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Metrics for Decision-Making in Energy Justice

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Abstract

Energy equity and justice have become priority considerations for policymakers, practitioners, and scholars alike. To ensure that energy equity is incorporated into actual decisions and analysis, it is necessary to design, use, and continually improve energy equity metrics. In this article, we review the literature and practices surrounding such metrics. We present a working definition for energy justice and equity, and connect them to both criteria for and frameworks of metrics. We then present a large sampling of energy equity metrics, including those focused on vulnerability, wealth creation, energy poverty, life cycle, and comparative country-level dynamics. We conclude with a discussion of the limitations, gaps, and trade-offs associated with these various metrics and their interactions thereof.

Contents

1. INTRODUCTION

Inequities associated with energy systems are pervasive and long standing. Production inequities manifest in exposure to air and water pollution near polluting energy facilities; consumption inequities include disparate access to energy services. While these issues are ubiquitous across the world, it is routinely the same groups who bear the burden of these disparities and lack access to the benefits. In the United States, for example, racial-ethnic minorities are significantly more likely to face exposure to fine particulate air pollution (1) and other criteria air pollutants (2) due to proximity to major roadways, industrial facilities, agricultural operations, and energy production operations. Low-income households and households of color are significantly more likely to experience conditions of energy poverty, including being unable to adequately heat or cool their homes as well as avoid utility disconnection (3–7).

In the international context, countries with advanced economies have traditionally benefited from more energy infrastructure compared to those with developing economies. There is a large gap in energy access (8), electrification of productive uses (9), and energy consumption per capita (10) between developed and developing countries; however, all countries are expected to ensure and finance the transition to decarbonization. Moreover, those who are most disadvantaged are less frequently engaged in decision-making processes about energy infrastructure siting, development, and alternative energy futures (11).

While these findings relate to historic and ongoing inequities, scholarship on the current energy transition toward a decarbonized future has raised concerns about scenarios in which these issues are not addressed, and perhaps exacerbated (12–15). In a recent review article that assessed 20 years of literature on low-carbon energy transitions, Sovacool (14) found that the "victims" (i.e., those who lose) of low-carbon energy production operations across the world are often host communities, disadvantaged households, the rural poor, individuals from Indigenous groups, and ethnic and racial minorities, among other sociodemographic groups. Certain sociodemographic populations are routinely not granted access to clean energy technologies and the corresponding government subsidies, and thus these populations cannot benefit from such wealth-generating opportunities (16–18).

To tackle these challenges, it is necessary to have appropriately designed metrics—that is, quantities that are measured—to identify vulnerable populations; design and analyze possible policy, technology, and business solutions; and monitor and evaluate the outcomes of such efforts (19–23). Metrics need to account for historic trends and enable forward-looking analysis; be granular enough to provide information on human impacts; be inclusive in design and use of disadvantaged communities; and be user-friendly in a way that enables a range of stakeholders to engage in discussion and evaluation, among other conditions. These metrics must also account for energy justice factors to help yield just decision-making outcomes and meet energy justice demands moving forward. The task of identifying and constructing such metrics, thus, is immense.

In this article, we review the current state of the art and discuss gaps, trade-offs, and data requirements. We focus on energy justice and equity as a key component of environmental justice, and as an emerging field that will benefit from a synthesizing review that lays out what exists and clearly identifies the holes in the literature. Such information will be valuable to scholars as well as government officials and practitioners who are working on energy justice initiatives around the world.

We begin in Section 2 by defining the dimensions of energy justice and what it means to be vulnerable in the energy justice domain. We then turn to a discussion about energy justice metric frameworks in Section 3. In Section 4, we present a suite of metrics and put each one in context. We conclude with a discussion about challenges, including trade-offs, limitations, and gaps in our understanding and use of energy justice metrics.

Energy justice: the pursuit of equity and minimalization of disparities across individuals and groups in all aspects of energy systems, markets, and operations

Energy justice tenets: the three tenets include (*a*) distributional justice, the way that benefits and burdens are distributed across groups; (*b*) procedural justice, who is involved in and leading the decision-making processes; and (*c*) recognition justice, an understanding of past and present disparities within energy systems and the root causes thereof

2. FOUNDATIONS OF ENERGY JUSTICE

2.1. Conceptual Theories of Energy Justice

Energy and environmental justice are inherently linked. Environmental justice resulted from the need to address unequally distributed exposure to air and other pollution and environmental risks (24, 25), which disproportionately burden minority and low-income communities. In the United States, environmental justice was catapulted into the national debate in 1982 when civil rights activists in North Carolina protested contaminated soil being disposed in a landfill in Warren County, a county with the highest proportion of African Americans in the state (24, 26). Energy justice builds on the environmental justice movement to address the inequities that stem from energy systems and related extractive economies that span multiple sectors. These inequities are associated with different commonly invoked energy justice tenets: procedural, distributional, and recognitional.

Procedural energy justice is primarily concerned with asking whether the processes, including policy-making, are fair (13, 27). The focus is on rules and participation. One key to achieving a just and fair energy system is ensuring that disadvantaged and underserved communities participate in or lead decision-making processes. This may involve having control over the types of energy end-use systems adopted in the community (e.g., gas furnace or heat pump) and participating in the design of energy programs (e.g., rate pricing, energy assistance programs). Another example of considerations in procedural equity is the degree to which clean energy industries are inclusive of underrepresented populations in their workforces and leadership.

Distributional energy justice is concerned with how the benefits and burdens of the energy transition are allocated across groups. For example, some of the burdens of a shifting gas system include the risk of methane leaks, risk of job loss following decommissioning, and the costs of the transition and technology adoption. Benefits can include reducing air pollution emissions, increasing security of energy supply, providing access to clean and efficient energy technologies, and increasing job access through new technology deployment. Often the distribution of the benefits and burdens stems from power plant and infrastructure siting and the associated exposure to pollutants (28), technology design, and rate design (29). Distributional justice also relates to who benefits from the economic and financial systems created around new energy infrastructure. As we make evident below, metrics for evaluating energy justice tend to focus most often on the distributional lens given the easier quantification of distributional measures vis-à-vis other measures.

The objective of recognitional energy justice is acknowledging and fully considering the needs of social groups that have been marginalized and disadvantaged as a consequence of past systemic injustices; furthermore, recognitional energy justice provides opportunities for these groups in the form of reparations. Previous work on the production of electricity has focused on the unfair location of power plants in the vicinity of ethnic minorities or Indigenous peoples, who are often excluded from decision-making and not provided agency to advocate for their own rights and needs, including clean air and water. In the context of the clean energy transition, these communities may be further burdened by new energy developments and decisions, or may benefit if recognition is given its place.

Energy equity, rooted in the principles of energy justice, upholds the goal of achieving an equitable energy future that integrates justice principles, fairness, and social equity into energy systems, energy decision-making, and energy transitions. As a direct outcome, achieving energy equity leads to improved well-being and reduced community vulnerability.

2.2. Who Is Vulnerable?

Vulnerability is a state of being susceptible to harm from exposure to environmental, social, and economic change (e.g., climate change or energy market shifts), and without the ability or capacity to adapt (30–32). Vulnerability is shaped by changes in the elements of socioecological resilience, the autonomy of self-organization, and the ability to prepare and respond to shocks (8, 13, 30, 33). In general, one can define vulnerability as a combination of exposure, sensitivity, and adaptive capacity (30). Exposure is the degree to which a system experiences environmental or sociopolitical stress. Sensitivity is how a system is modified or affected by exposure and, in particular, an accounting of who and what is particularly susceptible to the adverse effects of exposure. Adaptive capacity is the ability of a system to evolve, cope, and build resilience to environmental hazards or policy change.

There are similarities and differences in how energy vulnerabilities and inequities manifest intranationally and internationally. Intranationally, energy vulnerable populations are most typically based on income (8, 33, 34); other variables include gender, disability (34), age, family dynamics (35), geographical location, or race (8) and immigration status. Internationally, income is again prevalent, but other variables include energy dependency (8) and energy access.

3. CRITERIA AND FRAMEWORKS FOR DECISION-FOCUSED ENERGY EQUITY METRICS

In this review, we focus on decision-relevant metrics, the primary goal of which is to inform and evaluate decisions. More specifically, we focus on metrics to understand, account for, and track the justice and equity implications of current and future energy decisions, including specific projects, policies, regulations, research, and investments, as well as their outcomes as they translate from source to end-use. In this section, we discuss criteria and frameworks for developing such metrics.

Identifying and correcting systemic inequalities requires (*a*) equality of access (e.g., eliminating systemic barriers to receiving benefits) and (*b*) equality of capability (e.g., having access to opportunity and means to receive the benefits), as argued by Nussbaum & Sen (36). Metrics can help correct systemic inequalities by identifying important features and developing standards, such that actions can be informed and geared toward meaningfully improving the quality of life as well as monitoring its evolutions.

