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CONCEPTUAL ISSUE OF THE DYNAMIC GWP INDICATOR AND SOLUTION

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ABSTRACT

Purpose

Dynamic LCIA has been developed in the past 12 years almost exclusively for climate change impact assessment, and especially the Global Warming Potential (GWP) indicator. Recently, discussions have taken place in France on the issue of integrating a dynamic GWP indicator in the 2020 regulation (noted RE2020) on new buildings. This regulation uses a combination of static and dynamic indicators. Discussions to produce a standard on a dynamic GWP indicator could be soon launched at European level. This close perspective of using dynamic indicator into regulation recalls the importance using scientifically sound indicators. Therefore, this article re-examines the fundamentals concepts of the dynamic GWP indicator on which the future regulation is based.

Method

Three basic principles of LCA are recalled: (i) no inventory flow should be omitted from an assessment, (ii) all impacts of all substances contributing to an impact category should have the same Time Horizon of the Impact (*THI*) in the indicator used for that impact category, and (iii) the time horizon of the impact has no reason to change as a function of time. It is then shown that the current and common version of the dynamic GWP (Levasseur et al. 2010) does not respect these principles. A new expression of dynamic GWP is provided in order to respect the three basic principles.

Results

Both dynamic GWP indicators are compared according to their meaning and according to the decrease that they quantify compared to static GWP. The initial dynamic GWP indicator (Levasseur et al. 2010) sets a fixed Time of Observation Duration (*TOD*), chosen subjectively, after which nor flows nor impacts on climate change are assessed. The new dynamic GWP sets a *TOD* according to the Life Cycle Duration (*LCD*) and the *THI*, that avoids any flow omission and guarantees the full account of the impact of all flows. *THI* and *LCD* have independent values, but both time entities are related chronologically: *THI* has to be considered to account for the full effect for the very last emission of the product's life cycle. Thus, the total observation duration (*TOD*) to consider for any dynamic approach is $TOD = LCD + THI$. The initial dynamic indicator overestimates the effect of temporary carbon storage of around 25% at the time 50 years. The raised issue is not only an implementation issue due to the choice of *TOD*, it is a conceptual issue, because even in the case of $TOD > LCD$, the value of *THI* would still be variable according to the moment of emissions. Finally, the notation between dynamic and static GWP are not harmonised which can lead to confusion.

Conclusion

The initial GWP indicator (Levasseur et al. 2010) represents an assessment of the impact within a subjectively chosen observation period and neither the flows nor the effects of these flows on climate change are taken into account beyond this limit. The new equation provided for the dynamic indicator takes into account the totality of the flows and the entirety of their impact according to the value of *THI*, it thus represents only and exclusively

the effect of delaying emissions compared to the static GWP. This new method is totally applicable for the regulation, as only new $F_{RE2020}(t)$ coefficients, produced in this paper, have to be changed.

At a time when the dynamic GWP indicator is being considered as a regulatory tool on a French or even European scale, it seems crucial to consider its scientific relevance, because using the wrong method could lead to an overestimation of the possible beneficial effects of temporary carbon storage in the construction sector as a whole.

1 INTRODUCTION

In the dictionary, the adjective “dynamic” describes a temporal evolution. In LCA, the word “dynamic” has been used with two meanings. First, it was used for considering the evolutions and changes in time of systems and of their constitutive processes (Pehnt 2006), that provides, as a matter of fact, the temporal evolution of the life cycle inventory. Later, the word “dynamic” was also introduced to consider the time evolution of characterization factors to model impact assessment (Levasseur et al. 2010) for which dynamic LCIA consists of observing the impacts on the ecosphere according to the kinetics of effects of the elementary flows in the ecosphere. In fact, to obtain a dynamic model of impact assessment, having a dynamic life cycle inventory is necessary, and thus both aspects have to be considered. In this article, the word “dynamic” LCA is used and, although it focuses on dynamic impact assessment, it englobes a dynamic life cycle inventory as well.

The dynamic approach is justified by the fact that the environmental impact of a pulsed emission is certainly different from that of the same quantity emitted but spread over time. Whereas, static LCIA considers that all of the elementary flows in a product's life cycle are emitted at the same time, dynamic LCIA is used to assess the environmental impacts at different time steps, according to both different moments of emissions and kinetics of their effects inside the ecosphere.

The interest of dynamic LCI occurs when there can be important and rapid changes in production and/or consumption temporal rates. This can either generate under or overproductions at different moments, leading to different adaptation scenarios in the technosphere. For example, photovoltaic energy has an intrinsic random production rate, due to meteorology. Regular overproduction of photovoltaic electricity can be balanced by shutting down different types of power plants, that there is a considerable difference between considering this at a given moment or as a year average (Roux et al. 2016).

The interest of dynamic LCIA is also important. As an example, for human toxicity or ecotoxicity (Müller et al. 2017; Saouter et al. 2017), it can be notably different to be exposed once to a high concentration of a toxic substance (acute effects), or to be exposed regularly to small amounts of the same substance for a very long period of time (chronic effects).

Thus, dynamic approaches should be more developed to better assess impacts and help a better control of the systems in order to lower the impacts.

In fact, dynamic LCIA has been developed in the past 12 years almost exclusively for climate change impact assessment, and especially the Global Warming Potential (GWP) indicator. It has been initiated to consider the question of biofuels (Benoist 2009) and then been subject to more generic developments with a dynamic GWP (Levasseur et al. 2010; Levasseur 2011). In the same period, a GWPbio was also suggested to account for the rotation of cultivations (Cherubini et al. 2011). Other approaches were also developed since then, especially recommending using different indicators like GWP or Global Temperature change Potential (GTP) (Cherubini et al. 2013) according to short or long time perspectives respectively (Levasseur et al. 2016).

Recently, discussions have taken place in France on the issue of integrating, in addition to other constraints notably related to energy consumption, a dynamic GWP indicator in the 2020 regulation on new buildings (called RE 2020

is the rest of this article). The RE2020 regulation provides for an assessment using a combination of static and dynamic indicators that will be detailed later in that article. At the request of the French Minister of Ecological Transition, discussions to produce a standard on a dynamic GWP indicator could be launched at European level (NORM'EN LIGNE 2021).

This close perspective of using dynamic indicator into regulation recalls the importance using scientifically sound indicators. Therefore, although several other dynamic approaches of climate change impact assessment exist (Breton et al. 2018), this article re-examines the fundamentals of the dynamic GWP indicator only. After recalling some basic principles of LCA, it is showed, using an example, why and how some present dynamic GWPs do not comply with those fundamentals. Then, some changes into conceptual basis of these indicators are suggested, that respect fundamentals of LCA, without changing the principle of a dynamic indicator. The French regulation is then reconsidered and new characterization factors are proposed on this new conceptual basis.

