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Introduction to evaluating energy justice across the life cycle: A social life cycle assessment approach

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HIGHLIGHTS

- Social sustainability must be addressed along the life cycle of low-carbon energy.
- Addressing disproportionate burdens by group is crucial to social sustainability.
- A social life cycle assessment (LCA) framework for energy justice is proposed.
- Social LCA indicators that address energy justice are introduced.
- The relevance of indicators to low-carbon electrical energy systems is discussed.

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ABSTRACT

As our energy systems are transitioning towards low-carbon energy sources and their environmental and economic sustainability are assessed, their potential social impacts must also be determined. These social impacts may be disproportionate to a population, leading to energy justice concerns. The social life cycle assessment framework can be used to comprehensively address energy justice concerns by different stakeholder groups and at all life cycle stages associated with a low-carbon energy system. Indicators for a social life cycle assessment framework that addresses energy justice are introduced and discussed. These indicators are organized by four categories of stakeholders for electrical energy systems: workers, electricity consumers, local communities, and society as a whole. The social life cycle assessment framework allows for variations in justice and equity to be determined not only at the generation stage, but through multiple points in the life cycle of the same energy system, from raw material extraction, through manufacturing, transportation, distribution, electricity generation, and waste management. This framework can address potential energy justice issues along the life cycle of new energy systems and assist in their design and planning for optimizing their social sustainability without overlooking vulnerable populations.

1. Introduction

As new energy systems are planned and implemented, sustainability analyses are performed to address potential environmental impacts. Environmental life cycle assessment has been the primary method used to quantify direct and indirect emissions across the life cycle of energy systems. Similarly, social life cycle assessment (social LCA) addresses the social component of sustainability while accounting for the various life cycle stages of products and systems. This method evaluates the positive and negative social impacts on stakeholders throughout the life

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cycle of a system or product. A set of guidelines for social LCA has been developed by the United Nations Environmental Programme, which include flexibility in designing the assessment and in setting indicators to determine the social impacts of systems from cradle to grave [1]. The continued development of indicators for social LCA is necessary in order to assess the social sustainability of energy systems in a comprehensive way.

Energy justice is a crucial component that should be addressed when assessing the social sustainability of energy systems. Energy justice, an extension of environmental justice activism and scholarship, advocates for the provision of safe, affordable and sustainable energy to consumers [2], while paying explicit attention to the equitable distribution of costs and benefits of energy services as well as procedural considerations related to decision-making that is impartial, democratic, and inclusive [3]. It further applies an equity framework to various energy considerations, including: policy, production and systems, consumption, activism, security and climate change [4]. Understanding the social and environmental justice issues in conventional energy systems uncovers the links between energy supply- and demand-side dynamics and vulnerable communities along the entirety of energy production and consumption spectrum [5]. To this end, Hernandez issued a “call for energy justice” identifying four basic rights, or the basis of demands, along the energy spectrum: first, the right to healthy, sustainable energy production; second, the right to the best available energy infrastructure; third, the right to affordable energy; and fourth, the right to uninterrupted energy services [5]. Energy justice’s emphasis on providing “all individuals, across all areas, with a safe, affordable and sustainable energy” promotes social sustainability.

Energy justice activists already tackle the issues of who is impacted and how they are impacted by conventional energy systems, but replacing these systems with a renewable energy source does not mean that they will fall short of the same injustices. Transitioning towards renewable energy systems involves more than just changing machines. It also involves the people who develop the machines, participate in decision-making, and consume the energy. This transition has a social impact [6]. Renewable energy systems are not absent a menu of potential injustices, particularly as it pertains to safety and affordability. Siting of these new systems, and concerns for procedural fairness in decision-making related to renewable energy, are also significant concerns [7]. The social outcomes may result in an unequal distribution of the cost and benefits of low-carbon energy systems. Energy justice addresses these issues across the mechanisms of distributional justice (where injustices occur), procedural justice (if and how communities have been engaged fairly in decision-making), and recognition justice (who may be misrepresented or not represented at all in decision-making) [4].

Although energy justice studies incorporate different mechanisms of social justice, they have traditionally focused on one level of the operations of a given energy system at a time, such as the combustion of a fuel to generate electricity or the mining activities. While there are exceptions, including calls for a capabilities-based approach to the framing of energy use, services, and outcomes [8], and the development of the Energy Justice Metric for assessing justice across a number of scales (including national level) [9], these advances do not connect impacts systemically across the life cycle of an energy system or energy transition. Recent meta-reviews of the concept of energy justice as a research agenda call for a whole systems approach [4]. Energy justice concerns do not currently have a framework for holistic assessment across the multiple interconnected activities involved in an energy system. Social LCA offers a framework to address justice issues for energy systems. This set of methods can be applied to the planning of future energy systems to maximize justice across their life cycles, or to existing energy systems to identify areas for improvement. The main advantages of the social LCA framework for addressing energy justice are that differences in impacts between individual categories of stakeholders can be identified, and that variations in equity and justice at multiple points in the life cycle of the same energy system can be determined.

