ARUP

# The time-value of carbon

## An introductory exploration to support better decision making

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> “Each decision made… must now be made with climate change in mind, and the more we learn to measure and assess climate impacts the more nuanced these choices become.”

# Foreword

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Climate change mitigation, arguably humanity's greatest and most crucial challenge, is paradoxically both fundamentally simple and infinitely complex.

In essence, we must ensure that atmospheric concentrations of greenhouse gasses rapidly stop rising, and this means keeping more carbon stored elsewhere - in fossil reserves, in soil, in living organisms and in certain materials. We know that burning fossil fuels is the dominant source of emissions, so avoiding this should be prioritised. However, transitioning away from such deep-rooted aspects of today's world will profoundly impact social, economic and natural systems. Each decision made within these complex spheres must now be made with climate change in mind, and the more we learn to measure and assess climate impacts the more nuanced these choices become.

Building and infrastructure projects are inherently long-term, with the best lasting hundreds or even thousands of years. These are timescales over which both the climate and emissions can change completely. In the last decade alone, the emissions intensity of the UK's electricity grid has more than halved, whilst global average temperatures have risen by around 0.5°C. Intuitively, the timing of emissions feels important. Earlier emissions will cause a warming effect for longer, giving greater cumulative impacts, and the benefits of biogenic carbon sequestration surely grow with a longer storage period. The issue of uncertainty is also relevant; how should we equate an emission today we have agency over with an uncertain future emission based on the assumed behaviour of an unknown decision maker?

This report empowers us to explore these questions, by clearly articulating the climate principles behind temporal emission impacts, the existing approaches to incorporating them into life cycle assessments, and the rationales behind them. Again, tensions between simplicity and complexity arise, and we find that no methodology avoids the need to make some sort of arbitrary value judgement. However, we also see opportunities to make climate judgements which better reflect the reality of the challenge we face, which is vital work given one thing we know for certain - time is short.

> “Should we value upfront embodied carbon savings higher than operational carbon savings?”

# Executive summary

Whole life carbon assessments provide a framework to assess the carbon footprint of a building. These assessments aggregate the greenhouse gas emissions of a building throughout its life.

These assessments commonly assume that the *time* at which these carbon emissions are released to the atmosphere has no influence on the environment burden resulting from those emissions. This report aims to unpack this assumption by exploring the question: “Should we value upfront embodied carbon savings higher than operational carbon savings?”. More precisely, “How much should we value the delaying of emissions?”

Drawing on knowledge from both climate science and economics, this report introduces the topic of the ‘time-value of carbon’, provides an appreciation of the underpinning arguments, and explores the existing approaches for implementation in practice.

This report distils three discernible arguments for valuing future carbon emissions lower than those of the present (i.e. arguments for valuing the delay of emissions). These arguments have been characterised as:

**The *buying time* argument:**
“In delaying emissions, we buy time to avert these delayed emissions.”

**The *static time-horizon* argument:**
“Delaying emissions reduces their cumulative impacts between the present and a fixed point in the future.”

**The *social time preference* argument:**
“We should value the welfare of today’s society higher than that of tomorrows.”

Notably, all the arguments presented include a degree of subjective value judgement and therefore it should be acknowledged that the strength of the arguments depends in part on the extent to which persons agree with the value judgements made.

The report identifies four alternative approaches from academia for evaluating these arguments and explores the extent of adoption of these approaches in the industry.

As counting carbon becomes increasingly normalised, industry practitioners are scrutinising the underpinning assumptions in pursuit of minimising the environmental burden of building projects. By introducing and unpacking the ‘time-value of carbon’ this report aims to support these in practitioners in grappling with this complexity.

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Chapter 1.

# Context

The built environment is increasingly recognised as a critical sector for climate action, with the buildings and construction sector responsible for 21% of global greenhouse gas emissions [1].

The sectors' transition to net zero is gaining traction with developing policy, regulation, and finance starting to shift the environment within which the sector operates. These changes are driving the uptake of Whole-Life Carbon Assessments (WLCA) to quantify the carbon footprint of built assets. By considering Global Warming Potential of emissions released throughout the life cycle of the built asset, from construction, through operation, to end-of-life, these assessments provide a means to monitor and reduce the environmental impact of projects.

Most WLCA methodologies commonly assume that the timing of the carbon emissions has no impact on the environment burden resulting from those emissions.

This report aims to unpack this assumption by exploring the question:

> "Is carbon saved today more valuable than carbon saved tomorrow?"

This question could alternatively be framed "How much should we value the delaying of emissions?".

Answering this question is foundational to minimising environmental impact of buildings and gets at the root of what is known as the 'time-value of carbon'.

Whenever designers are comparing the burden of carbon emissions that occur at different times they are forced to take a position, often implicitly, on the relative value of present and future emissions. For example:

- Designers reporting on the benefit of sequestered carbon in timber.
- Engineers balancing the trade-off between upfront embodied emissions and operational carbon benefits.
- Consultants advising on the carbon payback period of on-site renewable options.
- Consultants advising on the value of carbon offsets schemes based on the temporary carbon storage schemes.

This report explores a range of arguments to advance understanding of the value of delaying emissions. Drawing on knowledge from both climate science, economics, and life cycle assessments, this report aims to provide designers with an appreciation for these underpinning arguments for the time-value of carbon and initial guidance insofar as this may inform better decision making.

The discussion presented herein does not pertain to be conclusive, nor capture the entirety of the discussion ongoing in the literature. Instead, this report aims to provide an introductory exploration of the topic to precipitate further discussion in the industry.

The red boxes used within the document are provided to identify and distinguish the opinions of the authors.

## Chapter 2.

# Arguments

## There continues to be considerable debate about the value delaying carbon emissions offers [2].

Some authors have argued that temporary storage has no value and that only permanent carbon sequestration is meaningful [3] [4]. Other authors have argued that there are multiple reasons, both economic and environmental, why it is advantageous to value temporary storage of emissions [5] [2]. Whilst consensus is building around the latter, there is much ongoing discussion on how this value is quantified.

This report has distilled three discernible arguments for valuing future carbon emissions lower than those of the present (i.e. arguments for delaying emissions). These arguments have been characterised as follows:

**The *buying time* argument:**
"In delaying emissions, we buy time to avert these delayed emissions."

**The *static time-horizon* argument:**
"Delaying emissions reduces their cumulative impacts between the present and a fixed point in the future."

**The *social time preference* argument:**
"We should value the welfare of today's society higher than that of tomorrows."

The next chapters will explore each of these arguments in turn.

A fourth argument of note considers the value of delaying emissions insofar as the delay avoids triggering climate tipping points (e.g. disintegration of polar ice sheets, shifting monsoon rains or dieback of the Amazon rainforest). These tipping points are understood to be triggered by specific levels of global warming, with this warming correlated to the peak concentration of greenhouse gases in the atmosphere. However, both the exact thresholds for these tipping points and the timing of peak greenhouse gas concentrations are difficult to predict with precision. While these uncertainties limit the ability to accurately quantify the benefits of delaying emissions, the broader argument highlights the importance of reducing the total volume of emissions. This argument will not be explored further in this report.

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## 2.1 Buying time

The buying time argument is characterised by the idea that through delaying emissions we retain the opportunity to avert them.

The frequency and intensity of extreme weather events driven by climate change are expected to increase [6]. Both human and natural systems require time to adapt to these changes. This may include constructing resilient buildings or facilitating the migration and evolution of ecosystems. However, immediate and significant climate change can overwhelm these systems beyond their adaptive capacity. Temporarily delaying emissions 'buys time' for these systems to adapt. [7].

The concept of 'buying time' is not about ignoring long term solutions, but rather about strategically managing the transition to alleviate immediate risks. Marland et al. [5] highlighted the following reasons for buying time may be of value in supporting a transition:

- Buying time for learning and developing alternatives.
- Buying time for advancement in technology, which could potentially make those future emissions avoidable or significantly reduced.
- Buying time for capital turnover, which could make emission reduction or permanent storage more accessible in the future.

In summarising this work, Dornburg and Marland [7] assert

> “In short, even temporary sinks put us on a lower path for climate change, a path that will not otherwise be accessible. They minimize impacts while we learn and develop alternatives, they may save money for other purposes, and they preserve a broader variety of options for the future”.

Notwithstanding the recognition of this argument, the methods for implementing the 'buying time' argument within life cycle assessments are limited (see Section 3). Notably some WLCA methodologies do consider the decarbonisation of the energy grid when assessing future operational emissions of a building. While the time value of carbon might often be interpreted only through the lens of energy grid decarbonisation, this method is merely one tangible and quantifiable manifestation of the broader 'buying time' argument.

The 'buying time' argument is valid and sound. The strength of the argument is highly dependent on the length and nature of the delay. (i.e. how long and by what means the emissions are delayed in practice).

Intuitively, delaying 1 ton of carbon emissions for 100 years is of more value that delaying 1 ton of carbon emission for 1 year. The longer delay provides more time to learn, progress and to avert such delayed emissions.

The value of delaying emissions is also sensitive to the nature of that delay. For example, if we compare delaying emissions in the sequestration of carbon in timber used in the structural frame, to delaying emissions in the trade-off between embodied and operational carbon in the building design, we may attribute more confidence in our ability to 'advert the delays' in one scenario over the other. Albeit this confidence can be hard to quantify.

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## 2.2 Static time-horizon

The static time-horizon argument is characterised by the idea that delaying emissions reduces their impact when viewed over a fixed period of time (also known as a static time-horizon).

This argument typically assumes a time horizon with a fixed start and end point and evaluates the extent to which emissions released at different times impact the energy balance of the atmosphere. In unpacking this argument, this section presents a short summary of the key underlying concepts.

‘Radiative forcing’ is a measure of the impact an event has on the energy balance of the Earth’s atmosphere. Specifically, it measures the amount of energy that is added or subtracted from the atmosphere resulting from an event. In context of carbon emissions, consider the event of the emission of a 1-ton pulse of carbon dioxide into the atmosphere at year ‘0’, illustrated in Figure 1.

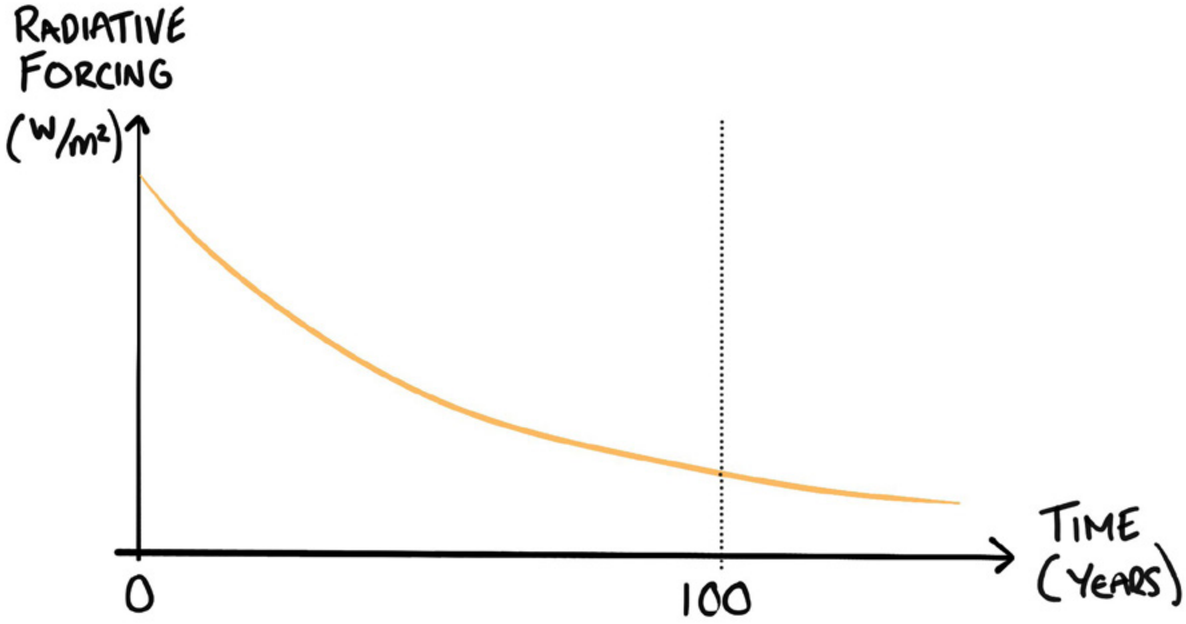

Figure 1
Sketch illustrating the radiative forcing of one ton of carbon dioxide over time

This reduction of radiative forcing over time is a function of both the decomposition of carbon dioxide molecules and its absorption within the complex climatic systems of the Earth.

It follows, a graph of the cumulative radiative forcing of 1 ton of carbon dioxide over time increases at a steadily decreasing rate, illustrated in Figure 2.