2 RECALL OF SOME BASIC PRINCIPLES OF LCA

In this part, three main principles are recalled and argued: (i) no elementary flow can be omitted by the mere will of a anyone, (ii) whatever the indicator, the Time Horizon of the Impact (*THI*) used to calculate the characterization factor must be the same for all substances contributing to that impact category, and (iii) whenever a substance is emitted, its characterization factor of a substance must be calculated on the totality of the *THI*.

2.1 First principle: no flow omission

One of the most important basic principle of LCA, concerns Life Cycle Inventory: on the basis of the study's objectives and of its functional unit, a system model is defined that will encompass all concerned processes and their elementary and intermediate flows. Thus, all inventory flows that are justified by the existence of a system model, must be included and any omission must be justified. Indeed, according to the ISO standard (ISO 2006, p. 14040), the Life Cycle Inventory "involves collection of the data necessary to meet the goals of the defined study". Because exhaustivity can be difficult to obtain in practise, the standard provides for this situation by demanding practitioners to define clear and transparent cut-off criteria defined as "specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study" (ISO 2006, p. 14040). The European standards complement the international standard by specifying more precise rules per sector. In the building sector, the EN 15804 standard specifies that "the input and output exclusion criteria (cut-off rules) [...] should not be applied to hide data. Any application of the input and output exclusion criteria must be documented." Furthermore, it specifies that "all inputs and outputs of a process for which data are available should be included in the calculation. Missing data can be replaced under conservative assumptions by average or generic data. All assumptions for such choices must be documented." The ILCD handbook also mention that "any exclusion of relevant individual processes or activity types shall be justified using the cut-off criteria" and that "in principle all processes are to be inventoried that are to be attributed to the system, as far as they relevantly contribute to the overall environmental impact of the analysed system" (European Commission 2012).

In other words, no flow can be omitted only by the subjective choice of a LCA practitioner or any other person involved into the LCA study or into the decisions related to that study. This principle guaranties the objectivity of the inventory flows and that all substance having an effect on the environment will be accounted.

2.2 Second principle: the same Time Horizon of Impact for all substances

GWP is part of so-called midpoint indicators (Frischknecht et al. 2016) that are expressed as an equivalence of a reference substance. For this type of indicator, there are two calculation steps (detailed below) in order to obtain their characterization factors.

First, the effect on the environment of any substance is modelled as a function of time, accounting that, once emitted, this substance will degrade with time. This time decay is modelled using a kinetic degradation law depending on the substance itself as well as on the receiving media. The effect on the environment of the substance is thus estimated as its cumulated effect during time as long as the substance is not degraded. This is calculated as the integral of the degradation curve over a given time period. This time period is called Time Horizon of the Impact (*THI*) it starts when the substance is emitted and ends when the *THI* time has elapsed.

To calculate a characterization factor, the value of *THI* must be the same for all substances: indeed, this is important to account for their different contributions to the impact category. This principle is not written in any general recommendation, neither standards nor handbooks. However, it is obviously and comprehensively applied, as none of the existing impact characterization methods provide any characterization factors that are calculated with different *THI* according to different elementary flows. The value of *THI* is debated in the literature and for all impact categories as an expression of preferences for short term or long-term impacts (Joint Research Centre 2010a, b; Frischknecht and Jolliet 2019), but it is never debated in terms of what *THI* for what substance.

This non-written principle (now it is at least written in the present article) has indeed a meaning that never obviously needed a debate. As shown in Figure 1, for the climate change impact category, the GHG represented in green has a quicker degradation law than the blue one, thus the integral below the green decay curve provides a lower value than the blue one, and, if their radiative efficiencies are close, the green GHG will have a lower characterization factor than the blue one. This is logical: if one substance rapidly degrades its contribution to the impact also rapidly decreases. In other words, the characterization factor includes a weighting factor that depends on the rate of degradation. If *THIs* were different for each substance, this would render this weighting meaningless.

2.3 Third principle: the same Time Horizon of Impact for all moments of emissions

Because LCA is conceived as a holistic approach, the laws used to model mobility and degradations of substances, i.e. their chemical fate, are globalized on typologies of average media called receiving compartments, and not on real media too numerous and too complex to be known in detail. Defining these receiving compartments typologies the transfer of substances between them and their specific degradation laws, has been the objective of many years of research conducted in particular within the Society of Environmental Toxicology and Chemistry (SETAC), and later leading to the development of calculation models such as usetox for human toxicity and ecotoxicity (Birkved and Heijungs 2011). The usetox approach is based on the definition of parameters for nested receiving

compartments from regional to global. Globally, whatever the emission-based impact category, the modelling approach is the same: it does not aim at reflecting observed impacts, but at calculating potential impacts based on the generic assumption of LCA that if a substance is emitted, its potential impact can and has to be assessed as long as its characterization factor is available.

If these existing models are defined considering characteristics of both substance and receiving compartments, the question of dynamic approaches concerns the moment of emission: can it influence the chemical fate? This is a legitimate question. Many researches have focused on providing models integrating compartments specificities at regional scales (Frischknecht et al. 2019) because it allows to better take into account the diversities of the receiving compartments. In a similar way to spatial differentiation, the development of dynamic indicators raises the question of the temporal evolution of the receiving compartments. However, this is a much more complex problem, as the time evolution characteristic of receiving compartments are not predictable in the long term: they especially depend on their own chemical composition, including changes in concentrations of the pollutants under study. This is the case for the climate change impact category. The radiative efficiencies of GHGs depend on the chemical composition of the receiving compartment, that is the Earth's atmosphere, which constantly evolves mainly due to GHGs emissions themselves (Forster et al. 2007). As an example, radiative efficiency of methane was updated relatively to nitrous oxide concentration (Etminan et al. 2016). The kinetics of CO₂ degradation have also evolved in the past years accounting for the changes of both CO₂ sinks and emissions, themselves modifying biogeochemical carbon cycle (Joos et al. 2001, 2013). This is the reason why the IPCC regularly updates characterisation factors of GHGs.

In this context of current knowledge, it is not possible to predict future changes in receiving compartments characteristics nor changes in degradation kinetics. The current practise consists in assuming that chemical fates of emissions will remain identical as today's in the long term and possibly integrate updates of characterisation factors when they are validated and available. Thus, this is equivalent to considering that the chemical fate will be the same no matter when the emission occurs. Although this may not accurately reflect existing phenomena, this is in line with the general LCA framework aiming at assessing *potential* impacts (ISO 2006). *Potential* means that the modelled impacts are essentially related to amounts of emissions of elementary flows and do not represent real effects on the environment (Hauschild and Huijbregts 2015). This assumption of potentiality is equivalent to considering that an impact occurs with certainty after an elementary flow is emitted, whereas in reality it could not necessarily occur, or not occur with the same intensity as obtained from the chemical fate model, because local or moment's specific context, possibly from outside the studied system, could emphasize, lower or even cancel this impact.

