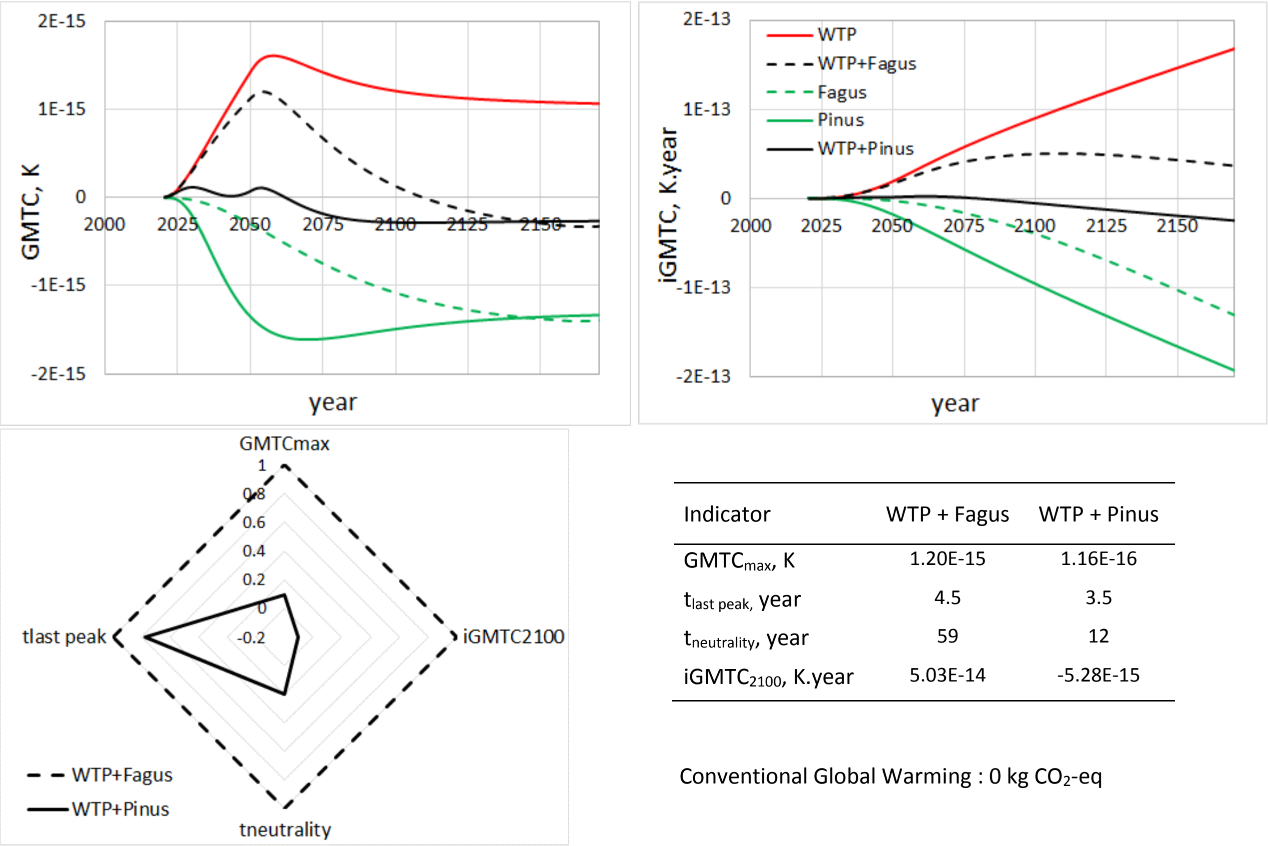
3.5.1. A climate change mitigation scenario

The first case study concerns a water treatment plant (WTP) for drinking water production by seawater desalting with reverse osmosis process. This technology, albeit its high performance and treatment potential, has the disadvantage of high electricity consumption. For existing and future WTPs, the question of energy consumption and climate change mitigation, or even the neutrality, arises. At present, the only large scale operational CCS method is the afforestation, i.e. planting of trees on places which have not been forested recently (Terlouw et al., 2021). Hence, afforestation is considered here as the solution for the mitigation of GHG emissions from WTP system and for achieving neutrality.

Conventional LCA. The LCA product system encompasses the WTP lifecycle (plant construction, functioning and dismantling) and the forest planting and management as natural ecosystem. The functional unit is the production of 1m^3 drinking water during 30 years, and starting in year 2020. Data sets already existent in ecoinvent 3.7 were used for WTP and forest (details on the inventory are given in SI). The "amount" of forest to be planted was calculated on the base of kg CO_2 -eq LCA results in order to offset the WTP impact, i.e. to achieve neutrality as zero kg CO_2 -eq. So, for the functional unit: WTP counts for 2.33 kg CO_2 -eq and the forest system for -2.33 kg CO_2-eq from which -2.341 kg CO_2 -eq corresponds to CO_2 captured and stored in biomass (a new forest) and +0.0081 kg CO_2-eq corresponds to GHG emissions from forest management.

Dynamic LCA. In conventional LCA, the tree species doesn't play an important role (except for small differences in management operations). However, two species are considered here, Fagus and Pinus, with 140 and 50 years to maturity respectively. In this example, the temporalized inventory includes the WTP construction and forest planting during the first year (in 2020), WTP functioning over 30 years followed by infrastructure's end-of-life (landfill). Tree growth was modeled in function of time according to the Chapman-Richards model with species-specific constants (Winrock International, 2014). The results in terms of climate change indicators are presented in figure 7. Spider diagram clearly shows that WTP+Pinus afforestation is more performant that WTP+Fagus. More, effective climate neutrality could be achieved only after t_{goalN} (2050), 12 and 59 years after WTP dismantling, with Pinus and Fagus respectively. Despite the long term (theoretically infinity) convergence of the two systems towards zero GMTC, for the time scale of interest, i.e. this century, undesired behavior is observed especially for WTP+Fagus system. The temporality of CO_2 capture by Pinus is more adequate to the behavior of GHG emissions by WTP.