The same energy transition can have disproportionate impacts that vary across the different stakeholders of workers, the local community, society, and consumers. For example, a coal power plant shutting down will lead to a negative impact on its workers, but possibly a positive impact on the local community from the reduction in air pollutant emissions. Society at large may benefit from the transition due to a lower climate change impact across the life cycle of the more sustainable electrical generation system that would replace the coal power plant. If the substituted low-carbon energy systems cannot meet the demand that the coal power plant previously met with the same reliability and price of electricity, then consumers may be negatively impacted. However, if the planning of a new energy system to replace the coal power plant includes a population that was previously underserved, electricity consumers and the local community benefit. The transition will also impact workers at coal mines and at mines for materials needed for the substituted energy system; truck drivers who bring the materials between sites; workers at manufacturing plants; and the local community near each site involved. The social LCA framework can be used to comprehensively address these intersections of potential positive and negative impacts on different stakeholders at various life cycle stages of an energy transition instead of focusing on one stage or one stakeholder type.

The second advantage of using a social LCA framework to address energy justice is that disproportionate burdens on different populations can be addressed along all of the life cycle stages involved in the deployment of new energy systems. The life cycle of electrical energy systems includes processes from cradle to grave: (1) raw material extraction and refining or processing (e.g., mining and refining metals for renewable energy infrastructure and extracting and processing natural gas for natural gas-fired power generation), (2) manufacturing of components and infrastructure, (3) electrical power generation, (4) transportation and distribution of energy and materials at multiple points along the life cycle, and (5) waste management. The life cycles of energy systems span across geographic boundaries and have impacts beyond the timespan of the power generation stage. The life cycle perspective also accounts for changes over time at any given life cycle stage throughout its lifetime. Furthermore, this framework matches the system boundary utilized in environmental life cycle assessment, thus facilitating complimentary analyses for environmental and social sustainability.

The objective of this paper is to discuss how social LCA can address energy justice for four stakeholder categories across the life cycle of electrical energy systems: workers, local communities, electricity consumers, and society at large. There have been very few social LCAs on electrical energy systems in the literature [10,11], and none have adapted an energy justice perspective to the selection of social impact categories and the development of indicators. Specific indicators are suggested to quantify energy justice concerns by stakeholders at various life cycle stages, and the potential justice issues that may arise along the life cycle of electrical energy systems are discussed in context. These metrics can be used to plan the low-carbon energy transition by addressing the social pillar of sustainability from an equity and justice perspective to avoid disproportionate social burdens.

2. Stakeholders and indicators

The suggested indicators apply separately to four stakeholder categories for people who may be impacted by low-carbon electrical energy systems across their life cycles: workers, electricity consumers, society, and local communities. In social LCA, a fifth stakeholder category exists which refers to value chain actors. This stakeholder category is not included in this methodology because these actors cannot be fully identified and assessed in the fast-developing field of sustainable energy. They involve investors, suppliers, contractors, and competitors which vary project-to-project. Addressing this stakeholder category would involve determining companies' respect of intellectual property rights, supplier relationships, fair competition practices, and commitment to social responsibility [12]. This is an area for future development.

The suggested indicators across the four selected stakeholder categories span from qualitative and semi-quantitative metrics to quantitative metrics. The use of qualitative, quantitative, and semi-quantitative indicators is common across social LCA methodologies [13]. Furthermore, although some of the indicators answer a yes or no question, the answer depends on data collection and quantitative analysis. In a social LCA, these metrics are assessed at each stage across the life cycle of an energy system and based on site-specific information collected across these stages which are typically geographically separate [13,14]. Table 1 summarizes where different stakeholders exist along the life cycle of an electrical energy system and suggested indicators to assess potential disproportionate burdens and benefits to the stakeholders from their interaction with the electrical energy system's life cycle. The suggested indicators are partially informed by the United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry's Methodological Sheets for Sub-categories in Social Life Cycle Assessment [15], adapted for relevance to a

Table 1
Suggested indicators for a framework for social LCA to address energy justice across the life cycle of an energy system and for four stakeholder categories. The numbered life cycle stages are as follows: (1) raw material extraction and processing, (2) manufacturing, (3) electrical power generation, (4) transportation and distribution, and (5) waste management. The list was adapted for an energy justice focus from suggested indicators in the United Nations Environment Programme and the Society of Environmental Toxicology and Chemistry's Methodological Sheets for Sub-categories in Social Life Cycle Assessment [15].