Metrics and their variations (e.g., indices referring to combinations of metrics; indicators aimed at assessing forward movement) help measure or evaluate things and allow for comparison across space and time. Unless the metric itself embodies meaningful energy justice tenets (e.g., distributional, recognition, or procedural measures), it can be misleading or undermine just decision-making outcomes. For example, income is often used as a placeholder for marginalization; however, wealth is often more relevant for financial marginalization, and income alone may not reveal the true level of need. Similarly, research found that racial composition was a predictor of the length of the blackouts in Texas in 2021, while income was not (37). In both of these cases, results based only on income might lead to the conclusion that there is no inequity, whereas the broader analysis indicates there is. Indices, which incorporate several metrics, can also fail to support just decision-making practices if the index's embedded metrics are misweighted or fail to integrate important equity factors.

Energy equity metrics: measures and tools used to assess energy equity, i.e., (*a*) individual metrics that are specific and focused on one aspect of well-being; (*b*) specifically defined indices with specific weights over specific individual metrics, and (*c*) user-defined indices and mapping tools with user-defined weights over specific individual metrics; there are also conceptual frameworks that can be used to design specific or user-defined indices

3.1. Criteria and Categories for Metrics

There is a robust literature on criteria for metrics. Kenney et al. (38) lay out a set of design criteria for climate indicators: inclusion of sectors that have mature literature and reflect views of importance from stakeholders; justification by a transparent conceptual model; a documented relationship with the topic of interest; correspondence to an area of national interest; and relevance to users. Similarly, Feng & Joung (39) discuss principles for good indicators, including being (*a*) measurable, (*b*) relevant and comprehensive, (*c*) understandable and meaningful, (*d*) manageable, (*e*) reliable, (*f*) cost-effective, and (*g*) timely.

Building on this, we propose a set of criteria for energy equity metrics that we employ in the present analysis. Metrics should be decision-relevant; grounded in the preferences of vulnerable and marginalized communities; understandable; and measurable, even if qualitatively. Moreover, sets of metrics used to inform decisions should be comprehensive enough to address key questions for key groups, yet manageable enough to be realistically used (39).

Decision relevance, in the context of ecosystem service science, has been defined as "effectively predicting the impacts of specific decisions. . .across beneficiary groups" (40, p. 161). In climate science, decision-relevant metrics are those that "are both actionable for practitioners as well as tractable for modelers" (41, p. 1579). We focus on the category of decision for which a metric is predictive and actionable. Drawing on the Initiative for Energy Justice (IEJ) (**https://iejusa.org**), we consider decisions relevant to identifying populations that can benefit from equity actions and also assessment of programs and policies, both retrospectively and prospectively. We build on the category of investment decision-making, combining it with planning and siting. As discussed in

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Section 4 and shown in **Supplemental Table 1**, some metrics may have relevance in more than one category. Finally, some metrics may not be directly decision-relevant but, rather, aimed at assessing energy systems in order to influence the design of future policies and programs.

In terms of comprehensiveness, one can classify energy equity metrics according to five categories.

1. **Tenets of equity and justice**: These include distributional, recognition, and procedural as discussed in Section 2. Of importance is the need to go beyond distributional, the most common type of metric.
2. **Spatial and temporal**: An important aspect is scale. The scale of energy justice analysis has implications for effective metrics. Injustice occurs at local (e.g., family and community livelihood), national, and global spatial scales (33). The metric must match the scale of the system analysis to facilitate just outcomes. Temporal considerations include the degree to which historic wrongs are considered and whether impacts are in the near term or longer term.
3. **Sectoral:** The energy system contains numerous sectors, including electricity, transportation, and industrial applications, among others.
4. **Impacts on people:** The energy system can impact the well-being of people in a variety of ways, both negative and positive. These impacts can be financial (e.g., energy burden, wealth creation, shut-offs); physical (e.g., air and water pollution, environmental degradation, safety); technical (e.g., access, supply, reliability); or cultural/psychological, where psychological is at the individual level and cultural is at a societal or community level, and relates to autonomy and decision-making agency. There are important impacts at the intersections of these categories, and multiple ways these categories can impact quality of life. Most importantly, all of the categories above can have impacts on human health.
5. **Life cycle**: Energy injustices can be committed not only at the point of adoption of an energy technology or the end-use but also throughout the full life cycle of technologies or services. Metrics like research and development, mining, conversion, transportation, generation, and waste should be included throughout the life cycle and through all levels of workforce and business development, investment capacity, and government contracts (42).

A key distinction is whether a metric is used for retrospective or prospective analysis. Retrospectively, they can be used to evaluate past policies, regulations, and actions, including insights that can help identify future trends and clarify the systemic effects previous actions have had on present day systems (43). Prospectively, metrics can be used in models and what-if scenarios, as well as in forecasting. Of particular importance are energy equity metrics that can be used to evaluate net-zero pathways and the actions needed to get there (19). Some integrated assessment models (IAMs), an influential class of models that combine climate, economic, and energy system models in order to assess and inform policy, have included metrics for income inequality, but there is a lack of metrics relevant to other dimensions of energy equity (20). Finally, metrics can help decision-makers generate creative alternatives—once it is clear what is important, it is easier to develop alternatives that specifically address those issues (44).

3.2. Frameworks for Decision-Focused Metrics

Scholars have proposed different frameworks to support decision-making through appropriate metrics. Here we present a selected summary of these frameworks.

One example of a framework for developing decision-relevant metrics is value-focused thinking (45). This framework elicits values from stakeholders, whereby values are defined as the "principles used for evaluation. . .to evaluate consequences of action or inaction" (45, p. 6). For example, Baker et al. (46) found that stakeholder values in Ghana around electrification included aspects such as cost, reliability, local air pollution, and safety. The framework operationalizes the values by stating them as directional goals, such as "minimize local air pollution." Finally, what Keeney calls attributes are derived from objectives; these are the actual measures and what we are calling metrics. For example, the objective to "minimize local air pollution" might be measured in terms of pounds of sulfur per kilowatt hour of generation in a given year. This framework provides a set of metrics for evaluating decisions. The values, objectives, and metrics can be used in a variety of ways to support decision-making; to generate creative alternatives (44); in mathematical models that evaluate alternatives based on how well the outcomes match preferences; or to understand how a system has been performing in the past. This framework has been used in the energy realm in a top-down expert-based analysis of energy efficiency (47), to structure the energy objectives of West Germany (48), and to develop a value hierarchy for Ghana around energy access (46).

This framework is particularly useful when applied to energy equity, since this is a complex multidimensional concept that elicits input from affected stakeholder communities. This framework is decision-centric and category-neutral; it will include the categories of energy equity discussed above to the degree that the decision-makers find these important.

There are numerous prospective frameworks centered around energy justice explicitly. The Initiative for Energy Justice (2021) adapts and applies a framework focusing on three categories of purpose for equity metrics (49): (*a*) "Target population identification"; (*b*) "Investment decision-making"; and (*c*) "Program impact assessment." Ford et al. (50) conceptualize the progression of processes that comprises the energy transformation process, from source to end-use to disposal, including the three categories of purpose across the progression (**Figure 1**). This proposed framework, which adopts elements from Gorman & Dzombak (51), Lu et al. (52), and the OECD (53), suggests the need to capture the energy system broadly through its life cycle while identifying the population impacted at each stage, documenting the benefits of policy interventions and evaluating investments that can enhance relevant capabilities. The life cycle of the energy system can be

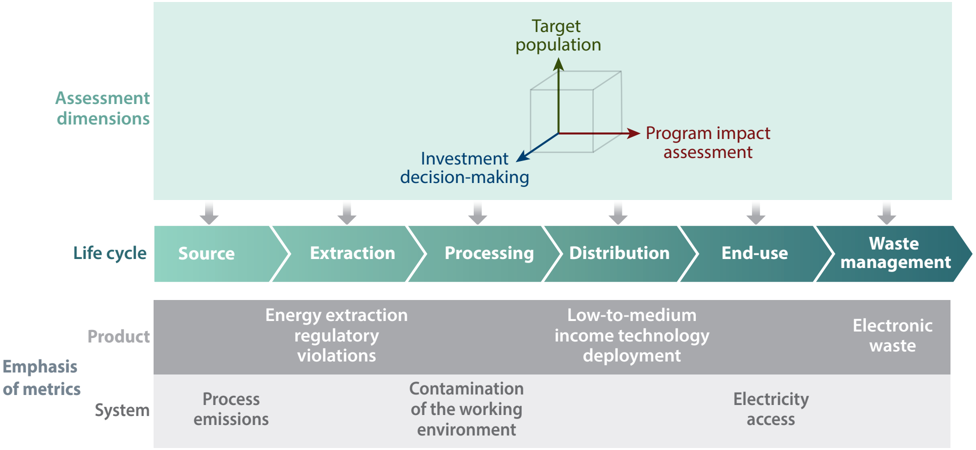

Figure 1

Energy spectrum in need of metrics. This figure provides a stylized depiction of a life cycle of an energy system, from source to waste management, and the areas that require probing for equity advancement. These areas include the impacted population, investments and their decision-making process, and assessment of the impact of a given intervention. Figure adapted with permission from Reference 50.

