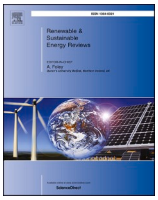
Renewable and Sustainable Energy Reviews 198 (2024) 114428

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Developing individual carbon footprint reduction pathways from carbon budgets: Examples with Wallonia and France

N. Paulus

Department of Electromechanics, Industrial Engineering Higher Education Institution of the Province of Liège (HEPL), Liège, Belgium

ARTICLE INFO

Keywords:
Carbon budget
Carbon footprint
Greenhouse gases
Territorial absorption
Nationally determined contributions
Imported emissions
Carbon uptake
Energy transition
Mitigation pathways
SDG
Climate action

ABSTRACT

Traditional climate strategies focus on long-term emissions targets, neglecting cumulative CO_2 emissions and often limiting their scope to territorial emissions. Additionally, individual citizens struggle to connect with community targets. This study addresses these issues by computing a comprehensive carbon footprint pathway that, as a main contribution, can be easily personalized and associated with common carbon footprint calculators. This approach innovatively leverages inverted "S-shaped" patterns based on logistic functions that, unlike common linear patterns, have been documented as relevant for diffusion mechanisms of social or ecological transformations. One challenge lies in efficiently aligning the carbon footprint figures, expressed in CO_{2eq}, with IPCC's +2 °C carbon budgets, expressed in CO_2-only. This work first retrieves the current share of CO_2-only footprint and then defines two mitigation pathways: one focusing solely on CO_2 emissions and one addressing residual GHGs. Except for initial and final emission levels, both targeted pathways are defined by the same logistic function, based on the assumed intrinsic link between CO_2 and the other GHGs. As final targets, the CO_2-only pathway considers the common net-zero emission goal while the second pathway considers a level of 1 tCO_{2eq}/year per capita of unmitigated non-CO_2 emissions, in alignment with IPCC's latest assumptions and anticipated population growth. Besides the new +2 °C compatible suggested pathways, developing this method for France and Wallonia has also revealed that they should reach territorial (nature-based) carbon uptake of at least three times their current levels, necessitating deep land-use changes in their policies (implementing intensive urban vegetation, alternative agriculture techniques, *etc*).

1. Introduction

In its Sixth Assessment Report (AR6), the IPCC has established a remaining carbon budget of 890 $GtCO_2$ for humanity to emit from January 1, 2020 to limit global warming to +2 °C compared to preindustrial levels, with a likelihood of 67 % [1]. Indeed, as shown in Fig. 1 (a), reported by the IPCC, it is common practice to express the likelihood of not exceeding a specific temperature threshold as a percentage. The IPCC also associates these thresholds with a corresponding cumulative carbon emissions limit, thereby introducing the notion of carbon budgets [2–4]. Fig. 1 actually depicts GHG emissions mitigation patterns as reported in several studies conducted by recognized organizations. Unlike the example given in Fig. 1(c), the patterns shown in Fig. 1(a) and (b) do not explicitly refer to the notion of carbon budgets. They are, however, associated with temperature thresholds, which are implicitly associated with carbon budgets as represented by the area enclosed by the GHG emissions mitigation curves.

Although carbon budgets are generally expressed in terms of CO_2-only emissions [2–4], it is not the only GHG. In fact, non-CO_2 contribution to global warming is usually related to short-lived climate pollutants (SLCPs), such as methane. As shown in Fig. 2, it is well established that, unlike CO_2, it is the annual rate of emissions, rather than the cumulative total, that has the strongest effect on peak warming [5]. Therefore, IPCC's reported remaining carbon budget includes an additional margin of safety to account for the impact of short-lived climate pollutants (SLCPs) like methane [6,7]. This necessitates the estimation of non-CO_2 GHG emissions at the point when global CO_2 emissions are projected to reach net-zero—an inevitability required to adhere to the (finite) carbon budget paradigm [8].

In the studies collected in IPCC's work, those estimations were performed by computing different non-CO_2 mitigation scenarios all consistent with a carbon neutral future (implied by the carbon budgets) [6]. This means that IPCC's CO_2 budgets (implicitly) infer that other non-CO_2 GHG should also be mitigated.

One acknowledged difficulty lies in allocating the carbon budget among countries [11]. For example, two well-known approaches are the "grandfathering" principle (which involves measures of "inertia") and

---

E-mail address: nicolas.paulus@hepl.be.

https://doi.org/10.1016/j.rser.2024.114428
Received 14 April 2023; Received in revised form 28 March 2024; Accepted 6 April 2024

Nomenclature

Abbreviations

AR6	Sixth Assessment Report (from IPCC)
GHG	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contribution
SLCP	Short-Lived Climate Pollutant

Notations

$Abs(y)$	Projected territorial carbon absorption level of the region/nation for the year y
b	Optimization parameter related to the maximum slope achieved by the “S-curve” GHG mitigation pathway
c	Optimization parameter related to the year for which the “S-curve” GHG mitigation pathway reaches its maximum slope (inflection point)
CF_f	Final yearly carbon footprint level target
CF_i	Initial level of yearly carbon footprint
$CF_{(\sim)CO_2f}$	Final yearly CO_2-only (or non-CO_2 GHG) footprint level target
$CF_{(\sim)CO_2i}$	Initial level of yearly CO_2-only (or non-CO_2 GHG) footprint
$CF_{(CO_2)}(y)$	Carbon (or CO_2-only) footprint level for the year y
$CF_{\sim CO_2}(y)$	Non-CO_2 GHG footprint level for the year y
$K1$	Regional/national individualized carbon footprint latest data
$K2$	Share of CO_2-only radiative forcing in the total radiative forcing (or, similarly, the current share of CO_2-only in the total GHG emissions)
$K3$	Unmitigable per capita non-CO_2 emissions according to IPCC’s AR6
$K4$	Regional/national territorial yearly carbon absorption latest available data
$K5$	Required yearly regional/national territorial carbon absorption to achieve GHG neutrality in 2050
$Pop(y)$	Projected population level of the region/nation for the year y
y	Year of focus for the yearly carbon footprint GHG pathways

Units

°C	Degree Celsius
(Gt)CO_2	(Gigatons of) carbon dioxide
(Gt)$CO_{2e(q)}$	(Gigatons of) carbon dioxide equivalent
ha	hectare
$MtCO_2$	Megatons of carbon dioxide
$MtCO_{2eq}$	Megatons of carbon dioxide equivalent
tC	Tons of carbon
tCO_{2eq}	Tons of carbon dioxide equivalent

the “equity” principle [12]. The “grandfathering” principle suggests allocating the carbon budget to countries proportionally to their current emission levels, whereas the “equity” principle advocates for allocation based on population levels, asserting that each human being has the same “right to pollute”. The “grandfathering” principle faces significant criticism, mainly because it favours “the perpetuation of an unjust allocation of rights based on the previous unjust allocation of the same rights” [13]. This suggests that historical emissions per capita have been sufficiently uneven among countries that they should not serve as a benchmark for subsequent carbon budget allocation. Consequently, when countries are considering carbon budgets in their climate strategies—as they should [14]—they usually adopt the “equity” principle. For instance, this is the case for France and Wallonia [7], one of the three regions of Belgium, which constitute the two case studies undertaken in this work.

Regrettably, like many others, these regions/nations have focused solely on mitigating emissions within their territories in their climate policies. However, a recent study indicated that if emissions associated with international trade are not as vigorously addressed as territorial emissions, the AR6 “equity” +2 °C carbon budget is likely to be exceeded [7]. It is worth mentioning that, at this point, only the +2 °C carbon budget compatible scenarios are considered realistic because IPCC’s AR6 has lately reported that “global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 would make it likely that such warming level will be exceeded during the 21st century” [1]. That same paper [7] has also identified other potential problems of most current NDCs, i.e. nationally determined contributions [17]. Firstly, commitments to long-term emission rates, such as the 2050 carbon neutral goal pledged by Wallonia and France [7], will not suffice to keep the cumulative CO_2 emission below IPCC’s “equity” carbon budgets [18]. Securing these budgets is likely unfeasible without establishing short-term carbon budget targets [19]. This is mainly due to the need for increasingly stringent—and potentially unrealistic—policies in the long-term [20], as suggested by Fig. 1(c).

Secondly, NDCs usually assume linear emissions mitigation pathways towards their long-term targets [7]. However, GHG mitigation has been known to face barriers and might be more accurately depicted by a decreasing “S-shaped” pathway [21], which can, for instance, be defined by a logistic function [22]. This pattern features a reduced slope in the beginning (important mitigation projects take years to be implemented and to be efficient) and in the end (further CO_2 emission reduction will be harder close to the carbon neutrality goal as the main mitigation projects will already be in place). Indeed, as observable in Fig. 1, those (inverted) “S-curves” or “S-shaped” patterns constitute the commonly represented GHG emissions pathways in the consulted studies, at least for the realistic scenarios aligned with the +2 °C carbon budget. Similar inverted “S-shaped” GHG mitigation patterns have also been reported as realistic scenarios in other studies [4,20,23–26], but none of those have explicitly defined or modelled their exhibited “S-shaped” mitigation pattern. Oppositely, this study seeks to offer such a model through a straightforward equation.

Furthermore, populations will hardly relate to territorial objectives, as they will rightly consider that those apply primarily to public authorities and private companies. Indeed, some kind of “whataboutism” sentiment [27] is likely to occur: “Why should I mitigate my emissions since my carbon footprint is only a small part of the national emissions?”. In fact, it is well established that solving the climate crisis relies on changing human behaviour [28]. To achieve this without insurmountable resistance, applied policies and economics must meet people where they are, with “audience-specific messaging and framing” [29], and individualized carbon footprint targets therefore seem relevant in that regard.

Another potential issue of common climate strategies comes from the fact that they may focus primarily on CO_2-only emissions, whereas it has been established, through the explanations of the carbon budget paradigm, that other GHG should also be (at least partially) mitigated. Similarly, targets should also be considered for territorial carbon absorption levels (natural and/or technological), which is currently not always the case in many Nationally Determined Contributions (NDCs).

The primary contribution of this study, as demonstrated through case studies in Wallonia and France, is the development of a documented method designed to address the common limitations of many current

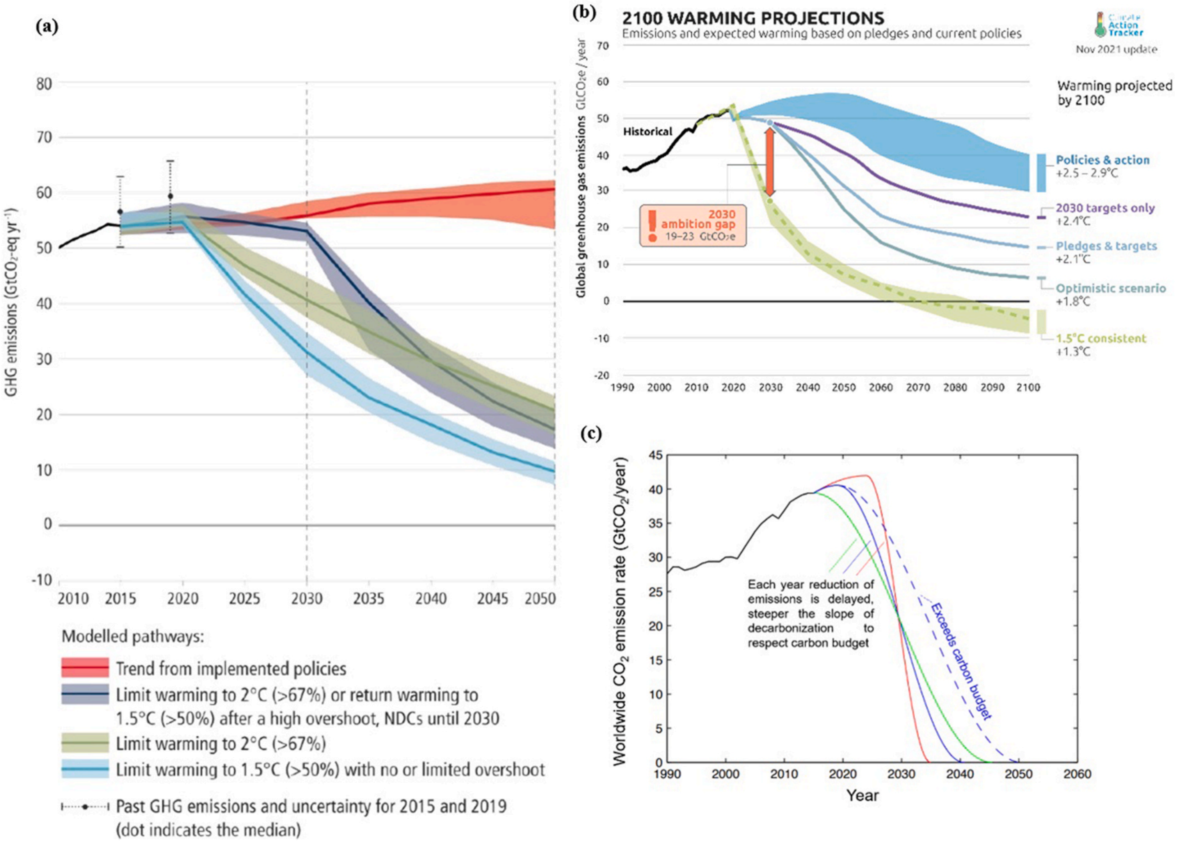


Fig. 1. Global GHG emissions scenarios depicted through inverted "S-curve" theoretical pathways: (a) Reproduced from IPCC's AR6 [1], (b) Reproduced from Carbon Action Tracker [9], (c) Reproduced and adapted from the Rare organization [10].