As figure 7 shows, the curves' analysis is quite simple. The added value of the indicator method lies in the clarity of the ranking: instead of a visual/empirical conclusion from curves, the indicators provide in few data (key parameters and climate goals) the necessary information for decision-making. On the other hand, this example illustrates the complexity of providing effective mitigation solutions, their evaluation in conventional LCA, and the added value of the dynamic approach based on meaningful parameters.



Indicator	WTP + Fagus	WTP + Pinus
$GMTC_{max}$, K	1.20E-15	1.16E-16
$t_{last\ peak}$, year	4.5	3.5
$t_{neutrality}$, year	59	12
$iGMTC_{2100}$, K.year	5.03E-14	-5.28E-15

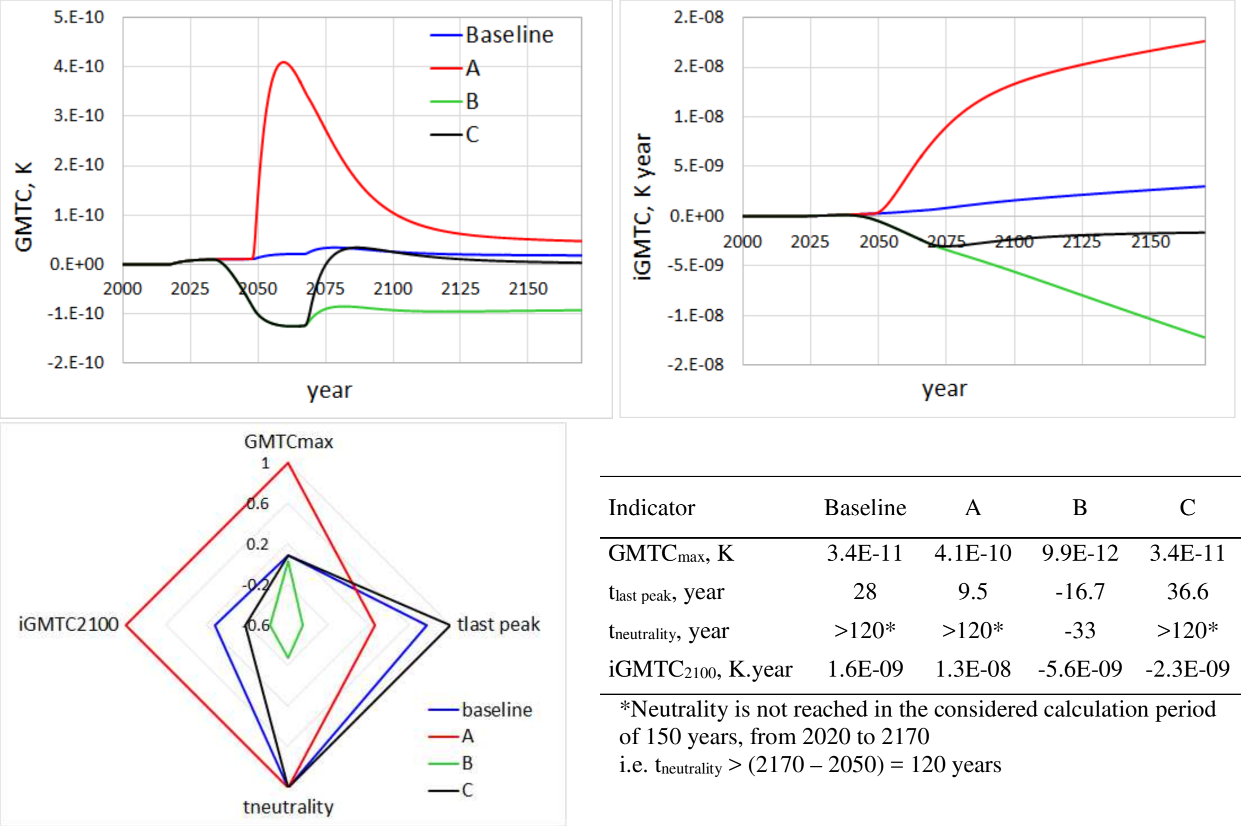
Conventional Global Warming : 0 kg CO_2-eq

Figure 7. Results of the proposed method applied to LCA case study on climate mitigation.

3.5.2. LCA of comparable, alternative systems

The case study concerns the life cycle (including manufacture, utilization during the lifetime of the house, periodic replacements, and end of life) of insulation materials used for a house. The functional unit is the production, utilization, and end of life of the insulation products for a house with a total net floor area of 414 m^2 and a lifetime of 50 years (Negishi et al., 2019). The reference time zero is the start time of material (building) usage. Therefore, the construction of the building occurs at a negative time on this scale. The replacement of the insulation materials (Insulation 1) occurs at 30 years, meaning that the manufacturing of new products (Insulation 2) takes place prior to year 30 and the end-of-life processes of the older products (Insulation 1) take place starting from year 30. At year 50, the building is dismantled and the insulation products (Insulation 2) are processed for their end of life. The DLCA analysis was conducted with SimaPro 8.3 with ecoinvent 3.2 for the inventory and the DyPLCA tool (Pigné et al., 2019) for the temporal inventory calculation (detailed timeline and inventory are presented in SI). In the present work we confine ourselves to the description of the application of the proposed climate change evaluation method.

Four scenarios are envisioned for the insulation system. In the Baseline scenario, commonly used insulation products (Insulation 1: composed of mineral wool, glass wool, and polyurethane) are considered over the entire lifetime of the building (with replacement at year 30 with the same material), with landfill as the actual end-of-life process. Scenario A replaces the current materials (Insulation 1) at year 30 with synthetic polymers (Insulation 2: extruded polystyrene), with landfill as the end-of-life process. Scenarios B and C replace the current insulation 1 with a wood-based material (Insulation 2), with two end-of-life possibilities for this wood-based material: landfilling in Scenario B and incineration in Scenario C. The majority of the GHG emissions occur at four distinct moments: prior to time zero due to the manufacturing of Insulation 1, prior to year 30 due to the manufacturing of Insulation 2, after year 30 for the end of life of Insulation 1, and around year 50 for the end of life of Insulation 2 (graphical representation in SI- figure S4). The most important GHGs are non-fossil CO_2 emission and capture, especially for Scenarios B and C, fossil CO_2 emissions, especially in the manufacturing processes, and low CH_4 emissions in the end-of-life or other background processes. Other GHG emissions occur in very low quantities. The proposed method was applied to the four scenarios and the results are presented in Figure 8. Other detailed results are available in the SI.