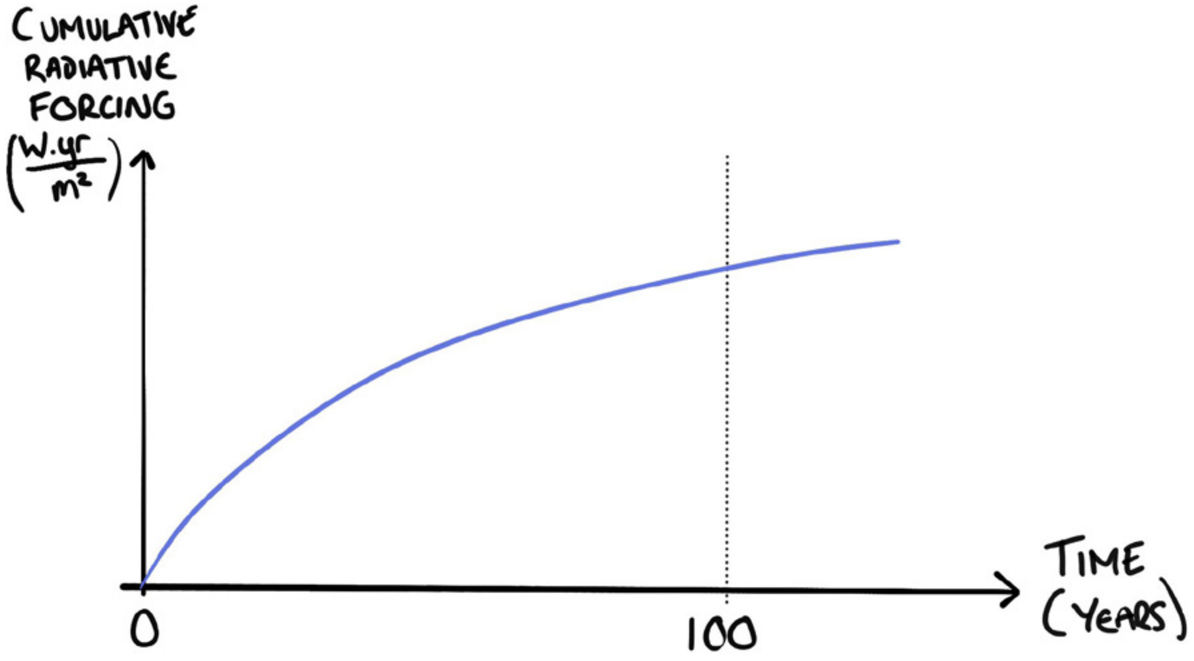

Figure 2
Sketch illustrating the cumulative radiative forcing of one ton of carbon dioxide over time

The static horizon argument takes this cumulative radiative forcing curve (shown in Figure 2) and considers how the delaying of emissions acts to reduce the cumulative radiative forcing when viewed over a fixed time period. These two curves are then used to derive a 'weighting factor' through which future emissions are reduced relative to those today.

There exist multiple methods for interpreting ‘weighting factors’ from this argument. One such approach is illustrated in Figure 3, this and other interpretations are discussed later in this report.

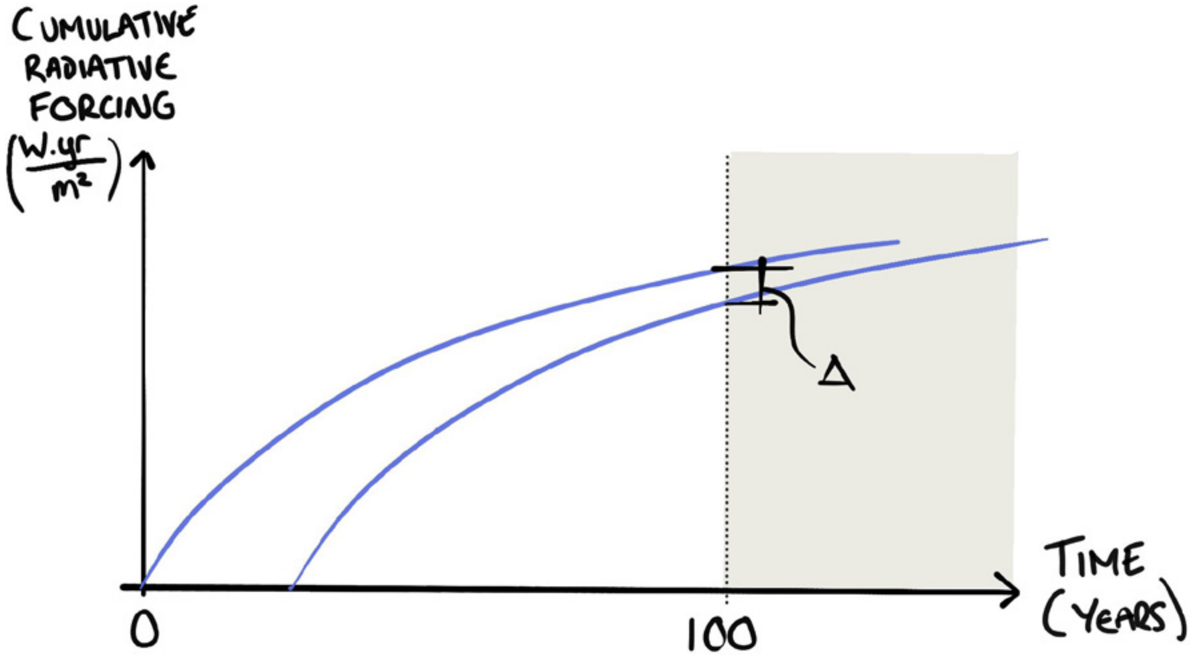

Figure 3
Sketch illustrating the cumulative radiative forcing of one ton of carbon dioxide emitted at year zero and another emitted some time later

The radiative forcing curves (characterised in Figure 1 and Figure 2) have undergone several refinements since their inception in climate change discussions [9] [10] [11]. The Bern Simple Climate Model [11] has been referenced and utilised as the primary model for estimating the distribution of carbon over time. This model has been accepted by the Intergovernmental Panel on Climate Change (IPCC) as the standard for assessing the atmospheric impact of carbon dioxide over a fixed time horizon of 100 years [12].

This has led to the Bern Simple Climate Model sometimes being referred to as the "IPCC Radiative Forcing" curve [13].

It is worth noting here that the cumulative radiative forcing of different greenhouse gases varies, with some gasses (like methane) more impactful but short-lived than carbon dioxide. Global Warming Potential (GWP), the environmental indicator used in WLCAs, is measured in units of mass of 'carbon-equivalence' which normalises the contribution of each greenhouse gas based on an equal cumulative radiative forcing at 100 years.

The static time-horizon argument has received a number of valid criticisms.

Firstly, the argument requires the definition of a 'time-horizon', beyond which further impacts are ignored. The selection of an appropriate time-horizon is inherently subjective [14]. Moreover, the calculated weighting factors are very sensitive to this selected time-horizon [15]. Notably this criticism has also been made of the GWP indicator directly, which benchmarks the impact of different greenhouse gases over a 100-year timeframe. To this end, the selection of a 100-year time horizon has a degree of consistency in the field, albeit this consistency has been described as "inadvertent" [16].

Secondly, many of the methods derived from this argument are based solely on the cumulative radiative forcing of carbon dioxide. As a result, where the greenhouse gas emissions include a significant proportion of non-carbon dioxide gasses these methods will be less accurate [13].

Thirdly, this argument presupposes that 'cumulative radiative forcing' is the only climate indicator we should care about. Other climate indicators exist, including some which track the absolute amount of carbon dioxide in the atmosphere [4], or Global Temperature Change Potential [17].

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## 2.3 Social time preference

The topic of 'social time preference' considers the relative value we place on the welfare of society today over society tomorrow. The concept is commonly used in the field of economics to enable policymakers to compare the cost of policy decisions where those costs are borne at different times.

In giving guidance to policymakers in the UK, the HM Treasury's Green Book [18] identifies the following reasons why a society may value the welfare of the present higher than that of the future.

- 'Pure time preference' – The measured behavioural tendency of people to prefer something today over tomorrow.
- 'Catastrophic risk' – The likelihood of societal collapse such that there is no society to enjoy future welfare. The Stern Review [19] used the metaphor of meteorite strike to characterise this risk.
- 'Wealth effect' – The expected growth in wealth (per capita consumption) over time.

'Discounting' is the method by which social time preference is accounted for in economics. In such circumstances, arguments for a social time preference are used to guide the selection of a 'discount rate'. This discount rate is used to factor down future costs to establish a 'present value'. This 'present value of future costs' provides a consistent basis for comparing costs borne at different times. To this end, the discount rate is a reflection of the relative value society attaches to the present over the future.

In economics, the use of discounting extends to the evaluation of policy decisions with environment impacts. In such instances, the discount rate can be used to derive a financial estimate on the cost resulting from emitting one ton of carbon dioxide. This estimate is referred to as the 'Social Cost of Carbon' and is very sensitive to the discount rate assumed. Figures for a proposed discount rate vary from 0% to nearly 6%.

The selection of an appropriate discount rate is a rich source of debate, it is not simply a matter of science and requires ethical considerations for inter-generational impacts [20] [21].

In 2005, Hal Varian wrote in the New York Times:

> "The choice of an appropriate social time discount rate has long been debated. Some very intelligent people have argued that giving future generations less weight than the current generation is "ethically indefensible." Other equally intelligent people have argued that weighting generations equally leads to paradoxical and even nonsensical results." [22]

In the UK, the Green Book [18] provides guidance on the use of discounting and includes adjustments for environmental assessments. The Green Book encourages assessors to undertake a sensitivity analysis which includes excluding any account for a 'pure time preference' when considering intergenerational effects which "could include irreversible changes to the natural environment" [18]. Furthermore, the Green Book advocates for excluding the 'wealth effect' when considering risks to health and life.

The Stern Review [19], which in large part informed the development of the Green Book, included an allowance of 0.1% for the possibility of catastrophic risk and suggested that such estimate represents a generous allowance [23]. Similarly, representatives at the World Bank have argued that a 0% discount rate should be used in the assessment of climate-sensitive projects, particularly those with long-term impacts. This recommendation reflects the view that future generations should not be disadvantaged in the evaluation of investments aimed at mitigating climate change, given the existential threat it poses and the uncertainty around long-term economic growth [24].

Several countries, including the UK and France, have adopted a 'declining discount rate' approach in policy-making. This method involves applying higher discount rates to near-term costs and benefits, and lower rates to long-term costs and benefits. In comparison to constant discount rates, declining discount rates give more weight to the welfare of future generations. In doing so, declining discount rates go some way to addressing concerns about intergenerational inequality. This approach is also better suited to accounting for increased uncertainty over longer time horizons, which are particularly relevant when dealing with long-term issues like climate change.

Whilst discounting was historically intended to be applied to fiscal costs, measured in pounds and dollars, some authors have proposed approaches for interpreting discounting to physical carbon emissions [25] [2]. Criticisms have been raised insofar as how this application this would divorce the relationship between emissions and their physical climate outcomes and to this end invalidate any claim to physical equivalence [26].


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The 'social time preference' argument has a long history of debate in the field of environmental economics [21]. The factors which contribute to the selection of an appropriate discount rate are largely value driven, requiring ethical considerations. For instance, to what extent does valuing the welfare of current generations over future generations perpetuate environmental intergenerational injustice?

Whilst the practice is more established in assessing the impact of future monetary costs, some evidence has been found demonstrating an approach to applying discounting to future carbon emissions. Albeit with valid criticisms raised on the extent to which this invalidates claims of physical equivalence.

The selected discount rate can strongly influence the value of future carbon and consequently influence decision making. The selection of an appropriate discount rate is notoriously subjective. Strong arguments have been made to suggest a zero or near-zero discount rate is appropriate for assessing decisions with environmental impacts. Furthermore, it could be argued that valuing future generations equally (i.e. a zero discount rate) is inherent within the definition of sustainable development established by the Brundtland Report: *"...development that meets the needs of the present without compromising the ability of future generations to meet their own needs."* [27].

Fearnside et al. poignantly concludes that *"The moral choice for specifying a value for time, zero or otherwise, cannot be avoided."* [8].

## Chapter 3.

# Approaches

The term “dynamic LCA” is used inconsistently in the industry to refer to different approaches. Loosely, the term is used to refer to any LCA that uses an annual weighting factor on future emissions. Conversely LCAs that do not adopt an annual weighting factor are sometimes termed “static LCAs”.

This report has identified five alternative dynamic approaches to quantifying the arguments for the time-value of carbon. In this report, the various approaches will be identified by the name of the first author who initially applied the approach in an original literature.

- The energy grid decarbonisation approach considers the buying time argument, using the forecast decarbonisation of energy grids as an example to quantify the benefits of delaying carbon emissions.
- The Lashof approach explores the application of the static time-horizon argument to the radiative forcing of emissions released at different times.
- The Moura-Costa approach explores the application of the static time-horizon argument by drawing equivalence between the radiative forcing that results from a unit of emission against that which would be avoided through the temporary storage of emissions.
- The Hawkins approach builds on the Lashof approach by expanding the application beyond carbon dioxide to other greenhouse gases.
- The Parisa approach explores applying the social time preference argument to the physical impact of carbon in the atmosphere.