Within this LCA conceptual context, whenever a substance is emitted, it is systematically considered to provoke an impact, with an initial increase of its effect at the moment it is emitted, that will then decrease with time with a given kinetic law that is known at the time of the study and considered stable. Thus, the characterization factor of a substance must be calculated on the totality of the chosen *THI* because the potentiality of the impact has to be the identically considered. Although a time frame has to be defined for any dynamic impact assessment method, this time frame should include the entire time decay according to the chosen *THI*, of the totality of the elementary

flows. Considering different *THI*s for the same substance emitted at different moments is not meaningful, unless one can provide a dynamic prediction of the characteristics of the receiving compartment that would justify so.

2.4 Application to GWP

For GWP, the modelled effect is radiative forcing that is the concentration of the greenhouse gas multiplied by its radiative efficiency (as schemed in Figure 1). The *THI* value is of course a critical point in the calculation of the indicators. As most substances completely degrade after a certain time, their effect tends to zero at an infinite time. An infinite *THI* value is therefore recommended to consider the full effect on the environment. This is possible for almost all indicators. However, for climate change impact, the carbon dioxide CO₂ emitted in air, does not fully degrades (as illustrated in Figure 1). Because of its biogeochemical cycle, CO₂ concentration in the atmosphere is linked to a complex balance between emission sources and natural carbon sinks. According to the latest models (Joos et al. 2013), about 22% of an emitted amount of CO₂ remains in the atmosphere. Thus, there is no *THI* that can account for the full effect. Many scientific debates were conducted to discuss of the *THI* value for climate change indicators, leading to recommendations of scientists to use GWP100 to account for short term effects, and GTP100 to account for long term effects (Levasseur et al. 2016). The choice of *THI* for climate change is thus a convention, resulting from a scientific consensus.

However, whatever conventional value is chosen for *THI*, as for other impact categories, the three fundamental principles detailed above must be respected.

3 PROBLEMS AND SOLUTIONS CONCERNING DYNAMIC GWP

3.1 Why today's Dynamic GWP does not comply with basic LCA principles

The dynamic GWP indicator was developed and fully described earlier (Levasseur et al. 2010). The purpose here is not to describe this research in details but to focus on calculation principles.

The calculation principle is schemed in Figure 2: a Total Observation Duration (*TOD*) is fixed and defined as the time integration value for the denominator. At the numerator, for a substance emitted at time zero, the time integration value is equal to the one at the denominator; whereas for a substance emitted later, at time t , the time integration value is equal to $TOD - t$.

TOD is defined as a fixed temporal horizon of the study and is arbitrarily chosen by decision makers (Levasseur et al. 2010). In order to distinguished this dynamic indicator based on fixed *TOD* (Levasseur et al. 2010) from the new method described in the next part, let's note this indicator $GWP_{dyn_fixed_TOD}$. Although the authors do not recommend any value of *TOD*, it is commonly chosen $TOD = 100$ years by decision makers, probably because static GWP is currently calculated at this value. However, *TOD* is not *THI*. In fact, the very concept of *THI* has vanished with the $GWP_{dyn_fixed_TOD}$ indicator, because the time integration value is different between substances according to the moment they are emitted. This does not respect the third principle stated earlier. Furthermore, if some flows are emitted after the chosen *TOD* they are not accounted, thus not respecting the first principle also stated earlier.

3.2 Solution to comply with basic LCA principles

Considering that no flow should be omitted leads to consider the duration of the product's life cycle as a necessary information to define *TOD*. In a static LCA, this duration is not a critical information, however, for a dynamic approach, the moments of all emissions have to be known. As shown in Figure 3, it is possible to define the Life Cycle Duration (*LCD*) that extends from the very first emission to the very last in a given system model of a given product's life cycle. Thus, to respect the first principle stated earlier, *TOD* should at least be equal or superior to *LCD*. It is important to notice that *LCD* must not be confused with the product's life duration, because some emissions can occur before the product is manufactured, as well as after the product is disposed.

Respecting the third principle, leads to impose that *THI* has to be equal for each single emission, thus to consider a sliding integration time at each moment a substance is emitted as shown in Figure 3. Let's recall, according to fundamental concepts of LCA about potential impacts (see section 2.3) that any GHG emitted at any moment, even several hundreds of years from today, will surely have an effect with a degradation kinetic, and that an impact will occur with an absolute certainty.

These two principles being respected, one can see that *TOD* cannot be chosen as a value that is suitable to a decision maker, but exactly as $TOD = LCD + THI$. In addition, the dynamic GWP should be calculated using full *THI* integration time for all emissions at the numerator, and the time integration at the denominator should extend from zero to $THI + t$ for each substance. This is represented in Figure 4. To be distinguished from the indicator described in the previous part, let's note it $GWP_{dyn_fixed_THI}$.

3.3 What about the dynamic indicator of the RE2020 regulation?

The dynamic indicator, here noted GWP_{dyn_RE2020} , proposed by the French RE2020 regulation is a simplified approach of the method with a fixed *TOD* (Levasseur et al. 2010; Levasseur 2011) made to be able to calculate the dynamic indicator from the value of the static one that is better known from the economic actors.

The simplification consists in applying a time dependant correction factor, here noted $F_{RE2020}(t)$, t being the year at which the emission occurs, that multiplies the static GWP with a $THI = 100$ years and here noted $GWP_{stat_THI=100}$.

$$GWP_{dyn_RE2020}(t) = F_{RE2020}(t) \cdot GWP_{stat_THI=100}$$

The value of $F_{RE2020}(t)$ is calculated by the ratio of the difference between the classic static indicator and the here noted (see section 3.1) $GWP_{dyn_fixed_TOD=100}$ dynamic indicator chosen from (Levasseur et al. 2010; Levasseur 2011), divided by the static $GWP_{stat_THI=100}$. The value of *TOD* is chosen equal to 100 years in the regulation.

$$F_{RE2020}(t) = 1 - \frac{GWP_{static_THI=100} - GWP_{dy_fixed_TOD=100}(t)}{GWP_{static_THI=100}}$$

Thus, GWP_{dyn_RE2020} combines both static and dynamic methods. This simplified dynamic indicator GWP_{dyn_RE2020} is applied only during the use phase of the building, i.e. product's life duration set to 50 years, and time zero is set at the beginning of the building use phase (i.e. when the building is delivered).

In order to respect the first principle stated in section 2 of that paper, and avoid any omission of flows:

- all flows emitted before time zero, are considered emitted at time zero (thus with a characterization factor corresponding to an integration time of $TOD = 100$ years thus equivalent to $GWP_{stat_THI=100}$),
- all flows emitted after the product's life duration (50 years) are considered emitted at time 50 years (thus with a characterization factor corresponding to an integration time of $TOD - 50$).

For buildings, this approximation, probably chosen to make the regulation applicable, appears reasonable as construction materials are generally produced on demand, and possible end of life GHG emission would not occur too long after building's end of life. However, reuse of building wood elements for example, is clearly disadvantaged by this rule.

Although there is no flow omission in the regulation, it remains that the integration time for assessing impacts of all delayed flows is still truncated. Thus, coefficients have been compared for the two indicators.

