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Life cycle assessment of electricity generation: A systematic review of spatiotemporal methods

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A R T I C L E I N F O

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A B S T R A C T

Life cycle assessments (LCAs) of electricity generation are increasingly incorporating more granular spatial and temporal information, enhancing the accuracy of both inventories and results. This systematic review determined contributions to LCA that improved spatial, temporal, or spatiotemporal resolution from 2009-2018. We analyzed 251 articles screened from an initial review of 6,519 to identify such contributions and determine areas in need of research. The geographic focus of the studies leans towards Europe, Asia, and North America, suggesting many regions remain understudied. As the impact categories were heavily weighted towards greenhouse gas emissions, the impacts that may benefit most from more granular analyses reflecting local environmental conditions were less studied (e.g., land use and eutrophication). While studies tend to focus more on spatial rather than temporal information, those that examine the most granular spatial and temporal scales (for this review, site and hourly) can result in more effective interventions that improve both environmental and economic outcomes. The two most common analysis tools used in the screened articles were optimization and Geographic Information Systems. The increasing use of these tools supported diverse improvements in LCA, such as more detailed investigations of grid interactions, enhanced characterization of impacts, and improved evaluation of resource availability. Analyses conducted at more refined spatiotemporal resolutions can provide more realistic representations of electricity generation, grid operations, and environmental impacts, supporting more effective interventions.

1. Introduction

Life cycle assessment (LCA) is a powerful decision support tool that evaluates the environmental burdens of a product or process from materials extraction to waste disposal (cradle-to-grave or even cradle-to-cradle) [1, 2]. Over time, LCA has increasingly addressed the environmental impacts of energy technologies [3-6]. With the growing role of LCA as a decision-support tool for energy policy, questions remain regarding how results should be used in the face of uncertain assumptions in a fast-paced and evolving sector. These questions take root in the fact that a typical LCA is neither spatially explicit nor temporally resolved (thus representing a snapshot in space and time or with general data that do not represent a location and particular time). In some cases, life cycle results have been impactful to the evolution of the energy sector by improving our knowledge of energy systems and even influencing policy decisions [5, 7-9]. But these assessments are challenged by a fast-paced, economically powerful, and highly innovative sector, and particularly by high regional and temporal variability of operations. Such variability [10] has been noted to contribute to unresolved problems in LCA [11]. Notably, the electric grid comprises highly diverse generation technologies – from nuclear to renewables and fossil fuels - resulting in different regional mixes. Such differences are highly influential on LCA results. We argue that LCAs of electricity generation need to better characterize spatial and temporal characteristics in order to be accurate. Our systematic review has been developed to identify the state-of-the-art in the field and contribute the identification of gaps in need of research.

Our review draws on three related unresolved problems identified in a 2008 survey that continue to hold importance for the advancement of LCAs of electricity generation: spatial variation, time horizons, and local technical uniqueness [11]. First, LCAs that do not capture spatial variation miss important factors that may influence results, such as transport needs, population distributions, and local environmental conditions (e.g., meteorology, topography, and hydrology). Second, the selection of time horizons can be highly influential on the results when discounting by either amplifying short-term costs and benefits or neglecting longer-term effects. Further, the choice of temporal resolution for each analysis can influence the accuracy of results. We add to this

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limitation temporal variation over time, since dynamic supply and demand of the electric sector means that impacts are variable across scales. Third and perhaps most important to the present analysis, local technical uniqueness of operations means that results vary across technologies used at the extraction, production, distribution, and end-of-life phases (e.g., resource demands, energy use, and waste management). We note the direct ties of these attributes to pedigree matrices, which serve as qualitative tools to assess uncertainty in LCA, as they already include temporal and geographic correlation as two categories to evaluate data quality [12]. Further, the International Organization for Standardization's (ISO) LCA standards refer to spatial and temporal attribute without specific guidance, suggesting that their development has yet to be thoroughly vetted to date [1]. In this paper, we undertake a systematic review to understand the advancement of spatiotemporal methods in LCA since the identification of these problems.

The aforementioned challenges are particularly salient for electricity generation, where spatial and temporal patterns of supply and demand can influence operations, economics, and environmental impacts. Examples of the influence of spatial variability include: local environmental conditions such as hydrology can influence operations and environmental impacts [13, 14]; population distribution and demand levels can do the same by shifting the burden of supply [15-17]; regional electricity mixes result in variable environmental impacts [18, 19]; fuel supply and distribution distances can amplify the impact of fuel transportation [20] but also the delivery of electricity to consumers [19]. Environmental releases from electricity generation depend on hourly, daily, and weekly demand cycles at subnational scales [3, 21]; seasonal cycles, both in environmental conditions and demand [22]; degradation of capital [19, 23]; and changes to the regional energy system, including fuel supply, production, and distribution [18]. Joint spatiotemporal factors are exemplified by supply and demand dynamics on the electric grid because interactions between consumers, power plants, transmission and distribution networks, and the fuel supply also depend on locations [18, 20, 23-25]. While these factors are known to be highly influential on LCA results, there has yet to be a systematic review that tracks methodological progress and determines research gaps for the power sector.

Already, the importance of spatial and temporal information for the power sector is broadly recognized; for example, the location and consumption of electricity by electric vehicles [18], the climate impacts of expanding LNG export for electricity generation [23, 26, 27], the trade-offs between local water consumption from hydraulic fracturing and electricity generation [13, 14, 28, 29], and even how land use and ecosystem impacts are evaluated when considering the choice between energy investments [30-32]. Recent studies have noted the need for improvements in both data and methods for LCAs of electricity generation [24, 25, 33, 34]. The present spatiotemporal limitations are set to change with the advent of more prolific data, broader use of data science, and integration with Geographic Information Systems (GIS) software, which has already commenced to influence the advancement of LCA methodology in energy research [35]. LCA is already a data-intensive field; yet, data availability in energy research has been noted as lagging other fields for a variety of reasons (e.g. ethical and security concerns, unwanted exposure, and additional workload) [36]. Resource limitations have been cited as one of the primary reasons why more detailed spatiotemporal datasets have not historically been a cornerstone of methodological improvement in LCA [3]. Nevertheless, an increasing number of LCAs are being published that integrate or improve spatiotemporal considerations [19, 37-39].

The central question of this article is: how has the methodology employed in life cycle assessment of electricity generation evolved in terms of consideration of space and time from the period of 2009 to 2018? To answer this question, we have conducted a systematic review to understand how life cycle assessments of electricity generation have evolved regarding consideration of space and time since Reap et al. The ten-year period from 2009 to 2018 was selected as the time horizon for the review, following the publication of Reap et al. and reaching to the end of the last full calendar year at the time of data collection. The evolution of LCA with respect to spatiotemporal improvements was then analyzed over time (i.e., by year of publication) in terms of the electricity generation type (e.g. natural gas, solar photovoltaic), whether the focus was the power plant or the supply chain, the geographical coverage of the analysis, whether the improvement was in the use of data or representation of results, the life cycle impacts quantified, and the LCA methods employed (e.g. input-output or process). We then completed an in-depth review across paper categories and energy types to determine advances in the field. Our key goal is to elucidate progress in not only spatial and temporal analysis independently, but also to determine major advances and research gaps in combined spatiotemporal analyses in LCA. Given the complexities of the grid and the associated supply chains, results will inform more accurate analyses of electricity generation by depicting how to improve upon more conventional, aggregate LCAs. With more accurate results, decision-makers can systematically reduce environmental impacts across the life cycle of different energy technologies (Fig. 1). Our findings illuminate not only methodological advancements (in particular, those important for the electric sector) but also provide insights into topics in need of development for LCA practitioners, scholars, and decision-makers.

