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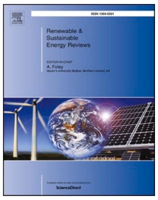

Paradigm shifts for environmental assessment of decarbonizing energy systems: Emerging dominance of embodied impacts and design-oriented decision support needs

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ABSTRACT

As energy systems decarbonize, their environmental impacts will change. Historically, energy consumption has been a reliable proxy for environmental impacts of interest due to the dominance of fossil fuel combustion. With a normative transition to decarbonized energy, however, environmental assessment of energy systems faces two major paradigm shifts: 1) environmental profiles are likely to be dominated by embodied rather than operational impacts; and 2) the primary analytical need is for prospective and trustworthy analysis to support system design decisions. Ensuring that analysis of diverse potential decarbonized futures is rigorous and granted legitimacy by potential users is critical if such analysis is to be used and useful as decision support. This review uses both computational and narrative methods to evaluate the English language literature on 12 environmental impact categories and 18 types of decarbonized energy resources or energy carriers to ask: what issues does environmental assessment need to be able to rigorously evaluate to support decisions about designing a decarbonized energy supply? We find that embodied impacts are likely to dominate. We suggest that land use metrics might displace energy consumption as the best single proxy for overall energy supply system impacts, though translating land use inventory data to environmental impacts requires significantly more contextualization than does fossil fuel combustion. Individual energy resources or energy carriers have diverse potential environmental impacts that are highly context dependent and dynamic under technological and environmental change, which suggests that mitigation pathways might depend on project design choices more than technological mitigation.

1. Introduction

The threat of climate change motivates an urgent shift from the historically fossil fuel-dominated industrial energy system to one that does not generate greenhouse gas emissions [1,2]. Though driven by climate change, this transition is further motivated by environmental justice and human health concerns associated with environmental impacts largely caused by fossil fuel extraction and combustion [3,4]. As energy systems change, so too will their environmental impacts. Future environmental impacts are likely to be more diverse (i.e., not predominantly combustion-driven) and more context-specific, in the sense that the impact of a given effect of energy systems will vary greatly depending on where, when, and to whom it happens [5–8]. As such, understanding what these effects and impacts might be, and how we might mitigate them, is highly relevant as we design new energy systems globally. Particularly given the context-specific nature of environmental impacts, creating decision support tools that can support project and system design in a way that reveals potential mitigation pathways before impacts are committed by new infrastructure is likely a valuable path forward for environmental assessment. Such decision support tools will require additional effort to ensure that input analysis is rigorous and fit for purpose if they are to achieve legitimacy and authority.

Achieving broad legitimacy for analytical tools is particularly relevant in the context of a deliberate acceleration of a transition with a normative goal [9–13]. Moving toward sustainability, including environmental, social, and financial elements, is a normative, goal-oriented process. As such, progress can be measured, and it is possible to evaluate whether a particular system is reaching goals. To do so, however, metrics, measurement strategies, and the foundations of decision support tools need to be agreed upon, which can be challenging in the context of multidimensional, long-term, uncertain, and dynamic transition [11]. Agreement on the core approaches and what constitutes both rigor and a legitimate fact base is particularly crucial given the vital role of value

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List of abbreviations:

CANDU	Canada Deuterium Uranium
CCUS	carbon capture for utilization and/or storage
CH_4	methane
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CSP	concentrating solar power
EGS	enhanced geothermal systems
GHG	greenhouse gas
GWP	global warming potential
HC	hydrocarbon
kg	kilogram
LCA	life cycle assessment
LDA	latent Dirichlet allocation
MALLET	MAchine Learning for LanguagE Toolkit
N_2O	nitrous oxide
PV	photovoltaic
SMR	steam methane reforming
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
US	United States

judgments in decision making, and the benefits of spending effort explicitly discussing values rather than contesting supporting data (e.g., how much land area a wind farm occupies) [14,15].

Currently, environmental impacts of energy systems are commonly evaluated by means of environmental assessment tools like life cycle assessment (LCA) that enjoy wide authority despite considerable latitude for practitioners to implement specific choices. In part, authority and legitimacy derives from widely referenced international standards (e.g., International Organization for Standardization standards for LCA [16]), regulation (e.g., environmental impact statements and environmental assessments for projects in the United States), long-standing softwares and analytical methods developed and supported by trusted organizations (e.g., the Environmental Protection Agency's LCA impact assessment method, TRACI [17]), and use in other authoritative processes (e.g., Leadership in Energy and Environmental Design building certification). In part due to a historical emphasis on product evaluation [18], LCA and similar tools designed for holistic, multicriteria evaluation of environmental (and perhaps broader [19]) impacts rely on per-unit estimates of environmental impact that can be linearly scaled [20]. In the context of a stable historical energy system where environmental impacts are dominated by fossil fuel consumption (in particular, via combustion) [21], this approach has functioned relatively well, as impacts of the dominant system have been driven by the use phase. Concern about the broad applicability of linear marginal change estimates to decision support about environmentally relevant impacts, however, has long been expressed [20,22].

As energy supplies undergo a paradigm shift under decarbonization, the challenge of estimating environmental impacts per unit of energy use is becoming increasingly clear: many of the resources expected to play major roles in decarbonization have large capitalized impacts (e.g., from construction and end-of-life), but limited impacts from operations. Tools adapted for estimating marginal impacts therefore likely need to be reevaluated under this paradigm shift, but both this observation and responses to it remain literature gaps—gaps that this review addresses. As we advance a decadal-scale transformation with a normative end point [23], recognizing both that the future remains uncertain given multiple potential pathways to success and that the end point has some predictable features given system and technology constraints [23,24] means that the nature of what is needed analytically is relatively clear. The specific path to decarbonization has major implications for different types of socioenvironmental outcomes [5], which motivates urgent attention to stewarding high-quality decision support tools that can support design choices suited to the types of technologies and systems that can advance a normative sustainability goal. That is, we know transformation is coming; we know decision support will be required; and we know enough about what will drive that transformation to improve the capabilities of our analysis tools to meet these needs.

The environmental impacts of energy systems are widely studied using LCA and other techniques. In part because multicriteria evaluations are extremely data intensive [25], climate change is a major priority [2], and fossil energy consumption has historically been an excellent proxy for environmental impact [21], development of authoritative, shared metrics, databases, and other inputs for rigorous multicriteria environmental impact evaluation for issues other than stoichiometrically verifiable per-unit combustion emissions has arguably lagged behind what is likely required to support design of decarbonized energy systems [26]. Although rigorous life cycle assessments of low-carbon energy systems have been conducted [8], there remains a significant gap in analyses that can effectively support design decisions at scale and in context. As Gibon et al. note [8], at a basic level, data for some of the most important issue areas are scarce, including for specific types of energy supplies and crucial impacts of interest (e.g., metal depletion).

The most widely legitimized impact categories in life cycle assessment frequently exclude issues that are highly meaningful both as environmental impacts of decarbonized energy supplies and as contributors to decisions about sociotechnical systems where co-benefits and disbenefits are highly relevant for design choices [9]. For example, water consumption (or any other measure of water use) is generally not evaluated (though see Refs. [27,28]), despite significant variation in prospective water futures associated with energy supply system design and climate change [5,29]. Land use evaluation in LCA focuses primarily on land area occupied, with contested measurement approaches and definitions of occupation, rather than on landscape changes, habitat impacts, displacement, allocation among competing uses, and other issues of substantial relevance for decarbonized energy systems (see, e.g. Ref. [30]). In general, impact categories in LCA tend to emphasize pollutant flows that can be quantified per unit of marginal impact, rather than resource use that is not easily linearly tied to a product.