4 RESULTS AND DISCUSSION

4.1 Results concerning French regulation coefficients

The corrective coefficient $F_{RE2020}(t)$ was calculated using both $GWP_{dyn_fixed_TOD=100}$ and $GWP_{dyn_fixed_THI=100}$ indicators and has been represented as a function of time in Figure 5 **Erreur ! Source du renvoi introuvable..**

It shows that its decrease due to delayed emissions, is overestimated by the method based on $GWP_{dyn_fixed_TOD=100}$. This is not surprising because the difference between $GWP_{stat_THI=100}$ and $GWP_{dyn_fixed_TOD=100}$ are due to both delayed emissions and truncated integration time, whereas the difference between $GWP_{stat_THI=100}$ and $GWP_{dyn_fixed_THI=100}$ is only due to delayed emissions. At time 50 years after building construction, the difference between the two indicators is around 25%, by using a correction factor of 0.52 instead of 0.72 as shown in Figure 5.

The new method is totally applicable for the regulation, as only new coefficients $F_{RE2020}(t)$ are produced in this paper (Figure 5).

4.2 What is the meaning of these dynamic indicators?

The two indicators $GWP_{dyn_fixed_TOD}$ and $GWP_{dyn_fixed_THI}$ have different meanings.

The indicator $GWP_{dyn_fixed_TOD}$ represents the radiative forcing generated by a set of emissions occurring at different moments t cumulated between time t and TOD , divided by the radiative forcing of one kg of CO₂ cumulated between time zero and TOD . The emissions and the effects of these emissions occurring after that chosen TOD are not accounted. The value of the denominator is constant for all emissions.

The indicator $GWP_{dyn_fixed_THI}$ represents the radiative forcing generated by a set of emissions occurring at different moments t cumulated between time t and $t + THI$, divided by the radiative forcing of one kg of CO₂ cumulated between time zero and $t + THI$. All emissions and all their effects are accounted with the same integration time THI . The value of the reference at the denominator is variable for each moment of emission: the "full" effect of

each emitted substance is related to that of one kg of CO₂ emitted at time zero and integrated up to the time corresponding to the end of the effect of the substance.

One could say, in order to respect the first principle, that *TOD* could be imposed equal or superior to *LCD* for the $GWP_{dyn_fixed_TOD}$ indicator, in order to account for all flows. However, the third principle would still not be respected as the effects of emissions occurring at later moments would still not be fully accounted do to truncation of the integration time.

One could also criticise the fact that the reference to the denominator becomes variable with the $GWP_{dyn_fixed_THI}$ indicator. However, it should not be forgotten that this reference is only a unit conversion, and not the phenomenon to be represented, which is linked to the life cycle inventory and represented in the numerator. In fact, the $GWP_{dyn_fixed_THI}$ exactly represents the effect of delaying an emission, in comparison with a static indicator with the same *THI*, the reference being the emission of one kg of CO₂ that would have been considered to have occurred at time zero. The numerator is the important information linked to the inventory, and thus has to be fully represented, i.e. full account of all flows and full account of the impacts of these flows.

4.3 Why choosing a fixed total observation period *TOD* in the present version of dynamic GWP?

The calculation of the dynamic $GWP_{dyn_fixed_TOD}$ is justified by a temporal inconsistency according to its authors (Levasseur et al. 2010). When one takes a "rolling" time horizon in the GWP calculation, the authors argue that, for emissions occurring after time zero, the time horizon of the impact exceeds the total observation time. The authors (Levasseur et al. 2010) thus justify the use of the $GWP_{dyn_fixed_TOD}$ indicator, which avoids exceeding this limit.

However, there appears to be an inconsistency in scientific reasoning in the approach to defining $GWP_{dyn_fixed_TOD}$: while the values of *THI* and *LCD* are justified and/or factual, the total observation period *TOD* is subjectively chosen according to the authors themselves (Levasseur et al. 2010). Therefore, it is scientifically inconsistent to require that justified or factual values be submitted and modified to meet a constraint imposed by a subjective value. In a rigorous scientific approach, a subjective value should be subject to objective constraints and not the other way around. Thus, the observation period *TOD* should be adjusted to those of the life cycle duration *LCD* and the time horizon of the impact *THI*, which are justified and/or factual values.

The life cycle duration of the product under consideration *LCD* is a factual value: it can be determined if the chronology of materials and products manufacturing as well as other operations related to the life cycle of a product is known. Although objective and factual, the value of *LCD* can practically be difficult to know since the chronology of each part of the LCA system would have to be known.

The time horizon of the impact *THI* and the life cycle duration of the product *LCD* are independent values: although they are chronologically related (i.e. the environmental impact occurs after the emission), their respective time frame values are not causally related.

An international workshop held in 2010 about the temporary carbon storage (Brandão et al. 2011, 2013). Experts examined the question of how - and if - the effect of temporary carbon storage should be considered in LCA.

Although temporary carbon storage is one target issue of dynamic LCA, it would be more relevant to mention that dynamic LCA addresses the question of delayed emissions with reference to a time zero. Although no methodology was recommended, the experts did, however, identify points of agreement and disagreement. Among them, they concluded that although the dynamic aspect is important, “the definition of the time horizon [of the study] is a subjective choice to which the results are extremely sensitive” (Brandão et al. 2011, 2013). However, the time so-called “time horizon of the study”, i.e. *TOD* in the present article, is not precisely defined and the distinction between time horizon of the study *TOD* and time horizon of the impact *THI* is not discussed. In fact, it seems that the community (Breton et al. 2018) is not aware of the distinction between total observation duration (*TOD*), time horizon of the impact (*THI*) and life cycle duration (*LCD*), as the different literature still discusses time horizon in general. *THI* and *LCD* have independent values, but are related chronologically, whereas *TOD* does depend on them if the three principles enounced earlier are to be respected.

4.4 Conceptual issue or implementation issue?

The authors of the existing dynamic method do not provide any recommendation concerning the value of *TOD*. Thus, one could argue that this method can be kept and recommend a value of *TOD* that would be superior to *LCD*. This is represented in Figure 6. Because no distinction is clearly made between *THI* and *TOD* by the authors, using their approach by setting a fixed value of *TOD* at the denominator, whatever this value is, would still result having truncated integration time at the numerator thus not respecting identical *THIs* for all emissions (principles 2 and 3 explained in sections 2.2 and 2.3). Thus, this is the design of the indicator itself that is required to be changed, and not only the value of *TOD*.

Another solution to maintain a fixed value of *THI* at the denominator would be to use *THI* as a fixed time horizon at both the numerator and the denominator. This is represented in Figure 7. With that choice, every substance at the numerator is integrated on a time frame of *THI* and divided by the CO_2 integrated on the same time frame of *THI*. This is in fact not different from the static indicator, and is thus not relevant to observe a change of effect due to delayed emissions.