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captured at a product level and at a system level, and **Figure 1** provides examples of metrics that could be used at different stages of the life cycle (**see Supplemental Table 1** for a more detailed listing of metrics).

Frameworks that map to justice tenets can take different points of reference. For example, Romero-Lankao & Nobler (23), on the basis of Litman (54), Van Dort et al. (55), and Karpouzoglou et al. (56), introduce an approach that considers five justice tenets (distributional, procedural, recognition, plus cosmopolitan and restorative) across four stages: identify factors that lead to inequalities; enhance factors that foster communities' capabilities; codevelop adaptive and inclusive governance and policy systems; and evaluate and monitor performance. Although this framework is aimed at the transportation sector, their work documents a breadth of useful examples that can be equally applicable to multiple sectors and processes addressing inequities.

Other frameworks, such as the Energy Equity Project (57, p. 29), adopt a point of reference from the decision-making bodies' perspective to develop "equity measurement, reporting, and tracking that drives clean energy investment and impact for BIPOC and frontline communities." Similar to other frameworks, common justice tenets (e.g., distributional, procedural, recognition, restorative) are employed and broken down into indices and metrics across energy efficiency and clean energy programs, but it is done among utilities, state regulatory agencies, and other practitioners in the energy space.

A potential enhancement to the frameworks above is to apply the perspective of systemic equity (see **Figure 2**), which argues that to be comprehensive across justice tenets, metrics must either explicitly acknowledge which core concepts are not addressed or coalesce with complementary metrics to meet each of the three core justice tenets (e.g., an apt index that addresses distributional, procedural, and recognition equity). This perspective augments the other frameworks by identifying the problems as follows: In cases where only two of the three core concepts are addressed, ostensible (i.e., where distributional and procedural aspects are addressed, but recognition is ineffective), aspirational (i.e., where procedural and recognitional aspects are addressed, but

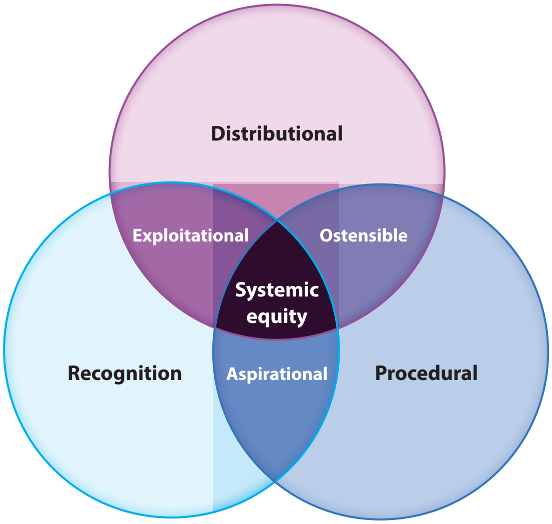

Figure 2

The equity concepts that must be achieved to meet systemic equity (i.e., distributional, recognition, and procedural equity), including terms associated with the ineffective addressing of equity (i.e., ostensible, aspirational, and exploitational equity). Figure adapted from Reference 58 (CC BY 4.0).

distribution is ineffective), or exploitational (i.e., where recognitional and distributional factors are addressed, but procedures are ineffective) outcomes will manifest. It is unlikely a single metric will effectively address all of these dimensions simultaneously.

The frameworks above have different strengths and weaknesses, and they are not necessarily mutually exclusive. In selecting and using a metric, one should evaluate each potential metric according to the assigned objectives, with careful attention to how they will satisfy the criteria presented above.

4. ENERGY JUSTICE METRICS

In this section, we provide a sample of metrics that can be used in energy decision-making. We use the term "metrics" broadly, to refer to a progression of measures and tools used to assess energy equity. First, there are individual metrics, which are specific and focused on one aspect of well-being. Second, there are specifically defined indices, which have specific weights over specific individual metrics. Third, there are user-defined indices and mapping tools, which have user-defined weights over specific individual metrics. Fourth, there are conceptual frameworks that can be used to design specific or user-defined indices: They identify categories of individual metrics to be combined.

We begin with a discussion of environmental justice metrics since environmental justice is a core foundation to the energy justice field. For each example metric that we discuss, we relate it back to key criteria in **Supplemental Table 1**.

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4.1. Existing Environmental Justice Metrics

Foundational studies on environmental injustice have demonstrated that various environmental disamenities (e.g., industrial pollution sources, contaminated sites) are disproportionately located in communities of color and low-income communities (24, 59). In domestic contexts, these studies typically examine patterns within a specific city, state, or region, and the standard approach is to investigate either the correlation between an outcome and a demographic characteristic or the proximity of an outcome to a specific community—in both cases, controlling for factors that might confound these relationships. One might track the siting of new infrastructure, the localized pollution that infrastructure may produce, and the sociodemographic populations in the surrounding area that would experience that pollution. In international contexts, studies may consider the flow of environmental disamenities across jurisdictional boundaries from more to less affluent countries (e.g., trade in hazardous waste, or pollution spillovers).

This empirical literature, combined with pressure from environmental justice advocates and public policies such as Executive Order 12898, has provided impetus for government agencies to begin to consider race, income, and other factors in their environmental decision-making. To facilitate such consideration, agencies have developed metrics to help identify environmental injustice.

A key example is EJScreen (60), an environmental justice screening and mapping tool. Tools such as this provide user-specified visualizations of metrics and indices, to support analysis and decision-making, and thus can themselves be considered a version of an index. EJScreen includes demographic indicators (e.g., people of color, low-income linguistic isolation), environmental indicators (e.g., air quality, cancer, and respiratory risk), and environmental justice indexes that combine demographic attributes with individual environmental factors. EJScreen presents the information in an interactive map form at the census tract level with comparisons to state or national percentiles. Recent updates to EJScreen have expanded its indicators to include measures of health disparities, climate risks, and critical service gaps (e.g., broadband, food access, and medical services).

Certain sensitivities and limitations of these types of tools are worth noting, since they carry over to the energy justice domain as well. First, the underlying datasets and the way they are weighted put greater emphasis on certain aspects (e.g., urban versus rural areas). Second, national and state percentile approaches can influence whether communities or populations are compared against local jurisdictions or national populations. Third, the use of thresholds determines what portion of populations are identified as being the most underserved or vulnerable.

Many US states have developed similar environmental justice screening and mapping tools. Some rely on demographic indicators to identify vulnerable communities, whereas others include environmental, health, and climate indicators (61). Several of these state-level tools use indexes that combine environmental indicators, enabling consideration of the cumulative impacts of multiple burdens. Combining indicators across environmental media, often measured at different geographical scales or on different time horizons, is complicated, but reflects that many communities simultaneously experience more than one burden.

To date, the manner in which these environmental justice screening and mapping tools are used varies. The tools are used internally by agencies to inform regulatory decision-making, permitting decisions, and enforcement priorities, and more formally to support laws that require agencies to take into account vulnerable populations in decision-making (62). For instance, the state of New Jersey enacted a permitting law in 2020 that provides metrics for identifying overburdened communities based on the percentage of low-income households, minority residents or members of a state recognized tribal community, or households with limited English proficiency.

4.2. Energy Justice Vulnerability Indices

The lessons from and experiences with environmental justice screening and mapping tools, as well as the underlying metrics, have informed a recent effort by the US federal government to develop a new mapping index, the Climate and Economic Justice Screening Tool (CEJST) (60), to support the implementation of the Biden Administration's Justice40 Initiative. The CEJST, still in beta form, incorporates several pollution-related datasets from EJScreen as well as climate change–related natural hazard risks to identify disadvantaged communities, but uses only a single metric specific to energy justice—energy burden.

Beyond mapping tools, there are a variety of ways to quantify and identify vulnerable communities in terms of exposure, sensitivity, and adaptive capacity. These fall under the fourth category defined above of conceptual frameworks. There are no predefined metrics for these concepts; rather, they are user-specified, depending on the situation or case for which the user seeks to measure vulnerability. For example, a measure of exposure may be the incidence of fuel poverty or the increase in the price of energy and thus consumer bills; the measure of sensitivity may be the sociodemographic groups that are most prone to experiencing fuel poverty; and the adaptive capacity is a measure of government assistance to help those households that experience such fuel poverty.

Several scholars have devised vulnerability scores relating to energy systems and justice. All of these combine individual metrics of exposure and sensitivity—some also include adaptive capacity as well, though researchers note that this is harder to measure—usually through a series of calculations to derive multiplicative estimates of impacts. One study proposes a vulnerability scoring metric that assesses the vulnerability to price shocks associated with energy policy interventions and compares across counties. It incorporates three variables, including energy price increases as the measure of exposure, specific sociodemographics as the measures of sensitivity, and weatherization and low-income bill assistance programs as the measure of adaptive capacity (63). The end result is a score for each county in the United States, allowing the identification of vulnerable counties. In other studies, scholars calculate the vulnerability of communities to employment and economic decline from the closure of fossil fuel operations (64–66).