2. Methods

The scope of our review of LCAs is focused specifically on electricity generation, comprising all key generation types either individually or at the scale of grids (Fig. 2).

Our systematic review follows guidelines set out in prior literature [40, 41], with the goal of understanding spatiotemporal advances in LCA methodology of electricity generation over the past decade. Literature was searched via major LCA journals' websites, Web of Science, and Google Scholar. Google Scholar was selected as the primary method of data collection as it returned the most comprehensive list in comparison to CrossRef, the Publish or Perish software, and piecemeal searches of individual journal websites. LCA journals that were manually searched for relevant articles that might have been missed in the Scholar search included the International Journal of Life Cycle Assessment, the Journal of Cleaner Production, the Journal of Industrial Ecology, Environmental Science and Technology, and Environmental Science and Policy.

To handle searches with 1,000+ results in Scholar, a Python-based web scraper was developed and is available for use on GitHub [42]. The Python script was created to search Scholar and scrape key result data: the title, author(s), year of publication, description, journal, publisher, and URL. Additionally, the script recorded the keywords used for the search instance, as well as the page number on which the article appeared and its position on that page, which were used for tracking purposes.

Search terms were selected to reflect whether spatial and temporal information was considered for LCAs of the power sector. They were also chosen to ensure sensitivity to a large number of papers, rather than a more specific search strategy [43]. The latter has been known to produce more relevant studies but miss a higher share. "Spatial" and "temporal" were selected as terms to capture the intent to advance methodology. Similarly, "electricity", "life cycle assessment" and "LCA" were meant to catch a comprehensive set of articles. "Life cycle assessment" was used to reflect the most broadly accepted and used terminology (i.e., by ISO and the United Nations). While "life cycle analysis" was not used as a separate term, such articles also employ the acronym "LCA" and would thus be captured with the acronym "LCA." The following sets of search terms were used (including quotation marks and capitalization):

- "life cycle assessment" OR LCA, electricity, spatial
- "life cycle assessment" OR LCA, electricity, temporal
- "life cycle assessment" OR LCA, electricity, spatiotemporal OR spatio-temporal

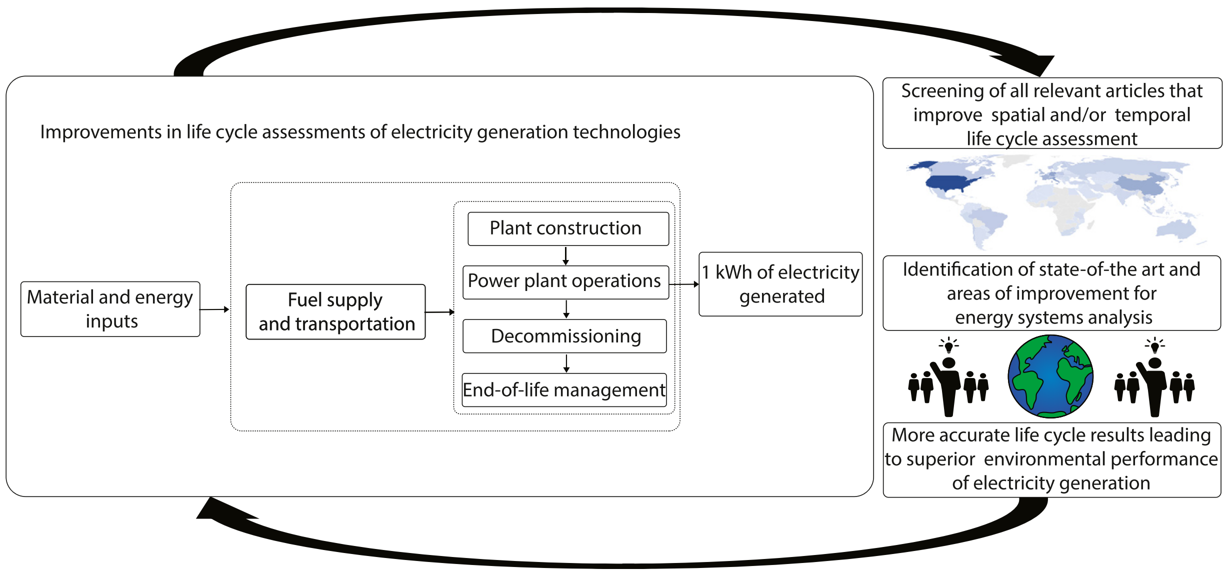

Fig. 1. The overall structure of this paper and its significance to the energy system. The people icon was sourced from the Noun Project and developed by Wilson Joseph. The icon of the Earth was sourced from the Integration and Application Network (ian.umces.edu/media-library).

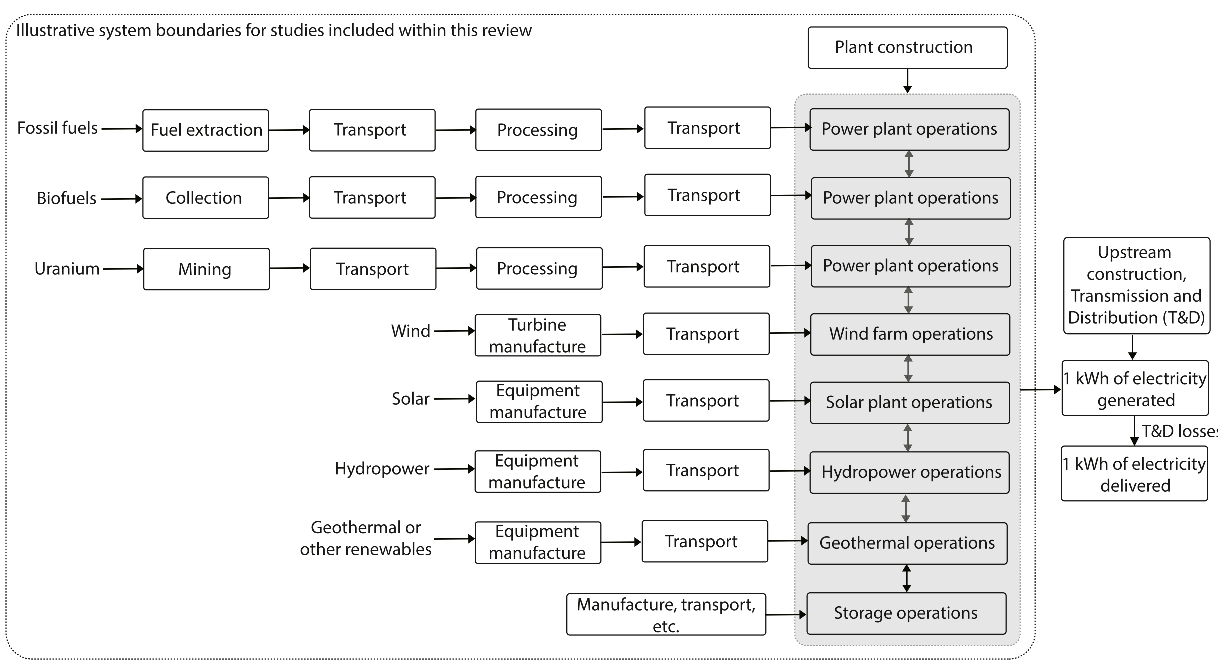

Fig. 2. An illustrative scope of our review, including all electricity generation types represented in the literature surveyed. The scope is illustrative as the screening process included any LCA that examined two or more life cycle stages in the analysis. The grey area represents the grid and interactions between power generation units. The systems boundaries of each study in our review might comprise a small component of this system or a larger more comprehensive analysis.

