Climate Change Impact tool for dynamic LCA

Principles, data used and examples of application

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Summary

1. Introduction

The bio-based sector has as particularity the use of carbon from the short carbon biogeochemical cycle, with capture and emission flows with different temporalities. Using the GWP metrics is not adapted to capture the implications of the biomass and carbon lifecycle. Typically, steps like the in-use lifetime of bio-based materials, tree growth, or end of life stage, are incorrectly evaluated. On one hand, the effects of carbon captures and emissions and of their temporalities are more difficult to unveil, and on another hand, the mitigation solutions need careful design. For these reasons, the dynamic approach in evaluating the climate change impact stands out as more relevant.

We propose a method to evaluate the climate change impact in dynamic LCA based on a time-dependent model. The static GWP metric has significant limitations especially when dealing with biogenic carbon emissions and capture processes, and when the time horizon of the evaluation is shorter than 100 years, which is the case of the present and future years and of our whole century. Criticism of the GWP metrics have been expressed from the outset of its use, however, the complexity of climate models has hampered the use of more relevant metrics. However, the reduced models released by climatologists allow the use of alternative climate indicators, closer to physical parameters and with more consistent meaning, like time dependent radiative forcing or time dependent temperature change. More development on this discussion in the realm of dynamic LCA is available elsewhere (Tiruta-Barna, 2021).

A tool (CCI-tool) was previously developed to calculate global climate parameters, i.e. radiative forcing and global mean temperature change and applied with dynamic LCA (Shimako et al., 2016). In the

context of LCA4BIO, this tool was improved and completed with the most recent developments in the field (IPCC AR5 and AR6, and related bibliography), as explained in this report.

2. The principles of the 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 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 :

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

The 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. We call the RF of direct GHG 'direct RF' RFd:

$$RFd_s(t) = A_s(t)\, B_s(t) = A_s(t)(g_s * IRF_s) \quad (1)$$

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. For direct GHG substances, we call this parameter 'direct GMTC' GMTCd:

$$GMTCd_s(t) = RFd_s * IRFT \quad (3)$$

IRFT(t) is defined by:

$$IRFT(t) = \sum_{j=1}^{2} \frac{cj}{dj} e^{-t/dj} \quad (4)$$

with the parameter values updated in AR6 WG1 (ch 6SM). 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.

In the followings, we present the developments performed in the framework of LCA4BIO.

In AR5 Ch 8, 8.7.1.4. it is recommended to include the indirect effects and the carbon cycle feedback in the effect of the considered compound. For example, for CH_4, include direct effect, indirect effects (oxidation to water) and the neo-formed CO_2 effect, plus the carbon cycle feedback. According to the IPCC AR6 report, the carbon-climate feedback effect on the radiative forcing, RF_CCF, is added to the direct radiative forcing (and the other cascade indicators), for all climate forcers (except CO_2) as follows:

$$RF\_CCF_s(t) = A_{CO2}(GMTCd_s * IRFCCF * IRF_{CO2}) \quad (5)$$

$$RF_s(t) = RFd_s(t) + RF\_CCF_s(t) \quad (6)$$

$RF\_CCF_s(t)$ is the contribution of substances to the supplementary RF of CO_2 due to the temperature elevation generated by s. It is accounted for s together with the RF generated directly by s.

The same holds for the temperature :

$$GMTC\_CCF_s(t) = RF\_CCF_s * IRFT \quad (7)$$

$$\mathrm{GMTC_s(t)} = \mathrm{GMTCd_s} + \mathrm{GMTC\_CCF_s} \quad (8)$$

Where IRFCCF is the impulse response function (CO_2 flux perturbation following a unit temperature pulse), in kg CO_2 yr^{-1} K^{-1}.

$$\mathrm{IRFCCF\ (t)} = \gamma\ \delta(\mathrm{t}) - \gamma\ \sum_{i=1}^{3} \frac{\alpha_i}{\tau_i}\ e^{\frac{-t}{\tau_i}} \quad (9)$$

See Gasser et al, 2017; and IPCC AR6, 7.SM.5.