ACCOUNTING FOR TIME IN MITIGATING GLOBAL WARMING THROUGH LAND-USE CHANGE AND FORESTRY

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**Abstract.** Many proposed activities for mitigating global warming in the land-use change and forestry (LUCF) sector differ from measures to avoid fossil fuel emissions because carbon (C) may be held out of the atmosphere only temporarily. In addition, the timing of the effects is usually different. Many LUCF activities alter C fluxes to and from the atmosphere several decades into the future, whereas fossil fuel emissions avoidance has immediate effects. Non-$CO_2$ greenhouse gases (GHGs), which are an important part of emissions from deforestation in low-latitude regions, also pose complications for comparisons between fossil fuel and LUCF, since the mechanism generally used to compare these gases (global warming potentials) assumes simultaneous emissions. A common numeraire is needed to express global warming mitigation benefits of different kinds of projects, such as fossil fuel emissions reduction, C sequestration in forest plantations, avoided deforestation by creating protected areas and through policy changes to slow rates of land-use changes such as clearing. Megagram (Mg)-year (also known as ‘ton-year’) accounting provides a mechanism for expressing the benefits of activities such as these on a consistent basis. One can calculate the atmospheric load of each GHG that will be present in each year, expressed as C in the form of $CO_2$ and its instantaneous impact equivalent contributed by other gases. The atmospheric load of $CO_2$-equivalent C present over a time horizon is a possible indicator of the climatic impact of the emission that placed this load in the atmosphere. Conversely, this index also provides a measure of the benefit of *not* producing the emission. One accounting method compares sequestered $CO_2$ in trees with the $CO_2$ that would be in the atmosphere had the sequestration project not been undertaken, while another method (used in this paper) compares the atmospheric load of C (or equivalent in non-$CO_2$ GHGs) in both project and no-project scenarios. Time preference, expressed by means of a discount rate on C, can be applied to Mg-year equivalence calculations to allow societal decisions regarding the value of time to be integrated into the system for calculating global warming impacts and benefits. Giving a high value to time, either by raising the discount rate or by shortening the time horizon, increases the value attributed to temporary sequestration (such as many forest plantation projects). A high value for time also favors mitigation measures that have rapid effects (such as slowing deforestation rates) as compared to measures that only affect emissions years in the future (such as creating protected areas in countries with large areas of remaining forest). Decisions on temporal issues will guide mitigation efforts towards options that may or may not be desirable on the basis of social and environmental effects in spheres other than global warming. How sustainable development criteria are incorporated into the approval and crediting systems for activities under the Kyoto Protocol will determine the overall environmental and social impacts of pending decisions on temporal issues.

**Keywords:** carbon dioxide, deforestation, discount rate, global warming, greenhouse effect, land-use change, mitigation, time preference

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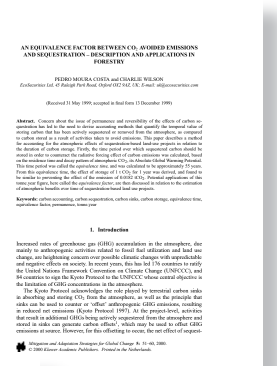

AN EQUIVALENCE FACTOR BETWEEN $CO_2$ AVOIDED EMISSIONS AND SEQUESTRATION – DESCRIPTION AND APPLICATIONS IN FORESTRY

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**Abstract.** Concern about the issue of permanence and reversibility of the effects of carbon sequestration has led to the need to devise accounting methods that quantify the temporal value of storing carbon that has been actively sequestered or removed from the atmosphere, as compared to carbon stored as a result of activities taken to avoid emissions. This paper describes a method for accounting for the atmospheric effects of sequestration-based land-use projects in relation to the duration of carbon storage. Firstly, the time period over which sequestered carbon should be stored in order to counteract the radiative forcing effect of carbon emissions was calculated, based on the residence time and decay pattern of atmospheric $CO_2$, its Absolute Global Warming Potential. This time period was called the *equivalence time,* and was calculated to be approximately 55 years. From this equivalence time, the effect of storage of 1 t $CO_2$ for 1 year was derived, and found to be similar to preventing the effect of the emission of 0.0182 $tCO_2$. Potential applications of this tonne.year figure, here called the *equivalence factor*, are then discussed in relation to the estimation of atmospheric benefits over time of sequestration-based land use projects.

**Keywords:** carbon accounting, carbon sequestration, carbon sinks, carbon storage, equivalence time, equivalence factor, permanence, tonne.year

1. Introduction

Increased rates of greenhouse gas (GHG) accumulation in the atmosphere, due mainly to anthropogenic activities related to fossil fuel utilization and land use change, are heightening concern over possible climatic changes with unpredictable and negative effects on society. In recent years, this has led 176 countries to ratify the United Nations Framework Convention on Climate Change (UNFCCC), and 84 countries to sign the Kyoto Protocol to the UNFCCC whose central objective is the limitation of GHG concentrations in the atmosphere.

The Kyoto Protocol acknowledges the role played by terrestrial carbon sinks in absorbing and storing $CO_2$ from the atmosphere, as well as the principle that sinks can be used to counter or ‘offset’ anthropogenic GHG emissions, resulting in reduced net emissions (Kyoto Protocol 1997). At the project-level, activities that result in additional GHGs being actively sequestered from the atmosphere and stored in sinks can generate carbon offsets[1], which may be used to offset GHG emissions at source. However, for this offsetting to occur, the net effect of sequest-

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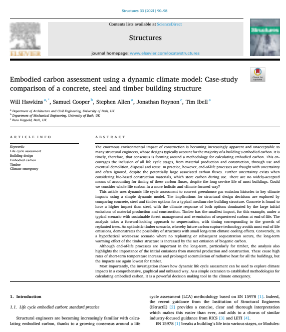

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Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure

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ABSTRACT

The enormous environmental impact of construction is becoming increasingly apparent and unacceptable to many structural engineers, whose designs typically account for the majority of a building's embodied carbon. It is timely, therefore, that consensus is forming around a methodology for calculating embodied carbon. This encourages the inclusion of all life cycle stages, from material production and construction, through use and eventual demolition, disposal and reuse. In practice, however, end-of-life processes are fraught with uncertainty and often ignored, despite the potentially large associated carbon fluxes. Further uncertainty exists when considering bio-based construction materials, which store carbon during use. There are no widely-accepted means of accounting for timing of these carbon fluxes, despite the long service life of most buildings. Could we consider whole-life carbon in a more holistic and climate-focused way?

This article uses dynamic life cycle assessment to convert greenhouse gas emission histories to key climate impacts using a simple dynamic model. The implications for structural design decisions are explored by comparing concrete, steel and timber options for a typical medium-rise building structure. Concrete is found to have a higher impact than steel, with the climate response of both options dominated by the large initial emissions of material production and construction. Timber has the smallest impact, for this example, under a typical scenario with sustainable forest management and re-emission of sequestered carbon at end-of-life. The analysis takes a forward-looking approach to sequestration, with timing corresponding to the growth of replanted trees. An optimistic timber scenario, whereby future carbon-capture technology avoids most end-of-life emissions, demonstrates the possibility of structures with small long-term climate cooling effects. Conversely, in a hypothetical worst-case scenario where no replanting or subsequent sequestration occurs, the long-term warming effect of the timber structure is increased by the net emission of biogenic carbon.

Although end-of-life processes are important in the long-term, particularly for timber, the analysis also highlights the importance of the initial emissions from material production and construction. These cause high rates of short-term temperature increase and prolonged accumulation of radiative heat for all the buildings, but the impacts are again lowest for timber.

Most importantly, the investigation shows how dynamic life cycle assessment can be used to explore climate impacts in a comprehensive, graphical and unbiased way. As a simple extension to established methodologies for calculating embodied carbon, it is a powerful decision making tool in the climate emergency.

1. Introduction

1.1. Life cycle embodied carbon: standard practice

Structural engineers are becoming increasingly familiar with calculating embodied carbon, thanks to a growing consensus around a life cycle assessment (LCA) methodology based on EN 15978 [1]. Indeed, the recent guidance from the Institution of Structural Engineers (IStructE) [2] provides a concise, clear and thorough interpretation which makes this easier than ever, and adds to a chorus of similar industry-focused guidance from RICS [3] and LETI [4].

EN 15978 [1] breaks a building's life into various stages, or Modules:

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The time value of carbon storage

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Ton-years
Short-term storage

ABSTRACT

Widespread concern about the risks of global climate change is increasingly focused on the urgent need for action, and natural climate solutions are a critical component of global strategies to achieve low temperature targets. Yet to date, the full potential of natural systems to store carbon has not been leveraged because policymakers have required long-term contracts to compensate for permanence concerns, and these long-term contracts substantially raise costs and limit deployment. In this paper, we lay out the rationale that our time preference for early action leads to the conclusion that multiple tons of short-term storage of carbon in ecosystem stocks can be considered to have equal value – as measured by the social cost of carbon – as 1 ton of carbon sequestered permanently. This equivalence can be used to quantify the value of short-term carbon storage, thereby removing one of the most significant barriers to participation in the carbon market and enabling the full climate mitigation potential of the land sector to be realized.

1. Introduction

Widespread concern about the risks of global climate change is increasingly focused on the urgent need for action (IPCC, 2018). The IPCC's recent Working Group I report, for example, finds that "unless there are immediate, rapid and large-scale reductions in greenhouse gas emissions, limiting warming to close to 1.5°C or even 2°C will be beyond reach" (IPCC, 2021). Most scenarios for the future suggest that limiting global-average warming to 1.5°C will require massive deployment of negative emissions technologies (NETs) (Gasser et al., 2015; Hilaire et al., 2019; IPCC, 2018). Negative emissions technologies, such as growing trees to remove carbon from the atmosphere, have long been recognized as a potential mechanism for limiting the amount of carbon dioxide ($CO_2$) in the atmosphere. A number of studies have now shown that at relatively low cost, Natural Climate Solutions (NCS) in the form of improved land stewardship practices could provide as much as one-third of the emissions reductions needed through 2030 to achieve a high likelihood of holding warming to less than 2 °C (Fuss et al., 2014; Griscom et al., 2017; Roe et al., 2019).

Recent studies have shown that for the global land-use, land-use change, and forestry (LULUCF) sector to achieve its potential contribution, it must become carbon neutral by 2030, it must provide net abatement for the remainder of the century, and forest area may need to increase by up to 900 million hectares (Roe et al., 2019). Numerous studies have suggested this level of abatement is possible through application of forest conservation (Busch and Engelmann, 2017), improved forest management (Griscom et al., 2017), afforestation and reforestation (Bastin et al., 2019; Lewis et al., 2019), soil carbon storage, and other land-based practices. Furthermore, the commitments in country-level Nationally Determined Contributions for the Paris Agreement show that national policymakers also expect that the LULUCF sector will play a critical role (Forsell et al., 2016; Fyson and Jeffery, 2019). To date, however, progress toward widespread implementation of these solutions has fallen well short of what will be required (IPCC, 2022).

In response to concern over the rising concentration of atmospheric $CO_2$ and the likely impacts of climate change, countries, communities, and corporations are committing to aggressive emissions reduction goals, for example through net-zero commitments. Progress toward near-term emission reduction targets for a given entity often involves carbon offsets – including tradeable emission reductions or carbon storage credits that one entity can purchase from another to reduce their net carbon emissions.

A critical factor that has slowed implementation of LULUCF options

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## 3.1 Energy grid decarbonisation approach

The decarbonisation of energy grids illustrates one tangible and quantifiable way of assessing the value of ‘buying time’ in a whole life carbon assessment.

Many countries are actively working to reduce the carbon intensity of their national energy grids, with several having publicly available forecasts for their decarbonisation scenarios. In the UK, the National Grid develops Future Energy Scenarios (FES) present a range of different credible decarbonisation scenarios for the energy system. RICS Whole Life Carbon Assessment advises designers in the UK to use the ‘falling short scenario’ (shown in Figure 4) to integrate the effect of grid decarbonisation into the results of the operational energy emissions of the building.

Factoring future emissions down based on these forecast scenarios, provides a way to integrate the benefits of buying time in the context of a buildings operational energy consumption.