NDCs. It establishes personalized inverted "S-shaped" carbon footprint pathways that are directly aligned with IPCC's +2 °C "equity" carbon budget. This approach facilitates a deeper understanding among individuals regarding their role in climate action, enabling them to more effectively engage with and contribute to these efforts.

It is noteworthy that, besides the rationale behind carbon budget allocation (among countries), GHG emissions accounting methods can also be subject to debate, as this will affect how much of the established budget is spent year after year. A dedicated study [30] presented four main GHG accounting methods, i.e. the "production-based", the "consumption-based", the "extraction-based", and the "income-based" method. Each one of these methods involves some shortcomings and assigns the responsibility for the emissions to a particular type of agent (producer, consumer, extractor, or income beneficiary). Although that study [30] acknowledged that none of these methods (or their combination) is perfect, it reported that consumption-based accounting is generally considered "fairer" because it allocates a larger share of global emissions to industrialized regions/countries, such as the ones used as case studies in this work. Indeed, in such regions/nations, imported emissions can even be greater than territorial emissions [7], and consumption-based accounting methods are arguably better suited to address them. By suggesting GHG mitigation pathway targets expressed in terms of carbon footprint, this work also implicitly favours consumption-based accounting methods.

In essence, one main advantage of the conceived method is that it remains simple enough for the population to relate to. In addition, those proposed pathways have been designed to be adapted to different scales, even down to the simple household or the individual, for everyone to comprehend their part in the global emissions mitigation challenge. This has notably been made possible by linking the global IPCC's +2 °C "equity" carbon budget to individual targets, which can be implemented as a reference for carbon footprint calculators (which are consistently also based on consumption-based accounting methods [31]). Therefore, by (regularly) monitoring one's emissions and the outcomes of one's mitigation efforts through such calculators, it is hoped that each individual can set their own GHG reduction targets on both a short-term and a long-term basis. Although this work focuses on Wallonia and France, its applicability is wider, as it will be demonstrated that the suggested method to compute relevant GHG mitigation pathways is based on easily available data. Therefore, it can be readily adapted for most nations and/or regions.

It can be noted that this work mainly contributes to three Sustainable Development Goals (SDGs) [32] directly. Firstly, in addition to potentially facilitating individual and collective climate action (SDG13), establishing and monitoring individualized carbon footprint pathways through the method developed in this work naturally supports sustainable consumption (and production) patterns (SDG12) [33]. Furthermore, establishing and monitoring individualized carbon footprint pathways through the method developed in this work also aims at reducing inequalities (SDG10), in a manner akin to personal carbon allowances (PCAs) [34]. Another reason for this lies in the fact that carbon footprint accounting typically involves consumption-based accounting methods [31], which are usually viewed, as stated, as "fairer" than other accounting methods [30]. In addition, the suggested method to compute GHG mitigation pathways aligned with IPCC's work is grounded in the "equity" principle [12] (and "equity" carbon budgets, i.e. emphasizing the same "right to pollute" for each human).

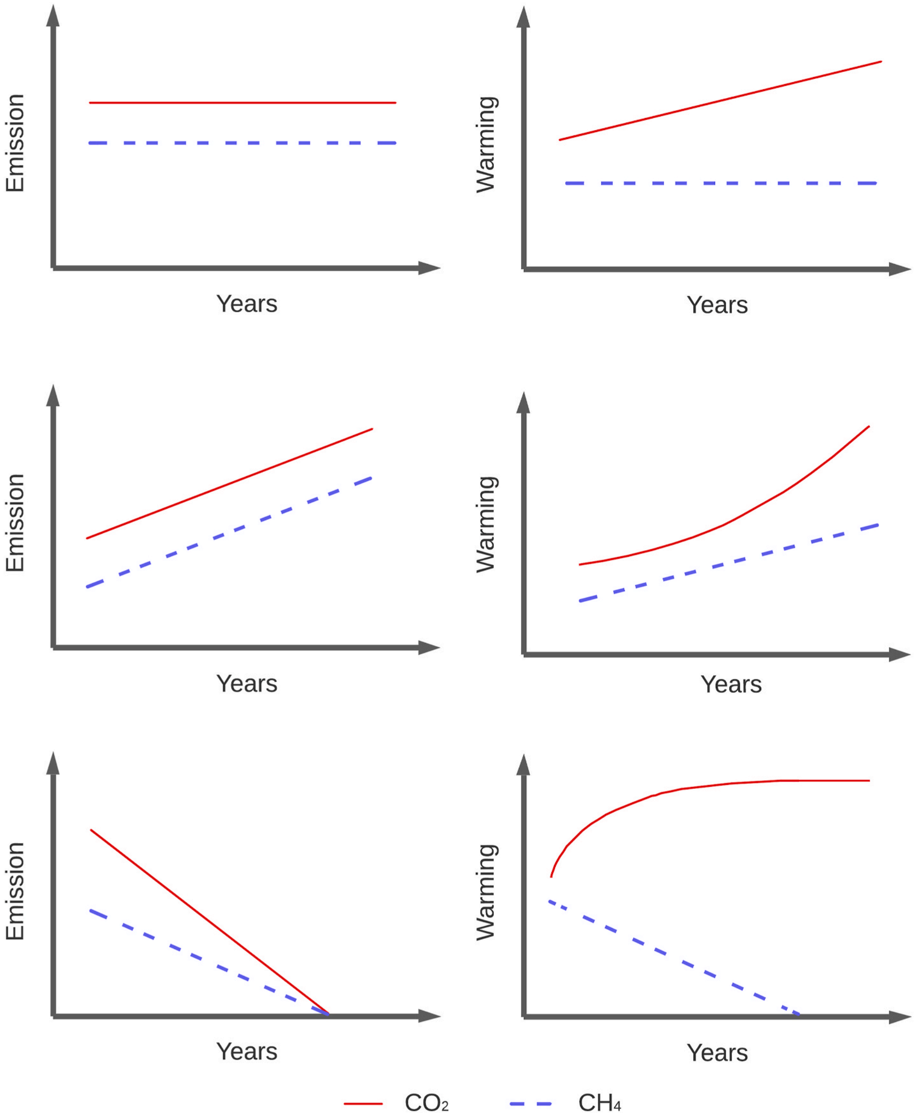


Fig. 2. Schematic illustration of how global mean temperatures respond to different emissions trends in carbon dioxide (CO_2) and methane (CH_4): (a) CO_2 and CH_4 emissions trends, (b) associated warming effects. The time-dependency of most non-CO_2 climate pollutants is therefore very different from the one of CO_2 as their annual rate rather than the cumulative emissions have the strongest effect on peak warming [5]. Adapted from several works [15,16].

2. Material and methods

2.1. *Mathematical function for inverted "S-shaped" carbon footprint pathways*

"S-curves" are used in this work because they are particularly relevant in cases of GHG emissions mitigation. Indeed, they have been particularly used for "ecological modelling" [22]. The same article [22] reports that "S-curves" are also used for "projecting the performance of technologies", "market penetration analyses", and "diffusion mechanisms of technological and social inventions", which are all also relevant to GHG emissions mitigation, because of their intrinsic link to the penetration of renewable technologies (both technologically and socially). For information, an "S-curve" can also be known as a "Verhulst-Pearl equation", a "Pearl curve", a "Growth curve", a "Gompertz curve", an "S-shaped pattern", a "Saturation curve", a "Foster's curve", a "Bass model", or as considered in this work, a "logistic curve" or a "sigmoid(al) function" [22].

Equation (1) is generally used to define a sigmoid (or a logistic) function between the [0,1] ordinate range [35]:

$$P(i) = \frac{1}{1 + e^{-(\alpha+\beta i)}} \tag{1}$$

i and *P(i)* are, respectively, the abscissa and the ordinate of the sigmoid function, i.e. the horizontal and vertical coordinates. Meanwhile, β and α are parameters that respectively control the slope, i.e. the rate [36], and the position on the horizontal axis of the "S-shaped" pattern, indicating the abscissa at which the curve deviates from a near-constant path to a more pronounced increase or decrease.

Decreasing (inverted) "S-shaped" functions necessitate the "inversion" of Equation (1). In addition, in carbon footprint yearly rate mitigation pathways applications, the range of the function shifts from [0,[0,1] to start at the current (initial) yearly carbon footprint (or GHG emissions) level, denoted as CF_i, and ends at the long-term (final) yearly carbon footprint (or GHG emissions) objective, denoted as CF_f. These manipulations result in Equation (2), wherein the α and β parameters have simply been renamed a and b, respectively. Additionally, the horizontal coordinate has been redefined as y to reflect the yearly discretization of the carbon footprint, with the carbon footprint yearly rate being represented by *CF(y)*.

$$CF(y) = CF_i - \frac{CF_i - CF_f}{1 + e^{-(a+by)}} \tag{2}$$

One last manipulation of the formula to make it more relevant for this application involves highlighting the year c $(= -ab^{-1})$ for which the ordinate achieves the “centre” of its scale. In other words, it is the moment at which the ordinate has reached 50 % of its range between its initial and final ordinate value [37], representing the year at which the “S-curve” reaches its maximum slope (i.e. the inflection point). This adjustment has been detailed in Equation (3):

$$CF(y) = CF_i - \frac{CF_i - CF_f}{1 + e^{-b(y-c)}} \tag{3}$$

However, this approach is not without its limitations. Indeed, “S-curves” GHG mitigation pathways, like all theoretical pathways, assume a relatively steady and predictable rate of adoption or progress. In reality, GHG mitigation efforts can be influenced by various unexpected external factors, such as economic conditions, political stability, policy changes, and health crises [38], making these models less effective at predicting sudden shifts or disruptions in GHG emission rates. Like other theoretical curves, “S-curves” are not particularly well-suited for modelling rebound effects in GHG emissions, which refer to situations where GHG reduction efforts in one area lead to unintended (sometimes even greater) increases in emissions in another [39]. At a regional or national scale, the GHG mitigation pathway involves multiple sectors, relying on the combination of several technologies and behavioural changes. Even though it can be considered that their respective diffusion and adoption rates could each be singularly modelled using an “S-curve”, their combined effect could diverge from this pattern. Technological breakthroughs associated with supporting policies could, for example, result in a curve exhibiting multiple inflection points (instead of only one, as in the defined logistic function). At the cost of increased complexity, a possible solution is to discretize the overall regional/national pathway into several logistic functions to better accommodate GHG mitigation effects featuring significantly different time constants.

2.2. *Linking IPCC’s “equity” carbon budgets to (individual) carbon footprint*

A major challenge lies in efficiently aligning the carbon footprint figures, expressed in CO_{2eq}, with IPCC’s carbon budgets, expressed in CO_2-only emissions, as well as with carbon absorption levels. Indeed, carbon sinks (with negative contributions) are not always considered in the common definitions of “carbon footprint” [40] and, to the knowledge of the author, are rarely, if ever, implemented in the available online carbon footprint individual calculators, which have already been highlighted as relevant tools for expressing personalized GHG emissions targets that are more accessible for individuals.

This section addresses the aforementioned challenge and presents a comprehensive flow chart in Fig. 3, detailing the method employed in this work to compute the appropriate individualized GHG mitigation pathways. The data underpinning the method depicted in Fig. 3 is further discussed in this section and summarized in Table 1, along with its application to the selected case studies.

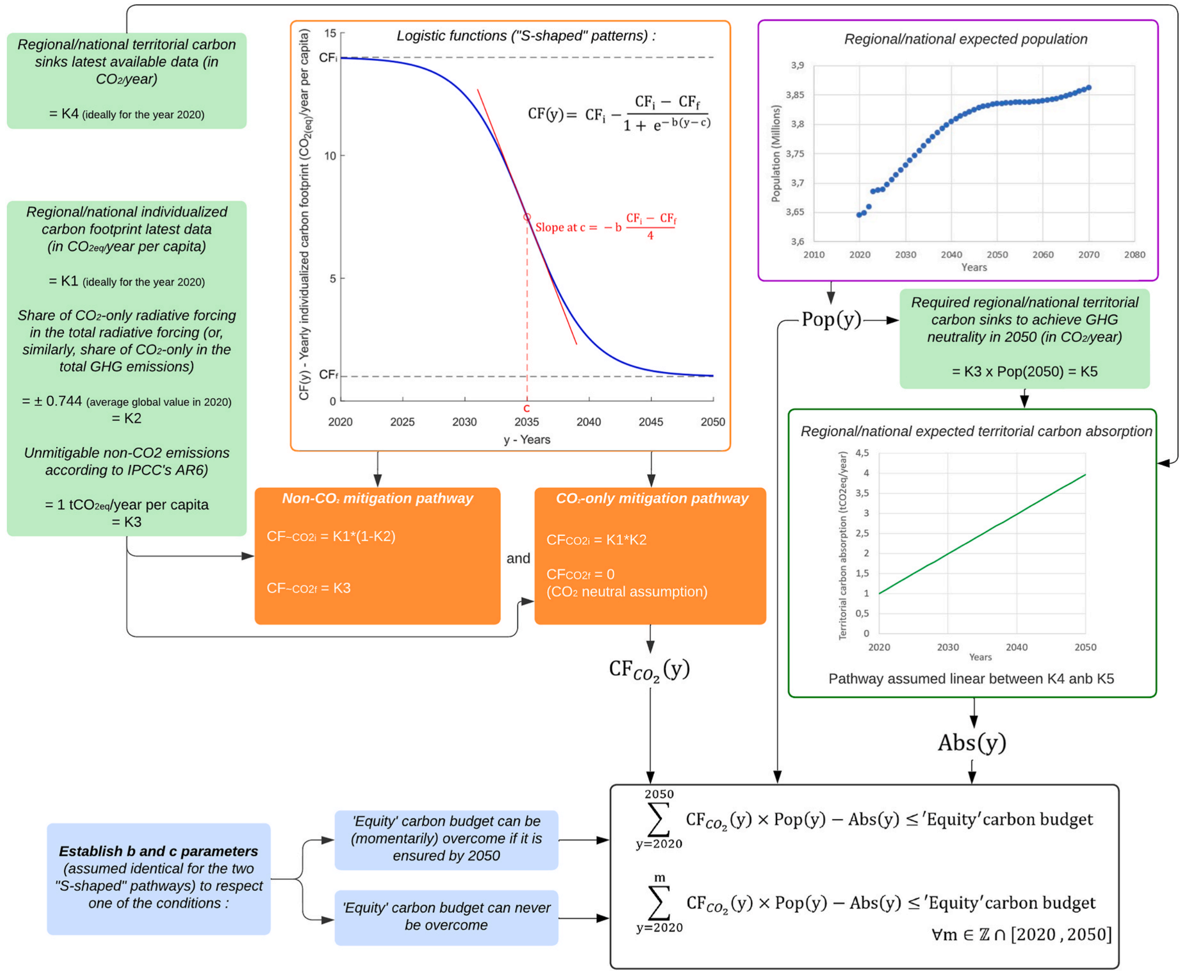


Fig. 3. Flow chart of the whole method used in this work to compute the appropriate individualized GHG mitigation pathways. This chart also demonstrates how individualized carbon footprint figures, expressed in CO_{2eq}, are linked with IPCC’s carbon budgets, expressed in CO_2-only, as well as with carbon absorption levels.