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

$$\mathrm{RF(t)} = \sum_s \mathrm{RF_s(t)} \quad (10)$$

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

$$\mathrm{iRF(TH)} = \int_{t=t_0}^{TH} RF(\mathrm{t})dt \quad (11)$$

The global mean temperature change at a given time t, GMTC (K), is obtained by aggregating values for all the concerned forcers:

$$\mathrm{GMTC(t)} = \sum_s \mathrm{GMTC_s(t)} \quad (12)$$

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

$$\mathrm{iGMTC(TH)} = \int_{t=t_0}^{TH} GMTC(\mathrm{t})dt \quad (13)$$

3. Specific IRFs for the climate forcers implemented in CCI-tool

3.1. Well-mixed GHG (WMGHG)

<u>CO_2</u>

$$\mathrm{IRF(t)} = a_0 + a_1 e^{-t/\tau 1} + a_2 e^{-t/\tau 2} + a_3 e^{-t/\tau 3} \qquad \text{and} \quad \sum_i \mathrm{a_i} = 1 \quad (1)$$

<u>Methane CH_4</u>

$$\mathrm{IRF(t)} = (1 + f1 + f2) e^{-t/\tau} \quad (2)$$

where f1 (0.5) and f2 (0.15) (IPCC AR5 8.SM.11.3.2) are corrections due to effects on ozone and stratospheric water, respectively.
Methane is oxidized to CO_2, which is included in the model. The yield of transformation is 75% , i.e. 1 kg of CH4 generates 2.1±0.7 kg CO_2; AR6 ch 7.

<u>Dinitrogen oxide (or nitrous oxide) N_2O</u>

$$\mathrm{IRF(t)} = \left(1 - 0.36\ (1 + f1 + f2) \frac{A_{CH4}}{A_{N2O}}\right) e^{-t/\tau} \quad (3)$$

With f1 and f2 as in eq (2).

<u>Other WMGHG</u>

$$\mathrm{IRF(t)} = e^{-t/\tau} \quad (4)$$

The constants used for all GHGs are taken from the last updates (IPCC AR5 and AR6). All the GHGs present in ecoinvent 3.9 LCA data base are included in the software.

3.2. Short-lived climate forcers SLCF

The IPCC AR5 ch 8.7.2.4. reveals large differences in emission metrics from air, land and sea emissions, for the SLCF compounds. In the following, the data used according to the emission compartment is mentioned.

The implemented model uses the specific effective radiative forcing (if available, if not, the specific radiative forcing), and the perturbation time (or lifetime) of the SLCFs. The regionality of the SLCF cannot be included in the modeling for the moment because of lack of regional values for the model parameters. In this work, the updated values of ERF per unit emission from Lee et al (2021) were used for aviation emissions. Data were completed for all the other SLCFs and for all lifetime values from Fuglestvedt et al (2010). Data from Lee et al. (2021) are evaluated based on the ERF (effective radiative forcing – evaluated at the TOA top of the atmosphere) while the more ancient data from Fuglestvedt et al (2010) are based on RF.

Nitrogen oxides NOx

The indirect climate contribution is due to four effects: the short-term ozone increase (STO), long-term effect of methane on ozone depletion (LTO), methane decrease (M), and stratospheric water decrease if the emission is in upper troposphere lower stratosphere (SW). Each of the components have a specific perturbation time τ. For a pulse unitary emission of NOx, 1 kg N:

$RF_{NOx} = STO + LTO + M + SW = A_{NOx}\ IRF(t)$

$$RF_{NOx}(t) = A_{STO}\ e^{-t/\tau 1} + A_{LTO}e^{-t/\tau 2} + A_{M}e^{-t/\tau 3} + A_{SW}e^{-t/\tau 4} \quad (1)$$

$$RF_{NOx}(t) = A_{STO}\ e^{-t/\tau 1} + (A_{LTO} + A_{M} + A_{SW})e^{-t/\tau 2} \quad (2)$$

For aviation emissions in high troposphere – low stratosphere, the data from Lee et al (2021) were used. For shipping emissions (surface of the sea), the data from Fuglestvedt et al (2010) were used. For all other compartments of emissions, data from Fuglestvedt et al (2010) were used.

Remark
Only for practical utilisation in CCI-tool, the formula can be re-written as:

$$RF_{NOx}(t) = A_{NOx}(a_0 + a_1e^{-t/\tau 1} + a_2e^{-t/\tau 2} + a_3e^{-t/\tau 3}) \quad (1')$$

With $a_0 = 0$, $A_{NOx} * a_1 = A_{STO}$ with short τ_1; $A_{NOx} * a_2 = A_{LTO} + A_M + A_{SW}$ with the same τ_2; and $a_3=0$.

LTO, M and SW have the same perturbation time τ_2 which is those of methane lifetime in the given conditions, so the three components can be aggregated in one e-fold term $e^{-t/\tau 2}$.

