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The push and pull of policy on life cycle assessment of low-carbon systems

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This perspective article explores the evolving challenges of conducting Life Cycle Assessments (LCAs) of low-carbon systems, to meet the requirements of emerging policy frameworks, such as the United States (U.S.) Inflation Reduction Act and the European Union (EU) Carbon Border Adjustment Mechanism. It emphasizes the need for LCA methodologies to incorporate temporality, regionality, and incrementality considerations to more accurately reflect real-world greenhouse gas (GHG) emissions and policy needs. The implications of these factors are discussed through illustrative examples for renewable energy, biofuels, plastics recycling, and carbon offsetting projects, while highlighting the challenge of designing flexible policies that support emerging technologies which may initially exhibit higher carbon footprints, but offer the potential for long-term emission reductions.

Sustainability spotlight

Ensuring that low-carbon technologies truly deliver GHG reductions is critical for meeting global climate targets. This work discusses how new policy frameworks introducing temporality, regionality, and incrementality will result in stricter life cycle evaluation of new, low-carbon technologies shaping LCA outcomes. It highlights the risk of overstated sustainability claims without these considerations, especially for electricity- and bio-based systems. By aligning LCA methods with emerging regulatory standards, this work can help advancing the robustness and policy relevance of environmental assessments. It can also contribute to sustainable decision-making under the United Nation's Sustainable Development Goal (SDG) 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), and promotes accountable climate solutions in increasingly complex energy and materials systems.

1 Introduction

Over its full life cycle, deployment of a "low carbon technology" should result in lower emissions of carbon dioxide (CO_2) and other greenhouse gases (GHG) compared to business as usual. Technologies discussed in this space include, among others, solar and wind power, biofuels, hydrogen, and electric vehicles. The GHG emissions of deploying such technologies depend on their production, use, and disposal, and on the changes resulting from their deployment. As a result, quantification of GHG emissions from new technology deployment, both in policies and in evaluative research studies, requires accounting for the full picture of potential emissions, including effects such as market responses.

Examples of policies and non-policy mechanisms, that require demonstration of lower GHG emissions to receive tax credits or to meet other policy aims, include the United States (U.S.) Department of the Treasury and Internal Revenue Service (IRS) Clean Fuels Production Credit (2025)[1] and Clean Hydrogen Production Tax Credit (2025),[2] the U.S. Inflation Reduction Act (IRA) (2022),[3] the European Union (EU) Carbon Border Adjustment Mechanism (CBAM) (2023),[4] and the Voluntary Carbon Markets (VCMs) Joint Policy Statement and Principles (2024).[5] These requirements build upon earlier policies, such as the U.S. Renewable Fuel Standard RFS2 (2007)[6] and the California Low Carbon Fuel Standard (approved in 2009 and implemented in 2011),[7] and are driving significant methodological and data advances in life cycle assessment (LCA).

A starting point for understanding the challenges of ensuring low carbon footprint is the supply of energy. Significantly changing product formulations, manufacturing processes, or the production location often affect the energy consumption profile. This profile includes the mix of energy types (*i.e.*, heat or electricity), and the timing, as power sources (*e.g.*, solar) may vary by time of day. Features of this profile that are important for GHG emissions, and have been coded into policy, are temporality, regionality, and incrementality. Temporality requires that the energy source claimed (*e.g.*, solar)

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is in fact generated at the time that the energy is used, regionality or deliverability requires the energy source claimed can be delivered to the site in question, while incrementality ensures that if a source of energy is claimed, this resource can't be already in use for other customers.

These concepts of temporality, regionality, and incrementality were codified in the final rules of the Section 45V Clean Hydrogen Production Tax Credit,[2] released in 2025 by the U.S. Department of Treasury and the IRS, as key criteria to qualify for tax credits. While originally proposed for renewable energy systems supporting clean hydrogen production, these concepts can be extended and applied to other low-carbon products and processes, relying on low-carbon feedstocks as their primary input instead of low-carbon electricity. Indeed, LCAs for systems utilizing biobased, recycled or renewably-sourced feedstocks need to account for similar issues with the same overall challenge: to assess the GHG emissions appropriately. Such assessments can follow two broad approaches: attributional LCAs (ALCAs) and consequential LCA (CLCAs), each requiring different analytical frameworks. ALCAs quantify the environmental burdens attributable to products or processes at a given point in time, whereas CLCAs evaluate how those burdens would change in response to decisions or actions, accounting for broader system-level effects.[8]

Two main challenges arise given these developments. The first one is the increasing requirement to demonstrate reductions from the specific process at hand (cradle/well-to-gate perspective), as opposed to system expansion to incorporate credits, offsets, or other lower-carbon processes. This shift necessitates comprehensive and standardized approaches to assessing the environmental impact of various production processes and pathways, ensuring that GHG emissions estimates meet both policy and physical criteria. The second challenge is the need to transition from ALCAs, which primarily focus on attributing impacts to systems, to CLCAs that consider the consequences of shifting from one system to another, including market-mediated effects. In this perspective, we discuss these emerging methodological challenges, illustrating them through examples under the concepts of temporality, regionality, and incrementality. Through this analysis, we aim to show how evolving policy frameworks are reshaping LCA practice and to highlight the implications of these concepts for future LCA applications.

2 Temporality – timing matters

Temporality can help ensure that resources are actually available and used during the time the process at hand occurs. Temporality constraints are not inherent to LCA methodology; rather, they reflect policy decisions. These choices can significantly influence impact assessments across various systems, from fuels and recycled materials to carbon offsets.