Indicator	Baseline	A	B	C
$GMTC_{max}$, K	3.4E-11	4.1E-10	9.9E-12	3.4E-11
$t_{last\ peak}$, year	28	9.5	-16.7	36.6
$t_{neutrality}$, year	>120*	>120*	-33	>120*
$iGMTC_{2100}$, K.year	1.6E-09	1.3E-08	-5.6E-09	-2.3E-09

*Neutrality is not reached in the considered calculation period of 150 years, from 2020 to 2170
i.e. $t_{neutrality} > (2170 – 2050) = 120$ years

Figure 8. Results of the proposed method applied to LCA case study of insulation materials.

Scenario A exhibits the largest temperature and accumulated heat effects, with the maximum peak attained around year 40, earlier than the peaks attained in the other scenarios. If the reference time zero is set to the year 2020, then only Scenario B complies with the requirement of decreasing and stabilizing temperature prior to 2050. In addition, Scenario B has the lowest $GMTC_{max}$ and $iGMTC_{2100}$ values. According to all the criteria, Scenario B is the best as a result of the long-term storage of biogenic carbon in the insulation 2 materials and partially because of landfilling, which results in a low and slow release of emissions over time. Scenario C is hampered by the incineration process at the end of life, with significant emissions of biogenic CO_2 after 2050. However, the early carbon capture (via wood growth, resulting in negative GMTC) compensates for the accumulated heat, resulting in Scenario C having no effect on the iGMTC-related damages. The Baseline scenario is slightly worse than Scenario C, according to $iGMTC_{2100}$, with GMTC always being positive. Globally, late end-of-life emissions are problematic and, for buildings arriving at their end of life around 2050 and later, dismantling and waste management need to promote zero emission solutions.

The proposed indicators use selected results of GMTC and iGMTC, calculated in function of time following the DLCA approach. The values selected (time, GMTC, iGMTC) are in relation to the climate targets and type of impacts. This indicators facilitate the DLCA results interpretation, which can otherwise be a difficult task especially for non-technical users.

3.6. Modeling aspects

The model used in this study does not consider the evolution of the atmospheric concentration at mean and long term. The GWP and GTP metrics also do not include this aspect. However, this behavior can be implemented in the GMTC model with a chosen trajectory for the CO_2 concentration increase and the associated variation in the specific RF of CO_2 (IPCC, 1990). This trajectory can be provided by global evolution models such as RCPs (van Vuuren, 2011). Such calculations have already been proposed by Kirschbaum (2014) and Jørgensen et al. (2014) for climate change impact evaluation in LCA. Including these evolutions, the calculated GMTC at a higher atmospheric CO_2 concentration (therefore, at later times) will be lower than GMTC for the current concentration, for the same emission amount. However, temperature peaks at later times or in the near term are more critical with respect to the climate goal of keeping the temperature increase below 1.5°C (UNFCCC, 2015; IPCC 2018).

The climate–carbon-cycle feedback is another phenomenon that has not yet been considered. The last IPCC assessment report (IPCC, 2013) proposed this improvement to the GWP and GTP metrics. The impulse response function approach proposed in recent studies (Gasser et al., 2017; Sterner and Johansson, 2017) can be implemented because it is compatible with the used GMTC model. This will allow a better estimation of GMTC induced by a system due to the effect of the non-CO_2 climate forcers on the carbon sinks and therefore on the CO_2 atmospheric concentration.

Overall, the advantage of the proposed metrics and calculation method is that other climate forcers can be integrated into the model because it is not necessary to calculate characterization factors and there is no normalization with CO_2.. If RF is known in time, it can be used as is in the temperature modeling and the indicator calculations. Moreover, the approach is flexible and allows a combination of different climate parameters for distinct forcers at the level of RF and GMTC without the need for a known RF impulse response function (e.g., the case of stratospheric-born forcers).

4. Conclusions

Our ability to restrict global warming to the established objectives in the third decade of this century is currently at stake. As a recognized and widespread methodology for environmental impact evaluation, LCA needs to provide efficient and unambiguous tools to measure the effects of our activities. It is imperative, therefore, to revisit the current climate change metrics in LCA.

This study proposes the use of the global temperature change in function of time as the basic parameter in the definitions of the indicators. This is justified by the physics of global climate drivers and by the scheduled climate goals. As the climate target approaches, our capability to measure the effects of our activities needs to be more precise. Moreover, climate goals, time targets, and related policies may evolve and, therefore, the impact indicators need to be intrinsically adaptive. A single indicator can no longer satisfy these requirements, making a multi-criteria evaluation necessary.

Admittedly, a multi-criteria approach introduces more complexity into the decision making process, but provides more quantitative information to aid decision making in an urgent or long-term policy context. The proposed method is part of the LCA framework, which is by nature multi-criteria. The proposed indicators are midpoints and, like other midpoints in LCA, combination/aggregation in a dynamic endpoint (dependent on time) is only possible if the current knowledge allows it with a reasonable accuracy.

Concerning the indicators, they are based on DLCA principles (temporal inventory and dynamic impact). We adopt calendar-related time targets rooted in reality instead of a fixed time horizon, as in conventional LCA. The systems are now analyzed with respect to a *climate-target point in time* (which can occur during the lifetime of the system or in its future), in contrast with conventional LCA, in which each system has its own temporal reference and time horizon disconnected from the calendar scale. The four indicators describe: (1) the amplitude of the temperature change induced by a system ($GMTC_{max}$); (2) the time at which GMTC starts to definitely decrease and therefore the distance with respect to the climate goal (t_{last_peak}); (3) for systems approaching neutrality, the time climate neutrality is reached and its distance with respect to the goal ($t_{neutrality}$); and (4) the accumulated warming until a targeted time ($iGMTC_{2100}$).