Carbon monoxide CO

Same modelling approach as in case of NOx. Three components are included in the indirect effect of CO: short-term ozone increase (STO), long-term effect of methane on ozone depletion (LTO) and methane decrease (M). Only tropospheric (surface) emissions are considered (from Fuglestvedt et al, 2010). For the unitary emission of 1 kg CO:

$$RF_{CO}(t) = A_{STO}\ e^{-t/\tau 1} + (A_{LTO} + A_M)e^{-t/\tau 2} \quad (3)$$

Volatile organic compounds others than methane (VOC or NMVOC)

The same approach and formulation as in (3), for 1 kg VOC emitted on surface air. The composition of VOC and the specific parameters are given in Fuglestvedt et al (2010).

Stratospheric water

In case of aviation emissions of water, the radiative forcing increases :

$$RF_{H2O}(t) = A_{H2O}\ e^{-t/\tau 1} \quad (4)$$

Hydrogen H_2

Hydrogen has an indirect climate effect due to interaction with OH. The radiative forcing of a 1kg H_2 emission is taken from Hauglustaine et al (2022):

$$RF_{H2}(t) = A_{H2}\ e^{-t/\tau 1} \quad (5)$$

Aerosols: Sulfate or sulfur dioxide SO_2; black carbon C; organic carbon C.

The direct effect of aerosols is considered (radiation reflection) in one e-fold term as:

$$RF_{aerosol}(t) = A_{aerosol}\ e^{-t/\tau 1} \quad (6)$$

For aviation emissions, data from Lee et al (2021) are considered.

For other emission compartments, data from Fuglestvedt et al (2010) are used.

For shipping SO_2, the indirect effect of modification of cloud properties and of the albedo from Lauer et al (2007) is included; for 1 kg SO_2 emission:

$$RF_{SO2/sulphate}(t) = (A_{direct} + A_{indirect})\ e^{-t/\tau 1} \quad (7)$$

In case of black carbon the base is kg carbon. For organic carbon, the parameters are also expressed per carbon, considering a ratio “particulate organic matter”/”organic carbon” = 1.4

Other aerosols : particulate matter

Most PMs are generated by combustion processes and are composed in majority by organic compounds (e.g. Perrone et al. 2013). We use the data from Fuglestvedt et al (2010) for “organic carbon” to model the behaviour of PMs. Equation (6) applies for particulate matter like PM2.5, PM10.

Since we don’t have models for mineral aerosols effect, only the organic part of the particulate matter is included. The composition from Perrone et al (2013) is considered here, i.e. 17 - 24% (w/w) of organic carbon, with no distinctions according to sites or seasons. With the average value of 20.5%, we obtain for the mass of carbon in PMs and for the radiative efficiency of PMs:

$$C = 0.205 * PM\ (kg) \quad \text{and} \quad A_{PM} = 0.205 * A_C \quad (8)$$

CCI-tool contains PMs in "Data files" with the following notation : "Particulates, 2.5 um"; "Particulates, 10 um"; "Particulates, 2.5 um-10 um". These notations are used in the template file; they are not exactly the same as in ecoinvent because of the incompatibility with programming rules (names of files can not contain special characters like > <, for instance). In the Data file, the radiative efficiency is A_C (those of organic carbon) but the correction factor 0.205 is applied.

Contrails and induced cirrus (aviation)

The model from Lee et al (2021) is considered on the base of 1 km hole flight:

$$RF_{\text{contrail cirrus}}(t) = A_{\text{contrail cirrus}}\ e^{-t/\tau 1} \qquad \text{with A in (W m}^{-2}\text{ km}^{-1}\text{)} \qquad (9)$$

3.3. Other physical phenomena

A literature survey was performed to address the prospective aspect in dynamic climate change indicators, i.e. the effect of the RCPs scenarios. The influence of the GHG concentrations in the atmosphere and of the temperature change on the climate emission metrics AGWP/GWP was studied in several papers. Several phenomena intervene in the CO2 radiative forcing behaviour: the radiative efficiency A_{CO2} which decreases when the concentration increases, and the CO2 distribution between compartments which depends on the concentration. Then the climate carbon cycle feedback acts as a response to the temperature increase.