Table 1
Data used to compute the fixed parameters of Equation (3), i.e. the equation of the chosen "S-shaped" GHG mitigation patterns.

Data	Notation	Wallonia	France	Units	Reference/Justification
Initial 2020 + 2 °C "equity" carbon budget	"Equity" carbon budget	382.7	6924	$MtCO_2$	[7]
Individual carbon footprint latest available data	K1	16.0	9.2	tCO_{2eq}/year per capita	[44,45]
Share of CO_2-only radiative forcing in the total radiative forcing	K2	0.744	0.744	–	[46]
Initial individual CO_2-only footprint (in 2020)	$CF_{CO_{2i}}$	11.90	6.84	tCO_2/year per capita	=K1 × K2
Individual CO_2-only footprint target (in 2050)	$CF_{CO_{2f}}$	0	0	tCO_2/year per capita	Net-zero CO_2 emissions commitment in 2050 from the Green Deal [42]
Initial individual non-CO_2 footprint (in 2020)	$CF_{\sim CO_{2i}}$	4.10	2.36	tCO_{2eq}/year per capita	=K1 × (1-K2)
Individual non-CO_2-only footprint target (in 2050)	$CF_{\sim CO_{2f}}$	1	1	tCO_{2eq}/year per capita	Unmitigable GHG emissions at net-zero CO_2 emissions [1] divided by the expected 2050 global population level [43]. This is equal to K3.
Population in 2020	Pop2020	3.65	67.06	Millions	[47–49]
Projected population in 2050	Pop2050	3.83	69.21	Millions	[47–49]
Current level of territorial carbon absorption, considering LULUCF emissions (also established "per capita", according to the 2020 populations levels)	K4 (K4/Pop2020)	1.0 (0.27)	14.0 (0.21)	$MtCO_{2eq}$/year (tCO_{2eq}/year per capita)	[50,51] ("per capita" levels deduced according to Pop2020)
Required level of territorial carbon absorption, considering LULUCF emissions, to achieve GHG neutrality in 2050 (also established "per capita", according to the 2050 populations levels)	K4 (K5/Pop2050)	3.8 (1.0)	67.1 (1.0)	$MtCO_{2eq}$/year (tCO_{2eq}/year per capita)	$CF_{\sim CO_{2f}} \times$ Pop2050 + $CF_{CO_{2f}} \times$ Pop2050 (K3)

In essence, the method depicted in Fig. 3 entails separating the individual carbon footprint into two mitigation pathways: one focusing solely on CO_2-only emissions and one addressing residual GHG. Beyond the initial and final emission levels (discussed in this section and reported in Table 1), it is assumed that both targeted pathways are defined by the same logistic function. This assumption is rooted in the intrinsic link between CO_2 and other GHGs, which are commonly co-emitted during most combustion processes [41]. As final targets (also reported in Table 1), the CO_2-only pathway considers the common net-zero emission goal, while the second pathway considers a level of 1 tCO_{2eq}/year per capita of unmitigated non-CO_2 emissions, in alignment with IPCC's latest assumptions and population expected growth. Indeed, at the point of net-zero CO_2 emissions (projected for 2050 in the case studies chosen in this work, in line with the European Green Deal [42]), the IPCC has indicated that not all GHGs can be mitigated as effectively as CO_2, leaving an estimated 8 $GtCO_{2eq}$ yearly footprint for humanity [1]. Adhering to the "equity" principle and projecting a 2050 global population of 7.735 billion people [43], this equates to an individual unmitigated 2050 footprint of about 1 tCO_{2eq}/year per capita, attributable solely to non-CO_2 GHG pollutants.

The yearly individual CO_2-only footprint defined by the optimized sigmoidal pathway is then multiplied by the anticipated population. This total is subsequently deducted from the remaining "equity" carbon budget (established for the nations/regions used as case studies in this work in a recent study [7] and also reported in Table 1). The yearly territorial carbon absorption, which is assumed to increase linearly over time, is however added to the remaining CO_2 budget, as it effectively reduces the accumulated CO_2 in the atmosphere permanently.

Two cases of constraints are established. Firstly, the nominal one, depicted at the bottom of Fig. 3, ensures that the remaining CO_2 budget is never exceeded. Secondly, an auxiliary case has also been proposed, which permits the CO_2 budget to temporarily dip into negative values, provided it returns to positive values by 2050. This case can be considered the most precarious, as it tends to postpone the GHG mitigation efforts and requires a higher GHG reduction slope, as already illustrated in Fig. 1(c).

In respect to each one of these cases of carbon budget constraints, two optimization parameters must be established: the *c* and *b* parameters defined in Equation (3), respectively corresponding to the year of maximum emissions mitigation rate (i.e. the inflection point of the "S-shaped" mitigation pattern) and to the parameter influencing the maximum emissions mitigation rate (i.e. the slope of the "S-shaped pattern" at year *c*). The obtained values of these optimization parameters will be explored in the "Results and discussion" section, with insights provided in Table 2.

Table 2
Values of optimizing parameters *b* and *c* of Equation (3), which constitutes the equation of the chosen "S-shaped" GHG mitigation patterns that prevent the +2 °C "equity" carbon budget from being exceeded. Along with the fixed parameters reported in Table 1, these optimizing parameters lead to the GHG mitigation pathways illustrated in Fig. 6(a) for Wallonia and in Fig. 8 for France.

Description	Notation	Wallonia	France	Units
Year of maximum emissions mitigation rate, i.e. inflection point of the "S-shaped" mitigation pattern	*c*	2028	2036	–
Parameter influencing the maximum emissions mitigation rate, i.e. the slope of the "S-shaped pattern" at year c	*b*	0.3	0.25	–

2.2.1. *Warming impact time-dependency of non-CO_2 climate pollutants*

As mentioned, linking carbon budgets (expressed in CO_2-only) to all-GHG emissions and therefore to carbon footprint is not straightforward. Indeed, the impact of non-CO_2 species, which is, as stated, accounted for at the time of net-zero CO_2 emissions through "an absolute security margin" [7], constitutes the largest source of uncertainty in the remaining carbon budget [3]. The reasons for this can be elucidated by the following key factors. Firstly, each non-CO_2 GHG species has a specific warming impact with a distinct time-dependency [7], that is significantly different from the one of CO_2. Indeed, as already demonstrated in Fig. 2, for example, it is the annual rate—rather than the cumulative emissions—of short-lived climate pollutants (SLCPs), such as methane, that exerts the greatest influence on peak warming [5]. Consequently, establishing a non-CO_2 GHG budget by assimilating their specific time-dependent impacts on global warming, to be integrated with IPCC's CO_2-only carbon budget, presents considerable challenges.

This complexity is amplified by the high levels of uncertainty associated with future emission pathways for each non-CO_2 GHG species [1].

Secondly, some SLCPs, particularly anthropogenic aerosols co-emitted in fossil fuel combustions, exhibit a negative radiative forcing effect [52]. This cooling effect significantly counteracts (masks)masks) the current global warming impact of non-CO_2 pollutants [53]. In fact, non-CO_2 pollutants have been reported to presently account for about 50 % of current positive radiative forcing, and “thanks” to negative forcing aerosols, they only account for about 25 % of current net forcing [54]. Those negative forcing aerosols will decrease with necessary fossil fuel emissions reduction (and effective air quality policies), therefore unmasking some radiative forcing of remaining non-CO_2 pollutants [55]. This “unmasking” effect represents an additional difficulty in correlating all-GHG emissions with CO_2-only carbon budgets.

Nevertheless, as non-CO_2 GHG emissions must be mitigated alongside CO_2 to meet global warming targets [56], many studies still report that the radiative forcing (i.e. the net warming) induced by non-CO_2 species has been (and might likely be in the future) linearly proportional in time to the radiative forcing of CO_2 only [57–61]. All those references report the non-CO_2 net warming impact to be between 22 and 30 % of that of CO_2-only. This linearity between the contribution of CO_2 and non-CO_2 GHG has been illustrated in Fig. 4 [62], established by computing non-CO_2 GHG mitigation scenarios compatible with a +2 °C maximum temperature increase. In Fig. 4, the slope of the all-anthropogenic forcers assimilated straight line is 26 % higher than that of CO_2-only, consistent with the other studies.

It must be stressed again that this proportionality between CO_2-only and non-CO_2 radiative forcing through time is, however, valid as long as non-CO_2 pollutants are also mitigated in +2 °C compatible scenarios. This will more suitably be ensured thanks to specific structural policies (implemented by public authorities) rather than by relying on individual consumption choices. For example, agriculture constitutes the main source of nitrous oxide (N_2O) emissions [63], which qualifies as a non-CO_2 GHG with a global warming potential (GWP) over 100 years evaluated at 300 times that of CO_2 [64]. Subsequently, individuals should not be required to conduct intensive studies to consider the non-CO_2 GHG impact of the upstream processes involved in their specific consumption choices. Indeed, the only mitigation effort that can realistically (partially) rely on individuals is the commonly called “sobriety”, which involves the necessary reduction of their carbon footprint through an overall reduction of their consumption levels and/or energy use [65].

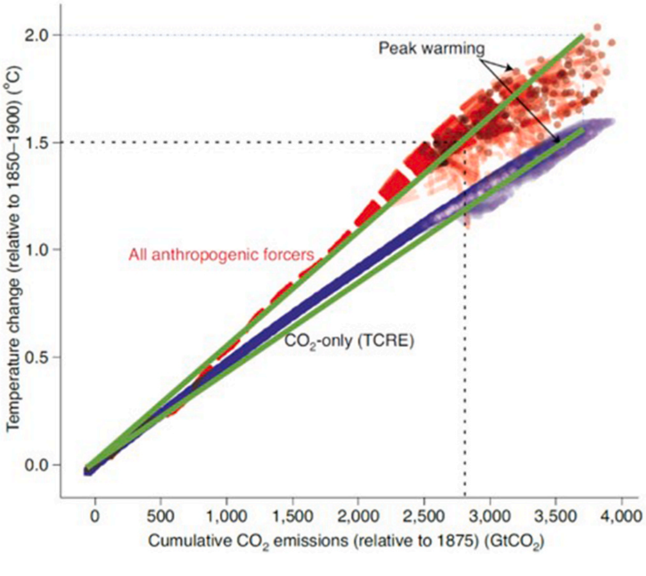


Fig. 4. Highlighted proportionality of the net warming impact of all-anthropogenic forcers and that of CO_2-only emissions. Dots represent multiple scenarios: they mark the peak warming and the lines end at the point of net-zero CO_2 emissions in each scenario. The larger spread of all-anthropogenic forcers (red) dots relative to CO_2-only (purple) dots is due to non-CO_2 emission scenarios that largely differ, which were all necessary to compute because of the great level of uncertainty in future non-CO_2 GHG emission pathways. TCRE means transient climate response (to cumulative emissions). It is widely used for climate change characterization and corresponds to the temperature change compared to preindustrial levels. Reproduced and adapted from Ref. [62].

Concurrently, based on global warming potential (GWP) over 100 years, it has been reported that non-CO_2 pollutants accounted for 25.6 % of the total GHG emissions in 2020 [46], which is a figure quite similar to that established for the proportionality between CO_2 and non-CO_2-forcing (deduced from Fig. 4). It could therefore be imagined that increasing IPCC’s “equity” carbon budget by that common figure (of about 26 %) and establishing an all-GHG budget (expressed in CO_{2eq} and based on GWP over 100 years) would allow for linking it to (individual) carbon footprint. However, in an expected net-zero CO_2 emissions future, the share of the non-CO_2 pollutants in the yearly total GHG emissions would no longer account for 25.6 % as it was in 2020 [46]. Since other GHGs will not be fully mitigated [66], they would trivially represent all the GHG emissions (and thus a 100 % share). As stated, because of cumulative emissions of long-lived CO_2, only the contribution of non-CO_2 GHG in the total radiative forcing may be considered constant over time (and between 22 and 30 % of that of CO_2-only [57–61]). Therefore, all-GHG budgets have no longer been considered in this study.