Prospective evaluation of impacts associated with potential future energy supply system designs can aid the decarbonization transition. A core challenge for prospective environmental assessments is to appropriately capture decision-relevant attributes for systems subject to significant dynamics, for example due to high learning rates, climate change, normative transitions toward preferable environmental profiles, and so on. For example, efforts to reach a circular economy for materials used in decarbonized energy technologies could dramatically change the environmental burden associated with material inputs [31]. Similarly, energy inputs that are currently heavily fossil fuel-based are expected to decarbonize [32], in part due to their use in constructing a new energy supply system. Particularly when systems are being compared, ensuring that differential rates of change and the potential for mitigative redesign are correctly captured for different contexts is important for identifying preferential pathways. The issue of capturing dynamics for rapidly changing renewable energy technologies has long been recognized as an area of need for LCA development [33]. In many cases, doing this in a manner that supports decisions will likely require scenario analysis reflecting multiple potential futures. For environmental impacts specifically, focusing methodological development of analysis and decision support tools on maturing the most critical issues needed for the specific tasks (e.g., supporting system design) and objects of analysis (e.g., decarbonized energy supplies) can enable such prospective evaluation. This review highlights and responds to some of these developmental needs.

In general, ensuring that environmental assessment tools like LCA are providing appropriate decision support for transformative system design decisions under a normative transition to decarbonized energy supplies will require adaptations to practices that have matured in the context of a relatively stable, fossil fuel-dominated system. The fossil fuel paradigm has meant that energy consumption has been a high quality proxy variable for environmental impacts of interest [21], and climate pollution has been a dominant and easily estimated metric [34, 35]. Outside of the CO_2-dominated climate change domain, environmental assessments are subject to enormous uncertainty: one recent meta-study showed results spanning five orders of magnitude for non-climate impact categories [36]. Particularly as the goals of environmental assessment of energy systems shift from characterization (what is the impact of using energy?) to design-oriented decision support (what energy system should we build in order to deliver energy services without worsening climate change?), this uncertainty about environmental impacts of energy systems poses a growing and urgent challenge for the environmental assessment community. Addressing it requires understanding what issues are most crucial to get right for a decarbonized energy system. This review aims to contribute to this understanding by conducting a targeted review of what is known about the environmental impacts of energy supply systems relevant for decarbonization, with the goal of evaluating which issues are most critical for environmental assessment methodologies to address, thus highlighting areas for methodological attention.

Specifically, in order to support developmental work in environmental assessment of decarbonizing energy supplies, this work reviews existing literature on environmental impacts of supply-side energy systems with zero- or very low greenhouse gas emissions. We use a combination of computationally-aided and narrative review to investigate English language academic literature attention to environmental impacts for eight decarbonized supply-side energy resources and ten potentially decarbonized energy carriers. Here, we define energy resources as primary energy resources and their capture technologies, which are equivalent to conversion technologies for electricity-oriented resources like wind and solar. We define energy carriers as manufactured energy carriers that are produced using energy resources, excluding electricity from resources where the capture and conversion step is identical. The remainder of this paper describes our review approach; findings; and recommendations for environmental assessment practice, supported by appendices that include a resource-by-resource referenced summary of environmental impacts for all 18 energy resources/carriers of interest.

2. Methods

2.1. Review scope

The specific environmental outcomes, energy resources, and energy carriers selected for evaluation within the scope of this review, focused on how the academic literature captures and describes environmental impacts associated with decarbonized energy resources and energy carriers, were identified iteratively. Initial lists were generated based on the authors' judgment, informed by the first author's expertise in life cycle assessment and energy systems. These lists were refined in consultation with external experts, with emphasis on ensuring that environmental outcomes and energy resources/energy carriers of broad public interest, regardless of current scale, were included. This refinement explicitly included discussion of environmental outcomes beyond typical life cycle assessment impact categories that, based on expert identification [15], might be decision-relevant under a paradigm shift associated with the declining dominance of fossil fuels [26].

In addition to direct discussion with experts, lists were further refined based on review of several recent deep decarbonization studies for the US, with the goal of validating which energy resources and carriers might be expected to play particularly major roles in decarbonization. Most studies include substantial roles for wind, solar, and biomass: as such, special attention was paid to these resources with the goal of identifying unusual or particularly dynamic environmental impacts that might not be evaluated in typical environmental assessments. In particular, the emphasis on biohydrogen in Williams et al. [24] and similar studies prompted further and specific investigation of biomass gasification for hydrogen production.

The final lists of environmental outcomes (Table 1) and the energy resources (Table 2) and carriers (Table 3) evaluated in this paper are presented below, alongside definitions for each term.

2.2. Corpus identification

The scope of inquiry associated with this review of multicriteria environmental impacts for numerous energy resources and carriers is large. As such, and particularly given that a major goal of this review is to identify broad trends in the literature on environmental impacts associated with decarbonized energy supplies in order to inform direction for environmental assessment practice under a major paradigm shift away from descriptive evaluation of largely operational environmental impacts associated with fossil fuel combustion, this review uses two complementary approaches: a computationally aided review and a narrative review. Accordingly, the review also takes two complementary approaches to identifying a corpus, or collection of documents, for review. The first is a comprehensive corpus for coarse analysis via computational aids, and the second is a targeted, curated corpus for fine-grained manual review. Computationally-aided reviews can be of significant value for high-volume fields, and can validate findings from manual reviews [37]. The following sections describe how each corpus was generated.

2.2.1. Computationally-aided review

The computationally-aided review prioritizes completeness, although the size of the relevant corpus necessarily means that analysis is coarse. For this work, the corpus for the computationally aided review

Table 1
Definitions of environmental outcomes evaluated in this review.

Environmental Outcomes	Definition
Water Use (quantity)	Quantity of freshwater consumed, withdrawn, or otherwise required in association with the energy resource/carrier of interest.
Water Pollution (quality)	Negative impacts to water quality associated with thermal, chemical, or physical discharges.
Air Pollution	Negative impacts to air quality associated with chemical or physical discharges.
Climate Risk	In the context of decarbonization resources, greenhouse gas emissions or reasonable potential for disparities between stated and actual greenhouse gas emissions.
Solid Waste Generation	Outputs of solid waste materials for management.
Land Use	Land occupation, related to quantity, habitat impacts, permanence of disturbance, and aesthetic impacts like noise, odors, and smells.
End-of-life Management	Challenges associated with facility closures, such as plant decommissioning.
Limits to Input Resource Bases	Potential constraining limits associated with key non-energy inputs, like minerals, not captured elsewhere.
Limits to Energy Resource Bases	Potential constraining limits associated with energy, including technical limitations like intermittency and ramp rate in addition to general availability.
Mining Requirements	Induced need for mining that could be constraining.
Hazard	Notable dangers to humans.
Areas of Controversy	Issues with substantial disagreement in the literature, or issues with significant influence on potential resource deployment that might not be cataloged as major within typical environmental assessment frameworks (e.g., relatively few, highly publicized avian mortalities at wind farms).

Table 2
Definitions of energy resources evaluated in this review.

Energy Resources	Definition
Wind	On- and offshore wind turbines for electricity generation. We do not specifically investigate distributed-scale architectures or vertical axis turbines.
Solar PV	Solar photovoltaics for electricity generation. Given the potential future role of perovskites, we do include them in this evaluation.
Solar CSP	Concentrating Solar Power for electricity generation, here meaning thermal (e.g., power towers, trough systems) rather than concentrating photovoltaics. Given the relatively small existing scale and projected role for this resource, we do not individually investigate the multiple architectures. We also do not evaluate impacts of on-site thermal storage approaches like molten salt.
Geothermal	Geothermal plants for electricity generation. We neither exclude nor emphasize potential future systems, like enhanced geothermal systems (EGS or "hot dry rock"), which has the effect of focusing on extant steam and binary systems.
Hydroelectricity	Dam-based hydroelectricity from freshwater. We do not investigate small, non-dam systems. We do not investigate ocean, tidal, salinity gradient, or other unusual water-based generating systems.
Nuclear	Existing nuclear fission technologies for electricity generation. We do not evaluate hypothetical future systems or architectures uncommon in the US (e.g., CANDU reactors).
Biomass	Solid biomass (e.g., forestry, agriculture/agriculture residues, energy crops) for further conversion to electricity, liquid fuels, or gaseous resources like biohydrogen and biomethane. Excludes municipal solid waste and aqueous organic biomass.
Fossil CCUS	Fossil fuel-fired electricity with carbon capture for utilization and/or storage.