Similarly, in the international context, scholars have introduced the Global Energy Vulnerability Index, which combines metrics about a country's energy intensity, carbon emissions, and degree of reliance on energy resources into a composite indicator that can be used for both identification of vulnerable regions and comparison across regions (31).

Vulnerability indices can be used in a variety of contexts, to evaluate prospective policies or to help policymakers and other organizations target their resources to communities or households most in need. For example, a vulnerability measure may be useful in siting decisions, to determine if impactful infrastructure is being sited in particularly vulnerable areas. Such measures are, thus, highly adaptable. The trade-off, however, is that the high degree of complexity may limit the manageability and replicability of the vulnerability scores and introduces subjectivity in the weighting of various elements within the vulnerability calculations.

4.3. Consumer Energy Metrics

Designing effective programs and policies for reducing energy poverty in vulnerable groups requires identifying who is energy poor, measuring the degree to which they are experiencing energy poverty, and identifying the underlying causes leading to energy poverty. Energy poverty is defined as the lack of access to physical energy technologies and modern energy, or financial resources required to consume energy at a desired level (67). Closely related concepts include fuel poverty, which is defined as the inability to afford adequate energy services and sufficiently warm or cool one's home (68), and energy insecurity, which is when a household is unable to meet its energy needs.

All of these are related to energy access, a multidimensional concept that involves five facets: supply (technology availability in the region), reliability (consistency of supply), quantity (number of appliances that can be used in the home), quality (if electricity is supplied at proper frequency), and affordability (whether a household has the ability to pay for a desired level of energy consumption). Inability to satisfy energy needs in one of the five facets can lead to a household experiencing energy poverty (68).

In the Global North, energy discussions often focus on affordability and, thus, energy burden, energy insecurity, and fuel poverty dominate the discussion (69). Metrics most often used in such contexts include simple measures of electricity access (e.g., the percent of households with access to modern sources of energy), rates of new household electrification, or total amount of electricity consumed per household. More complex metrics include the energy development index used by the International Energy Agency (70), which includes measures of the percentage of the population with access to electricity, commercial energy consumption per capita, and commercial share of energy use.

Energy insecurity is multidimensional and based on the interplay between physical housing infrastructure, household energy expenses, and behavioral responses to financial strain (69, 71, 72). The most commonly used metric for energy insecurity is the energy burden indicator. Energy burden is defined as the percent of income a household spends on satisfying their energy needs (5). A high energy burden of 6%, or a severe energy burden of 10% or more, is cause for concern in households (7). The U.S. Department of Energy tracks energy burden in their public-facing Low-Income Energy Affordability Data (LEAD) tool (73).

Clear distinctions on the type of income (i.e., pretax or post-tax) used to calculate energy burden metrics are important, because these will paint a different picture of energy poverty within a region. Another downfall of this metric is that it may miss whether households live in uncomfortable temperatures or engage in risky coping strategies to keep themselves warm or cool.

Other increasingly common, though more difficult to track, metrics of energy insecurity include whether a household reports struggling to pay an energy bill, receiving a notice for utility disconnection or being disconnected, whether a household has to forgo paying energy bills for other necessary expenses such as food or health care, and whether a household carries utility debt. These measures are typically gathered via household surveys, such as the Residential Energy Consumption Survey (74), the American Housing Survey (75), or the Pulse Survey (76), and have been used in empirical studies on energy insecurity (e.g., 4).

Energy deficits present themselves in households that underconsume energy and restrict energy use (77). A complete energy deficit is present when a household is disconnected by their energy service provider due to nonpayment. A partial deficit can stem from economic concerns and behavioral adaptations. Households that forgo energy consumption to pay for other necessities are exhibiting energy limiting behavior. If the energy deficit or energy limiting behavior is severe, this can lead households to put themselves at risk of heat-related illness or death (3, 78). One metric for measuring partial energy deficits in households is the energy equity gap (3), which measures the outdoor temperatures at which households turn on their cooling or heating units.

In summary, aggregate indicators can be used to identify abnormalities in behavior, spending patterns, and consumption habits. Highly aggregated indicators related to energy poverty may not be sufficient because impacts on individuals may be masked and may miss some who self-identify as energy poor. When possible, data at the household level and individuals' self-identified behavior should be used. Effective programs and policies will identify multiple forms of energy poverty and assess its underlying causes. Impactful analyses will combine individual metrics of exposure, vulnerability, and sensitivity to derive multiple estimates of impacts and injustices.

4.4. Wealth Creation, Ownership, Autonomy

Many metrics focus on avoiding harms, such as pollution or energy burden. Another important aspect of the energy system is its potential for wealth generation. For example, energy companies continue to be some of the richest in the world, but this wealth is concentrated in relatively few hands. An important question is whether a reimagined low-carbon energy system can change the distribution of wealth and generate wealth for traditionally marginalized communities. Wealth generation can be divided into two parts: resulting directly from business models around ownership of energy assets and resulting from access to energy. Closely related to wealth generation and procedural justice is community and individual autonomy: having a voice in energy decision-making. Owners and others with direct stakes, for example, are automatically key stakeholders; thus, understanding and improving ownership in the energy system among marginalized communities is important.

The distribution of ownership of energy assets is understudied, especially with regard to income and race (79). For example, Semieniuk et al. (80) note that the network of ownership of fossil-fuel assets is not well understood. They focus on the ownership of transition risk, but the flip side of this is ownership of assets. They find that this ownership is highly concentrated in wealthy economies and within wealthy sectors of those economies. Crago & Rong (81) examine financial returns to household solar and find that these vary systematically between owned and leased systems. Sunter et al. (18) measure rooftop photovoltaic (PV) deployment, relative to the average rooftop PV adoption of all census tracts in each state, and find that, even accounting for income and home-ownership, Black and Hispanic majority census tracts have significantly less deployment. O'Shaughnessy et al. (82) define two metrics to understand patterns of solar adoption: (*a*) adopter income bias, the difference between adopter incomes and county median household incomes, and (*b*) low-to-moderate income (LMI) solar PV penetration rate. These authors measure the number of LMI households that adopted PV as a proportion of the number of owner-occupied LMI households in a given zip code, without differentiating between owning or leasing a system. In transportation, ownership and investment equity have been inferred through observed mode shares (83).

Another way to approach ownership is to consider rebate policies. For example, Guo & Kontou (84) study the Gini coefficient and Suits index for clean vehicle rebates in California. Rebates may make ownership viable for LMI individuals. They find, however, that there are disparities in the adoption of electric vehicles across income and among disadvantaged communities.

For most of these metrics on ownership, income is by far the most common vulnerability considered, with a few emerging metrics that consider race or ethnicity. These metrics are primarily relevant to the design of adoption policies and useful for regulators in assessing and designing programs. Even though they are related to ownership, the focus is more distributional.

There are fewer metrics that are focused primarily on recognition justice. Fortier et al. (85) suggest, when looking at extractive resources, measuring the percentage of the ownership of resources by local community members. Community acceptance rating (86), a numeric representation of community satisfaction, could be a useful energy justice metric if it is focused on marginalized communities, or separates results by demographics. A commonly used metric is investment-generated jobs (87). To the degree that an accurate and meaningful assessment is possible, this metric could be useful for local communities and for the design of policies aimed at inducing investment. An interesting metric suggested by Sovacool & Mukherjee (88) is number of annual protests related to energy, which could represent recognition justice if it is tied to marginalized communities or to organizations who represent them. This metric has been used to understand the relationship between tactics and outcomes and to evaluate the sustainability of energy projects (89, 90). These metrics are focused on siting decisions, and may be relevant to a number of different stakeholders, including the communities themselves.

Metrics related to both ownership and recognition are top-down measures designed by researchers with intention to elucidate inequities, but there appears to be little interaction with members of marginalized communities in the design and use of these metrics. Although many of the metrics in this section are reproducible in theory, actually gathering and accessing the data is likely to be a challenge for all. Some metrics are highly localized or context specific and may require highly intensive data collection such as interviews, surveys, or focus groups.

Another set of metrics in this category are specifically related to procedural justice and individual autonomy. The IEJ 100 report lists numerous metrics, including metrics related to representation on advisory and decision-making bodies (i.e., diversity of planning organization boards); community engagement (i.e., percent of actions with prior consent from Indigenous communities), funding for participation of marginalized communities; and impact (i.e., percent of community recommendations that were meaningfully incorporated into final energy rules, policies, or decisions). Metrics such as these seem to be mostly lacking in the academic literature, potentially due to challenges of collecting reliable and reproducible data, and in some cases even measuring the effect. For example, the last metric provides significant challenges if there are diverse communities with different recommendations. These metrics are primarily relevant to planning and, in particular, to designing processes for ensuring fair representation.