2.1 Temporality of electricity sources

Temporality has primarily been used to help identify what electricity source is used in a process. However, current temporality requirements for electricity are often loosely defined, *i.e.*, the averaging period for energy resource use may exceed the time scale over which the resource supply varies. For instance, the U.S. Clean Hydrogen Production Tax Credit[2] mandates annual matching until 2027, shifting to hourly matching in 2028. Similarly, the EU's Renewable Fuels of Non-Biological Origin (RFNBO)[9] regulation requires monthly matching through 2029, with hourly matching starting in 2030. Canada's Clean Hydrogen Investment Tax Credit[10] has no time-matching requirement between electricity generation and use.

In intermittent energy systems, such as wind and solar, power production fluctuates over time. With monthly or annual time matching, such systems can provide extra power for other uses during sunny or windy times and borrow back from the grid at night or when the wind stops. But with hourly matching, low-CO_2 power would need to be stored and available to meet a process's operational needs at all hours. The choice of time-matching approach can lead to significant differences in calculated emissions, varying even by orders of magnitude and failing to meet policy requirements in certain cases. Looser time-matching assumptions can result in much lower assigned emissions compared to stricter approaches, which may require contributions from fossil-based electricity sources, and therefore exceeding relevant tax credit thresholds. For example, electrolytic hydrogen requires a theoretical minimum of about 40 kWh kg^{-1} of hydrogen.[11] The lifecycle emissions of electricity production from solar photovoltaics (PVs) are about 40 g CO_2-eq per kWh.[12] Assume we have sufficient solar capacity that the total amount of energy consumed by hydrogen generation can be met with the solar power averaged over a specific time period, *e.g.* one day. If looser annual time-matching for electrolytic hydrogen production is allowed, using electricity generated 100% by solar PVs, this results in a minimum of 1.6 kg CO_2-eq per kg of hydrogen. Whereas with stricter hourly time-matching calculations, where solar power is considered to be unavailable for 12 of the 24 hours, the same system could be considered to use electricity generated 50% by PVs and 50% by natural gas combined-cycle (NGCC). NGCC electricity generation has a carbon footprint of about 500 g CO_2-eq per kWh.[13] In the latter case, the carbon emissions of electrolytic hydrogen production would be, at minimum, 10.8 kg CO_2-eq per kg of hydrogen, which exceeds all tax credit thresholds, the least stringent of which being 4 kg CO_2-eq per kg.

2.2 Temporality of recycled and renewably-sourced feedstocks

One of the earliest examples of a lack of temporal matching was in recycled feedstocks. Often these feedstocks do not arise through smooth flows but are created by aggregating, sorting, and baling of wastes that could then be shipped and fed in batches into existing primary production systems. Given the intermittent flow of some of these recycled commodities and their occasional lack of availability, it is hard to know whether a specific product has exactly the average recycled content.[14] Claims of recycled content can be contentious because it is hard to guarantee that certain levels are achieved in every item.

Paper and cardboard recycling has achieved a level of maturity that enables dedicated pulp mills to be built. An average level of recycled content in products can be achieved, overcoming the problem of other industries, like polymer manufacturing.[14,15] There are still questions in the recycled plastics space as to whether temporal averaging of recycling content labelling should be allowed, and whether national or regional averages over long time periods are reasonable to use as claims on product recycled content.

Feedstocks used for biofuels production, such as waste, agricultural residues or crops, are also subject to temporality due to variations in biomass availability and harvestability throughout the year.[16,17] Seasonality significantly affects the GHG emissions associated with biofuel production by influencing various stages of the supply chain, from biomass collection and transportation to processing and storage.[17] Higher feedstock availability during peak seasons may lead to increased processing activities, prolonged equipment operation, and higher energy consumption, resulting in elevated GHG emissions. Moreover, the need to store surplus biomass can necessitate additional facilities or longer storage times, leading to increased emissions due to degradation or storage operations, such as energy consumption for ventilation systems to maintain appropriate moisture levels and prevent microbial growth.[18,19] Conversely, limited availability can also elevate emissions. For example, the seasonality of livestock manure has been estimated to increase GHG emissions from on-farm biomethane production from about −3 g of CO_2-eq per MJ in case of zero-grazing to about 7 g of CO_2-eq per MJ in pasture-based farming. This rise is attributed to the need for additional feedstock sources, such as grass silage with heightened cultivation emissions, or increased digestate recirculation requiring large amounts of electricity due to limited manure availability in the case of pasture-based farming.[20]

Similarly, the temporality in the supply and quality of wood feedstocks can significantly impact the carbon footprint of the pulp and paper industry.[21] During the winter months, the local availability of wood chips can be decreased due to adverse weather conditions. Consequently, paper mills may need to rely more heavily on stored wood chip reserves or import wood from more distant locations, leading to increased transportation-related emissions. The reduced wood chip supply during winter may also necessitate the use of alternative materials or processes, such as recycled fibers or chemical pulping methods, which can have different carbon intensity profiles. In addition, seasonal variations in wood moisture content (higher in winter and lower during the summer; moisture variation ranges 47–52% and 37–42% for softwood and hardwood respectively) have a significant impact on the yields of the pulping process resulting in lower pulp yields (∼0.5 more tons of green wood are required to produce one ton of bleached pulp compared to warmer months).[21] The amount of bark that is entrained in the good chips going to the digester tends to vary seasonally as well, exhibiting about 50% increase during winter, mostly due to the increased amounts of frozen wood being processed and decreases in the average diameter of the logs being processed during the winter months. Higher quantities of bark reduce pulp yield while requiring additional chemical treatments *e.g.*, increased white-liquor demand (a chemical solution primarily composed of sodium hydroxide and sodium sulfide), or processing steps to achieve desired pulp properties, which can further increase resource consumption and environmental impacts.[21]

2.3 Temporality of carbon offset projects

Temporality is being used in policy to distinguish low-carbon projects from high-carbon projects matched with offsets. Temporality considerations also arise for the evaluation of offsets, *i.e.*, mechanisms that allow individuals and organizations to offset their GHG-emitting activities by funding mitigating activities elsewhere. Types of carbon offsetting projects include renewable energy development, energy efficiency improvements, methane capture, biosequestration efforts like afforestation, as well as deployment of carbon capture and storage (CCS) technologies.[22] Carbon offset projects generate credits based on the amount of GHG emissions they are expected to sequester or avoid over their operational lifetime.