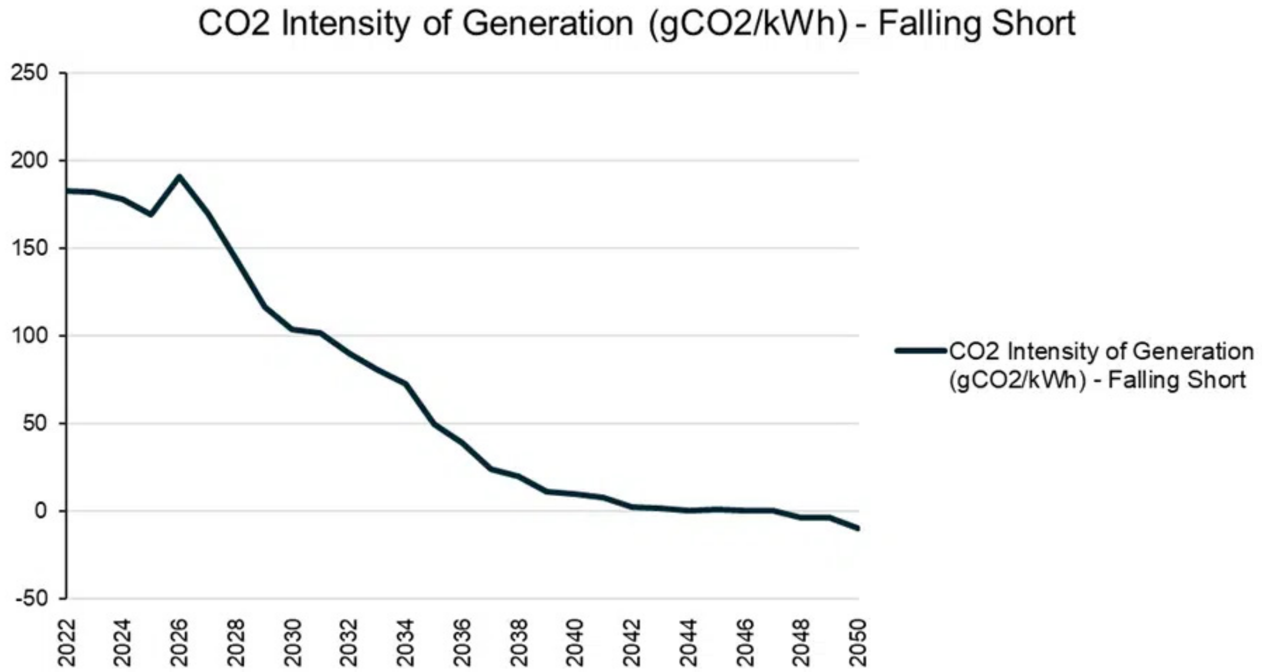


Figure 4
UK National Grid “Future Energy Scenarios”, $CO_2$ intensity of generation – Falling short scenario

## 3.2 Lashof approach

The Lashof Approach [8] provides a method for accounting for the static time-horizon argument. It is sometimes referred to as a “ton-year approach” that compares the cumulative impact of delaying carbon dioxide emissions measured over a 100 year period.

The longer the carbon dioxide emission is avoided under this accounting system, the more significant the avoided climate impacts.

To illustrate the Lashof approach, consider a graph of the cumulative radiative forcing from a one-ton carbon dioxide emission (shown in Figure 2 in Section 2.2). The Lashof approach considers this curve alongside an equivalent delayed (say by ‘n’ years) curve (Figure 5). This delayed curve is represented by the translation of the curve along the horizontal axis. It can be seen that at year 100, an emission 100 years hence has a greater cumulative radiative forcing than an equivalent emission ‘100-n’ years hence. The Lashof approach uses this difference in cumulative radiative forcing at 100 years to evaluate a weighting factor. In turn, this weighting factor is used to reduce future emissions.

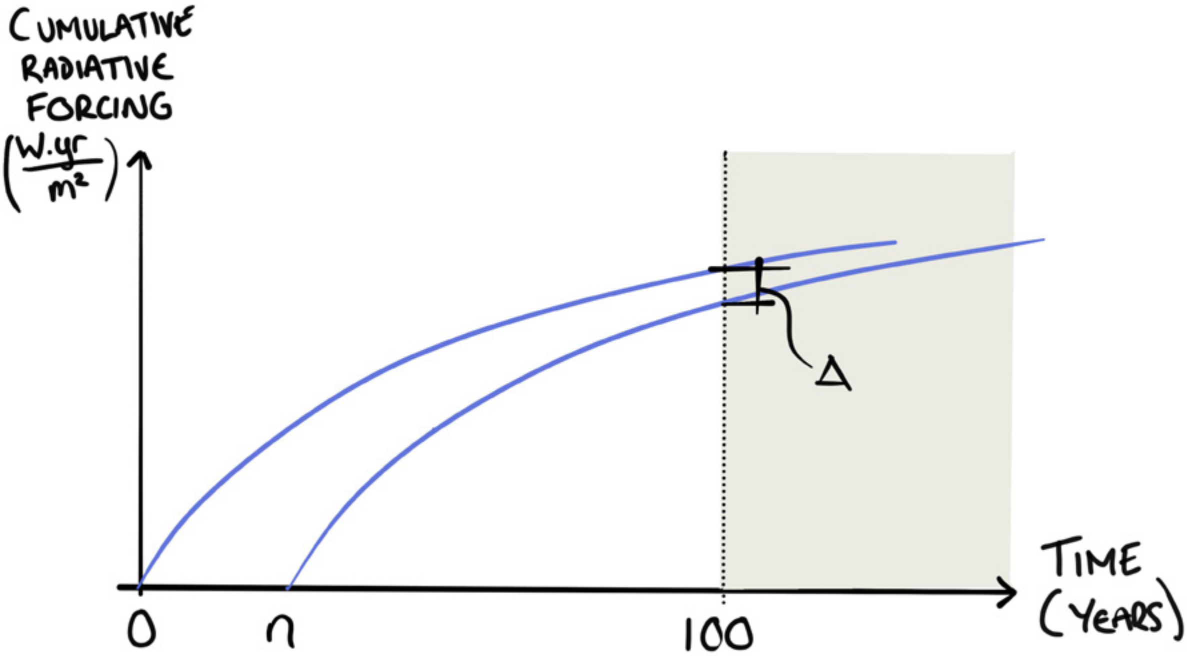


Figure 5
Sketch illustrating the cumulative radiative forcing of one ton of carbon dioxide emitted at year zero and another emitted ‘n’ years later

A weighting factor for the delayed emission at any given year under the time horizon of 100 years following the Lashof approach can be simplified in Equation:

$$WF_{L(n)} = \frac{\text{GWP}\ (100 - n)}{\text{GWP}\ (100)}$$

Where:

| | |
|---|---|
| $WF_{L(n)}$ | *Weighting factor for emissions delayed to year n accounted using the Lashof Approach* |
| *GWP (100 – n)* | *Cumulative radiative forcing of a unit mass of carbon dioxide with a delayed emission of n years (shown as approximately 25 years in Figure 5), at fixed time horizon (taken here as 100 years)* |
| *GWP (100)* | *Cumulative radiative forcing of a unit mass of carbon dioxide at fixed time horizon (taken here as 100 years)* |

The weighting factors that result from the Lashof Approach are presented in Figure 6. The weighting factor decreases in a slightly concave function from 1.0 at year zero to 0.0 at year 100. Beyond the 100-year time horizon the weighting factor remains at 0.0, this reflects the nature of the approach which ignores any consideration of emissions that extend beyond the time horizon.

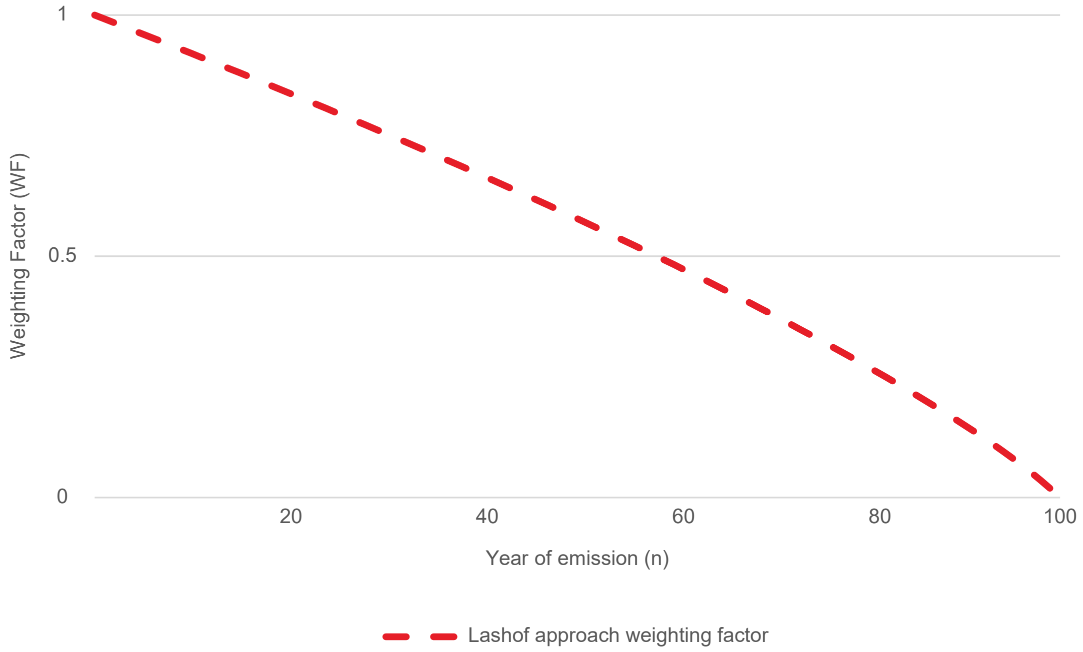


Figure 6
100-year weighting factor for delayed emission using the Lashof Approach

The Lashof approach has been internationally recognized and incorporated into France's national standards for WLCA of new constructions [30], providing a simple method to account for the benefits of delaying carbon dioxide emissions (See Section 4.14.1). However, some have argued that this method is not an accurate reflection of the true impact of carbon emissions [2]. Notably the approach is criticised for its arbitrary choice of time horizon, beyond which the impact of the emissions are completely ignored.

### 3.3 Moura-Costa approach

The Moura-Costa Approach [32] seeks to offer a simple linear equivalence through which to value temporary storage. It is another ton-year approach that was derived from the static time-horizon argument, specifically in the context of valuing the temporary storage of carbon in timber sequestration.

The method achieves a relatively concise solution by drawing an equivalence between the radiative forcing that results from a unit of emission over 100 years against that which would be avoided through the temporary storage of emissions (see Figure 1). Unlike the Lashof approach, the Moura-Costa Approach considers the fact that the radiative forcing of carbon dioxide in the atmosphere decreases over time while the benefits of avoided emissions remain constant.

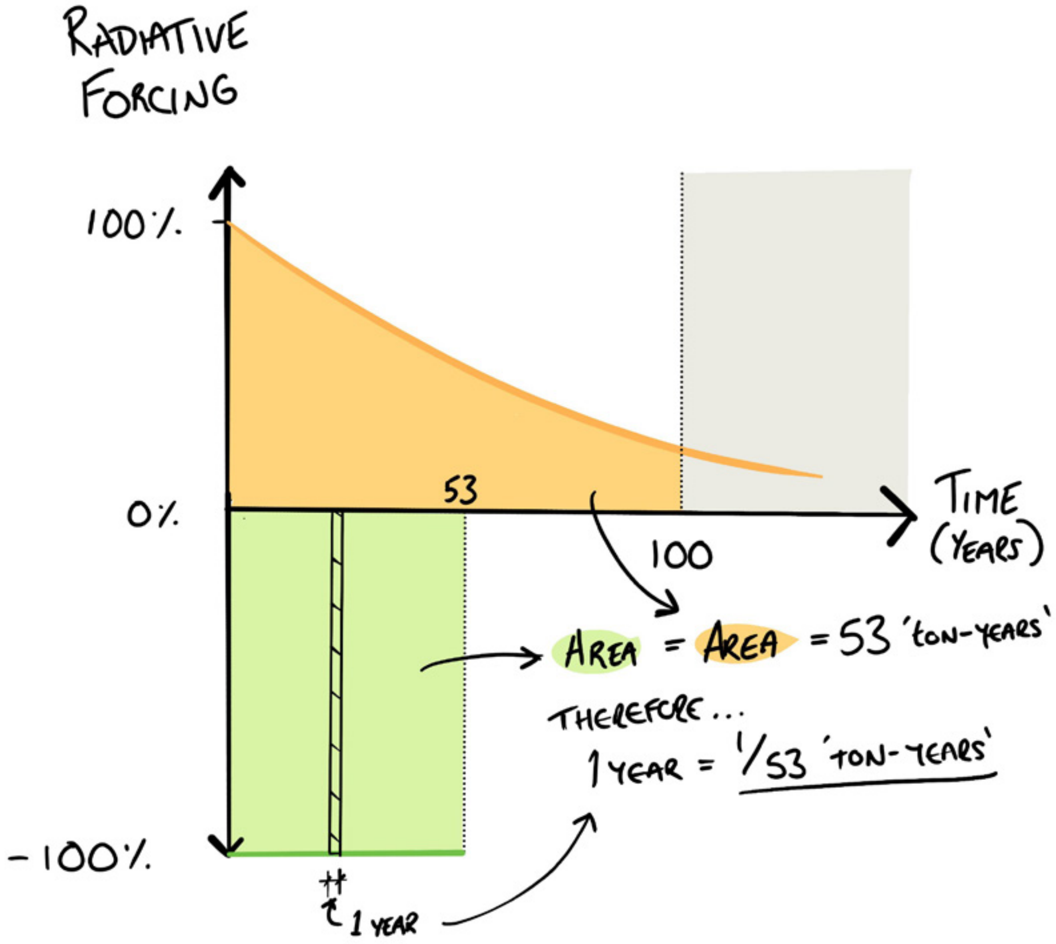


Figure 7
The Moura-Costa Approach equates the cumulative radiative forcing of a unit mass of carbon dioxide in the atmosphere over 100 years (shown in orange) with the cumulative avoided radiative forcing of keeping the same mass of carbon dioxide out of the atmosphere for 53 years (shown in green).