- "life cycle assessment" OR LCA, electricity, "geographical information system" OR GIS

Results were then screened according to the following criteria: (1) the focus of the article was electricity generation, reflected in the functional unit; (2) there was a clear contribution to spatial, temporal, or spatiotemporal aspects of LCA methodology; (3) the publication date was between January 1, 2009 and December 31, 2018. After the Scholar search, which ultimately yielded more than 6,000 results, the Web of Science and relevant journals were manually searched for missed results, with 17 discovered and manually added to the yield. The final search yield was 6,519 results (Fig. 3).

2.1. Manual screening and data labeling

Following the compilation of potentially relevant articles, results were treated in four stages: an initial screening, a full text review, and finally, a methodological screening. The initial screening identified and removed categorically out-of-scope entries, entries found to be out of scope based on review of the title and description, and entries with no online address. Categorically out-of-scope entries included citation-only entries, often marked by Scholar with the tag "[CITATION]" and a null URL, language titles that were not in English, and handbooks. Other out-of-scope entries failed to demonstrate any application to life cycle assessment or electricity in the title and description while clearly demonstrating other focuses. Entries without a clear focus at the ini-

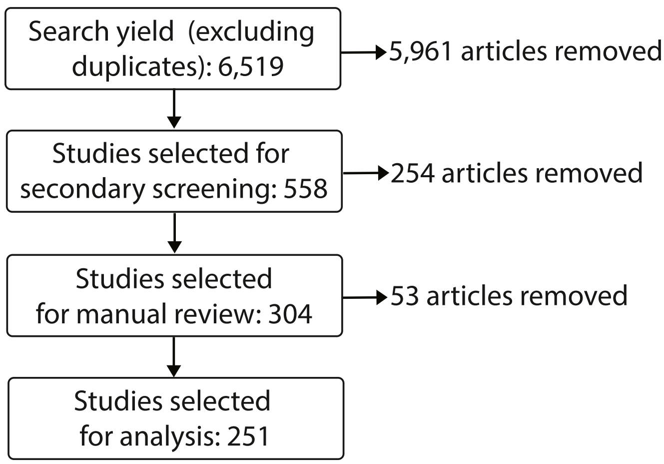

Fig. 3. The screening process used in this review. After removal of duplicates, primary screening removed articles that were out of scope or missing information. The manual review involved further refinement based on scope and type of publication.

tial screening stage were retained for more rigorous review, with the intentional bias of inclusivity for the preliminary screening. The initial screening yielded 558 results, with 5,961 entries removed, of which 145 had no URL and 5,816 were removed based on scope.

Results were then scrutinized during a full text review for relevance to life cycle assessment, focus on electricity generation, and appropriate form and publication. Consistent with prior systematic reviews of LCAs, conference papers of less than five double-spaced pages, conference proceedings and other summary documents, PowerPoint presentations, and full books were removed [44-48]. Anthologies and other collections of papers were reviewed for relevant articles, which were then extracted and, after ensuring no duplication, saved in the place of the anthology or collection. These categorical checks reduced the yield by 120 results. Results with broken URLs were then manually searched for elsewhere; 45 results were found to be inaccessible and consequently excluded. Finally, theses and dissertations were excluded from the study to reduce duplication with published results (removing those that did not result in published work), with an additional 89 results removed. In total, the full text yielded 304 remaining entries.

Entries found to be within scope were placed into one of four categories: “Full LCA,” “Mixed Methods Incorporating LCA,” “Non-LCA: LCA-Focused,” and “Non-LCA: Other Relevant Analysis.” While articles falling into the “Full LCA” category demonstrate advances in methods through application, mixed methods and both non-LCA categories provided interesting insight for how the field may evolve into the future.

“Full LCA” indicated that the article conducted a life cycle assessment including at least two life cycle phases (e.g., fuel supply and electricity generation) with the required focus on electricity generation, similar to prior systematic reviews [40, 49]. Thus, the analysis of this category is directly comparable to the results of standard systematic reviews; the other three categories provide additional information about relevant research.

“Mixed Methods Incorporating LCA” indicated that the article directly used life cycle methods to produce empirical results but did not conduct a full LCA with at least two life cycles phases. Such articles included studies that considered a single life cycle phase, studies of life cycle costing that did not employ standard LCA procedures, and analyses that used a life cycle framework but deviated from standard LCA practice. This category was introduced to allow the study to capture novel implementations and relevant contributions to life cycle methodology that would be excluded by the strict “Full LCA” category requirements.

“Non-LCA: LCA-Focused” articles advanced life cycle methodology without empirical life cycle results. The two broad cases of such articles are pure life cycle methodology papers and non-LCA papers with results expressly intended to guide or contribute to life cycle methodology. An example might present a means of improving the temporal resolution of emissions from electricity generation for use in future life cycle assessments. This category was introduced to observe relevant activity in the field beyond empirical deployment.

“Non-LCA: Other Relevant Analysis” articles neither employed LCA methods nor expressly intended to advance them, but nevertheless made contributions deemed to be of relevance to the field (i.e., their results could potentially be used in future LCAs). All articles in the review were detected based on keywords that included “LCA,” hence these articles also make such mention. They are distinct from “Non-LCA: LCA-Focused” articles in terms of intention and focus, and consequently in directness of application to LCA. While the most peripheral category, it was retained in the final analysis as a body of work that is poised to be part of the field’s evolution while not yet explicitly a part of it.

Finally, a methodological screening was run as a second full text review ensuring that all final selected articles were fully within methodological scope, unique (no duplicates) and appropriately focused on electricity generation (excluding storage and distribution unless in combination with generation). A total of 53 articles were removed during this final, most stringent review phase.

The final dataset included 251 articles [30, 34, 50-298]. These articles were then downloaded and entered in the MAXQDA mixed methods analysis software [299] for further analysis.

2.2. Analysis

The selected articles were coded in MAXQDA to analyze their distribution in terms of chronology, topical focus, regional focus, and methodological contribution(s). The manually coded categories were as follows:

- Year of publication
- Electricity generation type (e.g. natural gas, solar photovoltaic)
- Primary system of interest (e.g. thermal power plant, supply chain)
- Geographic focus (with nested codes from continental to country level)
- Type of methodological contribution (i.e. spatial resolution, temporal resolution)
- Uses of resolved information (input data, output data)
- LCA method (for LCAs only)
- Phase in which resolution is employed (for LCAs only)
- Impact categories (for LCAs only)

Finally, the entire set of documents was searched for instances of the key terms, including impact characterization methods (e.g., Traci and ReCiPe), databases (namely Ecoinvent), and models (e.g., GREET). Instances that were discovered were autocoded with the relevant labels.