For offsets, permanence of GHG benefits is a key issue. As stated in the recently released VCMs,[5] the emissions removed or reduced by a carbon offsetting activity should be kept out of the atmosphere for a specified time period, during which any credited results that are released back into the atmosphere are fully remediated. The standard benchmark for permanence is 100 years, although some protocols and registries may require longer time frames up to 1000 years, to ensure truly permanent offsets.[23] The idea is to prevent any credited emissions reductions from being reversed, thereby maintaining the environmental integrity of the carbon offset.

Assessing and proving the permanence of these benefits can be challenging as there are inherent uncertainties for different types of projects that are hard to address.[23] For example, nature-based solutions, like blue carbon coastal wetland restoration, reforestation and afforestation, are subject to natural and human disturbances, such as wildfires, pests, extreme weather events, and illegal logging. These disturbances can release stored carbon back into the atmosphere, undermining the permanence of the GHG benefits. Forestry projects use buffer pools as insurance, planting extra trees to compensate for potential losses.[24] However, a study of California's buffer pool[25] revealed that wildfires have already destroyed nearly all the offsets intended to last until the end of the century. To be effective, buffer pools must be redesigned to better account for the impacts of climate change on forests. The benefits of soil carbon sequestration projects, *e.g.,* regenerative agriculture practices,[26] might also be reversible as stored carbon may be released if land management practices change or due to soil degradation, erosion, drought and floods. The permanence of other types of projects might not depend on external factors, but on the integrity of the systems themselves. For instance, in the case of CCS there is a risk of leakage of the stored CO_2 over time due to geological instability or improper site management. Continuous monitoring and verification are needed to ensure permanence.

In addition, the temporality of carbon offset projects can significantly affect the GHG emissions that are being actually offset or reliably mitigated over time, as the timing of the claimed emission reductions may not align with the timing of the emissions being offset. A carbon offset project may begin sequestering carbon immediately upon implementation, but its full emission reduction potential may not be realized until several years into the future. For example, the rate at which forests sequester carbon changes over time, peaking when the trees are young to intermediate in age (30–70 years).[27] Conversely, emission reductions from renewable energy installations may be immediate but diminish over time as equipment ages or efficiency decreases.[28,29]

3 Regionality – location matters

Regionality can help ensure that resources are physically part of the production process. The location of production is a critical factor to consider when assessing the carbon footprint of products manufactured with regionally varying resources.

3.1 Regionality of electricity production

Policy drivers may require that the electricity be within the region in which it is used. The U.S. Clean Hydrogen Production Tax Credit[2] uses the Federal Energy Regulatory Commission (FERC) electricity council regions to determine these regional boundaries. For example, in the U.S. state of Georgia, located in Southeastern Electric Reliability Council (SERC), a facility making electrolytic hydrogen could not count wind energy from Oklahoma, which is outside of SERC, although it could count nuclear power from new in-state reactors.

3.2 Regionality of biofuels production and use

The location of production is a critical factor to consider when assessing biofuels' carbon footprint, especially for biofuels that are not yet widely available globally. Take, for instance, the production of a biofuel from used cooking oil (UCO) (Fig. 1A). Production-related GHG emissions can be ∼30% lower if the biofuel is produced in Europe (Netherlands) compared to production in Asia (China) (Fig. 1B). This difference arises from the varying impacts of energy inputs and raw material production in these regions. Now let's assume that this biofuel needs to be shipped to Singapore for use in shipping operations. While this scenario is not novel in the realm of global trade, the significance of transportation emissions may become more pronounced if the biofuel itself has a relatively low carbon footprint. In such cases, the emissions associated with transporting the biofuel over long distances could represent a larger fraction of the overall carbon footprint (Fig. 1B). Although advancements in technology and infrastructure are expected to reduce the carbon intensity of biofuels, the relative contribution of transportation emissions may still be substantial, albeit in relation to a smaller overall carbon footprint. Therefore, relevant assessments must consider both production location and transportation emissions to accurately evaluate the environmental impact of biofuels in global trade contexts.