The proposed indicators (rooted in DLCA) are able to measure the impact of a system and to discriminate and rank systems that are considered to be non-impacting, equivalently impacting, or neutral for the climate in conventional LCA due to the weaknesses of the GWP and GTP metrics. In addition, the indicators allow for easy interpretation of DLCA results, which can otherwise be a difficult task when several complex systems are to be compared, or for non-technical users.

At the present and in the near future, we will require such tools and metrics to correctly (avoid strong simplifications) and unambiguously (with unaltered physical parameters, closer to climate physics) evaluate the effect on climate, the neutrality and to support decision-making and mitigation actions.

The proposed method, based on current modeling approaches of the global mean temperature change for well-mixed GHGs, is implemented in a tool in Python language (available at https://www.insa-toulouse.fr/fr/recherche/labo/lisbp/outil-de-calcul-changement-climatique.html). It is flexible and can include other climate forcers via their RF directly in the temperature calculations or via a known temperature effect or any other impulse response function-based representation. Obviously, such an extension depends on the available knowledge and will be the next step in the tool development.

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Supplementary Information

A climate-goals-based, multicriteria method for system evaluation in Life Cycle Assessment

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Summary

1) Climate impact model
2) Results on emission examples
3) Application of the proposed method to two LCA case studies

1) Climate impact model

The model is based on the IPCC bibliography and uses the impulse response function (IRF) approach to calculate the radiative forcing RF and the global mean temperature change GMTC. The constants used for all GHGs listed in ecoinvent data base are taken from the last updates (IPCC, 2013).

The atmospheric burden of substance s, B_s, is calculated as the convolution product (symbol $*$) between the temporal emissions of the substance s, g_s (kg.year^{-1}) and the concentration - impulse response function of that substance, IRF_s :

$$\mathrm{B_s(t) = g_s * IRF_s = \int_0^t g_s(t') \, IRF_s(t-t')dt'} \quad (1)$$

RF is calculated as the product between the radiative efficiency, A_s, and the atmospheric burden, B_s. The radiative efficiency A_s (W.m^{-2}.kg^{-1}) can be considered as time-invariant for small emissions. In the followings, the convolution symbol will be used for simplicity and clarity.

$$\mathrm{RF_s(t) = A_s(t) \, B_s(t) = A_s(t)(g_s * IRF_s)} \quad (1)$$

The dynamic global RF (W.m^{-2}) for all gases taken together is then:

$$\mathrm{RF(t) = \textstyle\sum_s RF_s(t)} \quad (2)$$

Cumulated radiative forcing, iRF (W.m^{-2}.year), over a given time span TH is:

$$\mathrm{iRF(TH)} = \int_{t=t_0}^{TH} RF(\mathrm{t})dt \quad (3)$$

The global mean temperature change generated by the forcer s is defined as the convolution product between its radiative forcing and the temperature impulse response function IRFT:

$$\mathrm{GMTC_s(t)} = RF_s * IRFT_s \quad (4)$$

IRFT is independent of the type of GHG. However, it may be different if for specific forcers IRFT is determined by specific pathways, e.g. not including a burden – RF – GMTC modelling pathway. The mean temperature change at a given time t, GMTC (K), is obtained by aggregating values for all the concerned forcers:

$$GMTC(\mathrm{t}) = \textstyle\sum_s \mathrm{GMTC_s(t)} \quad (6)$$

Cumulated temperature change, iGMTC (K.year), is calculated as:

$$\mathrm{iGMTC(TH)} = \int_{t=t_0}^{TH} GMTC(\mathrm{t})dt \quad (7)$$

The model is solved numerically in Python language, with the tool developed in the work of Shimako et al., 2018.

IPCC, 2013, Climate Change. The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2013.

Shimako, A.H., Tiruta-Barna, L., Bisinella de Faria, A.B., Ahmadi, A., Spérandio, M., 2018. Sensitivity analysis of temporal parameters in a dynamic LCA framework, Science of The Total Environment 624 (2018) 1250–1262

2) Results on emission examples

RF, iRF, GMTC and iGMTC have been calculated for all examples described in the main document. Here the results for the neutral case examples N1 to N7 are shown.