Table 3
Definitions of energy carriers evaluated in this review.

Energy Carriers	Definition
Biomass CCUS	Solid biomass-fired electricity with carbon capture for utilization and/or storage.
Biomethane	Methane derived directly from organic material (excludes hydrogen methanated with biomass-derived CO_2, which is included in synthetic methane).
Synthetic methane	Methane manufactured in a power-to-gas process involving electricity + hydrogen + CO_2.
Biohydrogen with CCUS	Solid biomass-derived hydrogen accompanied by carbon capture for utilization and/or storage.
Green hydrogen	Hydrogen produced from renewable electricity and water via electrolysis.
Blue hydrogen	Hydrogen produced from fossil methane and water via Steam Methane Reforming.
Nuclear-based hydrogen	Hydrogen produced from water via thermochemical means using nuclear heat. We do not separately investigate hydrogen produced electrolytically using nuclear electricity.
Renewable ammonia	Ammonia produced from green hydrogen and nitrogen using renewable energy inputs.
Liquid biofuels	Non Fischer-Tropsch liquid fuels manufactured from biomass.
Synthetic liquid hydrocarbons	Fischer-Tropsch liquid fuels manufactured from hydrogen and CO_2.

Table 4
Bibliometric summary of publications on energy resources and carriers, based on Web of Knowledge.

Resource	WOK Keywords	Abstracts included in text analysis
Wind	wind	10588
Solar PV	solar, photovoltaic	4039
Solar CSP	solar, thermal and solar, concentrat*	5031
Geothermal	geothermal	1583
Hydroelectricity	hydroelectric* and hydropower	2445
Nuclear	nuclear	4566
Solid Biomass	biomass and bioenergy	15725
Fossil CCUS	carbon capture	2651
Biomethane	biogas and renewable natural gas and biomethane	5534
Synthetic Methane	synthetic methane	114
Biohydrogen	biohydrogen	374
Hydrogen	hydrogen	9368
Renewable Ammonia	renewable ammonia and green ammonia	355
Liquid Biofuels	biofuel	4986
Synthetic Liquid Hydrocarbons	Fischer-Tropsch and synthetic fuel	777
Coal	coal	6853
Natural gas	natural gas	6517
Oil	oil	11152
All		**92658**

was generated systematically using the Web of Science Core Collection, All databases, with topical search terms "environmental" + "energy" + resource words as shown in Table 4. This corpus includes data for the energy resources coal, natural gas, and oil to enable comparative computational analysis to ensure that characterizations of how decarbonized energy supplies are addressed in the academic literature are contextualized by similar analyses for conventional fossil energy supplies.

Full record results were downloaded for all searches, then pruned to abstracts for text mining analysis. As shown in Table 4, the corpus comprises 92,658 documents. These abstracts collectively contain about 21 million words for an average of about 230 words per document, which is consistent with the typical length of journal article abstracts.

Limitations of this corpus are primarily associated with a lack of specificity. For example, "hydrogen" is evaluated collectively due to challenges with keyword-based identification of articles on specific types of hydrogen (other than biohydrogen). Similarly, "fossil CCUS" is characterized by a search for "carbon capture," which includes some biomass-based carbon capture systems. For resources like "biogas" that were searched under multiple terms, some abstracts might be included more than once. Similarly, articles evaluating multiple energy resources and/or carriers could be included in multiple categories. In some cases, irrelevant articles are included: for example, 623 of the abstracts in the wind search (6%) were labeled as meteorology articles by the built-in Web of Science treemap chart accessible via the "Analyze Results" command, potentially due to discussions about hurricane energy. Due to a desire to generate a comprehensive, replicable, and internally consistent corpus, individual documents were not reviewed, though disciplinary distribution was spot checked to validate that results were primarily in the scope of environmental assessment of energy systems. At the level of the broad exploratory analysis conducted here, the impacts are minor, validated by spot checks with individual searches.

2.2.2. *Narrative review*

For the more targeted narrative review, curated to ensure coverage of the environmental impacts and energy resources/carriers of interest (Tables 1–3), we used a multi-stage approach to identify relevant sources for this review to ensure a broad and thorough literature search. These sources were limited to English-language articles in peer-reviewed journals and reports subjected to similarly rigorous levels of pre-publication review (e.g., US Department of Energy resource characterization studies). Initially, Google Scholar was used to identify existing multicriteria reviews of multiple energy technologies, with key search terms including, but not limited to: clean energy solutions, clean energy technologies, low-carbon technologies, zero-carbon technologies, sustainable energy, environmental impacts, environmental impact assessment, comparative assessment, life cycle assessment, sustainability, review. We initially emphasized comparative reviews, based on the assumption that definitions, analytical approach, and other characteristics would be more internally consistent within versus across studies, with a preference for quantitative over qualitative comparisons. Similar searches were conducted to identify technology- or impact-specific reviews to complement the multi-resource reviews. In particular, we searched Web of Science for "energy" + "environment*" + [name of resource and related terms] to fill gaps, drawing upon and further specifying within the computationally aided corpus described in Section 2.2.1. Subsequently, searches were performed on authors of selected articles to identify other relevant work. We also reviewed the references section of relevant articles to find additional resources. We note, however, that the goal of the narrative review portion of this work was focused on achieving conceptual saturation and specific coverage of our topics of interest rather than completeness, supplemented by the coarser but more comprehensive text analysis described above.

For the narrative review, we emphasize references published after 2010 because of the rapid and dynamic development of the decarbonized energy resources and energy carriers of interest, though some older references were included for issues we deemed unlikely to have changed substantially.

We read the articles collected via this procedure to identify sources addressing specific potential environmental outcomes by energy resource or carrier (Tables 1–3), discarding articles that did not address relevant issues. The final corpus is a collection of articles with high quality and meaningful descriptions of an issue of interest; additional articles meeting our criteria very likely exist, but we did not extensively continue the search once a recent and high quality article was identified.

2.3. Analytical approach

We evaluated both corpora described in Section 2.2 with techniques intended to identify broad themes rather than specific quantitative data. One of the core arguments of this review is that environmental assessment practice for decarbonized energy resources and carriers is not currently characterized by rigorous and authoritative quantification methods for decision-relevant impact categories using metrics that enjoy broad legitimacy in the community the way that many stoichiometrically-grounded pollution quantification metrics do. As such, the goal of this analysis is not to systematically evaluate quantitative impact estimates and harmonize them across studies, but rather to identify research and methodological improvement needs at a goal and scope level that can feed development of high quality inventory data collection and reporting. This section describes the specific analytical approaches associated both with our computationally-aided work and our narrative review.

2.3.1. Computationally-aided review

The comprehensive corpus collected for the computationally-aided review is beyond human readable, at about 90,000 documents (Table 4), motivating the use of digital tools for evaluation [37]. Text mining is not a substitute for human interpretation, and unsupervised or semi-supervised methods in particular require substantial human judgment to interpret, e.g., by hand-labeling results and using content knowledge to understand term groupings in context. These tools enhance human ability to interact with large volumes of text, rather than answer questions directly [38]. Just as with narrative review, curation and interpretation requires application of expertise, though the use of consistent mathematical structures improves transparency and replicability relative to narrative review [37].