The MAXQDA analysis produced 9,957 unique codes across the 251 articles studied. The final code data, consisting of counts of each code within each article, were exported to Excel for visualization. Within Excel, all codes were processed into binary form, such that multiple instances of a code in a single document would only be counted once (see supporting information). This procedure ensured that the automatically generated codes indicated whether a given term was present in an article.

In addition to an analysis of the coded articles, we conducted an in-depth review of the articles to determine what types of methodological advances have been made. In doing so, we completed a detailed review of the highest spatiotemporal resolution to determine the contribution of these studies (site and hourly). We then identified analysis tools that were mentioned across all types of articles that can be used in combination with LCA. To understand the emergence of integrated methods using these analysis tools, we completed a content analysis to determine how commonly the integrated approaches were mentioned over time. We then studied the articles that mentioned the most common analysis tools to determine their potential for improving LCA methods.

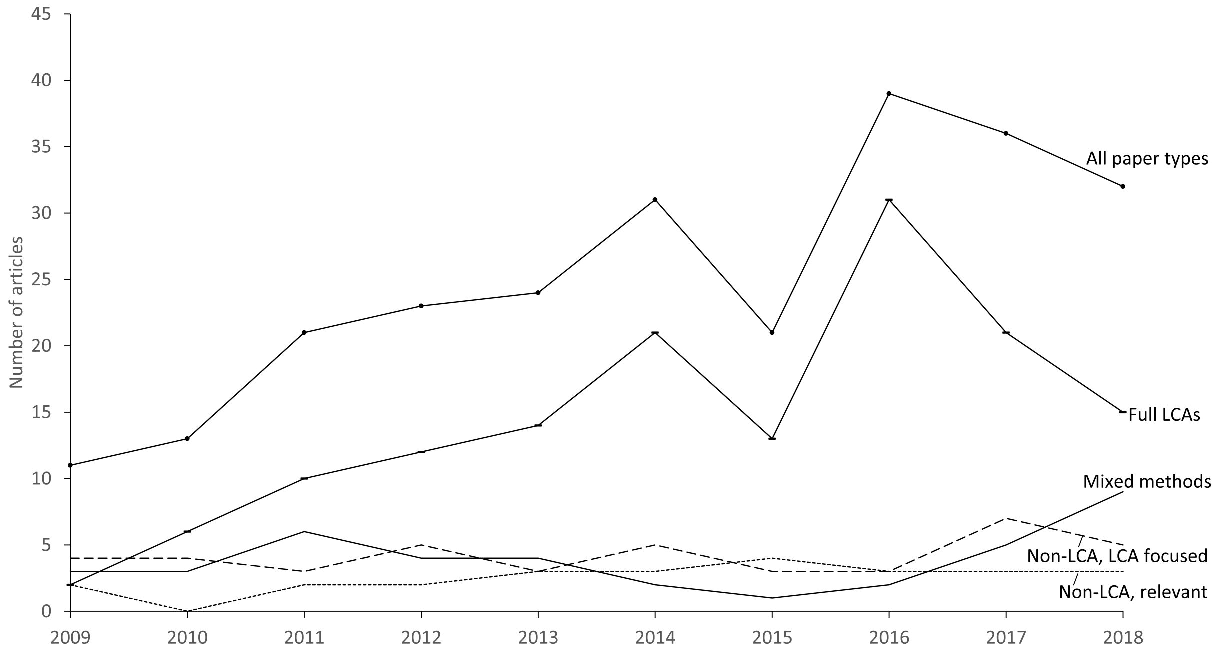

Fig. 4. Annual publications by category.

3. Results and discussion

3.1. Article categories and geographic coverage

Publications on this topic appear to be increasing over time (Fig. 4). Of the total 251 screened articles, 11 were published in 2008 and 32 in 2018. There was a more notable increase in the Full LCA category, which increased from 2 to 15 with the highest number to date being 32 in 2016. That said, there was a notable drop in publications in 2015, followed by a peak in 2016, making the overall trends challenging to discern. We do note that the drop in Full LCAs is slightly counteracted by increases in the “Mixed Methods” category from 2015 onwards.

Upon further examination of the papers, several factors contribute to the 2015 drop in publications. First, a higher number of conference papers met our screening criteria in 2014 (5 in 2014 and only 1 in 2015).

Second, a new journal (the Journal of Sustainable Production and Consumption) was launched in 2015. In 2016, publications spiked again, perhaps influenced by two focused special issues on other topics in the first year. Two articles focused on the 2013 release of Ecoinvent were published in the International Journal of Life Cycle Assessment. We attribute the lag to the publication process (i.e., writing through peer review and final publication). Finally, there was a notable decrease in publications focused on LCAs of coal, perhaps influenced by public discourse and policy related to the Paris Agreement.

Biofuels were the most represented fuel across all papers with 140 occurrences across all papers and only 79 in the Full LCA category, followed by 25 in "Mixed Methods", 24 in "Non-LCA: LCA-Focused" and 12 in "Non-LCA: Other Relevant Analysis". We note that while the majority of the bioenergy studies focused on biomass with and without combined heat and power (CHP) (100 and 10, respectively), biogas with or without CHP (30 and 4, respectively), waste-to-energy (31), biofuels (20), and plant-microbial fuel cells (1) were also examined. Biofuels were included if there was an emphasis on the characterization of electricity generation as a significant input to the conversion and results were considered based on a unit of electricity. The localized nature of feedstock supply chains was recognized as a critical constraint to the scaling of bioenergy, resulting in articles focused on optimization and market integration solutions that emphasized how location can result in lower environmental damages and higher economic performance.

The 251 publications focused on many different regions, often comparative in nature and spanning from site-level analysis through multi-country and multi-regional studies. In total, we counted 373 occurrences of European locations, 136 occurrences of Asian locations, 74 occurrences of North American locations, 45 occurrences of South American locations and 34 occurrences of African locations (Fig. 5a). By location, we refer to any study area ranging from site to continental, including cities, subnational jurisdictions, regions that cover multiple jurisdictions, and countries.

The highest number of country occurrences in the screened articles was the United States (52), followed by Italy (26), Germany (24), Spain (24), China (22), and France (19). In terms of the fuels represented, coal ranked first in Germany, China and France, while solar ranked first in the US and in Spain. Other highly represented fuels include natural gas, bioenergy, and oil. The least represented technologies in all countries were coal biomass to liquids (CBTL), hydrogen-related generation (noting that hydrogen is generally perceived as an energy carrier rather than fuel), peat, and tidal/wave power.

Our findings suggest that, while fuels were examined with relatively stable frequencies across all papers over the studied period, Full LCAs grew to examine a broader range of fuels in 2018 than in 2009 (Fig. 5b and c). Perhaps most importantly, increasing occurrences are observed in intermittent renewable energy as well as a more even distribution of occurrences across fuel types. For fuel types with few publications (such as geothermal), we note that inter-annual variability could be correlated to the productivity of a small number of specialized scholars.