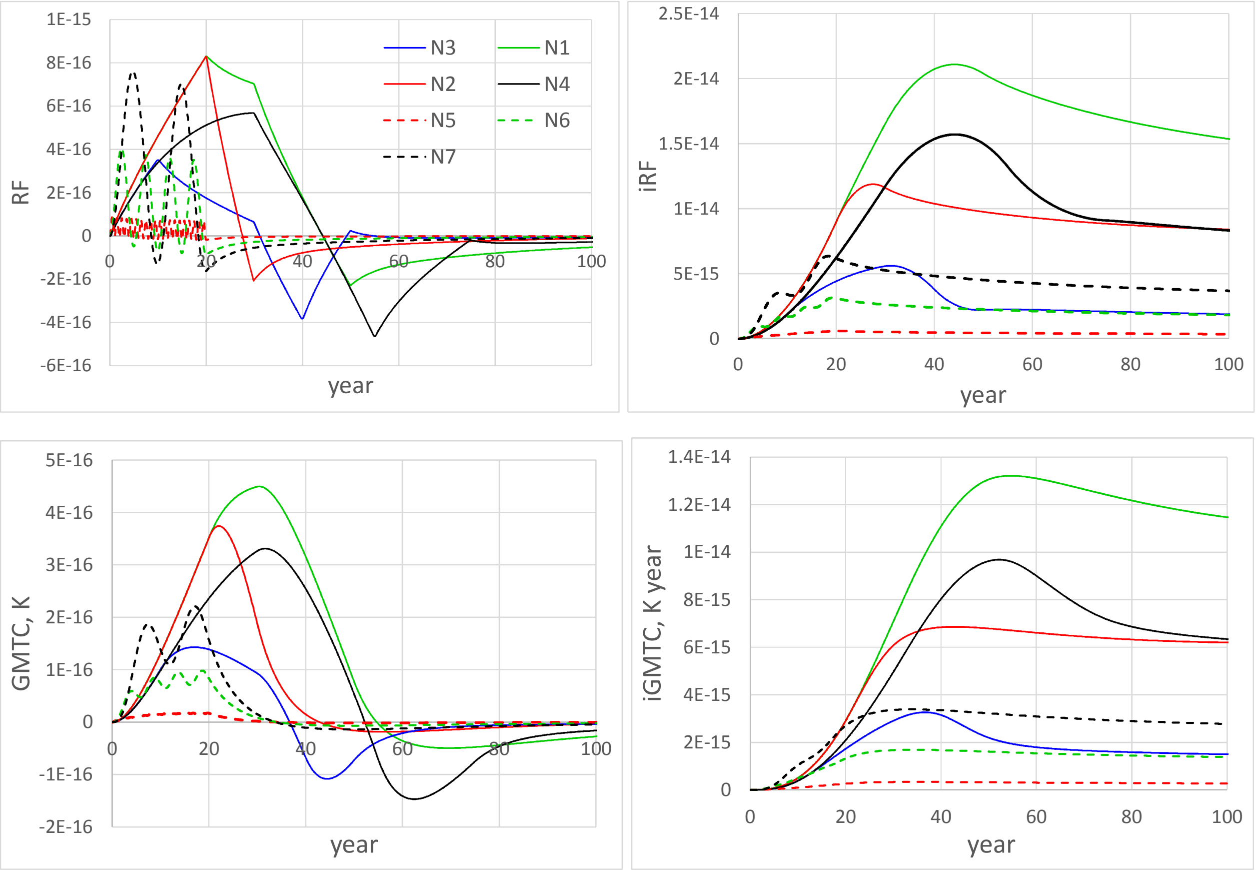
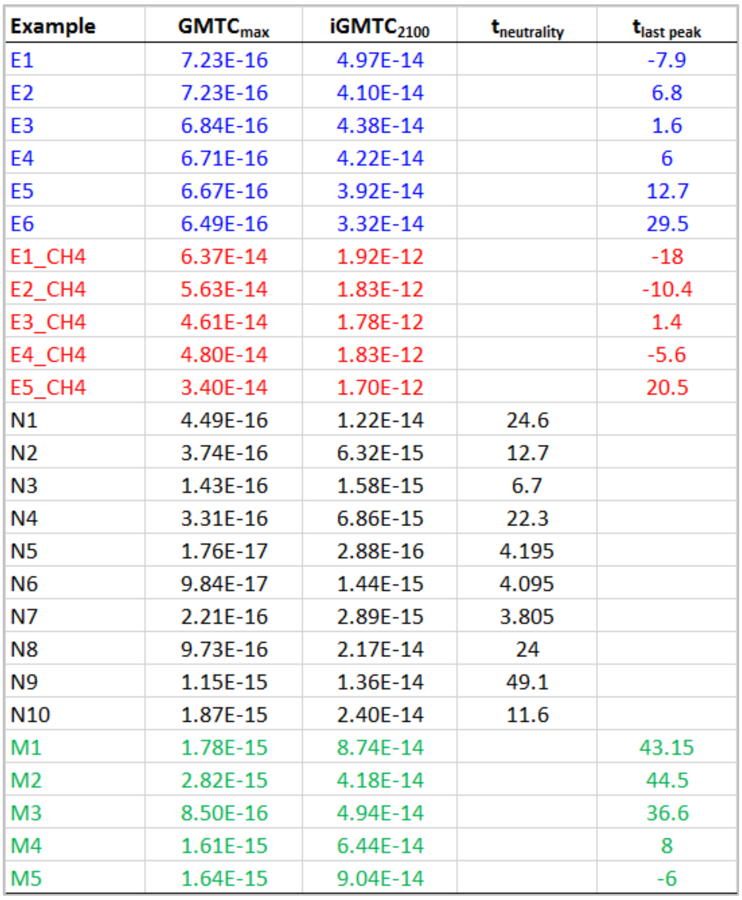


Figure S1. RF, iRF, GMTC and iGMTC results for the group of neutral examples N1 to N7

These examples show that the climate neutrality points cannot be judged on RF parameter since net zero or negative RF may correspond to positive GMTC and hence to no climate-neutral points. iRF and iGMTC exhibit similar shapes, therefore only iGMTC was selected as indicator.

The values of the three indicators obtained for all emission examples are listed in table below.

Table S1. Numerical results for the calculated indicators



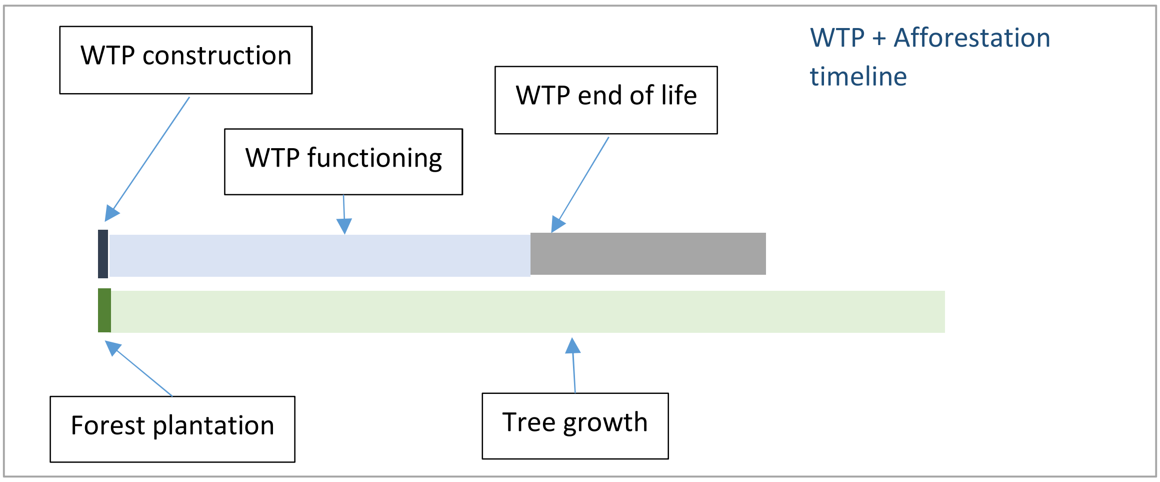
Example	$GMTC_{max}$	$iGMTC_{2100}$	$t_{neutrality}$	$t_{last\ peak}$
E1	7.23E-16	4.97E-14		-7.9
E2	7.23E-16	4.10E-14		6.8
E3	6.84E-16	4.38E-14		1.6
E4	6.71E-16	4.22E-14		6
E5	6.67E-16	3.92E-14		12.7
E6	6.49E-16	3.32E-14		29.5
E1_CH4	6.37E-14	1.92E-12		-18
E2_CH4	5.63E-14	1.83E-12		-10.4
E3_CH4	4.61E-14	1.78E-12		1.4
E4_CH4	4.80E-14	1.83E-12		-5.6
E5_CH4	3.40E-14	1.70E-12		20.5
N1	4.49E-16	1.22E-14	24.6	
N2	3.74E-16	6.32E-15	12.7	
N3	1.43E-16	1.58E-15	6.7	
N4	3.31E-16	6.86E-15	22.3	
N5	1.76E-17	2.88E-16	4.195	
N6	9.84E-17	1.44E-15	4.095	
N7	2.21E-16	2.89E-15	3.805	
N8	9.73E-16	2.17E-14	24	
N9	1.15E-15	1.36E-14	49.1	
N10	1.87E-15	2.40E-14	11.6	
M1	1.78E-15	8.74E-14		43.15
M2	2.82E-15	4.18E-14		44.5
M3	8.50E-16	4.94E-14		36.6
M4	1.61E-15	6.44E-14		8
M5	1.64E-15	9.04E-14		-6