Reisinger et al (2011) found that "the AGWP of CO2 decreases under all RCPs, although for longer time horizons this decrease is smaller than for short time horizons due to increased climate–carbon cycle feedbacks." For methane and N_2O, the effect is also about 10% to 30% depending on the RCP. The authors mention that "the declining radiative efficiency is more than counterbalanced by the increasing fraction of a CO2 pulse emission that remains in the atmosphere, due to particularly strong climate–carbon cycle feedbacks in this model. "Under the RCP3-PD, which is consistent with a best-estimate global average temperature increase of somewhat less than 2°C over preindustrial conditions, the 100-year AGWP of CO2 would decrease by only about 2% by 2100 relative to the year 2000 value. By contrast, under the highest RCP8.5, the CO2 100-year AGWPs would decrease by 36% by 2100."

From the three elements competing in the CO2 global effect, i.e. its radiative efficiency, redistribution between environmental compartments and climate -carbon cycle feedback, the redistribution can not be implemented because the necessary IRF functions (e.g. formula (1) in case of CO2) are not available for different concentration-temperature conditions (different RCPs).

In this sense, the approach of Lan and Yao (2022) cannot be validated. Indeed, in their publication, the authors used only the radiative efficiency variation, without any other parameter related to the environmental fate of the GHGs. Their results underestimate the effect of CO_2 for instance, for the different RCPs.

4. Data used with the model

Data were updated following the information available at present, especially from the IPCC AR6 report completing the AR5 (in which more detailed data are presented).

For IRFT(t) – formula (4), updated data in AR6 WG1 ch 6.SM are used:

d1 = 3.4 years c1 = 0.44 °C W^{-1} m^2
d2 = 285 years c2 = 0.32 °C W^{-1} m^2

All data are implemented in the "Data files" for use with CCI-tool. Concerning the SLCFs, the tables below indicate the main modelling features and present the data selected from bibliography according to the recommendations from the IPCC reports.

Table 1. Information extracted from AR6, ch 6 (table 6.1).

Table 6.1 | Overview of SLCFs of interest for Chapter 6. For each SLCF, its source types, lifetime in the atmosphere, and associated radiatively active agent is given. Source type can be primary (emitted) and/or secondary (formed through multiple atmospheric mechanisms). Unless otherwise noted, the stated lifetime refers to tropospheric lifetime.* Climate effect of increased SLCFs is indicated as '+' for warming and '–' for cooling. 'Direct' is used for SLCFs exerting climate effects through their radiative forcing and 'Indirect' for SLCFs which are precursors affecting the atmospheric burden of other climatically active compounds. Other processes through which SLCFs affect climate are listed where applicable. The World Health Organization (WHO) guidelines for air quality (AQ) are given, where applicable, to show which SLCFs are regulated for air-quality purposes.

Compounds	Source Type	Lifetime	Direct	Indirect	Climate Forcing	Other Effects on Climate[a]	WHO AQ Guidelines[b]
CH_4	Primary	~9 years ~12 years (perturbation time)	CH_4	O_3, H_2O, CO_2	+		No[c]
O_3	Secondary	Hours to weeks	O_3	CH_4, secondary organic and sulphate aerosols	+	Ecosystems	100 µg m^{-3} 8-hour mean
NO_x (= NO + NO_2)	Primary	Hours to days		O_3, nitrate aerosols, CH_4	+/–	Ecosystems	40 µg m^{-3} annual mean 200 µg m^{-3} 1-hour mean
CO	Primary + Secondary	1 to 4 months		O_3, CH_4	+		No
NMVOCs**	Primary + Secondary	Hours to months		O_3, CH_4, organic aerosols	+/–		No
SO_2	Primary	Days (trop.) to weeks (strat.)		Sulphate and nitrate aerosols, O_3	–	Ecosystems	20 µg m^{-3} 24-hour mean 500 µg m^{-3} 10-minute mean
NH_3	Primary	Hours		Ammonium Sulphate, Ammonium Nitrate	–	Ecosystems	No
HCFCs	Primary	Months to years	HCFCs	O_3	+/–		No[c]
HFCs	Primary	Days to years	HFCs		+		No[c]
Halons and Methylbromide	Primary	Years	Halons and Methylbromide	Stratospheric O_3	+/–		No[c]
Very Short-lived Halogenated Species (VSLSs)	Primary	Less than 6 months		O_3	–		No[c]
Sulphate aerosols	Secondary	Minutes to weeks	Sulphate		–	Clouds Ecosystems	as part of PM[d]
Nitrate aerosols	Secondary	Minutes to weeks	Nitrate		–	Clouds Ecosystems	as part of PM[d]
Carbonaceous Aerosols	Primary + Secondary	Minutes to Weeks	BC, OA		+/–	Cryo, Clouds Ecosystems	as part of PM[d]
Sea spray	Primary	Day to week	Sea spray		–	Clouds Ecosystems	as part of PM[d]
Mineral dust	Primary	Minutes to Weeks	Mineral dust		+/–	Cryo Cloud Ecosystems	as part of PM[d]

* For lifetimes reported in this table, it is assumed that the compounds are uniformly mixed throughout the troposphere, however, this assumption is unlikely for compounds with lifetimes <1 year and, therefore, the reported values should be viewed as approximations (Prather et al., 2001).