4.5. Multiscalar Supply Chain Inequities

Beyond the direct impacts of energy generation and use, there are many impacts across the stages of the energy system, starting at extraction and ending with final waste streams (see **Figure 1**). Many of these impacts are hidden from society, and many of them are borne out of a different place than where the energy commodities and services are actually consumed; however, there are ways to monitor and track them through various metrics. We provide example metrics and discuss their implications at three life-cycle stages: mining, processing, and refinement; manufacturing and factory pollution; and waste. The metrics themselves, such as those involving environmental performance or workplace safety, can be equity-neutral, but when combined with demographics to account for who faces these burdens or risks, they become equity metrics. Studies on energy projects, such as Sovacool's (14), find that vulnerable populations are most intensively exposed to hazards, pollution, and risks.

Mining, metals, and materials extraction and processing are important to low-carbon transitions but remain hidden within most environmental and social assessments. Although the literature on mining and its negative impacts on sustainability is vast, with many different decision frameworks and metrics, much of it is devoid of context and done without synthesis (91–93) or an eye toward energy and climate justice.

Mineral extraction connects to land disruption, dust, air pollution, water pollution, chemical and hazardous waste generation, and occupational safety that may compromise some populations more than others. One can further subdivide extraction into phases of exploration, operations, and closure, all of which involve their own set of equity dimensions and corresponding metrics. Although the list of metrics is extensive (92, 94–97), we highlight some of the most commonly used metrics that have strong equity implications. Regulatory violations, such as the number of annual violations of environmental or social statutes, can represent energy equity if they are correlated with harmed or marginalized communities; frequency rate and severity of accidents in the energy supply chain can as well, when associated with race or ethnicity and income. An important metric in the Global South is child labor, such as the percent of child labor in the supply chain.

Processes related to the manufacturing of energy systems involve inequities that cut across technical, social, and environmental dimensions, with a particular focus on occupational hazards. Grappling with inequities at the manufacturing stage can be difficult because it transcends different levels of a system, including the supply chain, the company, the factory, the production or assembly line, the work cell, or even a machine tool or particular process (39, 98). Example manufacturing metrics from more extensive lists (14, 52, 97, 99) include working and employment conditions, industrial process emissions such as tons of methane, and chemical contamination of the working environment such as the release of heavy metals in the air or water. The latter two metrics align with both traditional environmental justice frameworks and energy justice.

A third domain encompasses waste flows (e.g., waste sent for incineration, landfilling, discharge, e-waste, and nuclear or hazardous waste) as well as recycling and the afterlives of energy systems. Many streams of waste involve significant degrees of pollution and toxins, including some of the most hazardous forms of waste known to humankind (i.e., dioxins, carcinogens). Waste has a number of global impacts (97), and waste incineration has the most negative externalities in the energy supply chain, even more than coal (100). All energy technologies, including the most carbon-friendly, such as household solar panels, electric vehicles, and smart meters, generate large waste streams (92).

Some examples of specific metrics within the waste stream include landfill waste, waste incineration, electronic waste, nuclear waste, and mass recyclability. Although these metrics do not, by themselves, have equity implications, when combined with geographic and sociodemographic data, they can assess disparate incidence of waste across populations.

Circular economic principles could help to guide these three life-cycle stages, and their associated metrics, toward more symbiotic benefits in energy, environmental, and equity outcomes. Several metrics and methodologies are used for circular economic decision support as well (e.g., water footprint, embodied energy, emergy, exergy, and ecological footprints) (101).

Many of these metrics are specific to workers in the energy supply chain; some are relevant to local communities. Most are around physical impacts, such as health and safety. Child labor encompasses cultural and psychological well-being as well. These metrics can be used by regulators to improve conditions in the supply chain, firms to improve working conditions, local communities to inform activism, and energy researchers to inform the direction of research to aim for less destructive processes and materials. These metrics, when combined with geographic and sociodemographic data, primarily reflect distributional justice; measuring and accounting for child labor may be a form of recognition justice. Procedural justice is again rare but is represented in the measurement of regulatory violations; this metric can be used to revisit regulations and their implementation.

4.6. Comparative Country-Level Metrics

Comparing energy policy approaches across countries or jurisdictions is a useful way to identify equity leaders across the globe or to consider how countries may align, or not. Several studies have devised conceptual framework metrics that quantify and track country-level energy justice and equity efforts, and these same measures can be used for other geographic units as well. Current studies have used these metrics either to conduct comparative analysis across different country contexts or to serve as energy decision tools within a country in a way that allows the user to account for a set of trade-offs.

One metric, the Trilemma Index, is produced annually by the World Energy Council (102). This index combines energy security, energy equity, and environmental sustainability and can serve as a decision-making tool, helping countries balance across the three dimensions, and as a way to compare countries in their ability to achieve all three of these dimensions. Energy security refers to a country's ability to meet the energy demands of their current and future citizens, and to withstand energy system shocks. Energy equity refers to the country's ability to provide full access to sustainable, reliable, and affordable energy. Environmental sustainability refers to a country's actions on climate change mitigation and environmental preservation. Each country is ranked along these three dimensions with the highest score corresponding to the best energy system performance. Some scholars have noted the possible subjectivity of the scoring and proposed approaches to improve the weighting scheme behind the scores (103).

Heffron et al. (104, 105) have devised and tested what they call the energy justice metric, which combines a different trilemma: economics, politics, and environment. For each element, it categorizes all related costs and benefits for both present and future generations and creates a ternary plot of the scores. Such scores can serve as a decision-making tool for individual decisions, or a metric to compare justice and equity efforts across jurisdictions such as countries.

The Human Development Index is commonly used for intercountry comparisons and is essentially an international version of a vulnerability index that provides details on where vulnerable populations reside. This index encompasses income inequality, income level, political environment, and access to electricity metrics to evaluate how socio-techno-ecological factors (e.g., good governance) will affect human development (106). The Sustainable Development Index augments the Human Development Index by incorporating ecological metrics for carbon emissions and planetary boundaries in an effort to correct overweighting of gross domestic product growth (107). There are other index developments of this kind and it is anticipated that this evolution will continue. Nevertheless, the promotion of human development is important to energy justice since it helps to ensure equitable access to clean and modern technologies.

Scholars have long generated Lorenz curves and calculated their Gini coefficients to measure inequality of income or wealth. In the energy domain, researchers have adapted the Lorenz curve and Gini coefficient to measure electricity access and consumption inequality across income groups within countries, and then compared the resulting estimates across countries and over time (108).

All of these metrics are decision-relevant, typically used to target jurisdictions or for program evaluation, and account for a range of distributive, procedural, and recognition justice elements, depending on what the user decides to use as inputs. They are understandable, though with some inherent limitations due to the subjectivity of some of the scoring and the complexity of the indices, and they offer the opportunity for both spatial and temporal analysis that can be applied across sectors.

5. CHALLENGES

We identify three categories of challenges in the design, use, and availability of energy equity metrics. First, there are gaps in existing metrics in regards to sectors, dimensions of justice, decision-making, and well-being categories. Second, there are inherent trade-offs in the design and application of metrics. Third, populating metrics with meaningful data introduces user challenges. We address each in turn.

5.1. Gaps

The most commonly addressed justice tenet that we found in our review of equity measures was distributional, with fewer procedural and recognition metrics. Metrics addressing procedural justice were primarily defined in the gray literature, in projects and frameworks, and less so in the academic literature. Procedural justice presents a significant challenge in that it is highly context-dependent, making it difficult to compare across projects, communities, or energy systems. One direction for future work is to explore how to collect data on procedural justice in efficient and replicable ways, perhaps employing natural language processing or other techniques that account for voice, participation, inclusion, and substantive engagement. In terms of recognition justice, identifying marginalized or vulnerable communities based on outside interpretation can be fraught; ideally, communities would self-identify. Moreover, there may be fundamental challenges in cases where more than one vulnerable community is involved and these communities have different preferences.

A gap that presents a particular challenge is the creation of a feedback loop with vulnerable communities when designing energy policies and programs. Ideally, communities would help define and prioritize metrics as well as populate them, and then validate that benefits were actually received.

In terms of impacts on people, the category that is least well-represented is cultural and psychological impacts. There are a few overarching metrics, such as vulnerability indices or the Trilemma Index, that may or may not reflect cultural and psychological well-being. There are a few, primarily in the gray literature, that expressly recognize Indigenous culture. However, explicit recognition of cultural impacts of the energy system appear, based on our search, to be rare in academic literature, highlighting a need for greater inclusion of Indigenous knowledge.

The scope and scale of many existing models is a challenge for implementing equity metrics. Global IAMs, for example, have little ability to integrate or produce metrics of intranational inequality; even less so of procedural or recognition justice.

5.2. Trade-Offs in Designing and Applying Metrics

The choice and use of metrics requires making a number of trade-offs among the choice of metrics; whether to employ a simpler or a more complex metric; and whether to prioritize reproducibility, flexibility, user-friendliness, or other criteria. Here, we consider additional trade-offs that one may confront when employing energy equity metrics.

Justice and equity issues are multidimensional, requiring either complex metrics or a collection of metrics to fully capture the many dimensions. For example, while the energy burden metric provides useful information about how much a household spends on their energy bill, it does not give a complete picture of energy poverty: It does not reveal who must bear particularly hot or cold living conditions, who must face the decision of whether to "heat or eat," and who has been disconnected from service provision and living in the dark.