Stakeholder category	Life cycle stages	Example indicators to assess energy justice
Electricity consumers	3, 4	Yes/no: Do electricity consumers have a choice in the utility company or in generation methods used by their utility? Yes/no: Do consumers have a mechanism to provide feedback to their utility? Yes/no: Do electricity consumers have free access to objective information about energy use and sources of electricity? Yes/no: Does the electric utility act to address consumer feedback or complaints? Yes/no: Are all charges and possible penalties transparently described as part of a consumer's electric bill? Scale: What is the relative burden of penalties associated with late or missing payments? Yes/no: Does the burden of penalties significantly differ across populations served by the utility? Yes/no: Does the cost of electricity relative to household income significantly differ across populations served by the utility? Yes/no: Does the number of brownouts over time differ across populations served by the utility? Yes/no: Are the capital costs prohibitive for different populations to gain access to lower operational costs for electricity provision?
Local community	1, 2, 3, 4, 5	Scale: the extent to which the local community was involved and recognized in the decision to begin operations in an area Yes/no: Is the percentage of the local community that is displaced different by population group in the area? Scale: the extent to which relocation of local community members is involuntary Quantification of the percentage of the workers who reside in the local community and who did not migrate to the local community for employment at the company Quantification of the number of meetings with individual community groups or leaders prior to a company's decision-making that could affect a local community Quantification of the percentage of the resources in an area, including land, used by the company that are owned by members of the local community Yes/no: Does the local community still retain access to raw materials extracted at a site or have access to the final product (electricity) generated at a site? Scale: extent to which the activities of a company either positively or negatively affect the local community's sense of place and cultural heritage Quantification of the health and safety impacts on local community members by the activities of the company Yes/no: Is company information available in all local languages? Yes/no: Is company information easily accessible for local community members? Yes/no: Does the company have and enact policies that show respect for local culture including observance of cultural events? Quantification of the number and duration of protests of the company and the number of protesters that are from the local community
Workers	1, 2, 3, 4, 5	Percentage of labor that is child labor Percentage of labor that is unpaid Yes/no: Are employees paid at known and regular intervals? Yes/no: Are there deductions on employees' wages that were enacted for reasons beyond an employee's control? Quantification of wage gaps by sex, gender, nationality, cultural group, and race Percentage of workers earning a living wage based on their location Percentage of workers earning the legal minimum wage Percentage of workers with benefits such as health insurance Quantification of the number of workplace accidents resulting in injuries or death over a period of time Yes/no: Are appropriate safety education and training provided to employees? Yes/no: Is the appropriate safety equipment for workers' activities consistently available and accessible to employees? Yes/no: Do workers have the right to unionize? Yes/no: Are employees unionized? Quantification of the average and maximum numbers of hours worked per week by workers at different levels Quantification of the number of holidays and other paid time off available to workers annually Yes/no: Are workers free to end their employment and not tied by debt to a company, lack of mobility, monopoly of employment in the region by the company, or the company holding onto their legal documentation?
Society	1, 2, 3, 4, 5	Yes/no: Is the technology used accessible and affordable to developing countries? Yes/no: Are research and development results disseminated without barriers or monetary charges? Yes/no: Are the companies and actors involved connected to violent conflicts, including war? Yes/no: Have the companies and actors been sued or fined for, or known to be involved in corruption and unethical practices? Scale: What is the extent to which the activities along the life cycle of the electrical energy system have contributed to economic progress for different geographic regions or nations? Yes/no: Are the companies involved promoting the use of low-carbon energy systems over conventional fossil energy systems at their respective stages in the life cycle?

framework for energy justice along the life cycle of electrical energy systems.

2.1. Electricity consumers

The suggested energy justice social LCA indicators for electricity consumers are: (i) whether consumers have a choice in their utility company or in the generation method; (ii) whether consumers have a mechanism to provide feedback; (iii) whether consumers have access to free and objective educational materials about energy use and sources of electrical energy; (iv) whether actions are taken by the utility in response to consumer complaints and feedback; (v) the transparency in electricity bills; (vi) the relative burden of penalties associated with late or missing payments; (vii) whether burdens and penalties significantly differ across populations; (viii) the cost of electricity provision (capital costs and operational costs, separately assessed) relative to household income by population served by the utility; (ix) the reliability of electricity provision to consumers; and (x) whether capital costs are prohibitive for different populations to gain access to lower operational costs for electricity (Table 1). The level of transparency in electricity bills would encompass whether each charge, fee, and penalty is clearly described, and whether the potential penalties for late or skipped payments are defined in the literature included with a customer's bill. The consumer complaints would be assessed as the number of complaints per number of customers at a given time, and whether there is a significant difference in the percentage between consumers of the same electric utility by socioeconomic status, geographic area of electricity service, or race. The reliability of electricity provision would be assessed as the number of unplanned interruptions in electrical service, and whether the percentage of occurrences differs by socioeconomic, racial, or geographic groups of consumers.

The use of these indicators could reveal disproportionate impacts for electricity consumers as utilities and property owners increase their electricity generation from low-carbon sources. In particular, costs and affordability present equity challenges to renewable energy. Conventional energy sources are responsible for the majority of electricity generation within the US – approximately 85% of the over 4 trillion kilowatt-hours generated in 2016 came via non-renewable energy sources (nearly two-thirds from natural gas and coal and roughly 20% from nuclear power) [16]. While innumerable low-income earners struggle to pay fluctuating electricity costs and can be faced with serious budget constraints in maintaining a comfortable standard of living through electricity use in their homes, renewables present a different obstacle. For example, price floors on procuring technologies such as solar panels can make initial affordability, notwithstanding minimal recurring costs, an insurmountable obstacle for the poor. This also presents challenges for non-property owners to pursue solar strategies on the demand side; while property owners do not see a direct financial benefit as they are not typically responsible for recurring monthly energy bills, renters have no incentive to make long-term capital investments in properties that they will never own. For private landlords, making energy-related improvements becomes as an unprofitable proposition, considering 86% of renters pay all or some of their own energy costs (i.e. neither heat nor electricity is paid by the landlord) (EIA, 2013). Equitable adoption and just implementation of new energy technology and systems require recognition of the unique characteristics and needs of people and place [17].