** Some NMVOCs are biogenic volatile organic compounds (BVOCs).

[a] Clouds: effect on clouds through aerosol–cloud interactions, Ecosystems: effect on ecosystems through changes in radiation and deposition, Cryo: effect on planetary albedo through deposition on snow and ice; [b] Krzyzanowski and Cohen (2008); [c] regulated through Kyoto/Montreal protocols; [d] For Particulate Matter with diameter <2.5 µm ($PM_{2.5}$): 10 µg m^{-3} annual mean or 25 µg m^{-3} 24-hour mean (99th percentile) and for Particulate Matter with diameter <10 µm (PM_{10}): 20 µg m^{-3} annual mean or 50 µg m^{-3} 24-hour mean (99th percentile).

Table 2. Specific SLCF emissions in air sub-compartments in ecoinvent, relevant literature and literature recommended by IPCC AR5 (WG1, ch 8).

Compartments	**Elementary flows in ecoinvent**	**Specific from literature**	**Cited in IPCC AR5, WG1, ch8 (2013)**
Air/lower stratosphere + upper troposphere	e.g. From aviation All gases	NOx , Water, Contrails, AIC (Fuglestvedt et al 2010) NOx, Soot (BC), Sulphate, Water, Contrail cirrus (Lee et al, 2021)	NOx (Fuglestvedt et al 2010 ; Kohler et al 2013 ; Myhre et al 2011)
All others air/sub-compartments	All gases	CO (Fuglestvedt et al 2010) VOC (Fuglestvedt et al 2010) BC (Fuglestvedt et al 2010) OC (Fuglestvedt et al 2010) SO2-aerosols (Fuglestvedt et al 2010) H2 (Hauglustain et al 2022)	CO (Fuglestvedt et al 2010) CO (Shindell et al 2009) VOC (Fuglestvedt et al 2010) BC (Fuglestvedt et al 2010) BC (Bond et al, 2013, 2011) OC (Bond et al 2011) OC (Fuglestvedt et al 2010)
NEW air/sub-compartments	**Not existent in ecoinvent**		
Emission from the surface - land		NOx (Fuglestvedt et al 2010)	NOx (Fuglestvedt et al 2010) NOx (Shindell et al 2009) NOx (Shindell et Faluvegi, 2010) SO2 (Shindell et Faluvegi, 2010) BC (Bond et al, 2011) OC (Bond et al, 2011)
Emission from shipping (surface-sea)		NOx (Fuglestvedt et al 2010) SO2-aerosols (Fuglestvedt et al 2010)	NOx (Fuglestvedt et al 2010) NOx (Collins et al 2010) SO2 (Fuglestvedt et al 2010)

Table 3. Parameter values for SLCFs used in this work.

Air sub-compartment Climate forcer	**Forcing parameter**	**Perturbation time (or lifetime or adjustment time) (years)**	**Specific forcing A (W m^{-2} kg^{-1})**	**Name used in ecoinvent**
Air/all compartments	**Radiative forcing**	**Lifetime (years)**	**Specific forcing (W m^{-2} kg^{-1})** used in this work	