3) Application of the proposed method to two LCA case studies

3.1. Example on climate change impact mitigation: Water Treatment Plant (WTP) and Afforestation

Data sets used from ecoinvent 3.7:

WTP : tap water production, seawater reverse osmosis, ultrafiltration pretreatment, enhance module, two stages [GLO]; 1000kg tap water
Fagus (beech): hardwood forestry, beech, sustainable forest management (DE); 1.292 kg wood
Pinus (pine): the same module as for beech, but with a different temporality for CO_2 capture.



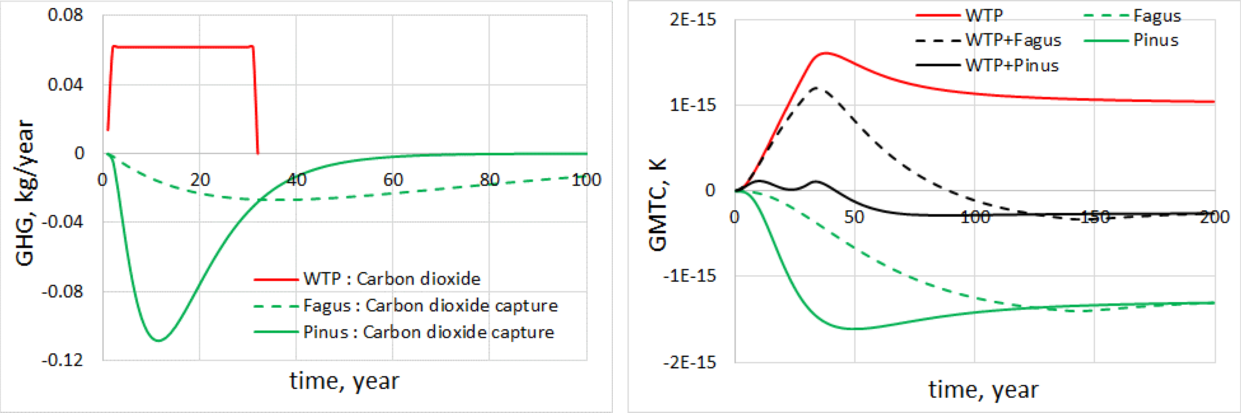


Figure S2. Timeline of the WTP+Forest system (top). Emission/capture profiles for the most contributing substances (left) and GMTC results (right) for the WTP system with afforestation with Pinus or Fagus species.

Table S2. Inventory results

Process	kg CO_2 -eq	total kg CO_2 -eq
infrastructure building	0.012	
WTP functioning	2.32	
infrastructure end of life	0.000039	
		2.33
afforestation works	0.008	
tree growth	-2.34	
		-2.33
Total		0

Constants for Chapman-Richards equation*:
Growth rate = $(1-\exp(-k.t))^{(1/1-m)}$
(time t in years)

Fagus (warm temperate): k =0.21, m=0.63
Pinus (warm temperate) : k=0.1, m=0.63

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* Winrock International, 2014 AFOLU Carbon Calculator. The Afforestation/Reforestation Tool: Underlying Data and Methods. Prepared by Winrock International under the Cooperative Agreement No. EEM-A-00-06-00024-00.

