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Beyond carbon in socioenvironmental assessment: Life cycle assessment as a decision support tool for net-zero energy systems

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ABSTRACT

Decarbonizing the energy system is a crucial task for mitigating climate change. Although sustainability assessment methods like life cycle assessment (LCA) are designed for multicriteria sustainability evaluation, greenhouse gas (GHG) emissions tend to dominate recommendations and analyses because of the clear relationship between a simple indicator and the many serious impacts of climate change. When faced with a choice among multiple net-zero GHG infrastructure options, however, GHG emissions are no longer available as an overall proxy for sustainability. The socioenvironmental assessment community thus faces a challenge in robustly evaluating relative sustainability for net-zero GHG energy systems and the systems that use them. Methodological issues like data collection and management, context-specific impact assessment, normalization, and multicriteria prioritization remain underdeveloped in part because they are less important in contexts where GHG emissions are assumed to dominate decisions. Broadly, the ability to robustly and rigorously manage and communicate epistemic uncertainty in true multicriteria sustainability assessment contexts remains underdeveloped in LCA because GHGs have been such a reliably dominant indicator. This piece argues that to survive as a relevant, useful tool in a zero-GHG future, LCA ought to mature as a decision support tool rather than as a pure assessment tool. Methodological attention focused on decision support, including robust approaches to sensitivity and scenario analysis, is particularly needed. Issue areas for LCA “beyond carbon” are categorized by LCA phase, illustrated with examples from carbon capture and storage (CCS) evaluations. Leveraging existing strengths of multicriteria sustainability assessment methodologies like LCA, and investing effort in strengthening their value for decision support, could improve long-term sustainability outcomes.

1. Introduction

The urgent need to decarbonize the energy system in light of ongoing anthropogenic climate change motivates a major analytical interest in understanding the greenhouse gas (GHG) intensity of energy systems. Particularly for designing rapid and deep decarbonization, understanding relative GHG intensity, including life cycle emissions [1], is useful for evaluating decisions about increasingly low-GHG energy resources when climate change is the dominant driver of action. But what of a future with net-zero GHG energy systems? Without GHG intensity as a dominant decision constraint, non-financial socioenvironmental considerations become relatively more important for evaluating the sustainability of energy resources and other systems. As such, methods for rigorously and robustly evaluating often non-commensurable impacts across alternatives will be more important for understanding sustainability in a zero-GHG world.

Net-zero GHG energy systems still have social and environmental constraints, even if the urgency of climate impact is eliminated. Designing and managing a sustainable energy future requires understanding those constraints and their relative importance, particularly given the simultaneous need to manage climate impacts in a net-zero but still climate changed world. Multicriteria socioenvironmental assessment methods like LCA can provide substantial value as shared frameworks for evaluating impacts in decision settings, but such benefits depend on methodological advancements that have not been prioritized in a GHG-dominated context. This work discusses the need for “beyond carbon” socioenvironmental assessments in a net-zero GHG world, and highlights some of the specific needs in LCA and similar evaluation methods. These needs are illustratively discussed in the context of carbon capture and storage (CCS) technologies, with the goal of concretely demonstrating methodological gaps. This piece argues that to survive as a relevant, useful tool in a zero-GHG future, LCA ought to mature as a decision support tool rather than as a pure assessment tool.

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1.1. Life cycle assessment beyond GHGs

Although LCA is explicitly a multicriteria sustainability assessment method, recent applications of LCA and environmental life cycle analyses generally have focused on GHG emissions [2]. The types of issues that LCA considers, called impact categories, are relatively well established in the environmental sphere, with ongoing work to establish meaningful social impact categories [3]. (Life cycle costing (LCC), sometimes considered a separate method, is widely used.) Despite the existence of generally accepted environmental impact categories, and their integration with softwares, databases, and other LCA tools, major data gaps persist both for inventory data (how much impact there is) and characterization data (how important the impacts are relative to other impacts in the same and other categories).

In a methodological context, it is relevant to understand that combustion-based carbon dioxide (CO_2), which accounts for the majority of anthropogenic GHG emissions, is both easier to analyze and more widely accepted as decision-relevant than essentially any other impact indicator. For one, combustion CO_2 emissions can be relatively easily estimated based on well-established chemical relationships, using data that are meticulously collected and maintained in part for market exchange reasons. For example, CO_2 emissions from burning natural gas can be closely approximated from a utility bill. Huge and consistently updated databases of CO_2 emissions associated with a variety of flows are not necessary, because analysts can calculate CO_2 emissions from easily obtainable or easily approximated, rarely contested facts like fuel carbon content and fuel combustion. Notably, GHG emissions not associated with stoichiometric relationships like this are much more difficult to estimate, with large uncertainties [4].