Except for aviation and shipping				
NOx :	W m^{-2} kg_N^{-1} y Fuglestvedt et al (2010) citing Wild et al (2001)	Fuglestvedt et al (2010)	W m^{-2} kg_N^{-1}	Nitrogen oxides
Short-term O3 increase	4.59 10^{-12}	0.267	1.720 10^{-11}	
Long-term O3 decrease	-1.79 10^{-12}	14.2	-1.261 10^{-13}	
CH4 decrease	-3.80 10^{-12}	14.2	-2.676 10^{-13}	
CO :	W m^{-2} kg_{CO}^{-1} y Fuglestvedt et al (2010) citing Derwent et al 2001		W m^{-2} kg_{CO}^{-1}	Carbon monoxide
Short-term O3 increase	6.00 10^{-14}	0.267	2.247 10^{-13}	
Long-term O3 decrease	-	-	-	
CH4 decrease	1.30 10^{-13}	14.2	1.057 10^{-14}	
VOC :	W m^{-2} kg_{VOC}^{-1} y Fuglestvedt et al (2010) citing Collins et al (2002)		W m^{-2} kg_{VOC}^{-1}	NMVOC, non-methane volatile organic compounds, unspecified origin
Short-term O3 increase	2.13 10^{-13}	0.267	7.978 10^{-13}	
Long-term O3 decrease	-	-	-	
CH4 decrease	1.77 10^{-13}	14.2	1.451 10^{-14}	
Aerosols : Fuglestvedt et al (2010)	W m^{-2} kg^{-1}			
Black carbon BC	1.96 10^{-9} (W m^{-2} kg_C^{-1})	0.020		Not existent as Air emission
Organic carbon OC	-2.90 10^{-10} (W m^{-2} kg_C^{-1})	0.021		Not existent as Air emission
SO2	-3.2 10^{-10} (W m^{-2} kg_{SO2}^{-1} y)	0.011		Sulfur dioxide Sulfate
Hydrogen (Hauglustaine et al 2022)	1.30 10^{-4} (W m^{-2} $ppbv^{-1}$)	2.5	3.66 10^{-13}	Hydrogen
Aviation Air/lower stratosphere + upper troposphere	**ERF sensitivity to emissions (W m^{-2} $kg\_emission^{-1}$ y)** Lee et al. (2021)*	**Lifetime (years)** Fuglestvedt et al (2010)	**Specific forcing (W m^{-2} kg^{-1})** used in this work	
NOx :	W m^{-2} kg_N^{-1} y		W m^{-2} kg_N^{-1}	Nitrogen oxides
Short-term O3 increase	3.44 10^{-11}	0.267	1.288 10^{-10}	
Long-term O3 decrease	-9.30 10^{-12}	12.02	-7.737 10^{-13}	
CH4 decrease	-1.87 10^{-11}	12.02	-1.556 10^{-12}	

Stratospheric water vapor decrease	-2.80 10^{-12}	12.02	-2.329 10^{-13}	
Aerosols :				
SO2	-1.99 10^{-11} (W m^{-2} kg_{SO2}^{-1} y)	0.011	-1.810 10^{-9} (W m^{-2} kg_{SO2}^{-1})	Sulfur dioxide Sulfate
Soot (or BC)**	1.007 10^{-10} (W m^{-2} kg_{C}^{-1} y)	0.02	5.035 10^{-9} (W m^{-2} kg_{BC}^{-1})	Not existent
Stratospheric water vapor increase	5.20 10^{-15} (W m^{-2} kg_{H2O}^{-1} y)	0.08 (Lifetime at 12km, north hemisphere)	6.50 10^{-14} (W m^{-2} kg_{H2O}^{-1})	Water
Contrail cirrus***	9.36 10^{-13} (W m^{-2} km^{-1} y)	0.00057	1.64 10^{-9} (W m^{-2} km^{-1})	
Emission from shipping Air/low Air/unspecified Air/….	**Radiative forcing**	**Lifetime (years)**	**Specific forcing (W m^{-2} kg^{-1})** used in this work	
Aerosols SO2: Fuglestvedt et al (2010)	W m^{-2} kg_{SO2}^{-1}			
SO2 direct effect	-3.43 10^{-10}	0011		
SO2 indirect effect	-3.54 10^{-9} (citing Lauer et al 2007, inventory A)	0.011		
NOx :	W m^{-2} kg_{N}^{-1} y Fuglestvedt et al (2010) citing Fuglestvedt et al (2008)		W m^{-2} kg_{N}^{-1}	
Short-term O3 increase	7.19 10^{-12}	0.267	2.692 10^{-11}	
Long-term O3 decrease	-1.88 10^{-12}	10.2	-1.843 10^{-13}	
CH4 decrease	-7.56 10^{-12}	10.2	-7.412 10^{-13}	

*AR6 ch 6. indicates Lee et al 2021 as the best estimate of ERF from aviation

**Soot = BC and OC (Lee et al, 2021)

***Contrail cirrus : the value in Lee 2021, is in mW/m2/km. This unit is not correct, it should be mW/m2/(km/y). Demonstration from the GWP 100, 50, 20 values , using CO2 AGTPs (8.89526E-14; 5.1477E-14; 2.42365E-14). From the GWPs given by Lee, the iRFs (A/tau values) are in average 9.50096E-13. At 20 y, there is no more RF (contrails disappear), so iRF20=iRF50=iRF100. The specific ERF is thus 9.50096E-13/tau (0.00057 y).