It is nevertheless worth mentioning that conducting such a method with all-GHG budgets is still possible. To that end, some studies indeed report methods that evaluate the future radiative forcing of all the GHG based on their year of emission, usually through GWP alternatives metrics, denoted “GWP*” [16,67–70] or $CO_{2\text{-fe}}$, i.e. CO_2-forcing-equivalent [58]. Unfortunately, even in their simplest forms, those methods would greatly complexify the accounting of carbon footprints. Those methods are indeed not yet compatible with available online carbon footprint calculators, which have already been inferred as relevant tools to express personalized GHG emissions targets that individuals can better relate to.

2.2.2. *Initial individual carbon footprint of the studied regions/nations*

Unfortunately, there is a lack of recent studies on Wallonia’s carbon footprint. This study has considered that its individual 2020 carbon footprint is equal to the 2007 average one of Belgium [7], amounting to 16 tCO_{2eq}/year per capita [44], as reported in Table 1. By comparison, The Belgian carbon footprint was evaluated by another study atat 16.5 tCO_{2eq}/year per capita back in 2001 [71]. It should be noted that, recently, a new study has evaluated Wallonia’s carbon footprint slightly lower, specifically at 15 tCO_{2eq}/year per capita in 2011 [72], but this has no impact on the statements made in this work. Since Belgium’s carbon footprint (or, by extension, Wallonia’s carbon footprint) has not significantly decreased in ten years (between 2001 and 2011) [7], there is no tangible reason to think that Wallonia’s 2020 carbon footprint is significantly lower than the 2007 value considered in this study.

From 1995 to 2018, the figure for the French individual carbon footprint has been reported to remain quite constant and around 11 tCO_{2eq}/year per capita [7]. However, the methodology has been very recently revised (especially regarding how imported CH_4 emissions are accounted for), resulting in a slight decrease in the French individual carbon footprint [50]. The 2020 French carbon footprint projection has therefore been established to 8.2 tCO_{2eq}/year per capita, but it is only a provisional unverified estimate [50]. In addition, that particularly low figure considers the COVID-19 (temporary) public health crisis impact on carbon (and other pollutant) emissions, which was significant in the case of France with about two months of complete lockdown [38]. Therefore, this work will consider the last verified calculation of the

French carbon footprint, which has been evaluated atat 9.2 tCO_{2eq}/year per capita for the year 2018 [45], as reported in Table 1.

2.2.3. *Initial and final values of the CO_2-only mitigation pathway*

As stated, it has been decided to retain IPCC's CO_2-only carbon budget and establish, in parallel, the CO_2-only footprint (and the non-CO_2 footprint) from the all-GHG carbon footprint. For example, the 2020 CO_2-only carbon footprint level can be determined by subtracting the already stated share of worldwide non-CO_2 emissions in 2020 from all-GHG emissions, i.e. 25.6 % [46], as reported in Table 1.

As mentioned, this study assumes a completely decarbonized economy by 2050, the target year of the European Green Deal [42]. Therefore, the final CO_2-only carbon footprint is projected to be 0 in 2050, as reported in Table 1. It is worth noting that the European Green Deal unfortunately only commits to a 2050 territorial carbon neutral future, but in this study, it will be assumed that the European Union will (hopefully) adopt trading policies compelling imported emissions to also achieve carbon neutrality by 2050. This could be feasible if European countries opt to import exclusively from other countries that have also committed to a 2050 territorial carbon neutral future (such as Canada, the United States, or New Zealand) [73].

2.2.4. *Population expected growth in the studied regions/nations*

The historical and projected population growth in Wallonia and France used as input data (as depicted in Fig. 3) have respectively been illustrated in Fig. 5(a) and (b). Demographic assumptions up to 2050 are quite similar. Notably, after 2050, Wallonia's population is projected to continue increasing whereas France's population is expected to decrease, according to their respective national institutes responsible for demographic projections.

2.2.5. *Negative emissions accounting (carbon sinks/absorption)*

Remaining carbon budgets, as reported by the IPCC, inherently consider territorial sinks (carbon absorption) because they are based on cumulative net CO_2 emissions [62]. Therefore, one could have directly established the mitigation pathways of the carbon footprint based on land-use, land-use change, and forestry (LULUCF [75]) related net CO_2 emissions. Indeed, they constitute commonly available data since the adoption of the Kyoto Protocol by the parties of the United Nations Framework Convention on Climate Change (UNFCCC) [76]. However, as depicted in the methodology flowchart presented in Fig. 3, this study considers separately the positive CO_2 emissions through carbon footprint accounting and the ones of territorial sinks (negative).

Furthermore, the separated accounting of carbon sinks enables detailed investigations into the current and future territorial carbon absorption levels of the studied regions/nations, thus aiding in the formulation of pertinent targets within climate policies. It is noteworthy that it is still often reported that carbon sink accounting methods should include LULUCF emissions data [77], as defined since the adoption of the Kyoto Protocol [76].

2.2.6. *Territorial absorption pathway*

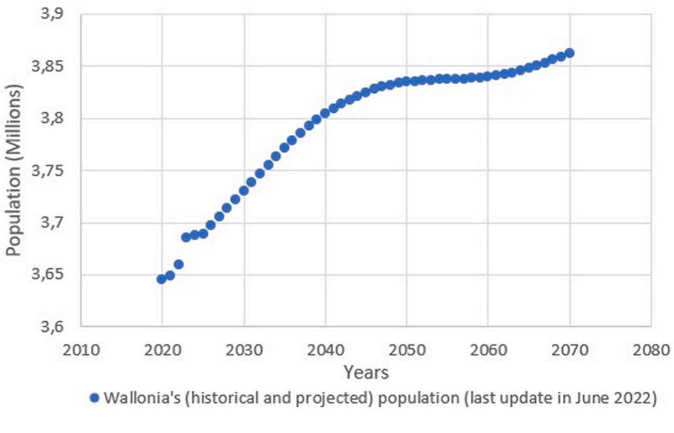
As noted, yearly territorial absorption is modelled with a linear pathway from the initial 2020 value to the 2050 final value. This latter has been stated to be equal to 1 tCO_{2eq}/year per capita, in line with the GHG-neutral European Green Deal commitment [42], to match the previously mentioned unmitigated non-CO_2 GHG footprint in a net-zero CO_2 emissions future [1].

Besides carbon capture and storage, i.e. CCS [82], which is applied at the exhaust of high-carbon emission processes, territorial absorption mainly consists of carbon dioxide removal (CDR) techniques [78], which can be either nature-based [79] or technological [80]. CO_2 is indeed inherently the main GHG targeted by both natural, through photosynthesis, and technological CDR techniques, such as direct air capture, i.e. DAC [81]. Hence, carbon absorption pathways can be expressed equivalently in terms of CO_2-only negative emissions or in terms of CO_{2eq} negative emissions.

However, those latter negative emissions technologies raise questions, mainly because of their immaturity and their scaling-up capabilities, and they are often deemed to constitute an "unjust gamble against the future" [83]. Indeed, it has been recently reported that more than 80 % of technological carbon absorption projects fail [84]. Facing the challenge of global warming, it has thus been advised for climate policies to rely on negative emissions only if they are sufficiently mature [7] and present lower risks, such as those associated with nature-based carbon sinks. Therefore, an assessment of these technologies is necessary for the regions/nations examined in this work.

2.2.7. *Nature-based carbon sinks of the studied regions/nations*

The current level of Wallonia's territorial carbon sinks has been reported to be about 1 $MtCO_2$/year [7], a figure considered in this work in Table 1. Another source reports about 1.8 $MtCO_2$/year [85]. Given Wallonia's future population shown in Fig. 1(a), the 2050 absorption level should reach about 4 $MtCO_{2eq}$/year for GHG neutrality. Therefore, Wallonia's carbon yearly uptake needs to be increased by about 3 $MtCO_{2eq}$/year (+300 %). Although very challenging, especially considering only natural sinks, this does not seem unrealistic for the following reasons. Firstly, it has been reported that agroecological methods that rebuild organic components in soil, such as permaculture, can increase carbon uptake to 8.23 tCO_{2eq}/ha per year [86]. This can be compared to the average European harvested crop absorbing 1.96 tC/ha per year [87], equivalent to 7.2 tCO_{2eq}/ha per year [88]. Both zero-tillage agriculture and the conversion to permanent crops or perennial grasses have also been reported to increase carbon



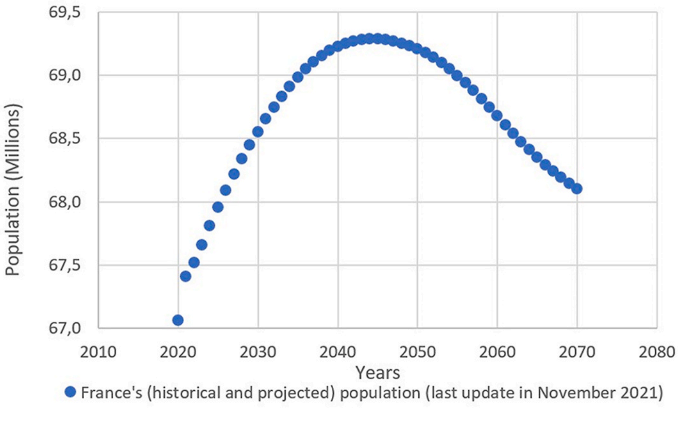


Fig. 5. Historical and projected population for the regions/nations used as case studies in this work: (a) Wallonia [49], (b) France [47,48]. Unlike Wallonia, France's population data do not take into account immigrants due to the Ukraine-Russia conflict that started in 2022 [74].

sequestration. Specifically, increases of up to 1.47 tCO_{2eq}/ha per year and 2.2 tCO_{2eq}/ha have been noted, respectively [89]. Another study confirms these figures, reporting that improved grazing management, introduction of legumes and improved grass species, irrigation, and conversion of croplands into pasture lands can increase soil carbon sequestration by more than 1 tC/ha per year [90], which is equivalent to 3.67 tCO_{2eq}/ha per year [88]. Given the 762 120 ha devoted to agriculture in Wallonia [91], and assuming an average increase of carbon sequestration of 1 tCO_{2eq}/ha per year through alternative agricultural techniques, territorial absorption of agriculture lands could be increased by about 0.76 $MtCO_2$/year.

Secondly, lawns and green roofs have been reported to exhibit minimum carbon uptakes of 2.7 tCO_{2eq}/ha per year, with green roofs potentially reaching up to 10.2 tCO_{2eq}/ha per year [92]. Given the 225 900 ha of urbanized lands in Wallonia (residential lawns not considered) [93], and with an average increase of carbon sequestration of 5 tCO_{2eq}/ha per year through intensive urban vegetation, territorial absorption could again be increased by approximately 1.95 $MtCO_2$/year. In addition, private lawns can also significantly absorb more carbon, since their carbon uptake has been reported toto range from 3 to 11 tCO_{2eq}/ha per year [94].

This demonstrates that the implementation of alternative agriculture techniques and intensive urban vegetation (potentially with deeper revegetation of private laws) may significantly increase the current territorial absorption of Wallonia. However, achieving the targeted absorption level of 4 $MtCO_{2eq}$/year, necessary to balance the unmitigated non-CO_2 GHG emissions rate in a net-zero CO_2 emissions future [1], would require nearly every territorial area to be optimized to maximize carbon absorption, depending on the chosen land-use. It is worth mentioning that positive carbon sequestration feedbacks with global warming have not been considered, such as increased wildfire risks [95] or the potential reduction of carbon uptake through vegetation increased respiration [96].

It should also be pointed out that Wallonia has only planned a +32 % increase of nature-based carbon sinks in its current NDC (versus current levels) [97], falling short of the +300 % objective discussed herein. Thus, even if Wallonia states that the lack of nature-based carbon sinks will be compensated with potential technological carbon absorption methods to ensure carbon neutrality [51], the commitment to natural sinks is extremely low, placing Wallonia's climate strategy at risk due to reliance on unproven technologies.

Unlike Wallonia, France has implemented a territorial absorption objective pathway up to 2050 in its climate strategy [7]. It assumes a linear increase from the current level to a 2050 target of 80 $MtCO_{2eq}$/year [7], involving 67 $MtCO_{2eq}$/year from nature-based carbon sinks [50]. The current level of absorption considered in France's current climate strategy is 38 $MtCO_{2eq}$/year, but it has recently been calculated to be 63 % lower, to 14 $MtCO_{2eq}$/year [50]. In terms of area, this carbon uptake level is similar to Wallonia's (considered equal to 1 $MtCO_{2eq}$/year), albeit slightly lower. Therefore, this initial carbon uptake figure of 14 $MtCO_{2eq}$/year has been considered for France in this work along with the 2050 target of 67 $MtCO_{2eq}$/year of nature-based carbon sinks, as reported in Table 1. Technological carbon sinks are again considered immature; therefore, the full 80 $MtCO_{2eq}$/year absorption level reported in France's climate strategy is not considered.

This implies a required increase in territorial carbon uptake of +370 % from current levels, likely leading a recent study [50] to view the 2050 target of 67 $MtCO_{2eq}$/year for nature-based carbon sinks as unrealistic. However, the same reference [50] also indicates a historical level of nature-based carbon uptake of nearly 50 $MtCO_{2eq}$/year in 2005, which already represented 75 % of the final 2050 target considered in this work. The carbon absorption target is thus not unrealistic, although still very challenging.