Almost as important as ease of use is that CO_2 emissions are an excellent and relatively space- and time-invariant proxy for a large variety of other socioenvironmental impacts of interest, through climate change. In LCA practice, an indicator (like CO_2) that is measured and cataloged because of its contribution to an impact (like excess mortality, poverty, ecosystem loss, and more due to climate change), rather than a measurement of the impact itself, is called a midpoint indicator. The impacts of interest are known as endpoint indicators and are generally much more difficult to measure directly (see, e.g., [5]). CO_2, and GHGs in general, is a valuable midpoint indicator specifically because it serves as an easily measured proxy for a large number of endpoint indicators that are considered to be important, in the form of climate change. Further, CO_2 emissions are relatively easily allocated to a given product, process, system, or service—the functional unit, or thing that is being analyzed, in LCA—which makes them well suited for sustainability assessment at a variety of scales.

These characteristics of combustion CO_2 emissions—ease of estimation and direct link to many important sustainability outcomes—are rare for sustainability indicators. Evaluative metrics for socioenvironmental impacts beyond quantification of CO_2 emissions from combustion, and more broadly, beyond quantification of fossil fuel combustion byproducts, have not been a high priority, long-term methodological focus for LCA and other assessment methods in practice. As a result, many of the types of impacts likely to dominate a net-zero GHG energy system are difficult to rigorously evaluate in shared frameworks like LCA. Time, location, exposure probabilities, and who exactly is exposed to some amount of impact are often important for understanding what the endpoint impact of a midpoint indicator will be. One unit of CO_2 emitted at 2 pm in an urban area under still wind conditions has roughly the same impact as one unit of CO_2 emitted at midnight in a windy rural area in a completely different country. That is, to first order, GHG emissions have the same impact across space and time at the time scales of immediate relevance. The same cannot be said for most other environmental indicators of interest. This high variability in the impact of a given stressor that can be inventoried is even more pronounced for social impact categories. For example, an easily measured quantitative indicator like appreciation in property values is highly context dependent: is $10,000 a lot, or a little? Furthermore, the impact of property value appreciation might be positive for some groups and negative for other groups. Indicators that more closely match social scientific understanding of important contributors to social sustainability, like social and cultural identity, governance and locus of control, community cohesion, and so on, are difficult and potentially inappropriate to quantify—let alone evaluate in the context of comparing impacts across different kinds of energy resources or other systems of interest for sustainability assessment [6].

Questions of how to evaluate sustainability beyond carbon is important not only for future sustainability assessments in a net-zero GHG world where a system's contributions to climate change are not the dominant sustainability question, but also for prospectively assessing the sustainability of that future during the transition period. Today's planned infrastructure contributes tomorrow's long-term committed impacts [7], and many of those impacts are foreseeable in a way that would be useful to rigorously consider during the decision making process. Prospectively evaluating sustainability impacts is challenging, however. As Luderer et al. note, prospective approaches like integrated assessment models are often limited in their treatment of non-GHG impacts, but approaches like LCA that aim to evaluate sustainability more holistically are often constrained by a focus on conditions as they currently exist, failing to account for potential systematic changes in the future [8]. Some methodological attention in the LCA community has focused on developing approaches more capable of accounting for system changes and dynamic conditions (often called consequential, rather than attributional, LCA) [9,10], but more work is needed to establish such approaches as rigorous and consistent across users.

This work uses socioenvironmental assessment literature on carbon capture and storage (CCS) to illustrate the methodological challenges of sustainability assessment beyond carbon faced by analysts across technology spaces. These challenges are then discussed in the context of LCA, a well-defined method, as a decision support tool for net-zero GHG energy systems, with recommendations for methodological attention.

2. Methods

The primary goal of this article is to articulate development priorities for multicriteria socioenvironmental assessment in a world where GHGs do not dominate the interpretation of sustainability assessments and the decisions made based on those assessments, using a life cycle assessment (LCA) framework and carbon capture and storage (CCS) as an illustrative example. Specifically, this work uses a nonsystematic review of literature on non-GHG social and environmental impacts of CCS to illustrate areas of methodological need for LCA as a quantitative multicriteria decision support tool in a future where combustion CO_2 emissions are no longer appropriate as a proxy for multicriteria sustainability.

2.1. Life cycle assessment as sustainability analysis framework

LCA is an ISO-defined multicriteria assessment method that aims to evaluates all contextually relevant impact categories across all life cycle stages for whatever is being analyzed – the functional unit (Figure 1).