4.5 Notations of GWP indicators

It is noteworthy that for $GWP_{stat_THI=100}$ and $GWP_{dyn_fixed_THI=100}$ the number 100 indicates the time horizon of the impact, whereas for $GWP_{dyn_fixed_TOD=100}$, it indicates the total observation time. However, $GWP_{stat_THI=100}$ is commonly noted “static GWP100” and $GWP_{dyn_fixed_TOD=100}$ commonly noted “dynamic GWP100”.

These two inhomogeneous notations suggest that $GWP_{dyn_fixed_TOD=100}$ would be the dynamic equivalent of $GWP_{stat_THI=100}$, which is not the case. This difference in notations may have led to confusion, leading to the wrong choice of observation period for GWP_{dyn_RE2020} that combines the two methods.

Since the observation period is variable and depends on the length of the life cycle, it would be preferable to use the same notation for all GWPs, i.e. GWP100 should refer to the dynamic indicator corresponding to the 100-year *THI* (time horizon of the impact), and not to the *TOD* (total observation time).

5 CONCLUSIONS AND RECOMMENDATIONS

If one wants to respect three basic principles of LCA, i.e. that (i) no inventory flow should be omitted from an assessment, (ii) all impacts of all substances contributing to an impact category should have the same Time Horizon of the Impact in the indicator used for that impact category, and (iii) the time horizon of the impact has no reason to change as a function of time, then it is shown that the current and common version of the dynamic GWP (Levasseur et al. 2010) does not respect these principles.

Although it is difficult to explain why these principles were not initially laid down and respected, the assumption is that the scientific community has not made it clear that there are three different and distinct quantities of time. The time horizon of the impact (*THI*) and life cycle duration (*LCD*) of a product, are distinct. Whereas *THI* is chosen by convention with an inevitable part of subjectivity for the climate change impact category at least, its value should be kept constant whenever a substance is emitted in order to respect the physicochemical reality of the impact. The value of *LCD* extends from the very first emission to the very last that are defined for a given product: although these values may be difficult to obtain, they do exist and are thus objectively defined. *THI* and *LCD* have independent values, but both time entities are related chronologically: *THI* has to be considered to account for the full effect for the very last emission of the product's life cycle. Thus, the total observation duration (*TOD*) to consider for any dynamic approach is $TOD = LCD + THI$.

A new term of the dynamic GWP, based on the relationship between *TOD*, *THI* and *LCD*, is proposed in order to respect the three basic principles. Of course, the two dynamic indicators do not have the same meaning. The current indicator (Levasseur et al. 2010) represents an assessment of the impact within a subjectively chosen observation period and neither the flows nor the effects of these flows on climate change are taken into account beyond this limit. The difference between that current indicator (Levasseur et al. 2010) and the static GWP is due to both the delay of emissions and to the truncated impact assessment. The new expression of the dynamic indicator takes into account the totality of the flows and the entirety of their impact according to the value of *THI*, it thus represents only and exclusively the effect of delaying emissions compared to the static GWP. The current GWP indicator (Levasseur et al. 2010), on which the French regulation is based, overestimates the effect of delaying emissions. This overestimation is around 25% at time 50 years after building's construction. The new method is totally applicable for the regulation, as only new coefficients, produced in this paper, have to be changed.

Current notations are also confusing, because static GWP100 refers to *THI* = 100 years, whereas dynamic GWP100 from (Levasseur et al. 2010) refers to *TOD* = 100 years. To harmonise notations in order to compare comparable entities, it is recommended to use only *THI* as an index in the symbol of both static and dynamic indicators.

At a time when the dynamic GWP indicator is being considered as a regulatory tool on a French or even European scale, it seems crucial to consider its scientific relevance, because using the wrong method could lead to an overestimation of the possible beneficial effects of temporary carbon storage in the construction sector as a whole.

Declaration

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6 REFERENCES

- Benoist A (2009) Eléments d'adaptation de la méthodologie d'analyse de cycle de vie aux carburants végétaux: cas de la première génération - Adapting life-cycle assessment to biofuels: some elements from the first generation case. École Nationale Supérieure des Mines de Paris
- Birkved M, Heijungs R (2011) Simplified fate modelling in respect to ecotoxicological and human toxicological characterisation of emissions of chemical compounds. *Int J Life Cycle Assess* 16:739–747. <https://doi.org/10.1007/s11367-011-0281-y>
- Brandão M, Levasseur A, European Commission, et al (2011) Assessing temporary carbon storage in life cycle assessment and carbon footprint: outcomes of an expert workshop, 7th-8th October 2010, Ispra (Italy). JRC scientific and technical reports
- Brandão M, Levasseur A, Kirschbaum MUF, et al (2013) Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *Int J Life Cycle Assess* 18:230–240. <https://doi.org/10.1007/s11367-012-0451-6>
- Breton C, Blanchet P, Amor B, et al (2018) Assessing the Climate Change Impacts of Biogenic Carbon in Buildings: A Critical Review of Two Main Dynamic Approaches. *Sustainability* 10:2020. <https://doi.org/10.3390/su10062020>
- Cherubini F, Bright RM, Strømman AH (2013) Global climate impacts of forest bioenergy: what, when and how to measure? *Environ Res Lett* 8:014049. <https://doi.org/10.1088/1748-9326/8/1/014049>
- Cherubini F, Peters GP, Berntsen T, et al (2011) CO₂ emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. *GCB Bioenergy* 3:413–426. <https://doi.org/10.1111/j.1757-1707.2011.01102.x>
- Etminan M, Myhre G, Highwood EJ, Shine KP (2016) Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing: *Greenhouse Gas Radiative Forcing*. *Geophys Res Lett* 43:12,614–12,623. <https://doi.org/10.1002/2016GL071930>
- European Commission (2012) ILCD Handbook Specific guide for Life Cycle Inventory. Joint Research Center and Institute for Environment and Sustainability, Ispra (Italy)

Anne Ventura (2022) *Conceptual issue of the dynamic GWP indicator and solution*, *The International Journal of Life Cycle Assessment*, <https://doi.org/10.1007/s11367-022-02028-x>

Forster P, Ramaswamy V, Artaxo P, et al (2007) *Changes in Atmospheric Constituents and in Radiative Forcing*. In: Solomon SD, Manning M, Chen Z, et al. (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press. Cambridge (UK) and New York (USA)

Frischknecht R, Jolliet O (eds) (2019) *Global Guidance for Life Cycle Impact Assessment Indicators - Volume 2*, UNEP Life Cycle Initiative. UNESCO/CLD

Frischknecht R, Jolliet O, Mila i Canals L, et al (2016) Chapter 1. Motivation, context and summary. In: Frischknecht R, Jolliet O (eds) *Global Guidance for Life Cycle Impact Assessment Indicators*, UNEP Life Cycle Initiative. UNESCO/CLD, pp 30–39