In addition, comparing areas with Wallonia, this figure of 67 $MtCO_{2eq}$/year of French nature-based carbon sinks in 2050 is quite similar to the 4 $MtCO_{2eq}$/year of carbon uptake assumed for Wallonia in 2050, demonstrated to be feasible with alternative agricultural techniques and intensive urban vegetation (although, again, challenging). Also, considering France's 2050 projected population presented in Fig. 5 (b), this 67 $MtCO_{2eq}$/year target level of absorption coincides with the absorption target of 1 tCO_{2eq}/year per capita implied by the Green Deal [42] to match the "equity" unmitigated non-CO_2 GHG footprint in a net-zero CO_2 emissions future [1].

It is often considered that the 2050 individual carbon footprint should be capped between 1 and 2 tCO_{2eq}/year per capita [98]. For instance, a target of 2 tCO_{2eq}/year per capita is commonly adopted by online carbon footprint calculators [99]. However, the analysis conducted in this study underscores that, to achieve GHG neutrality in regions/nations like France and Wallonia, it is preferable to reduce the individual carbon footprint target to approximately 1 tCO_{2eq}/year per capita. Attaining such a threshold with the capacities of the nature-based carbon sinks (of the studied regions/nations) will indeed be sufficiently challenging as it is (to ensure GHG neutrality).

3. Results and discussion

As depicted in the flowchart in Fig. 3, two cases have been proposed. Firstly, the nominal one never allows for the remaining CO_2 budget to be exceeded. Secondly, an auxiliary case has also been computed, which allows for the CO_2 budget to slightly go into negative values, as long as it returns to positive values by 2050.

Both of these cases have been illustrated for Wallonia in Fig. 6 (and in the associated Fig. 7). Only the nominal case has been computed for France and is represented in Fig. 8. The optimization parameters *b* and *c* of Equation (3) used to compute the nominal case for Wallonia and for France, respectively depicted in Fig. 6(a) and in Fig. 8, have been reported in Table 2.

Figs. 6 and 8 show the all-GHG individual carbon footprint pathways (in CO_{2eq}/year per capita) and the corresponding (decreasing) remaining carbon budget over time. It can be perceived from those figures that it would be quite straightforward for individuals who use carbon footprint calculators to report their results on the suggested individual carbon footprint target pathways, therefore better relating to IPCC's carbon budget.

All proposed cases are securing the "equity" carbon budget because the latter is positive in 2050 (the end of the end of the studied timeframe). It is worth mentioning that Figs. 6 and 8 also show the non-CO_2 GHG footprint mitigation, which is as intended defined by an "S-shaped" pattern similar to that of the all-GHG individual carbon footprint pathways, using the same *b* and *c* parameters in the logistic function of Equation (3), as reported in Table 2. The 2050 CO_2 neutral target can be verified by the fact that both patterns converge in 2050, reaching a value of 1 tCO_{2eq}/year per capita, corresponding to the unmitigable non-CO_2 GHG emissions deduced from IPCC's AR6 [1].

Fig. 7 shows the GHG positive and negative emissions patterns corresponding to the cases illustrated in Fig. 6 at the regional scale, for the entirety of Wallonia. Positive GHG emissions are obtained from the product of the all-GHG individual carbon footprint pathways and the population projections reported in Fig. 5(a). Negative emissions correspond to the territorial carbon absorption pattern, which is presumed to evolve linearly from the current level to the target value. As explained, this target value is set to achieve full climate neutrality by 2050, compensating for the 1 tCO_{2eq}/year per capita unmitigable non-CO_2 emissions as inferred by IPCC's AR6 [1]. As demonstrated in Fig. 6, this carbon absorption target is calculated by multiplying that 1 tCO_{2eq}/year per capita figure by the 2050 projected population of the region, as indicated for Wallonia from Fig. 5(a). It should be mentioned that, even though the proposed scenarios are compatible with IPCC's +2 °C carbon budget, it is still advised for climate policies to target even more aggressive GHG mitigation pathways to provide a margin regarding the carbon budget.

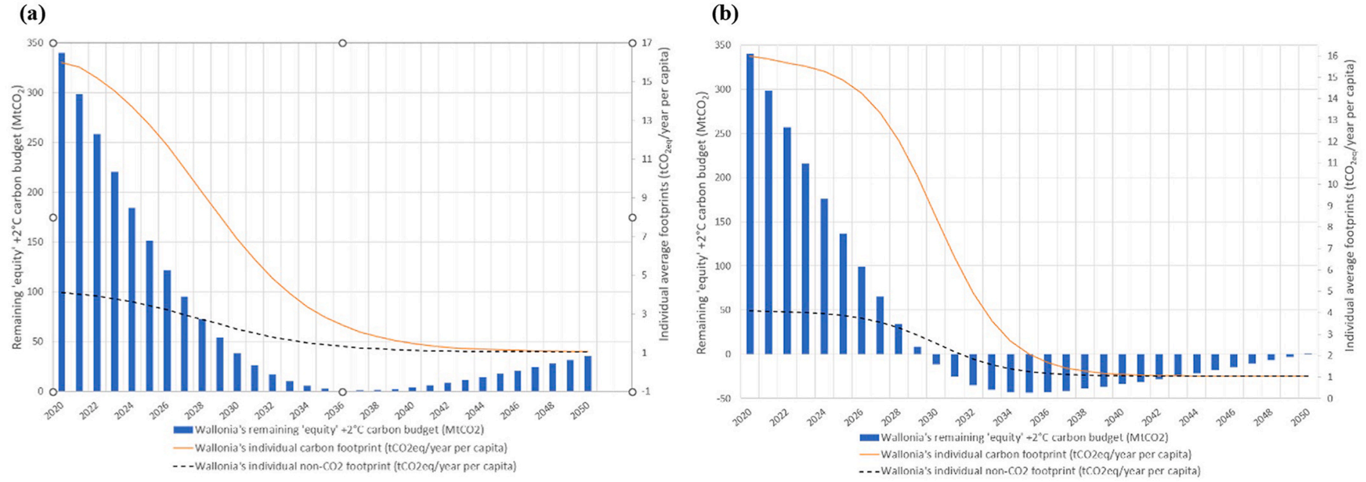


Fig. 6. Two cases of proposed sigmoidal GHG mitigation pathways for Wallonia and the corresponding remaining carbon budget over time: (a) Safer case with the carbon budget never exceeded and early GHG mitigation starting in 2020, allowing for a gentler slope of the mitigation effort, (b) Riskier case where the carbon budget is (slightly) exceeded, due to delayed GHG mitigation, leading to a relatively steep slope of the mitigation effort.

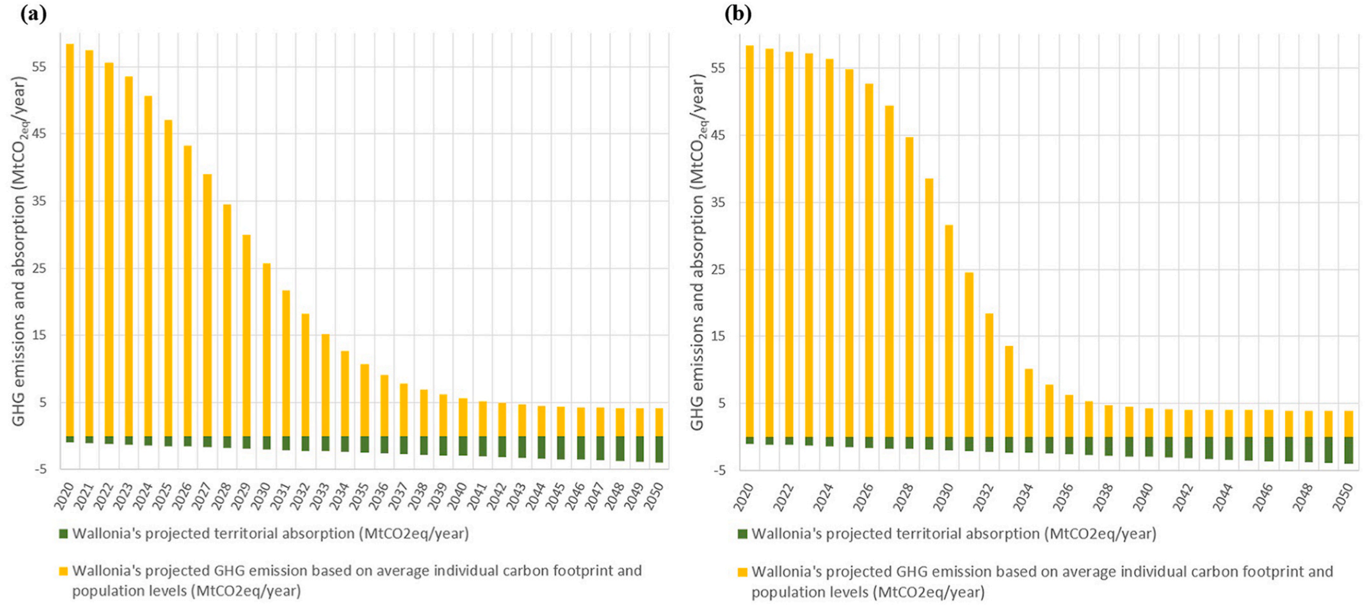


Fig. 7. Resulting yearly GHG emissions and territorial absorption of the two cases proposed in Fig. 6: (a) Safer case with the carbon budget never exceeded and early GHG mitigation starting in 2020, allowing for a gentler slope of the mitigation effort, (b) Riskier case where the carbon budget is (slightly) exceeded, due to delayed GHG mitigation, leading to a relatively steep slope of the mitigation effort.

3.1. Nominal case for Wallonia - CO_2 budget never exceeded

This case is presented in Figs. 6(a) and 7(a). The *b* (slope) parameter has been set to 0.3, and the *c* parameter has been set to 2028, as reported in Table 2. As it can be observed in Fig. 6(a), this case implies that carbon neutrality will nearly be achieved by 2040, i.e. ten years before the Green Deal commitment [42], for the "equity" carbon budget never to be exceeded. This is the "safest" case of the two, offering a carbon budget margin in 2050. It also entails earlier GHG mitigation efforts beginning as early as 2020, with the resulting benefits in terms of accumulated CO_2 avoided, allowing for a less steep mitigation effort slope.

According to Table 3, the maximum slope of the mitigation effort in the resulting CO_2-only pathway is projected to be close to 0.89 tCO_2/year per capita (in 2028), while for the non-CO_2 pathway, it is expected to be around 0.23 tCO_{2eq}/year per capita (also in 2028). It is noteworthy that, by derivation of Equation (3), the maximum slope of the sigmoidal pathways is linearly dependent on the *b* parameter and on the initial individual carbon footprint level (as demonstrated in Fig. 3).

3.2. Riskier case for Wallonia - CO_2 budget just positive in 2050

This case is presented in Figs. 6(b) and 7(b). The *b* (slope) parameter has been set to 0.52 while the *c* parameter has been set to 2030, as reported in Table 2. As observed in Fig. 6(b), this case implies that carbon neutrality will be nearly achieved by 2038, i.e. twelve years before the Green Deal commitment [42], enabling the "equity" carbon budget to return to positive values in 2050.

This case is risky as it inevitably relies on negative emissions (which can be ethically contentious [83]) for the carbon budget to return to positive values, but also because of the very steep mitigation effort that would have to be performed due to delayed GHG reduction. A delayed

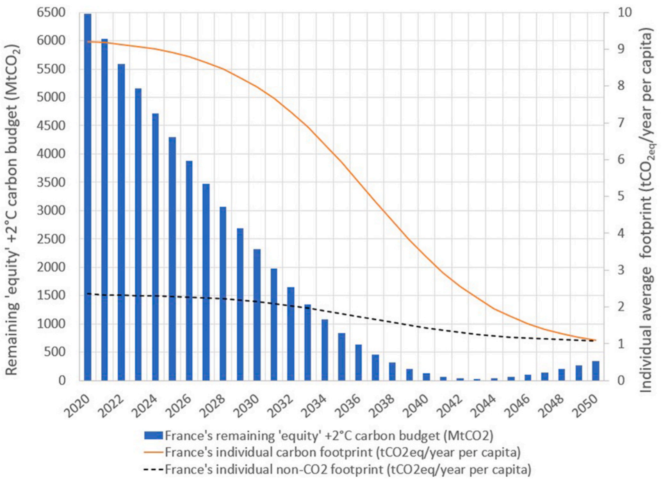


Fig. 8. Example of sigmoidal GHG mitigation pathways for France and the corresponding remaining carbon budget (nominal case, with the carbon budget never allowed to be exceeded).

Table 3
Maximum slope of the GHG mitigation pathways illustrated in Fig. 6(a) for Wallonia and Fig. 8 for France, as defined by Equation (3) and based on the parameters provided in Tables 1 and 2.

Description	Notation	Wallonia	France	Units
Maximum CO_2-only emissions mitigation rate	Slope at *c*	−0.89	−0.43	tCO_2/year per capita
Maximum non-CO_2 emissions mitigation rate	Slope at *c*	−0.23	−0.08	tCO_{2eq}/year per capita

mitigation of only two years (represented by the *c* parameter) compared to the nominal case actually requires significantly steeper GHG mitigation pathways, as depicted by Fig. 1(c). Indeed, the slope needs to be about twice as steep as that of the nominal case, as reflected by the *b* parameter being twice as large. In addition, carbon neutrality needs to be achieved approximately two years earlier than in the nominal case.