Analytically, LCA takes on a matrix structure given that material inputs to each stage associated with the functional unit's life cycle themselves have a life cycle: that is, for example, conversion infrastructure associated with the generation of one unit of electricity involves material production, processing, transportation, and so on, all of which are associated with impacts, causing LCA to be iterative and highly complex. Figure 1 shows a simplified framework, highlighting common impact assessment categories which are themselves not exhaustive, or even necessarily sufficient, in practice: for example, water quantity is rarely included in formal life cycle inventories or impact assessment methods [11]. LCA can be bottom-up (process LCA); top down (input-output LCA); or a blend (hybrid LCA), with varying

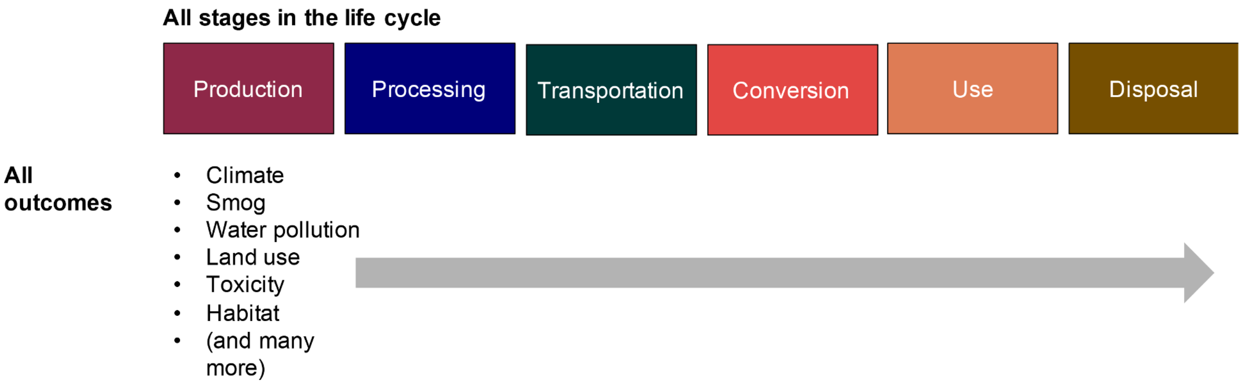

Fig. 1. Life cycle assessment as multicriteria sustainability assessment framework, with common example impact assessment categories.

strengths and weaknesses primarily related to data resolution and boundary constraints [12]. LCA focused on systems that largely do not yet exist, or do not exist at full maturity—such as zero-carbon energy systems—faces major data challenges regardless of approach, as neither high-specificity process data nor prospective data about the overall structure of the economy (required for input-output LCA) are available. As such, robustness checks are particularly relevant for these types of analysis.

Most LCA focuses on environmental impacts (environmental, or E-LCA), although work on social impact assessment also contributes to social LCA (S-LCA) and life cycle sustainability assessment (LCSA), which aims to evaluate environmental, social, and financial aspects of sustainability simultaneously [13,14]. LCA is chosen as the sustainability assessment framework of interest for this investigation of needs for methodological innovation to evaluate sustainability issues beyond carbon, largely because of its aspiration toward comprehensiveness. As such, many other quantitative sustainability assessment frameworks—including footprinting methods and similar—involve subsets or adaptations of the same principles involved with LCA.

One major note is that LCA (and many similar methods) are quantitative, which restricts the use of rigorous qualitative research that might be better suited to some aspects of sustainability assessment [15]. The origins of life cycle methods as focused on costs of military equipment, then energy demand (and later broader environmental impacts) of beverage containers persist in the structure of life cycle tools [14]. These origins are particularly noticeable in that LCA designs are better suited for investigating individual marketed products as functional units (e.g., a kilowatt-hour; a chair) rather than dynamic sociotechnical systems embedded in Political, Economic, Social, Technological, Legal, and Environmental (PESTLE) contexts that imbue deep uncertainty to prospective sustainability assessments in particular [16]. Relatedly, an LCA frame presumes relationships between capital and nature that tend to commodify nature [17] and exclude important social and cultural value frameworks [6,18].

This study uses the basic steps of ISO-defined LCA [19] – goal and scope definition, life cycle inventory, impact assessment, and interpretation – to frame observations about gaps and opportunities for successfully using LCA for sustainability assessment in contexts where climate change is no longer a dominant consideration. LCA is fundamentally a multicriteria assessment tool, first developed to evaluate non-climate considerations, largely for cost and compliance reasons. As such, this work suggests that the framework is likely among the best developed of the sustainability assessment methods for rigorous quantitative sustainability assessment. Rapid development and use of life cycle methods in the context of climate change, however, have arguably resulted in less methodological focus on critical issues for non-climate evaluations than might otherwise have occurred [2,14]. Thus, this work adopts the assumption that the general LCA framework is well adapted to multicriteria sustainability assessment and can be used to contextualize and describe persistent methodological gaps.