Although there are many types of text mining analyses, the two types of analysis used here are topic modeling and "most distinctive words" analysis. Topic models work via many-to-many mapping between documents and machine-generated topics and are well suited to thematic analysis of large bodies of text (see Ref. [34] for a more thorough description). In particular, topic modeling via latent Dirichlet allocation (LDA) using Gibbs sampling, as used here, is well adapted to analysis of journal article abstracts [39,40]. The goal of topic modeling in this case is to explore thematic relationships in the corpus, including both resource-specific and broadly applicable themes. Most distinctive words analysis, as a complement to the broad and collective topic modeling exercise, reveals which terms are most distinctively associated with specific groups of documents: in this case, the collection of abstracts associated with each energy resource or carrier derived via the search described in Table 4. The goal of this most distinctive words analysis is to uncover academic attention to issues specific to a given resource/carrier, in part to ensure that major resource/carrier impacts are accounted for in curating the more detailed narrative review.

This work uses two off-the-shelf academic text analysis softwares with specifical analytical functions for exploratory analysis. Using existing software enhances accessibility and replicability versus creating new code, given that the analyses selected for this work are standard text analysis functions. Topic modeling was conducted using the MAchine Learning for LanguagE Toolkit (MALLET) [41] via the Topic Modeling Tool User Interface [42]. Here, we conducted exploratory analysis on the full corpus and subsets of the corpus (e.g., the fossil resources coal, natural gas, and oil and the decarbonization resources and carriers described in Tables 2 and 3), with user-defined number of topics k ranging from 3 to 50; number of runs ranging from the default of 200 up to 1000; and topic threshold ranging from the default of 0.05–0.10. We used the standard English language stopword list packaged with MALLET, augmented with several corpus-specific terms that were not content-bearing in context and otherwise appeared high in many topics, to ensure capture of more specific patterns: electricity, elsevier, energy, environment, environmental, fossil, renewable, system, and systems. Numerous validation runs (e.g., to ensure the dataset was robust enough for the topic model to identify different resources, and to ensure results were stable across different random seeds) were conducted prior to analytical runs. The analytical runs included in Results are 1000-run, 0.05 topic threshold, 50 topic models of 1) the decarbonization resources and carriers and 2) the fossil resources coal, natural gas, and oil. Topics were manually reviewed for environmental focus by the first author and hand labeled as environmentally related, in accordance with typical LDA topic modeling practice [34]. For those topics identified as environmentally related, inputs contributing most to the topic were also identified using the "Docs in Topics" functionality.

Most distinctive words analysis was conducted using the Voyant Tools online environment [43], using the same corpus as for topic modeling. Using the "summary" function, we generated the maximum length list of "distinctive words" for each of the 18 resource/carrier-oriented subcorpora in Table 4, which is 59 words per subcorpus. These words were then reviewed for language related to environmental impacts by the first author, with the goal of identifying highly distinctive attention to particular environmental impacts.

2.3.2. Narrative review

To enhance specificity, ensure coverage of expert-defined issue areas, and directly evaluate themes in the literature, this work pairs a traditional, synthetic narrative review with the computational review described above. For the narrative review, our analytical approach was twofold, with the goal of creating an accessible synthesis of the large literature on environmental impacts of energy resources and carriers proposed for use in decarbonization. First, we mapped articles to a matrix with bibliographic entries for each environmental outcome of interest (Table 1) by energy resource or carrier (Tables 2 and 3), then briefly summarized key points. Second, we developed summaries of key issue areas by energy resource/carrier, structured as a four paragraph narrative with an 1) overview, including current scale, growth between 2000 and 2020, and reference to a recent key citation; 2) description of key challenges; 3) description of major dynamics; and 4) description of other relevant considerations.

2.3.3. Integration and synthesis

Based on the combined exploratory computational review (2.3.1) and targeted synthetic narrative review (2.3.2), we synthesize findings to characterize the relative scale of challenges associated with these potential environmental outcomes in two dimensions: whether the anticipated impact is likely to be salient at the project level (e.g., an individual power plant) or at the system level (e.g., for the US power grid). We select these two scales to illustrate the varying degree of decision relevance for environmental impacts of interest, emphasizing that particularly as energy supply systems are being refashioned in the context of decarbonization, and because of the many environmental considerations that are largely determined at the design stage, environmental assessment could play an important role as a decision support tool for system design at multiple scales. For example, mineral resource limitations are minor concerns at the project level for solar photovoltaics, but the scale of projected deployment means they could become a system-level challenge [31], though one that could possibly be mitigated by recognizing this risk and designing to counter it. Similarly, water consumption is a challenge for non-Fischer Tropsch liquid biofuels [44], but if this challenge is recognized and deemed too challenging to mitigate at scale, they might not be widely deployed – thus experiencing project- but not system-level water quantity challenges.

Although a decarbonized energy system could take many diverse forms, which is one rationale for designing assessments to support scenario analysis, we select a specific energy supply system future for illustration purposes: the 2050 US energy system modeled as the central decarbonization case by Williams et al. [24].

In general, there are often more and less sustainable pathways for using the same resources, so impacts and significance are speculative based on existing literature and current understanding of technology pathways. Further, we follow life cycle assessment practice in not explicitly considering the potential for positive environmental outcomes [45]. Also, in keeping with our goal of understanding needs within environmental assessment for supporting design decisions about decarbonized energy systems, we focus on decision-relevant outcomes anticipated to affect the future energy system, rather than those that have already been committed: for example, embodied GHG emissions in concrete for existing dams are not considered to be a significant climate threat associated with existing dams, regardless of their magnitude, although such emissions could be relevant for life cycle emissions estimates.

Note that our synthesis is qualitative and intended to support methodological work to strengthen environmental assessment's ability to evaluate decision-relevant environmental impacts associated with decarbonized energy system design. In part due to the lack of authoritative and widely agreed approaches for evaluating quantitative metrics relevant for our systems of interest, and in part due to our assertion that current practice is not designed for prospective assessment of still-maturing technologies whose environmental impacts are primarily capitalized, we do not attempt to harmonize what quantitative estimates exist. Relatedly, we focus on decision relevance for specific technologies and systems and do not attempt to characterize the relative scale of potential environmental challenges across technologies: that is, we evaluate whether an issue is salient relative to other issues for the same technology, and whether it is salient relative to other issues for the 2050 US energy system described by the central decarbonization case of Williams et al. [24], but not whether it is higher or lower than a similar impact for another resource. For example: noting that avian mortality is a salient consideration for wind farm deployment but not for some other resource does not mean that avian mortality is higher for wind farms, but rather that avian mortality is more relevant among evaluated environmental outcomes for wind than other resources.

3. Results

3.1. *Computationally-aided review*

For the decarbonized energy resources and carriers and for the non-decarbonized fossil resource subcorpora (Table 4), 50-topic models are presented in Appendix A, Tables A1 and A2. Of the 50 topics for the decarbonized energy resources and carriers model, 17 were labeled as environmentally related and tagged with one or more impacts of interest, and 9 for the fossil resources model (Table 5).

The exploratory topic modeling results suggest that overall, greenhouse gas emissions receive the most overall attention across the decarbonized and fossil subcorpora, which is consistent with general attention to greenhouse gas emissions in environmental assessment [34]. The next most common environmental outcome identified across the two topic models is land use: if habitat is included as a component of land use, this issue dominates the decarbonized subcorpus topics with 9 of 17 environmentally-oriented topics addressing land use or habitat, with diverse contributing resources of biomass, biofuels, wind, and hydroelectricity. By contrast, only 1 of 9 environmentally-oriented fossil topics addresses land use, but this topic is also clearly primarily concerned with biodiesel and appears in the oil documents due to discussion of biodiesel as a potential substitute. Just as land use is a major topic in the decarbonized but not fossil resource model, air pollution is a major topic (with 4 of 9 environmentally-oriented topics addressing it) in the fossil but not decarbonized resource model. Other issues are similarly split (Table 6).

Environmentally-oriented words identified in each resource/carrier's list of 59 most distinctive words (the longest list generatable by Voyant Tools) are summarized in Table 6. Resources and carriers not present in Table 6 did not have clearly environmentally-related distinctive words: see Appendix A, Table A3, for the full lists.