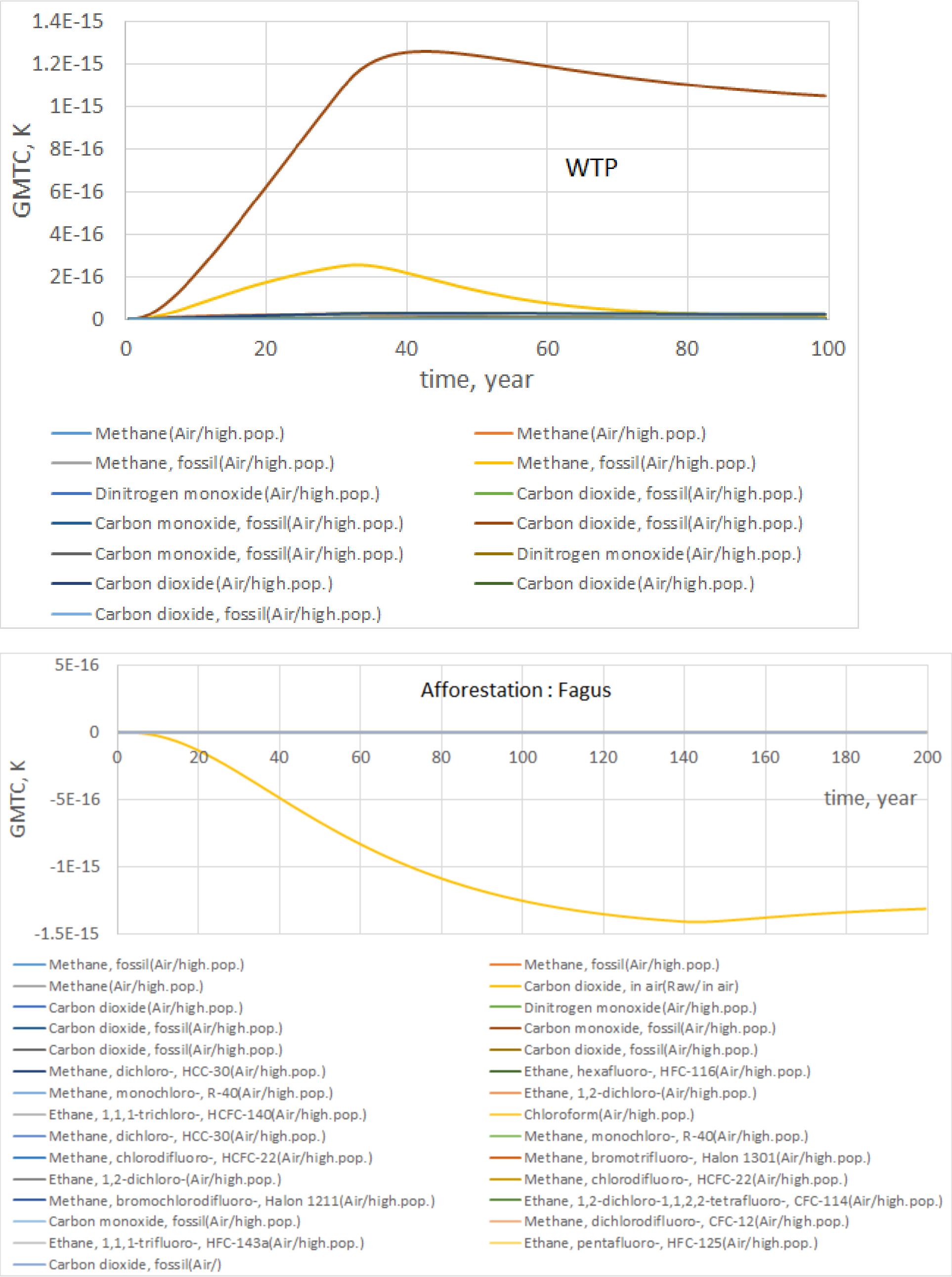
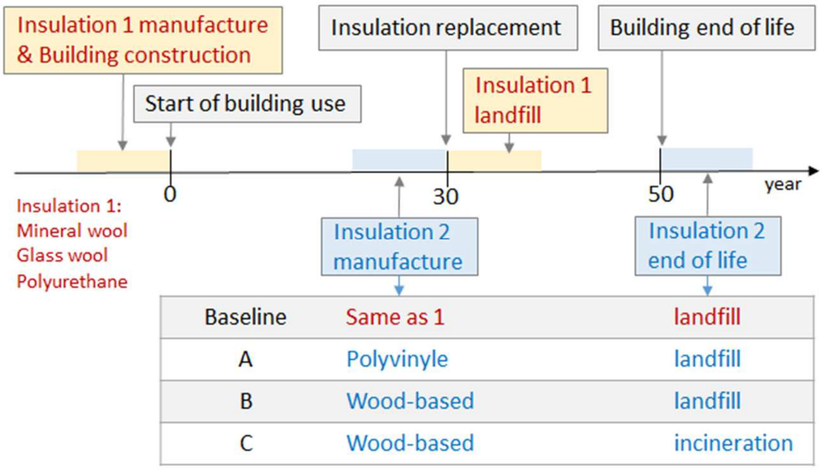


Figure S3. Global mean temperature change GMTC due to each GHG emission. Results for WTP and afforestation with Fagus.

3.2. Insulation system in a building



Baseline	Same as 1	landfill
A	Polyvinyle	landfill
B	Wood-based	landfill
C	Wood-based	incineration

Figure S4. Timeline of the insulation system and the replacement and end-of-life scenarios.

Scenarios Baseline, A and B are inspired from a previous work**.
Insulation 1 : 546 kg of mineral wool, 4984 kg of glass wool and 483 kg of polyurethane
Insulation 2: extruded polystyrene (HFC blown) 5099 kg; or bio based material 16835 kg of cork slab