Book and claim is used mainly in voluntary markets for aviation and maritime fuels, with some use in policy contexts. It allows for the decoupling of sustainable fuel use from its physical delivery, allowing companies to claim the environmental benefits of low-carbon fuels, that they are not directly using. In the shipping industry, this is a voluntary, market-based mechanism, which lacks recognition from major emission reporting frameworks like the IMO GHG Strategy.[30] Key challenges of this approach are ensuring robust traceability and preventing double counting, which currently relies on a high degree of trust in the system. Concerns about the legitimacy of book and claim have prompted calls for more transparent and auditable verification protocols, including the adoption of stronger chain-of-custody models (*e.g.*, mass-balance accounting) and standardized, third-party-verified tracking of sustainability attributes. Addressing these limitations is central to emerging governance discussions, which increasingly emphasize the need for internationally harmonized monitoring, reporting, and verification (MRV) requirements and closer alignment with compliance-grade fuel certification systems to ensure credibility at scale. In parallel with these governance developments, several private initiatives are attempting to operationalize book and claim in practice, such as the maritime book and claim registry, Katalist,[31] developed by the Fonden Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping and RMI, and analogous systems in aviation. In the Netherlands, the renewable energy units system[32] provides tax credits for marine biofuels, which can complement book and claim. In aviation, more stringent geographic requirements apply: to qualify for the California Low Carbon Fuel Standard,[7] fuels must be sold, supplied, or offered within California; and to qualify for the U.S. IRA tax credit[3] for Sustainable Aviation Fuels, the fuel must be both produced and used within the United States. Thus, book and claim arrangements in which a fuel is produced, sold or used outside the jurisdiction will not meet these policy requirements. LCA analyses taking a book-and-claim approach might not satisfy regionality criteria unless particular restrictions are followed. While global fleet assessments may demonstrate environmental improvements with increased biofuel use, they may fail to meet the requirements of policies mandating local production and use. Consequently, shipping and aviation companies may adjust their operations to comply with such policies.

Local feedstock availability can also affect the carbon intensity of biofuel production. For example, the use of lignocellulosic biomass for biofuels introduces crucial considerations regarding regionality and its impact on carbon intensity. Ensuring that the feedstock originates from certified locations is pivotal in assessing the environmental footprint of biofuel production. The sourcing of biomass from distant or uncertified regions can significantly escalate transportation emissions, counteracting the carbon benefits of biofuels. Moreover, the logistics involved in tracking certified wood sources demand substantial effort, from verifying origins to monitoring supply chains. Neglecting these regionality issues can compromise the sustainability credentials of biofuels, highlighting the

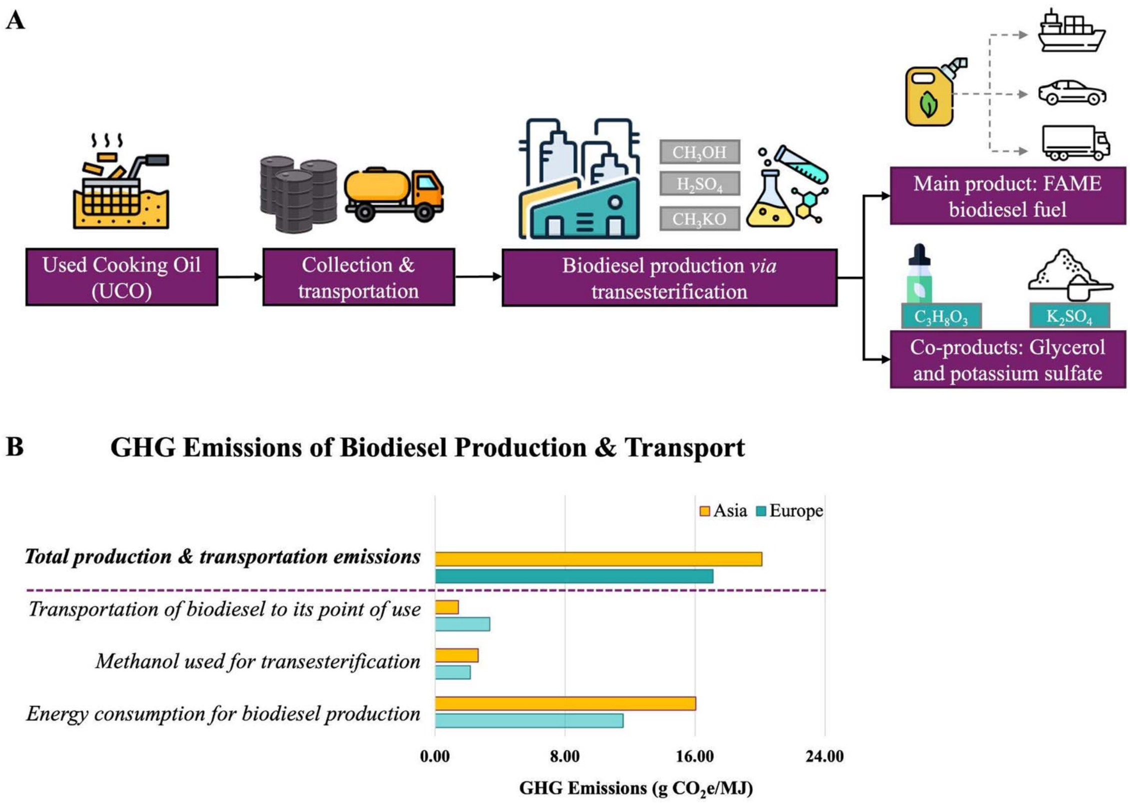

Fig. 1 Regionality impacts of Used Cooking Oil (UCO) biodiesel. (A) Main steps involved in biodiesel production.[33,34] UCO processing involves acid-catalyzed esterification using methanol (CH_3OH) and sulfuric acid (H_2SO_4) followed by base-catalyzed transesterification using CH_3OH and potassium methoxide (CH_3KO). The main product of this process is Fatty Acid Methyl Esters (FAME) biodiesel, which can be used in marine and road transport. The process also generates glycerol ($C_3H_8O_3$) and potassium sulfate (K_2SO_4) as co-products. (B) GHG emissions from biodiesel production in Europe (Amsterdam, Netherlands) and Asia (Fujian Province, China), considering only the dominant contributors, *i.e.*, energy use and methanol consumption, along with emissions from transporting the fuel to the port of Singapore for bunkering. Results were generated using the ecoinvent v3.12 database[35] (license required). Icons in panel A were adapted from free resources available at Flaticon (https://www.flaticon.com),[36] used in accordance with Flaticon's Free License with attribution (made by authors: Iconjam, Ylivdesign, Freepik, Three musketeers, Dewi Sari, and imaginationlol).

importance of locally sourced, certified biomass to mitigate carbon emissions effectively.