Although most of the most distinctive words are technical language specific to a given resource or carrier, including place and facility names (e.g., the Geysers for geothermal), this analysis produces results similar to those from the topic models. Bio-based resources are associated with distinctive land use, habitat, and related terms; nuclear is associated with nuclear safety and health terms; and coal is associated with air and water pollution and land degradation. One note is that the most distinctive words exercise is more sensitive than the topic model to out-of-scope abstracts: for example, although included as environmental terms in Table 7 for completeness, weather hazard terms associated with wind are likely from the small proportion of meteorology papers

Table 5
Summary of environmentally related themes identified in topic models.

Topic	Decarbonized resources/ carriers subcorpus	Dominant decarbonized resource/ carriers in topic	Fossil resources subcorpus	Dominant fossil resource/ carriers in topic
environmentally-related overall	17		9	
GHGs	6	biomethane, hydrogen, biomass, biofuels, CCUS	6	coal, natural gas, or balanced
land use	6	biomass, wind, biofuels	1	oil; but focused on biodiesel
air pollution	–		4	coal, natural gas, oil
habitat	3	biomass, hydro	–	
water	2	hydro, geothermal	1	oil; but focused on biodiesel
nutrients	2	biomass, biomethane	–	
nuclear safety	2	nuclear	–	
ash/solid waste	1	biomass	1	coal
toxicity/ hazardous waste	–		2	coal, oil

Table 6
Most distinctive words related to environmental considerations for energy resources and carriers.

wind	hydroelec-tricity	nuclear	biomass	fossil CCUS	liquid biofuels	coal	natural gas	oil
tornadoes	river	accident	forest	mercury	prairie	gangue	fracking	obesity
typhoon	streamflow	radioactivity	prey		edible	fly		caribou
squall	flood	radioactive	fertilized		forest	mining		arctic
hurricane	rivers	obesity	prairie			so2		edible
storms		insulin	ecosystems			mercury		
thunderstorms		adipose	plantations			fgd		
collision		hepatic				subsidence		
cyclones		cancer				hg		
supercell		liver				amd		

Table 7
Narrative review matrix, decarbonized energy resources.

Energy Resources	Wind key reading [46]:	Solar PV key reading [47]:	Solar CSP key reading [48]:	Geothermal key reading [49]:	Hydroelectricity key reading [50]:	Nuclear key reading [51]:	Biomass key reading [52]:	Fossil CCUS key reading [53]:
Water Use (Quantity)	[54–58]	[47,54–56,58]	[58,59] (See also: [48])	[5,58] (See also: [49,54,55,60])	[61] (See also: [54, 55,58])	[58] (See also: [51, 54–56,58])	[52] (See also: [55,58,62])	[63–65] (See also [53,54])
Water Pollution (Quality)	[8,46,55,57]	[66] (See also: [8,47,55])	[8]	[49] (See also: [8,55,60,67,68])	[8,55,69]	[8,55]	[52] (See also [8,55,62])	[8,54]
Air Pollution	[8,54,56,57,70]	[8,47,54,59, 66,70]	[8,59]	[49] (See also: [8,54,60,67,70])	[8,54,69,70]	[8] (See also: [51,54,70])	[52,71]. (See also: [8,62,72])	[8,54,73]
Climate Risk	[74] (See also: [8,46,54–57, 75])	[8,47,54,55, 59,66,76]	[8,59]	[49] (See also: [8,54,55,60,67])	[50] (See also: [8,54, 55,69])	[8] (See also: [51,54,55])	[52,77,78] (See also: [8,55,62, 70,79,80])	[53] (See also: [8,54, 73])
Solid Waste Generation	[81] (See also: [55,57])	[31] (See also: [55,66,82])		[49,55,67]	[55]	[8] (See also: [51,54,55])	[55,62]	
Land Use	[83–85] (See also: [8,46, 54–57,75])	[47,84,86] (See also: [8, 54,55,66,87])	[59] (See also: [8,86])	[8,49,54,55,60]	[50] (See also: [8,54, 55,69])	[8] (See also: [51,54,55])	[52] (See also: [8,55,62,79])	[8,54]
End-of-life Management	[81] (See also: [31,57])	[31] (See also: [66,82])	[48]	[49]		[8] (See also: [88])		
Limits to Input Resource Bases (e.g., minerals)	[31] (See also: [54,56,57,89])	[31,90,91] (See also: [54, 66])	[92]	[49,54,67]	[54]	[54]	[62,79]	[54,73]
Limits to Energy Resource Bases	[93]	[93]	[93]	[93,94] (See also: [49,60,68])	[95] (See also: [29, 93])	[93]	[52,96–99] (See also: [62,93])	[73,93,100, 101]
Mining requirements (incl. geopolitical constraints)	[31] (See also: [8,57, 102–105])	[31] (See also: [8,102,105])	[8]	[31] (See also: [8])	[8]	[8]	[8]	[8]
Hazard (e.g., radiation)	[89] (See also: [54,56])			[49] (See also: [60,67])	[106] (See also: [54])	[8] (See also: [54,107])	[62]	[54]
Areas of controversy	[46] (See also: [56,57,75,85])	[66]	[108,109]	[49,67]	[50]	[8] (See also: [51,107])	[72]	[54]

captured in the corpus (623/10588, or 6%), and health terms like "obesity" associated with oil are likely from the small number of biotechnology papers (507/11152, or 5%), as further evidenced by the presence of terms like "evoo" (extra virgin olive oil). A similar emphasis on medical use of nuclear materials is possible but was not readily identifiable from the disciplinary profile of the abstracts included.

3.2. Narrative review

Tables 7 and 8 present the summary referenced matrix of environmental impacts by energy resource (Table 7) and energy carrier (Table 8). Primary references are for pieces that directly address an issue; "see also" references are generally pieces that include but do not focus on the issue of interest. For an annotated version, please refer to Appendix B.1.

Summary narratives by resources and carriers, which synthesize the information from Tables 7 and 8, can be found in Appendix B.2.

Consistent with the computationally-aided review (Table 6), the narrative review portion of our investigation suggests that land use, not combustion, is emerging as a potentially dominant environmental impact driver associated with a decarbonized energy system. The transition from underground to surface energy resources [147] drives land use change, which affects water use and water quality, habitat impacts, air pollution, and more [52]. As land is not created or destroyed, net impacts depend substantially on how the land would otherwise have been occupied.

Particularly for biomass and synthetic fuels, zero GHG emissions are not guaranteed. Changes to soil organic carbon, methane emissions, nitrous oxide emissions, and accounting based on assumptions about climate-neutral carbon dioxide all challenge GHG neutrality. For example, the US' Billion Ton Report on bioenergy resources reports that bioenergy might only reduce GHGs by 4–9% relative to fossil fuels in investigated scenarios [52], but bioenergy is a cornerstone of highly visible deep decarbonization pathways [24].

Mineral and mining constraints could be limiting for specific system architectures, mitigated by ongoing work to diversify material requirements. Solar, wind, and renewable fuel catalysts all have potentially meaningful mineral resource constraints, but alternative designs (e.g., perovskite solar cells; new catalysts) and new mining complex development could qualitatively change these dynamics.

Individual energy resources or energy carriers have diverse potential environmental impacts that might be limiting for those pathways, but designs are dynamic. Most decarbonization pathways assume high reliance on solar and wind, which are relatively low impact, and likely

Table 8
Narrative review matrix, decarbonized energy carriers.