2.2. *Carbon capture and storage as topical example*

CCS is used as an example here partly because of its historical relationship with fossil fuel energy consumption, e.g., related to coal or natural gas CCS. The reason this is important is that LCA and similar methods were largely designed around energy assessment, within a fossil fuel-dominated energy context. As such, partly because of the many negative environmental impacts of fossil fuel combustion, impact categories, data, and methodological choices have been developed and applied with a general assumption that fossil fuel use is a major contributor to environmental impacts of interest—particularly in the energy sector. Outside agriculture, energy consumption (which, in practice, has been dominated by fossil energy consumption) is the dominant contributor to environmental impact as measured by LCA for most commodity groups [20]. As such, the level of sophistication for evaluating the socioenvironmental impacts of CCS using LCA is likely higher than for other low- to negative-GHG technologies. Further, CCS impacts are often assessed in relation to the capture and storage of one unit of CO_2 (e.g., [21]), which forces a sustainability assessment that goes beyond GHG emissions. That is, given that LCA has historically paid close attention to the impacts of fossil fuel use, CCS (which was initially evaluated primarily in the case of CCS for fossil fuels) is likely a “best case” for LCA of non-GHG energy impacts. For the purpose of this work, CCS is defined broadly, e.g., including for fuels like coal, natural gas, and biomass in addition to direct air capture (DAC) technologies.

2.3. *Evaluation approach*

Using LCA as a methodological frame, and CCS as a topical frame, this research uses a nonsystematic review to identify gaps and challenges for socioenvironmental assessment “beyond carbon” for net-zero GHG energy systems and their users. Given the goal of illustrating the scope of socioenvironmental impacts identified in the literature, and how they are treated in current LCA practice, the literature review is focused primarily on breadth of impacts and is not intended as a comprehensive review of the CCS literature. Discussions of CCS impacts outside the LCA literature were particularly sought due to an interest in identifying weaknesses in LCA practice that can inform methodological development for beyond carbon assessment in a net-zero GHG world. The social science journals *Society and Natural Resources* and *Energy Research and Social Science* were specifically searched for “carbon capture” and “CCS” to identify work on impacts that might not typically be captured with a purely environmental or industrial ecology frame.

3. Results

This investigation focuses on challenges for socioenvironmental assessment, specifically life cycle assessment, for net-zero GHG energy systems and their users when climate change impacts are not dominant for decision making. Results are presented in two sections: a description of issue areas for LCA "beyond carbon" (Section 3.1) and a vignette of sustainability assessment of carbon capture and storage that illustrates these issue areas in context (Section 3.2). The Discussion (Section 4) contextualizes these challenges and makes recommendations for advancing LCA and similar socioenvironmental assessment methods as decision support tools rather than pure measurement exercises.

3.1. Beyond carbon in LCA

Standard life cycle assessment consists of four phases: 1) goal and scope definition; 2) life cycle inventory; 3) impact assessment; and 4) interpretation. The current dominance of climate change as a collection of urgent, high priority socioenvironmental impacts, caused by relatively easily cataloged flows that are readily assigned to specific processes, masks many of the challenges of multicriteria analysis that are inherent to LCA and similar methods. One major note is that the challenges discussed here already exist, and already affect LCA results: the issue is not that these challenges are new, but rather that they become much more relevant for analysis if GHGs are not reliably considered the most important issue. Table 1 identifies several major issues for LCA at each phase, then describes major associated questions and why these issues are particularly relevant in the context of net-zero GHG systems.

As Table 1 shows, there are many real challenges to performing multicriteria sustainability analysis, particularly given the deeply embedded role of values in analytical choices and approaches [13, 22–25]. Some of the most fundamental challenges, including the basic orientation of LCA to measuring easily discretized negative environmental impacts in a commodity framework; the overwhelming need for highly specific, deeply contextualized data; and the basic truth that there cannot be a completely objective evaluation of "sustainability" in a multicriteria framework, are not analytically solvable questions. The issue, then, is how to enhance the best qualities of LCA—its role as a shared framework to holistically evaluate sustainability in a manner that can inform better outcomes—without making it impossible to use. As will be illustrated in Section 3.2, and further discussed in Section 4, one path forward is to focus methodological attention on using LCA to support decisions, rather than to measure sustainability.

3.2. Vignette: LCA for CCS

Evaluating the sustainability of CCS in an LCA framework poses a variety of challenges identified in Table 1, with the added complexity that CCS remains largely prospective and includes numerous technologies at varying maturity levels that might or might not have robust inventory data, posing further challenges for LCA as a typically highly empirical method. This vignette uses LCA phases to concretize some of the methodological challenges with using LCA to evaluate non-GHG impacts.