4 Incrementality – net improvements matter

Incrementality requires that a process or activity adds to the existing low-carbon infrastructure. This requirement aims to avoid accounting that makes a new project appear more sustainable by allocating existing renewable resources to the new project and fossil resources to existing customers. The concept of incrementality directly influences LCA outcomes by ensuring that emissions reductions are not overstated through resource reallocation or double-counting. Without adherence to incrementality, LCAs risk misrepresenting the environmental benefits of low-carbon technologies, undermining their credibility and alignment with policy requirements.

4.1 Incrementality of renewable electricity

If a new project claims resources from an existing renewable electricity generation asset, the current users might end up using non-renewable energy instead, and this can result in a net increase in fossil energy consumption. This risk is particularly pronounced in systems with shared grids and limited renewable capacity, where temporal mismatches and insufficient incrementality can undermine climate goals; a concern highlighted in recent analyses of electricity modeling under clean hydrogen policies.[37] The EU RFNBO,[9] U.S. IRA,[3] and the Canadian Clean Hydrogen Investment Tax Credit,[10] all require that renewable electricity assets used to produce green hydrogen must commence generation no more than one to three years before the hydrogen production facility begins operation.

4.2 A similar concept for carbon offset projects

Carbon offset projects need to be additional, meaning they wouldn't occur without revenue from carbon credits.[5] Determining additionality, which is analogous to incrementality for renewable electricity, is a major challenge faced by carbon markets to date.[38,39]

Additionality is determined by comparing the proposed project to its baseline scenario, which is a prediction of the future behavior of the actors proposing, and affected by, a project's activities in the absence of any carbon revenue incentives, holding all other factors constant.[39,40] It represents the scenario without the influence of the offset project. Some projects, like landfill methane capture in California, are legally required and would have occurred regardless of carbon credits. Others, such as renewable energy installations, might be implemented because they are profitable on their own, without needing carbon credits as an incentive.[40]

There are two main approaches to determining additionality:[40] project-specific and standardized. Project-specific approaches, *e.g.*, the Clean Development Mechanism tool under the Kyoto Protocol to the United Nations Convention on Climate Change,[41] analyze individual project characteristics, accounting for legal requirements, financial attractiveness, barriers to implementation, and common practice. While rigorous, these methods can be subjective and time-consuming. Standardized approaches, use predefined eligibility criteria to differentiate additional from non-additional projects, *e.g.*, lists of pre-defined technologies or practices that are considered additional without further evaluation. These approaches reduce administrative burdens but may lack precision for unique project characteristics. Programs like the Climate Action Reserve[42] primarily use standardized approaches, whereas others like the Gold Standard[43] employ a mix of both.

5 Implications for LCA methodology

Better-designed policies will promote technologies that lower GHG emissions; these can be supported by more robust GHG assessments, that demonstrate that such technologies actually result in lower emissions.

Dynamic LCA models factoring in temporality effects are needed to effectively assess the environmental impacts of hydrogen, plastics recycling, bioenergy systems, forest-based industries, and carbon-offsetting projects allowing for comprehensive assessments of forest management practices and industrial processes and informing sustainable resource use and management strategies. This involves incorporating high temporal and spatial resolutions into LCAs to capture variations in electricity and feedstocks supply or GHG sequestration patterns throughout the year and across different regions.

To address data limitations in dynamic LCAs, alternative modeling and forecasting approaches, such as leveraging natural vegetation cycles, can be used. For example, Sadr *et al.*, (2024)[17] utilized the natural vegetation cycle to refine yearly biomass availability into shorter time frames by recognizing the distinct growth stages of plants and their dependence on specific environmental conditions to assess biomass seasonality impact on bioenergy production in Germany. Such dynamic modeling techniques and process optimization strategies can further enhance the accuracy of LCAs by simulating seasonal variations in feedstock supply and identifying opportunities to minimize GHG emissions, while providing more realistic GHG projections.

For carbon offset projects, such dynamic approaches would involve evaluating not just the initial sequestration but also the longevity and stability of potential benefits over the project's lifetime including scenarios where carbon storage might be compromised due to events like wildfires, pest infestations, or land-use changes. Appropriate monitoring systems that have the temporal resolution and scale must be developed along with the governance structures to ensure their implementation.

LCAs should address regionality issues arising from the physical connectivity between different activities across various locations. For example, local offsets may not qualify for hydrogen tax credits if there is no direct link between production and consumption sites, raising important questions about how regional actions influence overall sustainability calculations. Additionally, understanding the impacts of transportation and storage is vital, particularly in systems where these activities incur significant energy and emissions costs, such as hydrogen liquefaction or biofuels that require extensive logistics for distribution.

To effectively incorporate regionality concerns in LCAs, it is essential to use region-specific data and consider the entire supply chain from production to end use. This approach ensures that transportation and storage impacts are adequately reflected in the assessment. It may involve modeling the energy consumption and emissions associated with transporting commodities over long distances, as well as accounting for the infrastructure required for storage. It may also affect system boundaries and displacement calculations. Neglecting these factors can lead to inaccurate assessments and potentially misguided policy decisions.

Incrementality assessments are very uncertain. Adopting comprehensive transparency and robust data collection practices is essential to improve the reliability of such assessments.[44] For green hydrogen, careful consideration of grid dynamics is needed to ensure that the renewable electricity used for electrolysis does not inadvertently cause an increase in emissions elsewhere by displacing renewable electricity from other applications. Comprehensive data on the full life cycle impacts of renewable energy infrastructure, including manufacturing, installation, maintenance, and end-of-life disposal, must be integrated into the LCA to provide a holistic view. Failure to account for these aspects can result in misallocated resources and missed opportunities for genuine emission reductions, thereby compromising the environmental integrity of green hydrogen projects or other electricity–intensive activities.