Frischknecht R, Pfister S, Bunsen J, et al (2019) *Regionalization in LCA: current status in concepts, software and databases—69th LCA forum*, Swiss Federal Institute of Technology, Zurich, 13 September, 2018. *Int J Life Cycle Assess* 24:364–369. <https://doi.org/10.1007/s11367-018-1559-0>

Hauschild MZ, Huijbregts MAJ (2015) Chapter 1. *Introducing Life Cycle Impact Assessment*. In: Hauschild MZ, Huijbregts MAJ (eds) *Life Cycle Impact Assessment*. Springer, pp 1–16

ISO (2006) *ISO 14040 - Environmental management - Life cycle assessment - Principles and framework*

Joint Research Centre (2010a) *Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Impact Assessment*. European Commission, Luxembourg

Joint Research Centre (2010b) *Framework and requirements for life cycle impact assessment models and indicators*. European Commission, Luxembourg

Joos F, Prentice IC, Sitch S, et al (2001) *Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) Emission Scenarios*. *Glob Biogeochem Cycles* 15:891–907. <https://doi.org/10.1029/2000GB001375>

Joos F, Roth R, Fuglestedt JS, et al (2013) *Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis*. *Atmospheric Chem Phys* 13:2793–2825. <https://doi.org/10.5194/acp-13-2793-2013>

Levasseur A (2011) *Développement d'une méthode d'analyse du cycle de vie dynamique pour l'évaluation des impacts sur le réchauffement climatique*. École Polytechnique de Montréal

Levasseur A, de Schryver A, Hauschild M, et al (2016) Chapter 3. *Greenhouse gas emissions and climate change impacts*. In: Frischknecht R, Jolliet O (eds) *Global Guidance for Life Cycle Impact Assessment Indicators*, UNEP Life Cycle Initiative. UNESCO/CLD, pp 58–75

Anne Ventura (2022) *Conceptual issue of the dynamic GWP indicator and solution*, *The International Journal of Life Cycle Assessment*, <https://doi.org/10.1007/s11367-022-02028-x>

Levasseur A, Lesage P, Margni M, et al (2010) Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ Sci Technol* 44:3169–3174. <https://doi.org/10.1021/es9030003>

Müller N, de Zwart D, Hauschild M, et al (2017) Exploring REACH as a potential data source for characterizing ecotoxicity in life cycle assessment. *Environ Toxicol Chem* 36:492–500. <https://doi.org/10.1002/etc.3542>

NORM'EN LIGNE (2021) Appui de la normalisation à la nouvelle réglementation environnementale (RE2020). <http://extranet.normalisation.developpement-durable.gouv.fr/appui-de-la-normalisation-a-la-nouvelle-a1315.html>. Accessed 14 Sep 2021

Pehnt M (2006) Dynamic life cycle assessment (LCA) of renewable energy technologies. *Renew Energy* 31:55–71. <https://doi.org/10.1016/j.renene.2005.03.002>

Roux C, Schalbart P, Peuportier B (2016) Accounting for temporal variation of electricity production and consumption in the LCA of an energy-efficient house. *J Clean Prod* 113:532–540. <https://doi.org/10.1016/j.jclepro.2015.11.052>

Saouter E, Aschberger K, Fantke P, et al (2017) Improving substance information in USEtox®, part 2: Data for estimating fate and ecosystem exposure factors. *Environ Toxicol Chem* 36:3463–3470. <https://doi.org/10.1002/etc.3903>

7 FIGURES

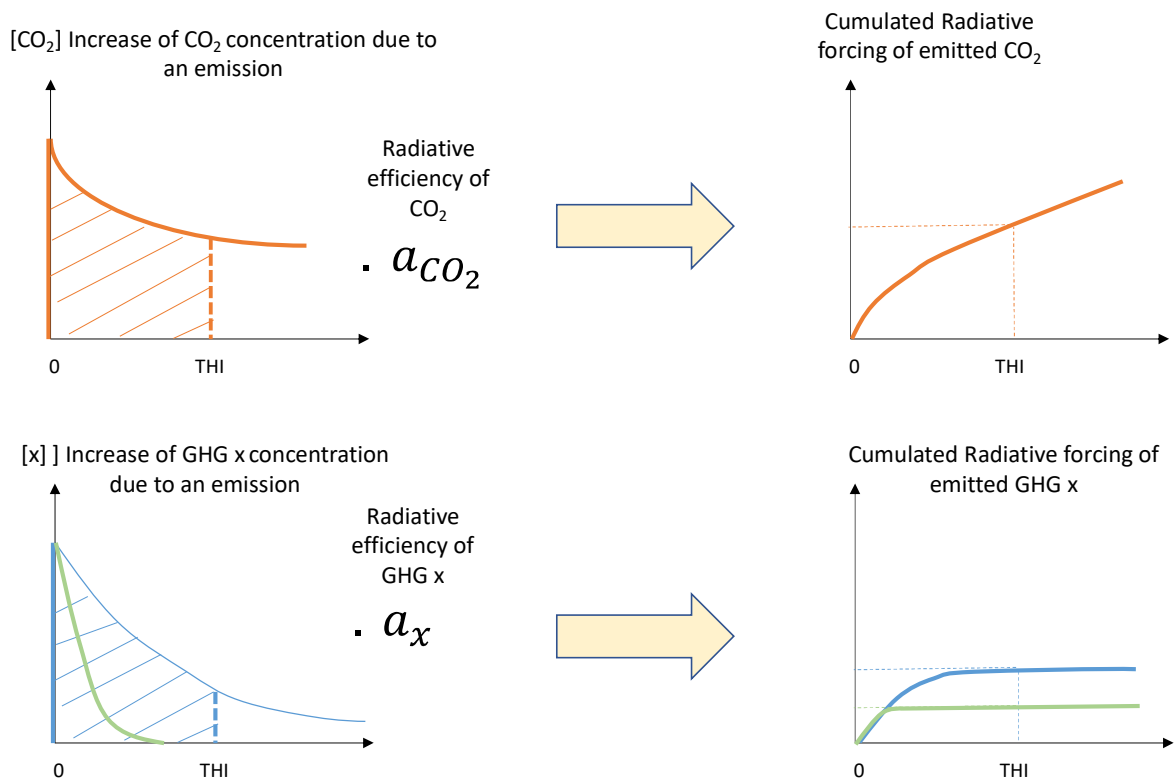


Figure 1. Schematic principles of calculation of Cumulated radiative forcing for GWP characterization factor - on the left the integral on THI of the time decay multiplied by the radiative efficiency, on the right the result of the calculation