3.2.1. Goal and scope

Assuming that CCS has been selected by someone as a reasonable topic of investigation, one of the immediate challenges is to determine which impact categories are relevant to the sustainability of CCS. Without deep experience with the technology, it is difficult to determine what kinds of emergent issues might be of interest, but likely impacts of interest include both typical LCA impact categories, like various pollution, resource consumption and ecosystem impacts, and less typical LCA impact categories. For example, considerations like social license, occupation of underground pore space, requirements for long-term commitment to managing and monitoring storage, job safety and security, and similar issues are likely important. Emergent issues are more challenging to anticipate. Would significant use of coal CCS be associated with negative corporate behavior, like discharge of environmental and labor liabilities [26]? What about land use issues and social dynamics [27]? Similarly, boundary conditions are somewhat challenging to identify given that the time scale of carbon sequestration is effectively infinite. How should end of life considerations be included in an LCA if an activity creates an indefinite management obligation?

One notable observation about existing CCS literature is that many evaluations claiming to perform a LCA exclude extremely important non-GHG upstream impacts. The CCS LCA literature frequently acknowledges the energy intensity of carbon capture processes [28,29], but only rarely engages with the full implications of that energy use for sustainability indicators beyond cost and energy consumption at the site of carbon capture, in large part due to methodological challenges and the reality that historically, LCA has informed decisions that will be made largely based on GHG intensity. For example, Pehnt and Henkel suggest that a reference case lignite-fired power plant in 2020 would have a net efficiency of 46% without CCS, and 27.8% with CCS – implying a 65% increase in coal demand to deliver the same amount of electricity [29]. Although the study includes mining impacts in impact categories deemed relevant to the CCS process itself, it excludes major mining impacts in other categories – like land occupation, water consumption, and others that might be significant at a full-system level. That is, both impact categories and boundaries need to be considered in the context of the life cycle, which can be extremely challenging.

Similar issues are present in LCA focused on carbon capture technologies that are truly net-zero or net-negative GHG, like DAC. Immense energy intensities are generally discussed mainly in terms of cost and (the absence of) combustion emissions from the grid, rather than with respect to the anticipated extreme additional power generation build out that is likely to be necessary, particularly for technologies with limited ability to ramp in response to renewable electricity generation profiles. Even beyond CCS, many prospective LCAs considering a net-zero GHG energy system uncritically speculate that perhaps impacts from energy use would be negligible, as the technology under evaluation would be able to use electricity that would otherwise be curtailed. In the context of quantitative sustainability assessments, such assertions need to be quantitatively supported before analysts can claim plausibly negligible impacts. In general, goal and scope definition ought to more carefully include determinations of which impacts, and out to which system boundaries, are to be included in evaluations.

3.2.2. Life cycle inventory

One of the most significant issues with life cycle inventories is a lack of available data. Drawing again on Pehnt and Henkel's evaluation of lignite CCS, that study notes that "data for emissions to water and soil – which are more difficult to anticipate compared to emissions to air – were not available and therefore could not be evaluated" [29]. Similarly, Young et al. exclude toxicity due to data limitations [21]. Such constraints are real, particularly in difficult-to-quantify contexts like impacts that do not discretely accrue in response to production of a functional unit like 1 kWh, or social impacts in general. Simply noting that a potentially major issue could not be evaluated, however, has the effect of excluding it from consideration. Potential solutions include the use of ranges of plausible impacts and a more explicit requirement to discuss data gaps during the interpretation phase.

One reason that inventory gaps are so relevant for beyond carbon LCA is that the dominant role of combustion CO_2 in modern LCA tends to mask the significance of inventory data gaps. Combustion CO_2 is a highly unusual indicator because it is so readily and specifically calculated from existing data that might not be collected specifically for measuring environmental impact, like fuel carbon content and consumption data. Because of its relationship with important endpoint outcomes in the form of climate change, it is also often reported directly, allowing for validation of overall estimates. It is also easily assigned to a given process in discrete amounts, enabling relatively simple impact allocation to a project. That is, as an indicator, combustion CO_2 suffers from very few of the complexities that make life cycle inventories

Table 1
Issues for LCA in net-zero GHG systems.