For carbon offset projects, additionality and baseline assessments rely on educated predictions influenced by factors like future commodity prices and can be affected by adverse selection and information asymmetry, where only the project developer knows the true impact of carbon credits.[40,45] Several studies have found overestimated credit generation of carbon offset projects due to inflated baseline emissions *e.g.,* California's prominent forest carbon offsets program,[25,46] Reducing Emissions from Deforestation and Forest Degradation (REDD+) projects[47,48] and improved cookstove projects.[49] Any additionality assessment will inevitably produce false positives (non-additional projects deemed additional) and false negatives (additional projects deemed non-additional).[38,50] While both types of errors impact economic efficiency, only false positives can harm environmental integrity by increasing emissions.

As currently defined, regionality, temporality, and incrementality of low-carbon electricity sources are all straightforward to evaluate and include in LCA. Regionality, if defined as a facility located in a specific region, is the easiest criterion to test. Determining the source of incremental resource consumption is more challenging, and is addressed in CLCA.[8] Evaluation of temporality can also be straightforward, and models and data exist to evaluate how well the generation from an electricity source matches with its intended use. All of these are largely within the scope of current LCA practice.

However, there may be additional GHG emissions changes beyond those attributed to a new product or technology following the ALCA approach. The consequences of deploying a new technology can include changes in markets or production systems that result in changes in GHG emissions, and capturing these system-wide effects requires the CLCA framework.[8] For example, careful consideration of grid dynamics is needed to ensure that the renewable electricity used for a new project does not inadvertently cause an increase in emissions allocated to other users. Products derived from biomass can result in changes in land use and agricultural practices. New energy products can affect costs, and changes in costs affect demand. Such assessments may require modeling of energy systems, grid dynamics, and economic interactions to capture system-wide effects. The outcomes can be sensitive to assumptions about future scenarios. Ensuring assessment robustness and consistency remains an unmet challenge.

If we consider other LCA metrics and impact categories beyond GHG emissions and global warming potential, such as particulate matter emissions and ecotoxicity, or for resource use beyond electricity, such as water, the principles of regionality, temporality, and incrementality are not yet as well-developed or consistently applied. These areas often lack the same level of modeling precision, data availability, and standardized methodologies, making comprehensive assessments more challenging. Moreover, incorporating social impacts and equity considerations of new, low-carbon systems and technologies, introduces another layer of complexity, as these factors are deeply contextual, requiring new frameworks and interdisciplinary approaches for meaningful inclusion in LCA evaluations.

6 Recommendations & future perspective: the right thing may not be right to start with†

In the above discussion, we have pointed out the challenges for new, low-carbon products and technologies to affirm that their widespread deployment will in fact result in lower GHG emissions. Partly this is a consequence of the complex system dynamics of technologies operating in the coupled economic and bio-geo-physical system of the Earth. Partly this is a consequence of introducing new technologies into an energy system at an early stage of de-fossilizing. Might we be willing to accept a new system with higher emissions for some short time period because it has the promise of longer-term reductions? Or will loose requirements lock in higher emissions?

Lock-in is particularly problematic with regards to the energy consumption of technologies, where at low scale the construction of dedicated renewable energy facilities with storage will increase costs relative to adding the facilities to the grid. We might accept hydrogen with a higher carbon footprint initially, expecting a greener future grid. Successful policy flexibility requires policy discipline, making the hard decisions in the future while taking a looser approach now. Strategic research and aggressive industrial and energy policies in other countries have yielded renewable energy technologies that have both low cost and low carbon footprint. With the right policy design, and aggressive research, development, and deployment, it is conceivable that costs for hydrogen, recycling infrastructure, and other technologies will come down, and that early deployment of mid-carbon technologies will support later deployment of low-carbon ones. Conversely, we have also seen, *e.g.* with the U.S. Clean Air Act,[51] that exempting existing facilities from some regulations resulted in sclerosis of the power system, with old systems kept on life support for decades beyond their design life simply to avoid pollution regulation.[52,53]

There are consequences of allowing imperfect technologies to proceed; there are consequences of blocking the development of imperfect technologies. There are sometimes calls to limit a new technology – the precautionary principle – to avoid potential negative impacts. On the other hand, when a technology is new and still at small scale, there could be benefits to allowing it to move forward without initially checking all the boxes. In the 1990s electric vehicles were designed using lead-acid batteries. Some argued against proceeding with electric vehicles due to the potential for greater lead release to the environment.[54,55] Others argued that electric vehicle technology should be encouraged to develop, albeit with incorporation of lead-acid batteries,[56] as allowing new technologies to flourish could support future innovations, overcome current challenges, and benefit other technologies. Twenty-five years later electric vehicles provide significant environmental and technological benefits, while also facing new material resource challenges. Other technologies deployed despite uncertainties about risks and benefits include nuclear power, biotechnological gain-of-function applications, and artificial intelligence.

Technology policy strives to create conditions under which technology develops to meet societal goals. LCA enables the measurement of progress of technologies toward those goals. This can lead to a virtuous cycle whereby more accurate and comprehensive assessments lead to more sharply formulated policies which in turn drive the science of LCA. Temporality, regionality, and incrementality, as features of policy instruments, are strengthening LCA as a scientific discipline and will spur its evolution.

† Augustine of Hippo, St., *Confessions*. ca 400. Book 8 Chapter 7.