3.2. Impact categories

We identified the impact categories that were examined in publications categorized as “All Papers” and “Full LCAs” (Fig. 6a and b). Our results for both types of paper show an increasing number of impact categories studied over time. Climate impacts have received the most attention with 183 cumulative occurrences of a total 729 across all 251 publications (“All Papers”) and 129 of 587 occurrences in the 147 “Full LCAs”. Acidification potential, human health, eutrophication potential, and resource depletion are also increasingly studied – all 4 reached 10 occurrences across all articles in 2018, only 5 fewer than climate-related impacts. The number of occurrences then drops off

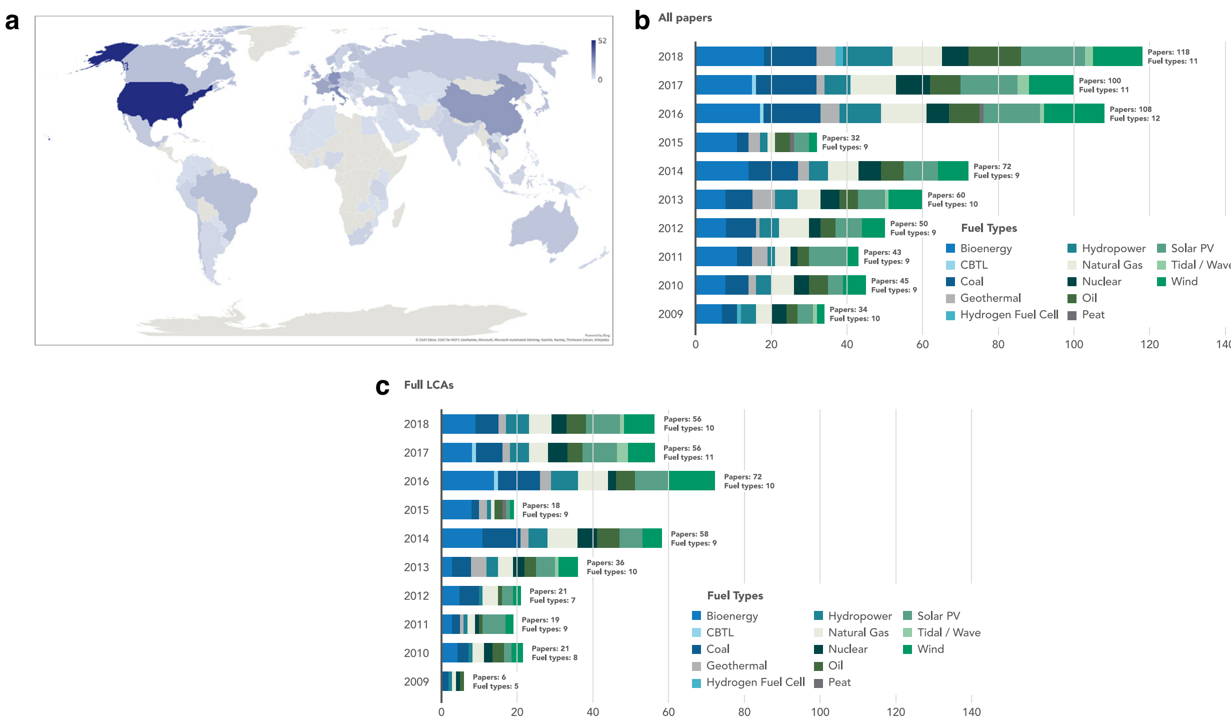

Fig. 5. (a, b, and c). Geographic variability and trends in fuel types. (a) presents the number of occurrences that specific locations were analyzed in our sample by county. (b) presents the changes in the fuel types analyzed between 2009-2018 for the "All Papers" category. (c) presents the changes in the fuel types analyzed between 2009-2018 for the "Full LCA" category.

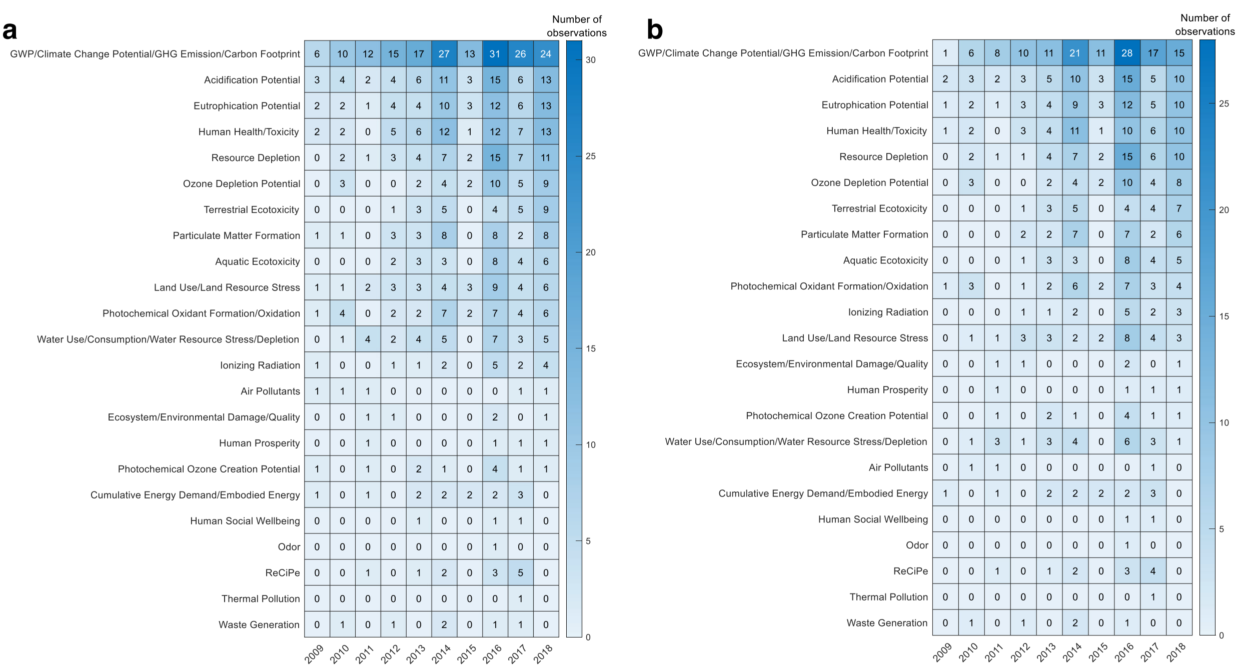

Fig. 6. (a, b). Occurrences of impact categories examined in the screened publications. (a) presents results for the publications in the "All Papers" category. (b) presents results for the "Full LCA" category.

quite quickly for the remaining impact categories. After the 2007 Nobel prize for Intergovernmental Panel on Climate Change (IPCC), it is logical to infer that it may have played a role in the emphasis on climate impacts through both public discourse and funding allocations. Additionally, due to the ongoing research by the IPCC and reporting by governments, industry, and other stakeholders, data availability may make climate impacts a more accessible impact category relative to others.