Energy Carriers	Biomass CCUS key reading [72,110]:	Bio-methane key reading [111]:	Synthetic Methane key reading [112]:	Bio-hydrogen key reading [113–115]:	Green Hydrogen key reading [116]:	Blue Hydrogen (Fossil SMR with CCUS) key reading [117,118]:	Nuclear-based Hydrogen key reading [119]:	Renew-able Ammonia key reading [120]:	Liquid Biofuels key reading [52,121]:	Synthetic Liquid HCs key reading [122,123]:
Water Use (Quantity)	[65,72,110] (See also: [52])	[111]	[124]	[71,125]	[71,125] (See also: [70,126])	[71,125] (See also: [126])	[71,125] (See also: [70,119])	[119]	[58,126]	[122]
Water Pollution (Quality)	[8,52]	[111]			[70]		[70]	[127]		[122,123]
Air Pollution	[8,52,72]	[111]		[128] (See also: [113–115])	[128] (See also: [70,129,130])	[128] (See also: [129,131])	[128] (See also: [70,129,130])	[120] (See also: [119,127,132])	[121]	[133] (See also [122,123]:)
Climate Risk	[65,72,110], (See also [8,52,134])	[135] (See also: [111,136])	[135]	[114,137]	[137] (See also: [70,129,130])	[137,138] (See also: [129,131])	[137] (See also: [70,119,129,130])	[132,139] (See also: [119,127,137])		[123,140] (See also: [122])
Solid Waste Generation		[111]		[114]	[70]		[119] (See also: [70])			
Land Use	[8,52,72,110,134]				[70]		[70]			[122]
End-of-life Management										
Limits to Input Resource Bases (e.g., minerals)	[72,134]	[111,136]	[141] (See also: [142])	[31,114] (See also [52])	[31,114] (See also: [143])	[31,114] (See also: [131])	[31,114]	[120]		[142,144] (See also: [122])
Limits to Energy Resource Bases	[65,72,110] (See also [52,93,96–98,134])	[93,111]	[112,116]		[116]	[35,145] (See also: [131])	[119]	[116]	[96–98]	[142,144] (See also: [116])
Mining Requirements	[8]		[141] (See also: [142])							[122,142,144]
Hazard (e.g., radiation)				[114]	[114]	[114]	[114,119]	[120,146] (See also: [119])		
Areas of Controversy	[72]								[72]	

on bioenergy, which has potentially low impact development pathways. The role of nuclear, geothermal, CCUS, and renewable fuels is contested in part due to specific environmental impacts.

Although this review specifically investigates the US context with respect to system-level expectations, general resource-level patterns are likely to be similar globally, as is the assumption that the future decarbonized energy system will rely heavily on solar, wind, and biomass.

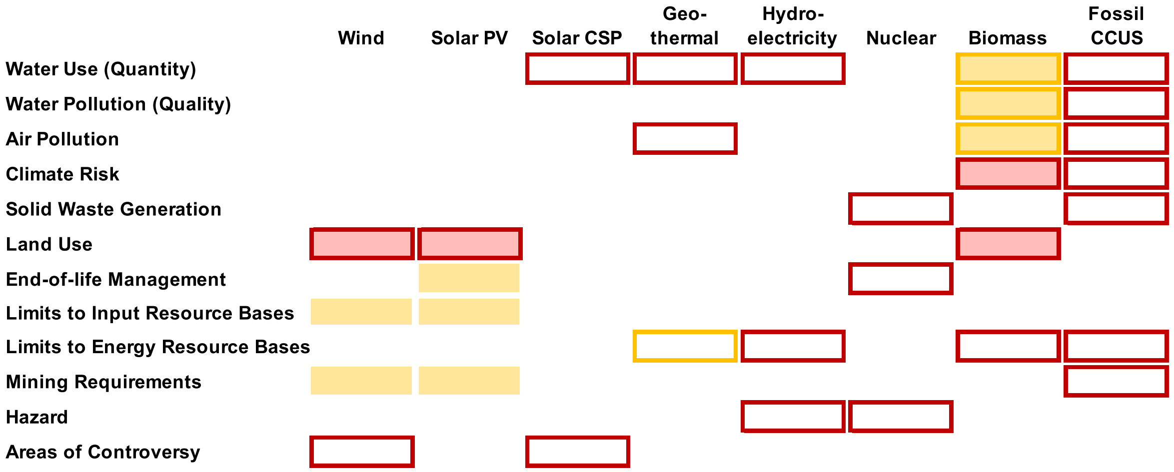


Fig. 1. Synthetic view of relative environmental challenges for selected supply side energy resources for decarbonization. Borders: project level challenge; fill: US energy system-level challenge, assuming 2050 central decarbonization pathway energy system from Ref. [24]. Red: anticipated major challenge; Yellow: anticipated major challenge, but very sensitive to expectations about future system design. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Decision-relevant environmental outcomes for decarbonized energy supplies

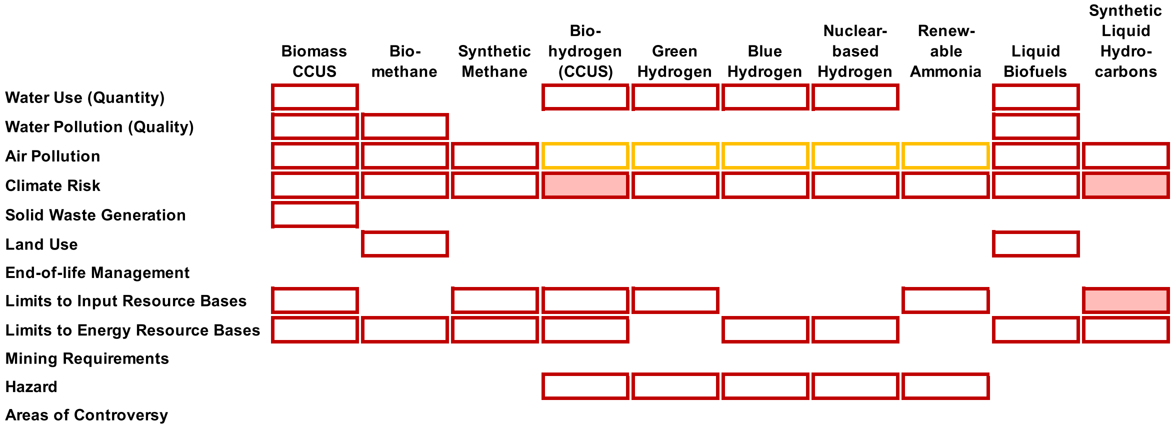
This section presents the results of our synthesis of the broad (computational review, Section 3.1) and targeted (narrative review, Section 3.2) literature, identifying project- and system-level challenges for supply side energy resources (Fig. 1) and energy carriers (Fig. 2) that environmental assessment will likely need to be able to rigorously evaluate in order to provide decision support for decarbonized energy supply system design.

Existing literature reflects that decarbonization-oriented energy resources and energy carriers have known or anticipated environmental impacts. The degree to which these impacts are decision-relevant varies by scale of evaluation: for example, resource-related impacts that might be minor for an individual project could be highly relevant for designing an overall decarbonized energy system if that system relies extensively on that resource. Here, we illustratively evaluate system-level impacts for the future US energy system as characterized by the 2050 central decarbonization case in Ref. [24], noting that of the energy carriers considered here, only biohydrogen (via gasification with CCUS) and synthetic liquid hydrocarbons play large roles. As Fig. 1 shows, land use is a significant environmental challenge at both the system and project level for dominant primary energy resources wind, solar PV, and biomass, given their relatively low energy density and location on the earth's surface rather than underground. To the extent these resources are used to create the carriers in Fig. 2, land use impacts could be indirectly driven by demand for specific energy carriers that require additional marginal primary resource development at scale, e.g., electrolytic hydrogen [148], but land use is a more significant direct challenge for carriers that are directly derived from biomass resources, like liquid biofuels (Fig. 2).

At the system level, material intensity and potentially limited resource bases for core inputs is another major challenge for the decarbonized energy supply scenario evaluated here. Notably, in practice, these are also land use constraints in many cases, though potentially more associated with occupation, contamination, and undesirable transformation than strict areal intensity. For wind and solar PV, input resources (i.e., metals, glass) could become limiting at scale, with associated mining impacts. Solar PV end-of-life management could become a system challenge in part due to the potential for toxic leaching from disposed panels, depending on how ongoing efforts to develop recycling procedures progress. Depending on the intensity of irrigation and fertilization practices, and on how land would otherwise have been used, biomass could pose both resource- and system-level challenges for water use, water pollution, and air pollution. Synthetic liquid hydrocarbons rely on decarbonized CO_2, decarbonized hydrogen, and decarbonized electricity, all of which could be limited in availability relative to demand.