2.2. Local community

The suggested energy justice social LCA indicators for the local community at each life cycle stage for electrical energy systems are: (i) the extent to which the local community was involved and recognized in decisions to begin operations at a site, (ii) whether the percentage of the local community that is displaced differs by population group; (iii) the extent to which relocation is involuntary; (iv) the percentage of the workers that are originally from the local community; (v) the number of meetings with individual community groups or leaders, including indigenous communities, in advance of a company's decision-making that could affect a local community; (vi) the percentage of the ownership of resources used by the company that are members of the local community; (vii) whether the local community still has access to raw materials extracted at the site or to the final product of electricity delivered by a company; (viii) whether the activities of a company affect the local community's sense of place; (ix) whether the health and safety of local community members are affected by the activities of the company; (x) whether company information is available in all local languages; (xi) whether company information is accessible for local community members; (xii) whether a company shows evidence of respect for local culture including observance of cultural events; and (xiii) the number and duration of protests of the company's activities or practices and the number of protesters that are from the local community (Table 1).

One of the most commonly assessed metrics in energy justice studies involves the disproportionate burdens of different groups due to their proximity to electricity generation sources or industrial sites and their associated pollution [18]. This issue would be addressed across the life cycle for the local community stakeholder category in the proposed social LCA framework. For example, in an energy justice-focused social LCA of electricity from coal, the potential disproportionate impacts on separate local communities near a coal mine, along the railways on which coal is transported, surrounding a coal-fired power plant, and adjacent to the coal ash management site would be included in the analysis. Another common theme in justice studies is the local community's access to raw materials or to the final product created at a site, which covers both sovereignty over the resources accessed by the company and ownership of the means of production. This would also be assessed as part of this methodology.

Deploying new renewable energy systems may disturb or enhance the emotional bond that people in a local community have to a site. The bond is considered place attachment, in which where the environment helps form the identity of an individual [19]. One study used surveys to assess the potential disruption to place attachment in two villages near the world's first commercial-scale tidal turbine, Seagen, installed in Northern Ireland in April 2008 [19]. Both populations supported the development of the technology, and there was a positive relation with place attachment and acceptance of the project [19]. This example of a positive social impact on a local community reinforces that social LCA must not only focus on negative social impacts, but also encompass any potentially positive social impacts [20].

However, renewable energy development can also oppose existing relationships with the land. The local community, including local indigenous communities, may not be appropriately integrated into the planning for new renewable energy and their land and traditions may be negatively affected by subsequent development. An example of this involves wind farms on historically significant indigenous land within the United States. On May 11, 2012, the official approval for the construction of the Ocotillo Wind Energy Facility on public land was signed. This land is sacred to the Quechan, Kumeyaay, and Cocopah Nations. The stories and songs of Creation and other traditions document the importance of the Coyote Mountain to the Quechan Tribe. The land also holds cultural significance as it houses historic artifacts and cremation and burial grounds [21]. The siting of this project creates injustice for the indigenous communities by going against their cultural way of life to continue energy generation for the benefit of those outside of the tribe.

The Quechan Tribe fought to address this injustice by filing a lawsuit to stop the project. They claimed the U.S. Department of Interior violated the California Desert Conservation Area plan because under it the land is considered sacred and protected [21]. The land has the potential to fall under the National Register of Historic Places, but the artifacts, prehistoric trails, and burial sites will be destroyed if construction continues. The Department of the Interior already claimed the

Coyote Mountains Wilderness Area as an archaeological site and for the historic presence of the Quechan Tribe of the Fort Yama Indian Reservation [21]. Even with this argument, the tribe's requests for additional surveys and their concern to protect their cultural resources and put a stop on the construction was disregarded [21]. By January 2014, the 112-turbine wind farm within 10,151 acres of public land was completed and operating [22]. The injustice of this action not only dismissed Quechan Tribe's cultural beliefs but also their voice. For these communities, the burden goes beyond the physical transformation of the land.

As in the Quechan case, the sites chosen for the implementation of renewable energy technologies may be suitable geographically because they are appropriate for the generation of electricity, but they may interfere with aesthetics for local landowners, economic interests, or the cultural values of indigenous communities. These issues may hinder the progress and ultimately end a project due to the opposition from local community stakeholders. In order to complete a project while promoting energy justice, it is essential for companies to recognize the stakeholders at risk and engage with them early on so they may consider their advice and concerns. An example of a productive strategy that included multiple stakeholders in the decision-making process is the tidal energy project in Cobscook Bay by Ocean Renewable Power Company (ORPC) [23]. Their first step was reaching out to the fishermen in the local community. This stakeholder group could be affected by the site of deployment because it might restrict navigation and take up prominent fishing spots at the bottom of the bay [23]. ORPC organized group meetings with the Cobscook Bay Fishermen's Association and the success of their early relationship is evident by their original proposed site moving to one that the fishermen and the company agreed upon [23]. Working directly with this stakeholder group helped ORPC gain credibility and reach their goal of being present and informative. This is based on their belief that "agencies give permits, communities give permission." They continued this approach by hiring local community members to be spokesmen, holding public meetings, and including updates in the newspaper [23]. This furthered endorsement from community members, fishermen, and the local Native American tribe. Their strategy provided opportunities for ORPC to listen to the local community and be upfront about their development plans.