3.3. Spatial and temporal resolution

We note that our results suggest that the temporal dimension has received less attention that the spatial dimension (Fig. 7). For example, of all fuel types studied, biomass received the most occurrences in both the "All Papers" category and the "Full LCA" category. While biomass was well represented across our defined spatial scales, there was roughly the same number of occurrences in sub-annual time scales as for several

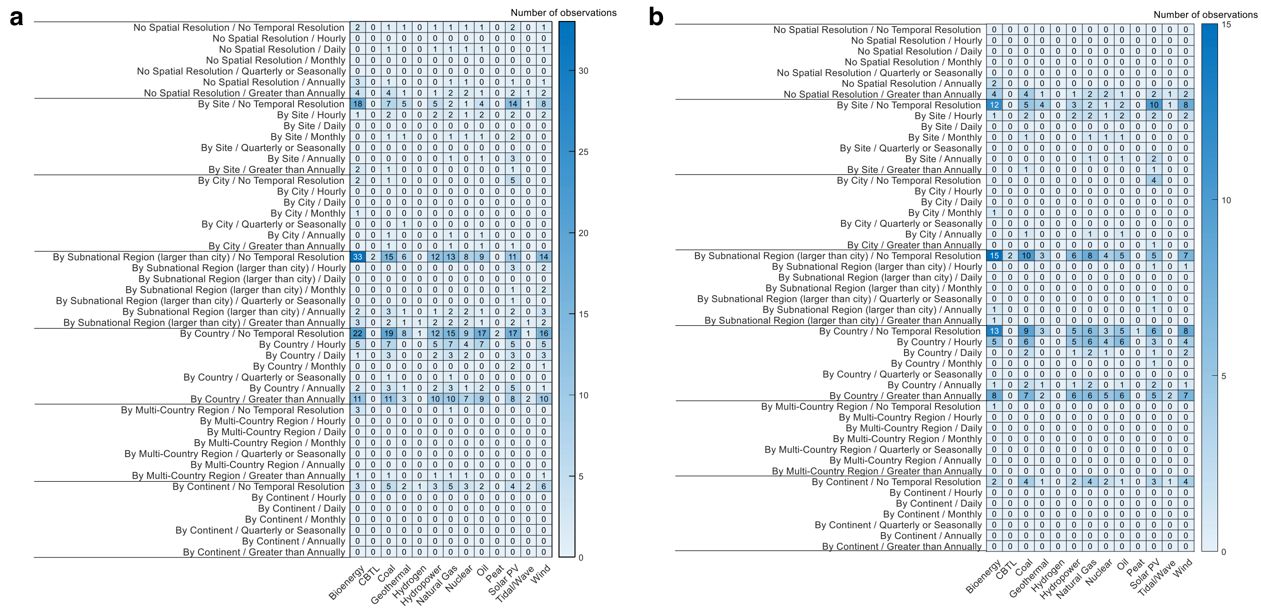

Fig. 7. (a and b). Spatiotemporal interactions observed in the screened publications. (a) presents results for the observations in the "All Papers" category. (b) presents results for the "Full LCA" category. The acronyms used in the figures are as follows: "Bio" represents biomass; "CBTL" represents coal biomass to liquids, where electricity was a co-product in the study; "Geo" represents geothermal; "H_2" represents hydrogen fuel cell, "Hydro" represents hydropower, "NG" represents natural gas. The color bars indicate the number of observations in for each combination of spatiotemporal resolutions.

other fuels (notably, coal, hydro, wind, solar, nuclear and oil). Temporal resolution was found to be most prevalent in solar and wind papers, with 45% of each directly incorporating temporal resolution. Related, the term "intermittent" in context of renewables only began to appear regularly in 2016, with one mention in each year except 2010 and 2015 prior and four to five mentions from 2016 through 2018. Together, 26% of papers that considered temporal resolution covered one or both of wind and solar. This proportion was exceeded only by fossil fuels (38%) compared to the third-most prevalent focus of bioenergy (13%).

Figs. 6 and 7 can both inform what has previously been studied, but they also can be used as roadmaps that illuminate pathways for future contributions and research. Specific locations in the figures without any results or low numbers highlight specific topics that may benefit from new research.

Very few analyses were completed at sub-annual timescales and those that did mostly occurred in country and site level analyses (with rare exceptions for city and subnational regions). Importantly, the highest spatiotemporal resolutions – hourly and site – were only observed in three of the publications reviewed. A closer look at these papers reveals important results. One article developed a model at this resolution specifically to more accurately understand how to reduce the emissions for data centers in operation to support cloud computing [300]. The model was developed to be specific to one data center in Ontario and was modeled at the hourly scale to determine how to minimize daily carbon emissions of an operating cloud computing network. Similarly, another examined site-level and hourly impacts but was focused on the demand of electricity in an energy efficient house and examined life cycle costs, global warming potential and Abiotic Depletion Potential (ADP) [153]. Notably, the consideration of time enabled the identification of specific actions in the use phase that could enable interventions from the consumer perspective. Consumers may change their use of electricity, for example, based on seasonal variation (heating and cooling activities) as well as weekly and hourly variations (on-site electricity generation, professional and personal activities). Impacts at aggregate, annual timesteps were found to underestimate environmental impacts primarily since the hourly data captures the higher share of coal and gas power in the electricity mix during the winter. The final article that was identified using our approach examined two rooftop solar PV panels and used field measurement of solar irradiance and electricity generation from 2010 to 2015 [89]. This article was the only one of the three to consider life cycle costs and payback period as well as environmental impacts (embodied energy and greenhouse gas emissions), demonstrating the environmental and economic benefits of investing in rooftop grid-connected solar PV in Hong Kong.

The results for all three articles at the site-hourly resolutions illustrate the importance site-level demand and the grid mixes of the supplied energy. Grid dynamics at hourly scales support the identification of the most impactful interventions for reducing emissions at specific sites, particularly where on-site generation and intermittency can influence results. Each study emphasized electricity use by a consumer, illustrating the importance of higher resolutions to more accurately present impacts to specific end users, to move beyond one-size-fits-all assessments and determine portfolios of solutions.

Of the studied population, 180 articles discuss the grid in some form, with focuses ranging from the impact of grid data uncertainties to methods of calculating grid connection impacts. These span the studied period, with early papers concentrated in LCA-focused non-LCA papers, including the two early studies noted here. In 2009, Weber et al. [3] assessed problems in GHG accounting caused by grid mix uncertainties and varying geographical boundaries inherent to the grid. Also in 2009, Heck et al. [295] proposed the use of GIS to resolve distances between plants and grid interconnections to assess the LCA burdens, noting its applicability to remote solar and wind farms and, ahead of its time, offshore wind.

By 2018, the focus on grids had evolved to implementing dynamic spatially resolved LCAs. Milovanoff et al., [56] for example, focused on integrating more dynamic electricity consumption factors. Hourly factors were determined to produce more accurate results by Vuarnoz and Jusselme, providing decision-support to system designers seeking to reduce emissions [53]. Such results support research that has emphasized the need for higher temporal resolutions in developing interventions that reduce emissions [21, 24]. Without granular data and analysis, impact analyses were found to be aggregate or incomplete and opportunities for optimization and efficiency im-