One major (though potentially tautological) system-level risk suggested by existing literature is that decarbonized energy resources and carriers might not be fully decarbonized in practice. Zero or near-zero climate risk from resources and carriers that have the potential to have zero or near-zero greenhouse gas emissions cannot be assumed without verification. In particular, the actual greenhouse gas intensity of biomass resources, accounting not only for energy inputs like harvesting and transportation fuels (which could decarbonize over time) but also for soil organic carbon storage changes and production of high global warming potential gases like methane (CH_4) and nitrous oxide (N_2O) (which likely would not be affected by decarbonizing the energy sector) is a major potential system-level challenge. Beyond risks associated with biomass production itself, biohydrogen with CCUS could fail to sequester CO_2, a meaningful risk for the Williams et al. [24] central decarbonization scenario. Both biohydrogen and synthetic liquid hydrocarbons (which take biohydrogen as a major input in Ref. [24]) could be inappropriately credited as carbon-neutral or carbon-negative, thereby serving as a system-wide offset that should not exist.

At the project level, decision relevant impacts depend heavily on design and context. In some cases, thoughtful design and/or technological advances could mitigate these impacts, though it is also possible that highly visible challenges or failures could reflect on similar projects in general and limit deployment. Wind and CSP both face controversy associated with highly visible animal impacts, most notably bird kill, though mortality intensities are limited compared with other anthropogenic activities. CSP, geothermal, hydroelectricity, and fossil CCUS are all highly water intensive. Fossil CCUS is environmentally intensive in general, given that it amplifies the challenges of fossil fuel use (due to high energy intensity) with incomplete elimination of greenhouse gas emissions. Geothermal reservoir contents could pose air pollution challenges. Nuclear has well-known challenges related to radioactivity management, posing solid waste, end-of-life (in part due to the cost and energy intensity of plant decommissioning), and hazard challenges. Hydroelectricity, biomass, and fossil fuels are all resource-limited, with significant mining challenges for increased fossil fuel demand due to carbon capture's energy intensity, and geothermal's potential depends on ongoing technological development focused on deep and/or low temperature resources. Like nuclear, hydroelectricity has very low probability but very high consequence hazard potential, largely related to the possibility of dam breaks.



	Biomass CCUS	Bio-methane	Synthetic Methane	Bio-hydrogen (CCUS)	Green Hydrogen	Blue Hydrogen	Nuclear-based Hydrogen	Renew-able Ammonia	Liquid Biofuels	Synthetic Liquid Hydro-carbons
Water Use (Quantity)	🟥			🟥	🟥	🟥	🟥		🟥	
Water Pollution (Quality)	🟥	🟥							🟥	
Air Pollution	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟥	🟥
Climate Risk	🟥	🟥	🟥	▣	🟥	🟥	🟥	🟥	🟥	▣
Solid Waste Generation	🟥									
Land Use		🟥							🟥	
End-of-life Management										
Limits to Input Resource Bases	🟥		🟥	🟥	🟥			🟥		▣
Limits to Energy Resource Bases	🟥	🟥	🟥	🟥		🟥	🟥		🟥	🟥
Mining Requirements										
Hazard				🟥	🟥	🟥	🟥	🟥		
Areas of Controversy										

Fig. 2. Synthetic view of relative environmental challenges for selected energy carriers for decarbonization. Borders: project level challenge; fill: US energy system-level challenge, assuming 2050 central decarbonization pathway energy system from Ref. [24]. Red: anticipated major challenge; Yellow: anticipated major challenge, but very sensitive to expectations about future system design. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

All carriers in Fig. 2 could be combusted for some applications, though fuel cell applications mean that hydrogen (and ammonia used as a hydrogen carrier) could be used without combustion in some configurations: as such, all have the potential to create air pollution impacts. Similarly, in addition to any resource-associated climate risk (e.g., from biomass feedstocks), all pose climate risks given either a potential failure to meet carbon sequestration performance expectations or influence on non-CO_2 gases with global warming potentials. Methane (GWP-100 30; biomethane, synthetic methane, blue hydrogen) and hydrogen (indirect GWP-100 5; biohydrogen, green hydrogen, blue hydrogen, nuclear-based hydrogen) emissions could both contribute to climate change. Ammonia combustion can generate nitrous oxide (GWP-100 \ 265). Other challenges include water use (for carbon capture, biorefining of non-Fischer Tropsch biofuels, and hydrogen production via electrolysis or water-gas shift reactions); water pollution associated largely with bioprocessing discharge; solid waste generation from biomass combustion; aesthetic land use challenges (e.g., smell) for biomethane and biofuel processing; and gas-related hazards (explosion for hydrogen; toxicity for ammonia). All carriers also face limits on both energy (biomass; nuclear; hydrogen) and non-energy input resource bases (carbon storage capacity; electricity; CO_2; catalysts).

4. Discussion

As energy supplies decarbonize in a normative transition oriented toward mitigating climate change, infrastructure systems will need to transform. Environmental assessment tools will be crucial for decision support if minimizing further environmental damage is a goal. Not only will transition launch the commitment of new environmental impacts for the decarbonized energy supply system, but it will also trigger end-of-life activities for the existing fossil system. In both cases, impacts are largely embodied, or capitalized: that is, impacts do not scale with marginal production. This situation is a significant departure from historical conditions, where environmental impacts of interest due to issues like climate change, health, and ecosystem degradation were largely associated with marginal production, i.e., fossil fuel combustion. As such, environmental assessment practice will need to focus on maturation of rigorous and widely legitimized methods for evaluating these embodied impacts if it is to provide useful and timely decision support.

One major implication of the shift to more embodied impacts, many of which have heavily context-dependent severity, is that project and system design (rather than technology alone) is likely to have significant influence on environmental impacts. Social life cycle assessment, which also deals with issues that are not linear with production and which are deeply contextual, sometimes emphasizes “hot spots” for further investigation rather than precise projected impacts [149,150]. Building on experience from this other challenging area of LCA methodological development could enhance progress as environmental assessment confronts some of these same issues. Relatedly, particularly given that construction-phase impacts like land transformation happen all at once and at the beginning of projects, the environmental assessment community ought to redouble our efforts at rigorously integrating justice, consent, governance, and institutional structures (see e.g. Refs. [151,152]) as core elements of sustainability—whether confined to environmental impacts or interpreted more broadly. When impacts are not associated with marginal production, they cannot be stopped simply by ceasing production, e.g., at a highly polluting power plant. As such, understanding metrics for “better” or “worse” environmental performance for construction phase-dominated issues as inextricably connected to questions of justice and social embeddedness is critical. Although the impacts associated with land use are not as directly linked to a numerical estimate (e.g., land area occupied or disturbed) as are the impacts associated with combustion, land use could potentially be the best single-metric proxy available for the future decarbonized energy system. Ensuring environmental assessment practice can effectively evaluate the impacts of land use with nuance is a core priority for environmental assessment of decarbonized energy supply.

4.1. Limitations

Although this work was designed to produce high-level, robust results, it is subject to limitations. Reliance on English-language literature and a focus on the US at the system level potentially excludes important findings from international contexts. Necessarily, reliance on existing literature means that impacts that have not been widely identified yet are excluded. Just because an issue is not identified in this work does not mean it would not pose a challenge, particularly because the existing literature is speculative about how systems that essentially do not yet exist would contribute to environmental impacts either at project or system scale. As these systems are highly dynamic and rapidly developing, the literature might meaningfully lag current practice with respect to both improved and degraded performance on environmental metrics. Relatedly, due to the particular focus on environmental outcomes, other relevant impacts and constraints such as economic viability or social justice considerations, among others, were not evaluated in this review. Further, this review focuses exclusively on supply side aspects of the evaluated energy technologies, with no consideration on the influence that demand side constraints and interventions may have on them. Similarly, many existing evaluations are based on comparisons to the current, fossil-based system, which might result in truncation of issues that are comparatively minor but could be meaningful under decarbonization. The system-level findings in this study are based on a single potential future pathway, despite our argument that environmental assessment needs to be able to compare prospective impacts across scenarios. Similarly, at the system level, we do not explicitly evaluate differential needs for support infrastructure (e.g., roads, power lines, energy storage) across resources and energy carriers.