Another trade-off is inherent in the difficulty of balancing subjective and objective information when populating metrics and indices. Many of the composite metrics that we discussed above, such as vulnerability scores, screening tools, and comparative country-level trilemma indices, must be user-populated with the "right" data and with weightings.

This trade-off between subjective and objective measurement also reveals the challenge of exactly who builds, uses, and controls various metrics. The quality of an analysis depends not only on the quality of the measurement, but also on the quality of the analyst who uses it and the degree to which the analyst understands the dimensions of the underlying equity challenge.

The user also chooses exactly which topics, and thus metrics, to include in their analyses, and which to exclude. For example, retiring fossil fuel power plants and associated air pollution emissions can improve environmental health, but there may be a loss of local jobs with possible effects on energy bill affordability. When analyzing the decision to close such a plant, should an analyst include all of these dimensions?

5.3. Populating Metrics

The data used to populate and calculate metrics are vital. Here, we highlight several challenges with acquiring and populating metrics. First, it is often necessary to include other factors besides energy that influence energy equity, such as in the case of energy poverty. An inclusive and holistic metric analysis should include household factors required to pay for energy bills, such as rent payments and taxes (109), and not just mere measures of energy bill payments. Energy poverty stems from both a lack of resources to meet basic energy needs, and—if resources are present—then a lack of the capability to use a desired level of energy to support well-being (110).

Second, to capture energy equity metrics, the microscale data collection must cover a broad regional area to allow for latitudinal comparisons. Specifically, these metrics should be able to identify which subgroups are the most afflicted by different types of energy inequities and how the degree of energy inequity has changed over time. This broad area will allow for an understanding of how the distribution of resources varies by region and demographic groups and for an investigation of the trade-offs different groups make.

In some country contexts, however, collecting data at the microscale is not feasible. For example, in remote villages that are off grid there may not be smart meters available to collect daily or hourly energy usage. In households without electricity connections, or with prepaid energy meters, there will be uncertainty regarding the level of unmet or latent demand that arose due to financial concerns (111, 112). Hourly data are useful for measuring behavioral shifts following procedural changes [i.e., COVID-19 mandates (113) or electrification policies], and climatic and employment shifts over time (3).

Third, another limitation and challenge in data collection is acquiring information about the lived experiences, such as those that pertain to quality of life and psychology. To be inclusive of equity aspects that are particularly important but understudied (e.g., more qualitative measures such as quality of participation in decision-making; quality of life due to living in thermal comfort) requires some form of measurement of these aspects, yet these items are inherently difficult to measure. Metrics that indicate how quality of life and well-being change over time often require individual interaction (e.g., interviews or survey work), which can be time-consuming, expensive, subjective, or hard to replicate. Some of these limitations can be overcome with sustained and consistent funding and others with a system that prioritizes relationship building and acknowledges the time required to do so.

Overcoming these limitations is vital because a set of inclusive metrics and microscale data can facilitate the evaluation of energy justice. Without diverse metrics and tools, numerous households and communities may remain suffering energy inequities and miss the needed support to overcome systemic barriers.

6. CONCLUSION

In this article, we have presented a review of energy equity and justice metrics that can be used to evaluate the progress of a jurisdiction's energy transition and offered insights on the limitations of these metrics and avenues for further development. Here, we offer a few concluding thoughts about the value of a focus on metrics for assessing equity and justice of systems and transitions.

First, it is important to measure what matters. If planners omit key quality of life indicators, for example, then those conditions that affect quality of life are unlikely to be addressed and mitigated. Second, evaluation tools (e.g., modeling tools) and evaluation systems are only as good as the metrics that serve as the inputs. Without metrics that account for equity, equality, and justice, the models that we use for planning will not account for or illuminate potential injustices. Finally, while there are some things that are difficult to measure (e.g., happiness), this article has covered a suite of metrics that can be evaluated to determine and assess energy system impacts on well-being. For a set of metrics to be high-quality, one must establish standards, such as (*a*) a focus on collecting data at the local level (i.e., the microscale); (*b*) investments in infrastructure to support the techniques for collecting and processing information about the population (e.g., surveys, smart meter data); and (*c*) a commitment to populating a variety of metrics to compare different aspects of energy justice. Energy planners should strive to achieve high-quality analysis in multiple categories of metrics and investigate trade-offs among different well-being indicators. Such efforts will provide a greater understanding of key places where injustices persist, and avenues for reducing both present and future inequities.

SUMMARY POINTS

1. This article reviews the current state of the field, corresponding literature on frameworks, and corresponding metrics used across a variety of energy justice topics and tenets.
2. Energy justice metrics are needed to identify disparities, predict vulnerability, design and analyze policy and other solutions, and monitor and evaluate the benefits and burdens that fall on specific populations.
3. There are several challenges facing the design and use of energy justice metrics. First, there are gaps in the energy justice metrics that exist to date, including in specific sectors, along certain dimensions of justice (e.g., procedural justice), in ways in which metrics are tied to decision-making, and within well-being categories. Second, there are inherent trade-offs in the design and application of metrics. Third, populating metrics with meaningful data introduces challenges.

FUTURE ISSUES

1. The literature will benefit from more focused attention on the challenges associated with the design and use of energy justice metrics, including in particular expanding metrics within the procedural justice domain, and introducing standards for using multiple distributional justice metrics.
2. Users of energy justice metrics must understand and acknowledge their trade-offs, and the literature can be more explicit about such trade-offs.
3. More data are needed to meaningfully address several energy justice challenges, since the measures and metrics are only as good as the underlying data.

DISCLOSURE STATEMENT

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LITERATURE CITED

1. Tessum CW, Paolella DA, Chambliss SE, Apte JS, Hill JD, Marshall JD. 2021. $PM_{2.5}$ polluters disproportionately and systemically affect people of color in the United States. *Sci. Adv.* 7(18):eabf4491
2. Liu J, Clark LP, Bechle MJ, Hajat A, Kim S-Y, et al. 2021. Disparities in air pollution exposure in the United States by race/ethnicity and income, 1990–2010. *Environ. Health Perspect.* 129(12):127005
3. Cong S, Nock D, Qiu YL, Xing B. 2022. Unveiling hidden energy poverty using the energy equity gap. *Nat. Commun.* 13(1):2456
4. Memmott T, Carley S, Graff M, Konisky DM. 2021. Sociodemographic disparities in energy insecurity among low-income households before and during the COVID-19 pandemic. *Nat. Energy* 6(2):186–93
5. Brown MA, Soni A, Lapsa MV, Southworth K, Cox M. 2020. High energy burden and low-income energy affordability: conclusions from a literature review. *Prog. Energy* 2(4):042003
6. Dogan E, Madaleno M, Inglesi-Lotz R, Taskin D. 2022. Race and energy poverty: evidence from African-American households. *Energy Econ.* 108:105908
7. Drehobl A, Ross L, Ayala R. 2020. *How high are household energy burdens? An assessment of national metropolitan energy burden across the United States. American Council For An Energy-Efficient Economy*. Rep., ACEEE, Washington, DC
8. Monyei CG, Jenkins K, Serestina V, Adewumi AO. 2018. Examining energy sufficiency and energy mobility in the global south through the energy justice framework. *Energy Policy* 119:68–76
9. Van-Hein Sackey C, Nock D. 2022. The need for agricultural productive uses in the national electrification plan of sub-Saharan African countries—a call to action for Ethiopia. *Environ. Res. Infrastruct. Sustain.* 2(2):023001
10. Grimsby LK. 2011. Securing energy equity. *Energy Policy* 39(11):6912–13