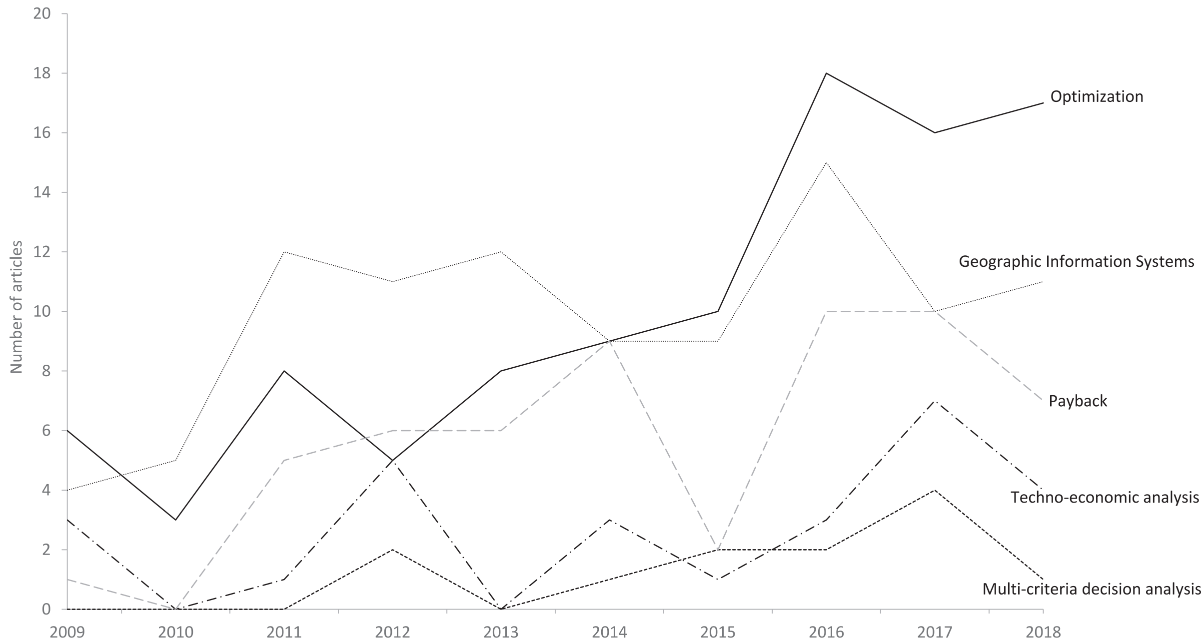

Fig. 8. Trends in the observations of methods mentioned that are being integrated or combined with LCA.

provements were overlooked across the plant, municipal, and grid levels.

The "Mixed Methods" category offered not only methodologies but concrete tools toward improved impact assessment and optimization. One article, for example, developed an interactive tool for web clients that undertakes multi-criteria LCAs of photovoltaic systems with the goal of increasing the accessibility of environmental assessment across different spatial and techno-economic conditions [102]. GIS has shown large potential for improving inventories with more accurate data for use in LCA and optimization models but also for improving spatial differentiation in characterization factors used for impact assessment. Unsurprisingly, it was frequently used, with less common methods including life cycle cost analysis, socioeconomic and techno-economic analysis, material-flow analysis, and novel plant and municipal-level optimization models. Economic analyses such as break-even analysis, payback time, and assessments of pricing and market penetration were common in mixed methods, used in at least half of the studies in all years but 2010, 2014 and 2017.

Compared to mixed methods, the focus of the contribution in the "Non-LCA: Other Relevant Analysis" paper category was more diverse. Two articles supported improving engineering design of energy processes and fossil fuel plants [79, 293]. Papers may not have been LCAs but they may have specific focus on supply chains associated with feedstocks and improving spatial differentiation in the characterization of bioenergy [201, 264, 289]. A number of papers focused on integrating optimization into decisions and decision-making frameworks relevant to LCA [210, 211, 256] which may be combined with multi-criteria analysis and/or GIS [161]. One paper incorporated interregional trade to support better estimates for consumption, not only generation [248]. Several papers offered new perspectives regarding the better characterization of existing or new impact categories, such as land use [157], social costs [231], the potential influence of evapotranspiration on water consumption estimates [118], and resource feasibility [124]. A number of papers focused on improving policies and/or determining payback [69, 88, 112, 230]. Three papers examined how improving either the spatial or temporal resolution can increase the accuracy of economic assessments of renewables, for example, by improved analyses of intermittencies [202] or solar panel orientation [131, 165].

3.4. Integration of analysis tools

Based on the methodological contributions we identified in each paper type noted in the preceding paragraphs, we further examined the articles regarding how commonly the analysis tool appeared. A focused content analysis of the screened articles revealed 100 articles mentioned "optimization" or "optimisation"; 98 articles mentioned "geographic information systems" or "GIS"; 56 articles mentioned "payback"; 27 articles mentioned "techno-economic analysis"; 14 mentioned "socioeconomic analysis"; and 15, 13, and 12 articles each were recorded respectively for "life cycle cost", "material flow analysis" or "material flow", and "multi-criteria analysis" or "multi criteria analysis." This approach thus recognizes methodological advances that integrated analysis tools when they were directly applied in an analysis or when they were explicitly mentioned. Upon further investigation of those that were mentioned in 30 or more articles, there were notable increases in optimization and geographic information systems, suggesting they have been playing a role in advancing analyses with more refined spatiotemporal resolutions (Fig. 8).

As the two most common and novel analysis tools, we examined how studies utilized optimization and GIS with an in-depth review of the articles. Optimization – a method used to maximize benefits or minimize costs – provided useful applications for integrating both spatial and temporal data and improving LCA results. Optimization was used to analyze how to reduce overall environmental and economic costs to grid operations (including time-dependent solutions) [53, 66, 67, 73, 75, 105, 109, 116, 120, 145, 160, 162, 177, 236, 273, 280, 288]; to better understand the most cost-effective transportation routes and logistics [87, 103, 132, 143, 147, 174, 211, 256, 260, 271]; to support multi-criteria decision-making [105, 290, 293]; in equilibrium models that support a better understanding of the supply and demand of energy resources [244, 276]; in process design improvements [140, 143, 146, 199, 270]; to support siting decisions [103, 114, 116, 208]; and to reduce economic and environmental costs of policies, [102, 249] energy supply chains, and resource extraction [52, 56, 60, 63, 68, 74, 96, 105, 125, 127, 128, 134, 135, 159, 174, 179, 185, 192, 210, 227, 235, 256, 268]. While optimization was used broadly across analyses with varying objectives, it enabled better evaluation of temporal variation (e.g., by modeling supply-demand dynamics and time-dependency), and also the incorporation of spatial constraints (e.g., more accurate modeling of transportation routes and siting considerations).

GIS presents more direct links to spatial attributes in LCAs, enabling more representative inventories and impact assessment (and, therefore, results). Studies mentioned GIS for many different applications: improving site-specific data collection for inventories, relevant models, and design [30, 88, 92, 94, 103, 104, 106, 117, 129, 135, 136, 145, 148, 154, 157, 163, 170, 196, 210, 232, 242, 243, 275, 295]; improving impact assessment models [104, 125, 139, 160, 220, 222, 223, 235, 236, 246, 251, 279]; developing hot spot analyses [125, 203]; determining the spatial distribution of energy resources [87, 95, 105, 124, 125, 132, 169, 185, 189-191, 201, 203, 211, 220, 221, 230, 240, 257, 259, 263, 268, 269] and how impacts may be reduced [175, 208, 264, 267]; analyzing more accurate transportation routes [174, 211, 256, 260] and cost implications [268]; understanding local environmental and ecological factors [284, 297]; optimizing using localized environmental constraints [135, 211]; determining systems boundaries [3]; and, creating platforms for users to interact with geospatial data and results [266].