Phase	Issue	Major questions	Relevance in a net-zero GHG system
Goal and Scope	who chooses?	• is the topic selected by a community, company, government, funding agency, researcher, etc.? why? who else could or should be involved?	• diversity of opinions, value systems, etc. is especially crucial for truly multicriteria assessment
	choose topic	• is the study conducted to support an active decision process, or to assess issues after the fact?	• with an infrastructural transition underway due to climate change, "how bad is the existing thing" is an extremely relevant question: beyond climate, "how can we make the planned thing better" is likely more relevant, especially given high uncertainty in assessing, allocating, and comparing difficult-to-quantify multicriteria impacts
	choose impact categories	• what issues are important for evaluating sustainability of the analyte, independent of questions about data availability and tractability?	• when there is not an assumed "highest priority" issue (like cost or climate change), careful consideration of what people need to know about a functional unit becomes critical
	choose system boundary	• what is the cutoff for considering impacts? is that boundary being applied consistently across impact categories?	• impacts of CO_2 do not really vary by place and time of emission, and CO_2 is relatively easy to allocate to an emitter: impacts and allocation through the life cycle are more challenging for other indicators, especially for complex systems
Life Cycle Inventory	data availability	• how are data being selected for investigation, collected, and stored? • are data available (or can they be available) for relevant inventory issues?	• data generation and maintenance is not academically rewarded, and many data required for robust LCA are not robustly available from public sources the way GHGs often are
	data robustness	• how do analysts know how reliable the data are?	• empirical data are difficult to validate, particularly given that LCA analysts are unlikely to have complete intuition across thousands of flows • many data cannot be formulaically validated the way that, e.g., combustion CO_2 emissions or water evaporation can be
	data specificity	• are data relevantly contextualized, e.g., with respect to location, time, and likely exposures?	• place, time, and exposure to most flows determines their impact, unlike for CO_2 • many flows of interest are not linearly related to a process in a way that can be characterized using a single, invariant intensity factor
	data maintenance	• how frequently are data reviewed and updated?	• nonlinear relationships between flows and processes are dynamic • data errors in major LCA databases can be easily propagated, particularly absent clear validation pathways
Impact Assessment	normalization within categories (characterization factors)	• are there robust, evidence-supported ways of comparing two indicators in the same impact category?	• even global warming potentials (GWPs)—probably the most studied characterization factors—remain contested: impact categories with numerous, qualitatively different indicators are more challenging
	normalization across categories	• how do we know whether a quantity in one category is a lot or a little relative to a quantity in a different category?	• non-GHG midpoint indicators are often associated with fewer endpoints, making it more relevant to evaluate multiple noncommensurable categories
	place, time, and exposure-aware impact assessment	• do impact assessment methods appropriately account for differential impacts of a flow based on place, time, and who is exposed?	• GHG impacts are, to first order, time- and space-invariant, which is rarely the case for other indicators of interest
	issue prioritization	• are judgments about the relative importance of impact categories explicit, or at least stress-tested?	• LCA is extremely sensitive to prioritization: in practice, climate is often prioritized, reducing the perceived need to explicitly consider this step
Interpretation	decision support, for and with whom?	• what is the goal of presenting LCA results, and who is being included and considered in that presentation?	• diversity of opinions, value systems, etc. is especially crucial for truly multicriteria assessment
	completeness	• how much of the original goal and scope was achieved, and how do gaps affect the interpretation of results?	• data gaps have historically been masked by the dominance of GHGs
	sensitivity checks	• how sensitive are results to different data? different impact assessment? different value systems? • what information would change the interpretation / recommendation?	• more indicators of relevance means more data, and likely less intuition about what specific data points represent • decisions do not evaluate infinite alternatives, so focusing on what changes outcomes can reduce data intensity
	consistency checks	• is the work internally consistent, e.g., in inventory data used for multiple processes; in expected direction of error (e.g., consistently over- vs under-estimated)? • is the work externally valid, given prior work on the topic?	• LCAs can include thousands of flows, which might be more relatively important when not dominated by combustion GHGs • value judgements are inherent to sustainability assessments, so explaining differences between new and old findings can help make these explicit
	relevancy checks	• does the interpretation serve specific relevant purposes? • based on the overall work, was the goal and scoping appropriate?	• for truly multicriteria sustainability assessment using data-intensive methods, assessing what outputs are relevant can shape inquiry

difficult. Its dominant role in modern LCA has tended to mask the significance of inventory data gaps.

Another major issue with life cycle inventories beyond carbon is that the impact of many indicators is highly dependent on the time, location, and specific context where they occur. For example, photochemical smog formation requires sunlight in addition to smog precursor emissions, and impacts of local pollutants like smog are much higher in densely populated areas with lots of outdoor activity than in remote areas with very little opportunity for human exposure. Getting more details on specific indicators, and carefully logging which types of information are important to collect or assume, is far more relevant for non-GHG indicators than for GHG indicators.