Table 4. Updated values for the specific effective radiative forcing taken from IPCC AR6 ch 7. Chemical effects of CH_4 and N_2O are included in the radiative efficiency.

Species	Lifetime (Years)	Radiative Efficiency (W m^{-2} ppb^{-1})	GWP-20	GWP-100	GWP-500	GTP-50	GTP-100
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1.	1.000	1.000	1.000	1.000
CH_4-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8	13.2 ± 6.1	7.5 ± 2.9
CH_4-non fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8	10.4 ± 6.1	4.7 ± 2.9
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64	290 ± 140	233 ± 110
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2693 ± 842	771 ± 292	220 ± 87	181 ± 83	142 ± 51
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4144 ± 1160	1526 ± 577	436 ± 173	733 ± 410	306 ± 119
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8321 ± 2419	6226 ± 2297	2093 ± 865	6351 ± 2342	3536 ± 1511
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5301 ± 1395	7380 ± 2430	10,587 ± 3692	7660 ± 2464	9055 ± 3128

5. An example of application

An example of application is presented here to illustrate how the method can respond the question : Does the studied system respect the European requirements to reduce impacts from 2030 and to be climate-neutral in 2050 ? (European Commission, 2025)

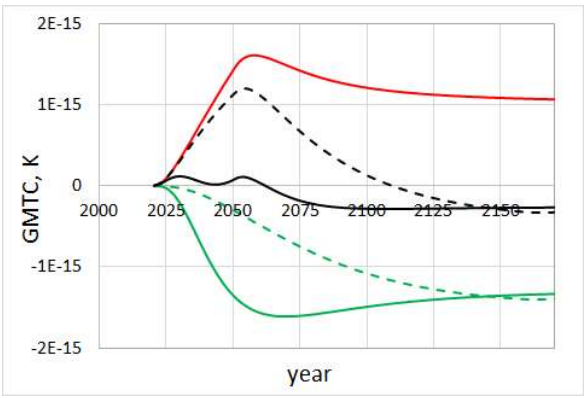
Additionally, it serves to respond the question: How to interpret the dynamic climate change results ?

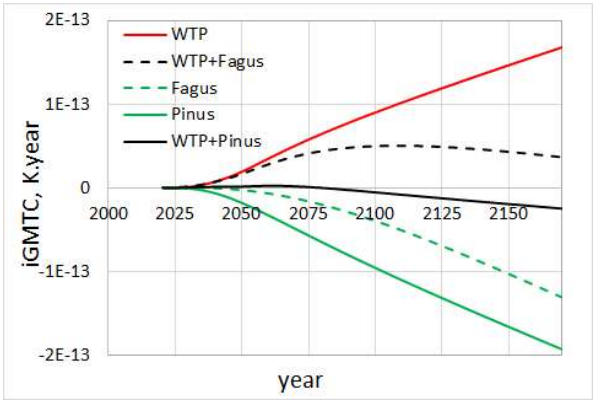
This example concerns a water treatment plant (WTP) for drinking water production by seawater desalting with reverse osmosis process. This technology, albeit its high performance and treatment potential, has the disadvantage of high electricity consumption. The afforestation is considered here as the solution for the mitigation of GHG emissions from WTP system and for achieving its climate neutrality. Details on the elaboration of this example are given elsewere (Tiruta-Barna, 2021).

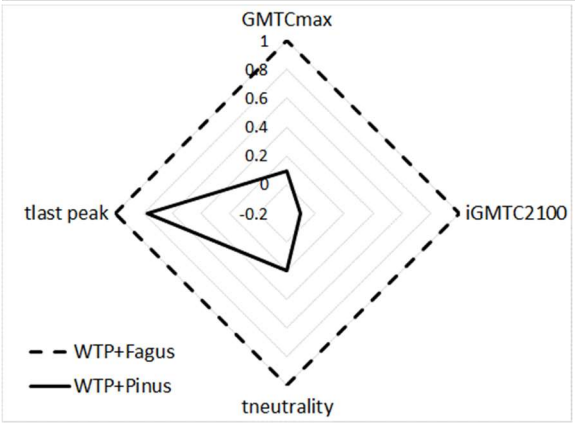
Conventional LCA. The LCA product system encompasses the WTP lifecycle (plant construction, functioning and dismantling) and the forest planting and management as natural ecosystem. The functional unit is the production of 1m^3 drinking water during 30 years, and starting in year 2020. Data sets already provided with ecoinvent 3.7 were used for WTP and forest. The "amount" of forest to be planted was calculated on the base of kg CO2 -eq LCA results in order to offset the WTP impact, i.e. to achieve neutrality as *zero kg CO2 -eq (GWP100)*. So, for the functional unit: WTP counts for 2.33 kg CO2 -eq and the forest system for -2.33 kg CO2-eq from which -2.341 kg CO2 -eq corresponds to CO2 captured and stored in biomass (a new forest) and +0.0081 kg CO2-eq corresponds to GHG emissions from forest management.