While there is an overall support for the tidal energy project, some fishermen still have concerns. They are worried about the future of their livelihood- How much more space will tidal energy consume? What will happen to the fish? These concerns were heightened when ORPC acquired preliminary permits for an additional area near Cobscook Bay without letting the community know beforehand [23]. This is another important area for the fisherman, and the company initially lost some creditability with this hasty move. The company explained that they pursued these permits so that they could acquire this land before another company that the community did not trust got it [23]. This rebuilt the relationships with most of the community members and fishermen, but this act shows how companies can lose support for development by keeping information from stakeholders. Tidal energy as a renewable energy source is still in the developing stage which means that sites, equipment used, and more will change continuously. Therefore, a company's initiative to communicate the developing tidal energy plans is crucial to gain the stakeholders support. This encourages community engagement which allows company to listen to the concerns of the stakeholders, providing recognition to originally and newly formed groups.

In 1994, US President Bill Clinton signed Executive Order 12898 on Environmental Justice (EO 12898) which directed federal agencies to develop broad strategies to identify and address disproportionate, negative impacts stemming from agency activities and decisions affecting minority and low-income communities. EO 12898 emphasized the need for widespread public participation to tackle both procedural and recognition justice issues concerning the environment, to include activities and decisions by the Department of Energy. An analysis of how federal agencies responded to environmental justice concerns in general, and energy justice related concerns in particular, over two decades of the EO's existence found discouraging results in regards to the extent of public participation in major decisions on everything from siting to transportation routes to waste storage and cleanup [24].

Community engagement is important in large part because the members of local communities may endure negative health effects or safety hazards due to a company's activities.

This is pertinent not only for electrical energy systems that have direct emissions during generation, but also for renewable energy installations. For example, those living near industrial wind turbines may be disproportionately impacted. The hazards of wind turbines are concentrated, while the benefits of the electricity is distributed to people who are not close to the site [25]. Industrial scale wind turbines are affiliated with health effects such as annoyance, stress, and sleep disturbance [26]. A study done by Nissenbaum et al. (2011) found that people in the United States had a worse night's sleep and were more tired throughout the day if they lived within 375–1400 m from the wind farm compared to 3–6.6 km from it [27]. Not getting enough sleep can impair human health. The health effect of annoyance is contributed by the low-frequency noise from the wind turbines. Low-frequency noise is characterized as a humming. It produces pressure in the ear and is associated with vibrations within homes [28]. Also, low-frequency noise is harder to suppress compared to higher frequency noise. Shutting doors and windows only worsens its effects [28]. The World Health Organization (WHO) supports the claim that annoyance is a health effect. The WHO was quoted by saying, "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [26]. Annoyance may not be characterized as a life threatening disease, but it can disrupt a person's mental well-being and degrade their quality of life.

Other potential health and safety concerns exist with renewable energy. For example, geothermal power plants can affect the local community where they are implemented in multiple ways. Amongst the most pronounced environmental and siting impacts include: noise pollution, disruptions to natural hydrothermal manifestations, induced landslides and seismic activity – particularly during the exploration phase – and the potential for land subsidence when water is removed from reservoirs without substitute fluids being reinjected [29]. Other threats include the potential for water pollution, constraints on land use, and induced seismicity [29]. Furthermore, potential impacts on local air quality exist, particularly in open-loop designed systems, in which an assortment of air emissions, including hydrogen sulfide (which ultimately converts to sulfur dioxide), boron, and ammonia, are emitted [30], and though the scale of these emissions are substantially lower than fossil fuel plants, the air pollution exists nonetheless.

Many proponents of renewable energy technology believe that this technology can potentially bring economic benefits which can replace the estimated economic loss that can happen from the transition from fossil fuels to low-carbon energy sources. Globally, renewable energy (including hydropower) has contributed nearly 10 million jobs [31]. The solar and wind industries have also provided a significant number of new jobs [32]. However, the replacement of existing fossil fuel-based electricity with renewable energy may lead to losses in employment for local communities. For example, the Navajo Generating Station, a coal-fired power plant employing over 700 people, is planned to close by the end of 2019 [33]. Lower carbon-emitting sources of electricity, including natural gas and the 27.3-MW Kayenta Solar Project in the same region, will replace its generation [33]. However, fewer jobs will be provided by solar power after the construction phase, and the area will experience fewer employment opportunities in the energy sector. There are gains in employment in mining, manufacturing, transportation, and other stages in the life cycle of these new energy systems, but there are also losses from the industries that they replace. The effects on employment in local communities must be addressed along the life cycle of energy systems.

2.3. Workers

The suggested energy justice social LCA indicators for workers are: (i) the percentage of labor that is child labor; (ii) the percentage of labor that is unpaid or slave labor; (iii) whether workers are paid regularly; (iv) whether wages are docked by the company for reasons beyond a worker's control; (v) whether wage gaps exist by sex, gender, nationality, and race; (vi) the percentage of workers earning a living wage based on their location; (vii) the percentage of workers earning the legal minimum wage based on their location; (viii) the percentage of workers with benefits such as health insurance; (ix) the number of workplace accidents resulting in injuries or death; (x) whether safety education and training is provided to employees; (xi) whether appropriate safety equipment is consistently available and accessible for employees; (xii) whether workers at different life cycle stages have the right to unionize; (xiii) whether workers are unionized; (xiv) the average and maximum numbers of hours worked per week by a single worker at different levels; (xv) the number of holidays and amount of paid time off available to workers each year; and (xvi) whether workers are free to end their employment and not tied by debt to a company, lack of mobility, monopoly of employment in the region by the company, or the company holding onto their passport or other legal documentation (Table 1). For all of these indicators, it is critical to also determine whether the result changes for workers by nationality, race, socioeconomic status, location, and stage along the life cycle of an electrical energy system.