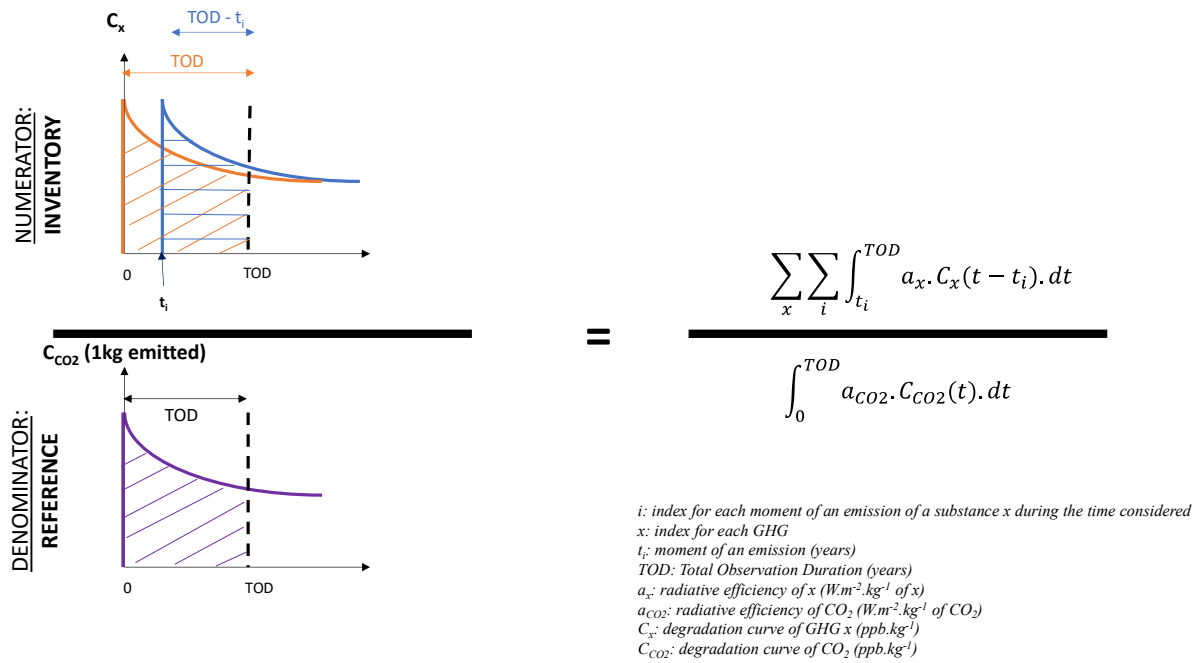


Figure 2. Schematic principles of calculation of dynamic $GWP_{dyn_fixed_TOD}$ characterization factor according to (Levasseur et al. 2010)

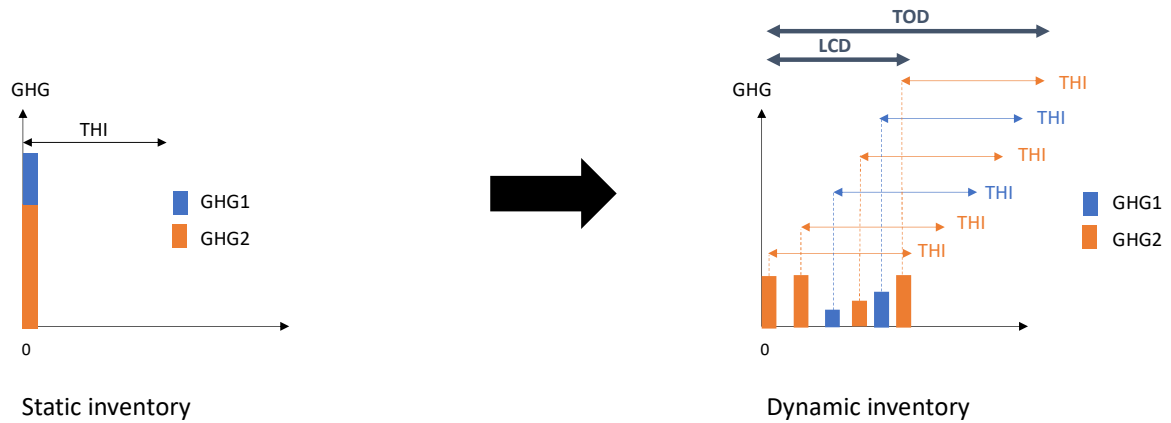


Figure 3. Schematic principles of transition from static to dynamic inventory - on the left a static inventory of two different GHGs where all emissions are considered occurring at time zero and the THI used for calculating their effect on climate change, on the right the same total emissions distributed in time for a dynamic assessment and their THIs used for calculating their effect on climate change

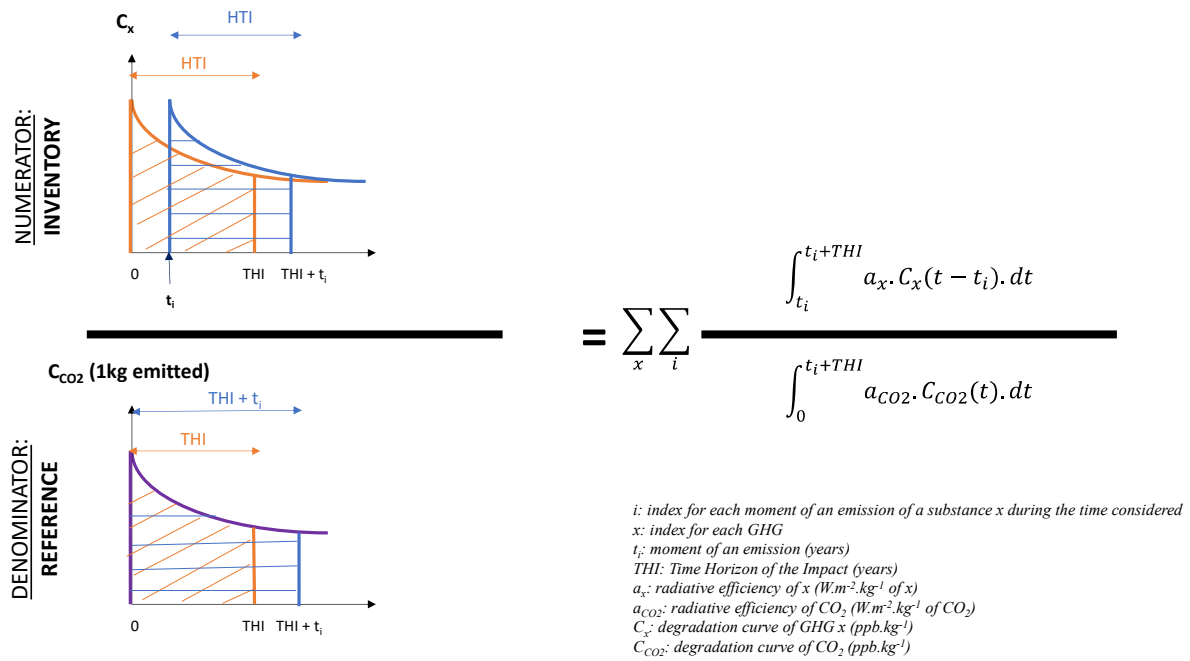


Figure 4. Schematic principles of calculation of dynamic $GWP_{dyn_fixed_THI}$ characterization factor respecting basic LCA principles