4.2. Recommendations for future work

Based on our review, we make several major recommendations for future environmental assessments of energy systems for decarbonization. A primary call is for the environmental assessment community to focus significant methodological attention on designing fit-for-purpose metrics and methods to evaluate and interrogate environmental impacts likely to be observed with a decarbonized, rather than fossil-based, energy supply system. Even now, however, some minor adaptations to environmental assessment practice can enable better forward compatibility, scenario design, and decision support during this dynamic transition period.

4.2.1. Collaboratively develop fit-for-purpose metrics and assessment methods

The types of environmental impacts likely to be caused by decarbonized energy supplies are different from those caused by historically dominant fossil fuel supplies. Many of these impacts are likely to be embodied rather than operational, such that per-unit estimates of impact will fail to capture important realities. These include the temporality of impact (e.g., because impacts occur before energy production), accurate pictures of intensity before facility lifespans and production history are known, and the impact of marginal energy use (e.g., because additional energy use drives embodied impact intensities down rather than up). Impact estimates that are useful for decision-makers will likely require more contextualization than has historically been true for fossil-based systems, necessitating effort to develop methods for consistently characterizing these impacts across studies. Emphasizing methods that can be applied across projects, enabling comparative work, will likely require collaboration and significant engagement with stakeholders, as has been true for prior and ongoing efforts to add new impact categories and methods to LCA (see, e.g. Refs. [28,153]).

4.2.2. *Design studies with decision support in mind*

Environmental assessment of energy systems is shifting from being valuable primarily as a descriptive tool to being valuable as a design and planning tool. Studies that account for this, for example by enabling flexible evaluation of impacts based on deployment timing, highlighting which impacts are inherent (e.g., water consumed during electrolytic water splitting) and which are dynamic (e.g., water consumed for electrolysis cooling), and otherwise anticipating how the research might be used to make decisions, are likely to be more useful than studies that do not.

4.2.3. *Recognize the role of considerations that are not technological, not supply side-focused, and not environmental*

Justice comes from nontechnological interventions, like ownership structure, consent and engagement strategies, cost/benefit distributions, and overall attention to power dynamics and systemic issues that inflect experiences of the energy system (e.g., energy burden is due both to energy costs and income/wealth). Demand side interventions can facilitate lower overall requirements on the supply side while also potentially improving comfort, safety, operational costs: supply side optimizations are not necessarily least cost solutions, but energy systems modeling often excludes demand side considerations [154]. Social impacts can be major drivers or constraints for system design and deployment and might not be captured by purely environmental or purely quantitative evaluations.

4.2.4. *Clearly state counterfactuals, and report impacts in sufficient detail for another analyst to evaluate alternative counterfactuals*

Impacts are often reported “relative to” a fossil fuel-fired system, an alternative land use, or some other counterfactual that is not simply “no impact.” Although net impacts can be useful to understand, inconsistent or unclear use of counterfactuals can lead to systematic bias. For example, reporting the water quality impacts of bioenergy relative to alternative displaced land uses, but not doing the same for wind energy, can conceal where a resource is actually driving new flows or not.

4.2.5. *Do not assume that current system characteristics are static*

System characteristics like the relationship between supply and demand (i.e., demand is not responsive), the relative value and/or impact of energy at a given time of day (e.g., nighttime electricity is cheap), and the likelihood of particular regulatory actions are not fixed. Characteristics of technological systems that are true today might not be inherent, whether due to design, technological, regulatory, or other changes. Where possible, contextualize results with a judgment of how stable they are to changing system conditions, and what potential system changes could lead to qualitatively different conclusions. When assumptions about system conditions are made for simplification, report this.

4.2.6. *Systematically consider where and why analyses are being truncated*

Embodied impacts are often much less evaluated for systems with operational emissions (e.g., biomass combustion) than for those without (e.g., wind generation). As a result, impressions of which resources have significant input constraints, mining needs, solid waste generation, etc. could be systematically biased. For example, the environmental impact of the concrete used for wind turbines is often included in assessments, but the environmental impact of concrete used for a natural gas plant is usually not, because it is seen as negligible relative to operational emissions.

4.2.7. *Separately and clearly report impacts associated with energy inputs*

Environmental impacts associated with fossil fuel inputs (e.g., for manufacturing solar panels) are dynamic as the energy system decarbonizes. Although it is very important to consider how the timing of manufacturing and decommissioning capital infrastructure for energy systems with limited or no operational emissions affects their life cycle impacts, it is also very important to separately understand which impacts are likely to improve with system decarbonization (e.g., GHG intensity of harvesting equipment for biomass) and which are not (e.g., nitrous oxide emissions from agriculture). Separately reporting energy- versus non-energy impacts can also facilitate sensitivity testing and scenario development accounting for the dynamic environmental profile of energy over time.

4.2.8. *Clearly report inventories in addition to transformed impacts (e.g., kg CH_4 in addition to kg CO_2e)*

In addition to indicator-level reporting, include as much detail as possible on spatiotemporal dynamics and distributional effects to enable future data transformations. For non-CO_2 flows, environmental impact is not as consistently related to flows as for CO_2. Reporting inventories in addition to impacts enables future data users to evaluate results using alternative impact assessment approaches, a potentially important task as impact assessment methodologies that emphasize spatiotemporal dynamics, justice, and other variabilities mature.

5. Conclusions

As transformative amounts of new infrastructure are deployed and existing systems are retired in service of a normative transition to decarbonized energy supplies, decision support tools that can inform multi-decade and uncertain project and system design decisions are needed. With effort, environmental assessment can inform these design decisions across multiple scenarios, expanding from a role as a descriptive tool focused on products to one that actively informs design choices at societally relevant scales. Energy-related environmental assessment practice will also need to reflect that the energy system is likely to shift from a combustion-dominated to land use-dominated paradigm for assessing and managing environmental impacts, with the important corollary that many impacts will happen all at once during infrastructure installation rather than marginally as more energy is produced. Major uncertainties about environmental impacts remain regarding dynamics associated with both the changing climate (e.g., water availability; crop productivity) and the changing energy system (e.g., novel system architectures; material circularity), in addition to uncertainties associated with projected environmental impacts for systems that do not currently exist at scale within a decarbonized economy. One major uncertainty is whether key resources like biomass and synthetic fuels can achieve GHG neutrality or near-neutrality in practice and at scale. Similarly, it is unclear whether mineral, mining, and disposal constraints will limit massive deployment of resource like wind and solar.

Even for impacts that might not appear to be system-limiting, and which might represent lower overall impacts relative to the current system overall, project-level dynamics like local air pollution; concerns over noise, smells, and lights; habitat disruption; and other issues could be significant impediments to project siting in a way that could have ramifications for system-scale deployment. In particular, we note that despite widespread support for decarbonized energy systems, host communities often have reasonable and well-informed opposition to specific projects due to characteristics that might or might not be addressable [155–157], and the sheer number of siting processes that supply side energy decarbonization will require could mean that even less common local impacts could limit deployment speed and scale. As the system changes, we recommend that the environmental assessment community focus on ensuring that rigorous and fit-for-purpose analysis of environmental impacts of energy supplies is available for decision support, embedded in legitimate and authoritative institutional contexts that recognize the centrality of societal embeddedness in evaluating environmental impacts.

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Declaration of competing interest

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Appendix A. Supplementary data

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