Dynamic LCA with dynamic climate change impact. 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).

The results are presented in figure 1. The spider diagram shows that WTP+Pinus afforestation is more performant that WTP+Fagus. Moreover, as shown in the top-left side chart, effective climate neutrality (defined as *zero temperature increase,* GMTC=0) could be achieved only after the neutrality goal 2050 (t_{goalN}), i.e. 12 and 59 years after WTP dismantling (year 2062 and year 2109), with Pinus and Fagus respectively. Despite the long term (theoretically infinity) convergence of the two systems towards zero GMTC, for the time scale of this century, undesired behavior is observed especially for WTP+Fagus system. The temporality of CO2 capture by Pinus is more adequate to the temporality of GHG emissions by WTP.







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 1. Results of the dynamic climate change impact method applied to the case study (for the signifacnce of parameters see the section below).

In the followings we propose a guide for how to interpret the results from the dynamic climate change approach.

6. A guide for interpreting the results

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. The impact indicators must be functions of time and adaptive with respect to the climate targets, and to respond to the need of adaptive mitigation.

The proposed climate impact indicators are based on the radiative forcing and on the global mean temperature change, and their integrated forms over the desired time horizons. The temperature is preferred to RF because: (i) the temperature is the measured physical parameter, and (ii) *the Paris Agreement focuses on temperature goals and its desired temporality*. However, care must be taken when using integrated metrics, because they give equal importance to climate impacts that occur at different points in time (the information about the peaks is lost).

The following aspects and rules could be considered when interpreting the results of dynamic LCA with dynamic climate change impact evaluation (adapted from Tiruta-Barna, 2021). The indicators are presented in Table 5. For all indicators, "smaller is better" is the ranking rule between the compared systems.

- three reference time points are proposed: (1) the time of temperature peak followed by temperature decline or stabilization in the short term (prior to 2050), t_{goalST}; (2) the time when climate neutrality

should be accomplished, t_{goalN}, for example, t_{goalN} = 2050; and (3) a time for an additional long-term target, t_{LT}, i.e. t_{LT} = 2100.

- The indicators need to discriminate between systems having the same global net emissions (commonly expressed in kg CO2-eq) but with different temporalities and consequently different climate effects (to avoid, for example, postponing GHG emissions beyond 2050, or accelerating the current warming).

- 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.).

- 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 tlast_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 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. GMTCmax 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.

Table 5. Proposed indicators for a multicriteria evaluation of climate change impact in dynamic LCA.

Category of impact & Parameter	**Indicator**	**Notation**
Radiative forcing		
"emission metrics"	Radiative forcing at a given moment	**RF**
	Integrated radiative forcing	**iRF**
Temperature		
Global mean temperature change (GMTC)	Temperature maximum peak registered	**$GMTC_{max}$**
	Paris Agreement - Climate neutrality Time of climate neutrality achievement when GMTC=0	$t_{GMTC=0}$
	-Deviation from the goal	**$t_{neutrality}$** = $t_{GMTC=0}$ - 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	**t_{last_peak}** = $t_{T\ starts\ decrease}$ - t_{goalST}
Heat		

Accumulated heat (iGMTC)	Integrated temperature change at long term, taken here as 2100	**$iGMTC_{LT}$** for t_{LT} = 2100

Appendix

Remarks on the modeling approach: Validation of the model for the SLCF

The validation could be performed by calculating the GWP20 and comparing with values provided by Lee et al 2021. However, the calculation involves a Dirac emission to be considered. In the numerical approach this takes the form of an emission of 1kg substance occurring in a given dt. The choice of dt is essential for a correct calculation. The time interval dt must be smaller than the characteristic time of the substance, tau τ. If not, the calculation occults the disappearance phenomena of the substance and the results are not relevant.

Besides, the case of NOx and CO (substances responsible of the ozone and methane modification) is specific. Their GWPs were calculated for a one-year constant emission (Fuglestvedt et al, 2010) and not for a Dirac. To be considered if a validation of the tool is foreseen.

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