3.3. Nominal case for France - CO_2 budget never exceeded

Similarly to Fig. 6(a), the nominal case for which the +2 °C "equity" carbon budget has been computed and illustrated in Fig. 8. Since the initial individual carbon footprint in France is roughly half of what was assumed for Wallonia, the necessity for early GHG mitigation is therefore less pronounced. Therefore, as indicated in Table 2, the year of maximum mitigation rate, i.e. *c* parameter of Equation (3), has been set to 2036 whereas the slope parameter, i.e. *b* parameter of Equation (3), has been set to 0.25. As outlined in Table 3, this results in maximum slopes of the mitigation pathways being at least half as steep as in Wallonia's nominal case.

The exploration of a second (riskier) case for France is considered less relevant. Indeed, delaying GHG mitigation (and allowing the "equity" carbon budget to temporarily dip into negative values), would necessitate once again a steeper GHG mitigation rate, echoing the scenario observed in Wallonia's case. However, it is still worth mentioning that, in line with Wallonia's findings, the slope of the GHG-decreasing emissions would also need to be about twice as steep, necessitating a nearly doubled *b* parameter in Equation (3).

3.4. Uncertainties

As it can be deduced from the flow chart summarizing the methodology used in this work (reported in Fig. 3), there are as many sources of uncertainties as data or projections that have been retrieved and incorporated into the method. First and foremost, it is crucial to emphasize that IPCC's +2 °C carbon budget (used as a reference in this work) is not an absolute prediction but rather indicates a likelihood, and it is furthermore reported with an inherent uncertainty of approximately ±30 % [1]. Fortunately, the effect of non-CO_2 GHG emissions, including the uncertainty linked with the time-dependency of their warming impacts (as illustrated in Fig. 2), is already accounted for in the carbon budget's overall uncertainty [1,7]. Similarly, the unmitigable non-CO_2 emissions are estimated in IPCC's AR6 with an uncertainty of ±37.5 % [1].

Likewise, current territorial carbon absorption levels are not yet well studied and are associated with high levels of uncertainty. For example, only two of such figures have been identified (and reported in this work) for Wallonia in the last 25 years, and they exhibit a ratio close to two (±30 % around the average) [51,85]. As another illustrative example, it has been reported that a recent estimation, conducted in 2022, revised the territorial carbon absorption level in France to be 67 % lower than the previously accepted value [50]. It is noteworthy that the IPCC has updated its guidelines for evaluating carbon absorption methods in 2019, which EU members are expected to adopt in their practices for the period following 2023 [50].

As explained, carbon footprint accounting methods may differ and none of them is perfect or garners unanimous scientific consensus [30]. For example, it has been stated that France's carbon footprint accounting methodology has been recently revised (mainly regarding methane emissions), which led to a decrease of 20 % in the carbon footprint (based on the results reported for 2018) [50,100]. Given the lack of carbon footprint studies for Wallonia, such uncertainty figures could not be established. However, it has been reported in one of the studies used in this work to establish Wallonia's carbon footprint that the carbon footprint of countries can be estimated within the ±15 % range [71].

As demonstrated, the uncertainties associated with the existing data are already significant and this does not even consider the projections in the 30-year range until 2050. For example, regarding the territorial carbon absorption pathway, it is well established that climate change may lead to positive carbon sequestration feedback loops, such as increased wildfire risks [95] or the potential reduction of carbon uptake due to increased vegetation respiration [96]. Therefore, to face those potential positive feedbacks, a security margin (yet to be quantified) could be added to the territorial carbon absorption target pathway. It is noteworthy that this would constitute a similar approach to the way the carbon budgets reported by the IPCC intrinsically consider some positive feedback risks over positive GHG emissions (such as the amount of GHG that could be released by the thawing of the permafrost) [6,7].

Population projections also come with significant uncertainties, stemming from very uncertain phenomena such as migration balances, life expectancy, fertility rates, *etc*. For example, the uncertainty over France's 2050 population can be estimated to be about ±8 % (with the available scenarios) [47,101]. The data used to compute Wallonia's population projection has not been reported with any uncertainty level [102] but the same figure as France can be considered given the fact that the two regions/nations are culturally, geographically, climatically, and economically close.

Although applying the NIST uncertainty propagation method [103] to all the data and its manipulation is possible, it has been decided for simplicity reasons to neglect the uncertainty associated with population levels. This is because it only reaches its maximum of ±8 % in 2050 and not over the whole timeframe. Furthermore, in 2050, the GHG emissions are supposed to be near zero or reach zero, minimizing the contribution of this uncertainty. The ±30 % uncertainty in the carbon budget must, however, be considered. This uncertainty level has been propagated for illustration purposes on the individualized carbon footprint mitigation pathway (CO_2-only curve) established earlier for Wallonia in Fig. 6(b). This has been reported in Fig. 9. As it can be observed, with a slope parameter of the logistic function unchanged, i.e. *b* in Equation (3), the

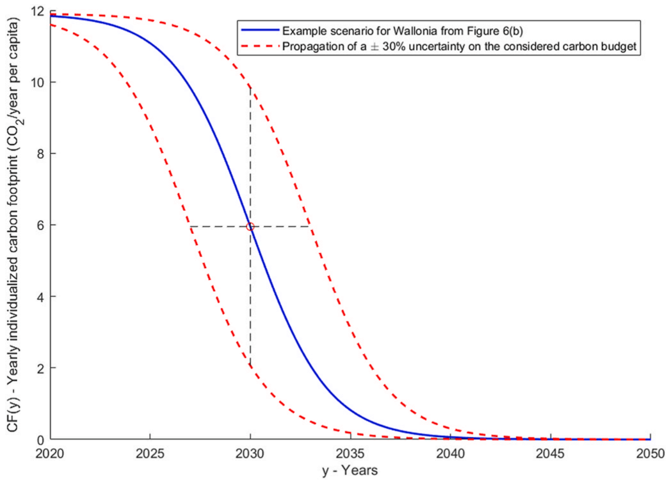


Fig. 9. ±30 % carbon budget uncertainty propagation on the individualized carbon footprint pathway established for Wallonia in Fig. 6(b). It can be remembered that this scenario was considered the riskiest, as it allowed the carbon budget to be (temporarily) exceeded.

reported ±30 % carbon budget uncertainty results in a ±65 % uncertainty zone on the carbon footprint, but more explicitly on a ±3 years uncertainty zone on the *c* parameter of the logistic function. This means that, if the remaining carbon budget was actually reevaluated 30 % lower than it currently is, the CO_2 mitigation efforts would need to be advanced by approximately 3 years.

4. Limitations and further works

It is worth mentioning that the cases computed in Fig. 6 (and in Fig. 8 for France) are examples of GHG pathways that are "just compatible" with IPCC's +2 °C "equity" carbon budget. These scenarios are yet considered as "opposite" in terms of the *b* and *c* parameters (slope and year of maximum mitigation rate) and other intermediate "just compatible" scenarios could be similarly computed, with intermediate *b* and *c* values. However, these would not change the inferences established in the previous sections. Also, as already stated, these "just compatible" scenarios must not prevent GHG policies from aiming for earlier or steeper GHG mitigation.

It has already been established in the methodology section that, in carbon budget and carbon footprint calculations, the use of GHG forcing-equivalent potential varying over time (to account for the future warming impact of short-lived climate pollutants, i.e. SLCPs) instead of traditional "absolute" GWP would be more relevant [58]. However, converting common carbon footprint figures, which could simply be derived for example from widely used individual carbon footprint calculators [99], was not in the scope of this work. Such GHG forcing-equivalent indicators could nevertheless be directly implemented at the carbon footprint calculator level.

Another limitation of the proposed method is that it assumes a carbon absorption target of 1 tCO_{2eq}/year per capita (mainly through natural sinks). Although deemed relevant (but challenging) for Wallonia and France, it would most likely be unrealistic for regions and nations with even higher population densities. These densities. These regions/nations might therefore require international collaboration to "share" carbon sinks (and possibly also "share" the initial "equity" carbon budget). It is worth mentioning that territorial carbon absorption pathways might not be linear, unlike those considered in this study for simplicity reasons. In further works, they might also be better modelled with their own inverted "S-shaped" patterns, potentially defined using Equation (3).

Regarding the data used as an input to the study (reported in Table 2), it has been established that Wallonia's carbon footprint of about 16 tCO_{2eq}/year per capita could be considered valid up to the year 2011 (last available data) [7]. That figure might therefore be considered obsolete, especially because it seems quite high compared to the 9.2 tCO_{2eq}/year per capita value established for France (which is one of its neighbouring countries). However, Belgium's carbon footprint (and, by extension, Wallonia's) has not significantly decreased in ten years between 2001 and 2011 [7], leaving no reason to believe that it has since then. Similarly, France's carbon footprint has also not been significantly reduced between 1995 and 2020 [50].

In addition, it must be noted that the resulting target individualized carbon footprint mitigation modelled through "S-shaped" pathways is purely theoretical. Indeed, it has already been established that more realistic pathways could probably be represented by modelling the combination of several technologies and behavioural changes, associated with their respective diffusion and adoption rates. At the cost of increased complexity, an identified solution to this would be to discretize the overall regional/national pathway into several logistic functions (several "S-shaped" patterns combined) to better accommodate GHG mitigation effects featuring significantly different time constants.

Furthermore, the suggested individualized carbon footprint approach is far from being perfect. This is primarily due to the lack of scientific consensus on the method of calculating carbon footprints [104] and the fact that one's capability of mitigating their GHG emissions can be quite different from another's. This risk has indeed been similarly identified for lower-income/vulnerable households with personal carbon allowance approaches (PCAs) [34].

Despite these limitations, this work successfully achieves its objective of providing individuals (and, by extension, collectives) with a straightforward approach to help understand the scale of reduction required in their carbon footprints, both in the short-term and long-term. It is noteworthy that in further works, the method developed in this work to link IPCC's carbon budget to individual carbon footprint is fully reproducible with other GHG pathways than the sigmoidal ones recommended in this study (such as exponential decay functions, for example).

A trivial limitation of this work lies in the fact that it mainly focused on the chosen case studies of France and Wallonia. Another improvement would be to extend this work to all countries of the European Union (and other regions of the world), especially regarding territorial carbon absorption capabilities that have been identified in this work as critical (to reach GHG neutrality). Fortunately, the suggested method relies on easily available data and is simple enough to be reproduced quite straightforwardly.

5. Conclusions

The method developed in this study allows for linking IPCC's "equity" carbon budgets [7] to individual carbon footprints and is therefore compatible with existing online individual carbon footprint calculators [99]. Thus, considering population levels, it can be used in climate policies at the scale of the community to establish GHG mitigation pathways compatible with those carbon budgets, which is not guaranteed with usual existing policies, mainly because of the lack of mitigation objectives set on imported emissions [7].

In addition to the consideration of imported emissions through total carbon footprint approaches (and not only territorial emissions), the method proposed in this work offers other advantages compared to most current climate policies. For instance, by committing to GHG mitigation pathways (over the 2020–2050 period) and not only to a late emission rate target [7], carbon budgets can more likely be secured, at least if those GHG pathways are respected. Indeed, essential short-term GHG mitigation targets are quite easily established with the method suggested in this work.

Even if those initial pathways are not respected from one year to the next (less mitigation than expected), yearly updates can easily be established once again using the same method. The slope of the required mitigation efforts will thus be increased (as inferred by Fig. 6). This requires carbon footprints to be monitored yearly and compared to the carbon budget compatible GHG emissions pathways.

In addition, the proposed GHG mitigation pathways follow inverted "S-shape" patterns modelled thanks to Equation (3) that, even though quite theoretical, are more realistic [22] than linear trends assumed in most climate policies [7]. This is mainly because "S-curves" consider "inertia" and "asymptotic" effects associated with the implementation of (renewable) technologies. It is noteworthy that this method has been stated to be reproducible with other realistic GHG mitigation patterns (such as exponential decay functions).

More importantly, the suggested method has been scaled down to the individual carbon footprint and can be reproduced easily on other levels (household, district, region, continent). As stated, the individual level allows for everyone to set their own yearly GHG mitigation targets and monitor them, thanks to the intrinsic compatibility with largely used carbon footprint calculators [99]. People can therefore relate more easily to climate policies set by public authorities and public resistance to climate policies can be reduced thanks to "audience-specific messaging and framing" [29]. In that matter, individuals should also be encouraged to regularly compute and compare their personal carbon footprint with the targeted one (and potentially also their cumulative historical emissions). In addition, the proposed method has the advantage of intrinsically considering projected population growth through its multiplication with the average individual carbon footprint. Three main Sustainable Development Goals (SDGs) [32] are thus directly addressed by this work: climate action (SDG13), sustainable consumption (SDG12), and reduced inequality (SDG10), achieved through the consideration of individual "equity" carbon budgets.

It is worth mentioning that developing this method over the chosen case studies of Wallonia and France has led to many general inferences. Firstly, this work has highlighted that it is preferable to consider 1 tCO_{2eq}/year per capita as the 2050 individual carbon footprint target rather than the 2 tCO_{2eq}/year per capita usually reported, for example, in well-known carbon footprint calculators [99]. This figure comes from the unmitigable non-CO_2 GHG emissions reported by the IPCC in its AR6 [7].

Secondly, through the Green Deal 2050 GHG-neutral commitment in Europe [42], those unmitigated non-CO_2 GHG emissions are assumed to be absorbed territorially. This could either be performed through nature-based, i.e. natural sinks [79], or technological methods [80]. However, the latter are still immature: they can be considered too risky [7] and ethically questionable [83] for climate policies to rely on them, even though their development is still highly needed in the context of risk mitigation.