Author contributions

M. J. R. conceptualized the focus of the perspective. All authors contributed to the discussed concepts and examples, prepared and reviewed the manuscript.

Conflicts of interest

There are no conflicts to declare.

Data availability

The authors of the manuscript confirm that the data presented in this manuscript are available within the article and/or in the references cited. Supporting calculations can be provided by the authors upon request.

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References

1 U.S. Department of the Treasury, *Guidance on Clean Fuels Production Credit*, 2025, https://home.treasury.gov/news/press-releases/jy2780.
2 U.S. Department of the Treasury, *Final Rules for Clean Hydrogen Production Tax Credit*, 2025, https://home.treasury.gov/news/press-releases/jy2768.
3 The United States Congress, *H.R. 5376—Inflation Reduction Act of 2022*, 2022, https://www.congress.gov/117/bills/hr5376/BILLS-117hr5376enr.pdf.
4 European Commission, *Carbon Border Adjustment Mechanism*, 2023, https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en.
5 The White House, *Voluntary Carbon Markets Joint Policy Statement and Principles*, 2024, https://home.treasury.gov/system/files/136/VCM-Joint-Policy-Statement-and-Principles.pdf.
6 The United States Congress, *H.R. 6—Energy Independence and Security Act of 2007*, 2007, https://www.congress.gov/bill/110th-congress/house-bill/6.
7 California Air Resources Board, *LCFS Regulation*, https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/lcfs-regulation.
8 National Academies of Sciences, Engineering, and Medicine, *Current Methods for Life-Cycle Analyses of Low-Carbon Transportation Fuels in the United States*, National Academies Press, Washington, DC, 2022, DOI: 10.17226/26402.
9 European Commission, *Renewable Fuels of Non-biological Origin in the European Union*, 2022, https://setis.ec.europa.eu/renewable-fuels-non-biological-origin-european-union_en.
10 Government of Canada, *Clean Hydrogen Investment Tax Credit (ITC)*, 2023, https://www.canada.ca/en/revenue-agency/services/tax/businesses/topics/corporations/business-tax-credits/clean-economy-itc/clean-hydrogen-itc/about-ch-itc.html.
11 H. Ozcan and H. Fazel, Cost assessment of selected nuclear driven hybrid thermochemical cycles for hydrogen production, *Int. J. Hydrogen Energy*, 2024, **54**, 554–561.
12 National Renewable Energy Laboratory (NREL), *Life Cycle Assessment Harmonization*, https://www.nrel.gov/analysis/life-cycle-assessment.html.
13 P. L. Spath and M. K. Mann, *Life Cycle Assessment of a Natural Gas Combined Cycle Power Generation System*, 2000, DOI: 10.2172/776930, http://www.osti.gov/servlets/purl/776930/.
14 S. S. Soomro, C. Hong and M. P. Shaver, Quantification of recycled content in plastics: a review, *Resour., Conserv. Recycl.*, 2025, **221**, 108426.
15 P. M. Stathatou, C. E. Athanasiou and M. J. Realff, From Circularity to Spirality: An Integrated, Systems-Level Approach to Address the Plastics Problem, *J. Am. Chem. Soc.*, 2025, **147**, 32299–32308.
16 Z. Liu, S. Wang and Y. Ouyang, Reliable Biomass Supply Chain Design under Feedstock Seasonality and Probabilistic Facility Disruptions, *Energies*, 2017, **10**, 1895.
17 M. Sadr, D. Esmaeili Aliabadi, B. Avşar and D. Thrän, Assessing the impact of seasonality on bioenergy production from energy crops in Germany, considering just-in-time philosophy, *Biofuels, Bioprod. Biorefin.*, 2024, **18**, 883–898.
18 E. Anerud, *et al.*, *Dry Matter Losses during Biomass Storage: Measures to Minimize Feedstock Degradation*, 2019.
19 L. M. Wendt and H. Zhao, Review on Bioenergy Storage Systems for Preserving and Improving Feedstock Value, *Front. Bioeng. Biotechnol.*, 2020, **8**, 370.
20 D. Ó Céileachair, R. O'Shea, J. D. Murphy and D. M. Wall, The effect of seasonal biomass availability and energy demand on the operation of an on-farm biomethane plant, *J. Cleaner Prod.*, 2022, **368**, 133129.
21 P. W. Hart, Seasonal variations in wood: perceived and real impacts on pulp yield, *Tappi J.*, 2009, **8**(3), 4–8.
22 R. Kim and B. C. Pierce, *Carbon Offsets: an Overview for Scientific Societies*, 2018.
23 CarbonBetter, *Permanence Considerations when Buying Carbon Credits*, 2023, https://carbonbetter.com/story/carbon-credit-permanence/.
24 A. Peters, *Carbon Offsets Have Serious Issues. Is it Even Possible to Fix Them?*, Fast Company, 2022, https://www.fastcompany.com/90781647/carbon-offsets-have-serious-issues-is-it-even-possible-to-fix-them.
25 G. Badgley, *et al.*, California's forest carbon offsets buffer pool is severely undercapitalized, *Front. For. Global Change*, 2022, 5.
26 P. M. Stathatou, L. Corbin, J. C. Meredith and A. Garmulewicz, Biomaterials and Regenerative Agriculture: A Methodological Framework to Enable Circular Transitions, *Sustainability*, 2023, **15**, 14306.
27 P. Catanzaro and A. D'Amato, *Forest Carbon: an Essential Natural Solution for Climate Change*, 2019, https://

necasc.umass.edu/biblio/forest-carbon-essential-natural-solution-climate-change.