Like fossil fuel-based energy systems, renewable energy systems may also pose challenges to human health at various points along their life cycles, from extraction to service delivery and consumption. Although materials do not have to be consistently mined and provided to a power plant for renewable electricity generation unlike fossil fuel-based electricity generation, materials must still be mined for the infrastructure of renewable energy technologies, which involves safety concerns for workers at the raw material extraction life cycle stage. The mining, quarrying, and oil and gas extraction industry had the third highest worker fatality rate in the US, according to the Bureau of Labor Statistics' 2015 Census of Fatal Occupational Injuries [34]. Furthermore, the Occupational Safety and Health Administration recognizes the assortment of work related hazards and toxic exposures that are endemic to green collar jobs, specifically related to energy production and delivery [35]. For example, the renewable energy industry leaves workers in industrial settings susceptible to a host of injuries including falls, burns and electrical shocks, along with respiratory issues, depending on the type of energy source [35].

Since 2008, photovoltaics manufacturing has shifted from the United States, Europe, and Japan to China, Malaysia, the Philippines and Taiwan. More than 60% of the world's photovoltaics are manufactured in China [36]. The growth of solar manufacturing in these countries has lead not only to manufacturing jobs, but also higher paying jobs in research and development [31]. However, the countries that produce the most photovoltaics, are also the ones that do the least to protect their workers and pay the lowest wages. As Fthenakis et al. summarized, photovoltaics contain some hazardous materials that have potential occupational health impacts which depend on the level of toxicity and explosiveness of certain gases [37].

As jobs in renewable energy have increased, so too has representation of women workers. According to the International Renewable Energy Agency (IRENA), women represent 35% of the renewable workforce, which is greater than the traditional energy sector, but still lower than the broader economy [31]. Further, women are less likely to be in management or technical positions and experience discrimination in pay equity, earning less than men in the same position [31]. These potentially disproportionate impacts by gender must be addressed along the life cycle of renewable electricity systems.

2.4. Society

The suggested energy justice social LCA indicators for society are: (i) whether the companies involved are within a sector and geographic region that are linked to conflicts, including war; (ii) the contribution to economic progress for a geographic region or nation; (iii) whether the companies have been sued or fined for corruption and unethical practices; (iv) open-source dissemination of research and development results and technological advances; and (v) whether the companies involved are promoting the use of low-carbon energy systems over conventional fossil energy systems at their respective stages in the life cycle of an electrical energy system (Table 1).

The decrease in greenhouse gas emissions made possible by companies along the life cycle of renewable energy systems leads to a positive impact to society. The promotion and continued development of more sustainable technology can also be a positive impact to society. However, if new technologies and research and development results are not accessible to certain groups, such as developing countries or the poor in a given nation, a justice issue emerges. When progressive transition to clean energy has been observed in most of developed countries, many developing countries still have to strive against their fragilities in many institutional aspects. Existing networks and coordination among energy-related stakeholders at the national level is believed to be the crucial condition to achieve success in the development of renewable energy technology [38].

A review by Urmee et al. compiled different issues in the implementation of renewable energy in developing countries in Asia and the Pacific [39]. Those issues were classified into three main categories of barrier which are economic, policy, and institutional [39]. The economic barriers include the high capital cost of renewable energy technology, limited availability of financing, and lack of subsidies, which make the progress of renewable energy project in developing countries highly dependent on foreign investment [39]. The policy barriers include lack of legal framework, inappropriate use of subsidies, and unrealistic political commitment [39]. Furthermore, low institutional capacity and technical knowledge fall into the category of institutional barrier [39]. The obstacles of who holds knowledge and the accessibility and cost of this knowledge for renewable energy deployment can lead to disproportionate impacts to global society, in which some countries gain the benefits of low-cost and low-emission electricity production more quickly and with less difficulty than others. The lack of a legal framework and prevention or deterrence of bribery in some regions may also lead to new avenues of exploitation and corruption as the energy transition progresses.

The social LCA framework can also address the hidden impacts to society from raw material extraction in the life cycle of a renewable energy system. For example, lithium-ion batteries that are often paired with solar photovoltaics for energy storage and used in electronic equipment contain a substantial amount of cobalt [40]. The majority of the world's cobalt supply is mined in the Democratic Republic of the Congo, where resource extraction is often linked to corruption, violence, and child labor [41]. An increase in cobalt price or demand as a result of increasing penetration of renewable energy storage globally could further empower actors involved in these practices in the Democratic Republic of the Congo, worsening social conditions for that nation.

3. Potential applications

The social LCA framework for energy justice can be used to assess new energy installations, potential substitutions of energy systems as society transitions towards renewable energy sources, and areas for improvement along the life cycle of existing energy systems from a cradle-to-grave perspective on energy justice concerns. New energy installations could be designed and sited to minimize injustices along the life cycle by performing a social LCA for energy justice. Suppliers, materials, and manufacturing practices could be selected based on minimizing injustice across the life cycle of an energy system. This could be applied in the design of a new energy system or in making improvements to current systems. Performing energy justice-focused social LCAs could contribute to both the life cycle management and corporate social responsibility goals of companies in the energy industry.