3.2.3. *Impact assessment*

Specificity in inventories is largely important because of its role in calculating impact. Converting a measured flow (an indicator) to an anticipated impact requires attention to relationships between that indicator and the impacts. Several key needs accrue during impact assessment: intracategory normalization (via characterization factors, e.g., [30]); intercategory normalization (as with distance-to-target methods, e.g., [31,32]); and prioritization, or preference-based weighting across categories [13,33].

Young et al. use a normalization technique based on total US national impacts as of 2008 for intercategory normalization [21]. Although this approach has the benefit of being grounded in often available data, it also fails to account for the point that existing impacts might be worse in some categories than others. For example, emitting 60% of a pollutant that is well controlled might not have worse relative impact versus emitting 5% of an uncontrolled pollutant causing severe harms. Distance-to-target methods aim to account for this issue by setting the reference to a standard target for total flows, rather than existing flows, but this method requires the existence of a target for all relevant impact categories. Normalization is a challenging and value-laden task that can be extremely important for overall results, and merits more attention in LCA.

Weighting, or prioritization based on preferences for certain kinds of impacts, is controversial in LCA but exists in any multicriteria decision context, whether explicitly or implicitly [2,13]. In practice, GHG emissions are often given priority in LCA, though sometimes not through explicit prioritization: for example, impact category selection during the Goal and Scope phase is itself a form of prioritization that sets priority of excluded categories to 0. In general, though, prioritization is either implicit or based on highly specific data gathering activities like stakeholder preference elicitation [34].

3.2.4. *Interpretation*

LCA interpretation is highly nonstandard, in some ways appropriately due to the specific context of individual studies. Moving beyond carbon in LCA probably does require additional attention to the kinds of activities that the Interpretation phase should include, such as validation, review of weaknesses in an analysis relative to needs and original goals, and robustness checks. Quantitative model results are often interpreted as authoritative, even when inputs and assumptions have not been extensively reviewed, checked, and validated within feasibility and other frames [35]. Recognizing issues like the uncertainty of prospective analyses within the context of risks, attitude formation, and trust [36] will likely become more relevant if LCA is used more to support future decisions rather than to assess existing conditions.

4. Discussion

In a multicriteria understanding of sustainability, sustainability cannot be objectively measured. It can, however, be evaluated in the social and cultural context of involved actors, participants, and affected parties, broadly construed. Those evaluations can be used to inform, adjust, and learn from decisions. LCA can play this decision support role, as a shared framework for collaborative governance [37,38] to holistically consider sustainability in a way that allows for questions, stress testing, and reevaluation to inform choices that ultimately must be made. To date, LCA for energy systems in particular has primarily been deployed in contexts with an implicit understanding that one process—fossil fuel combustion—dominates sustainability, primarily due to its contributions to a multicriteria endpoint (climate change), accompanied by relatively stable, negative impacts on other impact categories of interest, like air pollution, water consumption, water pollution, soil contamination, solid waste generation, and more. Particularly because much of the sustainability community is aligned on the notion of climate change as a dominant sustainability issue, and because measuring and allocating fossil fuel combustion is straightforward, LCA practice has not needed to grapple deeply with the implications of attempting to quantitatively evaluate "sustainability" in a multicriteria framework with contested value systems. Focusing on improving LCA as a true decision support tool rather than a sustainability measurement tool, designed to engage decision makers rather than to be used as a data input, can build on the many valuable advances of the field and provide value for evaluations of net-zero GHG energy systems and their users.

To quantitatively approach sustainability is to engage with epistemic uncertainty in addition to typical challenges associated with model uncertainty, parameter uncertainty, dynamism in inventory data, and other assessment challenges. That is, even under perfect data and impact assessment conditions, LCA and other sustainability assessment methods face major uncertainty associated with the point that environmental, social, and financial elements of sustainability are fundamentally non-commensurable. Some cannot, or should not, be effectively quantified. Others cannot be discretized and assigned as a specific amount of harm associated with the system being evaluated. This uncertainty can be named, and described, and considered, even if it cannot be solved. As such, considering the potential role of decision-oriented methods for expressing uncertainty, distinguishing among categories of uncertainty, and demonstrating the relative roles of different issues in decision contexts can improve the value of LCA, particularly as a deliberative tool for decision support (see, e.g., [6,39]). One major advantage of using LCA and similar tools in decision support roles is that real decisions rarely engage infinite options: specificity about what the options actually are can reduce the number of parameters that really need to be addressed if it is clear that certain issues will not affect the final decision.