11. Welton S, Eisen JB. 2019. Clean energy justice: charting an emerging agenda. *Harv. Environ. Law Rev.* 43:307–71
12. Carley S, Konisky DM. 2020. The justice and equity implications of the clean energy transition. *Nat. Energy* 5(8):569–77
13. Jenkins K, McCauley D, Heffron R, Stephan H, Rehner R. 2016. Energy justice: a conceptual review. *Energy Res. Soc. Sci.* 11:174–82
14. Sovacool BK. 2021. Who are the victims of low-carbon transitions? Towards a political ecology of climate change mitigation. *Energy Res. Soc. Sci.* 73:101916
15. Allen RC. 2012. Backward into the future: the shift to coal and implications for the next energy transition. *Energy Policy* 50:17–23
16. Borenstein S, Davis LW. 2016. The distributional effects of US clean energy tax credits. *Tax Policy Econ.* 30(1):191–234
17. Reames TG, Reiner MA, Stacey MB. 2018. An incandescent truth: disparities in energy-efficient lighting availability and prices in an urban U.S. county. *Appl. Energy* 218:95–103
18. Sunter DA, Castellanos S, Kammen DM. 2019. Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nat. Sustain.* 2(1):71–76
19. Baker E, Goldstein AP, Azevedo IM. 2021. A perspective on equity implications of net zero energy systems. *Energy Clim. Change* 2:100047
20. Emmerling J, Tavoni M. 2021. Representing inequalities in integrated assessment modeling of climate change. *One Earth* 4(2):177–80
21. Bednar DJ, Reames TG. 2020. Recognition of and response to energy poverty in the United States. *Nat. Energy* 5(6):432–39
22. Nussbaumer P, Bazilian M, Modi V. 2012. Measuring energy poverty: focusing on what matters. *Renew. Sustain. Energy Rev.* 16(1):231–43
23. Romero-Lankao P, Nobler E. 2021. *Energy Justice: Key Concepts and Metrics Relevant to EERE Transportation Projects*. Rep., Natl. Renew. Energy Lab.
24. Mohai P, Pellow D, Roberts JT. 2009. Environmental justice. *Annu. Rev. Environ. Resour.* 34:405–30
25. Bullard RD, Wright BH. 1987. Blacks and the environment. *Humboldt J. Soc. Relat.* 14(1/2):165–84
26. MacGurty EM. 2009. *Transforming Environmentalism: Warren County, PCBS, and the Origins of Environmental Justice*. New Brunswick, NJ: Rutgers Univ. Press
27. Graff M, Carley S, Pirog M. 2019. A review of the environmental policy literature from 2014 to 2017 with a closer look at the energy justice field. *Policy Stud. J.* 47(S1):S17–44
28. Sicotte D. 2010. Some more polluted than others: unequal cumulative industrial hazard burdens in the Philadelphia MSA, USA. *Local Environ.* 15(8):761–74
29. Walker G, Day R. 2012. Fuel poverty as injustice: integrating distribution, recognition and procedure in the struggle for affordable warmth. *Energy Policy* 49:69–75
30. Adger WN. 2006. Vulnerability. *Glob. Environ. Change* 16(3):268–81
31. Gatto A, Busato F. 2020. Energy vulnerability around the world: the global energy vulnerability index (GEVI). *J. Clean. Prod.* 253:118691
32. Bouzarovski S. 2014. Energy poverty in the European Union: landscapes of vulnerability: energy poverty in the European Union. *Wiley Interdiscip. Rev. Energy Environ.* 3(3):276–89
33. Sovacool BK, Hook A, Martiskainen M, Baker L. 2019. The whole systems energy injustice of four European low-carbon transitions. *Glob. Environ. Change* 58:101958
34. Gillard R, Snell C, Bevan M. 2017. Advancing an energy justice perspective of fuel poverty: household vulnerability and domestic retrofit policy in the United Kingdom. *Energy Res. Soc. Sci.* 29:53–61
35. Martiskainen M, Sovacool BK, Lacey-Barnacle M, Hopkins D, Jenkins KEH, et al. 2021. New dimensions of vulnerability to energy and transport poverty. *Joule* 5(1):3–7
36. Nussbaum M, Sen A, eds. 1993. *The Quality of Life*. Oxford, UK: Oxford Univ. Press
37. Carvallo J, Hsu FC, Shah Z, Taneja J. 2021. *Frozen out in Texas: blackouts and inequity*. Field Note, Rockefeller Found., New York
38. Kenney MA, Janetos AC, Gerst MD. 2020. A framework for national climate indicators. *Clim. Change* 163(4):1705–18

39. Feng S, Joung C. 2010. Development overview of sustainable manufacturing metrics. In *Proceedings of the 17th CIRP International Conference on Life Cycle Engineering 2010*, *May 19–21*, *Hefei*, *China*, ed. H-C Zhang, Z Liu, G Liu. Hefei: Univ. Technol. Press
40. Mandle L, Shields-Estrada A, Chaplin-Kramer R, Mitchell MGE, Bremer LL, et al. 2021. Increasing decision relevance of ecosystem service science. *Nat. Sustain* 4(2):161–69
41. Jagannathan K, Jones AD, Ray I. 2021. The making of a metric: co-producing decision-relevant climate science. *Bull. Am. Meteorol. Soc.* 102(8):E1579–90
42. Michener S, O'Neil R, Atcitty S, Jeffers B, Tarekegne B. 2021. *Energy storage for social equity roundtable report*. Rep. PNNL-31964, Pac. Northwest Natl. Lab., U.S. Dep. Energy, Richland, WA. **https://www.pnnl.gov/sites/default/files/media/file/Energy%20Storage%20for%20Social%20Equity%20Roundtable%20Report.pdf**
43. Primc K, Dominko M, Slabe-Erker R. 2021. 30 years of energy and fuel poverty research: a retrospective analysis and future trends. *J. Clean. Prod.* 301:127003
44. Siebert J, Keeney RL. 2015. Creating more and better alternatives for decisions using objectives. *Oper. Res.* 63(5):1144–58
45. Keeney RL. 1992. *Value-Focused Thinking: A Path to Creative Decisionmaking*. Cambridge, MA: Harvard Univ. Press
46. Baker E, Nock D, Levin T, Atarah SA, Afful-Dadzie A, et al. 2021. Who is marginalized in energy justice? Amplifying community leader perspectives of energy transitions in Ghana. *Energy Res. Soc. Sci.* 73:101933
47. Haydt G, Leal V, Dias L. 2013. Uncovering the multiple objectives behind national energy efficiency planning. *Energy Policy* 54:230–39
48. Keeney RL, Renn O, von Winterfeldt D. 1987. Structuring West Germany's energy objectives. *Energy Policy* 15(4):352–62
49. Tarekegne B, Pennell GR, Preziuso DC, O'Neil RS. 2021. *Review of energy equity metrics*. Rep. PNNL-32179, Pac. Northwest Natl. Lab., U.S. Dep. Energy, Richland, WA. **https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-32179.pdf**
50. Ford JC, Castellanos S, Nock D, Djokic D. 2022. *Working group: metrics in energy equity for NSF Energy Equity 2021 Workshop*. Work. Pap., NSF, Alexandria, VA
51. Gorman MR, Dzombak DA. 2018. A review of sustainable mining and resource management: transitioning from the life cycle of the mine to the life cycle of the mineral. *Resour. Conserv. Recycl.* 137:281–91
52. Lu T, Gupta A, Jayal AD, Badurdeen F, Feng SC, et al. 2011. A framework of product and process metrics for sustainable manufacturing. In *Advances in Sustainable Manufacturing*, ed. G Seliger, MMK Khraisheh, IS Jawahir, pp. 333–38. Berlin, Heidelberg: Springer Berlin Heidelberg
53. OECD (Organ. Econ. Co-op. Dev.). 2023. OECD sustainable manufacturing indicators. *Organisation for Economic Co-operation and Development*. **https://www.oecd.org/innovation/green/toolkit/oecdsustainablemanufacturingindicators.htm**
54. Litman T. 2022. *Evaluating transportation equity: guidance for incorporating distributional impacts in transport planning*. Rep., Vic. Transp. Policy Inst., BC
55. Van Dort L, Guthrie A, Fan Y, Baas G. 2019. *Advancing transportation equity: research and practice*. Rep., Univ. Minn., Twin Cities
56. Karpouzoglou T, Dewulf A, Clark J. 2016. Advancing adaptive governance of social-ecological systems through theoretical multiplicity. *Environ. Sci. Policy* 57:1–9
57. MSEAS (Univ. Mich. Sch. Environ. Sustain.). 2022. *Energy Equity Project Report*. Rep., MSEAS, Ann Arbor, Mich. **https://energyequityproject.com/wp-content/uploads/2022/08/220174_EEP_Report_8302022.pdf**
58. Bozeman JF, Nobler E, Nock D. 2022. A path toward systemic equity in life cycle assessment and decision-making: standardizing sociodemographic data practices. *Environ. Eng. Sci.* 39(9):759–69
59. Ringquist EJ. 2005. Assessing evidence of environmental inequities: a meta-analysis. *J. Policy Anal. Manag.* 24(2):223–47
60. U.S. Environ. Prot. Agency. 2014. EJScreen: Environmental Justice Screening and Mapping Tool. *United States Environmental Protection Agency*. **https://www.epa.gov/ejscreen**