The framework can also be used to compare utility companies by their relative social impacts across their life cycles in addition to their other metrics such as their environmental impacts. The results of an energy justice-focused social LCA could be utilized by companies for marketing to consumers who are concerned about the hidden impacts of their choices on others, and for marketing to other companies that are aiming for corporate social responsibility across their supply chains.

In addition, sustainable energy organizations or programs could utilize this framework for planning, implementation, and assessment. For example, Washington DC's Sustainable Energy Utility (DC SEU), which operates under within the DC Department of Energy and Environment (DOEE), could assess its implemented programs and plan future programs using the energy justice-focused social LCA model. The DC SEU provides technical guidance and support, promotes renewable energy financial incentives, and leads green jobs programs centered on broader energy efficiency and conservation goals [42]. Teron and Ekoh previously considered the DC SEU's potential as an energy democracy, and in doing so have recognized its attention to several life cycle stages that are also included in this proposed energy justice-focused social LCA framework, most prominently manufacturing and power generation [42]. Moreover, it is evident that the four stakeholder categories are considered within power generation through the activities of the DC SEU. All five energy system life cycle stages at least tangentially engage both local and societal stakeholders considering the DOEE's broader mission of resource conservation, pollution mitigation, and promoting renewable energy. There are considerable areas for workers to be further infused into the framework of the DC SEU's planning and assessment, beyond its considerable focus on the local workforce and towards workers at all life cycle stages. The green jobs program plays a principal piece in its overall strategy – including city resident hiring preferences, wage floors that were significantly ahead of the city's minimum wage for years, and technical job training, including solar installation [42]. However, due to the absolutely local focus of its mission, attention to workers beyond the local geographic and temporal boundaries, at different points of the life cycle continuum (e.g. at the extraction stage) are absent. The sustainability considerations in the social sphere could be enhanced by assessing programs from a life cycle approach for their energy justice impacts.

Across potential applications, the net effects on social justice emerging from a substitution of one electricity source for another in a given location can be assessed across the entire life cycle instead of only at the electricity generation stage using the proposed framework. For example, the net social justice impacts across the life cycle could be measured for a transition in which a peaking oil-fired power plant is decommissioned as solar photovoltaics with battery storage are installed to help meet the electricity demand that would otherwise have been met by the oil-fired power plant. The energy justice social LCA framework would take into account the net effects of this transition across life cycle stages and across the stakeholder categories (Table 2). In this example, the potential social impacts associated with the decommissioning of the oil-fired power plant should be investigated across its life cycle, followed by the impacts associated with the replacement of this electricity generation with solar panels and utility-scale battery storage. With more detailed information, the net effects can be subsequently assessed at each life cycle stage and for each stakeholder, which can ultimately be aggregated to net overall effects on energy justice.

Table 2
Example results matrix for a social LCA with a focus on energy justice. The matrix would be populated with a +, −, or * to indicate overall positive social justice, overall negative social justice, or mixed results, respectively, for each stakeholder category at each life cycle stage of an electrical energy system. n/a = not applicable.

Life cycle stages → Stakeholders ↓	Raw material extraction and processing (RE)	Manufacturing (M)	Electrical power generation (PG)	Transportation and distribution (TD)	Waste management (WM)	Total across the life cycle
Electricity consumers (1)	n/a	n/a	Σ PG1	Σ TD1	n/a	Σ PG1 + Σ TD1
Local community (2)	Σ RE2	Σ M2	Σ PG2	Σ TD2	Σ WM2	Σ RE2 + Σ M2 + Σ PG2 + Σ TD2 + Σ WM2
Workers (3)	Σ RE3	Σ M3	Σ PG3	Σ TD3	Σ WM3	Σ RE3 + Σ M3 + Σ PG3 + Σ TD3 + Σ WM3
Society (4)	Σ RE4	Σ M4	Σ PG4	Σ TD4	Σ WM4	Σ RE4 + Σ M4 + Σ PG4 + Σ TD4 + Σ WM4

4. Limitations and challenges

The aggregation of social justice indicator measurements for each combination of life cycle stage and stakeholder may be a complicated process due to several factors. First, each life cycle stage may involve multiple inputs or companies. For example, raw material extraction for an oil-fired power plant involves not only the continuous extraction of crude oil, but also the original extraction of raw materials for the infrastructure of the power plant. The social impacts associated with the activities of different companies in various locations and with practices that may have disparate impacts on multiple communities would all be combined into this single life cycle stage of raw material extraction and processing, unless a practitioner or researcher opts to divide this life cycle stage into multiple subcategories. This combination of inputs is depicted in the matrix in Table 2 by the summation symbols which denote that more than one measurement is considered in each entry.