Based on the latest Bern Simple Climate Model [11], the Moura-Costa Approach concludes that keeping 1 ton of carbon dioxide out of the atmosphere for one year can considered equivalent to 0.0189 (= 1/53) tonnes of carbon dioxide permanently avoided.

The method was derived specifically in the context of valuing sequestered carbon in timber, to this end the authors did not explore how the equivalence drawn could be used to evaluate a 'weighting factor' for emissions released at different times.

The challenges with interpreting such a weighting factor highlight some of the criticisms of the Moura-Costa Approach – in particular, the possibility of over-crediting sequestration [33].

> The Moura-Costa approach of deriving equivalence between one ton of temporary carbon storage for one year with 1/53 tonnes of permanent storage is appealing in its simplicity. However, the simplification proposed introduces challenges when an 'annual weighting factor' is interpreted and can lead to non-sensical results. Notably, the assumption that an instantaneous negative emission is representative of carbon storage of any kind except direct air capture is questionable.

## 3.4 Hawkins approach

Building on the Lashof approach, the Hawkins approach expands the static time-horizon argument to more greenhouse gases beyond carbon dioxide.

This approach was first proposed by Levasseur et al. in 2010 [34], further developed by Cooper [35] and adopted by Hawkins et al. [15] in 2021.

Although its core principles align with the Lashof Approach, the Hawkins Approach offers a more accurate reflection of reality by considering various indicators beyond cumulative radiative forcing. It could be used to consider impacts of any greenhouse gases (beyond carbon dioxide) and readily adapts to varying time horizons.

Cooper [35] has incorporated this methodology into an open-source spreadsheet tool. It accommodates the effects of prevalent greenhouse gasses including carbon dioxide, methane, and nitrous oxide, across three indicators: mass in the atmosphere, cumulative radiative forcing, and the rate of atmospheric temperature change. This tool was applied by Hawkins et al. to analyse and compare various structural design solutions of different building materials in the article “Embodied carbon assessment using a dynamic climate model: Case-study comparison of a concrete, steel and timber building structure” [15].

Some experts consider the Hawkins Approach as the most appropriate form of LCA for bio-based products, particularly because it can more accurately approximate forest growth rates [36]. Nevertheless, the complexity of this methodology could also be viewed as a drawback. Its practical implementation poses challenges due to the intricate relationship between various greenhouse gas emissions and impact indicators.

Industry practitioners assessing the WLC of buildings rely on data from supplier’s Environmental Performance Declarations (EPDs). The data in EPDs is insufficiently detailed to understand the composition of GHGs contributing to a products’ GWP and therefore this data limitation becomes a barrier to implementing this method in practice.

## 3.5 Parisa approach

In their 2022 paper, Parisa et al. [2] highlighted some of the criticisms of the static time-horizon approach and proposed an alternative. Their proposed approach – termed an “economically-efficient ton-year methodology” – aims to quantify the social time-preference argument by applying ‘discounting’ to cumulative radiative forcing curves.

The Parisa Approach takes the carbon dioxide cumulative radiative forcing curves, introduced in section 2.2, and discounts the radiative forcing that occurs in the future. The radiative forcing is discounted in accordance with a derived social cost of carbon for each successive year (Figure 8). Note, this social cost of carbon is largely guided by the assumed discount rate (see section 2.3).

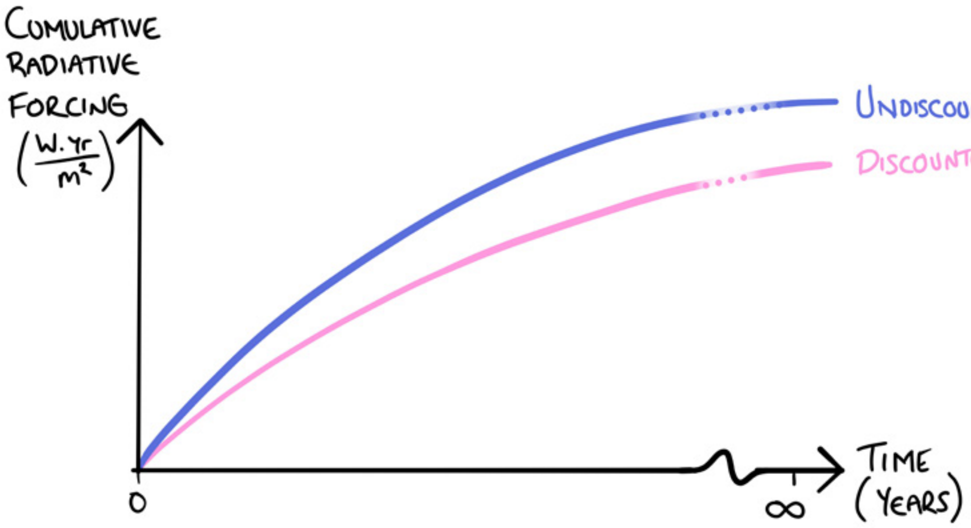


Figure 8
Sketch illustrating the cumulative radiative forcing of one ton of carbon dioxide emitted into the atmosphere. The second ‘discounted’ curve illustrates the Parisa approach of reducing future radiative forcing to reflect the reduced social cost of carbon in the future.

The Parisa approach takes a ‘discounted’ cumulative radiative forcing curve, starting at year zero, and compares this with a delayed curve. In doing so, it can be observed that the delayed curve tends towards a lower total cumulative emissions at an infinite point in the future (Figure 9).

By comparing the magnitude of cumulative radiative forcing between these two curves at an infinite time in the future, the Parisa approach derives a weighting factor for ‘valuing’ the temporary delay of emissions.

For the purpose of exploring the approach, their paper adopts a net discount rate of 3.3% and acknowledges the selection of a discount rate significantly affects the weighting factors derived. [2]

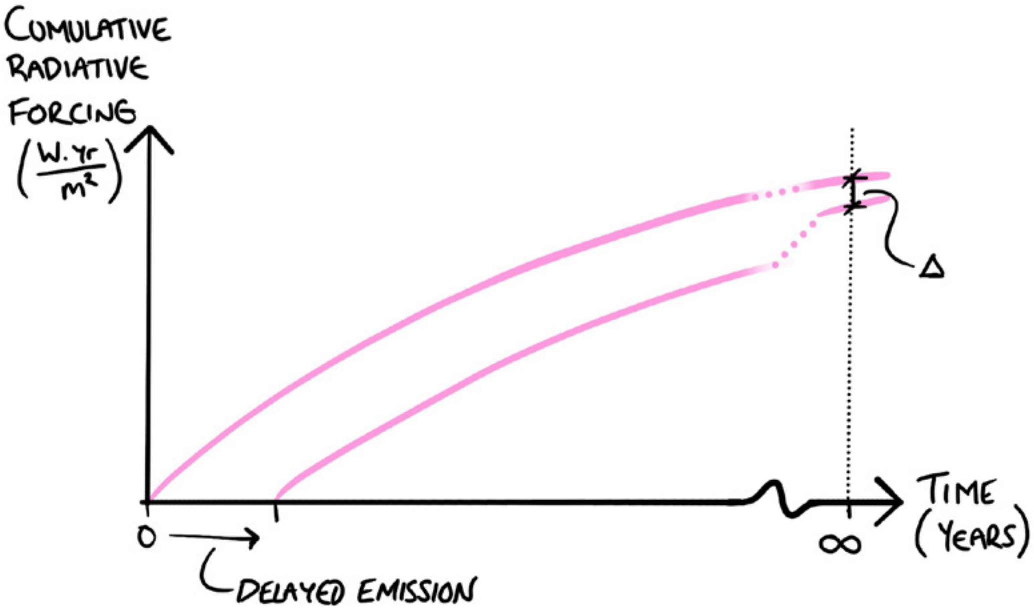


Figure 9
Sketch illustrating how cumulative radiative forcing of delayed emissions curve results is lower at an infinite point in the future based on the future discounting applied to the curve.

Compared to the other approaches discussed in this report, the Parisa approach is unique in its application of social time preference argument in valuing emissions. By avoiding having to adopt a fixed time period the approach avoids some of the criticisms levied at the other approaches. The paper acknowledges that the most important consideration for determining the value of delaying emissions is the discount rate, which remains a largely subjective decision (see section 2.3).

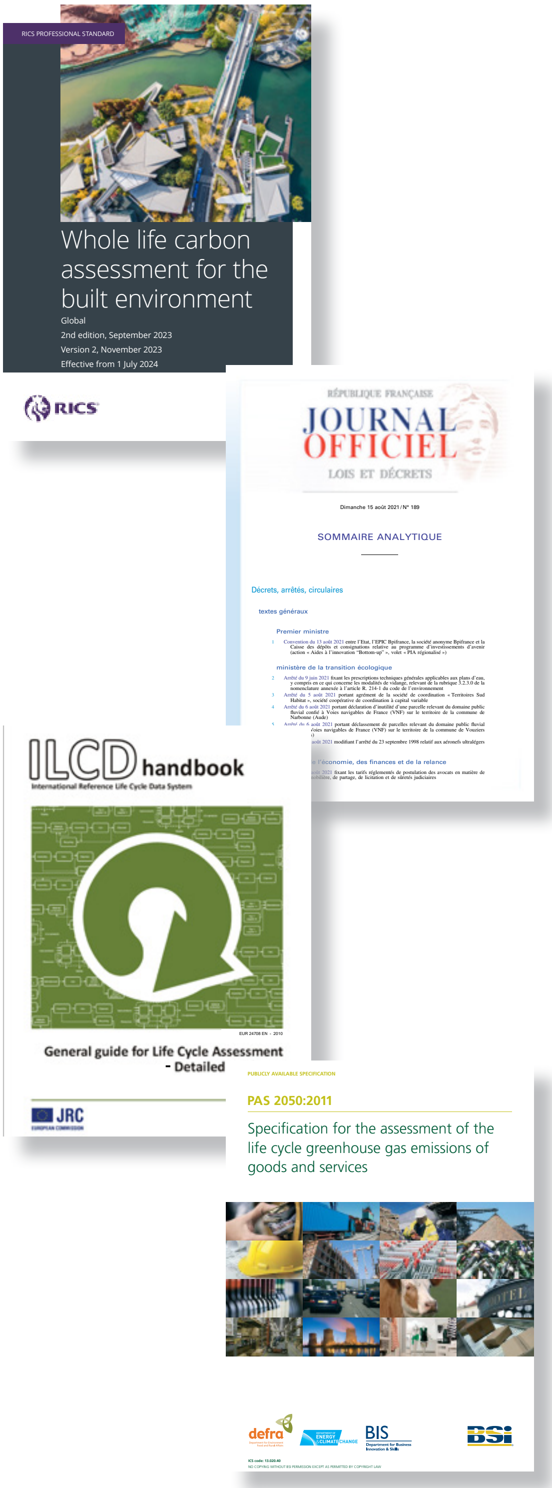
**Chapter 4.**

# Adoption

## Adoption of the presented approaches is generally limited to academia. The timing of emissions is not accounted for by most mainstream WLCA methods, including the guidance within the construction industry such as BS EN 15804, 15978, and PAS 2080.

Notwithstanding, this chapter spotlights three examples where the time-value of carbon has been adopted in industry:

- UK guidance (RICS) recommends the use of weighting factors designed to reflect the anticipated decarbonisation of both the energy grid and material production processes to capture the value of the buying time argument.
- French regulations (RE2020): France's RE2020 regulations mandate the use of weighting factors based on the Lashof approach for WLCA of new buildings.
- Industry standards (ILCD and PAS2050): The international reference to life cycle inventory and the British Standard for specification of goods and services recommends the use of weighting factors if or when considering the time value of carbon. These standards propose a simplified version of the Lashof approach weighting factors.



RICS PROFESSIONAL STANDARD

Whole life carbon assessment for the built environment

Global

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RICS

RÉPUBLIQUE FRANÇAISE

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General guide for Life Cycle Assessment - Detailed

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PUBLICLY AVAILABLE SPECIFICATION

PAS 2050:2011

Specification for the assessment of the life cycle greenhouse gas emissions of goods and services

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## 4.1 RICS

The Royal Institute of Chartered Surveyors (RICS) methodology [37] for assessing whole life carbon of assets within the built environment provides guidance on valuing the buying time argument by considering both grid and material decarbonisation.

When assessing the emissions associated with a building's operation in the UK within Module B6, RICS recommends the use of FES "falling short" scenario, as described in Section 3.1. This scenario captures the slowest plausible decarbonisation trajectory in the UK. Implementing grid decarbonisation pathways allows assessors to value the advantages of delaying energy consumption insofar as it provides the grid more time to decarbonise, but also emphasises the significance of generating renewable energy today rather than in the future. It should be noted that this approach is not recommended for the standard assessments submitted for planning with the Greater London Authority due to concerns regarding the reliability and uncertainty in decarbonisation pathways [38].