28 P. Rajput, G. N. Tiwari, O. S. Sastry, B. Bora and V. Sharma, Degradation of mono-crystalline photovoltaic modules after 22 years of outdoor exposure in the composite climate of India, *Sol. Energy*, 2016, **135**, 786–795.

29 M. S. Mathew, S. T. Kandukuri and C. W. Omlin, Estimation of Wind Turbine Performance Degradation with Deep Neural Networks, *PHM Society European Conference*, 2022, vol. 7, pp. 351–359.

30 International Maritime Organization (IMO), *2023 IMO Strategy on Reduction of GHG Emissions from Ships*, https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx.

31 Fonden Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping and RMI, *Katalist*, https://katalist.eco/https://katalist.eco/.

32 Netherlands Emissions Authority, *Renewable Energy Units*, https://www.emissionsauthority.nl/topics/energy-for-transport/general—energy-for-transport/renewable-energy-units.

33 S. Foteinis, E. Chatzisymeon, A. Litinas and T. Tsoutsos, Used-cooking-oil biodiesel: Life cycle assessment and comparison with first- and third-generation biofuel, *Renewable Energy*, 2020, **153**, 588–600.

34 P. M. Stathatou, S. Bergeron, C. Fee, P. Jeffrey, M. Triantafyllou and N. Gershenfeld, Towards decarbonization of shipping: Direct emissions & life cycle impacts from a biofuel trial aboard an ocean-going dry bulk vessel, *Sustainable Energy Fuels*, 2022, **6**, 1687–1697.

35 G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, The ecoinvent database version 3 (part I): overview and methodology, *Int. J. Life Cycle Assess.*, 2016, **21**, 1218–1230.

36 Flaticon, *Free Vector Icons and Stickers*, https://www.flaticon.com/.

37 M. A. Giovanniello, A. N. Cybulsky, T. Schittekatte and D. S. Mallapragada, The influence of additionality and time-matching requirements on the emissions from grid-connected hydrogen production, *Nat. Energy*, 2024, **9**, 197–207.

38 M. C. Trexler, *Fixing Carbon Offsets: Today's Carbon Offset Standards Undermine the Environmental Integrity of Carbon Markets; We Can Do (Much!) Better*, 2019, https://climatographer.com/wp-content/uploads/2019/10/2019-Trexler_Fixing-Carbon-Offsets.pdf.

39 M. Gillenwater, *What Is Additionality? Part 1: A Long Standing Problem*, 2012, https://ghginstitute.org/wp-content/uploads/2015/04/AdditionalityPaper_Part-1ver3FINAL.pdf.

40 Greenhouse Gas Management Institute & Stockholm Environment Institute, Additionality, *Carbon Offset Guide*, https://offsetguide.org/high-quality-offsets/additionality/.

41 United Nations Convention on Climate Change, *The Clean Development Mechanism*, https://unfccc.int/process-and-meetings/the-kyoto-protocol/mechanisms-under-the-kyoto-protocol/the-clean-development-mechanism.

42 Climate Action Reserve, *Climate Action Reserve*, https://www.climateactionreserve.org/.

43 Gold Standard, *Gold Standard*, 2024, https://www.goldstandard.org/.

44 P. Delacote, *et al.*, Strong transparency required for carbon credit mechanisms, *Nat. Sustainability*, 2024, **7**, 706–713.

45 B. Haya, *Methods for Assessing Carbon Offset Quality*, 2024, https://gspp.berkeley.edu/assets/uploads/page/Detailed-methods-for-assessing-carbon-offset-quality–Developed-for-University-of-California.pdf.

46 J. Stapp, *et al.*, Little evidence of management change in California's forest offset program, *Commun. Earth Environ.*, 2023, **4**, 1–10.

47 T. A. P. West, J. Börner, E. O. Sills and A. Kontoleon, Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon, *Proc. Natl. Acad. Sci. U. S. A.*, 2020, **117**, 24188–24194.

48 T. A. P. West, *et al.*, Action needed to make carbon offsets from forest conservation work for climate change mitigation, *Science*, 2023, **381**, 873–877.

49 A. Gill-Wiehl, D. M. Kammen and B. K. Haya, Pervasive over-crediting from cookstove offset methodologies, *Nat. Sustainability*, 2024, **7**, 191–202.

50 M. Gillenwater, *What Is Additionality? Part 2: A Framework for More Precise Definitions and Standardized Approaches*, 2012, https://ghginstitute.org/wp-content/uploads/2015/04/AdditionalityPaper_Part-2ver3FINAL.pdf.

51 The United States Congress, *Clean Air Act*, 1970, https://www.epa.gov/laws-regulations/summary-clean-air-act.

52 F. Ackerman, B. Biewald, D. White, T. Woolf and W. Moomaw, "Grandfathering and coal plant emissions: the cost of cleaning up the Clean Air Act," *Energy Policy*, 1999, **27**, 929–940.

53 P. Van Doren, *Air Pollution Regulation and Grandfathering*, 2018, https://www.cato.org/blog/air-pollution-regulation-grandfathering#:~:text=Emissions%20are%20emissions%20regardless%20of,political%20opposition%20to%20emission%20control.

54 L. B. Lave, C. T. Hendrickson and F. C. McMichael, Environmental implications of electric cars, *Science*, 1995, **268**, 993–995.

55 L. B. Lave, A. G. Russell, C. T. Hendrickson and F. C. McMichael, Battery-Powered Vehicles: Ozone Reduction versus Lead Discharges, *Environ. Sci. Technol.*, 1996, **30**, 402A–407A.

56 R. Socolow and V. Thomas, The industrial ecology of lead and electric vehicles, *J. Ind. Ecol.*, 1997, **1**, 13–36.