** Negishi, K., Lebert, A., Almeida D., Chevalier J., Tiruta-Barna, L., *Building and Environment*, 164, 2019, 106377

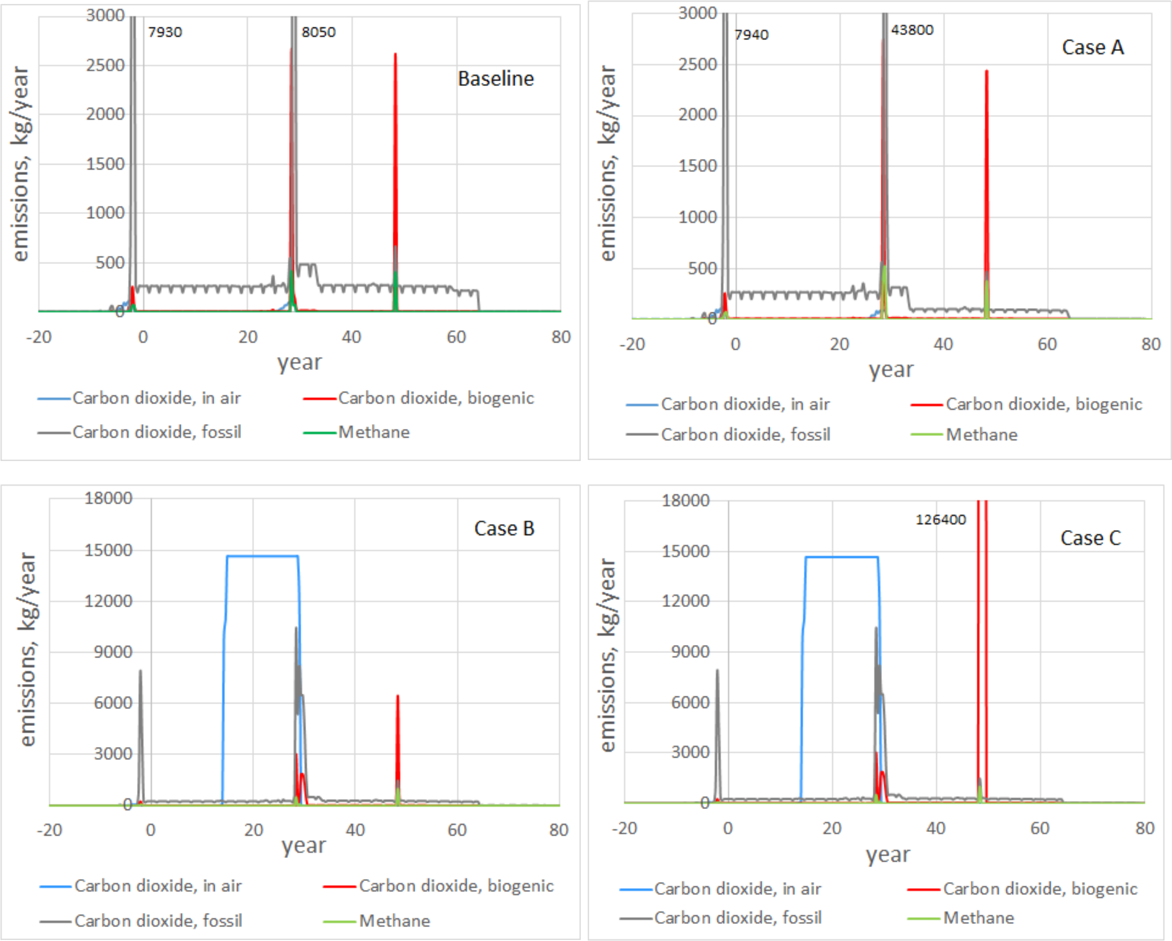


Figure S5. GHG emissions in the four scenarios

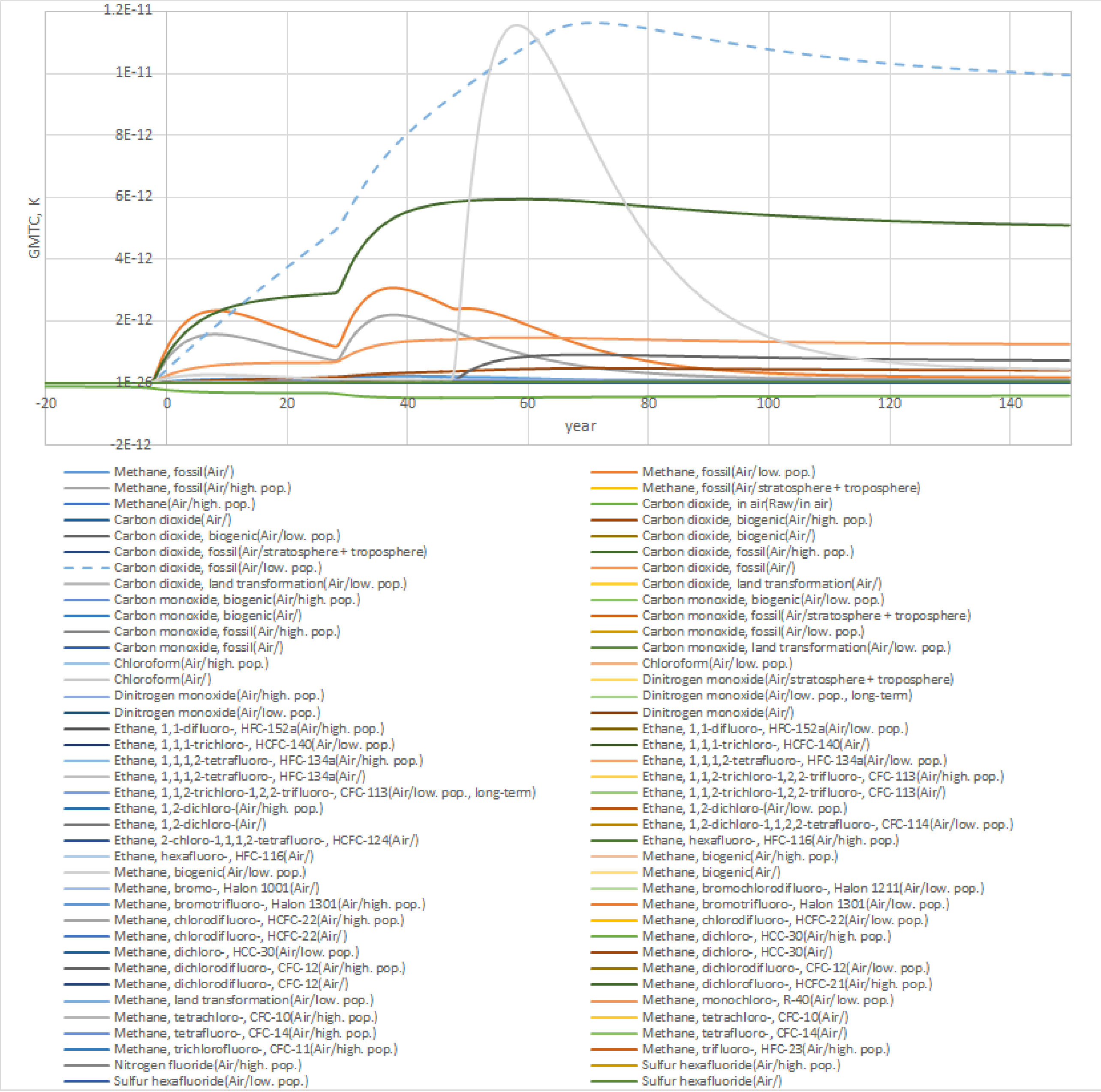


Figure S6. Global mean temperature change GMTC due to each GHG emission in scenario Baseline.