In addition to the decarbonisation of the energy grid, the processes involved in the production of materials are anticipated to undergo decarbonisation as well. This trend has already been observed in the steel industry, where the adoption of electric arc furnaces has significantly lowered the energy intensity involved in producing new steel products. The UK government has outlined roadmaps towards net zero for numerous sectors, both domestically and internationally. These roadmaps are founded on the optimistic prospects of developing and deploying new technologies, alongside shifts in consumer behaviours. To accurately reflect these strategies within the framework set by standards EN 15978 and EN 17472, which demand a "like-for-like" replacement, RICS introduced weighting factors for certain modules. These factors anticipate a decarbonisation ceiling of 50%, as detailed in the summary that follows:

| Life-cycle modules | Weighting Factor |
|---|---|
| B1.2 (fugitive refrigerant emissions) | 0.5 |
| B2-B4 | 0.5 |
| B5 (excluding biogenic carbon) | For replacement within 30 years:<br>1-(1.66a/100)<br>Where a is the year of change<br>e.g. if an MVHR is expected to be replaced in 15 years, its weighting factor would be 1-(1.66*15/100) = 0.751<br>For replacement beyond 30 years: 0.5 |
| C1-C2 | For end-of-life after 60 years: 0.5 |
| D1 | For end-of-life after 60 years: 0.5 |

## 4.2 French regulations (RE2020)

In 2022, France's RE2020 regulation came into force in response to the European Union's commitment to achieving carbon neutrality by 2050. The regulation establishes ambitious limits on embodied carbon for new construction and promotes a dynamic approach to life cycle assessments that considers the timing of carbon emissions [39].

Article 11 [39] mandates the application of a set of weighting factors based on the year of emission, with a separate set for emissions involving refrigerants. These weighting factors (rounded to 3 decimal points) are based on the Lashof approach . Unlike the Lashof approach, which allows for a delay until the end of the time horizon, RE2020 allows the estimation of emissions delayed by up to 50 years, this aligns with the building's reference life cycle set out in the regulation.

Figure 10 illustrates the RE2020 weighting factors overlain against those of the Lashof approach. Here it can be seen that the RE2020 weighting factor decreases at the same rate as the Lashof Approach, with a cut-off at 50 years. Beyond this point, it is assumed that no further carbon activities will occur since it surpasses the expected duration of one building life cycle.

The adoption of this approach has received commendation for favouring temporary storage of biogenic carbon, thereby promoting the use of bio-based materials [40]. It should be noted that the potential resulting net-negative carbon emissions of bio-based materials risks incentivising overconsumption.

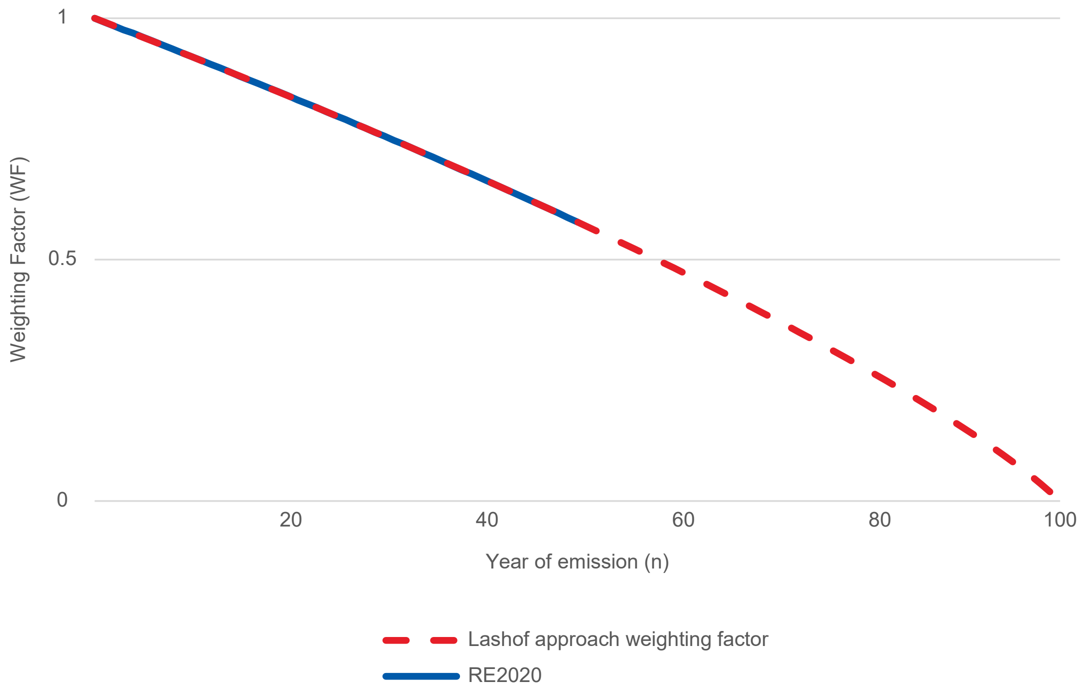

Figure 10
100-year weighting factor for delayed emission as recommended by RE2020, plotted against the Lashof weighting factors.

## 4.3 Industry standards (ILCD & PAS2050)

A number of industry standards provide guidance on accounting for the time-value of carbon.

The International Reference Life Cycle Data System (ILCD) [41] (a framework providing a consistent basis for life cycle assessment modelling) and PAS2050 [42] (a standard for businesses calculate the carbon footprint of their goods and services) both proposed simplified version of the Lashof approach.

Whilst ILCD recommends equal weighting for all impacts without discounting over time, it also recognises the need to incentivise temporary carbon storage and offers a simple correction factor (i.e. weighting factor) for delayed emissions [41].

PAS2050 offers two sets of weighting factors for delayed emissions: one for the general assessment of any delayed emissions within 100 years, and another further simplified approach for a single delayed release within 25 years of product formation [42].

Both standards propose a simple weighting factor that decreases linearly from 1.0 at year zero to 0.0 at year 100. This weighting factors is illustrated in Figure 8 alongside that of the Lashof approach and the RE2020.

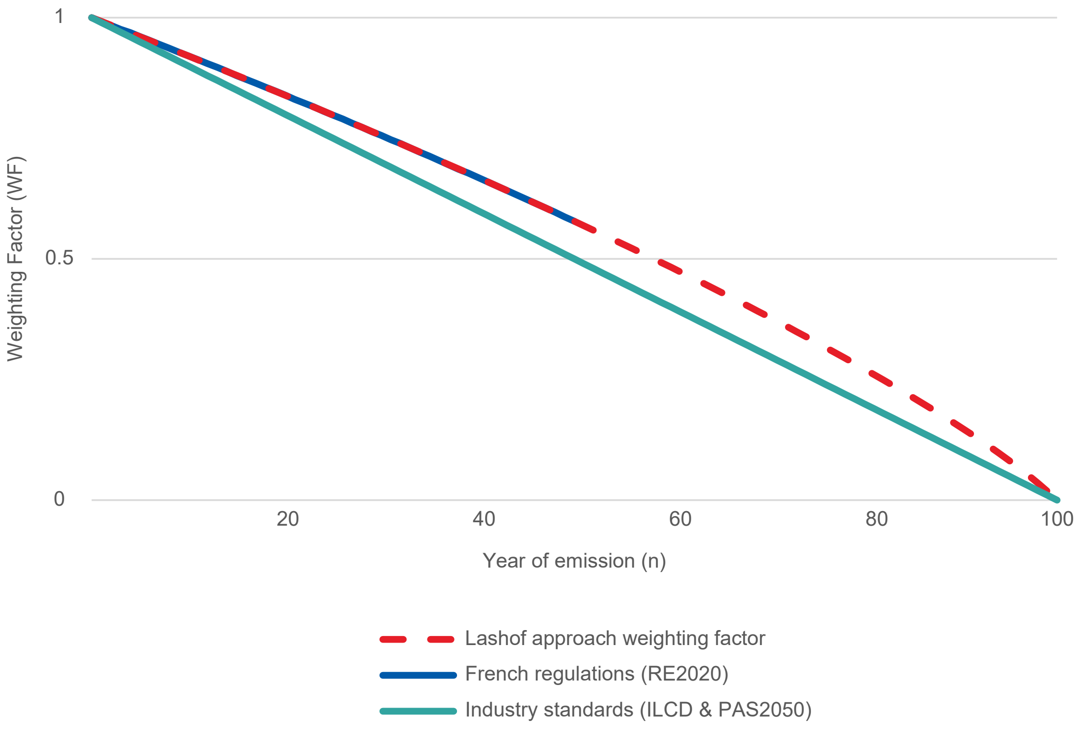

Figure 11
100-year weighting factor for delayed emission using the simple linear method, plotted against the Lashof and RE2020 weighting factors

Despite the different formulations presented in ILCD and PAS2050, the weighting factors for delayed emissions are identical in both standards. These factors can be expressed in a single equation, as shown in the equation below.

$$WF_{S(n)} = \frac{100 - (n - n_o)}{100}$$

Where:

| | |
|---|---|
| $WF_{S(n)}$ | *Weighting factor for emissions delayed to year n accounted using the Simplified Linear Weighting Method applicable to ILCD and PAS2050* |
| $n$ | *Year in which emissions occur* |
| $n_O$ | *Year of upfront carbon emissions* |

**Chapter 5.**

# Application

In introducing the time-value of carbon, this report touches on some of the complexity and subjectivity inherent in the topic. The methodologies presented could be incorporated into whole-life carbon assessments as has been done in French RE2020 regulations.

In reducing emissions of our building projects, the value whole-life carbon assessments offer is in enabling comparison between projects guided by benchmarks. To this end, at the time of publication, the authors feel introducing the time-value of carbon into whole-life carbon assessments risks fragmenting and confusing developing datasets when the industry needs to prioritise greater harmonisation.

Instead, it is recommended that the ‘time-value of carbon’ is considered only insofar as it can add value to aid specific decision making on projects. To support this, the subsequent examples illustrate the integration of the time-value of carbon into the decision-making process for project design decisions. These instances delve into using the concept to quantify the benefit of sequestration and to balance the impact of decisions across both embodied and operational emissions.

The examples provided here are streamlined to emphasise how the time-value of carbon can add value to project decision-making.

## 5.1 Quantifying the benefits of timber sequestration

Carbon sequestration occurs when plants absorb atmospheric carbon dioxide through photosynthesis and store it in their biomass. In doing so, this process helps reduce atmospheric carbon dioxide concentration.

In construction, mass timber is often referred to as a "carbon sink" material. By storing carbon from their growth phase within the timber product, the biogenic carbon can be held out of the atmosphere for the lifespan of the product. This scenario is akin to ‘delaying’ the carbon emission for the duration of the timber product’s lifespan. Without assurances on the end-of-life scenario, it is typically assumed the sequestered carbon will be emitted to the atmosphere at the end of its life. Whilst difficult to value, sequestration also preserves the opportunity to avert these sequestered emissions by buying time.

Many whole-life carbon assessment methodologies require biogenic carbon only to be included when evaluating end-of-life processes. Such assessments do not permit the ‘value’ of delaying the sequestered emissions to be quantified. The example presented below illustrates the same timber production life-cycle emissions with and without consideration for the time-value of carbon.

### Current practice

In BS EN 15804 standard for Environmental Product Declarations, sequestered (or “biogenic”) carbon has its own environmental impact category [43]. The use of both RICS [37] and EN 15804's guidelines result in an LCA of timber products that accounts for sequestration in Module A, alongside timber harvesting and production processes, and a full release in Module C, assuming combustion or decomposition at its end of life.

One of the most common and widely available sources of data for the global warming impact of timber products is a timber product's EPD. Table 1 displays a typical timber product's EPD [44] assessed according to the EN 15804 standard, highlighting the three climate change impact categories, grouped by life cycle modules. This data is interpreted in Figure 12 and Figure 13.

Table 1
Global warming potential of a timber product

| | Global warming potential (kgCO$_{2e}$/m$^3$) | | | |
|---|---|---|---|---|
| | A1-A5 | B1-B7 | C1-C4 | D |
| Fossil | 107 | 0 | 36 | -365 |
| Biogenic | -762 | 0 | 762 | 0 |
| Land use and land transformation | 1 | 0 | 0 | 0 |
| Sum | -654 | 0 | 798 | -365 |

In current LCA practices, the GWP of timber product over Modules A-C is net positive (See Figure 13). This is because the biogenic carbon sequestered in Module A is completely offset by remission in Module C.

## Consideration for the time-value of carbon

By factoring in the time-value of carbon when evaluating the global warming potential of timber products, it provides a means to quantify the benefits associated with the sequestered emissions. A weighting factor (see Table 3) is applied to the respective emissions based on the year in which they occur. This simplified example assumed the carbon is sequestered and year 0 and full re-emission at year 60, reflecting the expected building lifespan per RICS. In practice the lifespan of the timber product will depend on its intended use and environment.

The emissions for each year can be weighted using the equation below.

$$ECF_X = WF_{Ln} \times ECF_{x,n}$$

Where:

| | |
|---|---|
| $ECF_X$ | *Embodied carbon factor of the product at module X* |
| $n$ | *Year of emission associated with module X* |
| $WF_{L(n)}$ | *Weighting factor for the year n using the Lashof Approach* |
| $ECF_{x,n}$ | *Embodied carbon factor of the product at module X, weighted to account for the time-value of carbon* |

Table 2 provides an updated version of Table 1, factoring in the year of emission, the weighting factor, and the time-adjusted emission for each module.