61. Konisky D, Gonzalez D, Leatherman K. 2021. *Mapping for environmental justice: an analysis of state level tools*. Rep. Environ. Resil. Inst., Sch. Public Environ. Aff., Univ. Mich., Ann Arbor
62. Lee C. 2020. Another game changer in the making? Lessons from states advancing environmental justice through mapping and cumulative impact strategies. *Environ. Law Rep.* 2021:10676
63. Carley S, Evans TP, Graff M, Konisky DM. 2018. A framework for evaluating geographic disparities in energy transition vulnerability. *Nat. Energy* 3(8):621–27
64. Snyder BF. 2018. Vulnerability to decarbonization in hydrocarbon-intensive counties in the United States: a just transition to avoid post-industrial decay. *Energy Res. Soc. Sci.* 42:34–43
65. Raimi D. 2021. *Mapping the US energy economy to inform transition planning*. Rep. 21–10, Resour. Future, Washington, DC
66. Raimi D, Carley S, Konisky D. 2022. Mapping county-level vulnerability to the energy transition in US fossil fuel communities. *Sci. Rep.* 12(1):15748
67. Pachauri S, Spreng D. 2011. Measuring and monitoring energy poverty. *Energy Policy* 39(12):7497–504
68. Li K, Lloyd B, Liang X-J, Wei Y-M. 2014. Energy poor or fuel poor: What are the differences? *Energy Policy* 68:476–81
69. Hernández D, Yoon L, Simcock N. 2022. Basing "energy justice" on clear terms: assessing key terminology in pursuit of energy justice. *Environ. Justice* 15(3):127–38
70. IEA (Int. Energy Agency). 2010. *Energy poverty: How to make modern energy access universal?* Rep., World Energy Outlook, Paris. **https://iea.blob.core.windows.net/assets/fdbdd604-de2c-4977-8a3f-20f93e68e738/HowtoMakeModernEnergyAccessUniversal.pdf**
71. Graff M, Carley S. 2020. COVID-19 assistance needs to target energy insecurity. *Nat. Energy* 5(5):352–54
72. McGowan F. 2011. Putting energy insecurity into historical context: European responses to the energy crises of the 1970s and 2000s. *Geopolitics* 16(3):486–511
73. State Local Solut. Cent., Off. State Community Energy Progr. 2023. Low-Income Energy Affordability Data (LEAD) Tool. *U.S. Department of Energy*. **https://www.energy.gov/scep/slsc/lead-tool**
74. U.S. Energy Inf. Adm. 2023. Residential Energy Consumption Survey (RECS). *U.S. Energy Information Administration*. **https://www.eia.gov/consumption/residential**
75. U.S. Census Bur. 2023. *American Housing Survey (AHS)*. **https://www.census.gov/programs-surveys/ahs.html**
76. U.S. Census Bur. 2023. Measuring household experiences during the coronavirus pandemic. *United States Census Bureau*, June 7. **https://www.census.gov/data/experimental-data-products/household-pulse-survey.html**
77. Berger T, Höltl A. 2019. Thermal insulation of rental residential housing: Do energy poor households benefit? A case study in Krems, Austria. *Energy Policy* 127:341–49
78. Iverson SA, Gettel A, Bezold CP, Goodin K, McKinney B, et al. 2020. Heat-associated mortality in a hot climate: Maricopa County, Arizona, 2006–2016. *Public Health Rep.* 135(5):631–39
79. McNamara W, Passell H, Montes M, Jeffers R, Gyuk I. 2022. Seeking energy equity through energy storage. *Electr. J.* 35(1):107063
80. Semieniuk G, Holden PB, Mercure J-F, Salas P, Pollitt H, et al. 2022. Stranded fossil-fuel assets translate to major losses for investors in advanced economies. *Nat. Clim. Change* 12(6):532–38
81. Crago C, Rong R. 2022. *Behavioral preferences and contract choice in the residential solar PV market*. SSRN Pap 4088542. **https://ssrn.com/abstract=4088542**
82. O'Shaughnessy E, Barbose G, Wiser R, Forrester S, Darghouth N. 2021. The impact of policies and business models on income equity in rooftop solar adoption. *Nat. Energy* 6(1):84–91
83. SJCOG (San Joaquin Council Gov.). 2011. *2011 Regional Transportation Plan: the future of mobility for San Joaquin County*. Rep., SJCOG, San Joaquin, California. **https://www.ca-ilg.org/sites/main/files/file-attachments/sjcog_rtp.pdf?1383894514**
84. Guo S, Kontou E. 2021. Disparities and equity issues in electric vehicles rebate allocation. *Energy Policy* 154:112291
85. Fortier M-OP, Teron L, Reames TG, Munardy DT, Sullivan BM. 2019. Introduction to evaluating energy justice across the life cycle: a social life cycle assessment approach. *Appl. Energy* 236:211–19

86. Pac. Northwest Natl. Lab. 2021. Metrics for an equitable and just energy system. *Pacific Northwest National Laboratory*. **https://www.pnnl.gov/sites/default/files/media/file/Metrics%20for%20Energy%20Equity_0.pdf**
87. Better Buildings. 2023. Better Buildings Initiative. *United States Department of Energy*. **https://betterbuildingssolutioncenter.energy.gov**
88. Sovacool BK, Mukherjee I. 2011. Conceptualizing and measuring energy security: a synthesized approach. *Energy* 36(8):5343–55
89. Del Bene D, Scheidel A, Temper L. 2018. More dams, more violence? A global analysis on resistances and repression around conflictive dams through co-produced knowledge. *Sustain. Sci.* 13(3):617–33
90. Sovacool BK, Hess DJ, Cantoni R, Lee D, Claire Brisbois M, et al. 2022. Conflicted transitions: exploring the actors, tactics, and outcomes of social opposition against energy infrastructure. *Glob. Environ. Change* 73:102473
91. Petrie J, Cohen B, Stewart M. 2007. Decision support frameworks and metrics for sustainable development of minerals and metals. *Clean Technol. Environ. Policy* 9(2):133–45
92. Sovacool BK, Ali SH, Bazilian M, Radley B, Nemery B, et al. 2020. Sustainable minerals and metals for a low-carbon future. *Science* 367(6473):30–33
93. Lee J, Bazilian M, Sovacool B, Hund K, Jowitt SM, et al. 2020. Reviewing the material and metal security of low-carbon energy transitions. *Renew. Sustain. Energy Rev.* 124:109789
94. Kogel JE, Trivedi N, Herpfer MA. 2014. Measuring sustainable development in industrial minerals mining. *Int. J. Min. Miner. Eng.* 5(1):4
95. Lee J, Bazilian M, Sovacool B, Greene S. 2020. Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains. *Environ. Res. Lett.* 15(10):103009
96. Sovacool BK. 2019. The precarious political economy of cobalt: balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extr. Ind. Soc.* 6(3):915–39
97. Iacovidou E, Velis CA, Purnell P, Zwirner O, Brown A, et al. 2017. Metrics for optimising the multi-dimensional value of resources recovered from waste in a circular economy: a critical review. *J. Clean. Prod.* 166:910–38
98. Reich-Weiser C, Vijayaraghavan A, Dornfeld DA. 2008. Metrics for sustainable manufacturing. In *Proceedings of the ASME 2008 International Manufacturing Science and Engineering Conference*, Vol. 1, pp. 327–35. New York: Am. Soc. Mech. Eng.
99. Kim J, Ryu D, Sovacool BK. 2021. Critically assessing and projecting the frequency, severity, and cost of major energy accidents. *Extr. Ind. Soc.* 8(2):100885
100. Sovacool BK, Kim J, Yang M. 2021. The hidden costs of energy and mobility: a global meta-analysis and research synthesis of electricity and transport externalities. *Energy Res. Soc. Sci.* 72:101885
101. Elia V, Gnoni MG, Tornese F. 2017. Measuring circular economy strategies through index methods: a critical analysis. *J. Clean. Prod.* 142:2741–51
102. World Energy Council. 2021. *World Energy Trilemma Index 2021*. Rep., World Energy Council, London. **https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2021**
103. Song L, Fu Y, Zhou P, Lai KK. 2017. Measuring national energy performance via Energy Trilemma Index: a stochastic multicriteria acceptability analysis. *Energy Econ*. 66:313–19
104. Heffron RJ, McCauley D, Sovacool BK. 2015. Resolving society's energy trilemma through the Energy Justice Metric. *Energy Policy* 87:168–76
105. Heffron RJ, McCauley D, de Rubens GZ. 2018. Balancing the energy trilemma through the Energy Justice Metric. *Appl. Energy* 229:1191–201
106. Sarkodie SA, Adams S. 2020. Electricity access, human development index, governance and income inequality in Sub-Saharan Africa. *Energy Rep*. 6:455–66
107. Hickel J. 2020. The sustainable development index: Measuring the ecological efficiency of human development in the anthropocene. *Ecol. Econ.* 167:106331
108. Jacobson A, Milman AD, Kammen DM. 2005. Letting the (energy) Gini out of the bottle: Lorenz curves of cumulative electricity consumption and Gini coefficients as metrics of energy distribution and equity. *Energy Policy* 33(14):1825–32

109. Scheier E, Kittner N. 2022. A measurement strategy to address disparities across household energy burdens. *Nat. Commun.* 13(1):288
110. Day R, Walker G, Simcock N. 2016. Conceptualising energy use and energy poverty using a capabilities framework. *Energy Policy* 93:255–64
111. Garg S, Attia B, Handler B, Bazilian M. 2022. Demand in the dark: estimating the true scale of unmet electricity demand in Sub-Saharan Africa. *Electr. J.* 35(8):107189
112. Van-Hein Sackey C, Levin T, Nock D. 2022. Latent demand for electricity in sub-Saharan Africa: a review. *Environ. Res. Infrastruct. Sustain.* 2(2):022002
113. Lou J, Qiu Y(L), Ku AL, Nock D, Xing B. 2021. Inequitable and heterogeneous impacts on electricity consumption from COVID-19 mitigation measures. *iScience* 24(11):103231