At last, this work has led to findings specific to France and Wallonia's case studies (that may be relevant to other regions/nations). The first one is that Wallonia needs to conduct (and finance) studies on individual and/or total carbon footprint (considering imported emissions). To the knowledge of the author, the last carbon footprint available data for Wallonia was established for the year 2011 [72], whereas for France, carbon footprint data are regularly reported, and the latest was for the year 2018 [45].

Strong GHG mitigation, especially in Wallonia, is required to be implemented as soon as possible for the suggested pathways to be compatible with IPCC's "equity" carbon budget. Unlike France, the computed scenarios for Wallonia show that the initial carbon footprint is so high that carbon neutrality would have to be reached at least ten years before the 2050 climate-neutral European Green Deal commitment [42].

At last, considering technological carbon absorption methods too risky, both Wallonia and France need to maximize their natural carbon sinks to match as closely as possible the unmitigated "equity" non-CO_2 GHG footprint in a net-zero CO_2 future [1] and ensure the GHG-neutral commitment of the Green Deal [42]. That accounts for 1 tCO_{2eq}/year per capita, and this respectively represents a +300 % and a +370 % increase compared to the estimated current levels of Wallonia and France's territorial carbon absorptions. This could be performed by rethinking land-use in every single area of the territory. Carbon uptake can still be maximized without changing land affectation, especially for agricultural lands, through alternative agricultural techniques such as permaculture [86], or for urbanized areas, through intensive urban vegetation such as green roofs [92]. Residential lawns also have a good increase potential in carbon uptake [94] if specific encouraging policies were to be implemented.

Although this work focuses on Wallonia and France, its applicability is wider, as it has been demonstrated that the suggested method to compute relevant GHG mitigation pathways is quite simple and relies on easily available data. Therefore, it can be easily reproduced and can apply toto most nations and/or regions.

Data accessibility

All the sources of the data used for the analysis presented in this paper have been reported in the list of references.

Funding

This study did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

N. Paulus: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All the data has been referenced in the manuscript

References

[1] IPCC WGIII. Climate change 2022 mitigation of climate change - summary for policymakers. In: IPCC - Working Group III Technical Support Unit; 2022. https://doi.org/10.1017/9781009157926.001.

[2] Matthews HD, Wynes S. Current global efforts are insufficient to limit warming to 1.5°C. Science (1979) 2022;376:1404–9. https://doi.org/10.1126/SCIENCE.ABO3378.

[3] Martin MA, Sendra OA, Bastos A, Bauer N, Bertram C, Blenckner T, et al. Ten new insights in climate science 2021: a horizon scan. Glob Sustain 2021;4. https://doi.org/10.1017/SUS.2021.25.

[4] Liu Z, Deng Z, Davis SJ, Giron C, Ciais P. Monitoring global carbon emissions in 2021. Nat Rev Earth Environ 2022;3:217–9. https://doi.org/10.1038/s43017-022-00285-w.

[5] Smith SM, Lowe JA, Bowerman NHA, Gohar LK, Huntingford C, Allen MR. Equivalence of greenhouse-gas emissions for peak temperature limits. Nat Clim Change 2012;2:535–8. https://doi.org/10.1038/nclimate1496.

[6] Rogelj J, Forster PM, Kriegler E, Smith J. Estimating and tracking the remaining carbon budget for stringent climate targets. Nature 2019;571. https://doi.org/10.1038/s41586-019-1368-z.

[7] Paulus N. Confronting Nationally Determined Contributions (NDCs) to IPPC's + 2°C carbon budgets through the analyses of France and Wallonia climate policies. J Ecol Eng 2023;24. https://doi.org/10.12911/22998993/162984.

[8] Peters GP. Beyond carbon budgets. Nat Geosci 2018;11:378–80. https://doi.org/10.1038/s41561-018-0142-4.

[9] Stockwell C, Geiges A, Ramalope D, Gidden M, Hare B, de Villafranca Casas MJ, et al. Glasgow's 2030 credibility gap: net zero's lip service to climate action. Clim Action Track 2021. https://climateactiontracker.org/documents/997/CAT_2021-11-09_Briefing_Global-Update_Glasgow2030CredibilityGap.pdf.

[10] Williamson K, Satre-Meloy A, Velasco K, Green K. Climate change needs behavior change: making the case for behavioral solutions to reduce global warming. Rare 2018. https://rare.org/wp-content/uploads/2019/02/2018-CCNBC-Report.pdf.

[11] Gignac R, Matthews HD. Allocating a 2 °C cumulative carbon budget to countries. Environ Res Lett 2015;10. https://doi.org/10.1088/1748-9326/10/7/075004.

[12] Raupach MR, Davis SJ, Peters GP, Andrew RM, Canadell JG, Ciais P, et al. Sharing a quota on cumulative carbon emissions. Nat Clim Change 2014;4:873–9. https://doi.org/10.1038/NCLIMATE2384.

[13] Dooley K, Holz C, Kartha S, Klinsky S, Roberts JT, Shue H, et al. Ethical choices behind quantifications of fair contributions under the Paris Agreement. Nat Clim Change 2021;11:300–5. https://doi.org/10.1038/S41558-021-01015-8.

[14] van der Ploeg F. The safe carbon budget. Clim Change 2018;147:47–59. https://doi.org/10.1007/s10584-017-2132-8.

[15] Allen MR, Fuglestvedt JS, Shine KP, Reisinger A, Pierrehumbert RT, Forster PM. New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nat Clim Change 2016;6:773–6. https://doi.org/10.1038/nclimate2998.

[16] Lynch J, Cain M, Pierrehumbert R, Allen M. Demonstrating GWP*: a means of reporting warming-equivalent emissions that captures the contrasting impacts of short- and long-lived climate pollutants. Environ Res Lett 2020;15. https://doi.org/10.1088/1748-9326/AB6D7E.

[17] Mills-Novoa M, Liverman DM. Nationally Determined Contributions: material climate commitments and discursive positioning in the NDCs. Wiley Interdiscip Rev Clim Change 2019;10. https://doi.org/10.1002/WCC.589.

[18] Hausfather Z, Moore FC. Climate science Commitments could limit warming to below 2 °C. Nature 2022;604. https://doi.org/10.1038/d41586-022-00874-1.

[19] Kriegler E, Bertram C, Kuramochi T, Jakob M, Pehl M, Stevanović M, et al. Short term policies to keep the door open for Paris climate goals. Environ Res Lett 2018; 13. https://doi.org/10.1088/1748-9326/AAC4F1.

[20] Riahi K, Kriegler E, Johnson N, Bertram C, den Elzen M, Eom J, et al. Locked into Copenhagen pledges - implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol Forecast Soc Change 2015;90: 8–23. https://doi.org/10.1016/J.TECHFORE.2013.09.016.

[21] Vandevyvere H, Nevens F. Lost in transition or geared for the S-curve? An analysis of flemish transition trajectories with a focus on energy use and buildings. Sustainability 2015;7:2415–36. https://doi.org/10.3390/su7032415.

[22] Kucharavy D, De Guio R. Application of S-shaped curves. Procedia Eng 2011;9: 559–72. https://doi.org/10.1016/J.PROENG.2011.03.142.

[23] van Vuuren DP, Stehfest E, Gernaat DEHJ, Doelman JC, van den Berg M, Harmsen M, et al. Energy, land-use and greenhouse gas emissions trajectories under a green growth paradigm. Global Environ Change 2017;42:237–50. https://doi.org/10.1016/J.GLOENVCHA.2016.05.008.

[24] Gambhir A, George M, McJeon H, Arnell NW, Bernie D, Mittal S, et al. Near-term transition and longer-term physical climate risks of greenhouse gas emissions pathways. Nat Clim Change 2021;12:88–96. https://doi.org/10.1038/s41558-021-01236-x.

[25] Grant N. The Paris Agreement's ratcheting mechanism needs strengthening 4-fold to keep 1.5°C alive. Joule 2022;6:703–8. https://doi.org/10.1016/j.joule.2022.02.017.

[26] Figueres C, Schellnhuber HJ, Whiteman G, Rockström J, Hobley A, Rahmstorf S. Three years to safeguard our climate. Nature 2017;546:593–5. https://doi.org/10.1038/546593a.

[27] Lamb WF, Mattioli G, Levi S, Timmons Roberts J, Capstick S, Creutzig F, et al. Discourses of climate delay. Glob Sustain 2020;3. https://doi.org/10.1017/SUS.2020.13.

[28] Semenza JC, Hall DE, Wilson DJ, Bontempo BD, Sailor DJ, George LA. Public perception of climate change: voluntary mitigation and barriers to behavior change. Am J Prev Med 2008;35:479–87. https://doi.org/10.1016/J.AMEPRE.2008.08.020.

[29] Moser SC. Communicating climate change: history, challenges, process and future directions. Wiley Interdiscip Rev Clim Change 2010;1:31–53. https://doi.org/10.1002/WCC.11.

[30] Steininger KW, Lininger C, Meyer LH, Muñoz P, Schinko T. Multiple carbon accounting to support just and effective climate policies. Nat Clim Change 2016; 6:35–41. https://doi.org/10.1038/nclimate2867.

[31] Salo M, Mattinen-Yuryev MK, Nissinen A. Opportunities and limitations of carbon footprint calculators to steer sustainable household consumption – analysis of Nordic calculator features. J Clean Prod 2019;207:658–66. https://doi.org/10.1016/j.jclepro.2018.10.035.

[32] Waage J, Yap C, Bell S, Levy C, Mace G, Pegram T, et al. Governing the UN sustainable development goals: interactions, infrastructures, and institutions. Lancet Global Health 2015;3:e251–2. https://doi.org/10.1016/S2214-109X(15)70112-9.

[33] Wiedmann T, Allen C. City footprints and SDGs provide untapped potential for assessing city sustainability. Nat Commun 2021;12:3758. https://doi.org/10.1038/s41467-021-23968-2.

[34] Fuso Nerini F, Fawcett T, Parag Y, Ekins P. Personal carbon allowances revisited. Nat Sustain 2021;4:1025–31. https://doi.org/10.1038/s41893-021-00756-w.

[35] Berkson J. Tables for the maximum likelihood estimate of the logistic function. Biometrics 1957;13:28. https://doi.org/10.2307/3001900.

[36] Ren J, McIsaac KA, Patel RV, Peters TM. A potential field model using generalized sigmoid functions. IEEE Trans Syst Man Cybern B Cybern 2007;37:477–84. https://doi.org/10.1109/TSMCB.2006.883866.

[37] Klimstra M, Zehr EP. A sigmoid function is the best fit for the ascending limb of the Hoffmann reflex recruitment curve. Exp Brain Res 2008;186:93–105. https://doi.org/10.1007/S00221-007-1207-6.

[38] Ikhlasse H, Benjamin D, Vincent C, Hicham M. Environmental impacts of pre/during and post-lockdown periods on prominent air pollutants in France. Environ Dev Sustain 2021;23. https://doi.org/10.1007/S10668-021-01241-2.

[39] van den Bergh JCJM. Energy conservation more effective with rebound policy. Environ Resour Econ 2011;48:43–58. https://doi.org/10.1007/s10640-010-9396-z.

[40] Birnik A. An evidence-based assessment of online carbon calculators. Int J Greenh Gas Control 2013;17:280–93. https://doi.org/10.1016/j.ijggc.2013.05.013.

[41] Rogelj J, Meinshausen M, Schaeffer M, Knutti R, Riahi K. Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. Environ Res Lett 2015;10. https://doi.org/10.1088/1748-9326/10/7/075001.

[42] Maris G, Flouros F. The green deal, national energy and climate plans in Europe: member states' compliance and strategies. Adm Sci 2021;11. https://doi.org/10.3390/admsci11030075.

[43] Turbat V, Gribble R, Zeng W. Population, Burden Of Disease, and Health Services. 2022. p. 59–77. https://doi.org/10.1007/978-3-031-02040-7_4.

[44] Hambÿe C, Hertveldt B, Michel B. Does consistency with detailed national data matter for calculating carbon footprints with global multi-regional input–output tables? A comparative analysis for Belgium based on a structural decomposition. J Econ Struct 2018;7:11. https://doi.org/10.1186/s40008-018-0110-6.

[45] Bourgeois A, Lafrogne-Joussier R, Lequien M, Ralle P. Un tiers de l'empreinte carbone de l'Union européenne est dû à ses importations. Insee Analyses 2022;74. https://www.insee.fr/fr/statistiques/fichier/6474294/ia74.pdf.

[46] Lannelongue L, Grealey J, Inouye M. Green algorithms: quantifying the carbon footprint of computation. Adv Sci 2021;8. https://doi.org/10.1002/ADVS.202100707.

[47] INSEE. Résultats détaillés des projections de population 2021-2070 pour la France – Scénario central. In: Projections de Population 2021-2070; 2021. https://www.insee.fr/fr/statistiques/5894083?sommaire=5760764. [Accessed 23 November 2023].

[48] INSEE. Évolution de la population. Tableaux de l'économie Française - Édition 2020. 2020. https://www.insee.fr/fr/statistiques/4277615?sommaire=4318291. [Accessed 26 November 2023].

[49] Bureau du Plan. Population par région et âge, au 1er janvier. Perspectives de Population 2021-2070. https://www.plan.be/databases/data-35-fr-perspectives_de_population_2021_2070. [Accessed 8 July 2022].

[50] Haut Conseil pour le Climat. Dépasser les constats. Mettre en oeuvre les solutions. 2022. https://www.hautconseilclimat.fr/wp-content/uploads/2022/06/Rapport-annuel-Haut-conseil-pour-le-climat-29062022.pdf.