Table 2

Global warming potential of a timber product with consideration to TVoC

| | Global warming potential ($kgCO_{2e}/m^3$) | | | |
|---|---|---|---|---|
| | A1-A5 | B1-B7 | C1-C4 | D |
| Sum (ECFx) | -654 | 0 | 798 | -365 |
| Year of emission (i) | 0 | - | 60 | 60 |
| Weighting Factor (WFi)<br>(See Table 3, Lashof approach) | 1.00 | - | 0.483 | 0.483 |
| Weighted Sum (ECFx, i) | -654 | - | 385 | -176 |

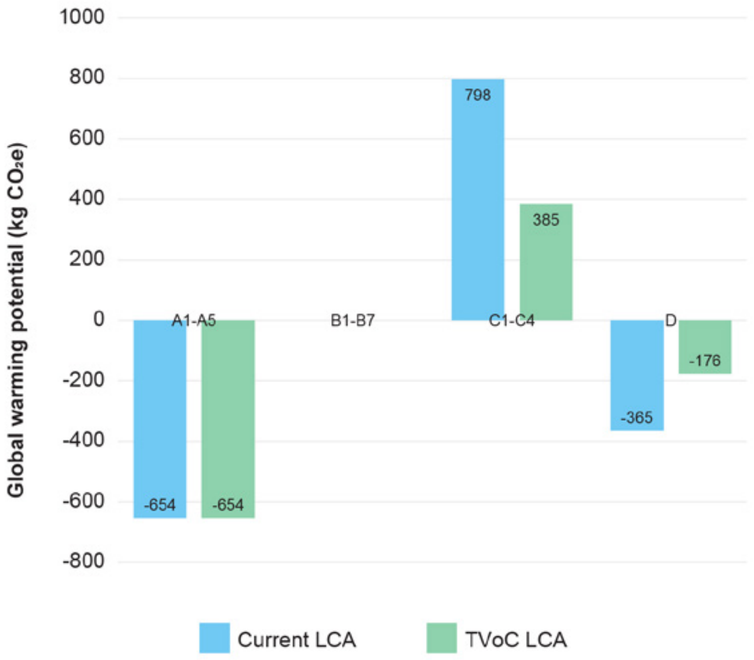

Figure 12
Global warming potential of $1m^3$ timber using current LCA and LCA with consideration to time value of carbon, grouped by life cycle modules

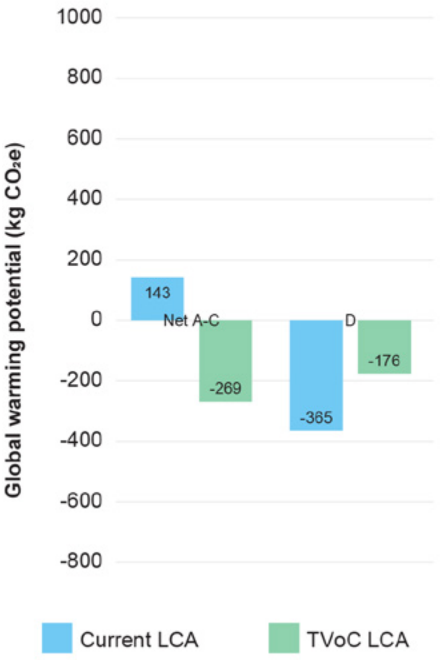

Figure 13
Net global warming potential of $1m^3$ timber using current LCA and LCA with consideration to time value of carbon

By considering the time-value of carbon, end-of-life emissions in Module C and Module D are substantially reduced compared to those presented in the current practice LCA approach (Figure 12). As a result, the total GWP over life cycle modules A to C is a negative value of approximately -270kg $CO_{2e}/m^3$ when considering the time-value of carbon, in contrast to a net positive value of roughly 140 kg $CO_{2e}/m^3$ observed with a current LCA.

This approach provides a means to quantify the benefits associated with delaying carbon emissions via timber sequestration. It should be noted the net-negative carbon emissions risk incentivising overconsumption of timber products to compensate for other areas of design – designers should be conscious of this risk.

There is considerable discourse on the timing of carbon sequestration, particularly when conducting a dynamic life cycle assessment. In typical static analysis, carbon sequestration is treated as an instantaneous carbon credit. However, this approach does not accurately capture the reality that trees grow and sequester carbon over years or decades, which a dynamic LCA could capture accurately. The debate extends, when a dynamic LCA is conducted, whether the credit should be allocated to trees that are being harvested (accounting for the sequestration before the timber product is manufactured), or to trees that are replanted (accounting for the sequestration following the product's creation.)

For the purpose of this simple case study, the sequestration of carbon in timber is credited instantaneously in Module A, in line with the recommendations provide by RICS and EN15804 for timber products when the full lifecycle of the timber product is considered. It is important to recognise that the impact of sequestered carbon can vary greatly depending on the interpretation of timber sequestration, when the time value of carbon is considered.

Further resources for more information on this topic are the works of Peñaloza et al. (2016) [45], Levasseur et al. (2013) [46], and Hawkins et al. (2021) [15].

## 5.2 Balancing embodied and operational emissions: carbon payback periods

Designers are often required to explore design decisions which impact both the embodied and operational emissions of a building. For example, triple-glazing versus double-glazing.

'Carbon payback periods' are increasingly being used to help designers balance these design decisions, by evaluating the time over which the additional upfront embodied emissions are compensated for by reductions in operational emissions, [47] [48].

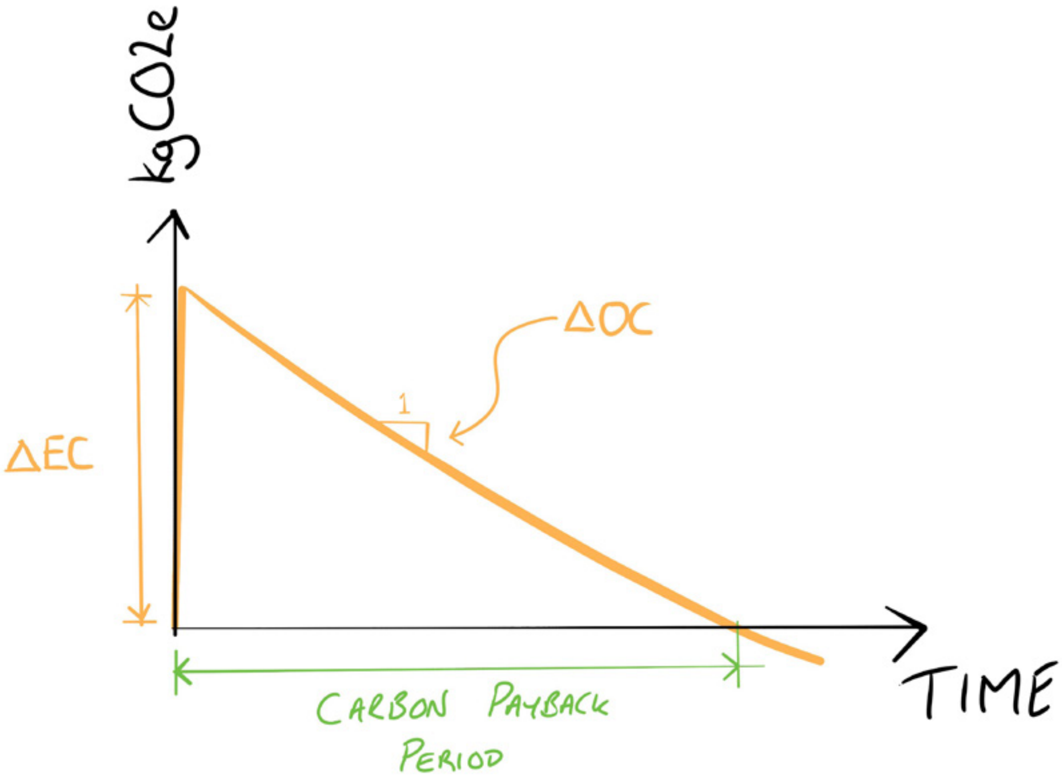

Figure 14
Sketch of the Carbon Payback Period where 'ΔEC' and 'ΔOC' refer to the difference in embodied and operational emissions resulting from a given design decision.

Assessing the carbon payback period can be enhanced by accounting for the time-value of carbon. This can be done by applying a weighting factor (see Appendix) to the emissions of each consecutive year. These weighting factors act to reduce emissions in the future and therefore increase the carbon payback period (see Figure 15).

Integrating the time-value of carbon into carbon payback periods provides designers with a deeper insight into payback times for decisions which impact both embodied and operational emissions.

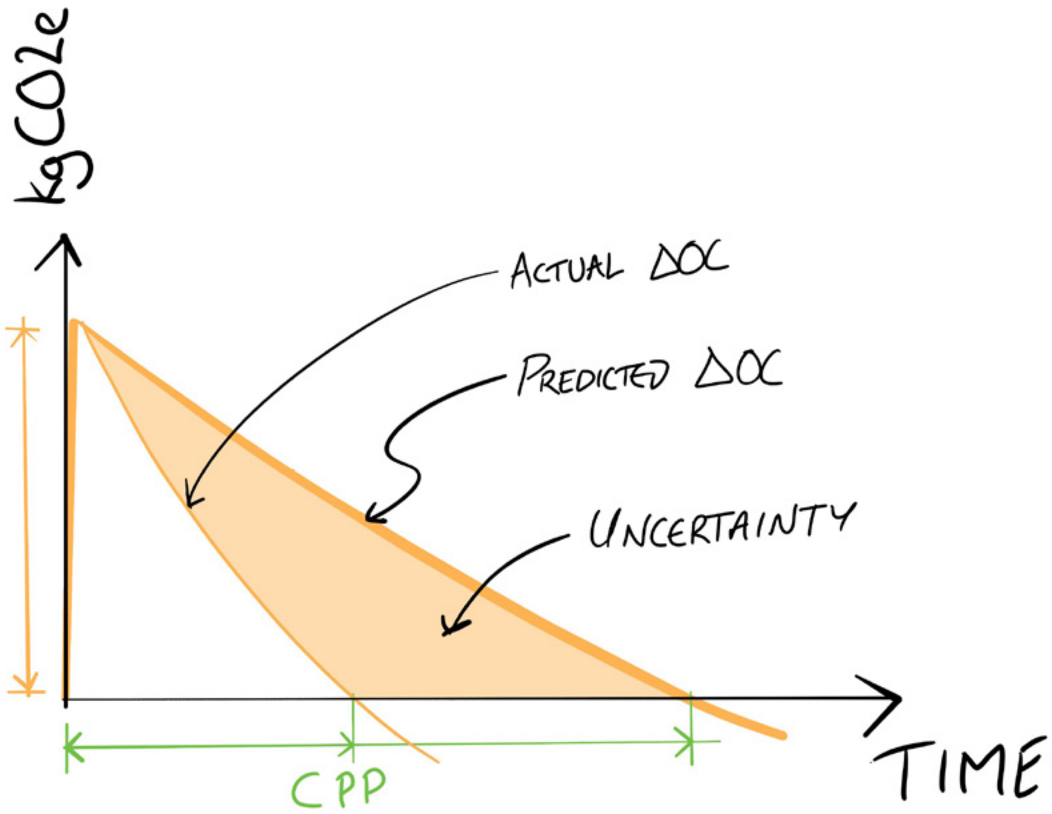

Figure 15
Sketch showing the indicative effect of accounting for the time-value of carbon on the carbon payback period (CPP)

**Chapter 6.**

# Summary

As the industry progresses in its decarbonization efforts, designers often face decisions requiring them to consider the relative value of emissions reductions that occur at different times. Drawing on knowledge from both climate science and economics, this report introduces the topic of the 'time-value of carbon', provides an appreciation of the underpinning arguments, and explores the existing approaches for implementation in practice.

## 6.1 Arguments

This report distils three discernible arguments for valuing the impact of future carbon emissions lower than those of the present (i.e. arguments for valuing the delay of emissions). These arguments are characterised as:

**The *buying time* argument:**
"In delaying emissions, we buy time to avert these delayed emissions."

**The *static time-horizon* argument:**
"Delaying emissions reduces their cumulative impacts between the present and a fixed point in the future."

**The *social time preference* argument:**
"We should value the welfare of today's society higher than that of tomorrows."

### The buying time argument

The buying time argument is characterised by the idea that through delaying emissions we retain the opportunity to avert them by 'buying time' for learning, technical progress, and capital turnover. The strength of the argument is highly dependent on the length and confidence of the delayed emissions. Delaying the emission for a longer period is of more value. Consideration also needs to be given to the assurance associated with 'how' the emissions are delayed.

### The static time-horizon argument

The static time-horizon argument is characterised by the idea that delaying emissions reduces their impact when viewed over a fixed period of time (i.e. static time-horizon).

This argument typically assumes a time horizon with a fixed start and end point and evaluates the extent to which emissions released at different times impact the energy balance of the atmosphere. In doing so, several authors argue that there is value to delaying carbon emissions.

In requiring the definition of a 'time horizon' - beyond which further impacts are ignored – this argument has been criticised for being subjective.

### The social time preference argument

By arguing that we should value the welfare of society today higher than the welfare of society tomorrow, 'social time preference' argues that costs borne in the future should be discounted relative to those borne today.