While these two analysis tools are reported separately in Fig. 8, it is important to note that combinations of geospatial data, optimization, and LCA can support the important methodological advances for understanding the environmental impacts of electricity generation [87, 135, 136, 160, 208, 210, 211].

4. Conclusions

Our systematic review examined how the methodology employed in LCAs of electricity generation has evolved in terms of consideration of space and time from the period of 2009 to 2018. Our results suggest that while there have been advancements, unresolved problems remain. These unresolved problems present opportunities for practitioners to advance the field. Recognizing these opportunities, trends in publication counts show increasing interest and contributions to the topics in question. Of note, there are increasing numbers of non-LCA and Mixed Methods articles published over time (with recent increases in the latter), suggesting there are contributions that may not yet have been applied directly in a full LCA. Over the timeframe we analyzed, the number of fuels and impact categories examined has reciprocally increased.

4.1. Towards a research roadmap

Our findings illuminate areas in need of additional research and can thus be used as a roadmap moving forward and an important signpost for LCA scholars interested in electricity generation. For example, research to date has predominantly been focused on Europe, Asia, and North America, presenting opportunities to examine the electric sector in regions other than those previously examined. Different regions, grid mixes, and technologies will have strengths and weaknesses, so focal areas should be prioritized for their unique spatiotemporal contexts. Across all studies, most publications focus on the scale of countries and sites, suggesting specific scales have been understudied (in addition to how results may vary across scales). In comparison to spatial considerations, temporal aspects remain understudied. LCAs at sub-annual time steps can reveal important considerations about how interventions may mitigate spikes in generation (and emissions) throughout the day [21]. We note that we likely underestimate the advancements in the field as much research remains unpublished; for example, studies internal to specific companies and industries may not be public.

The impact categories examined were heavily weighted towards greenhouse gas emissions where the outcome is quantified without site specificity, with impact categories that require more localized information being less studied. A number of impact categories that arguably may benefit most from improved spatiotemporal methods (e.g., land use, photo-chemical oxidant formation, particulate matter, and so on) remain comparatively under-studied, suggesting more focused research would benefit our understanding of such life cycle impacts. While our results show the field is steadily evolving, there is no apparent event triggering patterns of evolution in the field, other than the growing number of studies on climate change. Greater data availability provides more opportunity to improve methods and overcome resource constraints [36, 301], but challenges remain in data processing and in making the results relevant to decision-makers. For example, due to the nascency of spatiotemporal methods in LCA, decision-makers may be less aware of the importance of insights that can be revealed.

System-wide LCAs do not capture regional differentiation that may result in highly variable results; for example, results should be linked to specific grid mixes and capture localized impacts such as water consumption. Accordingly, site specificity is increasingly becoming more important for the credibility and uptake of LCA results by decision-makers. While several studies describe specific methods that scholars can follow, further refinement of these concepts would be an important next step for the field; for example, more specific coverage in data quality assessments (e.g., pedigree matrices) about spatial and temporal resolutions would simplify communication about regional applicability. Additional detail about spatial and temporal resolution would strengthen existing data quality assessments to ensure more reliable information about uncertainty is available to understand where data can be improved.

4.2. Advancements in LCA with the integration of analysis tools

Our findings support prior work that highlights the importance of understanding grid dynamics at higher temporal resolution than annual, such as hourly, to ensure that their effectiveness is accurately estimated [21, 302]. While such approaches offer greater accuracy in estimating impacts both for supply and demand of electricity, the temporal dimension has been less studied than spatial dimensions to date. Our review goes further to illuminate the importance of this finding for end-users in specific locations — the most effective interventions will likely require consideration of their impact during specific sub-annual time periods (e.g., hourly or seasonal) [21, 302]. Analyses that were at the site-hourly resolutions (amounting to only three) focused on demand or end use of electricity to account for more realistic grid mixes and impacts related to specific locations.

Importantly, we determined that optimization and GIS were the most common analysis tools observed in the screened articles. Each tool provides a variety of important improvements when used with LCA. Optimization can provide insights into how locations of power plants and their hourly dispatch can influence life cycle grid dynamics, for example [302]. GIS can assist with spatial data and analysis that better represents location-dependent variability (even variability in optimized facilities and logistics that depend on location). By integrating such analysis tools, the accuracy of LCA models can be increased with improved evaluation of energy resources, impact assessment that accounts for environmental variability, better depiction of the interactions between supply and demand, and more detailed site-level data. LCAs will benefit from combinations of improved data and analysis with GIS combined with optimization of grid interactions and improved costs analyses, providing important information for the most impactful environmental solutions. Our review shows that a better understanding of the specific location of energy projects can inform economic analyses, such as payback periods. Techno-economic analysis is being increasingly performed alongside LCAs in our screened sample, suggesting that these analyses may also benefit from such advances. Finally, the occurrences of multi-criteria decision analysis suggest that improving LCA can have implications for the interpretation stage and decision-making.

4.3. The importance of data

Arguably all such improvements in LCA will require new and/or improved data availability. As a result, we highlight the importance of papers that produce and make public datasets that support improved spatiotemporal analyses of the life cycle of electricity generation [75]. Further, more accurate and refined data can result in important improvements related to specific segments of the life cycle of electricity generation [303, 304]. While we were comprehensive and systematic in our approach, like other systematic reviews [43], there are articles that may not have been captured using our method [305]. Regardless, systematic reviews are noted as highly beneficial to better understanding advances in a field and our results demonstrate interesting trends. Literature published since 2019 shows similar direction, suggesting there is an opportunity for developing new systematic reviews related to this topic [306-309]. Focusing on specific fuel types or the grid may identify interesting advances which will yield interesting insights about what important topics may be overlooked. Valuable insights may be obtained from systematic reviews that focus specifically on the integration of tools such as optimization into LCA.

In the past, LCA has been challenged with data scarcity and limited integration with geospatial techniques.The field of LCA has the opportunity to improve accuracy, credibility, and methodology with increased data availability and more common ingration of geospatial analysis tools. LCAs should move towards greater characterization of variability within product systems while advancing towards more accurate impact assessment. Variability across product systems necessitates improved datasets and an understanding of grid interactions. Grid interactions can be modeled with present data or using optimization, where analysts can pinpoint how to reduce both environmental and economic costs to power systems and fuel operations. Since impact assessments often rely on generic characterization factors, including site-level information means that results can better reflect local environmental conditions and heterogeneity across a product system. Already, our analysis points to such improvements in areas such as impacts to land and water, signaling an opportunity to reflect actual impacts more accurately across the life cycle. GIS can support more comprehensive analyses of specific processes and their impacts, using data that characterize the environment.

Due to the numerous analysis tools and data challenges, we recommend LCA standards consider the development of spatial and temporal methods more seriously by developing additional guidance. Our review shows substantial gaps remain in LCA research that considers spatial and temporal factors — guidance from ISO may be warranted to ensure practitioners have robust methods to follow and build upon. Decision-makers, practitioners, and stakeholders would benefit from a greater understanding of how broadly applicable LCA results are or whether they are specific to a particular region or a snapshot in time. LCAs should be a pillar for decision-making in the electric sector, particularly due to regional variability and the fast-paced, evolving sectors across the supply chain. Specifications that consider spatial and temporal dimensions would support more sustainable decisions and environmentally sound supply chains and minimize the risk of overlooking mitigation opportunities.

Declaration of competing interest

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

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Supplementary materials

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