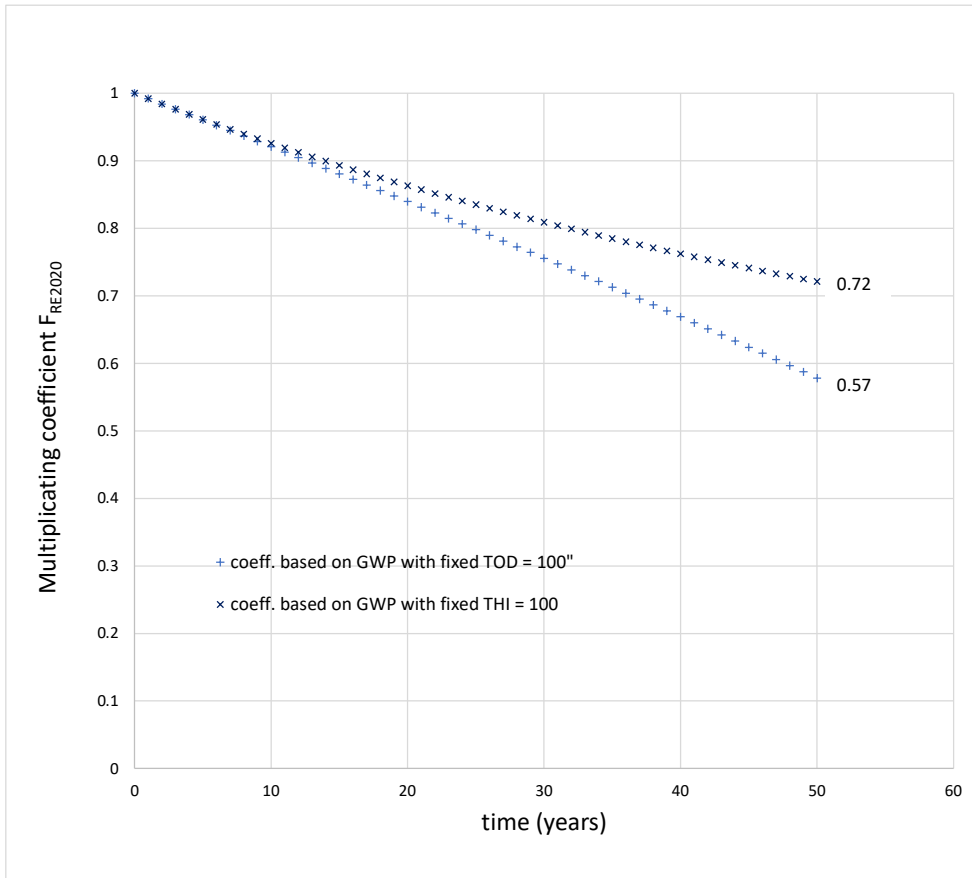


Figure 5. Corrective coefficient used for the GWP_{dyn_RE2020} indicator calculated with fixed TOD and fixed THI

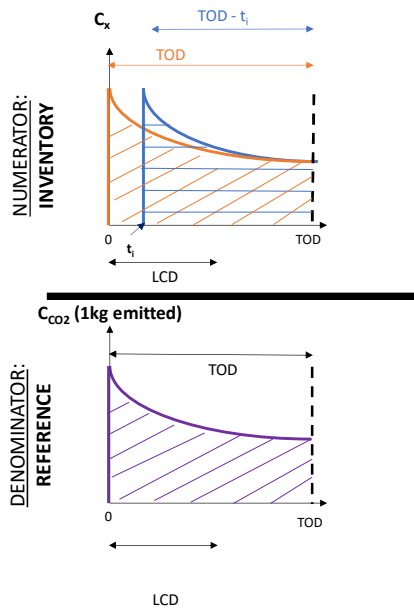


Figure 6. Schematic principles of calculation of dynamic $GWP_{dyn_fixed_TOD}$ characterization factor according to (Levasseur et al. 2010) in the case of a TOD that would be very superior to LCD

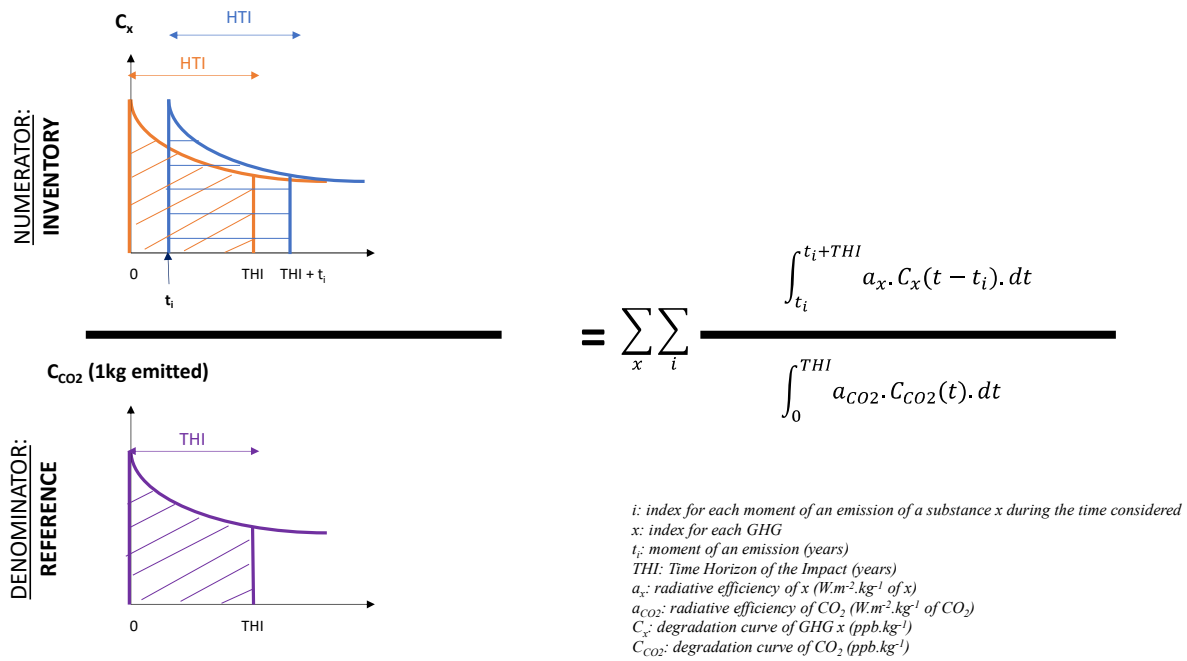


Figure 7. Schematic principles of calculation of dynamic $GWP_{dyn_fixed_THI}$ characterization with a fixed THI integration time at both numerator and denominator

Anne Ventura (2022) Conceptual issue of the dynamic GWP indicator and solution, The International Journal of Life Cycle Assessment, <https://doi.org/10.1007/s11367-022-02028-x>