Notwithstanding the barriers to obtaining more just, transparent and democratic energy regimes, social LCA enables a more equitable energy paradigm. There are several attributes that must inform its adoption; transparency across the industry sector is foremost amongst these features. It is critical that companies and affiliates are forthcoming with relevant data concerning a host of areas that would supplement information from other stakeholder groups and further indicators. This will allow for better information and analysis related to areas such as costs, policy directives such as siting decisions, and worker health and safety, that are not readily apparent or accessible from the outside. However, certain classes of industry data are proprietary, thus obscuring potential impacts. For example, exemptions that the Energy Policy Act of 2005 gave to hydraulic fracturing have shielded firms from having to comply with various environmental controls, including the National Environmental Policy Act, the Safe Drinking Water Act and the Clean Water Act. For information that is not publicly available, research must proceed with cooperation from a company and its affiliates in collecting relevant data.

Data collection across the life cycle may be difficult and ultimately less comprehensive for certain combinations of life cycle stages and stakeholder groups. The social LCA framework requires the identification of the companies, sites, and actors involved in the procurement of electricity from a particular energy system through all of its life cycle stages back to its "cradle" of raw materials extraction. Data must be accessed and collected at various points along the energy system life cycle, thus presenting a set of challenges to implementing social LCA. Although primary data provides higher quality for a social LCA, social hotspots databases may be necessary for proxy data if some actors along the complex life cycle of an electrical energy system are unable or unwilling to contribute primary data. The use of social hotspots databases may help to fill in data gaps, but it may not represent actual social justice conditions. For existing energy systems with infrastructure that was constructed decades ago, efforts towards data collection on the social impacts associated with the raw material extraction and processing, transportation, and construction of the infrastructure might not yield sufficient information. Some companies may no longer exist, and some existing companies may choose not to share data that can assist in measuring social impacts.

Direct access to workers and community members for interviews is also pertinent, in order for respondents to have confidence in the process and the ability to act anonymously, with the ultimate goal of workers and community members acting without fear of reprisal. On this note, sensitive information such as safety protocols and exposures, as well as other personally identifying information, that could affect respondents' livelihoods, including insurability and employment prospects, should be guarded through strict research protocols.

There are also challenges associated with quantifying (and qualifying) procedural justice and recognition on the local community scale. For example, development projects may adhere to best practices and meet legal obligations such as holding community meetings at appropriate times and environmental impact assessments associated with a particular project may be robust, but mere compliance may obscure basic realities such as the lack of faith that a community has in processes, thus limiting public participation and buy-in.

In a social LCA, suggested indicators should not be used individually to conclude a positive or negative social impact from an energy system, but the full range of suggested indicators for a stakeholder category should be addressed instead in order to prevent misinterpretation. For example, while electric consumers may have a choice in utility company or generation methods, without accompanying consumer education and knowledge, the practical implications of choice can be contested. However, even if the full range of indicators for each stakeholder category is addressed in a social LCA, it is possible for certain effects to be neglected due to their difficulty in quantifying or attributing to the suggested indicators. Chronic health effects or higher probabilities of health issues that emerge long after employment, or that can be exacerbated by other factors such as lifestyle and diet, would not be easily determined through a social LCA framework.

An associated difficulty is that the indicators assessed with each combination of stakeholder group and life cycle stage are a mixture of quantitative, semi-quantitative, and qualitative measurements (Table 1), for which the effects cannot be directly summed or quantified. Furthermore, certain aspects may be deemed more severe than others, or to have widespread impacts on more people or for a longer duration than others. This complexity provides a practitioner or researcher the flexibility to develop more detailed methodology for assessing the life cycle social justice of an energy system on a case-by-case basis. In general, a prudent approach is to complete a matrix such as the one in Table 2 with symbols such as +, −, and * to communicate overall positive, negative, or mixed results, respectively, for social justice impacts by stakeholder group and by life cycle stage. If a transition between energy systems is assessed, then the net social justice effects from decommissioning one system and implementing another system would be depicted.

Finally, in assessing social LCA for the stakeholder category of society, analysis must be careful in evaluating intra-society disparities related to access and affordability, both within developed and developing nations. While technologies can be affordable for and accessible to elites, those same technologies may not penetrate low-income populations. The same indicators should be assessed for different populations whenever possible to reveal whether justice issues emerge from the activities along the life cycle of an electrical energy system.

These challenges in conducting a social LCA focused on energy justice and in obtaining data along the life cycle should not limit the advancement of this methodology. Social LCAs are increasingly being performed to address social impacts beyond a single site or industrial stage [43]. In fact, social LCAs have recently been performed for electrical energy systems [10,11], which provides a precedent for moving forward with an energy justice framework for social LCA of electrical energy systems.

5. Concluding remarks

It is critical that energy justice play a substantive role in the energy transition. Considering that this transition is likely to be reliant on infrastructure and industry of a grand magnitude and a political economy that is not dissimilar than the status quo, with the transition's potential integral features mirroring the conventional energy in size and scope, the likelihood of replication of unjust paradigms exist if sufficient attention is not a central focus. Social LCA can play a responsible role in informing the energy transition by categorizing, qualifying, and quantifying justice considerations at numerous points along the life cycle and across the stakeholder spectrum. This comprehensive approach broadens the lens through which potential disproportionate social impacts are discovered, while mirroring the life cycle approach that has become standard for assessing the environmental impacts of systems.

The energy justice-focused social LCA framework can provide a means of evaluation for researchers and regulators and a planning tool for energy project developers. A social LCA framework for assessing justice issues along the life cycle of electrical energy systems offers the opportunity to compare potential energy justice concerns as we transition towards low-carbon energy sources and debate the implementation of new technologies.

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