The relative value of methodological investment in evaluating and communicating the robustness of LCA results in the face of various uncertainties, risk attitudes, and preferences [13] versus more traditional cataloging tasks (e.g., performing LCA of a variety of generalized product systems, gathering generalized data on indicator flows) is likely to be high, particularly given the robust base of investment in more data-oriented work. Scoping work in advance of inventory and impact assessment can help identify where data are truly needed, a particularly valuable contribution when impacts are likely to vary substantially across time, space, and affected parties. Simultaneously, developing robust strategies for managing situations where critical data might not be available, such as by identifying plausible quantitative ranges for specific impacts, can focus analysis (and resource use) on the most important issues. For example, if analysts know that a given water pollutant will be released to a rural freshwater lake, at an intensity of 0.1 to 0.3 kg per functional unit, and if no scenario in that bounded assessment changes the decision, highly accurate measurement of the water pollutant might not be needed.

This call to focus on improving process rather than outputs in LCA reflects a substantial body of work in decision science and related fields, including rejection of the deficit model of knowledge [40] and a focus on normative procedures for decision making [41]. The idea that quantitative estimates have value as sociologically mediated parameters that enable shared frameworks and entry points for participation in values-based decision making has been discussed in the context of global warming potential, a major characterization factor used in LCA [30]. Shackley and Wynne's caution that quantitative measures can be perceived as more robust than they are [30] remains highly relevant in the context of methodological development, which could address this challenge by focusing on clear presentation of sensitivities and ranges for quantitative estimates in key areas. Skjølsvold similarly discusses the point that environmental criteria are politically constructed and subject to contested claims of truth, as "matters of concern" rather than "matters of fact" [42]. One major observation from the nonsystematic review of CCS literature performed for this work is that the socially-focused contributions tend to focus on issues of power structures, embedded values, governance, perceptions, uncertainty, and complexity, rather than prospective quantification of social impacts. Nonetheless, social scientific perspectives have been relatively slow to enter energy policy planning spaces, aside from “functionalist assumptions” that justify particular frameworks [43].

By contrast, much of the environmentally-focused literature makes assumptions about technical parameters, impact intensities, and similar quantitative inputs to declare a measure of environmental sustainability. Both approaches provide value: but the point that social science investigation has focused on evaluating “Goal and Scope” and “Interpretation”-phase issues, rather than the “Life Cycle Inventory” and “Impact Assessment” focus on environmental science work, reinforces the claim that process and context are critically important to LCA’s relevance in decision contexts. That is, the silence in the social science literature on quantifying discretized social impacts associated with a product system is notable as evidence that perhaps such quantification is not the most theoretically robust approach. Simultaneously, as environmental evaluation of CCS is essentially prospective given the very limited deployment of CCS relative to potential scales generally discussed in energy systems analysis, the lack of careful and rigorous consideration of uncertainty, dynamism, and counterfactuals in the environmental literature is also noteworthy. Fundamental complexity in systems like these challenges expert judgment, which can be particularly problematic given that plausible parameters can be selected to justify particular outcomes [44]. For example, the commitment to bioenergy carbon capture and storage (BECCS) in quantitative models because of a need to fulfil a technical parameter (i.e., meeting a specific temperature target), despite analysts’ personal beliefs that BECCS at those scales is not feasible, manifests a sociotechnical imaginary that appears far more robust than it is because of quantitative legitimation that is not subjected to serious investigation of uncertainty, plausibility, and so forth [35]. Focusing on creating structures for such serious investigations can enhance LCA’s value as a decision tool in truly multicriteria sustainability contexts beyond carbon.

Viewing LCA as a decision support tool rather than simply an impact quantification methodology has major implications for how issues like preferences, priorities, and whether to account for decision-relevant issues that might not be readily usable as impact indicators are treated within the LCA framework. For example, considerations like the role of politics [45], lack of technology familiarity among stakeholders [36], planning timelines [46], suitability for particular existing governance structures [17,46], relative levels of uncertainty across decision alternatives, e.g., “reliance on miraculous breakthroughs” for CCS [43], and other similar issues might not be easily included as indicators but are certainly relevant in the context of project evaluation. As Bessette and Gregory note, some qualitative concerns can be effectively integrated to quantitative analyses via constructed metrics like scales [6]. Other approaches are likely to be needed, particularly for complex, large systems like energy infrastructure that need to be understood at scale [47].

Overall, moving socioenvironmental assessment beyond carbon to evaluate net-zero GHG energy systems and their users will require significant methodological attention. Focusing on process, including ways of making such assessments into true decision support tools rather than sustainability quantification approaches, can enhance the value of LCA and similar tools in the future.

Declaration of Competing Interest

I declare no conflicts of interest.

Author contributions

Emily Grubert: Conceptualization, Investigation, Data Curation, Visualization, Writing – Original Draft, Writing – Reviewing and Editing

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