[51] Gouvernement Wallon. Stratégie à long terme pour la Wallonie (SLT 2050): "Vers une Wallonie climatiquement neutre en 2050". 2019. https://ec.europa.eu/clima/sites/lts/lts_be_fr.pdf.

[52] Salzmann M. Global warming without global mean precipitation increase'. Sci Adv 2016;2. https://doi.org/10.1126/SCIADV.1501572.

[53] Allen RJ, Horowitz LW, Naik V, Oshima N, O'Connor FM, Turnock S, et al. Significant climate benefits from near-term climate forcer mitigation in spite of aerosol reductions. Environ Res Lett 2021;16. https://doi.org/10.1088/1748-9326/ABE06B.

[54] Dreyfus GB, Xu Y, Shindell DT, Zaelke D, Ramanathan V. Mitigating climate disruption in time: a self-consistent approach for avoiding both near-term and long-term global warming. Proc Natl Acad Sci U S A 2022;119. https://doi.org/10.1073/PNAS.2123536119.

[55] Lund MT, Myhre G, Samset BH. Anthropogenic aerosol forcing under the shared socioeconomic pathways. Atmos Chem Phys 2019;19:13827–39. https://doi.org/10.5194/ACP-19-13827-2019.

[56] Ou Y, Roney C, Alsalam J, Calvin K, Creason J, Edmonds J, et al. Deep mitigation of CO2 and non-CO2 greenhouse gases toward 1.5 °C and 2 °C futures. Nat Commun 2021;12:1–9. https://doi.org/10.1038/s41467-021-26509-z.

[57] Folini D, Kubler F, Malova A, Scheidegger S. The climate in climate economics. In: Proceedings of the 19th European geosciences union general assembly (EGU22); 2022. https://doi.org/10.5194/egusphere-egu22-2607.

[58] Jenkins S, Millar RJ, Leach N, Allen MR. Framing climate goals in terms of cumulative CO2-forcing-equivalent emissions. Geophys Res Lett 2018;45: 2795–804. https://doi.org/10.1002/2017GL076173.

[59] Mengis N, Matthews HD. Non-CO2 forcing changes will likely decrease the remaining carbon budget for 1.5 °C. NPJ Clim Atmos Sci 2020;3:1–7. https://doi.org/10.1038/s41612-020-0123-3.

[60] Leach NJ, Millar RJ, Haustein K, Jenkins S, Graham E, Allen MR. Current level and rate of warming determine emissions budgets under ambitious mitigation. Nat Geosci 2018;11. https://doi.org/10.1038/s41561-018-0156-y.

[61] Jenkins S, Cain M, Friedlingstein P, Gillett N, Walsh T, Allen MR. Quantifying non-CO2 contributions to remaining carbon budgets. NPJ Clim Atmos Sci 2021;4: 1–10. https://doi.org/10.1038/s41612-021-00203-9.

[62] Matthews HD, Tokarska KB, Nicholls ZRJ, Rogelj J, Canadell JG, Friedlingstein P, et al. Opportunities and challenges in using remaining carbon budgets to guide climate policy. Nat Geosci 2020 2020;13:769–79. https://doi.org/10.1038/s41561-020-00663-3.

[63] Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, et al. Global agriculture and nitrous oxide emissions. Nat Clim Change 2012;2:410–6. https://doi.org/10.1038/NCLIMATE1458.

[64] Paulus N, Lemort V. Experimental assessment of pollutant emissions from residential fuel cells and comparative benchmark analysis. J Environ Manag 2024. Accepted for publication.

[65] Ghisellini P, Passaro R, Ulgiati S. Environmental assessment of multiple "cleaner electricity mix" scenarios within just energy and circular economy transitions, in

Italy and Europe. J Clean Prod 2023;388:135891. https://doi.org/10.1016/j.jclepro.2023.135891.

[66] Gernaat DEHJ, Calvin K, Lucas PL, Luderer G, Otto SAC, Rao S, et al. Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. Global Environ Change 2015;33:142–53. https://doi.org/10.1016/J.GLOENVCHA.2015.04.010.

[67] Allen MR, Shine KP, Fuglestvedt JS, Millar RJ, Cain M, Frame DJ, et al. A solution to the misrepresentations of CO2-equivalent emissions of short-lived climate pollutants under ambitious mitigation. NPJ Clim Atmos Sci 2018;1:1–8. https://doi.org/10.1038/s41612-018-0026-8.

[68] Meinshausen M, Nicholls Z. GWP*is a model, not a metric. Environ Res Lett 2022;17. https://doi.org/10.1088/1748-9326/AC5930.

[69] Cain M, Lynch J, Allen MR, Fuglestvedt JS, Frame DJ, Macey AH. Improved calculation of warming-equivalent emissions for short-lived climate pollutants. NPJ Clim Atmos Sci 2019;2:1–7. https://doi.org/10.1038/s41612-019-0086-4.

[70] Smith MA, Cain M, Allen MR. Further improvement of warming-equivalent emissions calculation. NPJ Clim Atmos Sci 2021;4:1–3. https://doi.org/10.1038/s41612-021-00169-8.

[71] Hertwich EG, Peters GP. Carbon footprint of nations: a global, trade-linked analysis. Environ Sci Technol 2009;43. https://doi.org/10.1021/es803496a.

[72] Towa E, Zeller V, Merciai S, Schmidt J, Achten WMJ. Toward the development of subnational hybrid input–output tables in a multiregional framework. J Ind Ecol 2022;26. https://doi.org/10.1111/jiec.13085.

[73] Zhao Y, Su Q, Li B, Zhang Y, Wang X, Zhao H, et al. Have those countries declaring “zero carbon” or “carbon neutral” climate goals achieved carbon emissions-economic growth decoupling? J Clean Prod 2022;363:132450. https://doi.org/10.1016/j.jclepro.2022.132450.

[74] Dumont G-F. L'Ukraine face à la guerre : géopolitique et population. Popul Avenir 2022;758:17–9. https://doi.org/10.3917/POPAV.758.0017.

[75] Blujdea VNB, Viñas RA, Federici S, Grassi G. The EU greenhouse gas inventory for the LULUCF sector: I. Overview and comparative analysis of methods used by EU member states. Carbon Manag 2016;6:247–59. https://doi.org/10.1080/17583004.2016.1151504.

[76] García-Oliva F, Masera OR. Assessment and measurement issues related to soil carbon sequestration in land-use, land-use change, and forestry (LULUCF) projects under the Kyoto Protocol. Clim Change 2004;65:347–64. https://doi.org/10.1023/B:CLIM.0000038211.84327.d9.

[77] Cacho OJ, Hean RL, Wise RM. Carbon-accounting methods and reforestation incentives. Aust J Agric Resour Econ 2003;47:153–79. https://doi.org/10.1111/1467-8489.00208.

[78] Keller DP, Lenton A, Littleton EW, Oschlies A, Scott V, Vaughan NE. The effects of carbon dioxide removal on the carbon cycle. Curr Clim Change Rep 2018;4:250–65. https://doi.org/10.1007/S40641-018-0104-3.

[79] Matthews HD, Zickfeld K, Dickau M, MacIsaac AJ, Mathesius S, Nzotungicimpaye C-M, et al. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. Commun Earth Environ 2022;3:1–8. https://doi.org/10.1038/s43247-022-00391-z.

[80] Batres M, Wang FM, Buck H, Kapila R, Kosar U, Licker R, et al. Environmental and climate justice and technological carbon removal. Electr J 2021;34:107002. https://doi.org/10.1016/J.TEJ.2021.107002.

[81] McQueen N, Gomes KV, McCormick C, Blumanthal K, Pisciotta M, Wilcox J. A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future. Prog Energy 2021;3. https://doi.org/10.1088/2516-1083/ABF1CE.

[82] Nataly Echevarria Huaman R, Xiu Jun T. Energy related CO2 emissions and the progress on CCS projects: a review. Renew Sustain Energy Rev 2014;31:368–85. https://doi.org/10.1016/J.RSER.2013.12.002.

[83] Lenzi D. The ethics of negative emissions. Glob Sustain 2018;1:1–8. https://doi.org/10.1017/SUS.2018.5.

[84] Abdulla A, Hanna R, Schell KR, Babacan O, Victor DG. Explaining successful and failed investments in U.S. carbon capture and storage using empirical and expert assessments. Environ Res Lett 2021;16:014036. https://doi.org/10.1088/1748-9326/abd19e.

[85] Perrin D, Temmerman M, Laitat E. Calculation on the impacts of forestation, afforestation and reforestation on the C-sequestration potential in Belgian forests ecosystems. Biotechnologie, Agronomie, Société et Environnement 2000;4. https://popups.uliege.be/1780-4507/index.php/base/article/download/463/index.php?id=17509&file=1&pid=15054.

[86] Hathaway MD. Agroecology and permaculture: addressing key ecological problems by rethinking and redesigning agricultural systems. J Environ Stud Sci 2016;6:239–50. https://doi.org/10.1007/S13412-015-0254-8.

[87] Neumann M, Smith P. Carbon uptake by European agricultural land is variable, and in many regions could be increased: evidence from remote sensing, yield statistics and models of potential productivity. Sci Total Environ 2018;643:902–11. https://doi.org/10.1016/J.SCITOTENV.2018.06.268.

[88] Jyoti Nath A, Lal R, Kumar Das A. Fired bricks: CO2 emission and food insecurity. Glob Chall 2018;2. https://doi.org/10.1002/GCH2.201700115.

[89] Smith P, Andrén O, Karlsson T, Perälä P, Regina K, Rounsevell M, et al. Carbon sequestration potential in European croplands has been overestimated. Global Change Biol 2005;11:2153–63. https://doi.org/10.1111/J.1365-2486.2005.01052.X.

[90] Viglizzo EF, Ricard MF, Taboada MA, Vázquez-Amábile G. Reassessing the role of grazing lands in carbon-balance estimations: meta-analysis and review. Sci Total Environ 2019;661:531–42. https://doi.org/10.1016/J.SCITOTENV.2019.01.130.

[91] Delescaille L-M. Nature conservation and pastoralism in Wallonia. In: Pasture Landscapes and Nature Conservation; 2002. p. 39–52. https://doi.org/10.1007/978-3-642-55953-2_3.

[92] Seto KC, Churkina G, Hsu A, Keller M, Newman PWG, Qin B, et al. From low- to net-zero carbon cities: the next global agenda. Annu Rev Environ Resour 2021;46. https://doi.org/10.1146/annurev-environ-050120-113117.

[93] Alderweireld M, Rondeux J, Latte N, Hébert J, Lecomte H. Chapter 8 - Belgium (Wallonia). National forest inventories assessment of wood availability and use. Springer; 2016. p. 159–79. https://doi.org/10.1007/978-3-319-44015-6_8.

[94] Kuittinen M, Hautamäki R, Tuhkanen EM, Riikonen A, Ariluoma M. Environmental Product Declarations for plants and soils: how to quantify carbon uptake in landscape design and construction? Int J Life Cycle Assess 2021;26:1100–16. https://doi.org/10.1007/S11367-021-01926-W.

[95] Carnicer J, Alegria A, Giannakopoulos C, Di Giuseppe F, Karali A, Koutsias N, et al. Global warming is shifting the relationships between fire weather and realized fire-induced CO2 emissions in Europe. Sci Rep 2022;12(1):1–6. https://doi.org/10.1038/s41598-022-14480-8.

[96] Cox PM, Betts RA, Jones CD, Spall SA, Totterdell IJ. Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. Nature 2000;408:184–7. https://doi.org/10.1038/35041539.

[97] Gouvernement Wallon. Plan air climat energie (PACE) 2030. 2023. https://henry.wallonie.be/files/Documents/230321%20-%20PACE2030.pdf.

[98] Fawcett T, Hvelplund F, Meyer NI. Making it personal. Generating electricity in a carbon-constrained world. Elsevier; 2010. p. 87–107. https://doi.org/10.1016/B978-1-85617-655-2.00004-3.

[99] Auger C, Hilloulin B, Boisserie B, Thomas M, Guignard Q, Rozière E. Open-source carbon footprint estimator: development and university declination. Sustainability 2021;13. https://doi.org/10.3390/su13084315.

[100] Haut Conseil pour le Climat. Maîtriser l'empreinte carbone de la France - Réponse à la saisine du gouvernement. 2020. https://www.hautconseilclimat.fr/wp-content/uploads/2020/10/hcc_rapport_maitriser-lempreinte-carbone-de-la-france-1.pdf.

[101] INSEE. Résultats détaillés des projections de population 2021-2070 pour la France – Les quatre scénarios extrêmes. In: Projections de Population 2021-2070; 2021. https://www.insee.fr/fr/statistiques/5894087?sommaire=5760764. [Accessed 23 November 2023].

[102] Bureau du Plan. Perspectives démographiques 2019-2070: Population et ménages. 2020. https://www.plan.be/uploaded/documents/202003030902350.FOR_POP1970_12071_F.pdf.

[103] Taylor BN, Kuyatt CE. Guidelines for evaluating and expressing the uncertainty of NIST measurement results - 1994 edition. National Institute of Standards and Technology; 1994. https://nvlpubs.nist.gov/nistpubs/Legacy/TN/nbstechnicalnote1297.pdf.

[104] Pandey D, Agrawal M, Jai, Pandey S, Pandey D, Agrawal M, et al. Carbon footprint: current methods of estimation. Environ Monit Assess 2011;178:135–60. https://doi.org/10.1007/S10661-010-1678-Y.