In the field of economics, this argument is commonly used to inform a discount rate and, in turn, derive a 'net present value of future costs'. This is used to provide a common basis to compare the costs of policy options where the costs are borne over different timespans. The net present value is very sensitive to the discount rate chosen and consequently the selection of an appropriate discount rate can fundamentally impact policy decisions.

The social time preference argument has a long history of debate in the field of economics, especially in relation to consideration of intergenerational environmental impacts [21]. There is no single agreed discount rate, albeit strong arguments have been made to suggest a zero or near-zero discount rate is appropriate for assessing decisions with environmental impacts. The factors which contribute to the selection of an appropriate discount rate are largely value driven. One paper poignantly concludes that "The moral choice for specifying a value for time, zero or otherwise, cannot be avoided." [8].

## 6.2 Approaches

This report has identified four alternative approaches to quantifying the arguments for the time-value of carbon.

- The energy grid decarbonisation approach considers the buying time argument, using the forecast decarbonisation of energy grids as an example to quantify the benefits of delaying carbon emissions.
- The Lashof approach explores the application of the static time-horizon argument to the radiative forcing of emissions released at different times.
- The Moura-Costa approach explores the application of the static time-horizon argument by drawing equivalence between the radiative forcing that results from a unit of emission against that which would be avoided through the temporary storage of emissions.
- The Hawkins approach builds on the Lashof approach by expanding the application beyond carbon dioxide to other greenhouse gases.
- The Parisa approach explores applying the social time preference argument to the physical impact of carbon in the atmosphere.

## 6.3 Adoption

Whilst adoption of these approaches is generally limited to academia, a number of instances exists where the industry is starting to adopt these ideas:

- UK guidance (RICS) recommends the use of weighting factors designed to reflect the anticipated decarbonisation of both the energy grid and material production processes to capture the value of the buying time argument.
- France’s RE2020 regulations mandate the use of weighting factors based on the Lashof approach for WLCA of new buildings.
- Industry standards (ILCD and PAS2050): These industry standards offer a simplified version of the Lashof approach when valuing the temporary storage of emissions in assessing the carbon footprint of goods and services.

## 6.4 Application

Introducing the time-value of carbon into whole-life carbon assessments risks complicating and diverging datasets when the industry should focus on harmonisation. The report authors recommend to only consider the time-value of carbon when it enhances project-specific decision making. Two examples were provided to demonstrate its application:

- Quantifying the benefits of timber sequestration
- Adopting ‘carbon payback periods” to balance design decisions impacting both embodied and operational emissions of buildings

## 6.5 Concluding remarks

While efforts should focus on reducing the absolute quantity of greenhouse gas emissions, there are instances when designers are forced to consider the relative value of emission savings that occur at different times.

This report has highlighted a range of arguments and approaches for valuing the benefits associated with delaying greenhouse gas emissions. In doing so, the report highlights some of the complexity and subjectivity inherent in these approaches.

The report does not pertain to be conclusive, nor capture the entirety of the discussion ongoing in the literature. Instead, this report aims to provide an introductory exploration of the topic to precipitate further discussion in the industry and advance the sectors decarbonisation.

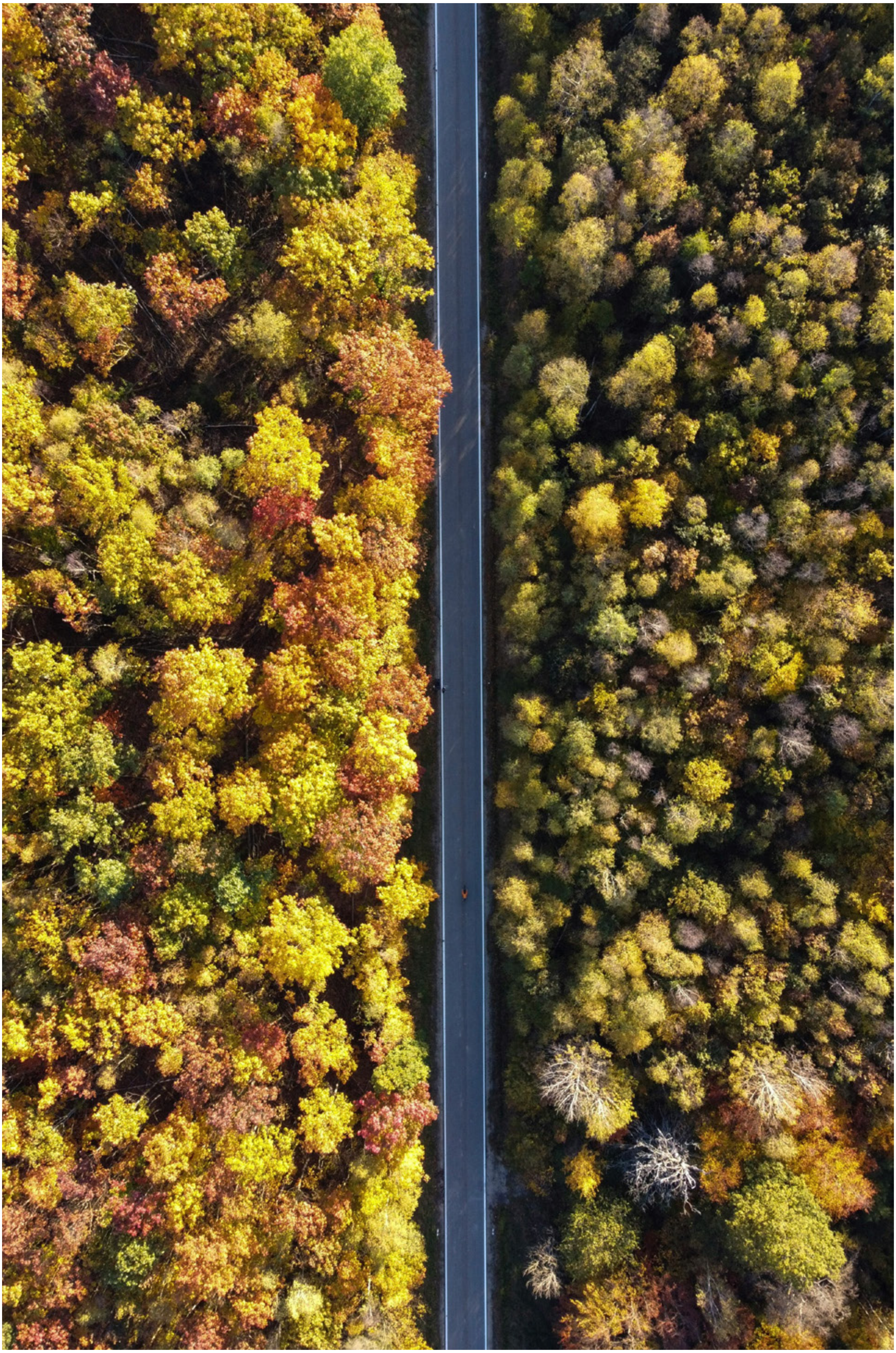

Photo by Luca J on Unsplash

## Appendix A.

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## Appendix B.

# Weighting factors

The weighting factors associated with the key methods referenced in this report have been reproduced for ease-of-use.

Table 3
Weighting factors

| Year | Lashof | RE2020 | ILCD/PAS2050 |
|---|---|---|---|
| 0 | 1.000 | 1.000 | 1.00 |
| 1 | 0.992 | 0.992 | 0.99 |
| 2 | 0.984 | 0.984 | 0.98 |
| 3 | 0.976 | 0.976 | 0.97 |
| 4 | 0.969 | 0.969 | 0.96 |
| 5 | 0.961 | 0.961 | 0.95 |
| 6 | 0.953 | 0.953 | 0.94 |
| 7 | 0.945 | 0.945 | 0.93 |
| 8 | 0.937 | 0.937 | 0.92 |
| 9 | 0.929 | 0.929 | 0.91 |
| 10 | 0.921 | 0.921 | 0.90 |
| 11 | 0.913 | 0.913 | 0.89 |
| 12 | 0.905 | 0.905 | 0.88 |
| 13 | 0.897 | 0.897 | 0.87 |
| 14 | 0.889 | 0.889 | 0.86 |
| 15 | 0.880 | 0.88 | 0.85 |
| 16 | 0.872 | 0.872 | 0.84 |
| 17 | 0.864 | 0.864 | 0.83 |
| 18 | 0.856 | 0.856 | 0.82 |
| 19 | 0.848 | 0.848 | 0.81 |
| 20 | 0.840 | 0.84 | 0.80 |
| 21 | 0.831 | 0.831 | 0.79 |
| 22 | 0.823 | 0.823 | 0.78 |
| 23 | 0.815 | 0.815 | 0.77 |
| 24 | 0.806 | 0.806 | 0.76 |
| 25 | 0.798 | 0.798 | 0.75 |
| 26 | 0.790 | 0.79 | 0.74 |
| 27 | 0.781 | 0.781 | 0.73 |
| 28 | 0.773 | 0.773 | 0.72 |
| 29 | 0.764 | 0.764 | 0.71 |
| 30 | 0.756 | 0.756 | 0.70 |
| 31 | 0.747 | 0.747 | 0.69 |
| 32 | 0.739 | 0.739 | 0.68 |

| Year | Lashof | RE2020 | ILCD/PAS2050 |
|---|---|---|---|
| 33 | 0.730 | 0.73 | 0.67 |
| 34 | 0.721 | 0.721 | 0.66 |
| 35 | 0.713 | 0.713 | 0.65 |
| 36 | 0.704 | 0.704 | 0.64 |
| 37 | 0.695 | 0.695 | 0.63 |
| 38 | 0.686 | 0.686 | 0.62 |
| 39 | 0.678 | 0.678 | 0.61 |
| 40 | 0.669 | 0.669 | 0.60 |
| 41 | 0.660 | 0.66 | 0.59 |
| 42 | 0.651 | 0.651 | 0.58 |
| 43 | 0.642 | 0.642 | 0.57 |
| 44 | 0.633 | 0.633 | 0.56 |
| 45 | 0.624 | 0.624 | 0.55 |
| 46 | 0.615 | 0.615 | 0.54 |
| 47 | 0.606 | 0.606 | 0.53 |
| 48 | 0.597 | 0.597 | 0.52 |
| 49 | 0.587 | 0.587 | 0.51 |
| 50 | 0.578 | 0.578 | 0.50 |
| 51 | 0.569 | N/A | 0.49 |
| 52 | 0.559 | N/A | 0.48 |
| 53 | 0.550 | N/A | 0.47 |
| 54 | 0.541 | N/A | 0.46 |
| 55 | 0.531 | N/A | 0.45 |
| 56 | 0.521 | N/A | 0.44 |
| 57 | 0.512 | N/A | 0.43 |
| 58 | 0.502 | N/A | 0.42 |
| 59 | 0.492 | N/A | 0.41 |
| 60 | 0.483 | N/A | 0.40 |
| 61 | 0.473 | N/A | 0.39 |
| 62 | 0.463 | N/A | 0.38 |
| 63 | 0.453 | N/A | 0.37 |
| 64 | 0.443 | N/A | 0.36 |
| 65 | 0.433 | N/A | 0.35 |
| 66 | 0.423 | N/A | 0.34 |
| 67 | 0.412 | N/A | 0.33 |
| 68 | 0.402 | N/A | 0.32 |
| 69 | 0.392 | N/A | 0.31 |

| Year | Lashof | RE2020 | ILCD/PAS2050 |
|---|---|---|---|
| 70 | 0.381 | N/A | 0.30 |
| 71 | 0.371 | N/A | 0.29 |
| 72 | 0.360 | N/A | 0.28 |
| 73 | 0.349 | N/A | 0.27 |
| 74 | 0.339 | N/A | 0.26 |
| 75 | 0.328 | N/A | 0.25 |
| 76 | 0.317 | N/A | 0.24 |
| 77 | 0.306 | N/A | 0.23 |
| 78 | 0.295 | N/A | 0.22 |
| 79 | 0.283 | N/A | 0.21 |
| 80 | 0.272 | N/A | 0.20 |
| 81 | 0.261 | N/A | 0.19 |
| 82 | 0.249 | N/A | 0.18 |
| 83 | 0.237 | N/A | 0.17 |
| 84 | 0.226 | N/A | 0.16 |
| 85 | 0.214 | N/A | 0.15 |
| 86 | 0.202 | N/A | 0.14 |
| 87 | 0.189 | N/A | 0.13 |
| 88 | 0.177 | N/A | 0.12 |
| 89 | 0.164 | N/A | 0.11 |
| 90 | 0.151 | N/A | 0.10 |
| 91 | 0.138 | N/A | 0.09 |
| 92 | 0.125 | N/A | 0.08 |
| 93 | 0.111 | N/A | 0.07 |
| 94 | 0.097 | N/A | 0.06 |
| 95 | 0.083 | N/A | 0.05 |
| 96 | 0.068 | N/A | 0.04 |
| 97 | 0.052 | N/A | 0.03 |
| 98 | 0.036 | N/A | 0.02 |
| 99 | 0.018 | N/A | 0.01 |
| 100 | 0.000 | N/A | 0.00 |

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